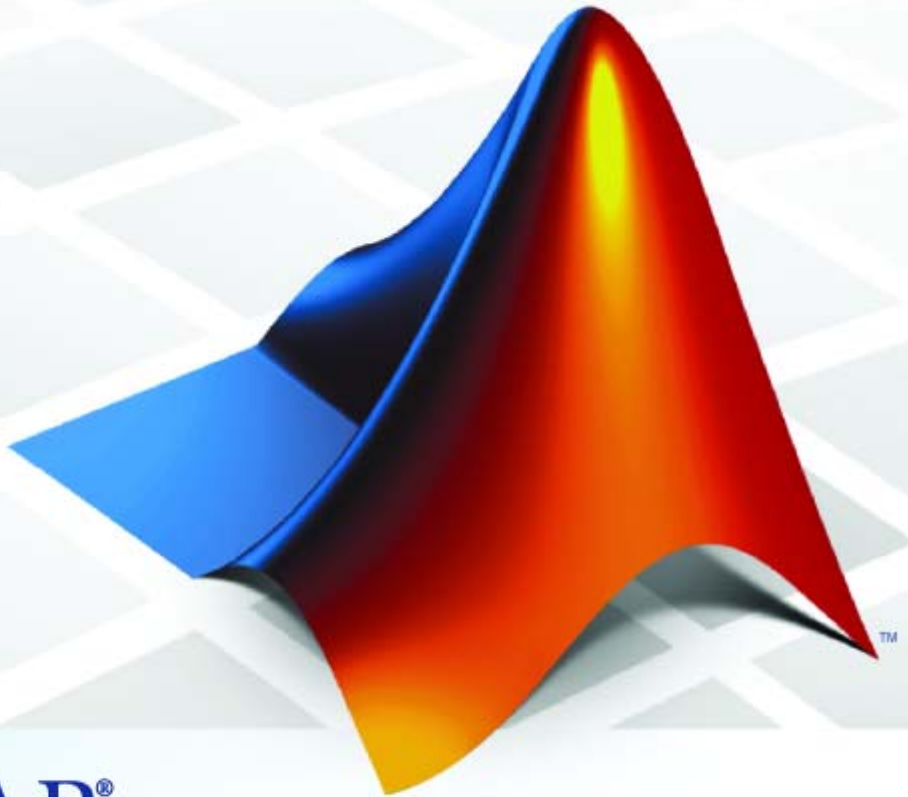


# SimPowerSystems™ 5

## Reference

*Hydro-Québec*



**MATLAB®**  
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## How to Contact The MathWorks



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*SimPowerSystems™ Reference*

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October 2008	Online only	Revised for Version 5.0 (Release 2008b)



## Block Reference

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<b>Applications</b> .....	<b>1-7</b>
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## Command Reference

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## Technical Conventions

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**A**

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# Block Reference

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Elements (p. 1-2)

Power Electronics (p. 1-5)

Machines (p. 1-5)

Applications (p. 1-7)

Measurements (p. 1-10)

Extras (p. 1-11)

Powergui (p. 1-13)

Generate electric signals

Linear and nonlinear circuit elements

Power electronics devices

Power machinery models

Access electric drives, FACTS, and distributed resources

Current and voltage measurements

Additional useful blocks, such as specialized measurement and control blocks

Opens graphical user interface for steady-state analysis of electrical circuits

## Electrical Sources

AC Current Source	Implement sinusoidal current source
AC Voltage Source	Implement sinusoidal voltage source
Battery	Implement generic battery model
Controlled Current Source	Implement controlled current source
Controlled Voltage Source	Implement controlled voltage source
DC Voltage Source	Implement DC voltage source
Three-Phase Programmable Voltage Source	Implement three-phase voltage source with programmable time variation of amplitude, phase, frequency, and harmonics
Three-Phase Source	Implement three-phase source with internal R-L impedance

## Elements

Breaker	Implement circuit breaker opening at current zero crossing
Connection Port	Create Physical Modeling connector port for subsystem
Distributed Parameter Line	Implement N-phase distributed parameter transmission line model with lumped losses
Ground	Provide connection to ground
Grounding Transformer	Implement three-phase grounding transformer providing a neutral in three-wire system
Linear Transformer	Implement two- or three-winding linear transformer



---

Multi-Winding Transformer	Implement multi-winding transformer with taps
Mutual Inductance	Implement inductances with mutual coupling
Neutral	Implement common node in circuit
Parallel RLC Branch	Implement parallel RLC branch
Parallel RLC Load	Implement linear parallel RLC load
PI Section Line	Implement single-phase transmission line with lumped parameters
Saturable Transformer	Implement two- or three-winding saturable transformer
Series RLC Branch	Implement series RLC branch
Series RLC Load	Implement linear series RLC load
Surge Arrester	Implement metal-oxide surge arrester
Three-Phase Breaker	Implement three-phase circuit breaker opening at current zero crossing
Three-Phase Dynamic Load	Implement three-phase dynamic load with active power and reactive power as function of voltage or controlled from external input
Three-Phase Fault	Implement programmable phase-to-phase and phase-to-ground fault breaker system
Three-Phase Harmonic Filter	Implement four types of three-phase harmonic filters using RLC components
Three-Phase Mutual Inductance Z1-Z0	Implement three-phase impedance with mutual coupling among phases
Three-Phase Parallel RLC Branch	Implement three-phase parallel RLC branch

Three-Phase Parallel RLC Load	Implement three-phase parallel RLC load with selectable connection
Three-Phase PI Section Line	Implement three-phase transmission line section with lumped parameters
Three-Phase Series RLC Branch	Implement three-phase series RLC branch
Three-Phase Series RLC Load	Implement three-phase series RLC load with selectable connection
Three-Phase Transformer (Three Windings)	Implement three-phase transformer with configurable winding connections
Three-Phase Transformer (Two Windings)	Implement three-phase transformer with configurable winding connections
Three-Phase Transformer 12 Terminals	Implement three single-phase, two-winding transformers where all terminals are accessible
Three-Phase Transformer Inductance Matrix Type (Three Windings)	Implement three-phase three-winding transformer with configurable winding connections and core geometry
Three-Phase Transformer Inductance Matrix Type (Two Windings)	Implement three-phase two-winding transformer with configurable winding connections and core geometry
Zigzag Phase-Shifting Transformer	Implement zigzag phase-shifting transformer with configurable secondary winding connection

## Power Electronics

Diode	Implement diode model
GTO	Implement gate turn off (GTO) thyristor model
Ideal Switch	Implement ideal switch device
IGBT	Implement insulated gate bipolar transistor (IGBT)
IGBT/Diode	Implements ideal IGBT, GTO, or MOSFET and antiparallel diode
MOSFET	Implement MOSFET model
Three-Level Bridge	Implement three-level neutral point clamped (NPC) power converter with selectable topologies and power switching devices
Thyristor	Implement thyristor model
Universal Bridge	Implement universal power converter with selectable topologies and power electronic devices

## Machines

Asynchronous Machine	Model the dynamics of three-phase asynchronous machine, also known as induction machine
DC Machine	Implement separately excited DC machine
Excitation System	Provide excitation system for synchronous machine and regulate its terminal voltage in generating mode

Generic Power System Stabilizer	Implement generic power system stabilizer for synchronous machine
Hydraulic Turbine and Governor	Model hydraulic turbine and proportional-integral-derivative (PID) governor system
Machine Measurement Demux	Split measurement signal of machine models into separate signals
Multiband Power System Stabilizer	Implement multiband power system stabilizer
Permanent Magnet Synchronous Machine	Model the dynamics of three-phase permanent magnet synchronous machine with sinusoidal or trapezoidal back electromotive force (back EMF)
Simplified Synchronous Machine	Model the dynamics of simplified three-phase synchronous machine
Single Phase Asynchronous Machine	Model the dynamics of single phase asynchronous machine with squirrel-cage rotor
Steam Turbine and Governor	Model the dynamics of speed governing system, steam turbine, and multimass shaft
Stepper Motor	Implement stepper motor model
Switched Reluctance Motor	Model the dynamics of switched reluctance motor
Synchronous Machine	Model the dynamics of three-phase round-rotor or salient-pole synchronous machine

## Applications

Electric Drives (p. 1-7)	AC and DC electric drives models
Flexible AC Transmission Systems (FACTS) (p. 1-9)	FACTS models
Distributed Resources (DR) (p. 1-10)	Wind turbine models

### Electric Drives

DC Drives (p. 1-7)	DC electric drives
AC Drives (p. 1-8)	AC electric drives
Shafts and Speed Reducers (p. 1-8)	Shafts and speed reducers
Extra Sources (p. 1-9)	Extra electrical sources

### DC Drives

Four-Quadrant Chopper DC Drive	Implement four-quadrant chopper DC drive
Four-Quadrant Single-Phase Rectifier DC Drive	Implement single-phase dual-converter DC drive with circulating current
Four-Quadrant Three-Phase Rectifier DC Drive	Implement three-phase dual-converter DC drive with circulating current
One-Quadrant Chopper DC Drive	Implement one-quadrant chopper (buck converter topology) DC drive
Two-Quadrant Chopper DC Drive	Implement two-quadrant chopper (buck-boost converter topology) DC drive

Two-Quadrant Single-Phase Rectifier DC Drive	Implement two-quadrant single-phase rectifier DC drive
Two-Quadrant Three-Phase Rectifier DC Drive	Implement two-quadrant three-phase rectifier DC drive

### **AC Drives**

Brushless DC Motor Drive	Implement brushless DC motor drive using Permanent Magnet Synchronous Motor (PMSM) with trapezoidal back electromotive force (BEMF)
DTC Induction Motor Drive	Implement direct torque and flux control (DTC) induction motor drive model
Field-Oriented Control Induction Motor Drive	Implement field-oriented control (FOC) induction motor drive model
PM Synchronous Motor Drive	Implement Permanent Magnet Synchronous Motor (PMSM) vector control drive
Self-Controlled Synchronous Motor Drive	Implement Self-Controlled Synchronous Motor Drive
Six-Step VSI Induction Motor Drive	Implement six-step inverter fed Induction Motor Drive
Space Vector PWM VSI Induction Motor Drive	Implement space vector PWM VSI induction motor drive

### **Shafts and Speed Reducers**

Mechanical Shaft	Implement mechanical shaft
Speed Reducer	Implement speed reducer

## Extra Sources

Battery	Implement generic battery model
Fuel Cell Stack	Implement generic hydrogen fuel cell stack model

## Flexible AC Transmission Systems (FACTS)

Power-Electronics Based FACTS (p. 1-9)	Power-electronics based models
Transformers (p. 1-10)	Transformer models

## Power-Electronics Based FACTS

Static Synchronous Compensator (Phasor Type)	Implement phasor model of three-phase static synchronous compensator
Static Synchronous Series Compensator (Phasor Type)	Implement phasor model of three-phase static synchronous series compensator
Static Var Compensator (Phasor Type)	Implement phasor model of three-phase static var compensator
Unified Power Flow Controller (Phasor Type)	Implement phasor model of three-phase unified power flow controller

## **Transformers**

Three-Phase OLTC Phase Shifting Transformer Delta-Hexagonal (Phasor Type)	Implement phasor model of three-phase OLTC phase-shifting transformer using delta hexagonal connection
Three-Phase OLTC Regulating Transformer (Phasor Type)	Implement phasor model of three-phase OLTC regulating transformer

## **Distributed Resources (DR)**

Wind Turbine	Implement model of variable pitch wind turbine
Wind Turbine Doubly-Fed Induction Generator (Phasor Type)	Implement phasor model of variable speed doubly-fed induction generator driven by wind turbine
Wind Turbine Induction Generator (Phasor Type)	Implement phasor model of squirrel-cage induction generator driven by variable pitch wind turbine

## **Measurements**

Current Measurement	Measure current in circuit
Impedance Measurement	Measure impedance of circuit as function of frequency
Multimeter	Measure voltages and currents specified in dialog boxes of SimPowerSystems™ blocks
Three-Phase V-I Measurement	Measure three-phase currents and voltages in circuit
Voltage Measurement	Measure voltage in circuit



## Extras

Signal Measurements (p. 1-11)	Specialized measurement blocks
Signal and Pulse Sources (p. 1-11)	Specialized source blocks

### Signal Measurements

abc_to_dq0 Transformation	Perform Park transformation from three-phase (abc) reference frame to dq0 reference frame
Active & Reactive Power	Measure active and reactive powers of voltage-current pair
dq0_to_abc Transformation	Perform Park transformation from dq0 reference frame to abc reference frame
Fourier	Perform Fourier analysis of signal
RMS	Measure root mean square (RMS) value of signal
Three-Phase Sequence Analyzer	Measure positive-, negative-, and zero-sequence components of three-phase signal
Total Harmonic Distortion	Measure total harmonic distortion (THD) of signal

### Signal and Pulse Sources

PWM Generator	Generate pulses for carrier-based two-level pulse width modulator (PWM) in converter bridge
Synchronized 12-Pulse Generator	Implement synchronized pulse generator to fire thyristors of twelve-pulse converter

Synchronized 6-Pulse Generator

Implement synchronized pulse generator to fire thyristors of six-pulse converter

Timer

Generate signal changing at specified transition times

## Powergui

Powergui

Graphical user interface for  
analysis of circuits and systems  
and environment block for  
SimPowerSystems models



# Blocks — Alphabetical List

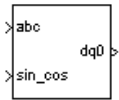
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# abc\_to\_dq0 Transformation

**Purpose** Perform Park transformation from three-phase (abc) reference frame to dq0 reference frame

**Library** Extras/Measurements  
A discrete version of this block is available in the Extras/Discrete Measurements library.

## Description



The abc\_to\_dq0 Transformation block computes the direct axis, quadratic axis, and zero sequence quantities in a two-axis rotating reference frame for a three-phase sinusoidal signal. The following transformation is used:

$$V_d = \frac{2}{3}(V_a \sin(\omega t) + V_b \sin(\omega t - 2\pi/3) + V_c \sin(\omega t + 2\pi/3))$$

$$V_q = \frac{2}{3}(V_a \cos(\omega t) + V_b \cos(\omega t - 2\pi/3) + V_c \cos(\omega t + 2\pi/3))$$

$$V_0 = \frac{1}{3}(V_a + V_b + V_c)$$

where  $\omega$  = rotation speed (rad/s) of the rotating frame.

The transformation is the same for the case of a three-phase current; you simply replace the  $V_a$ ,  $V_b$ ,  $V_c$ ,  $V_d$ ,  $V_q$ , and  $V_0$  variables with the  $I_a$ ,  $I_b$ ,  $I_c$ ,  $I_d$ ,  $I_q$ , and  $I_0$  variables.

This transformation is commonly used in three-phase electric machine models, where it is known as a Park transformation. It allows you to eliminate time-varying inductances by referring the stator and rotor quantities to a fixed or rotating reference frame. In the case of a synchronous machine, the stator quantities are referred to the rotor.  $I_d$  and  $I_q$  represent the two DC currents flowing in the two equivalent rotor windings (d winding directly on the same axis as the field winding, and q winding on the quadratic axis), producing the same flux as the stator  $I_a$ ,  $I_b$ , and  $I_c$  currents.

You can use this block in a control system to measure the positive-sequence component  $V_1$  of a set of three-phase voltages or

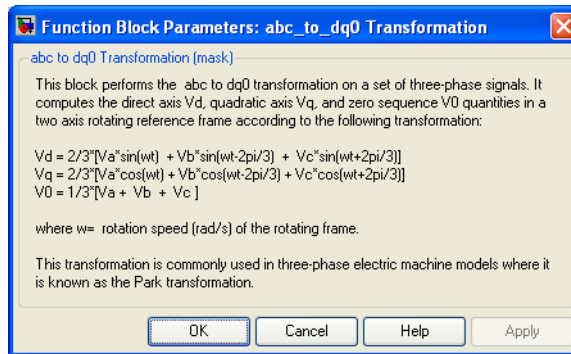
currents. The  $V_d$  and  $V_q$  (or  $I_d$  and  $I_q$ ) then represent the rectangular coordinates of the positive-sequence component.

You can use the Math Function block and the Trigonometric Function block to obtain the modulus and angle of  $V_1$ :

$$|V_1| = \sqrt{V_q^2 + V_d^2}$$
$$\angle V_1 = \text{atan2}(V_q/V_d)$$

This measurement system does not introduce any delay, but, unlike the Fourier analysis done in the Sequence Analyzer block, it is sensitive to harmonics and imbalances.

## Dialog Box and Parameters



## Inputs and Outputs

abc

Connect to the first input the vectorized sinusoidal phase signal to be converted [phase A phase B phase C].

sin\_cos

Connect to the second input a vectorized signal containing the [sin( $\omega t$ ) cos( $\omega t$ )] values, where  $\omega$  is the rotation speed of the reference frame.

dq0

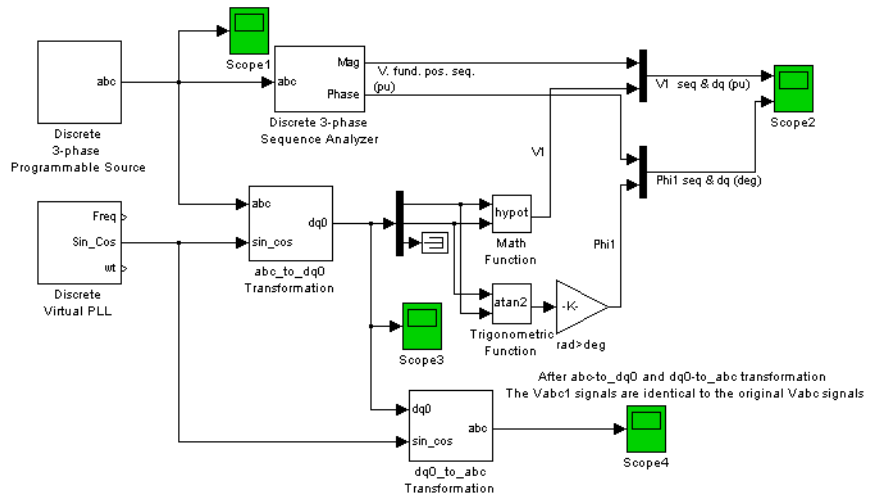
The output is a vectorized signal containing the three sequence components [d q o].

# abc\_to\_dq0 Transformation

## Example

The power\_3phsignaldq demo uses a Discrete Three-Phase Programmable Source block to generate a 1 pu, 15 degrees positive sequence voltage. At 0.05 second the positive sequence voltage is increased to 1.5 pu and at 0.1 second an imbalance is introduced by the addition of a 0.3 pu negative sequence component with a phase of -30 degrees. The magnitude and phase of the positive-sequence component are evaluated in two different ways:

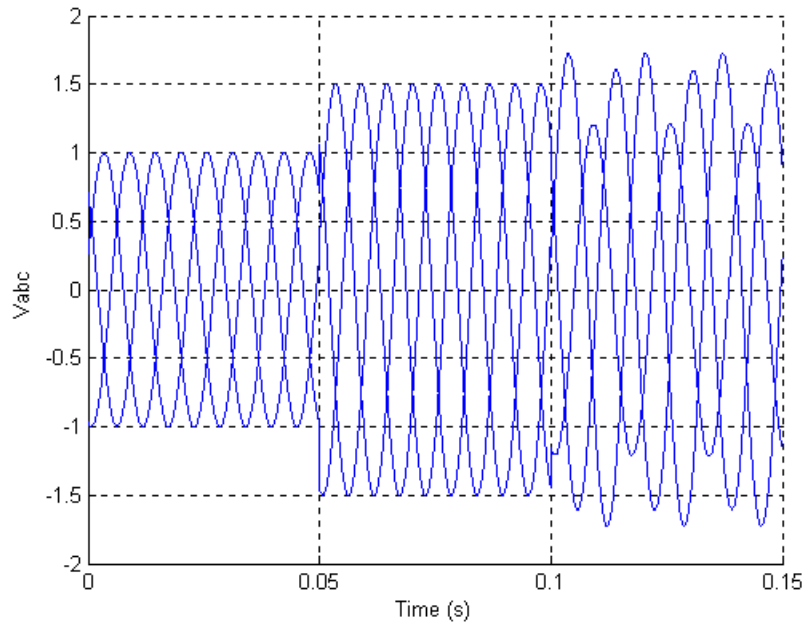
- Sequence calculation of phasors using Fourier analysis
- abc-to-dq0 transformation



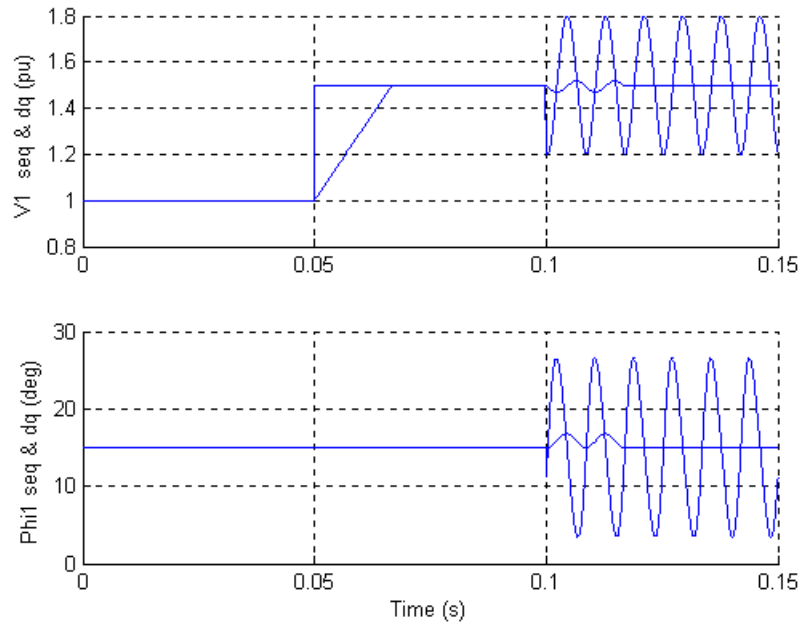
Start the simulation and observe the instantaneous signals  $V_{abc}$  (Scope1), the signals returned by the Sequence Analyzer (Scope2), and the abc-to-dq0 transformation (Scope3).



# abc\_to\_dq0 Transformation

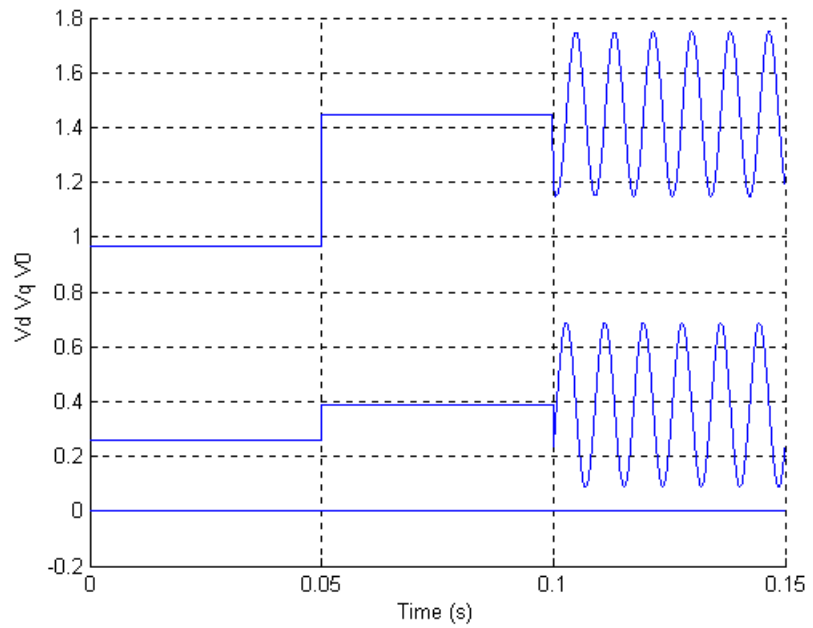


# abc\_to\_dq0 Transformation



Note that the Sequence Analyzer, which uses Fourier analysis, is immune to harmonics and imbalance. However, its response to a step is a one-cycle ramp. The abc-to-dq0 transformation is instantaneous. However, an imbalance produces a ripple at the V1 and Phi1 outputs.

# abc\_to\_dq0 Transformation



**See Also** [dq0\\_to\\_abc Transformation](#)

# AC Current Source

**Purpose** Implement sinusoidal current source

**Library** Electrical Sources

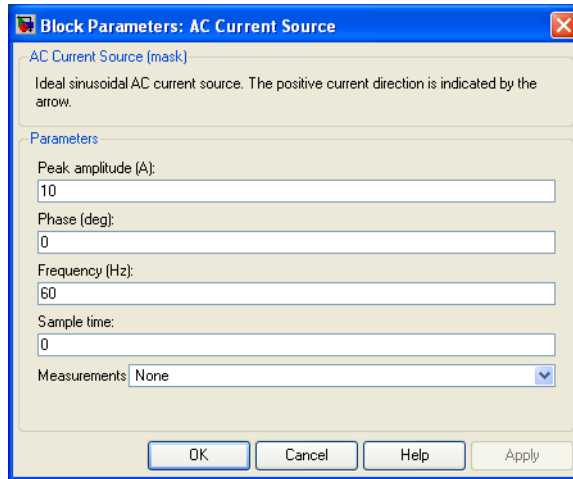
**Description** The AC Current Source block implements an ideal AC current source. The positive current direction is indicated by the arrow in the block icon. The generated current  $I$  is described by the following relationship:



$$I = A \sin(\omega t + \phi) \quad \omega = 2\pi f \quad \phi = \text{Phase in radians}$$

Negative values are allowed for amplitude and phase. A zero frequency specifies a DC current source. You cannot enter a negative frequency; the software returns an error in that case, and the block displays a question mark in the block icon. You can modify the first three block parameters at any time during the simulation.

## Dialog Box and Parameters



### Peak amplitude

The peak amplitude of the generated current, in amperes (A).

## Phase

The phase in degrees (deg). Specify a frequency of 0 and a phase of 90 degrees to implement a DC current source.

## Frequency

The source frequency in hertz (Hz). Specify a frequency of 0 and a phase of 90 degrees to implement a DC current source.

## Sample time

The sample period in seconds (s). The default is 0, corresponding to a continuous source.

## Measurements

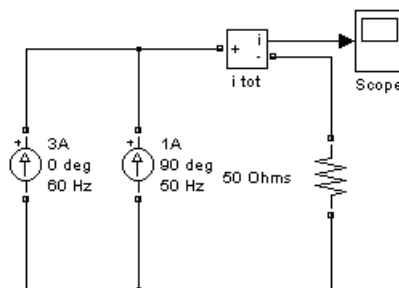
Select **Current** to measure the current flowing through the AC Current Source block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name.

Measurement	Label
Current	Isrc:

## Example

The power\_accurent demo uses two AC Current Source blocks in parallel to sum two sinusoidal currents in a resistor.



# AC Current Source

---

## **See Also**

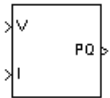
Controlled Current Source, Multimeter

**Purpose** Measure active and reactive powers of voltage-current pair

**Library** Extras/Measurements

A discrete version of this block is available in the Extras/Discrete Measurements library.

## Description



The Active & Reactive Power block measures the active power  $P$  and reactive power  $Q$  associated with a periodic voltage-current pair that can contain harmonics.  $P$  and  $Q$  are calculated by averaging the  $V I$  product with a running average window over one cycle of the fundamental frequency, so that the powers are evaluated at fundamental frequency.

$$P = \frac{1}{T} \int_{(t-T)}^t (V(\omega t) \times I(\omega t)) dt$$

$$Q = \frac{1}{T} \int_{(t-T)}^t (V(\omega t) \times I(\omega t - \pi/2)) dt$$

where  $T = 1/(\text{fundamental frequency})$ .

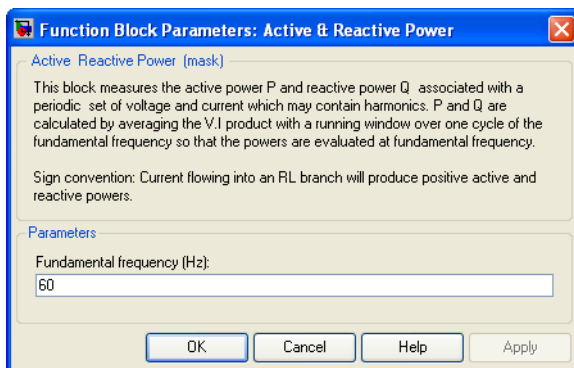
A current flowing into an RL branch, for example, produces positive active and reactive powers.

As this block uses a running window, one cycle of simulation has to be completed before the output gives the correct active and reactive powers.

The discrete version of this block, available in the Extras/Discrete Measurements library, allows you to specify the initial input voltage and current (magnitude and phase). For the first cycle of simulation the outputs are held constant using the values specified by the initial input parameters.

# Active & Reactive Power

## Dialog Box and Parameters



### Fundamental frequency (Hz)

The fundamental frequency, in hertz, of the instantaneous voltage and current.

## Inputs and Outputs

V

The first input is the instantaneous voltage.

I

The second input is the instantaneous current.

PQ

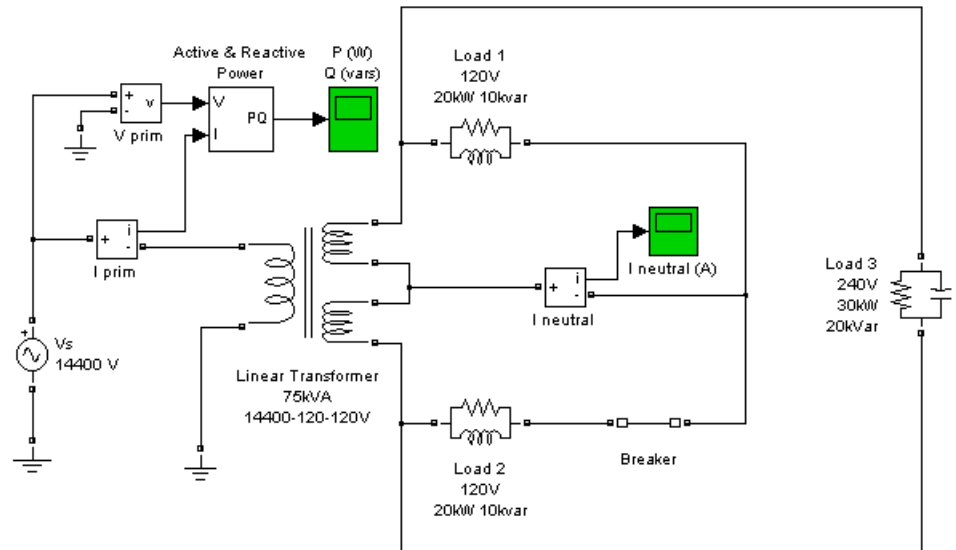
The output is a vector [P Q] of the active and reactive powers.

## Example

The power\_transfo demo simulates a three-winding distribution transformer rated at 75 kVA:14400/120/120 V. The transformer primary winding is connected to a high-voltage source of 14400 Vrms. Two identical inductive loads (20 kW-10 kvar) are connected to the two secondary windings. A third capacitive load (30 kW-20 kvar) is fed at 240 V.



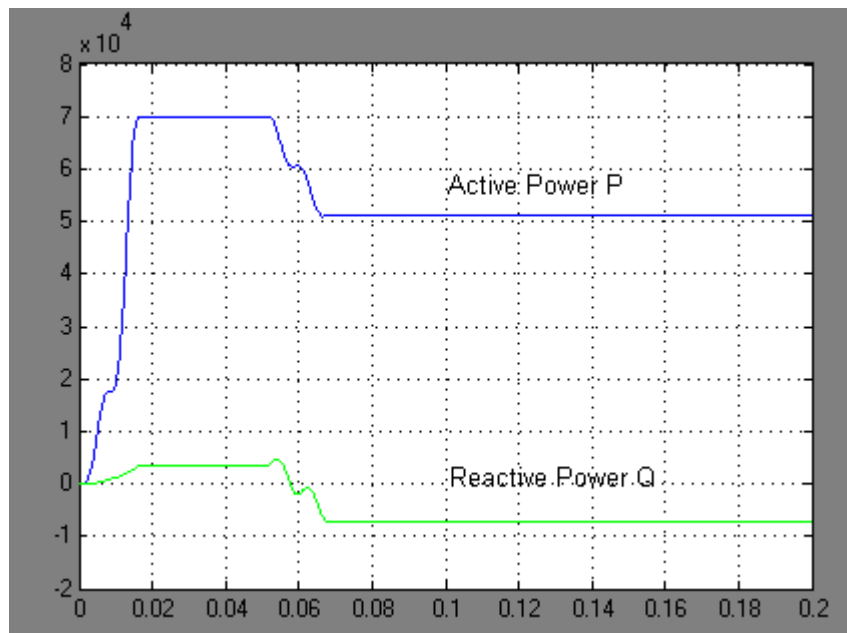
# Active & Reactive Power



Initially, the circuit breaker in series with Load 2 is closed, so that the system is balanced. When the circuit breaker opens, a current starts to flow in the neutral path as a result of the load imbalance.

The active power computed from the primary voltage and current is measured by an Active & Reactive Power block. When the breaker opens, the active power decreases from 70 kW to 50 kW.

# Active & Reactive Power



**Purpose** Implement sinusoidal voltage source

**Library** Electrical Sources

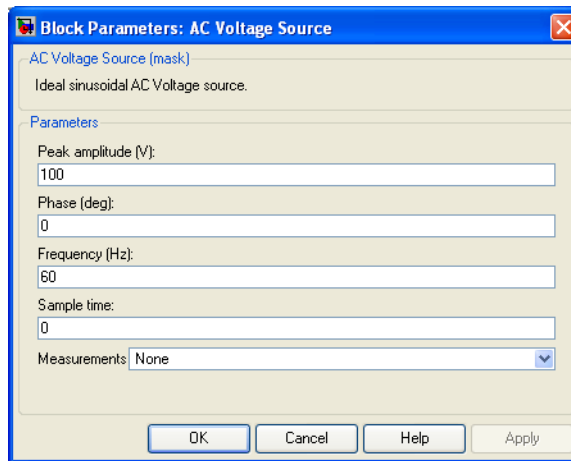
**Description** The AC Voltage Source block implements an ideal AC voltage source. The generated voltage  $U$  is described by the following relationship:



$$U = A \sin(\omega t + \phi) \quad \omega = 2\pi f \quad \phi = \text{Phase in radians}$$

Negative values are allowed for amplitude and phase. A frequency of 0 and phase equal to 90 degrees specify a DC voltage source. Negative frequency is not allowed; otherwise the software signals an error, and the block displays a question mark in the block icon.

## Dialog Box and Parameters



### Peak amplitude

The peak amplitude of the generated voltage, in volts (V).

### Phase

The phase in degrees (deg).

### Frequency

The source frequency in hertz (Hz).

# AC Voltage Source

## Sample time

The sample period in seconds (s). The default is 0, corresponding to a continuous source.

## Measurements

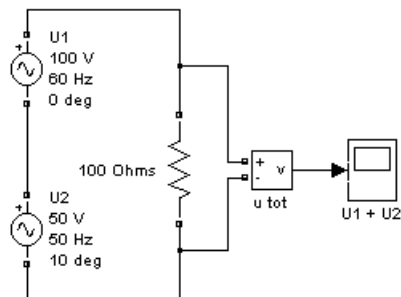
Select **Voltage** to measure the voltage across the terminals of the AC Voltage Source block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name.

Measurement	Label
Voltage	Usrc:

## Example

The power\_acvoltage demo uses two AC Voltage Source blocks at different frequencies connected in series across a resistor. The sum of the two voltages is read by a Voltage Measurement block.



## See Also

Controlled Voltage Source, DC Voltage Source, Multimeter

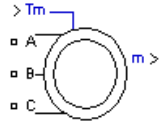
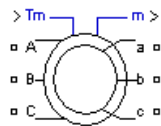
## Purpose

Model the dynamics of three-phase asynchronous machine, also known as induction machine

## Library

Machines

## Description



The Asynchronous Machine block operates in either generator or motor mode. The mode of operation is dictated by the sign of the mechanical torque:

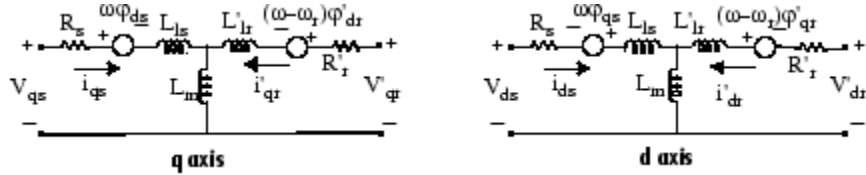
- If  $T_m$  is positive, the machine acts as a motor.
- If  $T_m$  is negative, the machine acts as a generator.

The electrical part of the machine is represented by a fourth-order state-space model and the mechanical part by a second-order system. All electrical variables and parameters are referred to the stator. This is indicated by the prime signs in the machine equations given below. All stator and rotor quantities are in the arbitrary two-axis reference frame (dq frame). The subscripts used are defined as follows:

Subscript	Definition
d	d axis quantity
q	q axis quantity
r	Rotor quantity
s	Stator quantity
l	Leakage inductance
m	Magnetizing inductance

# Asynchronous Machine

## Electrical System



$$V_{qs} = R_s i_{qs} + \frac{d}{dt} \phi_{qs} + \omega \phi_{ds}$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt} \phi_{ds} - \omega \phi_{qs}$$

$$V'_{qr} = R'_r i'_{qr} + \frac{d}{dt} \phi'_{qr} + (\omega - \omega_r) \phi'_{dr}$$

$$V'_{dr} = R'_r i'_{dr} + \frac{d}{dt} \phi'_{dr} - (\omega - \omega_r) \phi'_{qr}$$

$$T_e = 1.5 p (\phi_{ds} i_{qs} - \phi_{qs} i_{ds})$$

$$\phi_{qs} = L_s i_{qs} + L_m i'_{qr}$$

$$\phi_{ds} = L_s i_{ds} + L_m i'_{dr}$$

$$\text{where } \phi'_{qr} = L'_r i'_{qr} + L_m i_{qs}$$

$$\phi'_{dr} = L'_r i'_{dr} + L_m i_{ds}$$

$$L_s = L_{ls} + L_m$$

$$L'_r = L'_{lr} + L_m$$

## Mechanical System

$$\frac{d}{dt} \omega_m = \frac{1}{2H} (T_e - F \omega_m - T_m)$$

$$\frac{d}{dt} \theta_m = \omega_m$$

The Asynchronous Machine block parameters are defined as follows (all quantities are referred to the stator):

Parameter	Definition
$R_s, L_{ls}$	Stator resistance and leakage inductance
$R'_r, L'_{lr}$	Rotor resistance and leakage inductance
$L_m$	Magnetizing inductance
$L_s, L'_r$	Total stator and rotor inductances

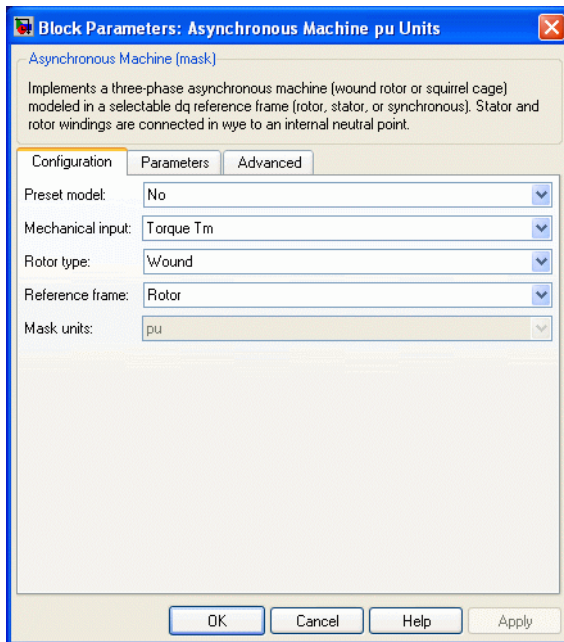
Parameter	Definition
$V_{qs}, i_{qs}$	q axis stator voltage and current
$V_{qr}, i_{qr}$	q axis rotor voltage and current
$V_{ds}, i_{ds}$	d axis stator voltage and current
$V_{dr}, i_{dr}$	d axis rotor voltage and current
$\Phi_{qs}, \Phi_{ds}$	Stator q and d axis fluxes
$\Phi_{qr}, \Phi_{dr}$	Rotor q and d axis fluxes
$\omega_m$	Angular velocity of the rotor
$\Theta_m$	Rotor angular position
p	Number of pole pairs
$\omega_r$	Electrical angular velocity ( $\omega_m \times p$ )
$\Theta_r$	Electrical rotor angular position ( $\Theta_m \times p$ )
$T_e$	Electromagnetic torque
$T_m$	Shaft mechanical torque
J	Combined rotor and load inertia coefficient. Set to infinite to simulate locked rotor.
H	Combined rotor and load inertia constant. Set to infinite to simulate locked rotor.
F	Combined rotor and load viscous friction coefficient

## Dialog Box and Parameters

You can choose between two Asynchronous Machine blocks to specify the electrical and mechanical parameters of the model, by using the pu Units dialog box or the SI dialog box. Both blocks are modeling the same asynchronous machine model. Depending on the dialog box you choose to use, SimPowerSystems software automatically converts the parameters you enter into per unit parameters. The Simulink® model of the Asynchronous Machine block uses pu parameters.

# Asynchronous Machine

## Configuration Tab



### Preset model

Provides a set of predetermined electrical and mechanical parameters for various asynchronous machine ratings of power (HP), phase-to-phase voltage (V), frequency (Hz), and rated speed (rpm).

Select one of the preset models to load the corresponding electrical and mechanical parameters in the entries of the dialog box. Select No if you do not want to use a preset model. Note that the preset models do not include predetermined saturation parameters.

### Mechanical input

Allows you to select either the torque applied to the shaft or the rotor speed as the Simulink signal applied to the block's input.

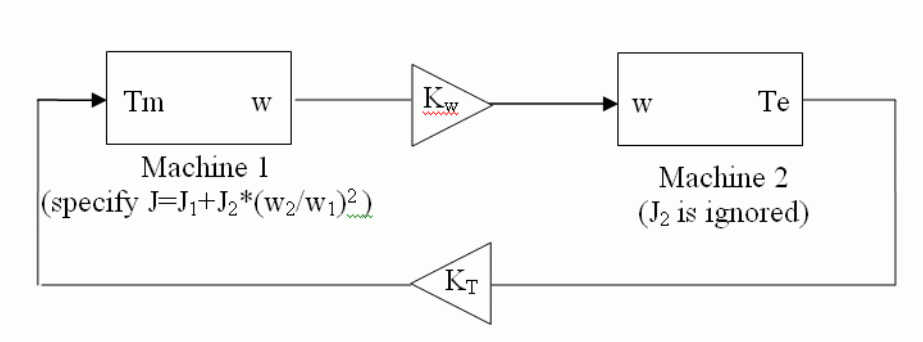


Select **Torque  $T_m$**  to specify a torque input, in N.m or in pu, and change labeling of the block's input to  $T_m$ . The machine speed is determined by the machine Inertia  $J$  (or inertia constant  $H$  for the pu machine) and by the difference between the applied mechanical torque  $T_m$  and the internal electromagnetic torque  $T_e$ . The sign convention for the mechanical torque is the following: when the speed is positive, a positive torque signal indicates motor mode and a negative signal indicates generator mode.

Select **Speed  $w$**  to specify a speed input, in rad/s or in pu, and change labeling of the block's input to  $w$ . The machine speed is imposed and the mechanical part of the model (Inertia  $J$ ) is ignored. Using the speed as the mechanical input allows modeling a mechanical coupling between two machines and interfacing with SimMechanics™ and SimDriveline™ models.

The next figure indicates how to model a stiff shaft interconnection in a motor-generator set when friction torque is ignored in machine 2. The speed output of machine 1 (motor) is connected to the speed input of machine 2 (generator), while machine 2 electromagnetic torque output  $T_e$  is applied to the mechanical torque input  $T_m$  of machine 1. The  $K_w$  factor takes into account speed units of both machines (pu or rad/s) and gear box ratio  $w_2/w_1$ . The  $K_T$  factor takes into account torque units of both machines (pu or N.m) and machine ratings. Also, as the inertia  $J_2$  is ignored in machine 2,  $J_2$  referred to machine 1 speed must be added to machine 1 inertia  $J_1$ .

# Asynchronous Machine



## Rotor type

Specifies the branching for the rotor windings.

## Reference frame

Specifies the reference frame that is used to convert input voltages (abc reference frame) to the dq reference frame, and output currents (dq reference frame) to the abc reference frame. You can choose among the following reference frame transformations:

- Rotor (Park transformation)
- Stationary (Clarke or  $\alpha\beta$  transformation)
- Synchronous

The following relationships describe the abc-to-dq reference frame transformations applied to the Asynchronous Machine phase-to-phase voltages.

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 \cos \theta & \cos \theta + \sqrt{3} \sin \theta \\ 2 \sin \theta & \sin \theta - \sqrt{3} \cos \theta \end{bmatrix} \begin{bmatrix} V_{abs} \\ V_{bcs} \end{bmatrix}$$

$$\begin{bmatrix} V'_{qr} \\ V'_{dr} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 \cos \beta & \cos \beta + \sqrt{3} \sin \beta \\ 2 \sin \beta & \sin \beta - \sqrt{3} \cos \beta \end{bmatrix} \begin{bmatrix} V'_{abr} \\ V'_{bcr} \end{bmatrix}$$

In the preceding equations,  $\Theta$  is the angular position of the reference frame, while  $\beta = \theta - \theta_r$  is the difference between the position of the reference frame and the position (electrical) of the rotor. Because the machine windings are connected in a three-wire Y configuration, there is no homopolar (0) component. This also justifies the fact that two line-to-line input voltages are used inside the model instead of three line-to-neutral voltages. The following relationships describe the dq-to-abc reference frame transformations applied to the Asynchronous Machine phase currents.

$$\begin{bmatrix} i_{as} \\ i_{bs} \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ \frac{-\cos \theta + \sqrt{3} \sin \theta}{2} & \frac{-\sqrt{3} \cos \theta - \sin \theta}{2} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix}$$

$$\begin{bmatrix} i'_{ar} \\ i'_{br} \end{bmatrix} = \begin{bmatrix} \cos \beta & \sin \beta \\ \frac{-\cos \beta + \sqrt{3} \sin \beta}{2} & \frac{-\sqrt{3} \cos \beta - \sin \beta}{2} \end{bmatrix} \begin{bmatrix} i'_{qr} \\ i'_{dr} \end{bmatrix}$$

$$i_{cs} = -i_{as} - i_{bs}$$

$$i'_{cr} = -i'_{ar} - i'_{br}$$

The following table shows the values taken by  $\Theta$  and  $\beta$  in each reference frame ( $\Theta_e$  is the position of the synchronously rotating reference frame).

Reference Frame	$\Theta$	$\beta$
Rotor	$\Theta_r$	0
Stationary	0	$-\Theta_r$
Synchronous	$\Theta_e$	$\Theta_e - \Theta_r$

The choice of reference frame affects the waveforms of all dq variables. It also affects the simulation speed and in certain

# Asynchronous Machine

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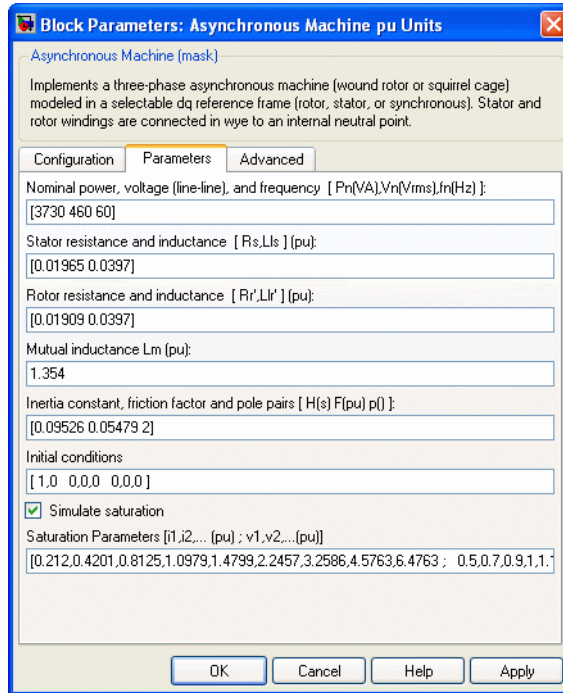
cases the accuracy of the results. The following guidelines are suggested in [1]:

- Use the stationary reference frame if the stator voltages are either unbalanced or discontinuous and the rotor voltages are balanced (or 0).
- Use the rotor reference frame if the rotor voltages are either unbalanced or discontinuous and the stator voltages are balanced.
- Use either the stationary or synchronous reference frames if all voltages are balanced and continuous.

## **Mask units**

Specifies the units of the electrical and mechanical parameters of the model. This parameter is not modifiable; it is provided for information purposes only.

## Parameters Tab



### Nominal power, voltage (line-line), and frequency

The nominal apparent power  $P_n$  (VA), RMS line-to-line voltage  $V_n$  (V), and frequency  $f_n$  (Hz).

### Stator resistance and inductance

The stator resistance  $R_s$  ( $\Omega$  or pu) and leakage inductance  $L_{ls}$  (H or pu).

### Rotor resistance and inductance

The rotor resistance  $R_r'$  ( $\Omega$  or pu) and leakage inductance  $L_{lr}'$  (H or pu), both referred to the stator.

### Mutual inductance

The magnetizing inductance  $L_m$  (H or pu).

# Asynchronous Machine

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## Inertia constant, friction factor, and pole pairs

For the **SI units** dialog box: the combined machine and load inertia coefficient  $J$  ( $\text{kg}\cdot\text{m}^2$ ), combined viscous friction coefficient  $F$  ( $\text{N}\cdot\text{m}\cdot\text{s}$ ), and pole pairs  $p$ . The friction torque  $T_f$  is proportional to the rotor speed  $\omega$  ( $T_f = F\cdot\omega$ ).

For the **pu units** dialog box: the inertia constant  $H$  (s), combined viscous friction coefficient  $F$  (pu), and pole pairs  $p$ .

## Initial conditions

Specifies the initial slip  $s$ , electrical angle  $\Theta_e$  (degrees), stator current magnitude (A or pu), and phase angles (degrees):

[slip, th,  $i_{as}$ ,  $i_{bs}$ ,  $i_{cs}$ , phase<sub>as</sub>, phase<sub>bs</sub>, phase<sub>cs</sub>]

For the wound-rotor machine, you can also specify optional initial values for the rotor current magnitude (A or pu), and phase angles (degrees):

[slip, th,  $i_{as}$ ,  $i_{bs}$ ,  $i_{cs}$ , phase<sub>as</sub>, phase<sub>bs</sub>, phase<sub>cs</sub>,  $i_{ar}$ ,  $i_{br}$ ,  $i_{cr}$ , phase<sub>ar</sub>, phase<sub>br</sub>, phase<sub>cr</sub>]

For the squirrel cage machine, the initial conditions can be computed by the load flow utility in the Powergui block.

## Simulate saturation

Specifies whether magnetic saturation of rotor and stator iron is simulated or not.

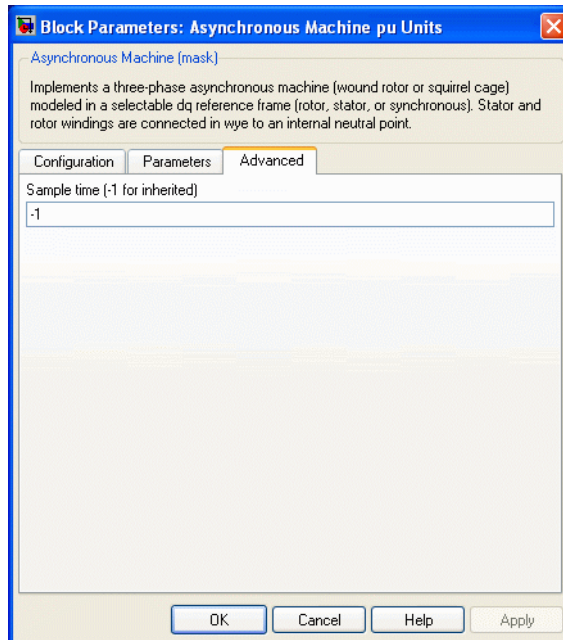
## Saturation parameters

Specifies the no-load saturation curve parameters. Magnetic saturation of stator and rotor iron (saturation of the mutual flux) is modeled by a nonlinear function (in this case a polynomial) using points of the no-load saturation curve. You must enter a 2-by- $n$  matrix, where  $n$  is the number of points taken from the saturation curve. The first row of this matrix contains the values of stator currents, while the second row contains values of corresponding terminal voltages (stator voltages). The first point

(first column of the matrix) must correspond to the point where the effect of saturation begins.

You must select the **Simulate saturation** check box to simulate saturation. If the **Simulate saturation** is not selected, the relationship between the stator current and the stator voltage is linear.

## Advanced Tab



### Sample time (-1 for inherited)

Specifies the sample time used by the block. To inherit the sample time specified in the Powergui block, set this parameter to -1.

# Asynchronous Machine

## Inputs and Outputs

$T_m$

The Simulink input of the block is the mechanical torque at the machine's shaft. When the input is a positive Simulink signal, the asynchronous machine behaves as a motor. When the input is a negative signal, the asynchronous machine behaves as a generator.

When you use the SI parameters mask, the input is a signal in N.m, otherwise it is in pu.

$m$

The Simulink output of the block is a vector containing 21 signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library. Depending on the type of mask you use, the units are in SI, or in pu.

Signal	Definition	Units	Symbol
1	Rotor current $i_{r\_a}$	A or pu	$i'_{ra}$
2	Rotor current $i_{r\_b}$	A or pu	$i'_{rb}$
3	Rotor current $i_{r\_c}$	A or pu	$i'_{rc}$
4	Rotor current $i_q$	A or pu	$i'_{qr}$
5	Rotor current $i_d$	A or pu	$i'_{dr}$
6	Rotor flux $\phi_{r\_q}$	V.s or pu	$\phi'_{qr}$
7	Rotor flux $\phi_{r\_d}$	V.s or pu	$\phi'_{dr}$
8	Rotor voltage $V_{r\_q}$	V or pu	$v'_{qr}$
9	Rotor voltage $V_{r\_d}$	V or pu	$v'_{dr}$
10	Stator current $i_{s\_a}$	A or pu	$i_{sa}$
11	Stator current $i_{s\_b}$	A or pu	$i_{sb}$
12	Stator current $i_{s\_c}$	A or pu	$i_{sc}$
13	Stator current $i_{s\_q}$	A or pu	$i_{qs}$
14	Stator current $i_{s\_d}$	A or pu	$i_{ds}$

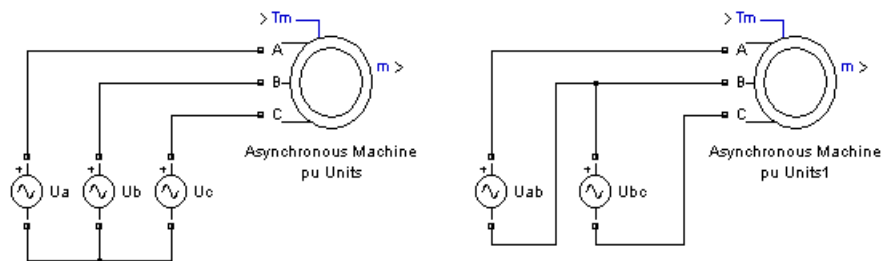


Signal	Definition	Units	Symbol
15	Stator flux phis_q	V.s or pu	$\Phi_{qs}$
16	Stator flux phis_d	V.s or pu	$\Phi_{ds}$
17	Stator voltage vs_q	V or pu	$v_{qs}$
18	Stator voltage vs_d	V or pu	$v_{ds}$
19	Rotor speed	rad/s	$\omega_m$
20	Electromagnetic torque Te	N.m or pu	$T_e$
21	Rotor angle thetam	rad	$\Theta_m$

The stator terminals of the Asynchronous Machine block are identified by the A, B, and C letters. The rotor terminals are identified by the a, b, and c letters. Note that the neutral connections of the stator and rotor windings are not available; three-wire Y connections are assumed.

## Limitations

- The Asynchronous Machine block does not include a representation of the saturation of leakage fluxes. You must be careful when you connect ideal sources to the machine's stator. If you choose to supply the stator via a three-phase Y-connected infinite voltage source, you must use three sources connected in Y. However, if you choose to simulate a delta source connection, you must use only two sources connected in series.



# Asynchronous Machine

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- 2 When you use Asynchronous Machine blocks in discrete systems, you might have to use a small parasitic resistive load, connected at the machine terminals, in order to avoid numerical oscillations. Large sample times require larger loads. The minimum resistive load is proportional to the sample time. As a rule of thumb, remember that with a  $25\ \mu\text{s}$  time step on a 60 Hz system, the minimum load is approximately 2.5% of the machine nominal power. For example, a 200 MVA asynchronous machine in a power system discretized with a  $50\ \mu\text{s}$  sample time requires approximately 5% of resistive load or 10 MW. If the sample time is reduced to  $20\ \mu\text{s}$ , a resistive load of 4 MW should be sufficient.

## Examples

### Example 1: Use of the Asynchronous Machine Block in Motor Mode

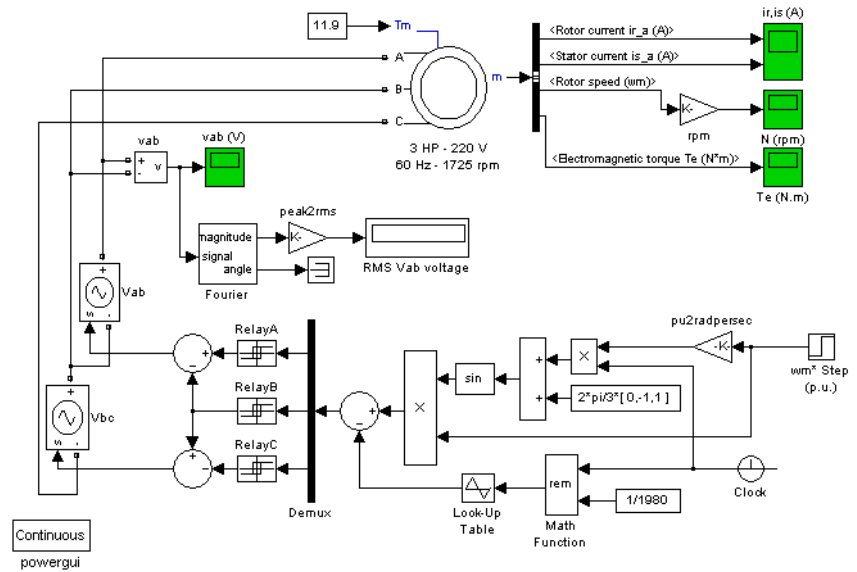
The power\_pwm demo illustrates the use of the Asynchronous Machine block in motor mode. It consists of an asynchronous machine in an open-loop speed control system.

The machine's rotor is short-circuited, and the stator is fed by a PWM inverter, built with Simulink blocks and interfaced to the Asynchronous Machine block through the Controlled Voltage Source block. The inverter uses sinusoidal pulse-width modulation, which is described in [2]. The base frequency of the sinusoidal reference wave is set at 60 Hz and the triangular carrier wave's frequency is set at 1980 Hz. This corresponds to a frequency modulation factor  $m_f$  of 33 ( $60\ \text{Hz} \times 33 = 1980$ ). It is recommended in [2] that  $m_f$  be an odd multiple of three and that the value be as high as possible.

The 3 HP machine is connected to a constant load of nominal value (11.9 N.m). It is started and reaches the set point speed of 1.0 pu at  $t = 0.9$  second.

The parameters of the machine are those found in the **SI Units** dialog box above, except for the stator leakage inductance, which is set to twice its normal value. This is done to simulate a smoothing inductor placed between the inverter and the machine. Also, the stationary reference frame was used to obtain the results shown.

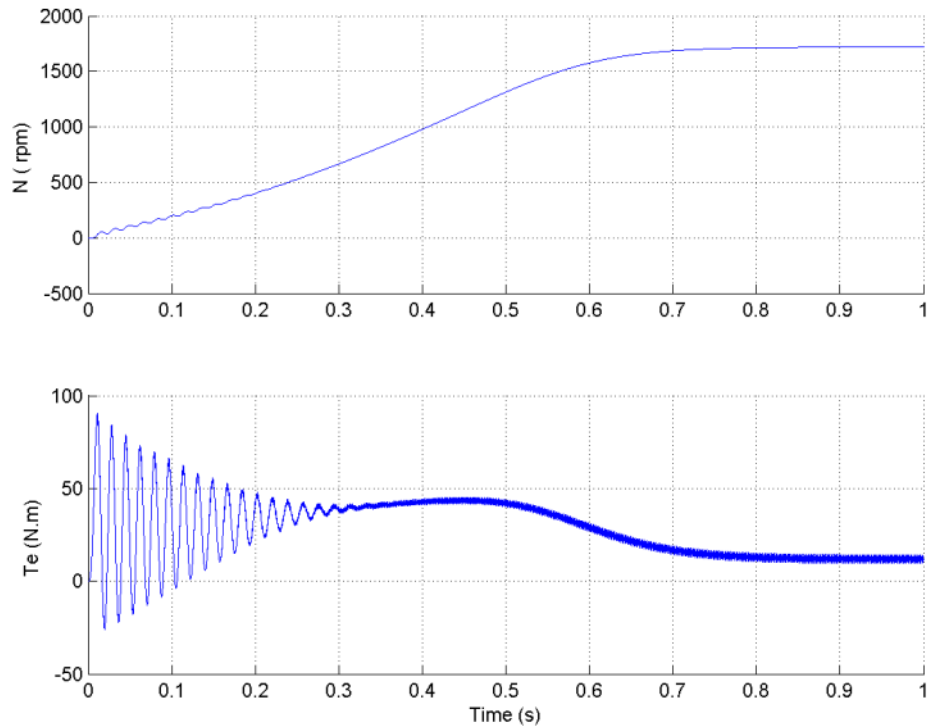
# Asynchronous Machine



Open the power\_pwm demo. Note in the simulation parameters that a small relative tolerance is required because of the high switching rate of the inverter.

Run the simulation and observe the machine's speed and torque.

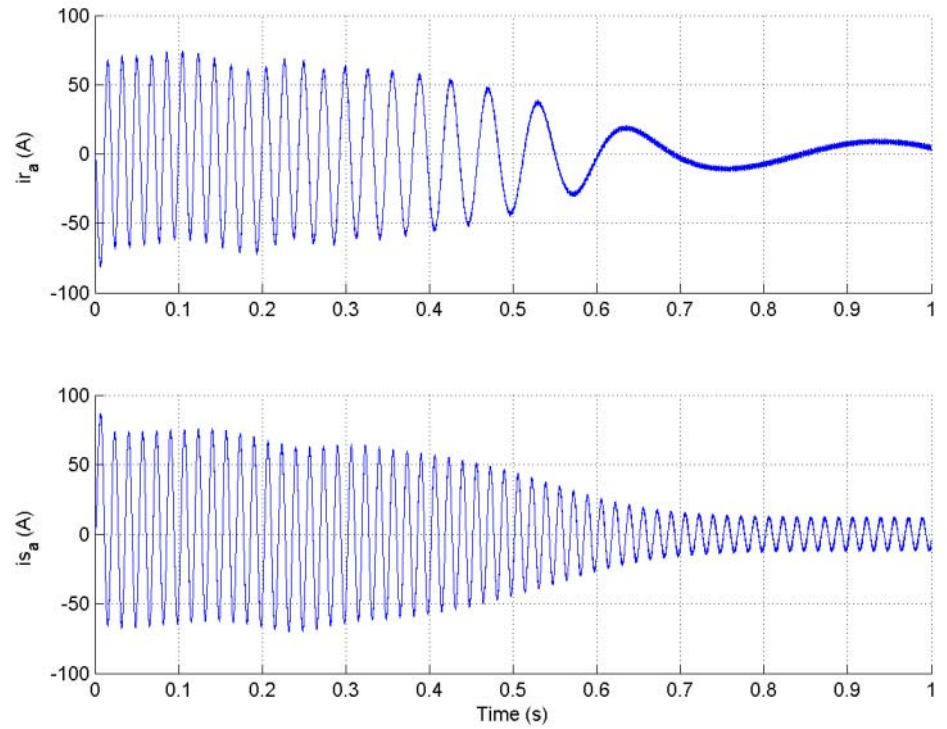
# Asynchronous Machine



The first graph shows the machine's speed going from 0 to 1725 rpm (1.0 pu). The second graph shows the electromagnetic torque developed by the machine. Because the stator is fed by a PWM inverter, a noisy torque is observed.

However, this noise is not visible in the speed because it is filtered out by the machine's inertia, but it can also be seen in the stator and rotor currents, which are observed next.

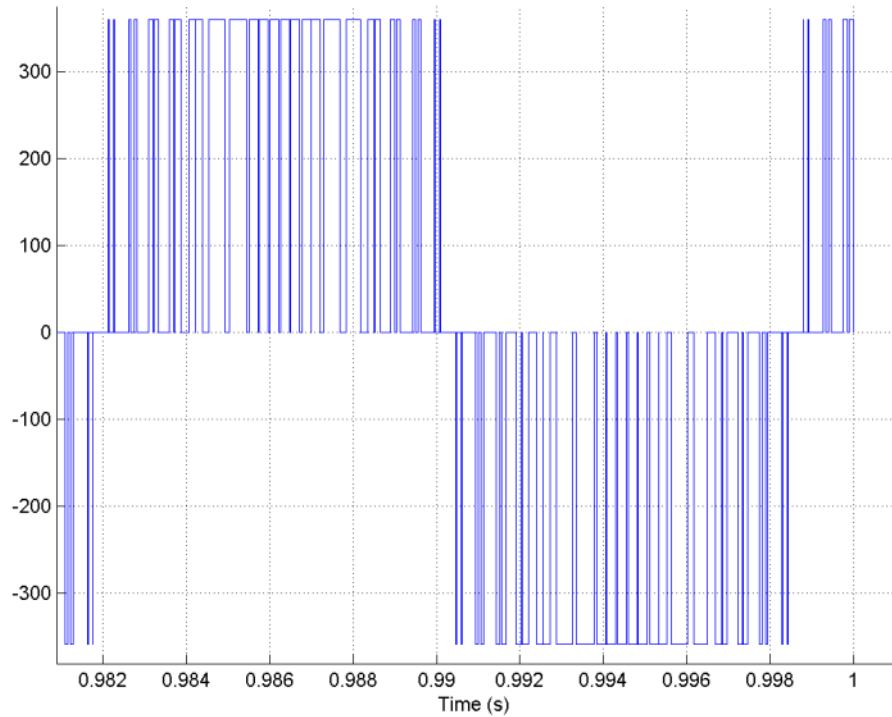
# Asynchronous Machine



Finally, look at the output of the PWM inverter. Because nothing of interest can be seen at the simulation time scale, the graph concentrates on the last moments of the simulation.

# Asynchronous Machine

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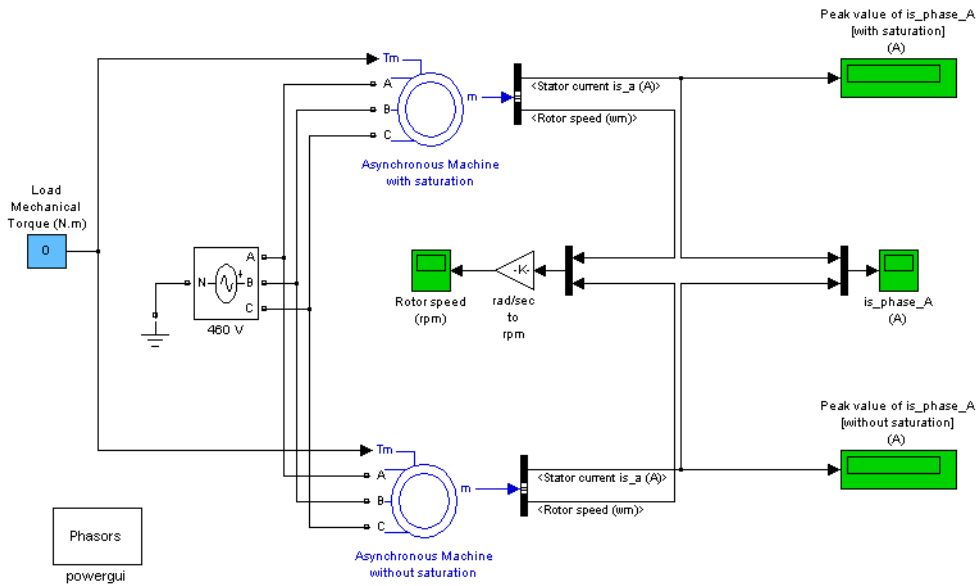


## Example 2: Effect of Saturation of the Asynchronous Machine Block

The power\_asm\_sat demo illustrates the effect of saturation of the Asynchronous Machine block.

Two identical three-phase motors (50 HP, 460 V, 1800 rpm) are simulated with and without saturation, to observe the saturation effects on the stator currents. Two different simulations are realized in the demo.

# Asynchronous Machine



The first simulation, is the no-load steady-state test. The table below contains the values of the **Saturation Parameters** and the measurements obtained by simulating different operating points on the saturated motor (no-load and in steady-state).

Saturation Parameters		Measurements	
Vsat (Vrms L-L)	Isat (peak A)	Vrms L-L	Is_A (peak A)
-	-	120	7.322
230	14.04	230	14.03
-	-	250	16.86
-	-	300	24.04
322	27.81	322	28.39
-	-	351	35.22

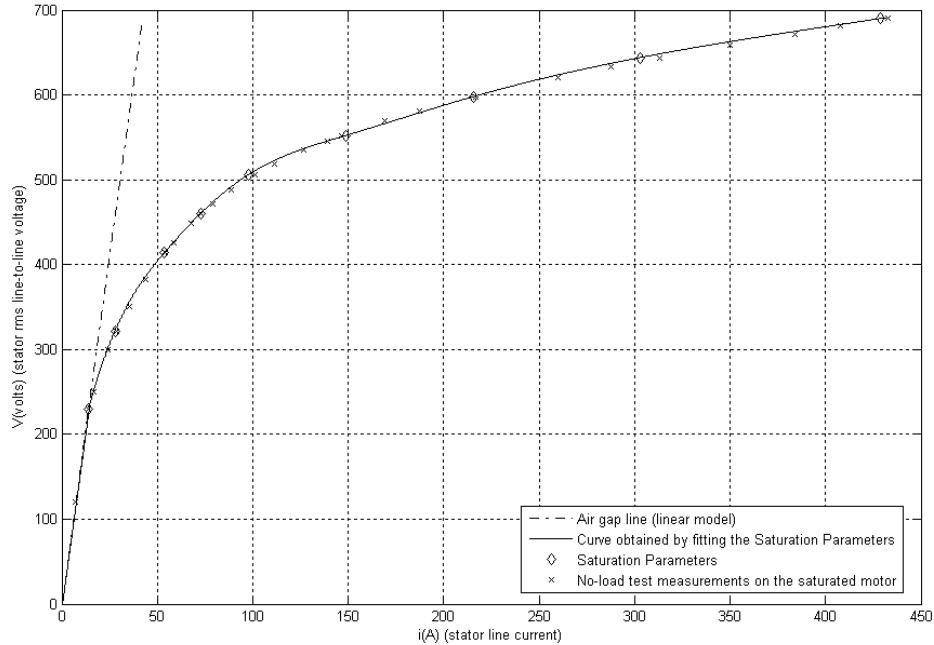
# Asynchronous Machine

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Saturation Parameters		Measurements	
Vsat (Vrms L-L)	Isat (peak A)	Vrms L-L	Is_A (peak A)
-	-	382	43.83
414	53.79	414	54.21
-	-	426	58.58
-	-	449	67.94
460	72.69	460	73.01
-	-	472	79.12
-	-	488	88.43
506	97.98	506	100.9
-	-	519	111.6
-	-	535	126.9
-	-	546	139.1
552	148.68	552	146.3
-	-	569	169.1
-	-	581	187.4
598	215.74	598	216.5
-	-	620	259.6
-	-	633	287.8
644	302.98	644	313.2
-	-	659	350
-	-	672	383.7
-	-	681	407.9
690	428.78	690	432.9



The graph below illustrates these results and shows the accuracy of the saturation model. As you can see, the measured operating points fit well the curve that is plotted from the **Saturation Parameters** data.



Running the simulation with a blocked rotor or with many different values of load torque will allow the observation of other effects of saturation on the stator currents.

## References

[1] Krause, P.C., O. Wasynczuk, and S.D. Sudhoff, *Analysis of Electric Machinery*, IEEE Press, 2002.

# Asynchronous Machine

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[2] Mohan, N., T.M. Undeland, and W.P. Robbins, *Power Electronics: Converters, Applications, and Design*, John Wiley & Sons, Inc., New York, 1995, Section 8.4.1.

## See Also

Powergui

## Purpose

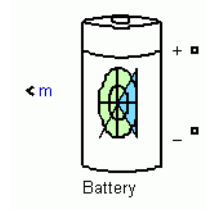
Implement generic battery model

## Library

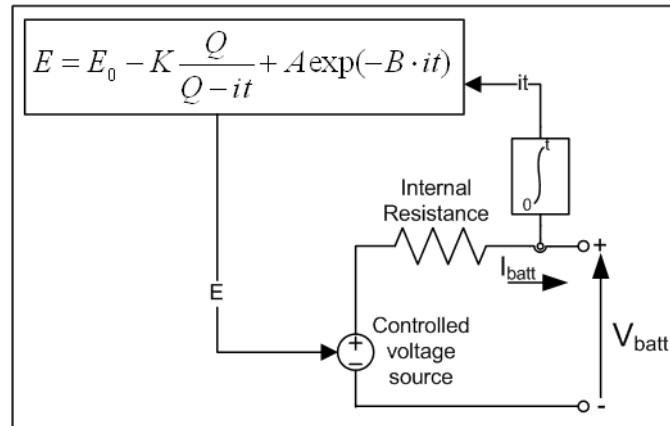
Electrical Sources, Electric Drives/Extra Sources

## Description

The Battery block implements a generic model parameterized to represent most popular types of rechargeable batteries.



The equivalent circuit of the battery is shown below:



where,

$E$  = No load voltage (V)

$E_0$  = Constant voltage (V)

$K$  = Polarization voltage (V)

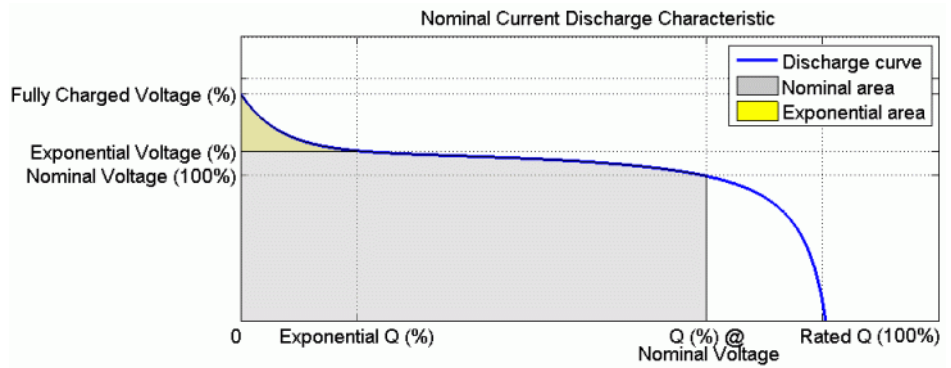
$Q$  = Battery capacity (Ah)

$A$  = Exponential voltage (V)

$B$  = Exponential capacity (Ah)<sup>-1</sup>

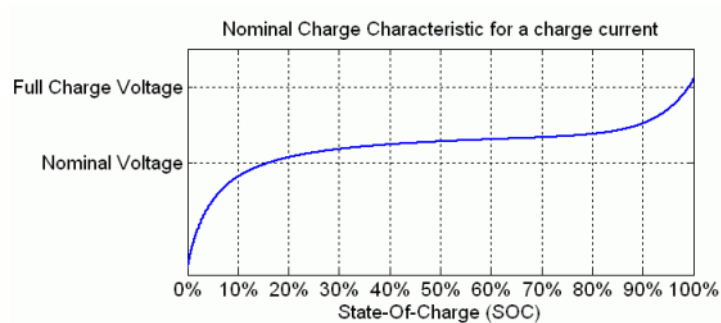
All the parameters of the equivalent circuit can be modified to represent a particular battery type, based on its discharge characteristics. A typical discharge curve is composed of three sections:

# Battery



The first section represents the exponential voltage drop when the battery is fully charged. The width of this region depends on the battery type. The second section represents the charge that can be extracted from the battery until the voltage drops below the battery nominal voltage. Finally, the third section represents the total discharge of the battery, when the voltage drops rapidly.

When the battery current is negative, the battery will recharge following a charge characteristic as shown below:



Note that all the parameters of the model are deduced from discharge characteristics and assumed to be the same for charging.

## Dialog Box and Parameters

**Block Parameters: Battery**

Battery [mask]  
Implements a generic battery model which can be modified to represent most popular battery type.  
Use a preset model to load typical discharge curve and enter the nominal voltage and the rated capacity of the desired battery

Parameters

Battery type: Nickel-Metal-Hydride

Nominal Voltage (V): 200

Rated Capacity (Ah): 6.5

Initial State-Of-Charge (%): 100

Show detailed parameters

Fully charged voltage (%): 117

Nominal Discharge Current (% of Rated Capacity): 20

Internal Resistance (Ohms): 0.76923

Capacity (% of Rated Capacity) @ Nominal Voltage: 80

Exponential zone [Voltage (%), Capacity (% of Rated Capacity)]: [105 20]

Plot Discharge Characteristics

Discharge current [i1, i2, i3,...] (amps): [6.5 13 32.5]

Units: Time

OK Cancel Help Apply

### Battery type

Provides a set of predetermined discharge curves for four types of battery:

- No (User-Defined)
- Lead-Acid
- Lithium-Ion
- Nickel-Cadmium

- Nickel-Metal-Hydride

Select one of these preset models to load the corresponding parameters in the entries of the dialog box. Select **No (User-Defined)** if you do not want to use a preset model.

When one of the preset models is used, the detailed parameters (that are visible when you select the **Show detailed parameters** check box) cannot be modified. If you want to modify the discharge curve, select the desired battery type to load the default parameters, and then select **No (User-Defined)** to access the detailed parameters.

### **Nominal Voltage**

The nominal voltage of the battery (Volts).

### **Rated Capacity**

The rated capacity (Q) of the battery in ampere-hour. The rated capacity is the minimum effective capacity of the battery. The maximum theoretical capacity (when the voltage crosses 0 volts) is generally equal to 105% of the rated capacity. So when you enter the rated capacity, the maximum Q is  $1.05 \cdot Q$ .

### **Initial State-Of-Charge**

The initial State-Of-Charge (SOC %) of the battery. 100% indicates a fully charged battery and 0% indicates an empty battery. This parameter is used as an initial condition for the simulation and does not affect the discharge curve.

### **Show detailed parameters**

If selected, the dialog box displays the detailed parameters of the Battery block. The detailed parameters can be modified by setting **Battery type** to **No (User-Defined)**.

### **Full charge voltage**

The voltage factor (% of the nominal voltage) corresponding to the fully charged voltage, for a given nominal discharge current. For example, a battery cell with a nominal voltage of 1 volt and a fully

charged voltage factor of 110% has a fully charged voltage of 1.1 volt. Note that the fully charged voltage is not the no-load voltage.

### **Nominal Discharge Current**

The nominal discharge current (% of the rated capacity/1hour), for which the discharge curve has been measured. For example, a typical discharge current for a 1.5 Ah NiMH battery is 20%: ( $0.2 * 1.5 \text{ Ah} / 1 \text{ h} = 0.3 \text{ A}$ ).

### **Internal Resistance**

The internal resistance of the battery (ohms). When a preset model is used, a generic value is loaded, corresponding to the nominal voltage and the rated capacity of the battery. The resistance is supposed to be constant during the charge and the discharge cycles and does not vary with the amplitude of the current.

### **Capacity @ Nominal Voltage**

The capacity (% of the rated capacity) extracted from the battery until the voltage drops under the nominal voltage. This value should be between 0% and 100%.

### **Exponential zone**

The voltage (% of the nominal voltage) corresponding to the end of the exponential zone. For example, a battery with a nominal voltage of 1 volt and an exponential voltage of 105% indicates that the exponential zone ends at 1.05 volt. The capacity (% of the rated capacity) extracted from the battery until the voltage drops under the exponential voltage. This value should be between 0% and 100%.

### **Plot Discharge Characteristics**

Plots a figure containing two graphs. The first graph represents the nominal discharge curve (at the **Nominal Discharge Current**) and the second graph represents the discharge curves at the specified discharge currents. When the check box is selected, the graph remains on and updates itself when a parameter changes in the dialog box. To clear the figure, clear the check box and close the figure.

# Battery

## Discharge current

Allows to specify different values of discharge current. The discharge characteristics for these currents are presented in the second part of the graph.

## Units

Choose either Time or Ampere-hour as the x-axis for the plot.

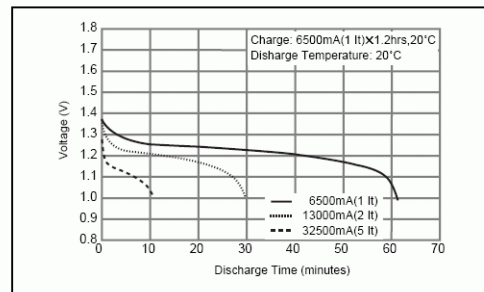
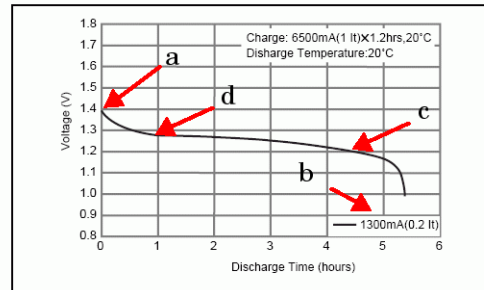
## How to Extract Parameters from Datasheet

Here is the procedure to extract the detailed parameters from a discharge curve. For this example, the Panasonic NiMH-HHR650D datasheet has been taken:

### Specifications

		mm	inch
Diameter		33.0+0/-0.1	1.3+0/-0.04
Height		61+0/-1.5	2.40+0/-0.08
Approximate Weight		Grams	Ounces
		170	6.0
Nominal Voltage		1.2V	
Discharge Capacity*	Average**	6800 mAh	
	Rated (Min.)	6500 mAh	
Approx. Internal impedance at 1000Hz at charged state.		2mΩ	
Charge	Standard	650mA (0.1It) x 16hrs.	
	Rapid	6500mA (1It) x 1.2 hrs.	
Ambient Temperature	Charge	Standard	0°C to 45°C 32°F to 113°F
		Rapid	0°C to 40°C 32°F to 104°F
	Discharge	Standard	-10°C to 65°C 14°F to 149°F
		Rapid	-20°C to 45°C -4°F to 113°F
Storage	< 2 years	-20°C to 45°C -4°F to 113°F	
	< 6 months	-20°C to 55°C -4°F to 131°F	

### Typical Discharge Characteristics





The nominal voltage is 1.2 V and the rated capacity is 6.5 Ah. The following detailed parameters are deduced from the Typical Discharge Characteristics above.

- Fully Charged voltage factor (a) =  $(1.4 \text{ Volt} / 1.2 \text{ Volt}) * 100 = 116.6\%$
- Nominal Discharge Current (b) =  $1.3\text{A} / (6.5\text{Ah} / 1\text{hr}) * 100 = 20\%$  (0.2 it)
- Internal Resistance (use the generic resistance of the model for a 1.2 V, 6.5 Ah) = 0.0046 ohms. This value fits better the three others discharge current shown in the second figure (6500 mA, 13000 mA and 32500 mA).
- Capacity @ Nominal Voltage (c) =  $(4.5 \text{ hours} / 5.5 \text{ hours}) * 100 = 81\%$
- Exponential Voltage factor (d) =  $(1.27 \text{ Volt} / 1.2 \text{ Volt}) * 100 = 105.8\%$
- Exponential Capacity factor (d) =  $(1 \text{ hour} / 5.5 \text{ hours}) * 100 = 18.18\%$

These parameters are approximate and depend on the precision of the points obtained on the discharge curve.

With these parameters (shown in the dialog box in the next figure), the discharge curves (dot lines) are similar to the datasheet curves.

# Battery

Parameters

Battery type: No (User-Defined)

Nominal Voltage (V): 1.2

Rated Capacity (Ah): 6.5

Initial State-Of-Charge (%): 100

..... Show detailed parameters .....  
 ..... Hide detailed parameters .....

Full charge voltage (%): 116.6

Nominal Discharge Current (% of Rated Capacity): 20

Internal Resistance (Ohms): 0.0046154

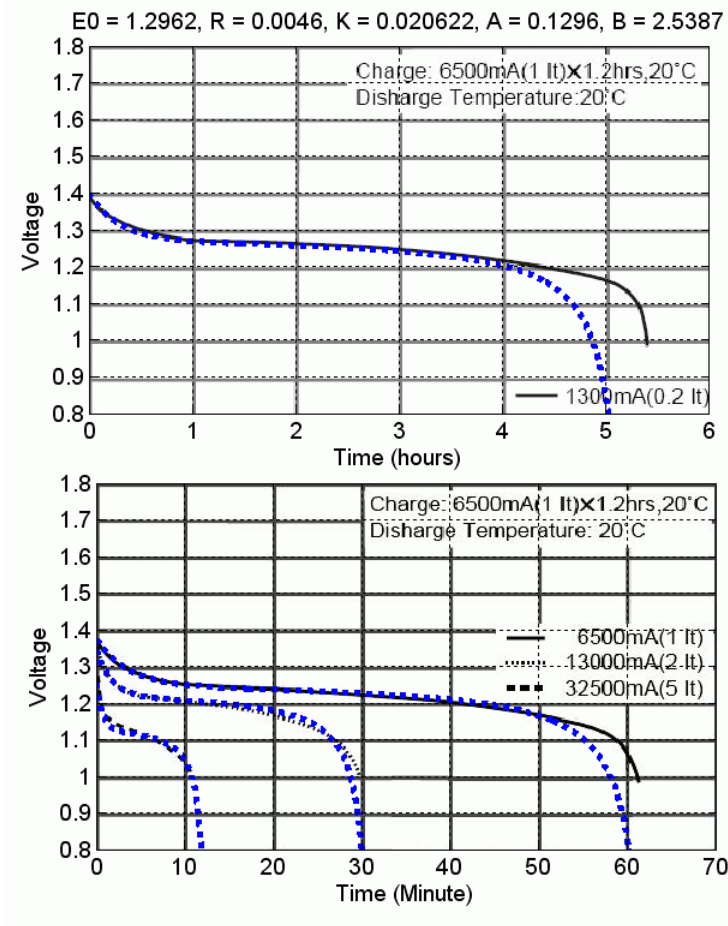
Capacity (% of Rated Capacity) @ Nominal Voltage: 81

Exponential zone [Voltage (%), Capacity (% of Rated Capacity)]: [105.8 18.18]

Plot Discharge Characteristics

Discharge current [i1, i2, i3...] (amps): [6.5 13 32.5]

Units: Time



## Block Inputs and Outputs

### SOC (%)

The State-Of-Charge of the battery (between 0 and 100%). The SOC for a fully charged battery is 100% and for an empty battery is 0%. The SOC is calculated as:

# Battery

---

$$SOC = 100 \left( 1 - \frac{Q \cdot 1,05}{\int i dt} \right)$$

V+, V-

The two electrical terminals of the battery.

## Assumptions

- 1 The internal resistance is supposed constant during the charge and the discharge cycles and does not vary with the amplitude of the current.
- 2 The parameters of the model are deduced from discharge characteristics and assumed to be the same for charging.
- 3 The capacity of the battery doesn't change with the amplitude of current (No Peukert effect).
- 4 The temperature doesn't affect the model's behavior.
- 5 The Self-Discharge of the battery is not represented. It can be represented by adding a large resistance in parallel with the battery terminals.
- 6 The battery has no memory effect.

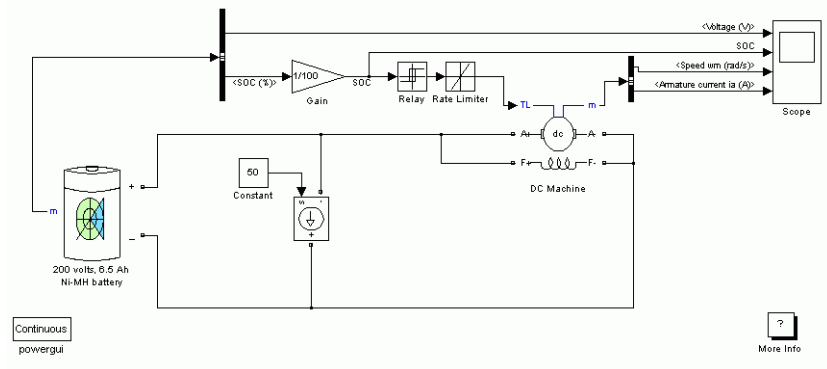
## Limitations

- 1 The minimum no-load battery voltage is 0 volt and the maximum battery voltage is not limited.
- 2 The minimum capacity of the battery is 0 Ah and the maximum capacity is not limited. So the maximum SOC can be greater than 100% if the battery is overcharged.

## Example

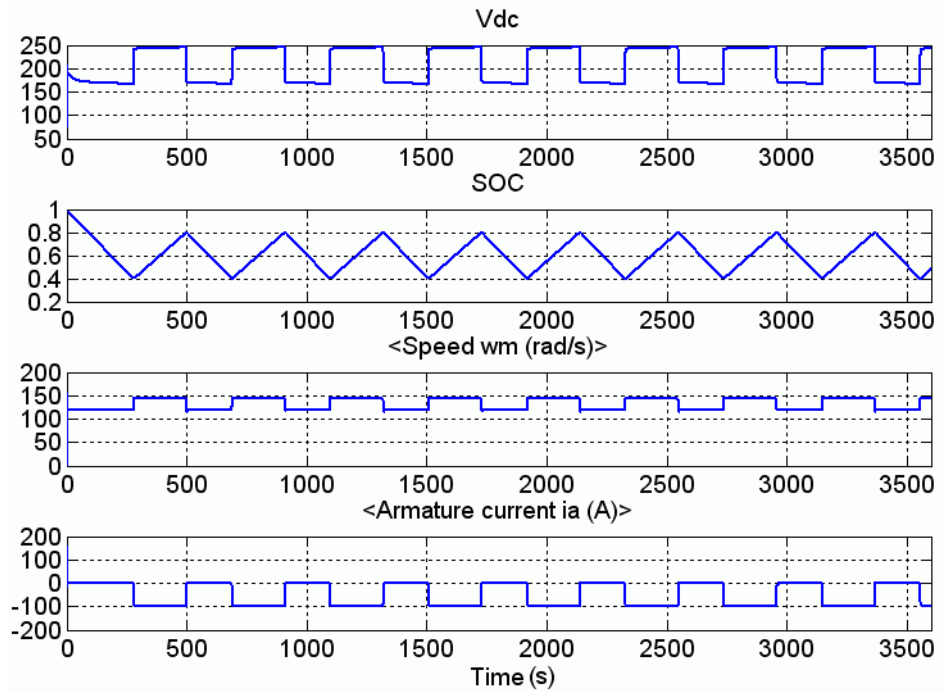
The power\_battery demo illustrates a 200 volts, 6.5 Ah NiMH battery connected to a constant load of 50 A. The DC machine is connected in parallel with the load and operates at no load torque. When the State-Of-Charge (SOC) of the battery goes under 0.4 (40%), a negative load torque of 200 Nm is applied to the machine so it acts as a generator

to recharge the battery. When the SOC goes over 80%, the load torque is removed so only the battery will supply the 50 amps load.



The simulation produces the followings results:

# Battery

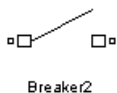
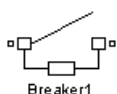
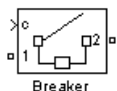


At the start of the simulation, the DC machine is started with the battery power. The speed increases to 120 rad/s. The battery is also discharged by the constant DC load of 50 amps. When the SOC drops under 0.4, a mechanical torque of -200 Nm is applied so the machine acts as a generator and provides a current of 100 amps. Hence, 50 amps goes to the load and 50 amps goes to recharge the battery. When the SOC goes over 0.8, the mechanical torque is removed and the machine operates freely. And then the cycle restarts.

**Purpose** Implement circuit breaker opening at current zero crossing

**Library** Elements

## Description



The Breaker block implements a circuit breaker where the opening and closing times can be controlled either from an external Simulink signal (external control mode), or from an internal control timer (internal control mode).

A series Rs-Cs snubber circuit is included in the model. It can be connected to the circuit breaker. If the Breaker block happens to be in series with an inductive circuit, an open circuit or a current source, you must use a snubber.

When the Breaker block is set in external control mode, a Simulink input appears on the block icon. The control signal connected to the Simulink input must be either 0 or 1 (0 to open the breaker, 1 to close it).

When the Breaker block is set in internal control mode, the switching times are specified in the dialog box of the block.

When the breaker is closed, it is represented by a resistance  $R_{on}$ . The  $R_{on}$  value can be set as small as necessary in order to be negligible compared with external components (a typical value is 10 mohms). When the breaker is open, it has an infinite resistance.

The arc extinction process is simulated by opening the breaker device when its current passes through 0 at the first current zero crossing following the transition of the Simulink control input from 1 to 0.

Operation	Conditions
The Breaker closes when	Control signal goes to 1 (for discrete systems, control signal must stay at 1 for at least 3 times the sampling period)
The Breaker opens when	Control signal goes to 0 Breaker current passes through 0

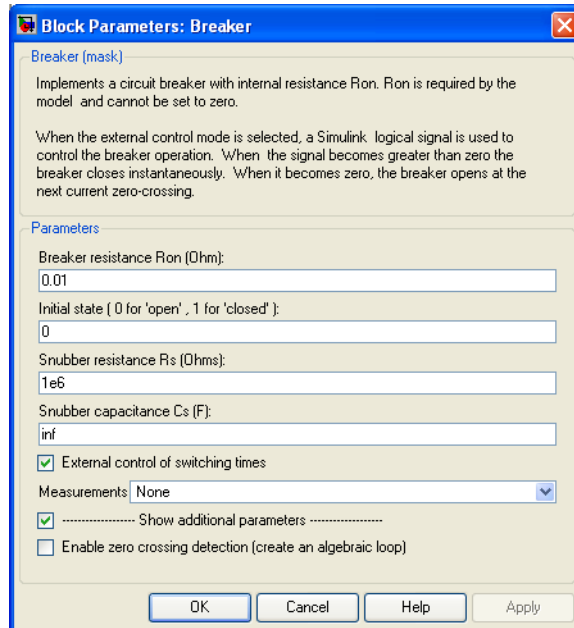
# Breaker

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**Note** The Breaker block may not be the appropriate switching device to use for DC circuits. For such applications, it is recommended that you use the Ideal Switch block as a switching device.

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## Dialog Box and Parameters



### Breaker resistance Ron

The internal breaker resistance, in ohms ( $\Omega$ ). The **Breaker resistance Ron** parameter cannot be set to 0.

### Initial state

The initial state of the breaker. A closed contact is displayed in the block icon when the **Initial state** parameter is set to 1, and an open contact is displayed when it is set to 0.



If the breaker initial state is set to 1 (closed), the software automatically initializes all the states of the linear circuit and the Breaker block initial current, so that the simulation starts in steady state.

### **Snubber resistance $R_s$**

The snubber resistance, in ohms ( $\Omega$ ). Set the **Snubber resistance  $R_s$**  parameter to `inf` to eliminate the snubber from the model.

### **Snubber capacitance $C_s$**

The snubber capacitance, in farads (F). Set the **Snubber capacitance  $C_s$**  parameter to `0` to eliminate the snubber, or to `inf` to get a resistive snubber.

### **Switching times**

Specifies the vector of switching times when using the Breaker block in internal control mode. At each switching time the Breaker block opens or closes depending on its initial state. For example, if the **Initial state** parameter is `0` (open), the breaker closes at the first switching time, opens at the second switching time, and so on. The **Switching times** parameter is not visible in the dialog box if the **External control of switching times** parameter is selected.

### **External control of switching times**

If selected, adds a Simulink input to the Breaker block for external control of the switching times of the breaker. The switching times are defined by a logical signal (`0` or `1`) connected to the Simulink input.

### **Measurements**

Select **Branch voltage** to measure the voltage across the Breaker block terminals.

Select **Branch current** to measure the current flowing through the Breaker block. If the snubber device is connected to the breaker model, the measured current is the one flowing through the breaker contacts only.

# Breaker

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Select **Branch voltage** and **current** to measure the breaker voltage and the breaker current.

Place a Multimeter block in your model to display the selected measurements during the simulation.

In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name:

Measurement	Label
Branch voltage	Ub:
Branch current	Ib:

## Limitations

When the block is connected in series with an inductor or another current source, you must add the snubber circuit. In most applications you can use a resistive snubber (**Snubber capacitance** parameter set to `inf`) with a large resistor value (**Snubber resistance** parameter set to `1e6` or so). Because of modeling constraints, the internal breaker inductance `Ron` cannot be set to 0.

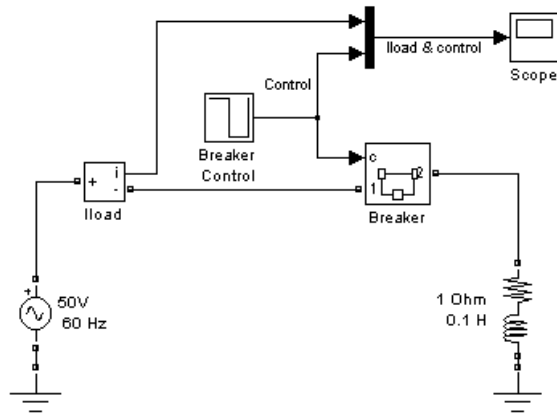
You must use a stiff integration algorithm to simulate circuits with the Breaker block. `ode23tb` with default parameters usually gives the best simulation speed.

For discretized models, the control signal must stay at 1 for a minimum of 3 sampling time periods to correctly close the Breaker block, otherwise the device stays open.

## Example

The `power_breaker` demo illustrates a circuit breaker connected in series with a series RL circuit on a 60 Hz voltage source. The switching times of the Breaker block are controlled by a Simulink signal. The breaker device is initially closed and an opening order is given at  $t = 1.5$  cycles, when current reaches a maximum. The current stops at

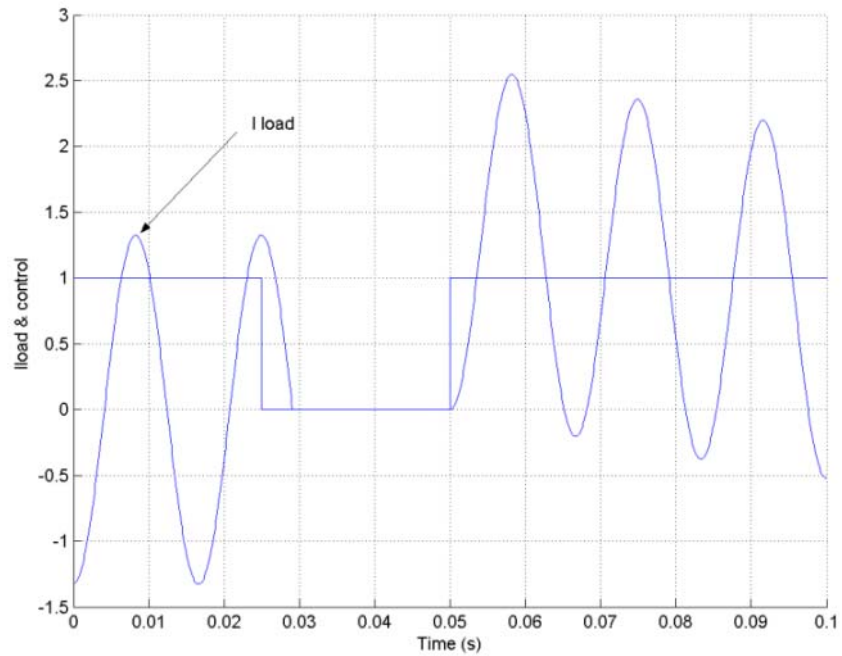
the next zero crossing, then the breaker is reclosed at a zero crossing of voltage at  $t = 3$  cycles.



Simulation produces the following results.

# Breaker

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Note that the breaker device opens only when the load current has reached zero, after the opening order.

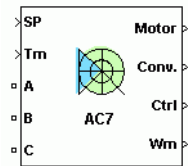
## See Also

Three-Phase Fault

**Purpose** Implement brushless DC motor drive using Permanent Magnet Synchronous Motor (PMSM) with trapezoidal back electromotive force (BEMF)

**Library** Electric Drives/AC drives

**Description**



The high-level schematic shown below is built from six main blocks. The PMSM, the three-phase inverter, and the three-phase diode rectifier models are provided with the SimPowerSystems library. The speed controller, the braking chopper, and the current controller models are specific to the Electric Drives library. It is possible to use a simplified version of the drive containing an average-value model of the inverter for faster simulation.

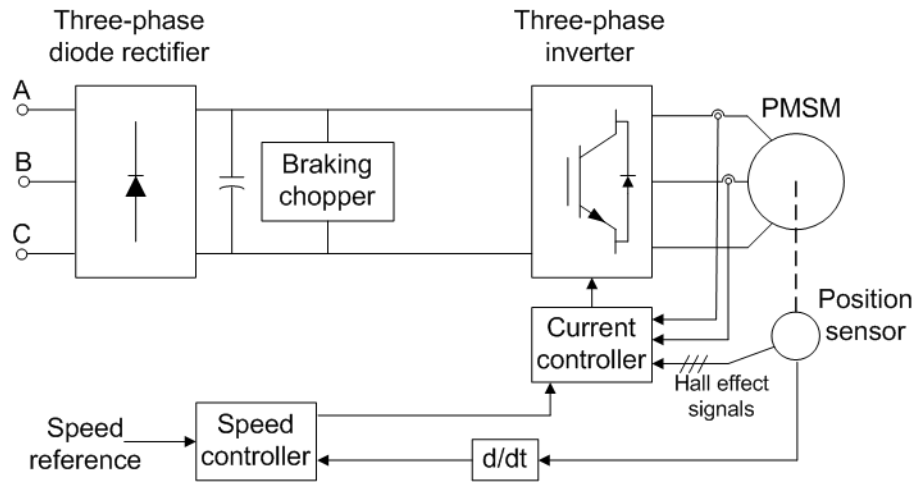
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**Note** In SimPowerSystems software, the Brushless DC Motor Drive block is commonly called the AC7 motor drive.

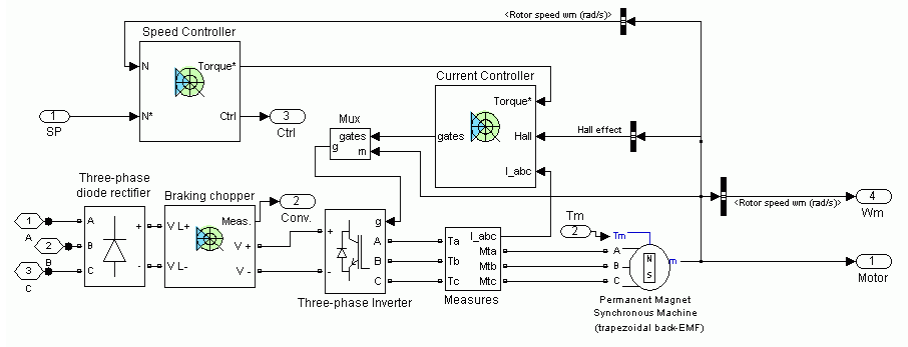
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# Brushless DC Motor Drive

## High-Level Schematic



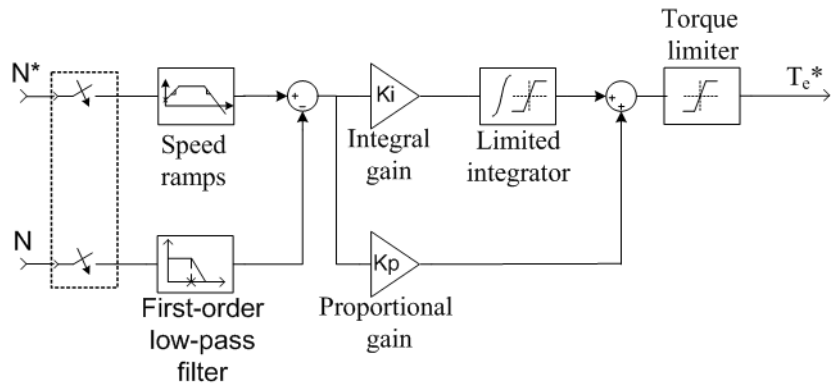
## Simulink Schematic



## Speed Controller

The speed controller is based on a PI regulator, shown below. The output of this regulator is a torque set point applied to the current controller block.

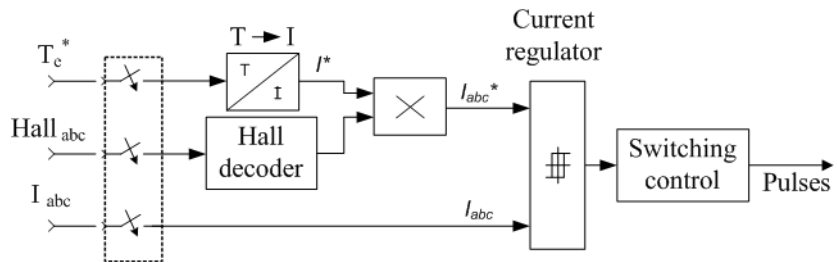
## Speed controller



## Current Controller

The current controller contains four main blocks, shown below. These blocks are described below.

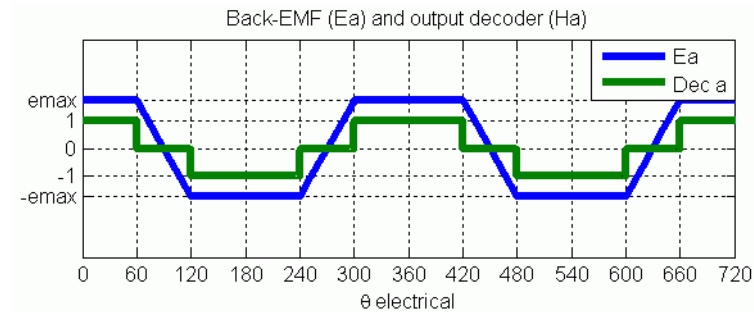
### Current controller



The  $T$ - $I$  block performs the conversion from the reference torque to the peak reference current. The relation used to convert torque to current assumes pure rectangular current waveforms. In practice, due to the motor inductance, it's impossible to obtain these currents. Therefore the electromagnetic torque may be lower than the reference torque, especially at high speed.

# Brushless DC Motor Drive

The *Hall decoder* block is used to extract the BEMF information from the Hall effect signals. The outputs, three-level signals (-1, 0, 1), represent the normalized ideal phase currents to be injected in the motor phases. These type of currents will produce a constant torque. The following figure shows the BEMF of phase A and the output of the Hall decoder for the phase A.



The *current regulator* is a bang-bang current controller with adjustable hysteresis bandwidth.

The *Switching control* block is used to limit the inverter commutation frequency to a maximum value specified by the user.

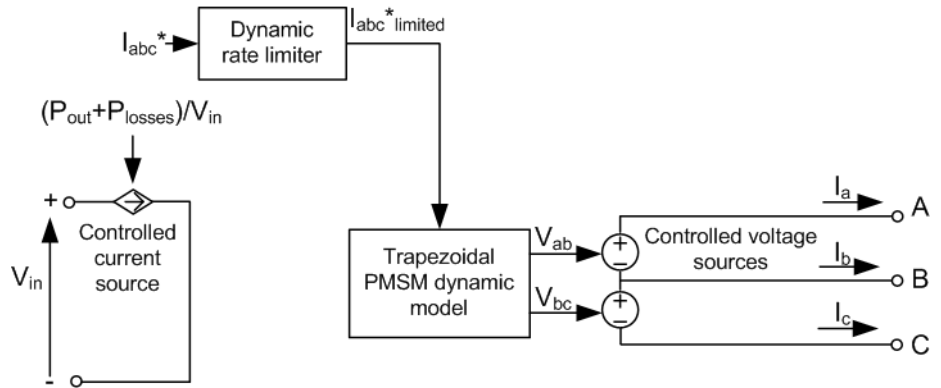
When using the average-value inverter, the *abc* current references are sent to the simplified inverter.

## Braking Chopper

The braking chopper block contains the DC bus capacitor and the dynamic braking chopper, which is used to absorb the energy produced by a motor deceleration.



**Average-Value Inverter** The average-value inverter is shown in the following figure.



It is composed of one controlled current source on the DC side and of two controlled voltage sources on the AC side. The DC current source allows the representation of the DC bus current behavior described by the following equation:

$$I_{dc} = (P_{out} + P_{losses}) / V_{in}$$

with  $P_{out}$  being the output AC power,  $P_{losses}$  the losses in the power electronic devices, and  $V_{in}$  the DC bus voltage.

On the AC side, the voltage sources are fed by the instantaneous voltages provided by the *Trapezoidal PMSM dynamic model* (see PMSM documentation for machine model). This dynamic model takes the reference currents (the rate of these currents has been limited to represent the real life currents), the measured BEMF voltages and the machine speed to compute the terminal voltages to be applied to the machine.

The *dynamic rate limiter* limits the rate of the reference currents when transitions occurs. The rate depends of the inverter saturation degree.

During loss of current tracking due to insufficient inverter voltage, the *dynamic rate limiter* saturates the reference current in accordance to this operation mode.

# Brushless DC Motor Drive

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## Remarks

The model is discrete. Good simulation results have been obtained with a  $2 \mu\text{s}$  time step. To simulate a digital controller device, the control system has two different sampling times:

- Speed controller sampling time
- Current controller sampling time

The speed controller sampling time has to be a multiple of the current controller sampling time. The latter sampling time has to be a multiple of the simulation time step. The average-value inverter allows the use of bigger simulation time steps since it does not generate small time constants (due to the RC snubbers) inherent to the detailed converter. For a current controller sampling time of  $40 \mu\text{s}$ , good simulation results have been obtained for a simulation time step of  $40 \mu\text{s}$ . The simulation time step can, of course, not be higher than the current controller time step.

## Dialog Box

### PM Synchronous Machine Tab

The screenshot shows a dialog box titled "Brushless DC Motor Drive" with a subtitle "Brushless DC Motor Drive". Below the title bar is a text area containing the following text: "The PM synchronous motor parameters are specified in the PMSM tab. The braking chopper, the diode rectifier and the inverter switches parameters are specified in the Converters and DC bus tab. Current controller and speed controller parameters are specified in the controller tab." Below the text area are three tabs: "Permanent Magnet Synchronous Machine" (selected), "Converters and DC bus", and "Controller". The "Permanent Magnet Synchronous Machine" tab is active and contains several parameter groups:

- Electrical parameters:**
  - Back electromotive force: Trapezoidal (dropdown)
  - Equivalent circuit parameters:
    - Resistance (ohm): 0.2
    - Inductance (H): 8.5e-3
    - Back EMF flat area (degrees): 120
  - Flux constant:
    - Specify: Flux linkage established by magnets (V.s) (dropdown), 0.175
  - Initial currents:
    - Phase A (A): 0
    - Phase B (A): 0
- Mechanical parameters:**
  - Rotor values:
    - Inertia (kg\*m<sup>2</sup>): 0.089
    - Friction (N-m-s): 0.005
    - Pole pairs: 4
  - Initial values:
    - Speed (rad/s): 0
    - Angle (deg): 0

At the bottom of the dialog box, there are two dropdown menus: "Model detail level" set to "Detailed" and "Mechanical input" set to "Torque Tm". Below these are "Parameters file options" with "Load" and "Save" buttons. At the very bottom are "OK", "Cancel", "Help", and "Apply" buttons.

The PM synchronous machine tab displays the parameters of the PM synchronous machine block of the powerlib library. Refer to Permanent Magnet Synchronous Machine for more information on the PM synchronous machine parameters.

#### Model detail level

Select between the detailed and the average-value inverter.

#### Mechanical input

Allows you to select either the load torque or the motor speed as mechanical input. Note that if you select and apply a load torque, you will obtain as output the motor speed according to

# Brushless DC Motor Drive

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the following differential equation that describes the mechanical system dynamics:

$$T_e = J \frac{d}{dt} \omega_r + F \omega_r + T_m$$

This mechanical system is included in the motor model.

However if you select the motor speed as mechanical input then you will get the electromagnetic torque as output, allowing you to represent externally the mechanical system dynamics. Note that the internal mechanical system is not used with this mechanical input selection and the inertia and viscous friction parameters are not displayed.

See for example “Mechanical Coupling of Two Motor Drives”.

## Converters and DC Bus Tab

The screenshot shows the 'Brushless DC Motor Drive' software window. The 'Converters and DC bus' tab is active. The interface is divided into several sections:

- Rectifier:** Includes 'Snubbers' (Resistance: 10e3, Capacitance: 20e-9) and 'Diodes' (On-state resistance: 1e-3, Forward voltage: 1.3).
- DC Bus:** Includes 'Capacitance (F): 2000e-6' and 'Braking chopper' (Resistance: 8, Chopper frequency: 4000, Activation voltage: 320, Shutdown voltage: 310).
- Inverter:** Includes 'Switches' (Device type: IGBT / Diodes, On-state resistance: 1e-3, Forward voltages: Main device: 0.8, Diode: 0.8, Turn-off characteristics: Fall time: 1e-6, Tail time: 2e-6) and 'Snubbers' (Resistance: 5000, Capacitance: inf).

At the bottom, there are controls for 'Model detail level' (set to Detailed), 'Mechanical input' (set to Torque Tm), and buttons for 'Load', 'Save', 'OK', 'Cancel', 'Help', and 'Apply'.

### Rectifier section

The rectifier section of the Converters and DC bus tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the Universal Bridge for more information on the universal bridge parameters.

### Inverter section

The inverter section of the Converters and DC bus tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the Universal Bridge for more information on the universal bridge parameters.

# Brushless DC Motor Drive

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The average-value inverter uses the following parameter.

## On-state resistance

The on-state resistance of the inverter switches (ohms).

## DC Bus Field — Capacitance

The DC bus capacitance (F).

## Braking Chopper Section

### Resistance

The braking chopper resistance used to avoid bus over-voltage during motor deceleration or when the load torque tends to accelerate the motor (ohms).

### Frequency

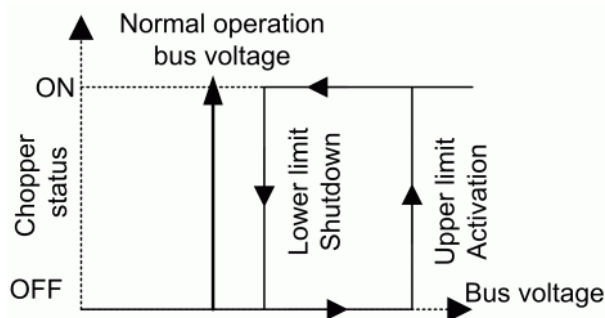
The braking chopper frequency (Hz).

### Activation Voltage

The dynamic braking is activated when the bus voltage reaches the upper limit of the hysteresis band. The following figure illustrates the braking chopper hysteresis logic.

### Deactivation Voltage

The dynamic braking is shut down when the bus voltage reaches the lower limit of the hysteresis band. The chopper hysteresis logic is shown in the following figure.



## Controller Tab

The screenshot shows the 'Controller' tab of the 'Brushless DC Motor Drive' software. The window title is 'Brushless DC Motor Drive'. Below the title bar, there is a text area explaining that PM synchronous motor parameters are in the PMSM tab, braking chopper, diode rectifier, and inverter switches parameters are in the Converters and DC bus tab, and current controller and speed controller parameters are in the controller tab. The 'Controller' tab is selected, with other tabs being 'Permanent Magnet Synchronous Machine' and 'Converters and DC bus'. The 'Regulation type' is set to 'Speed regulation', and a 'Schematic' button is visible. The 'Speed controller' section includes 'Speed ramps (rpm/s)' with 'Acceleration' (1000) and 'Deceleration' (-1000) fields, 'Speed cutoff frequency (Hz)' (285), and 'Speed controller sampling time (s)' (140e-6). The 'PI regulator' section has 'Proportional gain' (3.3) and 'Integral gain' (300). The 'Torque output limits (N-m)' section has 'Negative' (-17.8) and 'Positive' (17.8) fields. The 'Current control' section has 'Sampling time (s)' (20e-6), 'Current controller hysteresis band (A)' (0.01), and 'Maximum switching frequency (Hz)' (20e3). At the bottom, there is a 'Model detail level' dropdown set to 'Detailed', a 'Mechanical input' dropdown set to 'Torque Tm', and 'Parameters file options' with 'Load' and 'Save' buttons. At the very bottom are 'OK', 'Cancel', 'Help', and 'Apply' buttons.

## Regulation Type

This pop-up menu allows you to choose between speed and torque regulation.

## Schematic Button

When you press this button, a diagram illustrating the speed and current controllers schematics appears.

# Brushless DC Motor Drive

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## **Speed Controller section**

### **Speed cutoff frequency**

The speed measurement first-order low-pass filter cutoff frequency (Hz). This parameter is used in speed regulation mode only.

### **Speed controller sampling time**

The speed controller sampling time (s). The sampling time must be a multiple of the simulation time step.

### **Speed Ramps — Acceleration**

The maximum change of speed allowed during motor acceleration (rpm/s). An excessively large positive value can cause DC bus under-voltage. This parameter is used in speed regulation mode only.

### **Speed Ramps — Deceleration**

The maximum change of speed allowed during motor deceleration (rpm/s). An excessively large negative value can cause DC bus overvoltage. This parameter is used in speed regulation mode only.

### **PI Regulator — Proportional Gain**

The speed controller proportional gain. This parameter is used in speed regulation mode only.

### **PI Regulator — Integral Gain**

The speed controller integral gain. This parameter is used in speed regulation mode only.

### **Torque output limits — Negative**

The maximum negative demanded torque applied to the motor by the current controller (N.m).

### **Torque output limits — Positive**

The maximum positive demanded torque applied to the motor by the current controller (N.m).



## Current Controller Section

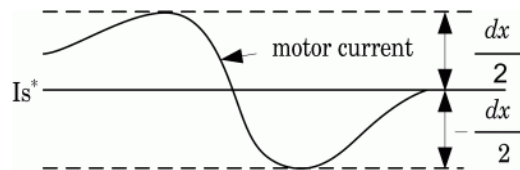
### Sampling Time

The current controller sampling time (s). The sampling time must be a multiple of the simulation time step.

### Current controller hysteresis band

The current hysteresis bandwidth. This value is the total bandwidth distributed symmetrically around the current set point (A). The following figure illustrates a case where the current set point is  $I_s^*$  and the current hysteresis bandwidth is set to  $dx$ .

This parameter is not used when using the average-value inverter.



---

**Note** This bandwidth can be exceeded because a fixed-step simulation is used. A rate transition block is needed to transfer data between different sampling rates. This block causes a delay in the gates signals, so the current may exceed the hysteresis band.

---

### Maximum switching frequency

The maximum inverter switching frequency (Hz). This parameter is not used when using the average-value inverter.

## Block Inputs and Outputs

SP

The speed or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration / deceleration ramps. If the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

# Brushless DC Motor Drive

---

$T_m$  or  $W_m$

The mechanical input: load torque ( $T_m$ ) or motor speed ( $W_m$ ).

A, B, C

The three phase terminals of the motor drive.

$W_m$  or  $T_e$

The mechanical output: motor speed ( $W_m$ ) or electromagnetic torque ( $T_e$ ).

Motor

The motor measurement vector. This vector allows you to observe the motor's variables using the Bus Selector block.

Conv

The three-phase converters measurement vector. This vector contains:

The DC bus voltage

The rectifier output current

The inverter input current

Note that all current and voltage values of the bridges can be visualized with the Multimeter block.

Ctrl

The controller measurement vector. This vector contains:

The torque reference

The speed error (difference between the speed reference ramp and actual speed)

The speed reference ramp or torque reference

# Brushless DC Motor Drive

## Model Specifications

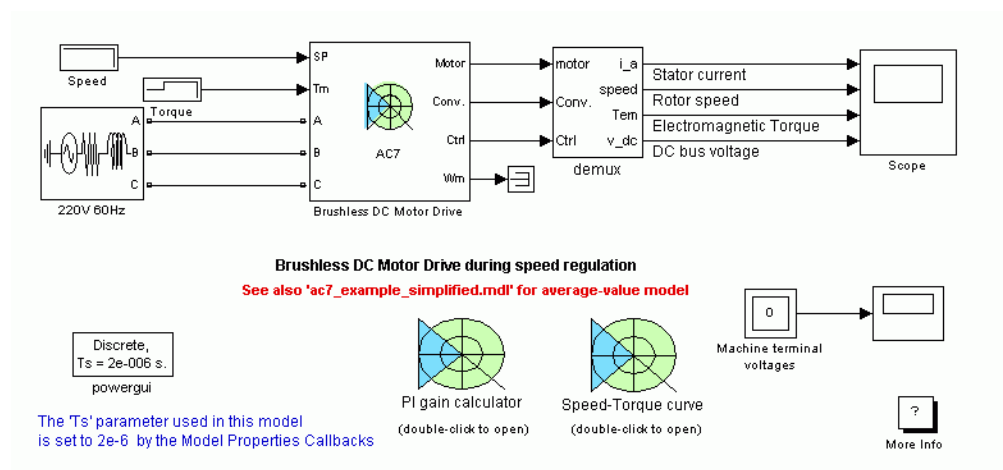
The library contains a 3 hp drive parameter set. The specifications of the 3 hp drive are shown in the following table.

### 3 HP Drive Specifications

Drive Input Voltage		
Amplitude		220 V
Frequency		60 Hz
Motor Nominal Values		
Power		3 hp
Speed		1650 rpm
Voltage		300 Vdc

## Example

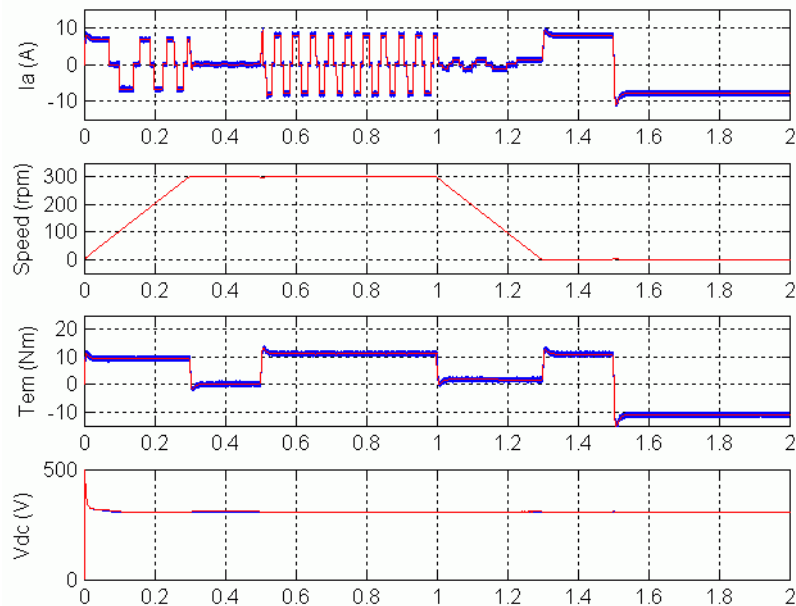
The ac7\_example demo illustrates an AC7 motor drive simulation with standard load condition. At time  $t = 0$  s, the speed set point is 300 rpm.



# Brushless DC Motor Drive

There are two design tools in this example. The first block calculates the gains of the speed regulator in accordance with your specifications. The second block plots the operating regions of the drive. Open these blocks for more information.

As shown in the following figure, the speed precisely follows the acceleration ramp. At  $t = 0.5$  s, the nominal load torque is applied to the motor. At  $t = 1$  s, the speed set point is changed to 0 rpm. The speed decreases to 0 rpm. At  $t = 1.5$  s., the mechanical load passes from 11 N.m to -11 N.m. The next figure shows the results for the detailed converter and for the average-value converter. Observe that the average voltage, current, torque, and speed values are identical for both models. Notice that the higher frequency signal components are not represented with the average-value converter.



**AC7 Example Waveforms (Blue: Detailed Converter, Red: Average-Value Converter)**

## References

- [1] Bose, B. K., *Modern Power Electronics and AC Drives*, Prentice-Hall, N.J., 2002.
- [2] Krause, P. C., *Analysis of Electric Machinery*, McGraw-Hill, 1986.
- [3] Tremblay, O., *Modélisation, simulation et commande de la machine synchrone à aimants à force contre-électromotrice trapézoïdale*, École de Technologie Supérieure, 2006.





# Connection Port


**Purpose** Create Physical Modeling connector port for subsystem

**Library** Elements

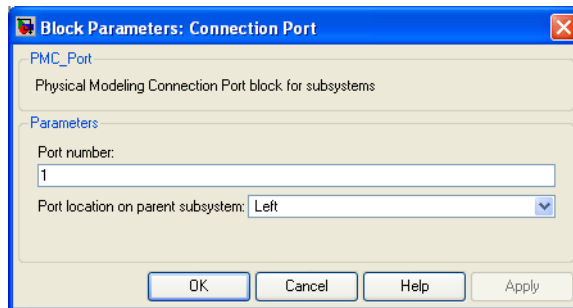
## Description



The Connection Port block, placed inside a subsystem composed of SimPowerSystems blocks, creates a Physical Modeling open round connector port  on the boundary of the subsystem. Once connected to a connection line, the port becomes solid . Once you begin the simulation, the solid port  becomes an electrical terminal port, an open square .

You connect individual SimPowerSystems blocks and subsystems made of SimPowerSystems blocks to one another with SimPowerSystems connection lines, instead of regular Simulink signal lines. These are anchored at the open, round connector ports . Subsystems constructed of SimPowerSystems blocks automatically have such open round connector ports. You can add additional connector ports by adding Connection Port blocks to your subsystem.

## Dialog Box and Parameters



### Port number

This field labels the subsystem connector port created by the block. Multiple connector ports on the boundary of a single subsystem require different numbers as labels. The default value for the first port is 1.

### Port location on parent subsystem

Choose which side of the parent subsystem boundary the port is placed on. The choices are *Left* or *Right*. The default is *Left*.

**See Also**      See “Creating Block Masks” in the Simulink documentation

# Controlled Current Source

---

**Purpose** Implement controlled current source

**Library** Electrical Sources

**Description** The Controlled Current Source block converts the Simulink input signal into an equivalent current source. The generated current is driven by the input signal of the block. The positive current direction is as shown by the arrow in the block icon.



You can initialize the Controlled Current Source block with a specific AC or DC current. If you want to start the simulation in steady state, the block input must be connected to a signal starting as a sinusoidal or DC waveform corresponding to the initial values.

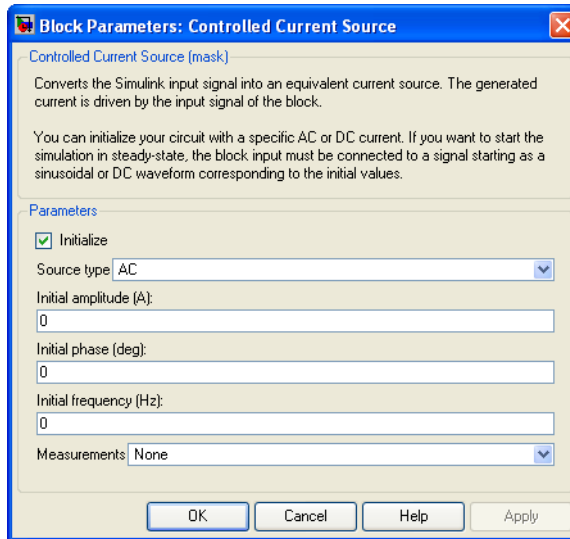
---

**Note** The Simulink input signal needs to be a complex value (phasor) when you are using the Controlled Current Source block in a phasor simulation, because in this case, SimPowerSystems software does not automatically convert the input signal from time-domain into complex (phasor) signal.

---



## Dialog Box and Parameters



### Initialize

If selected, initializes the Controlled Current Source block with the specified **Initial current**, **Initial phase**, and **Initial frequency** parameters.

### Source type

The **Source type** parameter is not visible if the **Initialize** parameter is not selected.

The type of current source. Select **AC** to initialize the Controlled Current Source Block as an AC current source. Select **DC** to initialize the Controlled Current Source block as a DC current.

### Initial current

The **Initial current** parameter is not visible in the dialog box if the **Initialize** parameter is not selected. The initial peak current for the initialization of the source, in amperes (A).

# Controlled Current Source

## Initial phase

The initial phase for the initialization of the source, in degrees.

The **Initial phase** parameter is not visible in the dialog box if the **Source type** parameter is set to **DC**.

## Initial frequency

The initial frequency for the initialization of the source, in hertz (Hz). The **Initial frequency** parameter is not visible in the dialog box if the **Source type** parameter is set to **DC**.

## Measurements

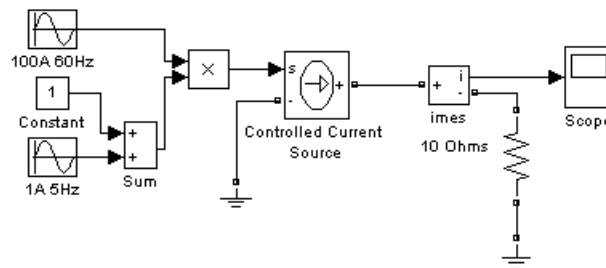
Select **Current** to measure the current flowing through the Controlled Current Source block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name:

Measurement	Label
Current	Isrc:

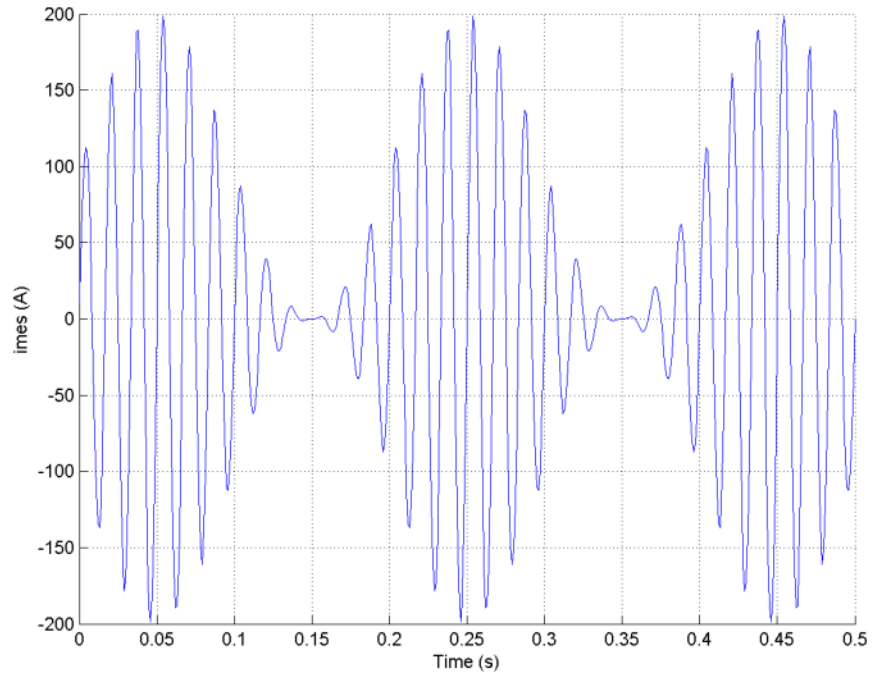
## Example

The power\_controlcurr demo uses a Controlled Current Source to generate a 60 Hz current modulated at 5 Hz.



# Controlled Current Source

Simulation produces the following waveforms:



## See Also

AC Current Source, Controlled Voltage Source, Multimeter

# Controlled Voltage Source

---

**Purpose** Implement controlled voltage source

**Library** Electrical Sources

**Description** The Controlled Voltage Source block converts the Simulink input signal into an equivalent voltage source. The generated voltage is driven by the input signal of the block.



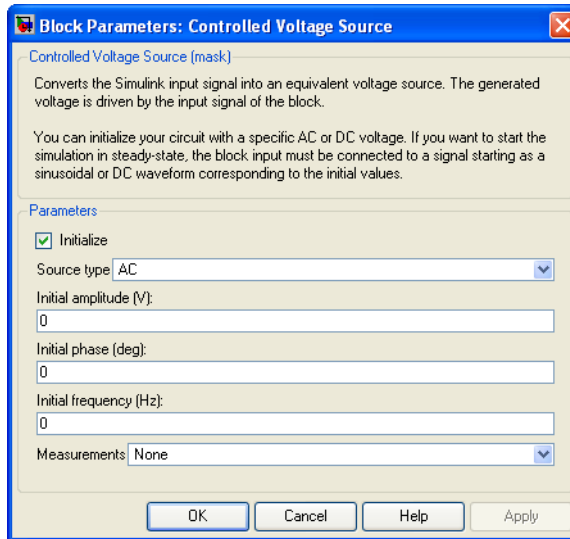
You can initialize the Controlled Voltage Source block with a specific AC or DC voltage. If you want to start the simulation in steady state, the Simulink input must be connected to a signal starting as a sinusoidal or DC waveform corresponding to the initial values.

---

**Note** The Simulink input signal needs to be a complex value (phasor) when you are using the Controlled Voltage Source block in a phasor simulation, because in this case, SimPowerSystems software does not automatically convert the input signal from time-domain into complex (phasor) signal.

---

## Dialog Box and Parameters



### Initialize

If selected, initializes the Controlled Voltage Source block with the specified **Initial voltage**, **Initial phase**, and **Initial frequency** parameters.

### Source type

The **Source type** parameter is not available if the **Initialize** parameter is not selected.

The type of voltage source. Select **AC** to initialize the Controlled Voltage Source block with an AC voltage source. Select **DC** to initialize the Controlled Voltage Source Block with a DC voltage.

### Initial voltage

The **Initial voltage** parameter is not available if the **Initialize** parameter is not selected. The initial voltage for the initialization of the source, in volts (V).

# Controlled Voltage Source

---

## Initial phase

The **Initial phase** parameter is not available if the **Source type** parameter is set to **DC**. The initial phase for the initialization of the source, in degrees.

## Initial frequency

The initial frequency for the initialization of the source, in hertz (Hz). The **Initial frequency** parameter is not available in the dialog box if the **Source type** parameter is set to **DC**.

## Measurements

Select **Voltage** to measure the voltage across the terminals of the Controlled Voltage Source block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name:

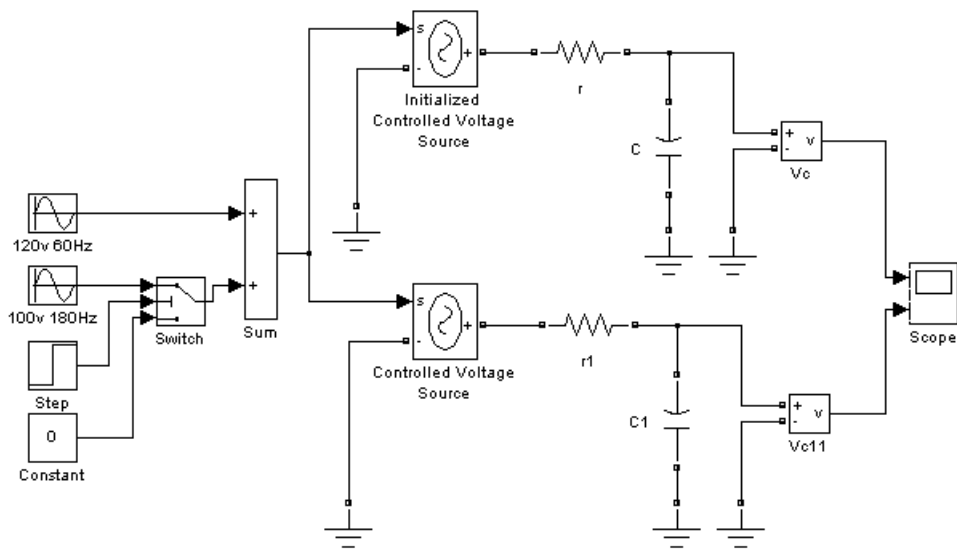
Measurement	Label
Voltage	Usrc:

## Example

The `power_controlvolt` demo uses Controlled Voltage Source blocks to generate a 60 Hz sinusoidal voltage containing a third harmonic. One Controlled Voltage Source block is initialized as a 120 V AC voltage source with an initial frequency of 60 Hz and initial phase set to 0. The second Controlled Voltage Source block is not initialized.

At  $t = 0.0333$  s a 100 V-180 Hz sinusoidal signal is added to the 120 V Simulink signal. The resulting capacitor voltages are compared on a Scope block.

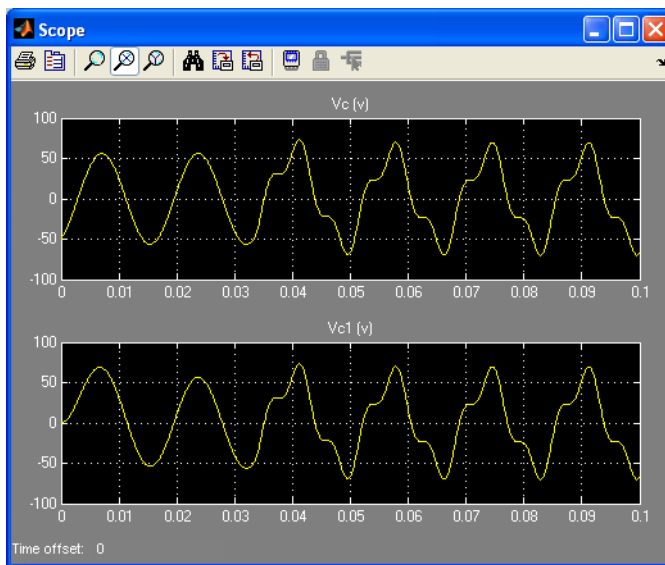
# Controlled Voltage Source



The  $V_c$  voltage starts in steady state, whereas the  $V_{c1}$  voltage contains a DC offset.

# Controlled Voltage Source

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## See Also

AC Current Source, Controlled Current Source, Multimeter



**Purpose** Measure current in circuit

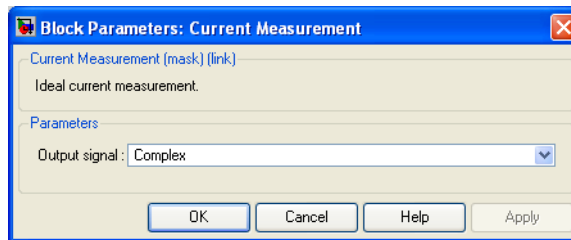
**Library** Measurements

## Description



The Current Measurement block is used to measure the instantaneous current flowing in any electrical block or connection line. The Simulink output provides a Simulink signal that can be used by other Simulink blocks.

## Dialog Box and Parameters



### Output signal

Specifies the format of the output signal when the block is used in a phasor simulation. The **Output signal** parameter is disabled when the block is not used in a phasor simulation. The phasor simulation is activated by a Powergui block placed in the model.

Set to **Complex** to output the measured current as a complex value. The output is a complex signal.

Set to **Real - Imag** to output the real and imaginary parts of the measured current. The output is a vector of two elements.

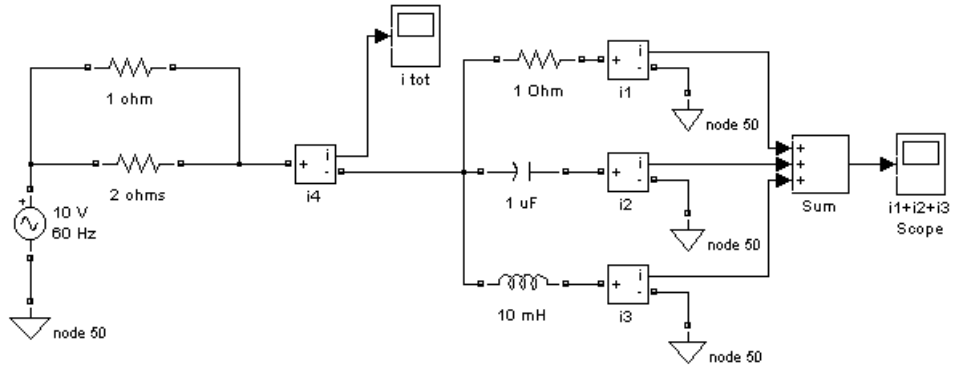
Set to **Magnitude - Angle** to output the magnitude and angle of the measured current. The output is a vector of two elements.

Set to **Magnitude** to output the magnitude of the measured current. The output is a scalar value.

# Current Measurement

## Example

The power\_currmeasure demo uses four Current Measurement blocks to read currents in different branches of a circuit. The two scopes display the same current.



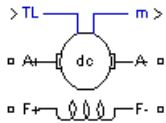
## See Also

Powergui, Three-Phase V-I Measurement, Voltage Measurement

**Purpose** Implement separately excited DC machine

**Library** Machines

## Description



The DC Machine block implements a separately excited DC machine.

An access is provided to the field terminals (F+, F-) so that the machine model can be used as a shunt-connected or a series-connected DC machine. The torque applied to the shaft is provided at the Simulink input  $T_L$ .

The armature circuit (A+, A-) consists of an inductor  $L_a$  and resistor  $R_a$  in series with a counter-electromotive force (CEMF)  $E$ .

The CEMF is proportional to the machine speed.

$$E = K_E \omega$$

$K_E$  is the voltage constant and  $\omega$  is the machine speed.

In a separately excited DC machine model, the voltage constant  $K_E$  is proportional to the field current  $I_f$ :

$$K_E = L_{af} I_f$$

where  $L_{af}$  is the field-armature mutual inductance.

The electromechanical torque developed by the DC machine is proportional to the armature current  $I_a$ .

$$T_e = K_T I_a$$

where  $K_T$  is the torque constant. The sign convention for  $T_e$  and  $T_L$  is

$$T_e T_L > 0 : \text{Motor mode}$$

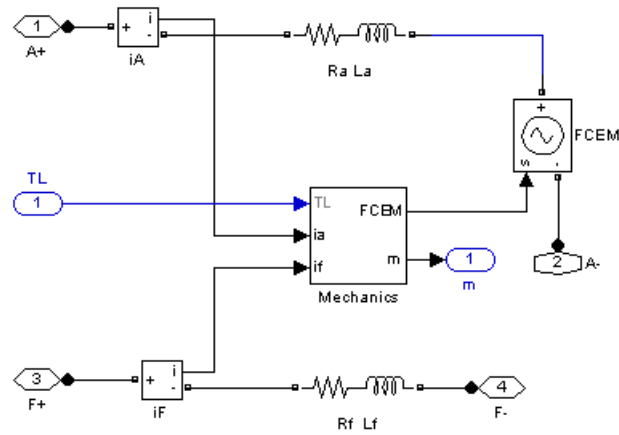
$$T_e T_L < 0 : \text{Generator mode}$$

The torque constant is equal to the voltage constant.

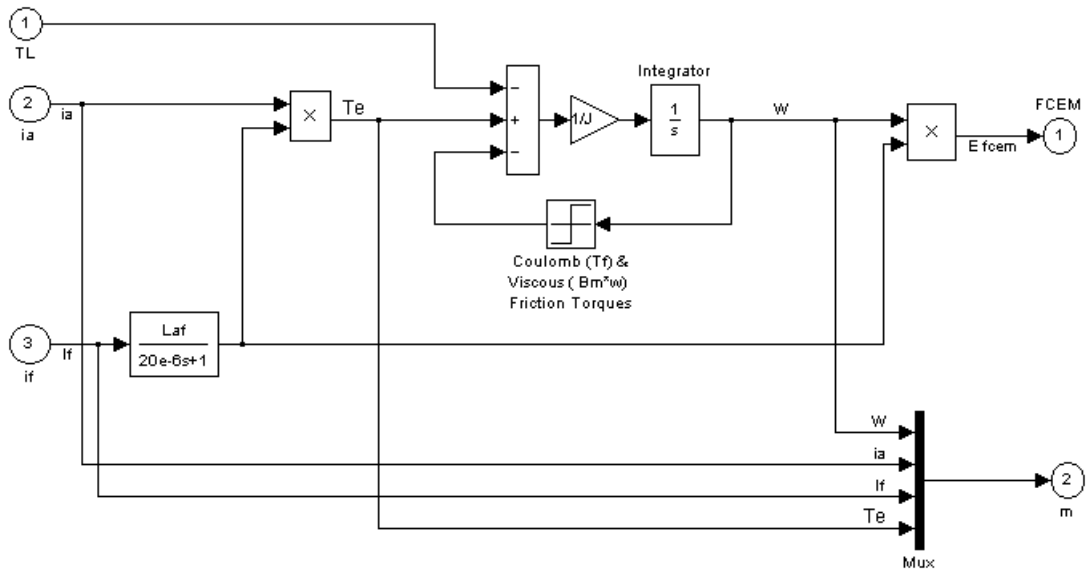
$$K_T = K_E$$

# DC Machine

The armature circuit is connected between the A+ and A- ports of the DC Machine block. It is represented by a series  $R_a L_a$  branch in series with a Controlled Voltage Source and a Current Measurement block.



Mechanical part:



The field circuit is represented by an RL circuit. It is connected between the F+ and F- ports of the DC Machine block.

The mechanical part computes the speed of the DC machine from the net torque applied to the rotor. The speed is used to implement the CEMF voltage E of the armature circuit.

The mechanical part is represented by Simulink blocks that implement the equation

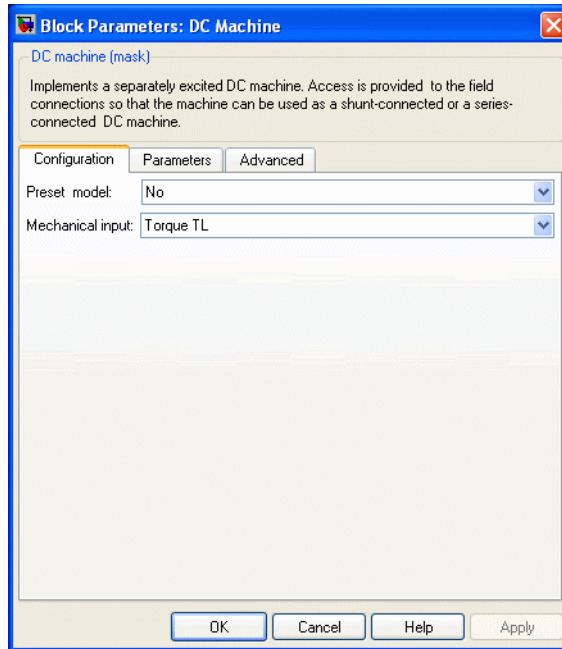
$$J \frac{d\omega}{dt} = T_e - T_L - B_m \omega - T_f$$

where  $J$  = inertia,  $B_m$  = viscous friction coefficient, and  $T_f$  = Coulomb friction torque.

# DC Machine

## Dialog Box and Parameters

### Configuration Tab



### Preset Model

Provides a set of predetermined electrical and mechanical parameters for various DC machine ratings of power (HP), DC voltage (V), rated speed (rpm), and field voltage (V).

Select one of the preset models to load the corresponding electrical and mechanical parameters in the entries of the dialog box. Select No if you do not want to use a preset model.

### Mechanical input

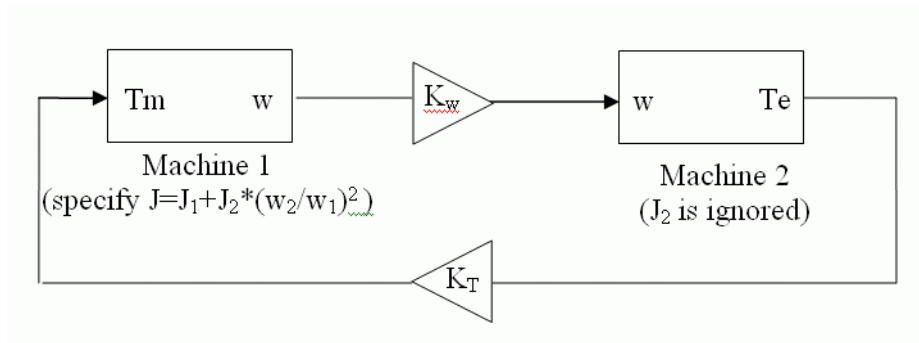
Allows you to select either the torque applied to the shaft or the rotor speed as the Simulink signal applied to the block's input.

Select **Torque  $T_m$**  to specify a torque input, in N.m or in pu, and change labeling of the block's input to  $T_m$ . The machine speed is determined by the machine Inertia  $J$  (or inertia constant  $H$  for the pu machine) and by the difference between the applied mechanical torque  $T_m$  and the internal electromagnetic torque  $T_e$ . The sign convention for the mechanical torque is the following: when the speed is positive, a positive torque signal indicates motor mode and a negative signal indicates generator mode.

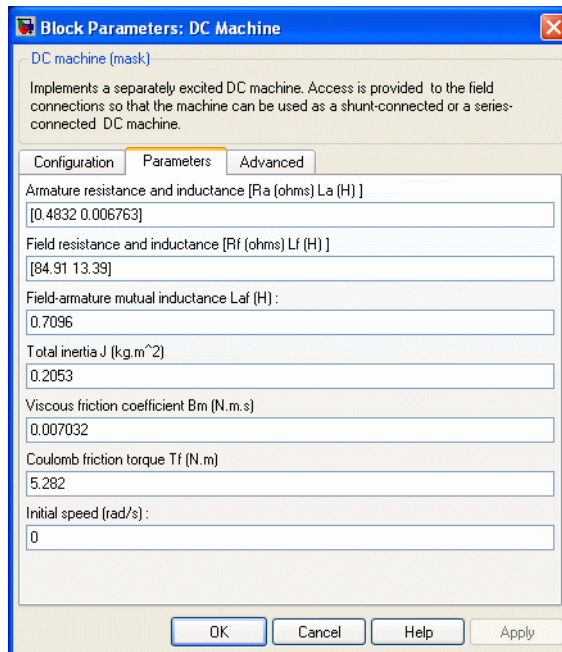
Select **Speed  $w$**  to specify a speed input, in rad/s or in pu, and change labeling of the block's input to  $w$ . The machine speed is imposed and the mechanical part of the model (Inertia  $J$ ) is ignored. Using the speed as the mechanical input allows modeling a mechanical coupling between two machines and interfacing with SimMechanics and SimDriveline models.

The next figure indicates how to model a stiff shaft interconnection in a motor-generator. The speed output of machine 1 (motor) is connected to the speed input of machine 2 (generator), while machine 2 electromagnetic torque output  $T_e$  is applied to the mechanical torque input  $T_m$  of machine 1. The  $K_w$  factor takes into account speed units of both machines (pu or rad/s) and gear box ratio. The  $K_T$  factor takes into account torque units of both machines (pu or N.m) and machine ratings. Also, as the inertia  $J_2$  is ignored in machine 2,  $J_2$  referred to machine 1 speed must be added to machine 1 inertia  $J_1$ .

# DC Machine



## Parameters Tab





**Armature resistance and inductance [Ra La]**

The armature resistance  $R_a$ , in ohms, and the armature inductance  $L_a$ , in henries.

**Field resistance and inductance [Rf Lf]**

The field resistance  $R_f$ , in ohms, and the field inductance  $L_f$ , in henries.

**Field armature mutual inductance Laf**

The field armature mutual inductance, in henries.

**Total inertia J**

The total inertia of the DC machine, in  $\text{kg}\cdot\text{m}^2$ .

**Viscous friction coefficient Bm**

The total friction coefficient of the DC machine, in N.m.s.

**Coulomb friction torque Tf**

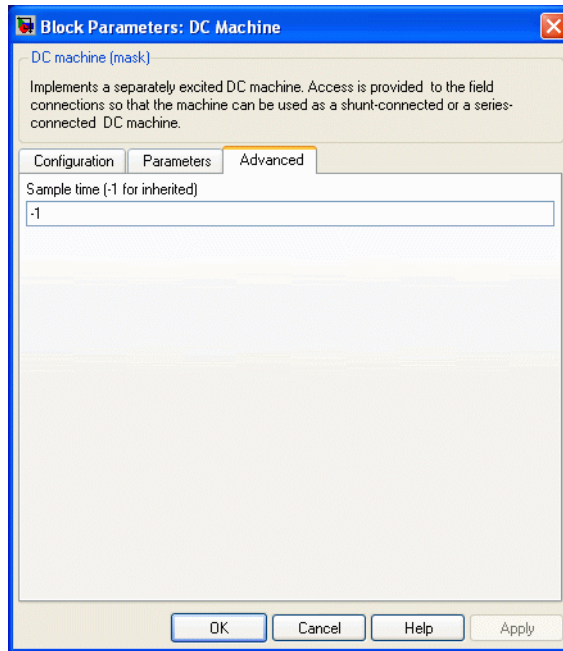
The total Coulomb friction torque constant of the DC machine, in N.m.

**Initial speed**

Specifies an initial speed for the DC machine, in rad/s, in order to start the simulation with a specific initial speed. To start the simulation in steady state, the initial value of the input torque signal  $T_L$  must be proportional to the initial speed.

# DC Machine

## Advanced Tab



### Sample time (-1 for inherited)

Specifies the sample time used by the block. To inherit the sample time specified in the Powergui block, set this parameter to -1.

## Inputs and Outputs

m

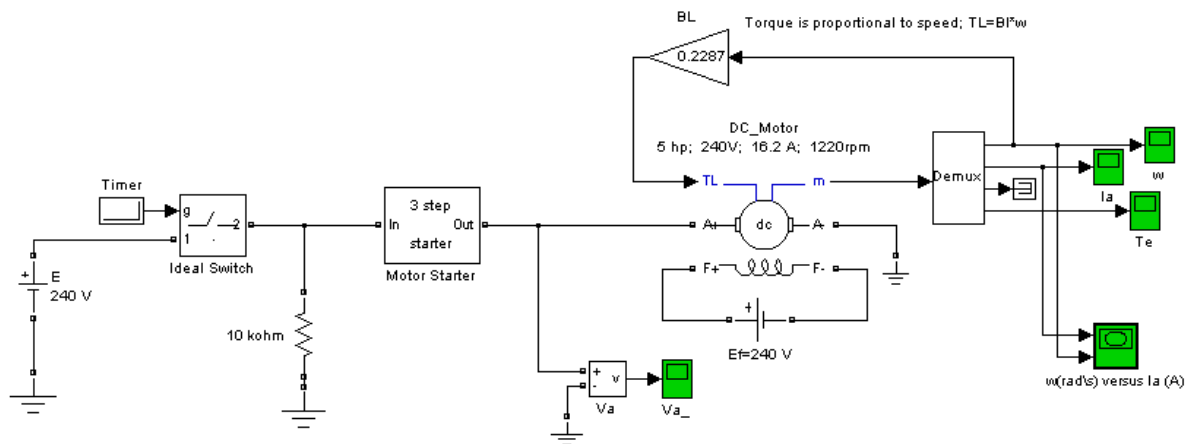
The Simulink output of the block is a vector containing four signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

Signal	Definition	Units
1	Speed $\omega_m$	rad/s
2	Armature current $i_a$	A

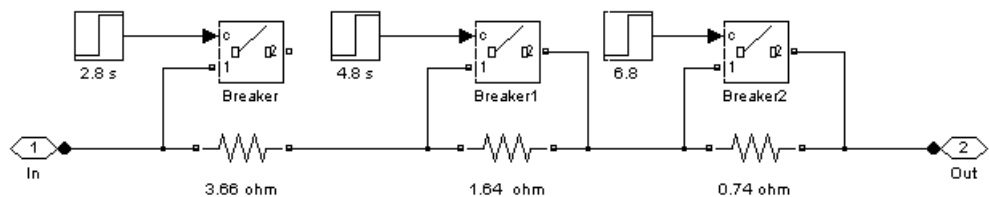
Signal	Definition	Units
3	Field current if	A
4	Electrical torque Te	N.m

## Example

The power\_dcmotor demo illustrates the starting of a 5 HP 240 V DC machine with a three-step resistance starter.

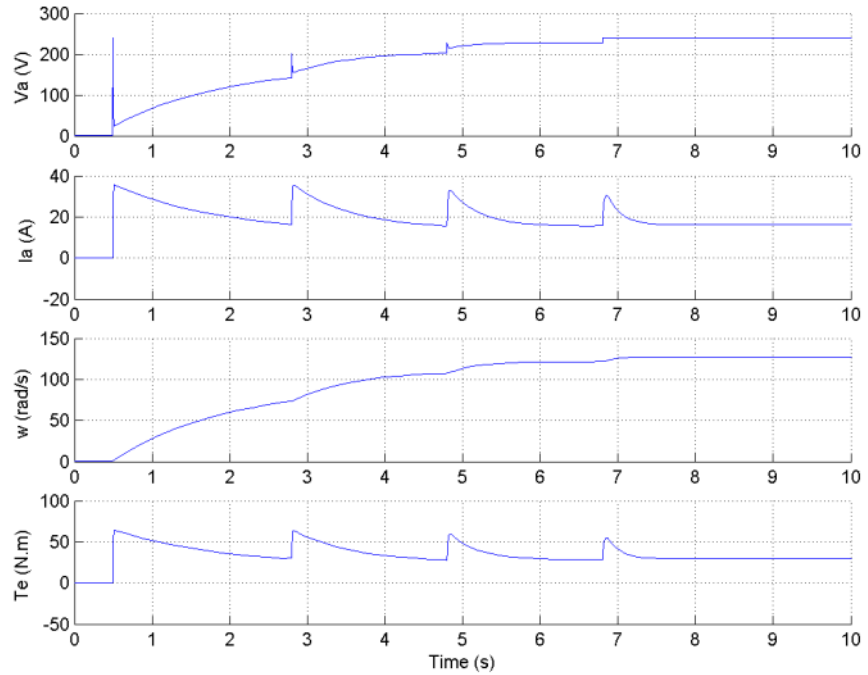


The Motor Starter subsystem is



# DC Machine

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## References

[1] *Analysis of Electric Machinery*, Krause et al., pp. 89-92.

## See Also

Asynchronous Machine, Synchronous Machine

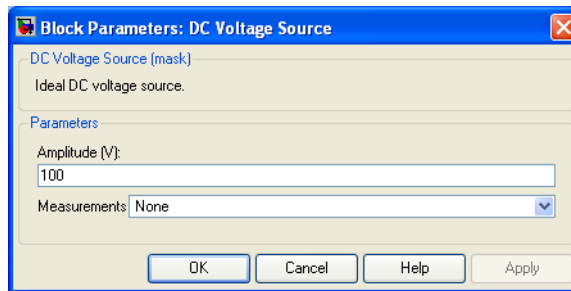
**Purpose** Implement DC voltage source

**Library** Electrical Sources

**Description** The DC Voltage Source block implements an ideal DC voltage source. The positive terminal is represented by a plus sign on one port. You can modify the voltage at any time during the simulation.



## Dialog Box and Parameters



### Amplitude

The amplitude of the source, in volts (V).

### Measurements

Select **Voltage** to measure the voltage across the terminals of the DC Voltage Source block.

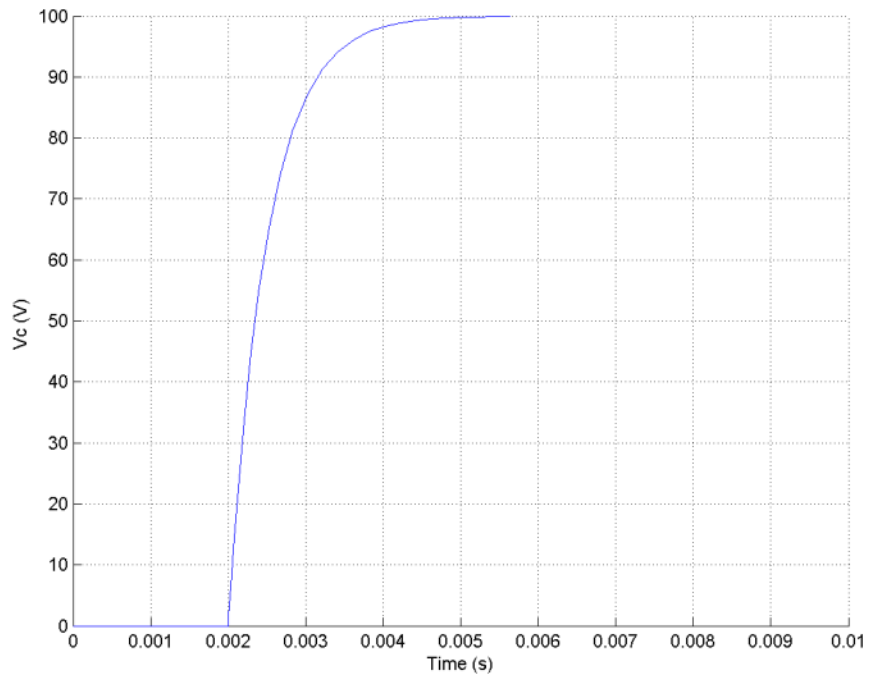
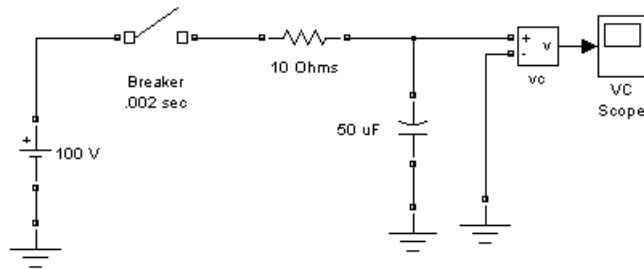
Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name:

Measurement	Label
Voltage	Usrc :

# DC Voltage Source

## Example

The power\_dc voltage demo illustrates the simulation of the transient response of a first-order RC circuit.



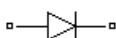
## See Also

AC Voltage Source, Controlled Voltage Source

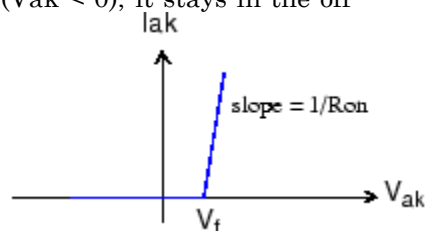
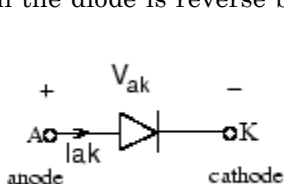
**Purpose** Implement diode model

**Library** Power Electronics

## Description

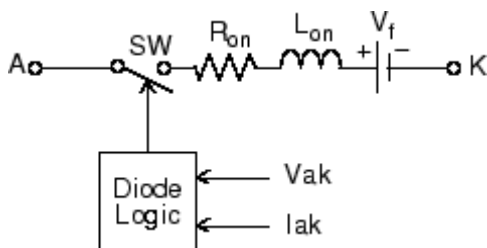


The diode is a semiconductor device that is controlled by its own voltage  $V_{ak}$  and current  $I_{ak}$ . When a diode is forward biased ( $V_{ak} > 0$ ), it starts to conduct with a small forward voltage  $V_f$  across it. It turns off when the current flow into the device becomes 0. When the diode is reverse biased ( $V_{ak} < 0$ ), it stays in the off



state.

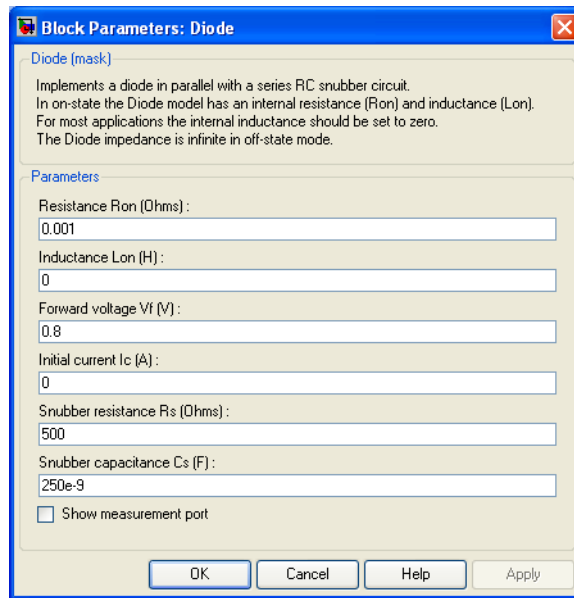
The Diode block is simulated by a resistor, an inductor, and a DC voltage source connected in series with a switch. The switch operation is controlled by the voltage  $V_{ak}$  and the current  $I_{ak}$ .



The Diode block also contains a series  $R_s$ - $C_s$  snubber circuit that can be connected in parallel with the diode device (between nodes A and K).

# Diode

## Dialog Box and Parameters



### Resistance Ron

The diode internal resistance  $R_{on}$ , in ohms ( $\Omega$ ). The **Resistance Ron** parameter cannot be set to 0 when the **Inductance Lon** parameter is set to 0.

### Inductance Lon

The diode internal inductance  $L_{on}$ , in henries (H). The **Inductance Lon** parameter cannot be set to 0 when the **Resistance Ron** parameter is set to 0.

### Forward voltage Vf

The forward voltage of the diode device, in volts (V).

### Initial current Ic

Specifies an initial current flowing in the diode device. It is usually set to 0 in order to start the simulation with the diode device blocked. If the **Initial Current IC** parameter is set to a value greater than 0, the steady-state calculation considers the initial status of the diode as closed.



Initializing all states of a power electronic converter is a complex task. Therefore, this option is useful only with simple circuits.

#### Snubber resistance $R_s$

The snubber resistance, in ohms ( $\Omega$ ). Set the **Snubber resistance  $R_s$**  parameter to `inf` to eliminate the snubber from the model.

#### Snubber capacitance $C_s$

The snubber capacitance in farads (F). Set the **Snubber capacitance  $C_s$**  parameter to `0` to eliminate the snubber, or to `inf` to get a resistive snubber.

#### Show measurement port

If selected, adds a Simulink output to the block returning the diode current and voltage.

## Inputs and Outputs

m

The Simulink output of the block is a vector containing two signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

Signal	Definition	Units
1	Diode current	A
2	Diode voltage	V

## Assumptions and Limitations

The Diode block implements a macro model of a diode device. It does not take into account either the geometry of the device or the complex physical processes underlying the state change [1]. The leakage current in the blocking state and the reverse-recovery (negative) current are not considered. In most circuits, the reverse current does not affect converter or other device characteristics.

Depending on the value of the inductance  $L_{on}$ , the diode is modeled either as a current source ( $L_{on} > 0$ ) or as a variable topology circuit ( $L_{on} = 0$ ). The Diode block cannot be connected in series with an inductor, a

# Diode

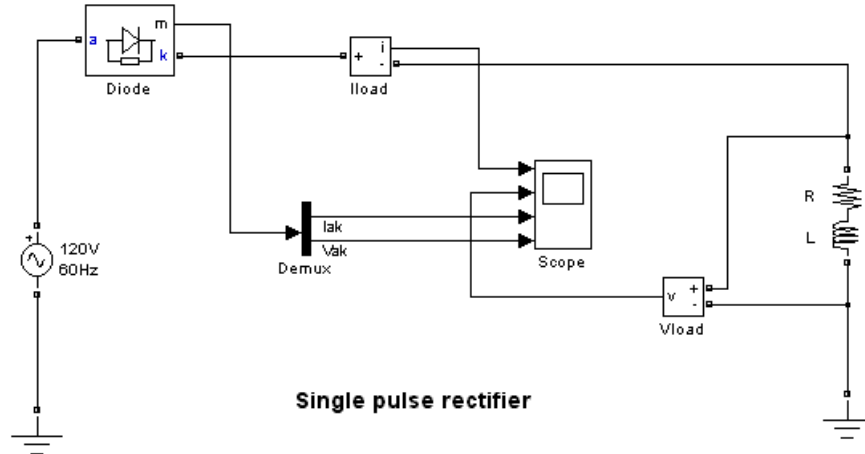
current source, or an open circuit, unless its snubber circuit is in use. See *Improving Simulation Performance* for more details on this topic.

Use the `powergui` block to specify either continuous simulation or discretization of your electrical circuit containing diodes. When using a continuous model, the `ode23tb` solver with a relative tolerance of  $1e-4$  is recommended for best accuracy and simulation speed.

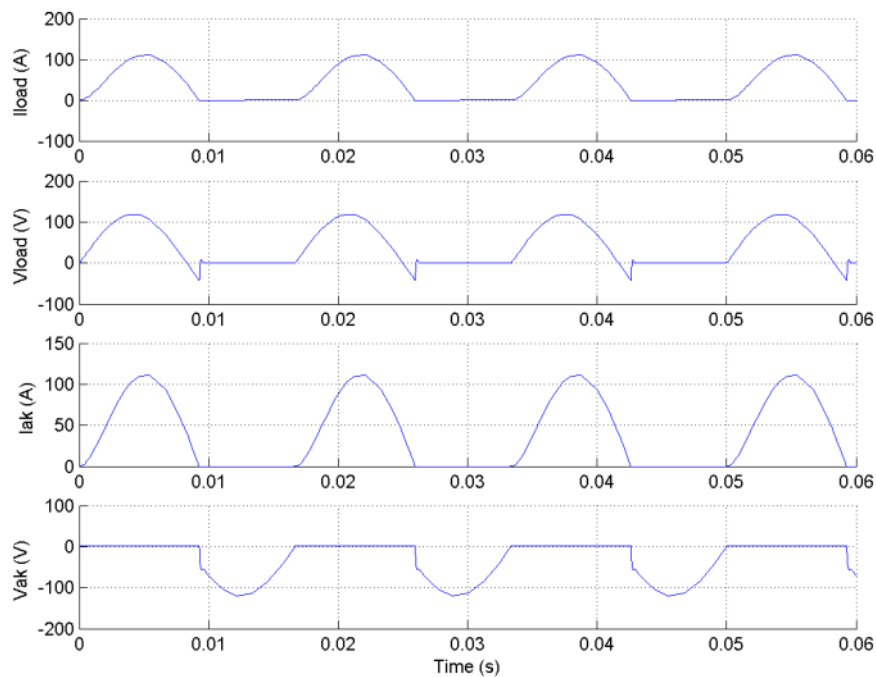
The inductance  $L_{on}$  is forced to 0 if you choose to discretize your circuit.

## Example

The `power_diode` demo illustrates a single pulse rectifier consisting of a Diode block, an RL load, and an AC Voltage source block.



Simulation produces the following results.



## References

- [1] Rajagopalan, V., *Computer-Aided Analysis of Power Electronic Systems*, Marcel Dekker, Inc., New York, 1987.
- [2] Mohan, N., T.M. Undeland, and W.P. Robbins, *Power Electronics: Converters, Applications, and Design*, John Wiley & Sons, Inc., New York, 1995.

## See Also

Thyristor, Universal Bridge

# Discrete System

---

**Purpose** Discretize state-space model of circuit

**Library** powerlib

**Description**

---

**Note** This block is now obsolete. Use the Powergui block to replace this block.

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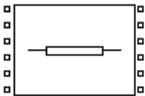
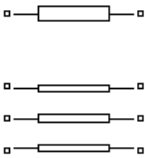
**See Also** Powergui

# Distributed Parameter Line

**Purpose** Implement N-phase distributed parameter transmission line model with lumped losses

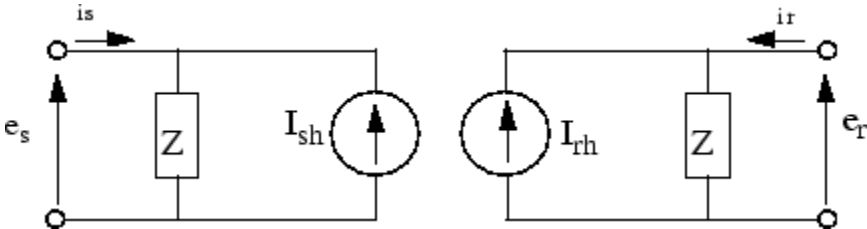
**Library** Elements

**Description**



The Distributed Parameter Line block implements an N-phase distributed parameter line model with lumped losses. The model is based on the Bergeron's traveling wave method used by the Electromagnetic Transient Program (EMTP) [1]. In this model, the lossless distributed LC line is characterized by two values (for a single-phase line): the surge impedance  $Z_c = \sqrt{L/C}$  and the phase velocity  $v = 1/\sqrt{LC}$ .

The model uses the fact that the quantity  $e+Zi$  (where  $e$  is line voltage and  $i$  is line current) entering one end of the line must arrive unchanged at the other end after a transport delay of  $\tau = d/v$ , where  $d$  is the line length. By lumping  $R/4$  at both ends of the line and  $R/2$  in the middle and using the current injection method of SimPowerSystems software, the following two-port model is derived,



$$\text{where } Z = Z_c + \frac{R}{4}, h = \frac{Z_c - \frac{R}{4}}{Z_c + \frac{R}{4}}, Z_c = \sqrt{\frac{L}{C}} \text{ and } \tau = d\sqrt{LC}.$$

For multiphase line models, modal transformation is used to convert line quantities from phase values (line currents and voltages) into

# Distributed Parameter Line

modal values independent of each other. The previous calculations are made in the modal domain before being converted back to phase values.

In comparison to the PI section line model, the distributed line represents wave propagation phenomena and line end reflections with much better accuracy. See the comparison between the two models in the Example section.

## Dialog Box and Parameters

**Block Parameters: Distributed Parameters Line**

Distributed Parameters Line (mask)

Implements a N-phases distributed parameter line model. The R,L, and C line parameters are specified by [N×N] matrices.

To model a two-, three-, or a six-phase symmetrical line you can either specify complete [N×N] matrices or simply enter sequence parameters vectors: the positive and zero sequence parameters for a two-phase or three-phase transposed line, plus the mutual zero-sequence for a six-phase transposed line (2 coupled 3-phase lines).

**Parameters**

Number of phases N  
3

Frequency used for R L C specification (Hz)  
60

Resistance per unit length (Ohms/km) [N\*N matrix] or [R1 R0 R0m]  
[0.01273 0.3864]

Inductance per unit length (H/km) [N\*N matrix ] or [L1 L0 L0m]  
[0.9337e-3 4.1264e-3]

Capacitance per unit length (F/km) [N\*N matrix] or [C1 C0 C0m]  
[12.74e-9 7.751e-9]

Line length (km)  
100

Measurements None

OK Cancel Help Apply

### Number of phases N

Specifies the number of phases, N, of the model. The block icon dynamically changes according to the number of phases that you specify. When you apply the parameters or close the dialog box, the number of inputs and outputs is updated.

## Frequency used for RLC specifications

Specifies the frequency used to compute the resistance  $R$ , inductance  $L$ , and capacitance  $C$  matrices of the line model.

## Resistance per unit length

The resistance  $R$  per unit length, as an N-by-N matrix in ohms/km ( $\Omega/\text{km}$ ).

For a symmetrical line, you can either specify the N-by-N matrix or the sequence parameters. For a two-phase or three-phase continuously transposed line, you can enter the positive and zero-sequence resistances [ $R1 R0$ ]. For a symmetrical six-phase line you can enter the sequence parameters plus the zero-sequence mutual resistance [ $R1 R0 R0m$ ].

For asymmetrical lines, you must specify the complete N-by-N resistance matrix.

## Inductance per unit length

The inductance  $L$  per unit length, as an N-by-N matrix in henries/km (H/km).

For a symmetrical line, you can either specify the N-by-N matrix or the sequence parameters. For a two-phase or three-phase continuously transposed line, you can enter the positive and zero-sequence inductances [ $L1 L0$ ]. For a symmetrical six-phase line, you can enter the sequence parameters plus the zero-sequence mutual inductance [ $L1 L0 L0m$ ].

For asymmetrical lines, you must specify the complete N-by-N inductance matrix.

## Capacitance per unit length

The capacitance  $C$  per unit length, as an N-by-N matrix in farads/km (F/km).

For a symmetrical line, you can either specify the N-by-N matrix or the sequence parameters. For a two-phase or three-phase

# Distributed Parameter Line

---

continuously transposed line, you can enter the positive and zero-sequence capacitances [ $C1 C0$ ]. For a symmetrical six-phase line you can enter the sequence parameters plus the zero-sequence mutual capacitance [ $C1 C0 C0m$ ].

For asymmetrical lines, you must specify the complete N-by-N capacitance matrix.

---

**Note** The Powergui block provide you a graphical tool for the calculation of the resistance, inductance, and capacitance per unit length based on the line geometry and the conductor characteristics.

---

## Line length

The line length, in km.

## Measurements

Select Phase-to-ground voltages to measure the sending end and receiving end voltages for each phase of the line model.

Place a Multimeter block in your model to display the selected measurements during the simulation.

In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name:

Measurement	Label
Phase-to-ground voltages, sending end	Us_ph1_gnd:, Us_ph2_gnd:, Us_ph3_gnd:, etc.
Phase-to-ground voltages, receiving end	Ur_ph1_gnd:, Ur_ph2_gnd:, Ur_ph3_gnd:, etc.

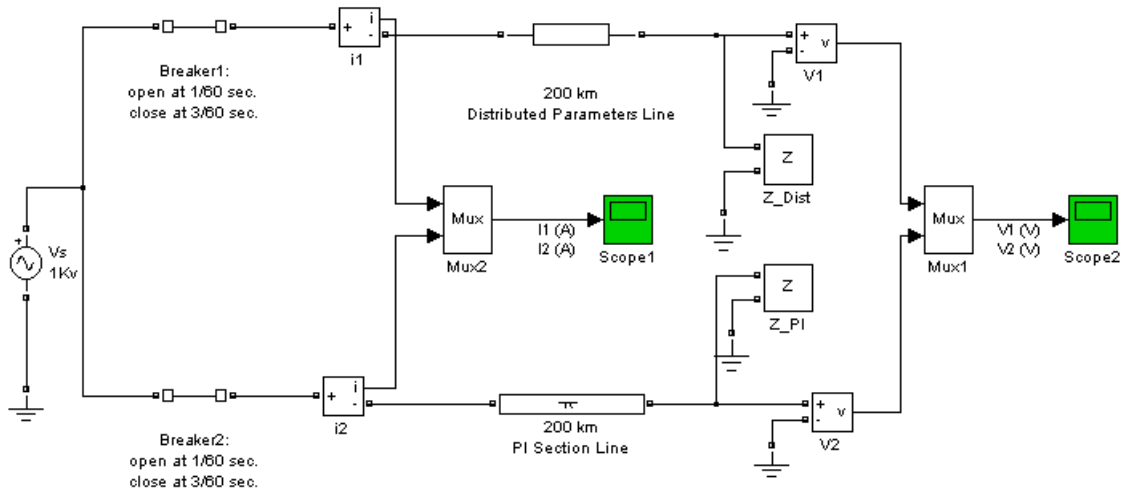


## Limitations

This model does not represent accurately the frequency dependence of RLC parameters of real power lines. Indeed, because of the skin effects in the conductors and ground, the  $R$  and  $L$  matrices exhibit strong frequency dependence, causing an attenuation of the high frequencies.

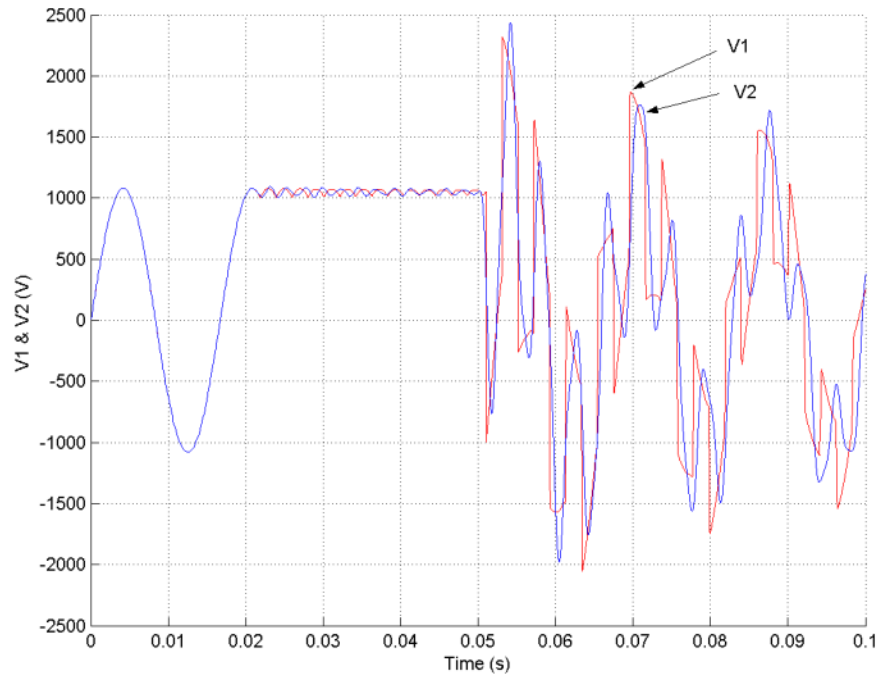
## Example

The `power_monophaseline` demo illustrates a 200 km line connected on a 1 kV, 60 Hz infinite source. The line is de-energized and then reenergized after 2 cycles. The simulation is performed simultaneously with the Distributed Parameter Line block and with the PI Section Line block.



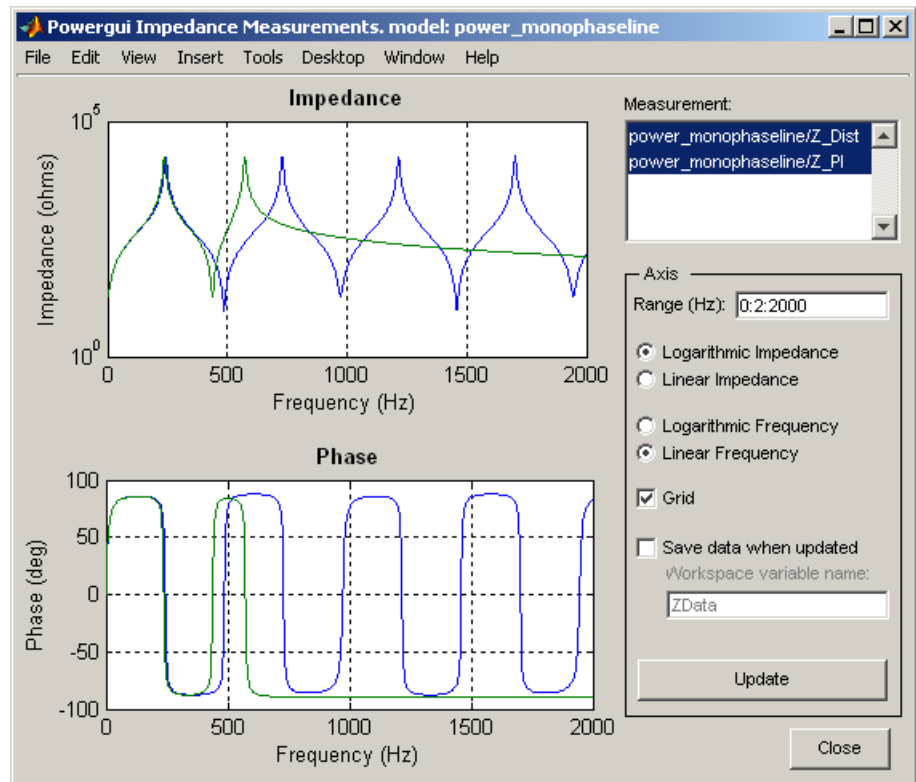
The receiving end voltage obtained with the Distributed Parameter Line block is compared with the one obtained with the PI Section Line block (two sections).

# Distributed Parameter Line



Open the Powergui. Click the **Impedance vs Frequency Measurement** button. A new window appears, listing the two Impedance Measurement blocks connected to your circuit. Set the parameters of **Impedance vs Frequency Measurement** to compute impedance in the [0,2000] Hz frequency range, select the two measurements in the list, then click the **Update** button.

# Distributed Parameter Line



The distributed parameter line shows a succession of poles and zeros equally spaced, every 486 Hz. The first pole occurs at 243 Hz, corresponding to frequency  $f = 1/(4 * T)$ , where

$$T = \text{traveling time} = l\sqrt{LC} = 1.028 \text{ ms}$$

The PI section line only shows two poles because it consists of two PI sections. Impedance comparison shows that a two-section PI line gives a good approximation of the distributed line for the 0 to 350 Hz frequency range.

# Distributed Parameter Line

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## References

[1] Dommel, H., "Digital Computer Solution of Electromagnetic Transients in Single and Multiple Networks," *IEEE® Transactions on Power Apparatus and Systems*, Vol. PAS-88, No. 4, April, 1969.

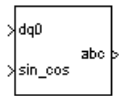
## See Also

PI Section Line

**Purpose** Perform Park transformation from dq0 reference frame to abc reference frame

**Library** Extras/Measurements  
A discrete version of this block is available in the Extras/Discrete Measurements library.

## Description



The dq0\_to\_abc Transformation block performs the reverse of the so-called Park transformation, which is commonly used in three-phase electric machine models. It transforms three quantities (direct axis, quadratic axis, and zero-sequence components) expressed in a two-axis reference frame back to phase quantities. The following transformation is used:

$$V_a = V_d \sin(\omega t) + V_q \cos(\omega t) + V_0$$

$$V_b = V_d \sin(\omega t - 2\pi/3) + V_q \cos(\omega t - 2\pi/3) + V_0$$

$$V_c = V_d \sin(\omega t + 2\pi/3) + V_q \cos(\omega t + 2\pi/3) + V_0$$

where

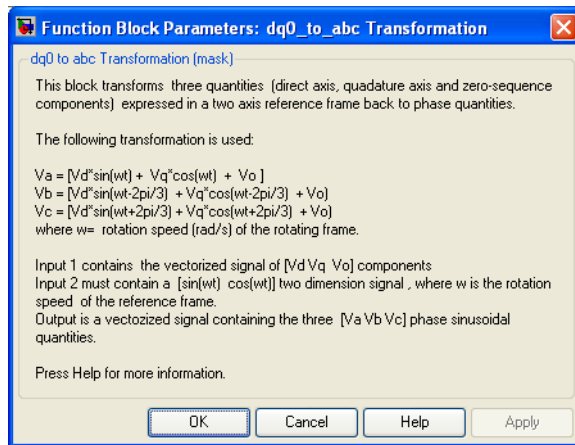
$\omega$  = rotation speed (rad/s) of the rotating frame

The transformation is the same for the case of a three-phase current; you simply replace the  $V_a$ ,  $V_b$ ,  $V_c$ ,  $V_d$ ,  $V_q$ , and  $V_0$  variables with the  $I_a$ ,  $I_b$ ,  $I_c$ ,  $I_d$ ,  $I_q$ , and  $I_0$  variables.

The dq0\_to\_abc Transformation block is used in the model of the Synchronous Machine block where the stator quantities are referred to the rotor. The Park transformation then eliminates time-varying inductances by referring the stator and rotor quantities to a fixed or rotating reference frame. The  $I_d$  and  $I_q$  currents represent the two DC currents flowing in the two equivalent rotor windings (d winding on the same axis as the field winding, and q winding in quadratic) producing the same flux as the stator  $I_a$ ,  $I_b$ , and  $I_c$  currents.

# dq0\_to\_abc Transformation

## Dialog Box and Parameters



## Inputs and Outputs

**dq0**

Connect to the first input a vectorized signal containing the sequence components [d q 0] to be converted.

**sin\_cos**

Connect to the second input a vectorized signal containing the [sin( $\omega t$ ) cos( $\omega t$ )] values, where  $\omega$  is the rotation speed of the reference frame.

**abc**

The output is a vectorized signal containing the three-phase sinusoidal quantities [phase A phase B phase C].

## Example

See the demo of the abc\_to\_dq0 Transformation block for an example using the dq0\_to\_abc Transformation block.

## See Also

abc\_to\_dq0 Transformation

# DTC Induction Motor Drive

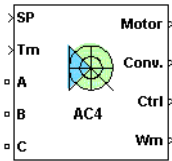
## Purpose

Implement direct torque and flux control (DTC) induction motor drive model

## Library

Electric Drives/AC drives

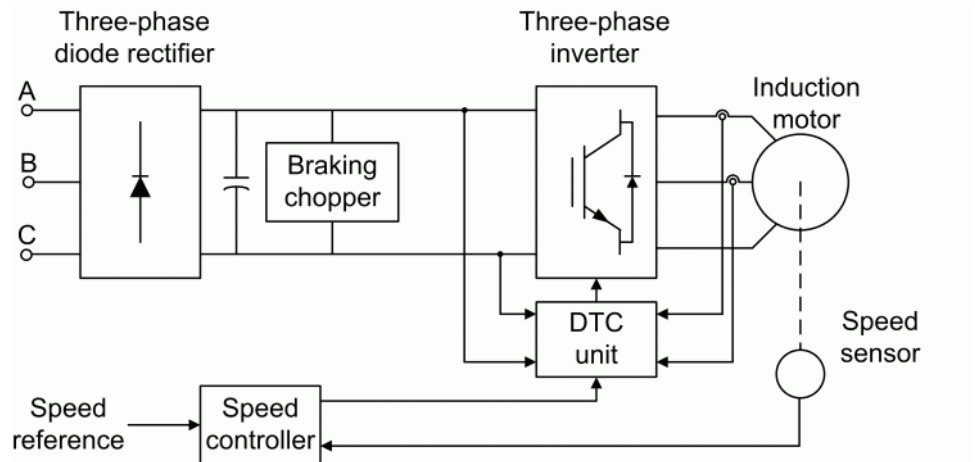
## Description



The high-level schematic shown below is built from six main blocks. The induction motor, the three-phase inverter, and the three-phase diode rectifier models are provided with the SimPowerSystems library. More details on these three blocks are available in the reference sections of each block. The speed controller, the braking chopper, and the DTC controller models are specific to the drive library.

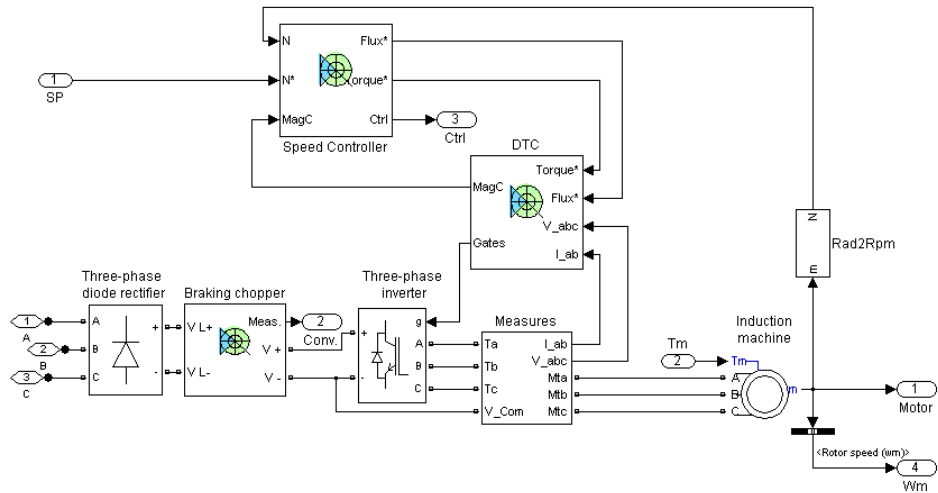
**Note** In SimPowerSystems software, the DTC Induction Motor Drive block is commonly called the AC4 motor drive.

## High-Level Schematic



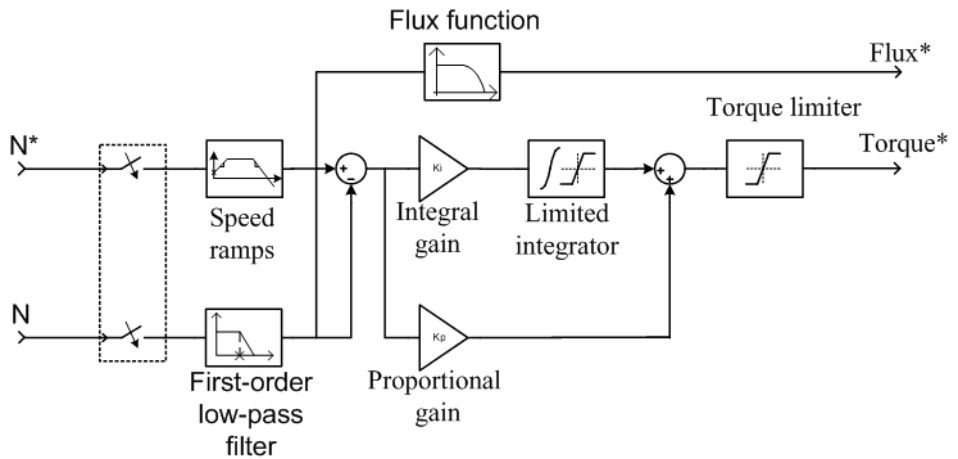
# DTC Induction Motor Drive

## Simulink Schematic



## Speed Controller

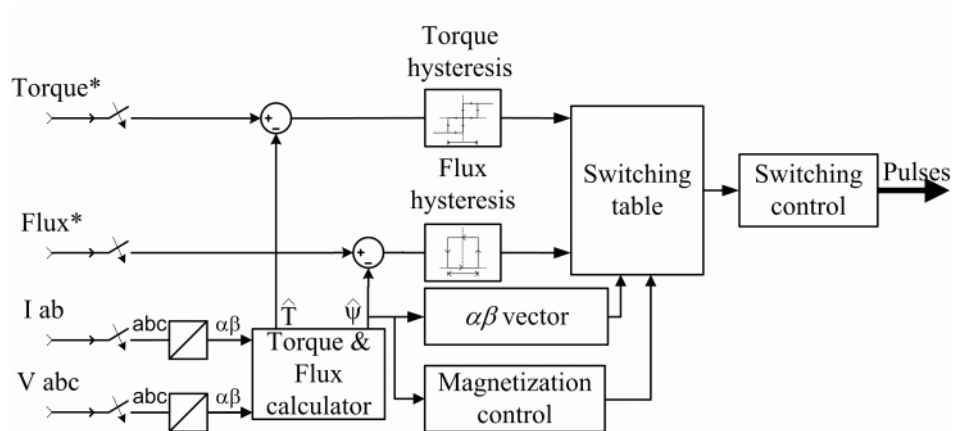
The speed controller is based on a PI regulator, shown below. The output of this regulator is a torque set point applied to the DTC controller block.





## DTC Controller

The Direct Torque and Flux Control (DTC) controller contains five main blocks, shown below. These blocks are described below.



The *Torque & Flux calculator* block is used to estimate the motor flux  $\alpha\beta$  components and the electromagnetic torque. This calculator is based on motor equation synthesis.

The  *$\alpha\beta$  vector* block is used to find the sector of the  $\alpha\beta$  plane in which the flux vector lies. The  $\alpha\beta$  plane is divided into six different sectors spaced by 60 degrees.

The *Flux & Torque Hysteresis* blocks contain a two-level hysteresis comparator for flux control and a three-level hysteresis comparator for the torque control. The description of the hysteresis comparators is available below.

The *Switching table* block contains two lookup tables that select a specific voltage vector in accordance with the output of the *Flux & Torque Hysteresis* comparators. This block also produces the initial flux in the machine.

The *Switching control* block is used to limit the inverter commutation frequency to a maximum value specified by the user.

# DTC Induction Motor Drive

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## **Braking Chopper**

The braking chopper block contains the DC bus capacitor and the dynamic braking chopper, which is used to absorb the energy produced by a motor deceleration.

## **Remarks**

The model is discrete. Good simulation results have been obtained with a  $2 \mu\text{s}$  time step. In order to simulate a digital controller device, the control system has two different sampling times:

- The speed controller sampling time
- The D.T.C. controller sampling time

The speed controller sampling time has to be a multiple of the D.T.C. sampling time. The latter sampling time has to be a multiple of the simulation time step.

## Dialog Box

### Asynchronous Machine Tab

The screenshot shows the 'DTC Induction Motor Drive' dialog box with the 'Asynchronous Machine' tab selected. The dialog box contains several sections for parameter configuration:

- Reference frame:** Stationary (dropdown menu)
- Nominal values:**
  - Power (VA): 2238
  - Voltage (Vrms): 220
  - Frequency (Hz): 60
- Equivalent circuit values:**
  - Stator: Resistance (ohm): 0.435, Leakage inductance (H): 2e-3, Mutual inductance (H): 69.31e-3
  - Rotor: Resistance (ohm): 0.816, Leakage inductance (H): 2e-3
- Initial currents:**
  - Phase A: Magnitude (A): 0, Phase (deg): 0
  - Phase B: Magnitude (A): 0, Phase (deg): 0
  - Phase C: Magnitude (A): 0, Phase (deg): 0
- Mechanical parameters:**
  - Rotor values: Inertia (kg·m<sup>2</sup>): 0.089, Friction (N·m·s): 0.005, Pole pairs: 2
  - Initial values: Slip: 1, Angle (deg): 0
- Mechanical input:** Torque Tm (dropdown menu)
- Parameters file options:** Load, Save buttons
- Buttons:** OK, Cancel, Help, Apply

The asynchronous machine tab displays the parameters of the asynchronous machine block of the powerlib library. Refer to the Asynchronous Machine for more information on the Asynchronous Machine tab parameters.

### Mechanical input

Allows you to select either the load torque or the motor speed as mechanical input. Note that if you select and apply a load torque, you will obtain as output the motor speed according to the following differential equation that describes the mechanical system dynamics:

## DTC Induction Motor Drive

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$$T_e = J \frac{d}{dt} \omega_r + F \omega_r + T_m$$

This mechanical system is included in the motor model.

However, if you select the motor speed as mechanical input then you will get the electromagnetic torque as output, allowing you to represent externally the mechanical system dynamics. Note that the internal mechanical system is not used with this mechanical input selection and the inertia and viscous friction parameters are not displayed.

See for example “Mechanical Coupling of Two Motor Drives”.

## Converters and DC Bus Tab

DTC Induction Motor Drive

The AC motor parameters are specified in the AC Machine tab. The braking chopper, the diode rectifier and the inverter switches parameters are specified in the Converter and DC bus tab. DTC and speed controller parameters are specified in the Controller Tab.

Asynchronous Machine    Converters and DC bus    Controller

**Rectifier**

Snubbers

Resistance (ohm): 10e3

Capacitance (F): 2e-9

Diodes

On-state resistance (ohm): 1e-3

Forward voltage (V): 1.3

**DC Bus**

Capacitance (F): 1500e-6

Braking chopper

Resistance (ohm): 8

Chopper frequency (Hz): 4000

Activation voltage (V): 340

Shutdown voltage (V): 320

**Inverter**

Switches

Device type: IGBT / Diodes

On-state resistance (ohm): 1e-3

Forward voltages (V)

Main device: 1.4

Diode: 1.4

Turn-off characteristics

Fall time (s): 1e-6

Tail time (s): 2e-6

Snubbers

Resistance (ohm): 10e3

Capacitance (F): inf

Mechanical input: Torque Tm

Parameters file options

Load    Save

OK    Cancel    Help    Apply

### Rectifier Section

The rectifier section of the Converters and DC Bus tab displays the parameters of the rectifier block of the powerlib library. Refer to the Universal Bridge for more information on the rectifier parameters.

### Inverter Section

The inverter section of the Converters and DC Bus tab displays the parameters of the Inverter block of the powerlib library. Refer to the Universal Bridge for more information on the inverter parameters.

# DTC Induction Motor Drive

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## DC-Bus Capacitance

The DC bus capacitance (F).

## Braking Chopper section: Resistance

The braking chopper resistance used to avoid bus over-voltage during motor deceleration or when the load torque tends to accelerate the motor ( $\Omega$ ).

## Braking Chopper section: Frequency

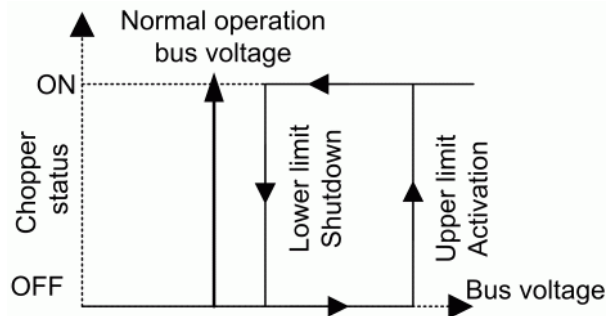
The braking chopper frequency (Hz).

## Braking Chopper section: Activation Voltage

The dynamic braking is activated when the bus voltage reaches the upper limit of the hysteresis band. The following figure illustrates the braking chopper hysteresis logic.

## Braking Chopper section: Shutdown Voltage

The dynamic braking is shut down when the bus voltage reaches the lower limit of the hysteresis band. The Chopper hysteresis logic is shown below:



## Controller Tab

The screenshot shows the 'Controller' tab of the 'DTC Induction Motor Drive' software. The window title is 'DTC Induction Motor Drive'. Below the title bar, there is a text box explaining that AC motor parameters are in the 'AC Machine' tab, braking chopper, diode rectifier, and inverter switches parameters are in the 'Converter and DC bus' tab, and DTC and speed controller parameters are in the 'Controller' tab. The 'Controller' tab is selected, and the 'Regulation type' is set to 'Speed regulation'. The 'Speed controller' section includes 'Speed ramps (rpm/s)' with 'Acceleration' at 1800 and 'Deceleration' at -1800; 'Speed cutoff frequency (Hz)' at 100; and 'Speed controller sampling time (s)' at 7\*20e-6. The 'PI regulator' section has 'Proportional gain' at 5 and 'Integral gain' at 10. The 'Torque output limits (N-m)' section has 'Minimum' at -17.8 and 'Maximum' at 17.8. The 'DTC controller' section includes 'Hysteresis bandwidth' with 'Torque (N-m)' at 0.5 and 'Flux (Wb)' at 0.01; 'Initial machine flux (Wb)' at 0.3; 'Maximum switching frequency (Hz)' at 20000; and 'DTC sampling time (s)' at 20e-6. The 'Mechanical input' is set to 'Torque Tm'. At the bottom, there are 'Load' and 'Save' buttons under 'Parameters file options', and 'OK', 'Cancel', 'Help', and 'Apply' buttons.

### Regulation type

This parameter allows you to choose between speed and torque regulation.

### Schematic

When you press this button, a diagram illustrating the speed and current controllers schematics appears.

# DTC Induction Motor Drive

---

## **Speed Controller section**

### **Speed cutoff frequency**

The speed measurement first-order low-pass filter cutoff frequency (Hz). This parameter is used in speed regulation mode only.

### **Speed controller sampling time**

The speed controller sampling time (s). The sampling time must be a multiple of the simulation time step.

### **Speed Ramps — Acceleration**

The maximum change of speed allowed during motor acceleration (rpm/s). An excessively large positive value can cause DC bus under-voltage. This parameter is used in speed regulation mode only.

### **Speed Ramps — Deceleration**

The maximum change of speed allowed during motor deceleration (rpm/s). An excessively large negative value can cause DC bus overvoltage. This parameter is used in speed regulation mode only.

### **PI Regulator — Proportional Gain**

The speed controller proportional gain. This parameter is used in speed regulation mode only.

### **PI Regulator — Integral Gain**

The speed controller integral gain. This parameter is used in speed regulation mode only.

### **Torque output limits — Negative**

The maximum negative demanded torque applied to the motor by the current controller (N.m).

### **Torque output limits — Positive**

The maximum positive demanded torque applied to the motor by the current controller (N.m).

## **DTC Controller Section**

### **Maximum switching frequency**

The maximum inverter switching frequency (Hz).



## Initial machine flux

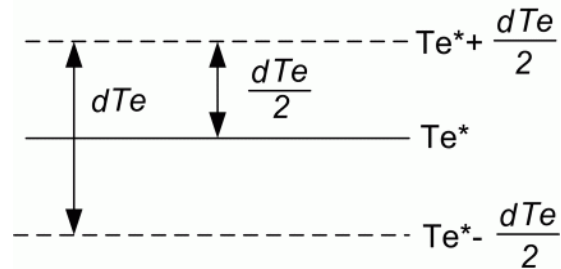
The desired initial stator flux established before the DTC drive module begins to produce an electromagnetic torque. This flux is produced by applying a constant voltage vector at the motor terminals (Wb).

## DTC sampling time

The DTC controller sampling time (s). The sampling time must be a multiple of the simulation time step.

## Hysteresis bandwidth — Torque

The torque hysteresis bandwidth. This value is the total bandwidth distributed symmetrically around the torque set point (N.m). The following figure illustrates a case where the torque set point is  $T_e^*$  and the torque hysteresis bandwidth is set to  $dT_e$ .

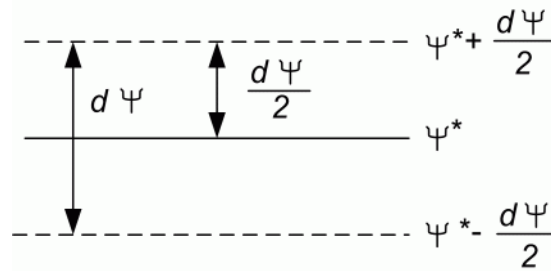


## Hysteresis bandwidth — Flux

The stator flux hysteresis bandwidth. This value is the total bandwidth distributed symmetrically around the flux set point (Wb). The following figure illustrates a case where the flux set point is  $\psi^*$  and the torque hysteresis bandwidth is set to  $d\psi$ .

# DTC Induction Motor Drive

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**Note** This bandwidth can be exceeded because a fixed-step simulation is used. A rate transition block is needed to transfer data between different sampling rates. This block causes a delay in the gate signals, so the current may exceed the hysteresis band.

---

## Block Inputs and Outputs

SP

The speed or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration / deceleration ramps. If the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

T<sub>m</sub> or W<sub>m</sub>

The mechanical input: load torque (T<sub>m</sub>) or motor speed (W<sub>m</sub>).

A, B, C

The three phase terminals of the motor drive.

W<sub>m</sub> or T<sub>e</sub>

The mechanical output: motor speed (W<sub>m</sub>) or electromagnetic torque (T<sub>e</sub>).

Motor

The motor measurement vector. This vector allows you to observe the motor's variables using the Bus Selector block.

## Conv

The three-phase converters measurement vector. This vector contains:

- The DC bus voltage
- The rectifier output current
- The inverter input current

Note that all current and voltage values of the bridges can be visualized with the Multimeter block.

## Ctrl

The controller measurement vector. This vector contains:

- The torque reference
- The speed error (difference between the speed reference ramp and actual speed)
- The speed reference ramp or torque reference

## Model Specifications

The library contains a 3 hp and a 200 hp drive parameter set. The specifications of these two drives are shown in the following table.

### Drive Specifications

	<b>3 HP Drive</b>	<b>200 HP Drive</b>
<b>Drive Input Voltage</b>		
Amplitude	220 V	460 V
Frequency	60 Hz	60 Hz
<b>Motor Nominal Values</b>		
Power	3 hp	200 hp

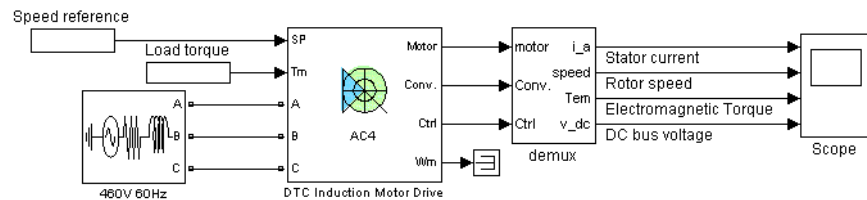
# DTC Induction Motor Drive

## Drive Specifications (Continued)

	3 HP Drive	200 HP Drive
<b>Drive Input Voltage</b>		
Speed	1705 rpm	1785 rpm
Voltage	220 V	460 V

## Example

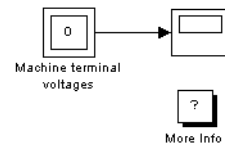
The ac4\_example demo illustrates the simulation of an AC4 motor drive with standard load condition.



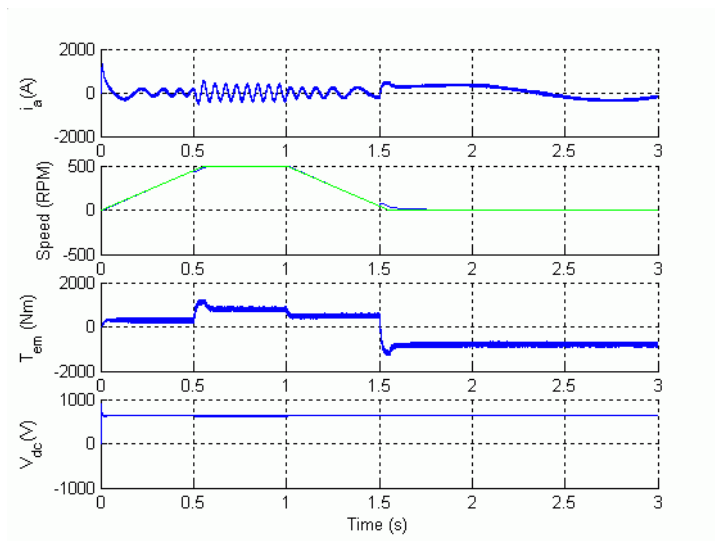
DTC Induction Motor Drive during speed regulation

Discrete,  
Ts = 2e-006 s.

The 'Ts' parameter used in this model is set to 2e-6 by the Model Properties Callbacks



At time  $t = 0$  s, the speed set point is 500 rpm. As shown in the following figure, the speed precisely follows the acceleration ramp. At  $t = 0.5$  s, the nominal load torque is applied to the motor. At  $t = 1$  s, the speed set point is changed to 0 rpm. The speed decreases to 0 rpm. At  $t = 1.5$  s, the mechanical load passes from 792 N.m to -792 N.m.



## References

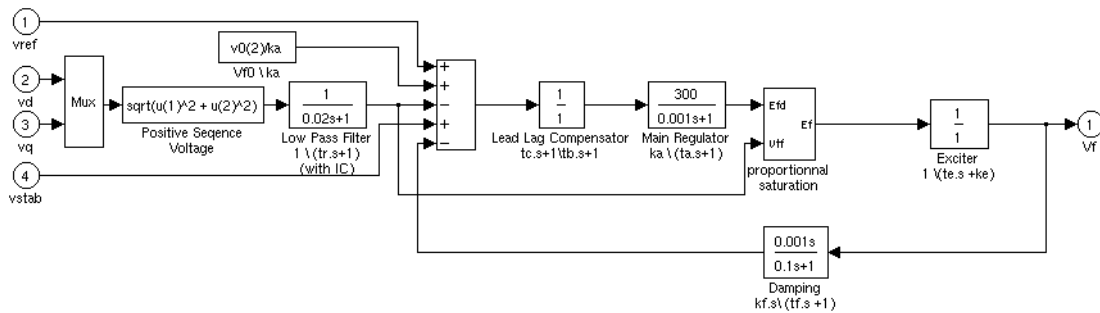
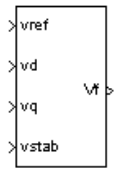
- [1] Bose, B. K., *Modern Power Electronics and AC Drives*, Prentice-Hall, N.J., 2002.
- [2] Grelet, G., and G. Clerc, *Actionneurs électriques*, Éditions Eyrolles, Paris, 1997.
- [3] Krause, P. C., *Analysis of Electric Machinery*, McGraw-Hill, 1986.

# Excitation System

**Purpose** Provide excitation system for synchronous machine and regulate its terminal voltage in generating mode

**Library** Machines

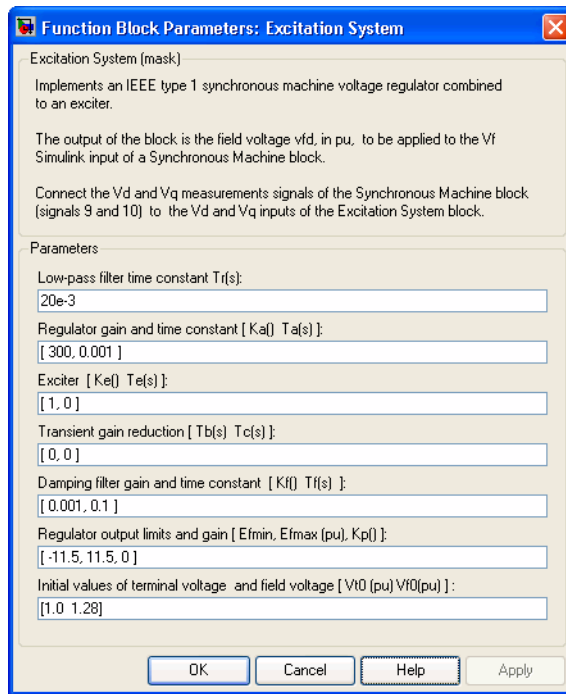
**Description** The Excitation System block is a Simulink system implementing a DC exciter described in [1], without the exciter's saturation function. The basic elements that form the Excitation System block are the voltage regulator and the exciter.



The exciter is represented by the following transfer function between the exciter voltage  $V_{fd}$  and the regulator's output  $ef$ :

$$\frac{V_{fd}}{ef} = \frac{1}{Ke + sTe}$$

## Dialog Box and Parameters



### Low-pass filter time constant

The time constant  $T_r$ , in seconds (s), of the first-order system that represents the stator terminal voltage transducer.

### Regulator gain and time constant

The gain  $K_a$  and time constant  $T_a$ , in seconds (s), of the first-order system representing the main regulator.

### Exciter

The gain  $K_e$  and time constant  $T_e$ , in seconds (s), of the first-order system representing the exciter.

### Transient gain reduction

The time constants  $T_b$ , in seconds (s), and  $T_c$ , in seconds (s), of the first-order system representing a lead-lag compensator.

# Excitation System

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## Damping filter gain and time constant

The gain  $K_f$  and time constant  $T_f$ , in seconds (s), of the first-order system representing a derivative feedback.

## Regulator output limits and gain

Limits  $E_{fmin}$  and  $E_{fmax}$  are imposed on the output of the voltage regulator. The upper limit can be constant and equal to  $E_{fmax}$ , or variable and equal to the rectified stator terminal voltage  $V_{tf}$  times a proportional gain  $K_p$ . If  $K_p$  is set to 0, the former applies. If  $K_p$  is set to a positive value, the latter applies.

## Initial values of terminal voltage and field voltage

The initial values of terminal voltage  $V_{t0}$  (pu) and field voltage  $V_{f0}$  (pu). When set correctly, they allow you to start the simulation in steady state. Initial terminal voltage should normally be set to 1 pu. Both  $V_{t0}$  and  $V_{f0}$  values are automatically updated by the load flow utility of the Powergui block.

## Example

See the Hydraulic Turbine and Governor block.

## Inputs and Outputs

$v_{ref}$

The desired value, in pu, of the stator terminal voltage.

$v_d$

$v_d$  component, in pu, of the terminal voltage.

$v_q$

$v_q$  component, in pu, of the terminal voltage.

$v_{stab}$

Connect this input to a power system stabilizer to provide additional stabilization of power system oscillations.

$V_f$

The field voltage, in pu, for the Synchronous Machine block.

## References

[1] "Recommended Practice for Excitation System Models for Power System Stability Studies," *IEEE Standard 421.5-1992*, August, 1992.



**See Also**

Generic Power System Stabilizer, Hydraulic Turbine and Governor, Multiband Power System Stabilizer, Steam Turbine and Governor, Synchronous Machine

# Field-Oriented Control Induction Motor Drive

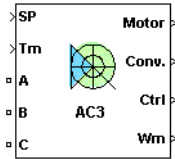
## Purpose

Implement field-oriented control (FOC) induction motor drive model

## Library

Electric Drives/AC drives

## Description



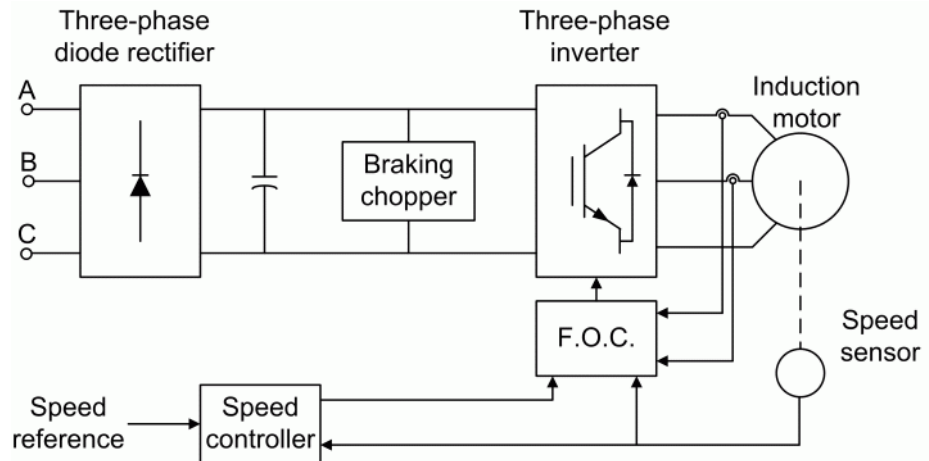
The high-level schematic shown below is built from six main blocks. The induction motor, the three-phase inverter, and the three-phase diode rectifier models are from blocks provided in the SimPowerSystems library. The speed controller, the braking chopper, and the FOC models are from blocks provided in the Electric Drives library. It is possible to use a simplified version of the drive containing an average-value model of the inverter and allowing faster simulation.

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**Note** In SimPowerSystems software, the Field-Oriented Control Induction Motor Drive block is commonly called the AC3 motor drive.

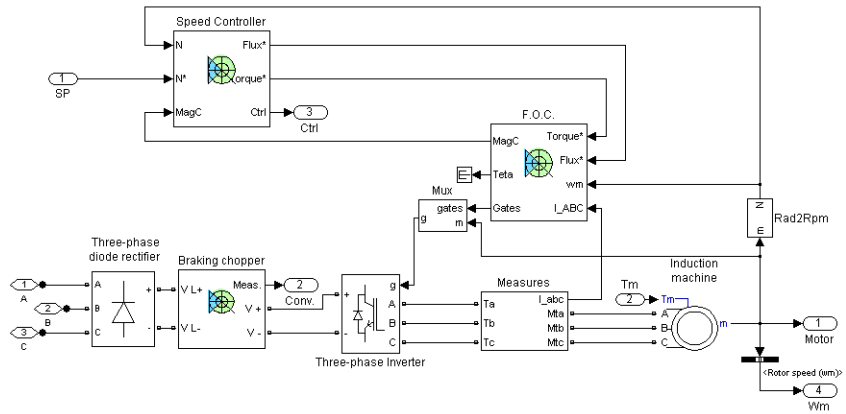
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## High-Level Schematic



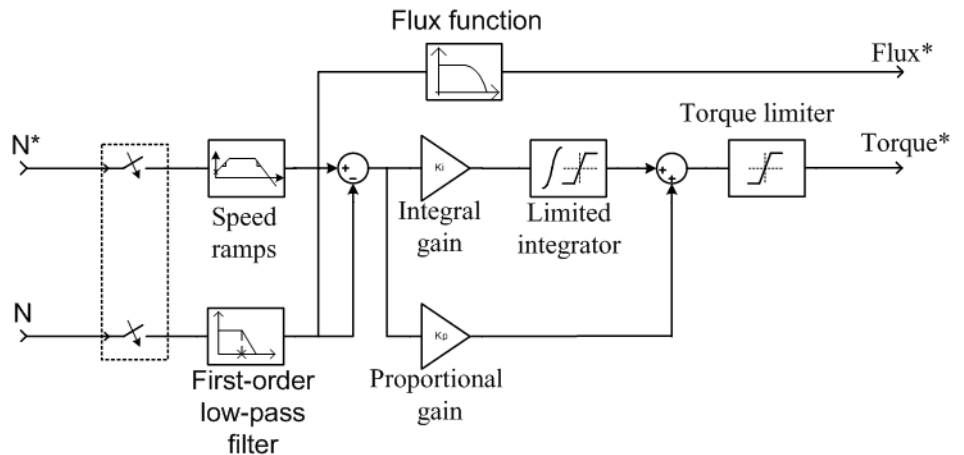
# Field-Oriented Control Induction Motor Drive

## Simulink Schematic



## Speed Controller

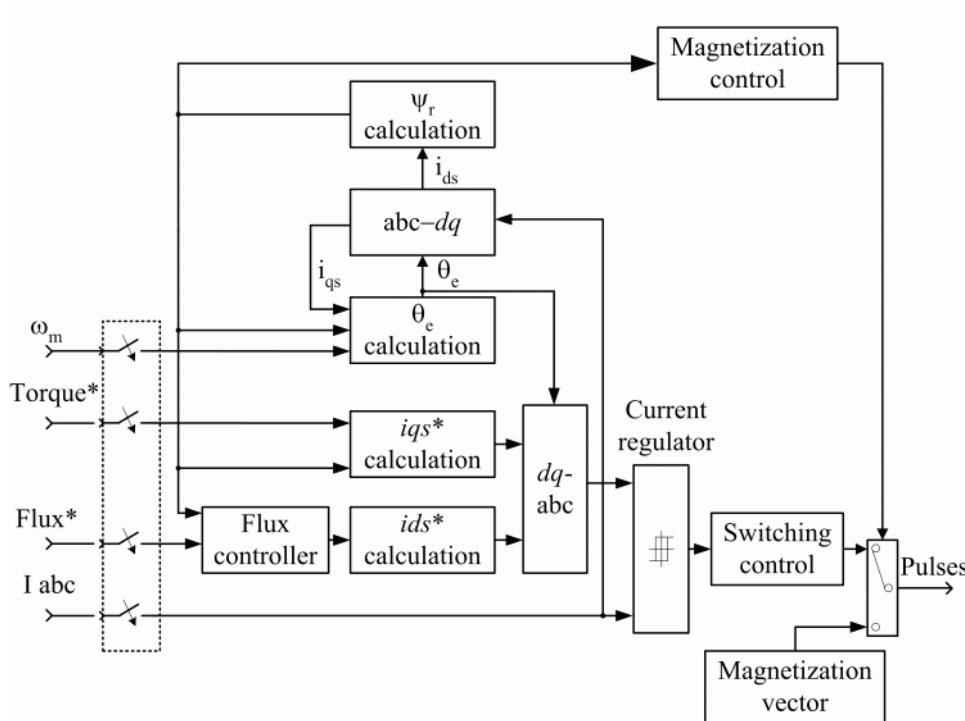
The speed controller is based on a PI regulator, shown below. The outputs of this regulator are set points for the torque and the flux applied to the FOC block.



# Field-Oriented Control Induction Motor Drive

## Field Oriented Controller

The FOC block contains eleven main blocks. These blocks are described below in the Indirect Vector Control Simulink Schematic.



The  $\psi_r$  calculation block is used to estimate the motor's rotor flux. This calculation is based on motor equation synthesis.

The  $\theta_e$  calculation block is used to find the phase angle of the rotor flux rotating field.

The  $abc-dq$  block performs the conversion of  $abc$  phase variables into  $dq$  components of the rotor flux rotating field reference frame.

The  $dq-abc$  block performs the conversion of the  $dq$  component of the rotor flux rotating field reference frame into  $abc$  phase variables.

The *iqs\*calculation* block uses the calculated rotor flux and the torque reference to compute the stator current quadrature component required to produce the electromagnetic torque on the motor's shaft.

The *ids\*calculation* block uses the rotor flux reference to compute the stator current direct component required to produce the rotor flux in the machine.

The *current regulator* is a bang-bang current controller with adjustable hysteresis band width.

The *switching control* block is used to limit the inverter commutation frequency to a maximum value specified by the user.

The *flux controller* is used to control the flux dynamics and to reduce the steady-state flux error.

The *magnetization vector* unit contains the vector used to create the motor initial flux.

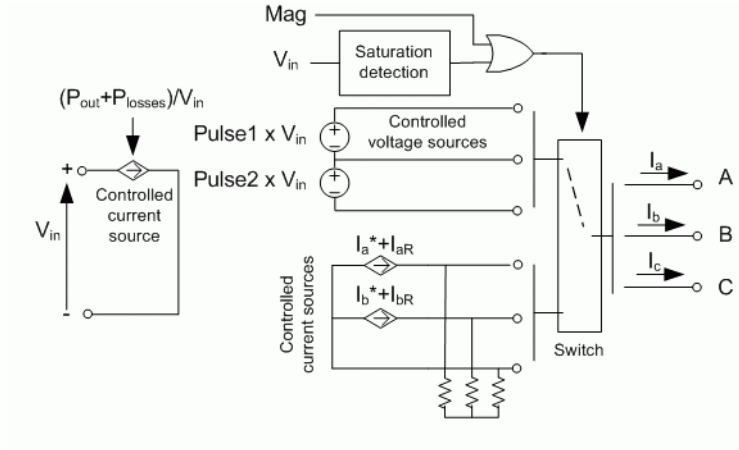
The *magnetization control* unit contains the logic used to switch between the magnetization and normal operation mode.

## Braking Chopper

The braking chopper block contains the DC bus capacitor and the dynamic braking chopper, which is used to absorb the energy produced by a motor deceleration.

# Field-Oriented Control Induction Motor Drive

**Average-Value Inverter** The average-value inverter is shown in the following figure.



It is composed of one controlled current source on the DC side and of two controlled current sources and two controlled voltage sources on the AC side. The DC current source allows the representation of the average DC bus current behavior following the next equation:

$$I_{dc} = (P_{out} + P_{losses})/V_{in}$$

with  $P_{out}$  being the output power and  $P_{losses}$  the losses in the power electronics devices and  $V_{in}$  the DC bus voltage.

On the AC side, the current sources represent the average phase currents fed to the motor. The regulation being fast, the current values are set equal to the current references sent by the current regulator. A small current is injected to compensate the current drawn by the three-phase load (needed because of the inverter current sources in series with inductive motor).

During loss of current tracking due to insufficient inverter voltage, the currents are fed by two controlled voltage sources. These voltage sources represent the square wave mode and allow good representation of the phase currents during inverter saturation. Each voltage source

outputs either  $V_{in}$  or 0, depending on the values of the pulses (1 or 0) sent by the current controller.

## Remarks

The model is discrete. Good simulation results have been obtained with a  $2 \mu\text{s}$  time step. To simulate a digital controller device, the control system has two different sampling times:

- Speed controller sampling time
- FOC sampling time

The speed controller sampling time has to be a multiple of the FOC sampling time. The latter sampling time has to be a multiple of the simulation time step. The average-value inverter allows the use of bigger simulation time steps since it does not generate small time constants (due to the RC snubbers) inherent to the detailed converter. For an FOC sampling time of  $60 \mu\text{s}$ , good simulation results have been obtained for a simulation time step of  $60 \mu\text{s}$ . This time step can, of course, not be higher than the FOC time step.

# Field-Oriented Control Induction Motor Drive

## Dialog Box

## Asynchronous Machine Tab

The screenshot shows a software dialog box titled "Field-Oriented Control Induction Motor Drive". It has three tabs: "Asynchronous Machine", "Converters and DC bus", and "Controller". The "Asynchronous Machine" tab is active. The dialog contains several sections for parameter configuration:

- Electrical parameters:**
  - Reference frame: Rotor (dropdown)
  - Nominal values: Power (VA): 2238, Voltage (Vrms): 220, Frequency (Hz): 60
  - Equivalent circuit values:

	Resistance (ohm)	Leakage inductance (H)	Mutual inductance (H)
Stator:	0.435	2e-3	69.31e-3
Rotor:	0.816	2e-3	
  - Initial currents:

	Phase A:	Phase B:	Phase C:
Magnitude (A):	0	0	0
Phase (deg):	0	0	0
- Mechanical parameters:**
  - Rotor values:
    - Inertia (kg\*m<sup>2</sup>): 0.089
    - Friction (N-m-s): 0.005
    - Pole pairs: 2
  - Initial values:
    - Slip: 1
    - Angle (deg): 0
- Model detail level: Detailed (dropdown)
- Mechanical input: Torque Trm (dropdown)
- Parameters file options: Load, Save buttons
- Buttons: OK, Cancel, Help, Apply

The **Asynchronous Machine** tab displays the parameters of the asynchronous machine block of the powerlib library. Refer to the Asynchronous Machine for more information on the Asynchronous Machine parameters.

### Model detail level

Select between the detailed and the average-value inverter.

### Mechanical input

Allows you to select either the load torque or the motor speed as mechanical input. Note that if you select and apply a load



torque, you will obtain as output the motor speed according to the following differential equation that describes the mechanical system dynamics:

$$T_e = J \frac{d}{dt} \omega_r + F \omega_r + T_m$$

This mechanical system is included in the motor model.

However, if you select the motor speed as mechanical input then you will get the electromagnetic torque as output, allowing you to represent externally the mechanical system dynamics. Note that the internal mechanical system is not used with this mechanical input selection and the inertia and viscous friction parameters are not displayed.

See for example “Mechanical Coupling of Two Motor Drives”.

# Field-Oriented Control Induction Motor Drive

## Converters and DC Bus Tab

Field-Oriented Control Induction Motor Drive

The AC motor parameters are specified in the AC Machine tab. The braking chopper, the diode rectifier and the inverter switches parameters are specified in the Converter and DC bus tab. F.O.C. and speed controller parameters are specified in the Controller Tab.

Asynchronous Machine    Converters and DC bus    Controller

**Rectifier**

Snubbers

Resistance (ohm): 10e3

Capacitance (F): 20e-9

Diodes

On-state resistance (ohm): 1e-3

Forward voltage (V): 1.3

**DC Bus**

Capacitance (F): 1500e-6

Braking chopper

Resistance (ohm): 8

Chopper frequency (Hz): 4000

Activation voltage (V): 340

Shutdown voltage (V): 320

**Inverter**

Switches

Device type: IGBT / Diodes

On-state resistance (ohm): 1e-3

Forward voltages (V)

Main device: 0.8

Diode: 0.8

Turn-off characteristics

Fall time (s): 1e-6

Tail time (s): 2e-6

Snubbers

Resistance (ohm): 5e3

Capacitance (F): inf

Model detail level: Detailed    Mechanical input: Torque Tm

Parameters file options

Load    Save

OK    Cancel    Help    Apply

### Rectifier Section

The **Rectifier** section of the **Converters and DC Bus** tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the Universal Bridge for more information on the universal bridge parameters.

### Inverter Section

The **Inverter** section of the **Converters and DC Bus** tab displays the parameters of the Universal Bridge block of the powerlib library.

# Field-Oriented Control Induction Motor Drive

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Refer to the Universal Bridge for more information on the universal bridge parameters.

The average-value inverter uses the following parameters.

## **Source frequency**

The frequency of the three-phase voltage source (Hz).

## **On-state resistance**

The on-state resistance of the inverter switches (ohms).

## **DC Bus Field – Capacitance**

The DC bus capacitance (F).

## **Braking Chopper section**

### **Resistance**

The braking chopper resistance used to avoid bus over-voltage during motor deceleration or when the load torque tends to accelerate the motor (ohms).

### **Frequency**

The braking chopper frequency (Hz).

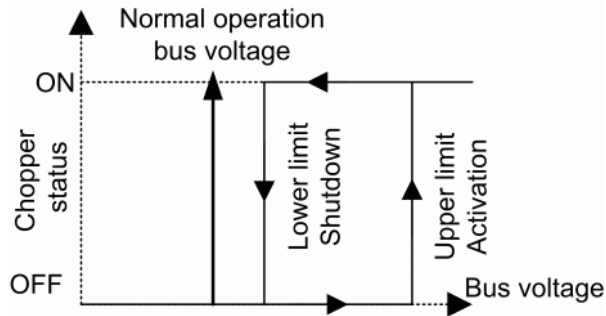
### **Activation Voltage**

The dynamic braking is activated when the bus voltage reaches the upper limit of the hysteresis band (V). The following figure illustrates the braking chopper hysteresis logic.

### **Deactivation Voltage**

The dynamic braking is shut down when the bus voltage reaches the lower limit of the hysteresis band (V). The Chopper hysteresis logic is shown in the next figure.

# Field-Oriented Control Induction Motor Drive



## Controller Tab

**Field-Oriented Control Induction Motor Drive**

Field-Oriented Control Induction Motor Drive

The AC motor parameters are specified in the AC Machine tab. The braking chopper, the diode rectifier and the inverter switches parameters are specified in the Converter and DC bus tab. F.O.C. and speed controller parameters are specified in the Controller Tab.

Asynchronous Machine    Converters and DC bus    **Controller**

Regulation type:     Schematic

Speed controller

Speed ramps (rpm/s)		Speed cutoff frequency (Hz):	Speed controller sampling time (s):	Machine flux (Wb)
Acceleration:	Deceleration:			
<input type="text" value="1800"/>	<input type="text" value="-1800"/>	<input type="text" value="100"/>	<input type="text" value="100e-6"/>	Initial:
PI regulator		Torque output limits (N-m)		Nominal:
Proportional gain:	Integral gain:	Negative:	Positive:	<input type="text" value="0.3"/>
<input type="text" value="5"/>	<input type="text" value="10"/>	<input type="text" value="-17.8"/>	<input type="text" value="17.8"/>	

Field oriented control

Flux controller		Flux output limits (Wb)	
Proportional gain:	Integral gain:	Negative:	Positive:
<input type="text" value="40"/>	<input type="text" value="50"/>	<input type="text" value="-2"/>	<input type="text" value="2"/>
Lowpass filter cutoff frequency (Hz):	Sampling time (s):	Current controller hysteresis band (A):	Maximum switching frequency (Hz):
<input type="text" value="16"/>	<input type="text" value="20e-6"/>	<input type="text" value="0.1"/>	<input type="text" value="20000"/>

Model detail level:     Mechanical input:

Parameters file options

# Field-Oriented Control Induction Motor Drive

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## **Regulation Type**

This pop-up menu allows you to choose between speed and torque regulation.

## **Schematic Button**

When you press this button, a diagram illustrating the speed and current controllers schematics appears.

## **Speed Controller section**

### **Speed cutoff frequency**

The speed measurement first-order low-pass filter cutoff frequency (Hz). This parameter is used in speed regulation mode only.

### **Speed controller sampling time**

The speed controller sampling time (s). The sampling time must be a multiple of the simulation time step.

### **Speed Ramps — Acceleration**

The maximum change of speed allowed during motor acceleration (rpm/s). An excessively large positive value can cause DC bus under-voltage. This parameter is used in speed regulation mode only.

### **Speed Ramps — Deceleration**

The maximum change of speed allowed during motor deceleration (rpm/s). An excessively large negative value can cause DC bus overvoltage. This parameter is used in speed regulation mode only.

### **PI Regulator — Proportional Gain**

The speed controller proportional gain. This parameter is used in speed regulation mode only.

### **PI Regulator — Integral Gain**

The speed controller integral gain. This parameter is used in speed regulation mode only.

### **Torque output limits — Negative**

The maximum negative demanded torque applied to the motor by the current controller (N.m).

# Field-Oriented Control Induction Motor Drive

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## **Torque output limits — Positive**

The maximum positive demanded torque applied to the motor by the current controller (N.m).

## **Field Oriented Control Section**

### **Flux Controller — Proportional gain**

The flux controller proportional gain.

### **Flux Controller — Integral gain**

The flux controller integral gain.

### **Flux output limits — Positive**

The flux controller maximum positive output (Wb).

### **Flux output limits — Negative**

The flux controller maximum negative output (Wb).

### **Lowpass filter cutoff frequency**

The flux estimation first-order filter cutoff frequency (Hz).

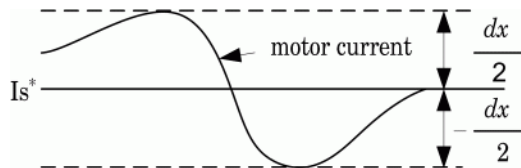
### **Sampling Time**

The FOC controller sampling time (s). The sampling time must be a multiple of the simulation time step.

### **Current controller hysteresis band**

The current hysteresis bandwidth. This value is the total bandwidth distributed symmetrically around the current set point <sup>(A)</sup>. The following figure illustrates a case where the current set point is  $I_s^*$  and the current hysteresis band is set to  $dx$ .

This parameter is not used when using the average-value inverter.



# Field-Oriented Control Induction Motor Drive

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## Block Inputs and Outputs

### Maximum Switching Frequency

The maximum inverter switching frequency (Hz). This parameter is not used when using the average-value inverter.

SP

The speed or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration / deceleration ramps. If the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

$T_m$  or  $W_m$

The mechanical input: load torque ( $T_m$ ) or motor speed ( $W_m$ ).

A, B, C

The three phase terminals of the motor drive.

$W_m$  or  $T_e$

The mechanical output: motor speed ( $W_m$ ) or electromagnetic torque ( $T_e$ ).

Motor

The motor measurement vector. This vector allows you to observe the motor's variables using the Bus Selector block.

Conv

The three-phase converters measurement vector. This vector contains:

- The DC bus voltage
- The rectifier output current
- The inverter input current

Note that all current and voltage values of the bridges can be visualized with the Multimeter block.

Ctrl

The controller measurement vector. This vector contains:

# Field-Oriented Control Induction Motor Drive

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- The torque reference
- The speed error (difference between the speed reference ramp and actual speed)
- The speed reference ramp or torque reference

## Model Specifications

The library contains a 3 hp and a 200 hp drive parameter set. The specifications of these two drives are shown in the following table.

### 3 HP and 200 HP Drive Specifications

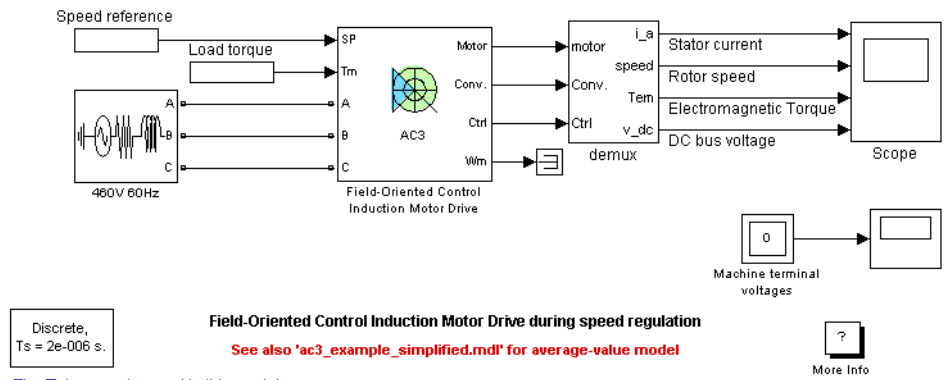
	<b>3 HP Drive</b>	<b>200 HP Drive</b>
<b>Drive Input Voltage</b>		
Amplitude	220 V	460 V
Frequency	60 Hz	60 Hz
<b>Motor Nominal Values</b>		
Power	3 hp	200 hp
Speed	1705 rpm	1785 rpm
Voltage	220 V	460 V

## Example

The `ac3_example` demo illustrates an AC3 motor drive simulation with standard load conditions for the detailed and average-value models.



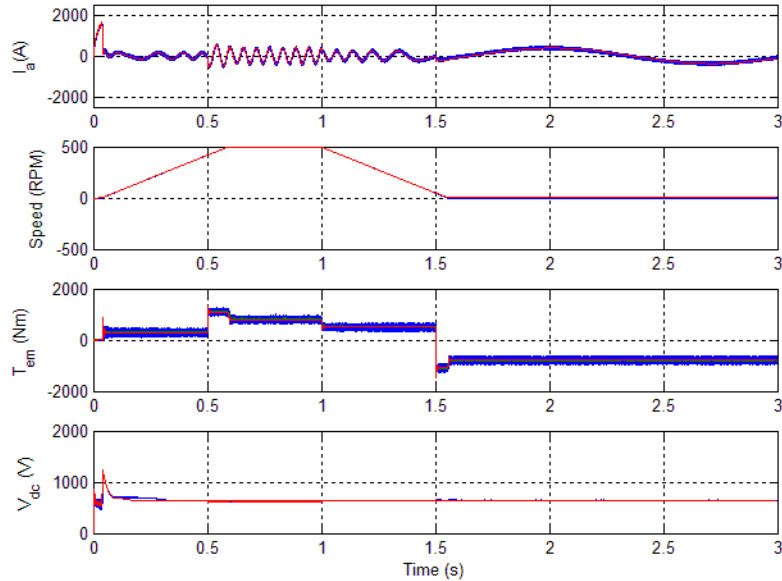
# Field-Oriented Control Induction Motor Drive



The 'Ts' parameter used in this model is set to 2e-6 by the Model Properties Callbacks

At time  $t = 0$  s, the speed set point is 500 rpm. As shown in the following figure, the speed precisely follows the acceleration ramp. At  $t = 0.5$  s, the nominal load torque is applied to the motor. At  $t = 1$  s, the speed set point is changed to 0 rpm. The speed decreases to 0 rpm. At  $t = 1.5$  s, the mechanical load passes from 792 N.m to -792 N.m. Notice that the results of the average-value model are similar to those of the detailed model except that the higher frequency signal components are not represented with the average-value converter.

# Field-Oriented Control Induction Motor Drive



**AC3 Example Waveforms (Blue : Detailed Converter, Red : Average-Value Converter)**

## References

- [1] Bose, B. K., *Modern Power Electronics and AC Drives*, Prentice-Hall, N.J., 2002.
- [2] Grelet, G., and G. Clerc, *Actionneurs électriques*, Éditions Eyrolles, Paris, 1997.
- [3] Krause, P. C., *Analysis of Electric Machinery*, McGraw-Hill, 1986.

**Purpose** Perform Fourier analysis of signal

**Library** Extras/Measurements

A discrete version of this block is available in the Extras/Discrete Measurements library.

## Description



The Fourier block performs a Fourier analysis of the input signal over a running window of one cycle of the fundamental frequency of the signal. The Fourier block can be programmed to calculate the magnitude and phase of the DC component, the fundamental, or any harmonic component of the input signal.

Recall that a signal  $f(t)$  can be expressed by a Fourier series of the form

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + b_n \sin(n\omega t)$$

where  $n$  represents the rank of the harmonics ( $n = 1$  corresponds to the fundamental component). The magnitude and phase of the selected harmonic component are calculated by the following equations:

$$|H_n| = \sqrt{a_n^2 + b_n^2}$$

$$\angle H_n = \text{atan2}\left(\frac{a_n}{b_n}\right)$$

where

$$a_n = \frac{2}{T} \int_{t-T}^t f(t) \cos(n\omega t) dt$$

# Fourier

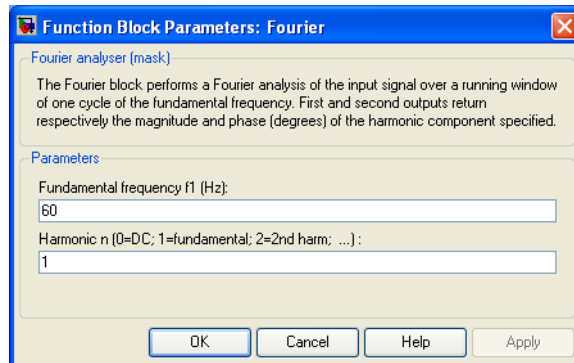
$$b_n = \frac{2}{T} \int_{t-T}^t f(t) \sin(n\omega t) dt$$

$$T = \frac{1}{f_1}$$

$f_1$  : Fundamental frequency

As this block uses a running average window, one cycle of simulation has to be completed before the outputs give the correct magnitude and angle. The discrete version of this block allows you to specify the initial magnitude and phase of the output signal. For the first cycle of simulation the outputs are held to the values specified by the initial input parameter.

## Dialog Box and Parameters



### Fundamental frequency f1

The fundamental frequency, in hertz, of the input signal.

### Harmonic n (0 = DC; 1 = fundamental; 2 = 2nd harm; etc.)

Specify the harmonic component you want to perform the Fourier analysis. Enter 0 if you want to analyze the DC component. Enter 1 if you want to analyze the fundamental frequency, or enter a number corresponding to the desired harmonic.

## Inputs and Outputs

### signal

Connect to the signal to be analyzed. Typical input signals are voltages or currents measured by Current Measurement blocks or Voltage Measurement blocks.

### magnitude

The first output returns the magnitude of the harmonic component specified, in the same units as the input signal.

### phase

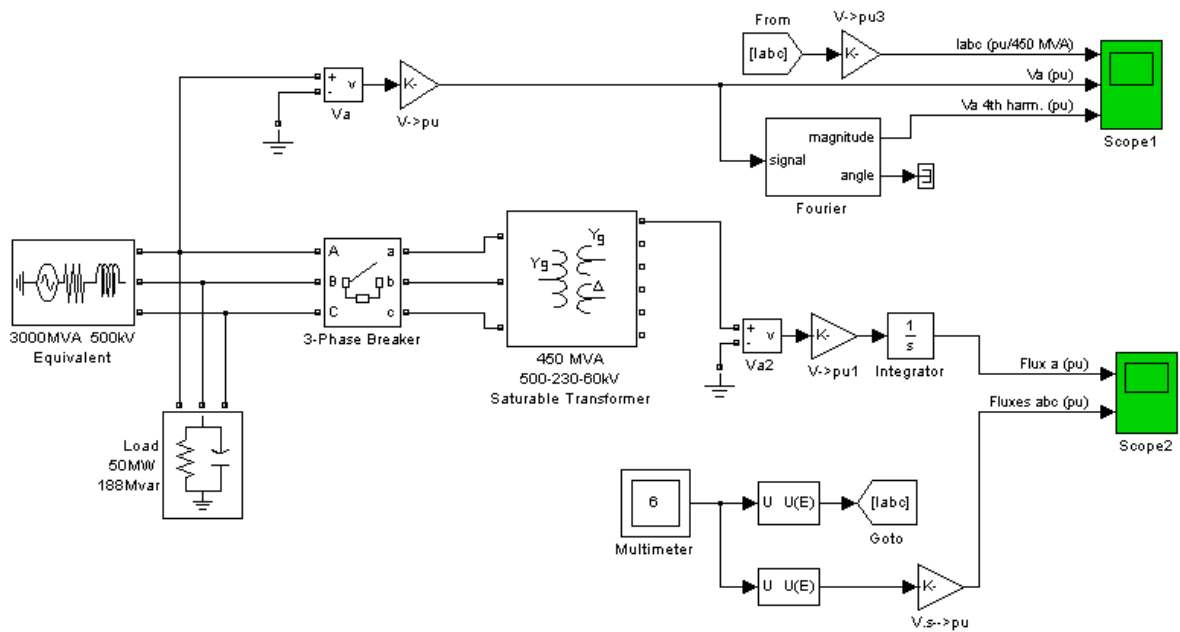
The second output returns the phase, in degrees, of the harmonic component specified.

## Example

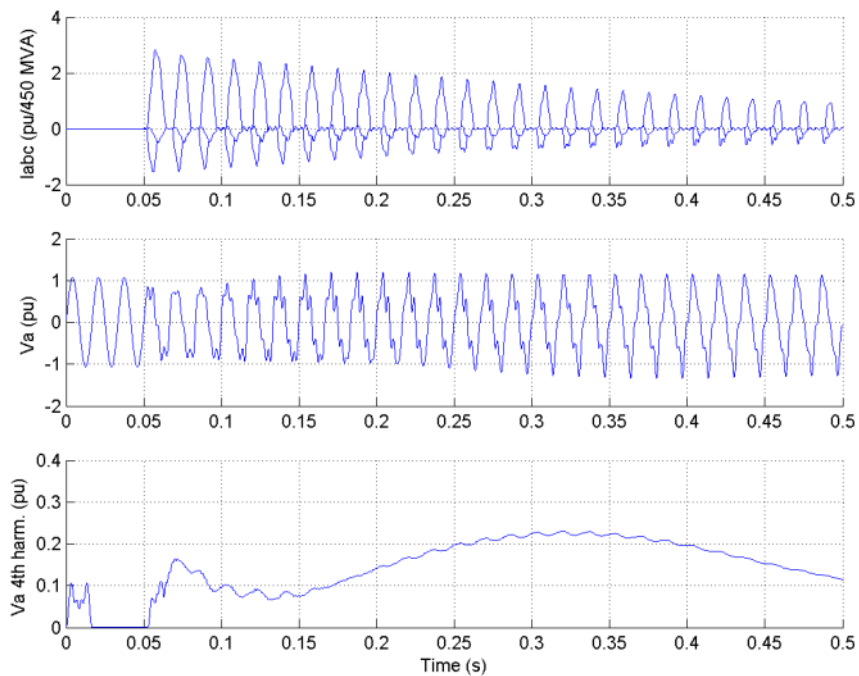
The power\_transfosat demo shows the energization of a 450 MVA three-phase transformer on a 500 kV network. The power system is simulated by an equivalent circuit consisting of an inductive source having a short-circuit power of 3000 MVA and a parallel RC load.

The load capacitance is set to produce a resonance at 240 Hz (fourth harmonic). A Fourier block is used to measure the fourth harmonic content of phase A of the primary voltage.

# Fourier



The Fourier block measures a high level fourth harmonic in the voltage (on the second trace of Scope1) because of the fourth harmonic content of the current injected into the network resonating at that particular frequency (240 Hz).

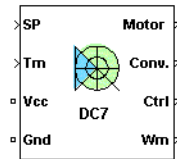


# Four-Quadrant Chopper DC Drive

**Purpose** Implement four-quadrant chopper DC drive

**Library** Electric Drives/DC drives

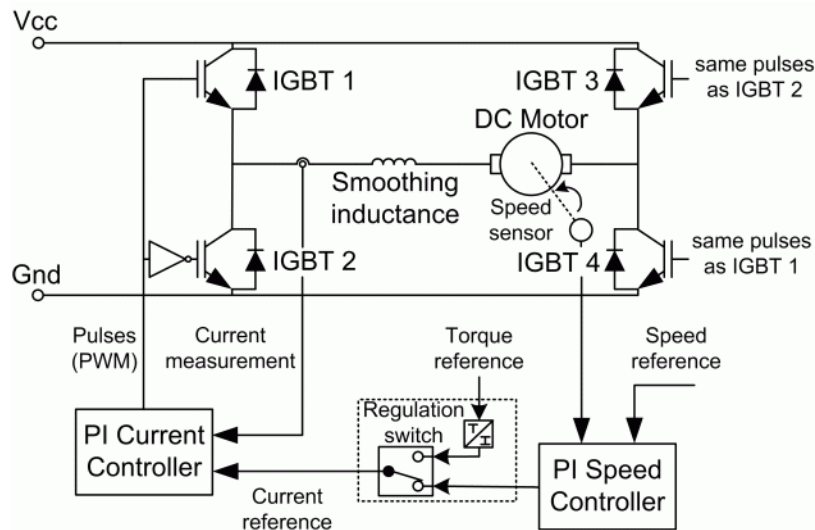
## Description



The high-level schematic shown below is built from four main blocks. The DC motor and the IGBT/Diode devices (within the Universal Bridge block) are provided with the SimPowerSystems library. More details on these two blocks are available in the reference sections of these blocks. The two other blocks are specific to the Electric Drives library. These blocks are the speed controller and the current controller. They allow speed or torque regulation. A “regulation switch” block allows you to toggle from one type of regulation to the other. During torque regulation the speed controller is disabled.

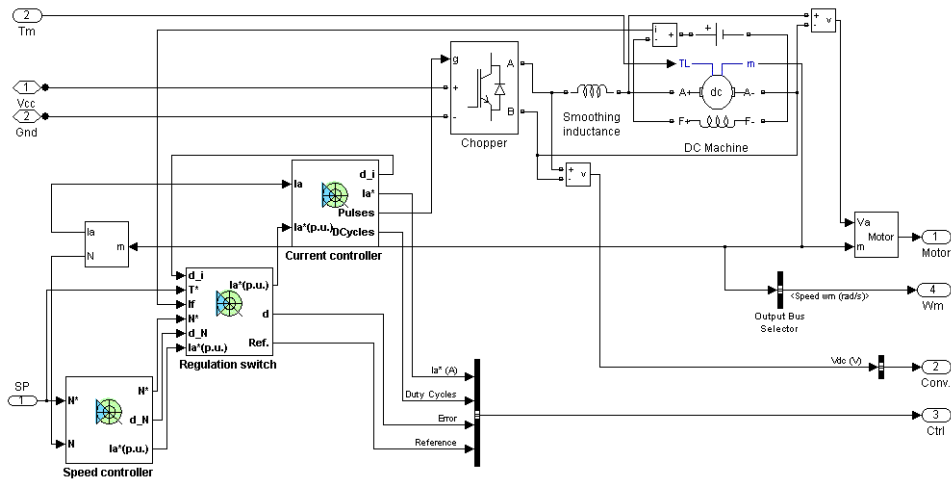
**Note** In SimPowerSystems software, the Four-Quadrant Chopper DC Drive block is commonly called the DC7 motor drive.

## High-Level Schematic





## Simulink Schematic



## Speed Controller

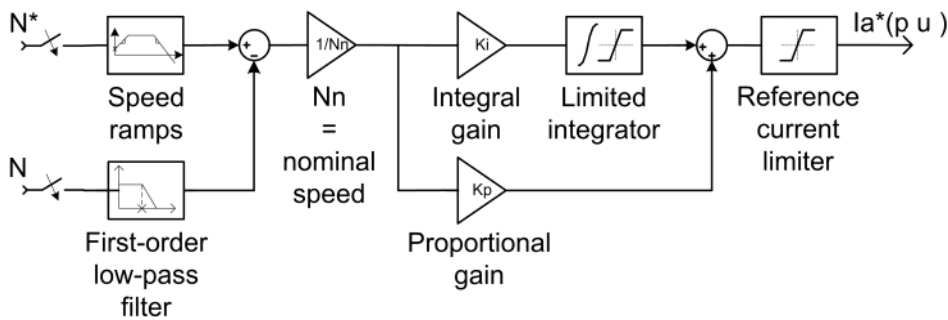
The speed regulator shown below uses a PI controller. The controller outputs the armature current reference (in pu) used by the current controller in order to obtain the electromagnetic torque needed to reach the desired speed. During torque regulation, the speed controller is disabled.

The controller takes the speed reference (in rpm) and the rotor speed of the DC machine as inputs. The speed reference change rate will follow user-defined acceleration and deceleration ramps in order to avoid sudden reference changes that could cause armature over-current and destabilize the system.

The speed measurement is filtered by a first-order low-pass filter.

The current reference output is limited between symmetrical lower and upper limits defined by the user.

# Four-Quadrant Chopper DC Drive



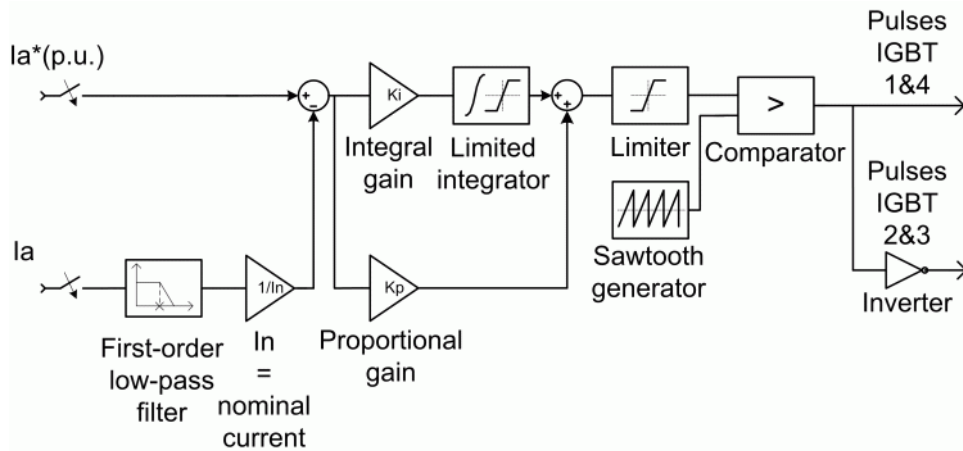
## Current Controller

The armature current regulator shown below is based on a second PI controller. The regulator controls the armature current by computing the appropriate duty ratios of the fixed frequency pulses of the four IGBT devices (Pulse Width Modulation). This generates the average armature voltage needed to obtain the desired armature current and thus the desired electromagnetic torque. For proper system behavior, the instantaneous pulse values of IGBT devices 1 and 4 are the opposite of those of IGBT devices 2 and 3.

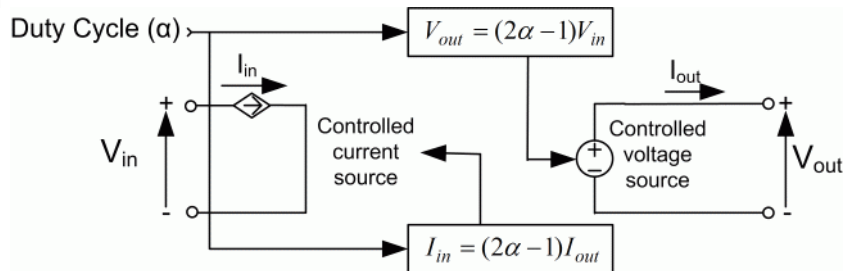
The controller takes the current reference (in pu) and the armature current flowing through the motor as inputs. The current reference is either provided by the speed controller during speed regulation or computed from the torque reference provided by the user during torque regulation. This is managed by the “regulation switch” block. The armature current input is filtered by a first-order low-pass filter.

The pulse width modulation is obtained by comparison of the PI output and a fixed frequency sawtooth carrier signal (as shown in the figure called Pulse Width Modulation (PWM) on page 2-161).

# Four-Quadrant Chopper DC Drive



**Average-Value Four-Quadrant Chopper** The average-value converter is shown in the following figure.



It is composed of one controlled current source on the DC source side and one controlled voltage source on the motor side. The current source allows the representation of the average input current value according to the following equation :

$$I_{in} = (2\alpha - 1)I_{out}$$

with  $\alpha$  being the firing angle value and  $I_{out}$  the armature current value. The voltage source on the motor side represents the average voltage value according to the next equation :

# Four-Quadrant Chopper DC Drive

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$$V_{out} = (2\alpha - 1)V_{in}$$

with  $V_{in}$  being the input voltage.

## Remarks

The machine is separately excited with a constant DC field voltage source. There is thus no field voltage control. By default, the field current is set to its steady-state value when a simulation is started.

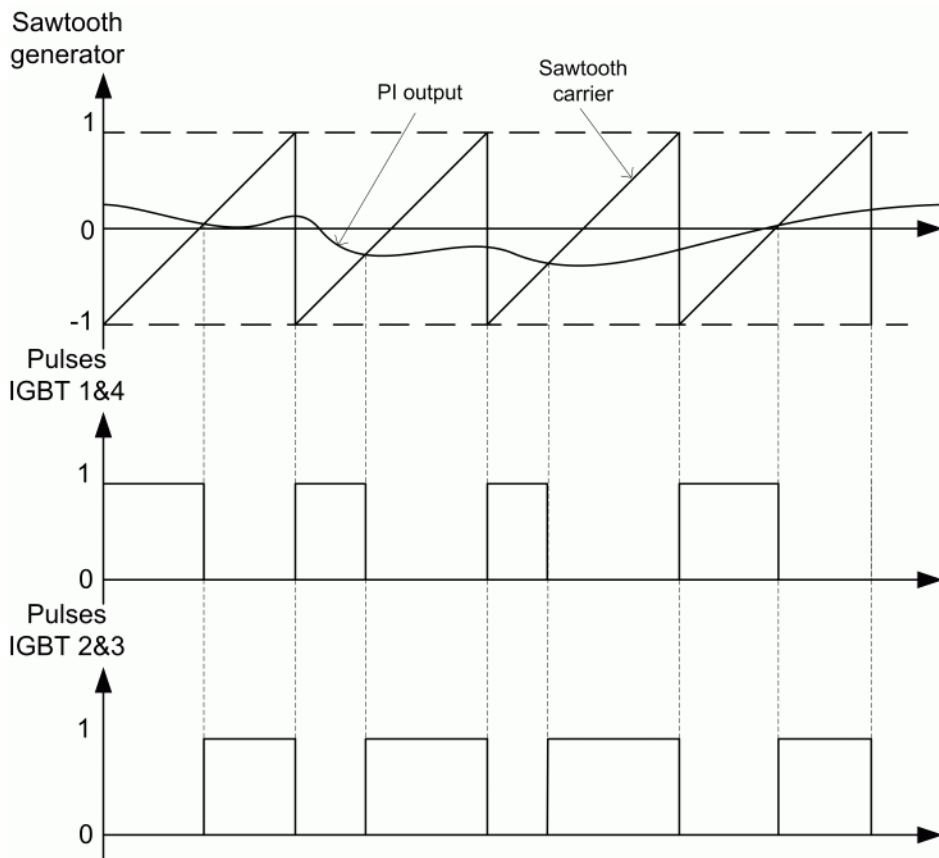
The armature voltage is provided by an IGBT converter controlled by two PI regulators. The converter is fed by a constant DC voltage source. Armature current oscillations are reduced by a smoothing inductance connected in series with the armature circuit.

The model is discrete. Good simulation results have been obtained with a  $1 \mu\text{s}$  time step. In order to simulate a digital controller device, the control system has two different sampling times:

- The speed controller sampling time
- The current controller sampling time

The speed controller sampling time has to be a multiple of the current sampling time. The latter sampling time has to be a multiple of the simulation time step.

# Four-Quadrant Chopper DC Drive



**Pulse Width Modulation (PWM)**

# Four-Quadrant Chopper DC Drive

## Dialog Box

### DC Machine Tab

The screenshot shows a dialog box titled "4-Quadrant Chopper DC Motor Drive". It has three tabs: "DC Machine", "Converter", and "Controller". The "DC Machine" tab is selected. The dialog contains the following fields and controls:

- Electrical parameters:**
  - Mutual inductance (H): 1.234
  - Armature:**
    - Resistance (ohm): 0.78
    - Inductance (H): 0.016
  - Field:**
    - Resistance (ohm): 150
    - Inductance (H): 112.5
- Mechanical parameters:**
  - Inertia (kg\*m<sup>2</sup>): 0.05
  - Viscous friction coefficient (N-m-s): 0.01
  - Coulomb friction torque (N-m): 0
  - Initial speed (rad/s): 0
- Model detail level: Detailed (dropdown)
- Mechanical input: Torque Tm (dropdown)
- Parameters file options: Load, Save (buttons)
- OK, Cancel, Help, Apply (buttons)

The DC Machine tab displays the parameters of the DC machine block of the powerlib library. Refer to the DC Machine for more information on the DC machine block parameters.

#### Model detail level

Select between the detailed and the average-value inverter.

#### Mechanical input

Allows you to select either the load torque or the motor speed as mechanical input. Note that if you select and apply a load torque, you will obtain as output the motor speed according to the following differential equation that describes the mechanical system dynamics:

$$T_e = J \frac{d}{dt} \omega_r + F \omega_r + T_m$$

This mechanical system is included in the motor model.

However, if you select the motor speed as mechanical input then you will get the electromagnetic torque as output, allowing you to represent externally the mechanical system dynamics. Note that the internal mechanical system is not used with this mechanical input selection and the inertia and viscous friction parameters are not displayed.

See for example “Mechanical Coupling of Two Motor Drives”.

# Four-Quadrant Chopper DC Drive

## Converter Tab

4-Quadrant Chopper DC Motor Drive

4-Quadrant Chopper DC Motor Drive

The DC motor parameters are specified in the DC Machine tab. The converter parameters, smoothing inductance and field voltage values are specified in the Converter tab. The speed and current regulator parameters are specified in the Controller tab.

DC Machine Converter Controller

Smoothing inductance and excitation circuit

Smoothing inductance (H): 10e-3 Field DC source (V): 150

IGBT/Diode devices

Snubbers

Resistance (ohm): 10e3 Capacitance (F): inf

IGBT/Diode

On-state resistance (ohm): 1e-3

IGBT

Forward voltage (V): 1.3

Current fall time (s): 0

Current tail time (s): 0

Diode

Forward voltage (V): 1.3

Model detail level: Detailed Mechanical input: Torque Tm

Parameters file options

Load Save

OK Cancel Help Apply

### IGBT/Diode Devices section

The IGBT/Diode section of the Converter tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the Universal Bridge for more information on the Universal Bridge block parameters.

### Smoothing Inductance

The smoothing inductance value (H).

### Field DC Source

The DC motor field voltage value (V).



# Four-Quadrant Chopper DC Drive

## Controller Tab

4-Quadrant Chopper DC Motor Drive

4-Quadrant Chopper DC Motor Drive

The DC motor parameters are specified in the DC Machine tab. The converter parameters, smoothing inductance and field voltage values are specified in the Converter tab. The speed and current regulator parameters are specified in the Controller tab.

DC Machine | Converter | **Controller**

Regulation type: Speed regulation

Speed Controller | Current Controller

Nominal speed (rpm): 1750 Initial speed reference (rpm): 0 Low-pass filter cutoff frequency (Hz): 40 Sampling time (s): 100e-6

PI regulator

Proportional gain: 50 Integral gain: 320

Speed ramps (rpm/s)

Acceleration: 900 Deceleration: -900

Model detail level: Detailed Mechanical input: Torque Tm

Parameters file options

## Schematic Button

When you press this button, a diagram illustrating the speed and current controllers schematics appears.

## Regulation Type

This pop-up menu allows you to choose between speed and torque regulation.

## Controller – Speed Controller Subtab

### Nominal Speed

The nominal speed value of the DC motor (rpm). This value is used to convert motor speed from rpm to pu (per unit).

# Four-Quadrant Chopper DC Drive

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## **Initial Speed Reference**

The initial speed reference value (rpm). This value allows the user to start a simulation with a speed reference other than 0 rpm.

## **Low-Pass Filter Cutoff Frequency**

Cutoff frequency of the low-pass filter used to filter the motor speed measurement (Hz).

## **Sampling Time**

The speed controller sampling time (s). This sampling time has to be a multiple of the current controller sampling time and of the simulation time step.

## **Proportional Gain**

The proportional gain of the PI speed controller.

## **Integral Gain**

The integral gain of the PI speed controller.

## **Acceleration**

The maximum change of speed allowed during motor acceleration (rpm/s). Too great a value can cause armature over-current.

## **Deceleration**

The maximum change of speed allowed during motor deceleration (rpm/s). Too great a value can cause armature over-current.

# Four-Quadrant Chopper DC Drive

## Controller – Current Controller Subtab

4-Quadrant Chopper DC Motor Drive

4-Quadrant Chopper DC Motor Drive

The DC motor parameters are specified in the DC Machine tab. The converter parameters, smoothing inductance and field voltage values are specified in the Converter tab. The speed and current regulator parameters are specified in the Controller tab.

DC Machine | Converter | **Controller**

Regulation type: Speed regulation

Speed Controller | **Current Controller**

Low-pass filter cutoff frequency (Hz):	Symmetrical reference limit (p.u.):	PWM switching frequency (Hz):	Sampling time (s):
500	1.5	5e3	20e-6

Nominal values

Power (VA):	5746	PI regulator	Proportional gain:	2
Voltage (V):	240		Integral gain:	200

Model detail level: Detailed

Parameters file options

### Low-Pass Filter Cutoff Frequency

Cutoff frequency of the low-pass filter used to filter the armature current measurement (Hz).

### Symmetrical Reference Limit

Symmetrical current reference (pu) limit around 0 pu. 1.5 pu is a common value.

### PWM Switching Frequency

The switching frequency of the four IGBT devices (Hz).

# Four-Quadrant Chopper DC Drive

---

## Block Inputs and Outputs

### Sampling Time

The current controller sampling time (s). This sampling time has to be a submultiple of the speed controller sampling time and a multiple of the simulation time step.

### Power and Voltage nominal values

The DC motor nominal power (W) and voltage (V) values. These values are used to convert armature current from amperes to pu (per unit).

### Proportional Gain

The proportional gain of the PI current controller.

### Integral Gain

The integral gain of the PI current controller.

### SP

The speed or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration / deceleration ramps. If the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

### Tm or Wm

The mechanical input: load torque (Tm) or motor speed (Wm).

### Vcc, Gnd

The DC voltage source electric connections. The voltage must be adequate for the motor size.

### Wm or Te

The mechanical output: motor speed (Wm) or electromagnetic torque (Te).

### Motor

The motor measurement vector. This vector is composed of two elements:

- The armature voltage

# Four-Quadrant Chopper DC Drive

- The DC motor measurement vector (containing the speed, armature current, field current, and electromagnetic torque values). Note that the speed signal is converted from rad/s to rpm before output.

## Conv

The IGBT/Diode device measurement vector. This vector includes the converter output voltage. The output current is not included since it is equal to the DC motor armature current. Note that all current and voltage values of the converter can be visualized with the Multimeter block.

## Ctrl

The controller measurement vector. This vector contains:

- The armature current reference
- The duty cycle of the PWM pulses
- The speed or torque error (difference between the speed reference ramp and actual speed or between the torque reference and actual torque)
- The speed reference ramp or torque reference

## Model Specifications

The library contains a 5 hp and a 200 hp drive parameter set. The specifications of these two drives are shown in the following table.

### 5 HP and 200 HP Drive Specifications

	5 HP Drive	200 HP Drive
<b>Drive Input Voltage</b>		
Amplitude	280 V	500 V
<b>Motor Nominal Values</b>		
Power	5 hp	200 hp

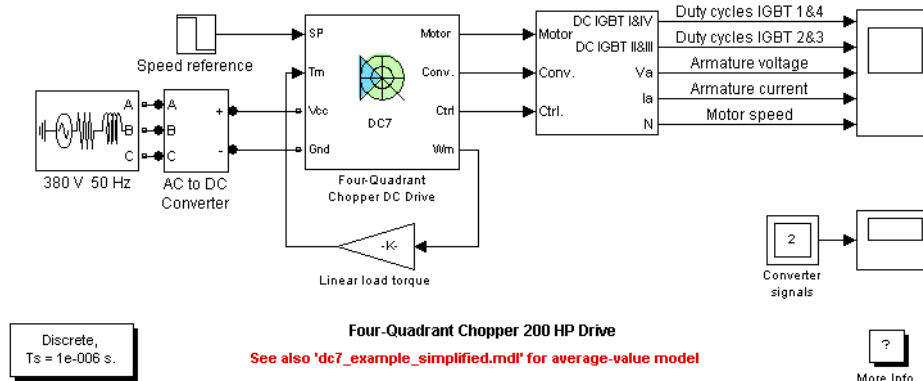
# Four-Quadrant Chopper DC Drive

## 5 HP and 200 HP Drive Specifications (Continued)

	5 HP Drive	200 HP Drive
<b>Drive Input Voltage</b>		
Speed	1750 rpm	1184 rpm
Voltage	240 V	440 V

### Example

The dc7\_example demo illustrates the four-quadrant chopper drive used with the 200 hp drive parameter set during speed regulation. A 5 hp parameter set is also available in the library.



The converter is fed by a 515 V DC bus obtained by rectification of a 380 V AC 50 Hz voltage source. In order to limit the DC bus voltage during dynamic braking mode, a braking chopper has been added between the diode rectifier and the DC7 block. The IGBT switching frequency is 5 kHz.

The motor is coupled to a linear load, which means that the mechanical torque of the load is proportional to the speed.

# Four-Quadrant Chopper DC Drive

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The speed reference is set at 500 rpm at  $t = 0$  s. Observe that the motor speed follows the reference ramp accurately (+400 rpm/s) and reaches steady state around  $t = 1.3$  s.

The armature current follows the current reference very well, with fast response time and small ripples. Notice that the current ripple frequency is 5 kHz.

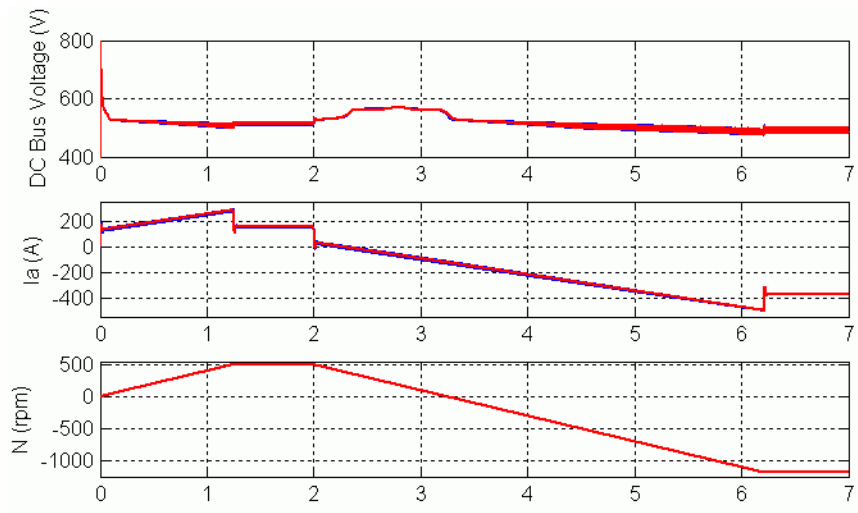
At  $t = 2$  s, speed reference drops to -1184 rpm. The current reference decreases to reduce the electromagnetic torque and causes the motor to decelerate with the help of the load torque.

At  $t = 2.2$  s, the current reverses in order to produce a braking electromagnetic torque (dynamic braking mode). This causes the DC bus voltage to increase.

At  $t = 3.25$  s, the motor reaches 0 rpm and the load torque reverses and becomes negative. The negative current now produces an accelerating electromagnetic torque to allow the motor to follow the negative speed ramp (-400 rpm/s). At  $t = 6.3$  s, the speed reaches -1184 rpm and stabilizes around its reference.

The following figure shows the DC bus voltage, armature current, and speed waveforms.

# Four-Quadrant Chopper DC Drive

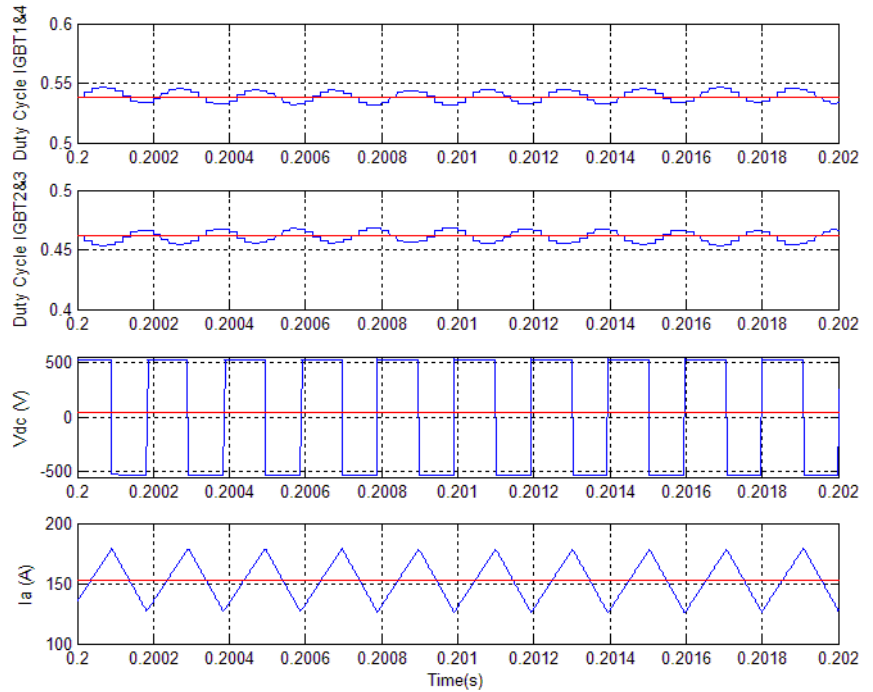


**DC7 Example – DC Bus Voltage, Current, and Speed Waveforms (Blue: Detailed Converter, Red: Average-Value Converter)**

The next figure shows the duty cycles of the chopper pulses and the corresponding armature voltage and current waveforms during a time interval of 2 ms.



# Four-Quadrant Chopper DC Drive



**DC7 Example – Duty Cycles, Armature Voltage, and Current Waveforms (Blue: Detailed Converter, Red: Average-Value Converter)**

## References

- [1] Boldea, Ion, and S.A. Nasar, *Electric Drives*, CRC Press LLC, 1999.
- [1] Séguier, Guy, *Electronique de puissance*, Dunod, 1999.

# Four-Quadrant Single-Phase Rectifier DC Drive

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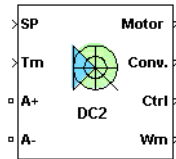
## Purpose

Implement single-phase dual-converter DC drive with circulating current

## Library

Electric Drives/DC drives

## Description



The high-level schematic shown below is built from six main blocks. The DC motor, the two single-phase full converters, and the bridge firing unit are provided with the SimPowerSystems library. More details on these blocks are available in the reference sections of these blocks. The two other blocks are specific to the Electric Drives library. These blocks are the speed controller and the current controller. They allow speed or torque regulation. A “regulation switch” block allows you to toggle from one type of regulation to the other. During torque regulation the speed controller is disabled. It is possible to use a simplified version of the drive, which contains an average-value model of the single-phase dual-converter and allows faster simulation.

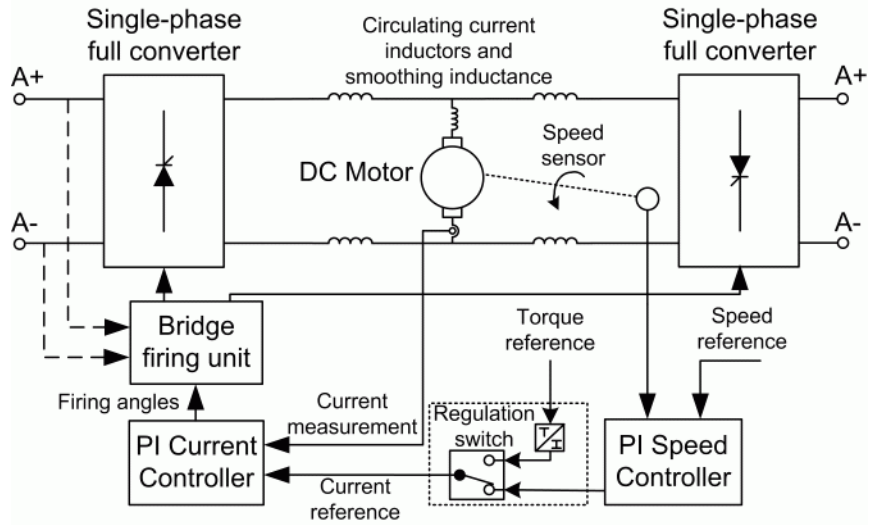
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**Note** In SimPowerSystems software, the Four-Quadrant Single-Phase Rectifier DC Drive block is commonly called the DC2 motor drive.

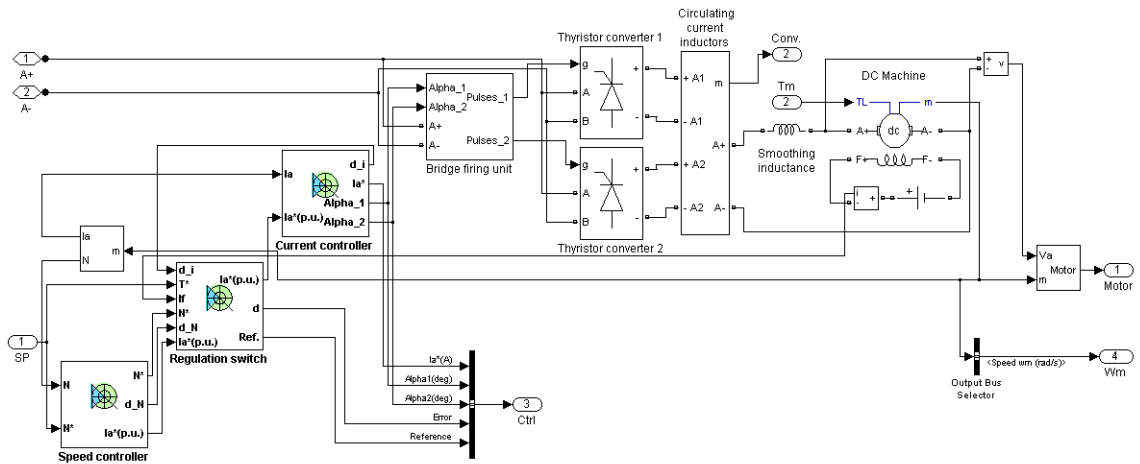
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# Four-Quadrant Single-Phase Rectifier DC Drive

## High-Level Schematic



## Simulink Schematic



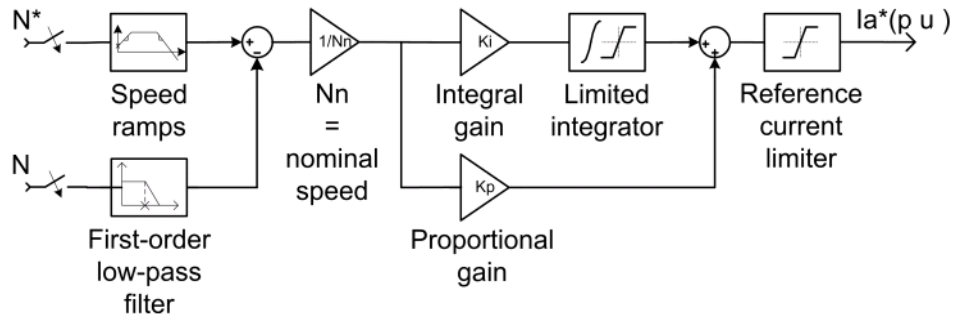
# Four-Quadrant Single-Phase Rectifier DC Drive

## Speed Controller

The speed regulator shown below uses a PI controller. The controller outputs the armature current reference (in pu) used by the current controller in order to obtain the electromagnetic torque needed to reach the desired speed. During torque regulation, the speed controller is disabled.

The controller takes the speed reference (in rpm) and the rotor speed of the DC machine as inputs. The speed reference change rate will follow user-defined acceleration and deceleration ramps in order to avoid sudden reference changes that could cause armature over-current and destabilize the system. The speed measurement is filtered by a first-order low-pass filter.

The current reference output is limited between symmetrical lower and upper limits defined by the user.



## Current Controller

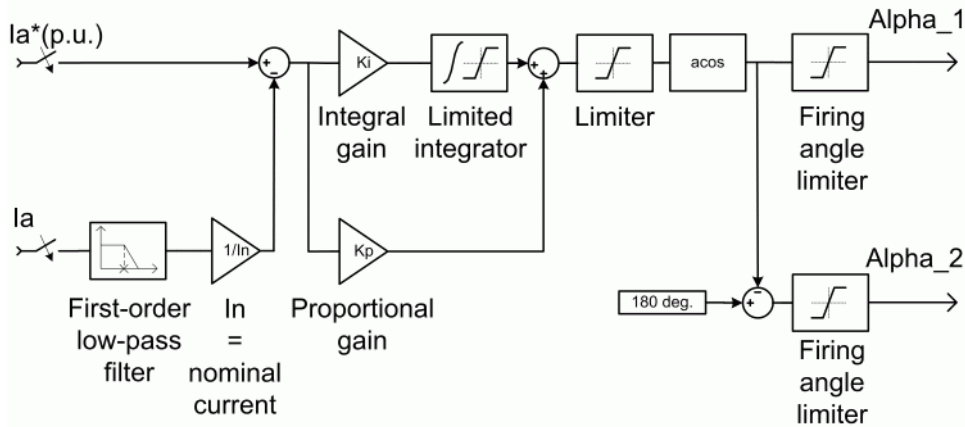
The armature current regulator shown below is based on a second PI controller. The regulator controls the armature current by computing the appropriate thyristor firing angles of the two full converters. This generates the converter output voltages needed to obtain the desired armature current and thus the desired electromagnetic torque.

The controller takes the current reference (in pu) and the armature current flowing through the motor as inputs. The current reference is either provided by the speed controller during speed regulation or computed from the torque reference provided by the user during torque regulation. This is managed by the “regulation switch” block.

# Four-Quadrant Single-Phase Rectifier DC Drive

The armature current input is filtered by a first-order low-pass filter. An arccosine function is used to linearize the control system. The firing angle can vary between 0 and 180 degrees. You can limit the lower and upper limits to intermediate values.

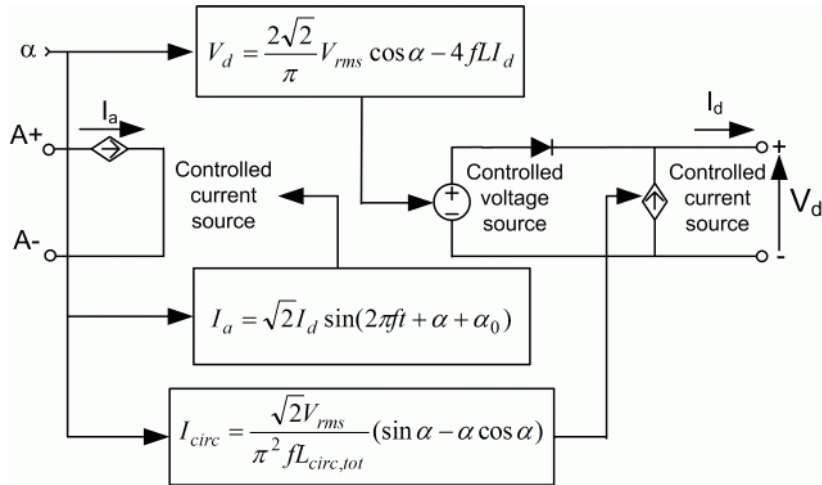
Both converters operate simultaneously, and the two firing angles are controlled so that the sum of their values stays equal to 180 degrees. This produces opposite average voltages at the converter DC output terminals and thus identical average voltages at the DC motor armature, the converters being connected in antiparallel. One converter is working in rectifier mode while the other is in inverter mode.



# Four-Quadrant Single-Phase Rectifier DC Drive

## Average-Value Single-Phase Rectifier

The average-value single-phase rectifier with circulating current is shown in the following figure.



It is composed of one controlled current source on the AC side and one controlled voltage and current source on the DC side. The AC current source allows the representation of the fundamental single-phase current behavior according to the following equation

$$I_a = \sqrt{2}I_d \sin(2\pi ft + \alpha + \alpha_0)$$

with  $\alpha$  being the firing angle value,  $\alpha_0$  the phase angle of the AC side,  $f$  the AC frequency and  $I_d$  the rectified output current value. The DC voltage source represents the average voltage value of the rectified voltage waveform according to the next equation

$$V_d = \frac{2\sqrt{2}}{\pi} V_{rms} \cos \alpha - 4fLI_d$$

with  $V_{rms}$  being the input RMS voltage value and  $L$  being the source inductance value. The controlled current source represents the circulation current due to the instantaneous voltage difference between both converter outputs of the dual-converter. This current is equal to

# Four-Quadrant Single-Phase Rectifier DC Drive

$$I_{circ} = \frac{\sqrt{2}}{\pi^2 f L_{circ, tot}} V_{rms} (\sin \alpha - \alpha \cos \alpha)$$

with  $L_{circ, tot}$  being the total circulation inductance of the circulation current loop.

## Bridge Firing Unit

The bridge firing unit converts the firing angles, provided by the current controller, to two series of four pulses applied respectively to the thyristor gates of each converter. The bridge firing unit block contains a band-pass filter on voltage measurement to remove voltage harmonics. Two discrete synchronized pulse generator blocks generate the pulses of each converter. Their architecture is based on the Discrete Synchronized 6-Pulse Generator block. Refer to the Synchronized 6-Pulse Generator for more information on this block. When using the average-value converter, the bridge firing unit simply outputs the firing angle value needed by the converter.

## Remarks

The machine is separately excited with a constant DC field voltage source. There is thus no field voltage control. By default, the field current is set to its steady-state value when a simulation is started.

The armature voltage is provided by two single-phase antiparallel-connected converters controlled by two PI regulators. The circulating current produced by the instantaneous voltage difference at the terminal of both converters is limited by inductors connected between these terminals. Armature current oscillations are reduced by a smoothing inductance connected in series with the armature circuit.

The average-value converter represents the average behavior of a single-phase rectifier for continuous armature current in a dual-converter topology. This model is thus not suitable for simulating DC drives under discontinuous armature current conditions. The converter outputs a continuous voltage value equal to the average-value of the real-life rectified voltage. The armature voltage, armature current and electromagnetic torque ripples are thus not represented. The input currents have the frequency and amplitude of the fundamental current component of the real-life input currents.

# Four-Quadrant Single-Phase Rectifier DC Drive

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The model is discrete. Good simulation results have been obtained with a 4  $\mu\text{s}$  time step. The control system (speed and current controllers) samples data following a user-defined sample time in order to simulate a digital controller device. Keep in mind that this sampling time has to be a multiple of the simulation time step.

The average-value converter allows the use of bigger simulation time steps since it does not generate small time constants (due to the RC snubbers) inherent to the detailed converter. For a controller sampling time of 100  $\mu\text{s}$  good simulation results have been obtained for a simulation time step of 100  $\mu\text{s}$ . This time step cannot be higher than the controller time step.



# Four-Quadrant Single-Phase Rectifier DC Drive

## Dialog Box

### DC Machine Tab

The screenshot shows a dialog box titled "4-Quadrant Single-Phase Rectifier DC Motor Drive". It has three tabs: "DC Machine", "Converters", and "Controller". The "DC Machine" tab is selected. The dialog contains the following fields and controls:

- Electrical parameters:**
  - Mutual inductance (H): 1.234
  - Armature:**
    - Resistance (ohm): 0.78
    - Inductance (H): 0.016
  - Field:**
    - Resistance (ohm): 150
    - Inductance (H): 112.5
- Mechanical parameters:**
  - Inertia (kg\*m<sup>2</sup>): 0.05
  - Viscous friction coefficient (N-m-s): 0.01
  - Coulomb friction torque (N-m): 0
  - Initial speed (rad/s): 0
- Model detail level: Detailed (dropdown)
- Mechanical input: Torque Tm (dropdown)
- Parameters file options: Load, Save (buttons)
- OK, Cancel, Help, Apply (buttons)

The DC Machine tab displays the parameters of the DC machine block of the powerlib library. Refer to the DC Machine for more information on the DC machine block parameters.

### Model detail level

Select between the detailed and the average-value inverter.

### Mechanical input

Allows you to select either the load torque or the motor speed as mechanical input. Note that if you select and apply a load torque, you will obtain as output the motor speed according to

## Four-Quadrant Single-Phase Rectifier DC Drive

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the following differential equation that describes the mechanical system dynamics:

$$T_e = J \frac{d}{dt} \omega_r + F \omega_r + T_m$$

This mechanical system is included in the motor model.

However, if you select the motor speed as mechanical input then you will get the electromagnetic torque as output, allowing you to represent externally the mechanical system dynamics. Note that the internal mechanical system is not used with this mechanical input selection and the inertia and viscous friction parameters are not displayed.

See for example “Mechanical Coupling of Two Motor Drives”.

# Four-Quadrant Single-Phase Rectifier DC Drive

## Converter Tab

4-Quadrant Single-Phase Rectifier DC Motor Drive

4-Quadrant Single-Phase Rectifier DC Motor Drive

The DC motor parameters are specified in the DC Machine tab. The converter parameters, circulating current inductors, smoothing inductance and field voltage values are specified in the Converter tab. The bridge firing unit, speed and current regulators parameters are specified in the Controller tab.

DC Machine   Converters   Controller

DC bus and Excitation circuit

Smoothing inductance (H):       Field DC source (V):       Circulating current inductors (H):

Converter 1

Snubbers      Thyristors

Resistance (ohm):       On-state resistance (ohm):

Capacitance (F):       Forward voltage (V):

Converter 2

Snubbers      Thyristors

Resistance (ohm):       On-state resistance (ohm):

Capacitance (F):       Forward voltage (V):

Model detail level:       Mechanical input:

Parameters file options

### Smoothing Inductance

The smoothing inductance value (H).

### Field DC Source

The DC motor field voltage value (V).

### Circulating Current Inductors

The four circulating current inductors inductance value (H).

# Four-Quadrant Single-Phase Rectifier DC Drive

---

## Converter sections

The Converter 1 and Converter 2 sections of the Converter tab display the parameters of the Universal Bridge block of the powerlib library. Refer to the Universal Bridge for more information on the Universal Bridge block parameters.

### RMS Voltage

RMS voltage of the single-phase voltage source connected to the A+,A- terminals of the drive (V). This parameter is not used when using the detailed rectifier.

### Frequency

Frequency of the single-phase voltage source connected to the A+,A- terminals of the drive (Hz). This parameter is not used when using the detailed rectifier.

### Source Inductance

Source inductance of the single-phase voltage source connected to the A+,A- terminals of the drive (H). This parameter is not used when using the detailed rectifier.

### Phase Angle

Phase angle of the single-phase voltage source connected to the A+,A- terminals of the drive (deg.). This parameter is not used when using the detailed rectifier.

# Four-Quadrant Single-Phase Rectifier DC Drive

## Controller Tab

4-Quadrant Single-Phase Rectifier DC Motor Drive

4-Quadrant Single-Phase Rectifier DC Motor Drive

The DC motor parameters are specified in the DC Machine tab. The converter parameters, circulating current inductors, smoothing inductance and field voltage values are specified in the Converter tab. The bridge firing unit, speed and current regulators parameters are specified in the Controller tab.

DC Machine | Converters | **Controller**

Regulation type:  Sampling time (s):

Speed Controller | Current Controller | Bridge Firing Unit

Nominal speed (rpm):  Initial speed reference (rpm):  Low-pass filter cutoff frequency (Hz):

PI regulator

Proportional gain:  Integral gain:

Speed ramps (rpm/s)

Acceleration:  Deceleration:

Model detail level:  Mechanical input:

Parameters file options

## Schematic Button

When you press this button, a diagram illustrating the speed and current controllers schematics appears.

## Regulation Type

This pop-up menu allows you to choose between speed and torque regulation.

## Sampling Time

The controller (speed and current) sampling time (s). The sampling time has to be a multiple of the simulation time step.

# Four-Quadrant Single-Phase Rectifier DC Drive

---

## **Controller – Speed Controller Subtab**

### **Nominal Speed**

The nominal speed value of the DC motor (rpm). This value is used to convert motor speed from rpm to pu (per unit).

### **Initial Speed Reference**

The initial speed reference value (rpm). This value allows the user to start a simulation with a speed reference other than 0 rpm.

### **Low-Pass Filter Cutoff Frequency**

Cutoff frequency of the low-pass filter used to filter the motor speed measurement (Hz).

### **Proportional Gain**

The proportional gain of the PI speed controller.

### **Integral Gain**

The integral gain of the PI speed controller.

### **Acceleration**

The maximum change of speed allowed during motor acceleration (rpm/s). Too great a value can cause armature over-current.

### **Deceleration**

The maximum change of speed allowed during motor deceleration (rpm/s). Too great a value can cause armature over-current.

# Four-Quadrant Single-Phase Rectifier DC Drive

## Controller – Current Controller Subtab

4-Quadrant Single-Phase Rectifier DC Motor Drive

4-Quadrant Single-Phase Rectifier DC Motor Drive

The DC motor parameters are specified in the DC Machine tab. The converter parameters, circulating current inductors, smoothing inductance and field voltage values are specified in the Converter tab. The bridge firing unit, speed and current regulators parameters are specified in the Controller tab.

DC Machine | Converters | Controller

Regulation type: Speed regulation Sampling time (s): 100e-6 Schematic

Speed Controller | Current Controller | Bridge Firing Unit

Low-pass filter cutoff frequency (Hz): 50 Symmetrical reference limit (p.u.): 1.5

Nominal values

Power (VA): 5746 Voltage (V): 240

PI regulator

Proportional gain: 1 Integral gain: 80

Model detail level: Detailed Mechanical input: Torque Tm

Parameters file options

Load Save

OK Cancel Help Apply

### Power and Voltage nominal values

The DC motor nominal power (W) and voltage (V) values.

The nominal power and voltage values are used to convert armature current from amperes to pu (per unit).

### Proportional Gain

The proportional gain of the PI current controller.

### Integral Gain

The integral gain of the PI current controller.

# Four-Quadrant Single-Phase Rectifier DC Drive

## Low-Pass Filter Cutoff Frequency

Cutoff frequency of the low-pass filter used to filter the armature current measurement (Hz).

## Symmetrical Reference Limit

Symmetrical current reference (pu) limit around 0 pu. 1.5 pu is a common value.

## Controller – Bridge Firing Unit Subtab

The screenshot shows a software window titled "4-Quadrant Single-Phase Rectifier DC Motor Drive". The window contains several tabs: "DC Machine", "Converters", and "Controller". The "Controller" tab is active, and within it, the "Bridge Firing Unit" subtab is selected. The interface includes a text area at the top explaining that parameters are specified in other tabs. Below this, there are fields for "Regulation type" (set to "Speed regulation"), "Sampling time (s)" (set to "100e-6"), and a "Schematic" button. The "Bridge Firing Unit" subtab contains two main sections: "Firing angle limits (degrees)" with "Alpha min" (20) and "Alpha max" (160) fields, and "Synchronized pulse generator" with "Frequency of synchronization voltages (Hz)" (60) and "Pulse width (degrees)" (20) fields. At the bottom, there are "Model detail level" (Detailed) and "Mechanical input" (Torque Tm) dropdowns, "Parameters file options" with "Load" and "Save" buttons, and "OK", "Cancel", "Help", and "Apply" buttons.

## Alpha Min

Minimum firing angle value (deg.). 20 degrees is a common value.



# Four-Quadrant Single-Phase Rectifier DC Drive

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## Block Inputs and Outputs

### Alpha Max

Maximum firing angle value (deg.). 160 degrees is a common value.

### Frequency of Synchronization Voltages

Frequency of the synchronization voltages used by the discrete synchronized pulse generator block (Hz). This frequency is equal to the line frequency of the single-phase power line. This parameter is not used when using the average-value converter.

### Pulse Width

The width of the pulses applied to the thyristor gates (deg.). This parameter is not used when using the average-value converter.

### SP

The speed or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration / deceleration ramps. If the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

### Tm or Wm

The mechanical input: load torque ( $T_m$ ) or motor speed ( $W_m$ ).

### A+, A-

The single-phase electric connections. The applied voltage must be adequate for the motor size.

### Wm or Te

The mechanical output: motor speed ( $W_m$ ) or electromagnetic torque ( $T_e$ ).

### Motor

The motor measurement vector. It is composed of two elements:

- The armature voltage
- The DC motor measurement vector (containing the speed, armature current, field current, and electromagnetic torque)

# Four-Quadrant Single-Phase Rectifier DC Drive

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values). Note that the speed signal is converted from rad/s to rpm before output.

## Conv

The single-phase converter measurement vector. This vector includes

- The output voltage of converter 1
- The output voltage of converter 2
- The output current of converter 1
- The output current of converter 2

Note that all current and voltage values of the detailed bridges can be visualized with the Multimeter block.

## Ctrl

The controller measurement vector. This vector contains:

- The armature current reference
- The firing angle computed by the current controller
- The speed or torque error (difference between the speed reference ramp and actual speed or between the torque reference and actual torque)
- The speed reference ramp or torque reference

## Model Specifications

The library contains a 5 hp drive parameter set. The specifications of the 5 hp drive are shown in the following table.

### 5 HP Drive Specifications

Drive Input Voltage		
Amplitude		320 V
Frequency		60 Hz

# Four-Quadrant Single-Phase Rectifier DC Drive

## 5 HP Drive Specifications (Continued)

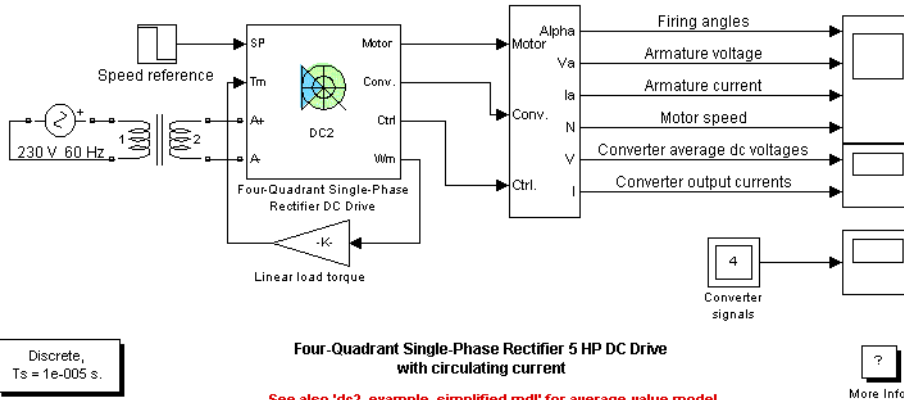
### Drive Input Voltage

### Motor Nominal Values

Power	5 hp
Speed	1750 rpm
Voltage	240 V

### Example

The `dc2_example` demo illustrates the single-phase dual-converter drive used with the 5 hp drive parameter set during speed regulation. The converters are fed by a 230 V AC 60 Hz voltage source followed by a linear transformer to boost the voltage to a sufficient value.



The 'Ts' parameter used in this model is set to 10e-6s by the Model Properties Callbacks

During this simulation, the motor is coupled to a linear load, which means that the mechanical torque produced by the load is proportional to the speed.

## Four-Quadrant Single-Phase Rectifier DC Drive

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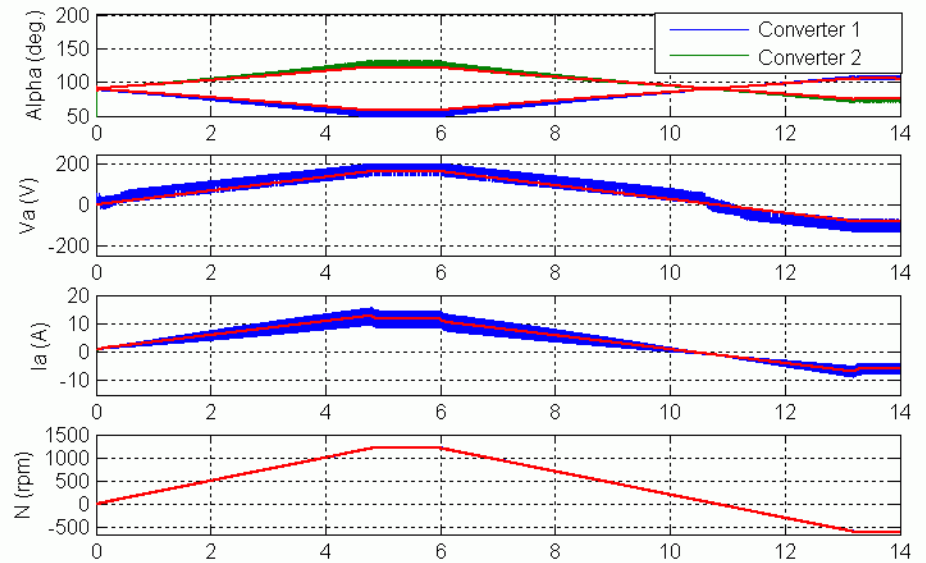
The speed reference is set at 1200 rpm at  $t = 0$  s. Observe that the firing angles are symmetrical around 90 degrees and that the converter average output DC voltages are of opposite signs. The armature current is supplied by converter 1, and the total current in this converter is the sum of load current and circulating current. Converter 2 simply carries the circulating current.

Observe that the motor speed follows the reference ramp accurately (+250 rpm/s) and reaches steady state after 5.5 s. The armature current follows the current reference very well and stabilizes around 12 A.

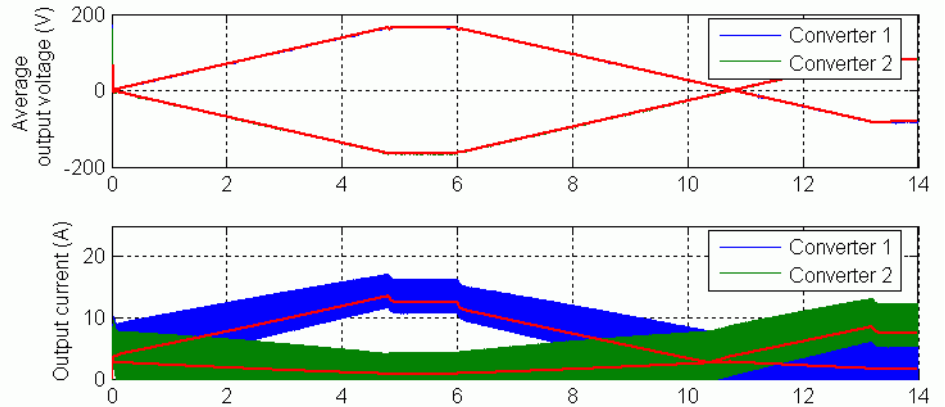
At  $t = 6$  s, speed reference drops to -600 rpm. The current reference decreases to reduce the electromagnetic torque, and the load torque causes the motor to decelerate. Around  $t = 8.5$  s, the armature current becomes negative and the electromagnetic torque reverses in order to brake the motor down to 0 rpm, the load torque being insufficient to decelerate the motor. The armature current is now provided by converter 2, converter 1 only handling the circulating current. At  $t = 10.8$  s, the motor reaches 0 rpm and the load torque becomes negative. The electromagnetic torque now produces an accelerating torque to allow the motor to follow the negative speed ramp (-250 rpm/s). The armature current is now provided by converter 2, converter 1 only handling the circulating current.

At  $t = 14$  s, speed stabilizes at -600 rpm.

# Four-Quadrant Single-Phase Rectifier DC Drive



**DC2 Example Waveforms (Blue/Green : Detailed Converter, Red : Average- Value Converter)**



## References

- [1] Sen, P.C., *Thyristor DC Drives*, J.Wiley and Sons, 1981.

# Four-Quadrant Three-Phase Rectifier DC Drive

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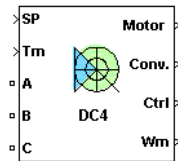
## Purpose

Implement three-phase dual-converter DC drive with circulating current

## Library

Electric Drives/DC drives

## Description



The high-level schematic shown below is built from six main blocks. The DC motor, the two three-phase full converters, and the bridge firing unit are provided with the SimPowerSystems library. More details on these blocks are available in the reference pages for each block. The two other blocks are specific to the Electric Drives library. These blocks are the speed controller and the current controller. They allow speed or torque regulation. A “regulation switch” block allows you to toggle from one type of regulation to the other. During torque regulation the speed controller is disabled. It is possible to use a simplified version of the drive containing an average-value model of the three-phase dual-converter and allowing faster simulation.

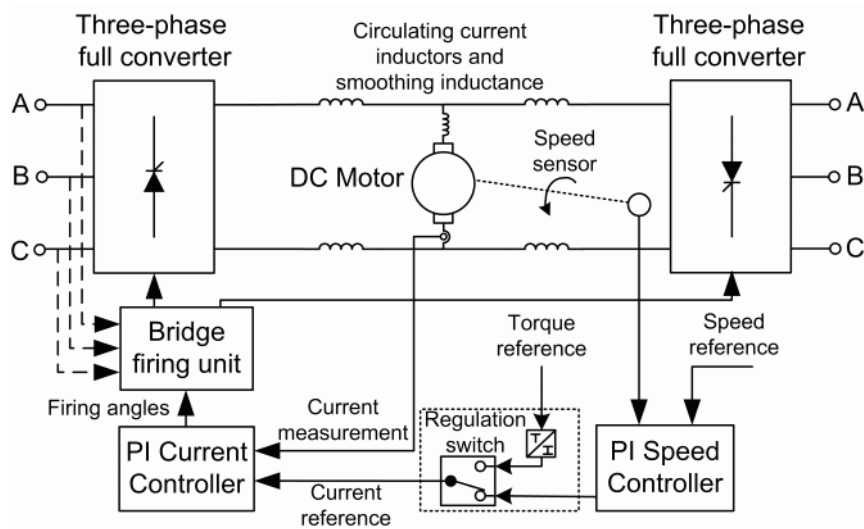
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**Note** In SimPowerSystems software, the Four-Quadrant Three-Phase Rectifier DC Drive block is commonly called the DC4 motor drive.

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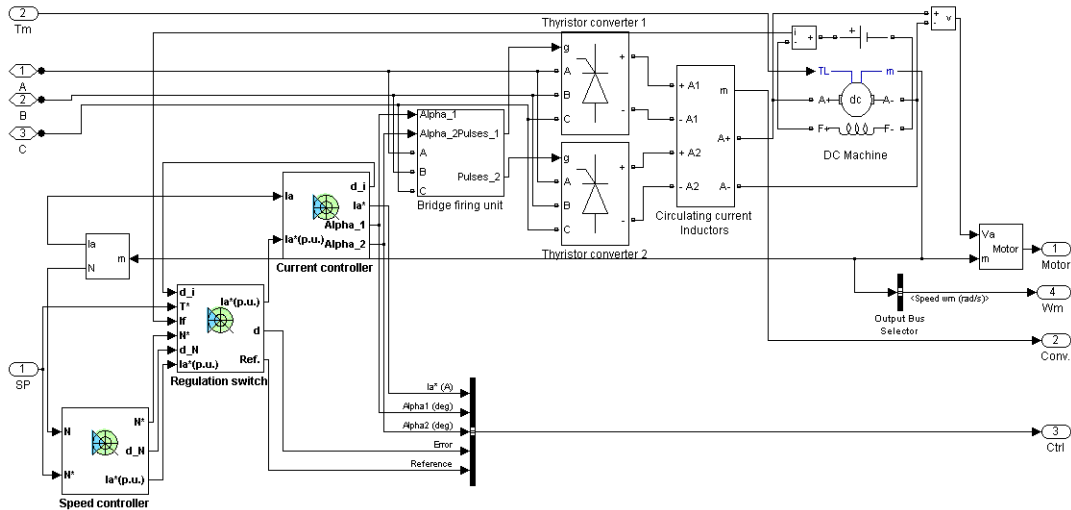
# Four-Quadrant Three-Phase Rectifier DC Drive

## High-Level Schematic



# Four-Quadrant Three-Phase Rectifier DC Drive

## Simulink Schematic



## Speed Controller

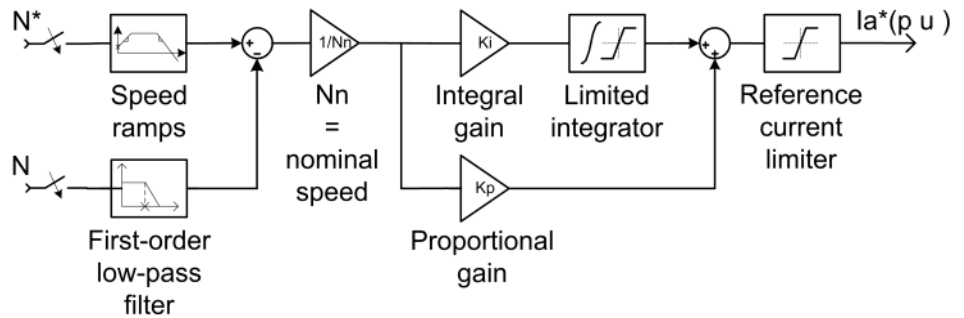
The speed regulator shown below uses a PI controller. The controller outputs the armature current reference (in pu) used by the current controller in order to obtain the electromagnetic torque needed to reach the desired speed. During torque regulation, the speed controller is disabled.

The controller takes the speed reference (in rpm) and the rotor speed of the DC machine as inputs. The speed reference change rate will follow user-defined acceleration and deceleration ramps in order to avoid sudden reference changes that could cause armature over-current and destabilize the system. The speed measurement is filtered by a first-order low-pass filter.

The current reference output is limited between symmetrical lower and upper limits defined by the user.



# Four-Quadrant Three-Phase Rectifier DC Drive



## Current Controller

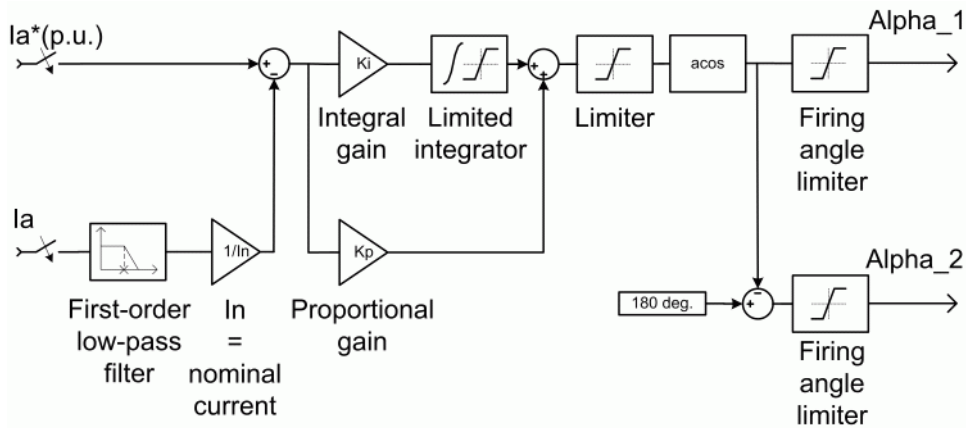
The armature current regulator shown below is based on a second PI controller. The regulator controls the armature current by computing the appropriate thyristor firing angles of the two full converters. This generates the converter output voltages needed to obtain the desired armature current and thus the desired electromagnetic torque.

The controller takes the current reference (in pu) and the armature current flowing through the motor as inputs. The current reference is either provided by the speed controller during speed regulation or computed from the torque reference provided by the user during torque regulation. This is managed by the “regulation switch” block.

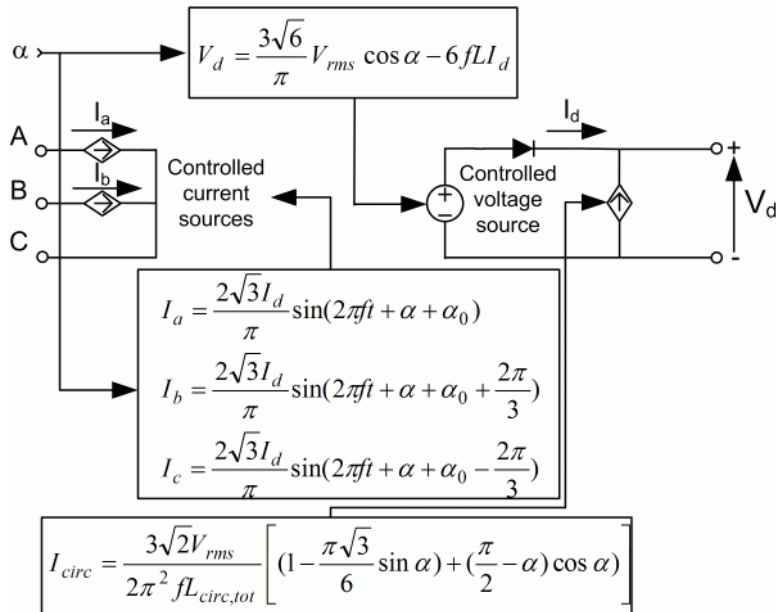
The armature current input is filtered by a first-order low-pass filter. An arccosine function is used to linearize the control system. The firing angle can vary between 0 and 180 degrees. You can limit the lower and upper limits to intermediate values.

Both converters operate simultaneously, and the two firing angles are controlled so that the sum of their values stays equal to 180 degrees. This produces opposite average voltages at the converter DC output terminals and thus identical average voltages at the DC motor armature, the converters being connected in antiparallel. One converter is working in rectifier mode while the other is in inverter mode.

# Four-Quadrant Three-Phase Rectifier DC Drive



**Average-Value Three-phase Rectifier** The simplified converter is shown in the following figure.



**Average-Value Three-Phase Rectifier with Circulating Current**

# Four-Quadrant Three-Phase Rectifier DC Drive

It is composed of two controlled current sources on the AC side and one controlled voltage and current source on the DC side. The AC current sources allow the representation of the fundamental three-phase current behaviors according to the following equations

$$I_a = \frac{2\sqrt{3}}{\pi} I_d \sin(2\pi ft + \alpha + \alpha_0)$$

$$I_b = \frac{2\sqrt{3}}{\pi} I_d \sin\left(2\pi ft + \alpha + \alpha_0 + \frac{2\pi}{3}\right)$$

with  $\alpha$  being the firing angle value,  $\alpha_0$  the phase angle of phase A,  $f$  the AC frequency and  $I_d$  the rectified output current value. The DC voltage source represents the average voltage value of the rectified voltage waveform according to the next equation

$$V_d = \frac{3\sqrt{6}}{\pi} V_{rms} \cos \alpha - 6fLI_d$$

with  $V_{rms}$  being the input phase-to-phase RMS voltage value and  $L$  being the source inductance value. The controlled current source represents the circulation current due to the instantaneous voltage difference between both converter outputs of the dual-converter. This current is equal to

$$V_d = \frac{3\sqrt{2}}{2\pi^2 f L_{circ,tot}} V_{rms} \left(1 - \frac{\pi\sqrt{3}}{6} \sin \alpha + \left(\frac{\pi}{2} - \alpha\right) \cos \alpha\right)$$

with  $L_{circ,tot}$  being the total circulation inductance of the circulation current loop.

## Bridge Firing Unit

The bridge firing unit converts the firing angles, provided by the current controller, to two series of six pulses applied respectively to the thyristor gates of each converter. The bridge firing unit block contains a band-pass filter on voltage measurement to remove voltage harmonics. Two Discrete Synchronized 6-Pulse Generator blocks generate the pulses. Refer to the Synchronized 6-Pulse Generator for more information on this block. When using the average-value

# Four-Quadrant Three-Phase Rectifier DC Drive

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converter, the bridge firing unit simply outputs the firing angle value needed by the converter.

## Remarks

The machine is separately excited with a constant DC field voltage source. There is thus no field voltage control. By default, the field current is set to its steady-state value when a simulation is started.

The armature voltage is provided by two three-phase antiparallel-connected converters controlled by two PI regulators. The circulating current produced by the instantaneous voltage difference at the terminal of both converters is limited by inductors connected between these terminals. No smoothing inductance is placed in series with the armature circuit, the armature current oscillations being quite small due to the three-phase voltage source.

The average-value converter represents the average behavior of a three-phase rectifier for continuous armature current in a dual-converter topology. This model is thus not suitable for simulating DC drives under discontinuous armature current conditions. The converter outputs a continuous voltage value equal to the average-value of the real-life rectified voltage. The armature voltage, armature current and electromagnetic torque ripples are thus not represented. The input currents have the frequency and amplitude of the fundamental current component of the real-life input currents.

The model is discrete. Good simulation results have been obtained with a 10  $\mu\text{s}$  time step. The control system (speed and current controllers) samples data following a user-defined sample time in order to simulate a digital controller device. Keep in mind that this sampling time has to be a multiple of the simulation time step.

The average-value converter allows the use of bigger simulation time steps, since it does not generate small time constants (due to the RC snubbers) inherent to the detailed converter. For a controller sampling time of 100  $\mu\text{s}$  good simulation results have been obtained for a simulation time step of 100  $\mu\text{s}$ . This time step cannot be higher than the controller time step.

# Four-Quadrant Three-Phase Rectifier DC Drive

## Dialog Box

### DC Machine Tab

4-Quadrant Three-Phase Rectifier DC Motor Drive

4-Quadrant Three-Phase Rectifier DC Motor Drive

The DC motor parameters are specified in the DC Machine tab. The converter parameters, circulating current inductors and field voltage values are specified in the Converter tab. The bridge firing unit, speed and current regulators parameters are specified in the Controller tab.

DC Machine | Converters | Controller

Electrical parameters

Mutual inductance (H): 1.234

Armature

Resistance (ohm): 0.78  
Inductance (H): 0.016

Field

Resistance (ohm): 150  
Inductance (H): 112.5

Mechanical parameters

Inertia (kg\*m<sup>2</sup>): 0.05

Viscous friction coefficient (N-m-s): 0.01

Coulomb friction torque (N-m): 0

Initial speed (rad/s): 0

Model detail level: Detailed

Mechanical input: Torque Tm

Parameters file options

Load Save

OK Cancel Help Apply

The DC Machine tab displays the parameters of the DC machine block of the powerlib library. Refer to the DC Machine for more information on the DC machine block parameters.

### Model detail level

Select between the detailed and the average-value inverter.

### Mechanical input

Allows you to select either the load torque or the motor speed as mechanical input. Note that if you select and apply a load torque, you will obtain as output the motor speed according to

## Four-Quadrant Three-Phase Rectifier DC Drive

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the following differential equation that describes the mechanical system dynamics:

$$T_e = J \frac{d}{dt} \omega_r + F \omega_r + T_m$$

This mechanical system is included in the motor model.

However, if you select the motor speed as mechanical input then you will get the electromagnetic torque as output, allowing you to represent externally the mechanical system dynamics. Note that the internal mechanical system is not used with this mechanical input selection and the inertia and viscous friction parameters are not displayed.

See for example “Mechanical Coupling of Two Motor Drives”.

# Four-Quadrant Three-Phase Rectifier DC Drive

## Converter Tab

4-Quadrant Three-Phase Rectifier DC Motor Drive

The DC motor parameters are specified in the DC Machine tab. The converter parameters, circulating current inductors and field voltage values are specified in the Converter tab. The bridge firing unit, speed and current regulators parameters are specified in the Controller tab.

DC Machine   Converters   Controller

DC bus and Excitation circuit

Field DC source (V): 150   Circulating current inductors (H): 50e-3

Converter 1

Snubbers   Thyristors

Resistance (ohm): 9e3   On-state resistance (ohm): 1e-3

Capacitance (F): 900e-9   Forward voltage (V): 1.3

Converter 2

Snubbers   Thyristors

Resistance (ohm): 9e3   On-state resistance (ohm): 1e-3

Capacitance (F): 900e-9   Forward voltage (V): 1.3

Model detail level: Detailed   Mechanical input: Torque Tm

Parameters file options

Load   Save

OK   Cancel   Help   Apply

### Field DC Source

The DC motor field voltage value (V).

### Circulating Current Inductors

The four circulating current inductors inductance value (H).

### Converter sections

The Converter 1 and Converter 2 sections of the Converter tab display the parameters of the Universal Bridge block of the powerlib library. Refer to the Universal Bridge for more information on the Universal Bridge block parameters.

# Four-Quadrant Three-Phase Rectifier DC Drive

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## **Phase-to-Phase RMS Voltage**

Phase-to-phase rms voltage of the three-phase voltage source connected to the A,B,C terminals of the drive (V). This parameter is not used when using the detailed rectifier.

## **Frequency**

Frequency of the three-phase voltage source connected to the A,B,C terminals of the drive (Hz). This parameter is not used when using the detailed rectifier.

## **Source Inductance**

Source inductance of the three-phase voltage source connected to the A,B,C terminals of the drive (H). This parameter is not used when using the detailed rectifier.

## **Phase Angle of Phase A**

Phase angle of phase A of the three-phase voltage source connected to the A,B,C terminals of the drive (deg). This parameter is not used when using the detailed rectifier.



# Four-Quadrant Three-Phase Rectifier DC Drive

## Controller Tab

4-Quadrant Three-Phase Rectifier DC Motor Drive

4-Quadrant Three-Phase Rectifier DC Motor Drive

The DC motor parameters are specified in the DC Machine tab. The converter parameters, circulating current inductors and field voltage values are specified in the Converter tab. The bridge firing unit, speed and current regulators parameters are specified in the Controller tab.

DC Machine | Converters | **Controller**

Regulation type: Speed regulation | Sampling time (s): 100e-6 | Schematic

Speed Controller | Current Controller | Bridge Firing Unit

Nominal speed (rpm): 1750 | Initial speed reference (rpm): 0 | Low-pass filter cutoff frequency (Hz): 40

PI regulator

Proportional gain: 10 | Integral gain: 50 | Speed ramps (rpm/s)

Acceleration: 1000 | Deceleration: -1000

Model detail level: Detailed | Mechanical input: Torque Tm

Parameters file options

Load | Save

OK | Cancel | Help | Apply

## Schematic Button

When you press this button, a diagram illustrating the speed and current controllers schematics appears.

## Regulation Type

This pop-up menu allows you to choose between speed and torque regulation.

## Sampling Time

The controller (speed and current) sampling time (s). The sampling time has to be a multiple of the simulation time step.

# Four-Quadrant Three-Phase Rectifier DC Drive

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## **Controller – Speed Controller Subtab**

### **Nominal Speed**

The nominal speed value of the DC motor (rpm). This value is used to convert motor speed from rpm to pu (per unit).

### **Initial Speed Reference**

The initial speed reference value (rpm). This value allows the user to start a simulation with a speed reference other than 0 rpm.

### **Low-Pass Filter Cutoff Frequency**

Cutoff frequency of the low-pass filter used to filter the motor speed measurement (Hz).

### **Proportional Gain**

The proportional gain of the PI speed controller.

### **Integral Gain**

The integral gain of the PI speed controller.

### **Acceleration**

The maximum change of speed allowed during motor acceleration (rpm/s). Too great a value can cause armature over-current.

### **Deceleration**

The maximum change of speed allowed during motor deceleration (rpm/s). Too great a value can cause armature over-current.

# Four-Quadrant Three-Phase Rectifier DC Drive

## Controller – Current Controller Subtab

4-Quadrant Three-Phase Rectifier DC Motor Drive

4-Quadrant Three-Phase Rectifier DC Motor Drive

The DC motor parameters are specified in the DC Machine tab. The converter parameters, circulating current inductors and field voltage values are specified in the Converter tab. The bridge firing unit, speed and current regulators parameters are specified in the Controller tab.

DC Machine | Converters | **Controller**

Regulation type: Speed regulation | Sampling time (s): 100e-6 | Schematic

Speed Controller | **Current Controller** | Bridge Firing Unit

Low-pass filter cutoff frequency (Hz): 120 | Symmetrical reference limit (p.u.): 1.5

Nominal values

Power (VA): 5746 | Voltage (V): 240

PI regulator

Proportional gain: 1.1 | Integral gain: 90

Model detail level: Detailed | Mechanical input: Torque Tm

Parameters file options

Load | Save

OK | Cancel | Help | Apply

### Power and Voltage nominal values

The DC motor nominal power (VA) and voltage (V) values. The nominal power and voltage values are used to convert armature current from amperes to pu (per unit).

### Proportional Gain

The proportional gain of the PI current controller.

### Integral Gain

The integral gain of the PI current controller.

# Four-Quadrant Three-Phase Rectifier DC Drive

## Low-Pass Filter Cutoff Frequency

Cutoff frequency of the low-pass filter used to filter the armature current measurement (Hz).

## Symmetrical Reference Limit

Symmetrical current reference (pu) limit around 0 pu. 1.5 pu is a common value.

## Controller – Bridge Firing Unit Subtab

The screenshot shows the '4-Quadrant Three-Phase Rectifier DC Motor Drive' software window. The 'Controller' tab is selected, and the 'Bridge Firing Unit' subtab is active. The interface includes the following elements:

- Regulation type:** A dropdown menu set to 'Speed regulation'.
- Sampling time (s):** A text input field containing '100e-6'.
- Schematic:** A button to view the schematic.
- Speed Controller, Current Controller, Bridge Firing Unit:** Three sub-tabs, with 'Bridge Firing Unit' selected.
- Firing angle limits (degrees):** A section with two input fields: 'Alpha min:' set to '20' and 'Alpha max:' set to '160'.
- Synchronized pulse generator:** A section with two input fields: 'Frequency of synchronization voltages (Hz):' set to '60' and 'Pulse width (degrees):' set to '10'.
- Model detail level:** A dropdown menu set to 'Detailed'.
- Mechanical input:** A dropdown menu set to 'Torque Tm'.
- Parameters file options:** A section with 'Load' and 'Save' buttons.
- Buttons:** 'OK', 'Cancel', 'Help', and 'Apply' buttons at the bottom.

## Alpha Min

Minimum firing angle value (deg). 20 degrees is a common value.

# Four-Quadrant Three-Phase Rectifier DC Drive

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## Block Inputs and Outputs

### Alpha Max

Maximum firing angle value (deg). 160 degrees is a common value.

### Frequency of Synchronization Voltages

Frequency of the synchronization voltages used by the discrete synchronized 6-pulse generator block (Hz). This frequency is equal to the line frequency of the three-phase power line. This parameter is not used when using the average-value converter.

### Pulse Width

The width of the pulses applied to the thyristor gates (deg.). This parameter is not used when using the average-value converter.

### SP

The speed or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration / deceleration ramps. If the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

### T<sub>m</sub> or W<sub>m</sub>

The mechanical input: load torque (T<sub>m</sub>) or motor speed (W<sub>m</sub>).

### A, B, C

The three-phase electric connections. The voltage must be adequate for the motor size.

### W<sub>m</sub> or T<sub>e</sub>

The mechanical output: motor speed (W<sub>m</sub>) or electromagnetic torque (T<sub>e</sub>).

### Motor

The motor measurement vector. This vector is composed of two elements:

- The armature voltage
- The DC motor measurement vector (containing the speed, armature current, field current, and electromagnetic torque)

# Four-Quadrant Three-Phase Rectifier DC Drive

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values). Note that the speed signal is converted from rad/s to rpm before output.

## Conv

The three-phase converter measurement vector. It includes:

- The output voltage of converter 1
- The output voltage of converter 2
- The output current of converter 1
- The output current of converter 2

Note that all current and voltage values of the detailed bridges can be visualized with the Multimeter block.

## Ctrl

The controller measurement vector. This vector contains:

- The armature current reference
- The firing angle computed by the current controller
- The speed or torque error (difference between the speed reference ramp and actual speed or between the torque reference and actual torque)
- The speed reference ramp or torque reference

## Model Specifications

The library contains a 5 hp and a 200 hp drive parameter set. The specifications of these two drives are shown in the following table.

### 5 HP and 200 HP Drive Specifications

	5 HP Drive	200 HP Drive
Drive Input Voltage		
Amplitude	230 V	380 V
Frequency	60 Hz	50 Hz

# Four-Quadrant Three-Phase Rectifier DC Drive

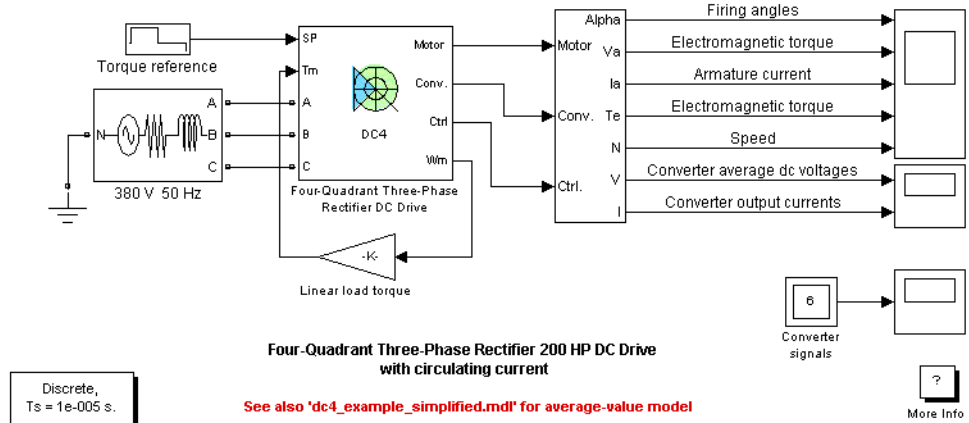
## 5 HP and 200 HP Drive Specifications (Continued)

	5 HP Drive	200 HP Drive
<b>Drive Input Voltage</b>		
<b>Motor Nominal Values</b>		
Power	5 hp	200 hp
Speed	1750 rpm	1184 rpm
Voltage	240 V	440 V

### Example

The dc4\_example demo illustrates the three-phase dual-converter drive with the 200 hp drive parameter set during torque regulation. A 5 hp parameter set is also available in the library.

The converters are fed by a 380 V AC 50 Hz voltage source.



# Four-Quadrant Three-Phase Rectifier DC Drive

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The motor is coupled to a linear load, which means that the mechanical torque of the load is proportional to the speed.

The initial torque reference is set to 0 N.m and the armature current is null. No electromagnetic torque is produced and the motor stays still.

At  $t = 0.2$  s, the torque reference jumps to 600 N.m. This causes the armature current to rise to about 180 A. The armature current is supplied by converter 1, and the total current in this converter is the sum of load current and circulating current. Converter 2 simply carries the circulating current. Notice that the armature current follows the reference current quite accurately, with fast response time and small overshooting. Observe also that the firing angles are symmetrical around 90 degrees and that the converter average output DC voltages are equal but of opposite signs.

The electromagnetic torque produced by the armature current flow causes the motor to accelerate. The speed rises and starts to stabilize around  $t = 4$  s at about 560 rpm, the sum of the load and viscous friction torques beginning to equalize the electromagnetic torque.

At  $t = 4$  s, the torque reference is set to 0 N.m and the load torque causes the motor to decelerate. Notice that the four reactors keep the current oscillations quite small.

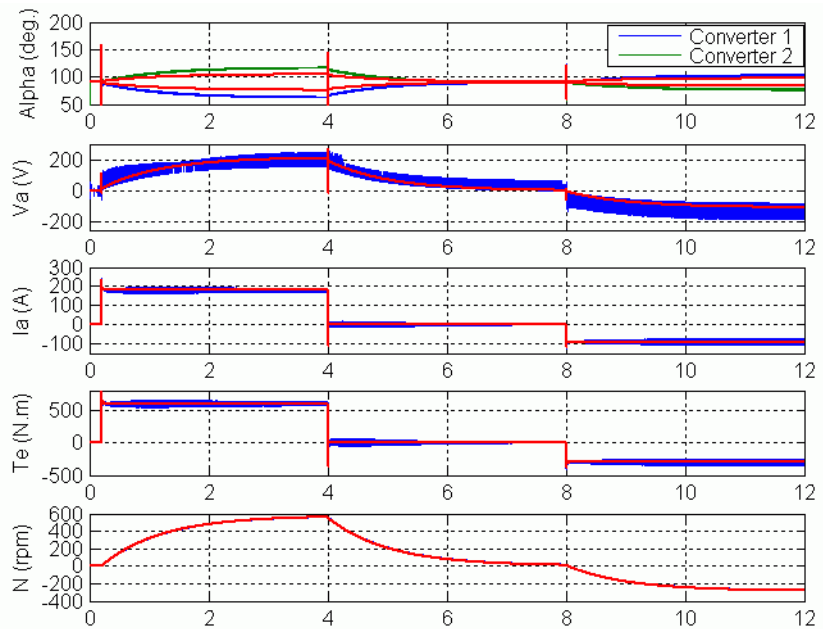
At  $t = 8$  s, the torque reference is set to -300 N.m. The armature current jumps down to -90 A and is now delivered by converter 2 while converter 1 only handles the circulating current. Converter 2 is now working in rectifier mode and converter 1 in inverter mode.

The negative electromagnetic torque produced allows the motor to accelerate in the negative speed plane.

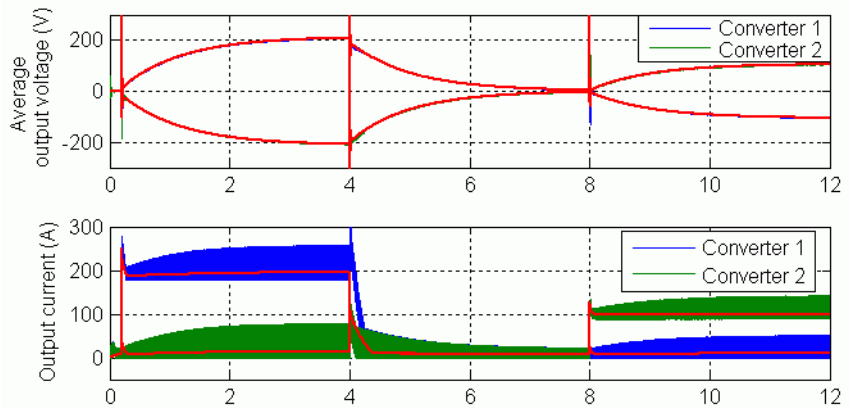
At  $t = 12$  s, speed starts to stabilize around -290 rpm.



# Four-Quadrant Three-Phase Rectifier DC Drive



**DC4 Example Waveforms (Blue/Green : Detailed Converter, Red : Average- Value Converter)**



# Four-Quadrant Three-Phase Rectifier DC Drive

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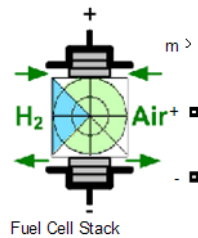
## References

- [1] Sen, P.C., *Thyristor DC Drives*, J.Wiley and Sons, 1981

**Purpose** Implement generic hydrogen fuel cell stack model

**Library** Electric Drives/Extra Sources

## Description

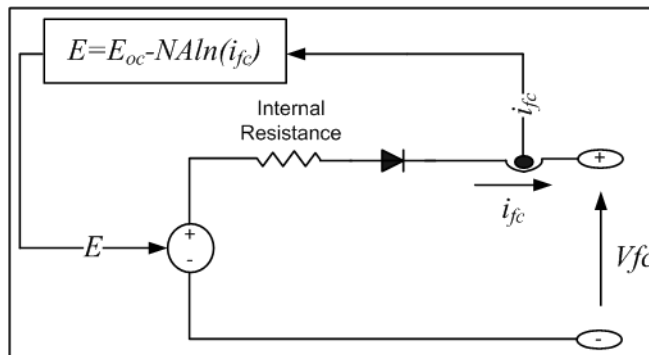


The Fuel Cell Stack block implements a generic model parameterized to represent most popular types of fuel cell stacks fed with hydrogen and air.

The block represents two versions of the stack model: a simplified model and a detailed model. You can switch between the two models by selecting the level in the mask under **Model detail level** in the block dialog box.

## Simplified Model

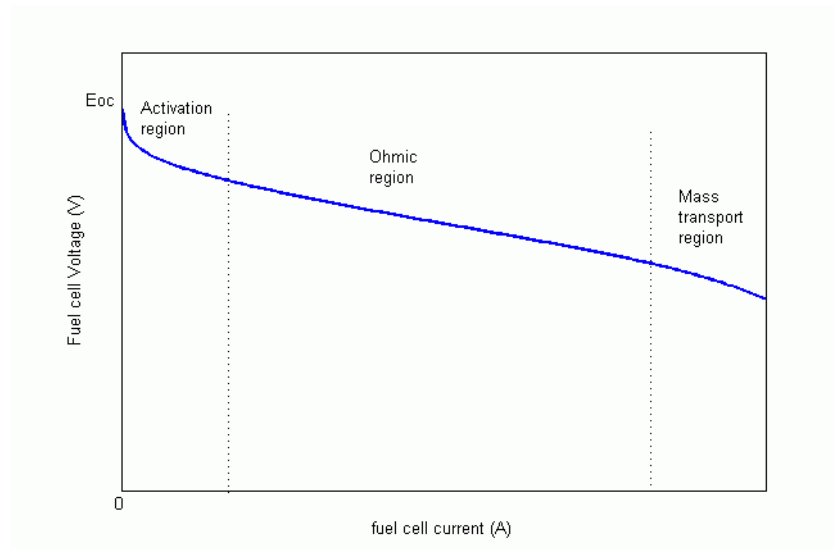
This model is based on the equivalent circuit of a fuel cell stack.



The simplified model represents a particular fuel cell stack operating at nominal conditions of temperature and pressure. The parameters of

# Fuel Cell Stack

the equivalent circuit can be modified based on the polarization curve obtained from the manufacturer's data sheet. You just have to input in the mask the value of the voltage at no load, as well as the nominal and the maximum operating points, for the parameters to be calculated. A diode is used to prevent the flow of negative current into the stack. A typical polarization curve consists of three regions:



The first region represents the activation voltage drop due to the slowness of the chemical reactions taking place at electrode surfaces. Depending on the temperature and operating pressure, type of electrode, and catalyst used, this region is more or less wide. The second region represents the resistive losses due the internal resistance of the fuel cell stack. Finally, the third region represents the mass transport losses resulting from the change in concentration of reactants as the fuel is used.

## Detailed Model

The detailed model represents a particular fuel cell stack when the parameters such as pressures, temperature, compositions, and flow rates of fuel and air vary. You can select which parameters to vary on

the **Signal variation** pane on the block dialog box. These variations affect the open circuit voltage as well as the Tafel slope. The open circuit voltage and the Tafel slope are modified as follows:

$$E_{oc} = N(E_n - A \ln(i_0))$$

and

$$A = \frac{RT}{z\alpha F}$$

where

$$R = 8.3145 \text{ J/(mol K)}$$

$$F = 96485 \text{ A s/mol}$$

$z$  = Number of moving electrons

$E_n$  = Nernst voltage, which is the thermodynamics voltage of the cells and depends on the temperatures and partial pressures of reactants and products inside the stack

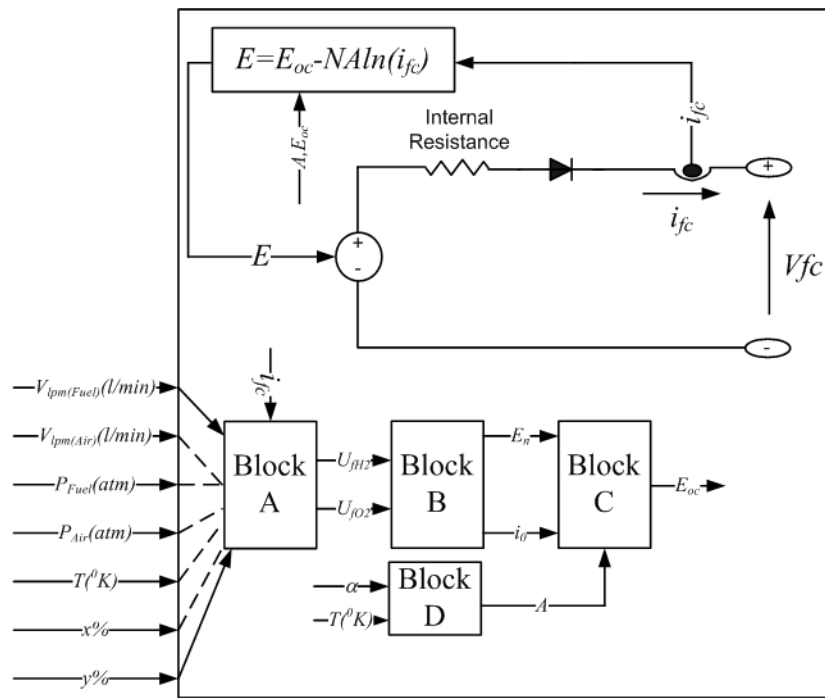
$i_0$  = Exchange current, which is the current resulting from the continual backward and forward flow of electrons from and to the electrolyte at no load. It depends also on the temperatures and partial pressures of reactants inside the stack.

$\alpha$  = Charge transfer coefficient, which depends on the type of electrodes and catalysts used

$T$  = Temperature of operation

The equivalent circuit is the same as for the simplified model, except that the parameters  $E_{oc}$  and  $A$  have to be updated online as shown below:

# Fuel Cell Stack



The rate of conversions (utilizations) of hydrogen ( $U_{\text{H}_2}$ ) and oxygen ( $U_{\text{O}_2}$ ) are determined in Block A as follows:

$$U_{f_{\text{H}_2}} = \frac{60000RTN i_{fc}}{zFP_{\text{Fuel}}V_{lpm(\text{fuel})} \times x\%} \quad 0 \leq U_{f_{\text{H}_2}} < 1$$

and

$$U_{f_{\text{O}_2}} = \frac{60000RTN i_{fc}}{2zFP_{\text{air}}V_{lpm(\text{air})} \times y\%} \quad 0 \leq U_{f_{\text{O}_2}} < 1$$

where

$P_{\text{Fuel}}$  = Absolute supply pressure of fuel (atm)

$P_{\text{air}}$  = Absolute supply pressure of air (atm)

$V_{\text{lpm(fuel)}}$  = Fuel flow rate (l/min)

$V_{\text{lpm(air)}}$  = Air flow rate (l/min)

$x$  = Percentage of hydrogen in the fuel (%)

$y$  = Percentage of oxygen in the oxidant (%)

The Nernst voltage and the exchange current density are calculated in Block B as follows:

$$E_n = \begin{cases} 1.229 + (T-298) \frac{-44.43}{zF} + \frac{RT}{zF} \ln \left( P_{H_2} P_{O_2}^{\frac{1}{2}} \right) & T \leq 100^0 C \\ 1.229 + (T-298) \frac{-44.43}{zF} + \frac{RT}{zF} \ln \left( \frac{P_{H_2} P_{O_2}^{\frac{1}{2}}}{P_{H_2O}} \right) & T > 100^0 C \end{cases}$$

and

$$i_o = \frac{zFk(P_{H_2} + P_{O_2})}{Rh} e^{-\frac{\Delta G}{RT}}$$

where

$P_{H_2}$  = Partial pressure of hydrogen inside the stack

$P_{O_2}$  = Partial pressure of oxygen inside the stack

$P_{H_2O}$  = Partial pressure of water vapor inside the stack

$k$  = Boltzmann's constant =  $1.38 \times 10^{-23}$  J/ $^0$ K

$h$  = Planck's constant =  $6.626 \times 10^{-34}$  J s

$\Delta G$  = Size of the activation barrier which depends on the type of electrode and catalyst used

# Fuel Cell Stack

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The partial pressures  $P_{H_2}$ ,  $P_{O_2}$ , and  $P_{H_2O}$  are determined in steady state as follows:

$$P_{H_2} = P_{Fuel} x \% (1 - U_{f_{H_2}})$$

$$P_{O_2} = P_{Air} y \% (1 - U_{f_{O_2}})$$

$$P_{H_2O} = P_{Air} (w \% + 2 y \% U_{f_{O_2}})$$

where

$w$  = Percentage of water vapor in the oxidant (%)

Block C and D calculate the new values of the open circuit voltage and Tafel slope, respectively.

The material parameters  $\alpha$ ,  $\Delta G$  are calculated based on the polarization curve at nominal conditions of operation along with some additional parameters, such as the low heating value (LHV) efficiency of the stack, composition of fuel and air, supply pressures and temperatures, etc. They can be easily obtained from the manufacturer's data sheet.

The nominal rates of conversion of gases are calculated as follows:

$$U_{f_{H_2}} = \frac{\eta_{nom} \Delta h^0(H_2O(gas)) N}{z F V_{nom}}$$

and

$$U_{f_{O_2}} = \frac{60000 R T_{nom} N I_{nom}}{2 z F P_{air, nom} V_{lpm(air)_{nom}} \times 0.21}$$

where

$\eta_{nom}$  = Nominal LHV efficiency of the stack (%)

$\Delta h^0(H_2O(gas)) = 241.83 \times 10^3$  J/mol

$V_{nom}$  = Nominal voltage (V)



$I_{\text{nom}}$  = Nominal current (A)

$V_{\text{lpm(air)nom}}$  = Nominal air flow rate (l/min)

$P_{\text{airnom}}$  = Nominal absolute air supply pressure (Pa)

$T_{\text{nom}}$  = Nominal operating temperature ( $^{\circ}\text{K}$ )

If you do not provide the fuel and air flow rate, it is assumed that the stack is operating at a fixed rate of conversion of gases (nominal rate of conversion), that is, the supply of gases is adjusted according to the current so that they are always supplied with just a bit more than needed by the stack at any load.

The maximum current the stack can deliver is limited by the maximum flow rates of fuel and air that can be reached. Beyond that limiting current, the voltage output by the stack decreases abruptly as more current is drawn.

The dynamics of the fuel cell are represented if you specify the response time of the stack on the **Fuel Cell Dynamics** pane on the dialog box. This response time is used to model the “charge double layer” phenomenon and it affects only the activation overvoltage.

# Fuel Cell Stack

## Dialog Box and Parameters

### Parameters Tab

The screenshot shows a dialog box titled "Block Parameters: Fuel Cell Stack" with a close button (X) in the top right corner. The dialog is divided into several sections. At the top, there is a link for "Fuel Cell Stack (mask) (link)". Below this, a text area describes the model: "Implements a generic hydrogen fuel cell model which allows the simulation for the following types of cells: - Proton Exchange Membrane Fuel Cell (PEMFC) - Solid Oxide Fuel Cell (SOFC) - Alkaline Fuel Cell (AFC)".

The main area contains a tabbed interface with three tabs: "Parameters" (selected), "Signal variation", and "Fuel Cell Dynamics". Under the "Parameters" tab, there are several input fields and checkboxes:

- Preset model:** A dropdown menu set to "No (User-Defined)".
- Model detail Level:** A dropdown menu set to "Detailed".
- Open circuit voltage (V):** A text field containing "35".
- Nominal operating point [Inom(A), Vnom(V)]:** A text field containing "[52, 24.23]".
- Maximum operating point [Iend(A), Vend(V)]:** A text field containing "[100, 20]".
- Number of cells:** A text field containing "42".
- Nominal stack efficiency (%):** A text field containing "46".
- Operating temperature (celcius):** A text field containing "55".
- Nominal Air flow rate (lpm):** A text field containing "2400".
- Nominal supply pressure [Fuel (bar), Air (bar)]:** A text field containing "[1.5, 1]".
- Nominal composition (%) [H2 O2 H2O(Air)]:** A text field containing "[99.95, 21, 1]".
- Plot V-I characteristic
- View Cell parameters

At the bottom of the dialog, there are four buttons: "OK", "Cancel", "Help", and "Apply".

### Preset model

Provides a set of predetermined polarization curves and parameters for particular fuel cell stacks found on the market:

- No (User-Defined)
- PEMFC - 1.26 kW - 24 Vdc

- PEMFC - 6 kW - 45 Vdc
- PEMFC - 50 kW - 625 Vdc
- AFC - 2.4 kW - 48 Vdc

Select one of these preset models to load the corresponding parameters in the entries of the dialog box. Select No (User-Defined) if you do not want to use a preset model.

### **Model detail level**

Provides access to the two versions of the model:

- Simplified
- Detailed

When a simplified model is used, no variables are available under the **Signal variation** pane.

### **Open circuit voltage**

The voltage at no load of the stack (V).

### **Nominal operating point**

The rated current (Ampere) and rated voltage (V) of the stack.

### **Maximum operating point**

The current (A) and voltage (V) of the stack at maximum power.

### **Number of cells**

The number of cells in series in the stack. This parameter is available only for a detailed model.

### **Nominal stack efficiency**

The rated efficiency of the stack relative to the low heating value (LHV) of water. This parameter is available only for a detailed model.

### **Operating temperature**

The nominal temperature of operation in degrees Celsius. This parameter is available only for a detailed model.

# Fuel Cell Stack

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## **Nominal air flow rate**

The rated air flow rate (l/min). This parameter is available only for a detailed model.

## **Nominal supply pressure**

Rated supply pressure (absolute) of fuel and air in bars. This parameter is available only for a detailed model.

## **Nominal composition**

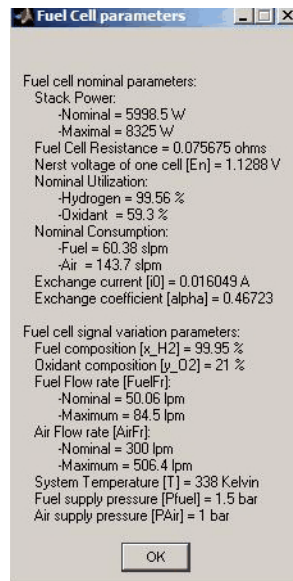
The rated percentage of hydrogen (x) in the fuel, oxygen (y) and water (w) in the oxidant. This parameter is available only for a detailed model.

## **Plot V-I characteristic**

Plots a figure containing two graphs. The first graph represents the stack voltage (V) versus current (A) and the second graph represents the stack power (kW) versus current (A). To plot the graphs, select the check box. This check box is available only for a detailed model.

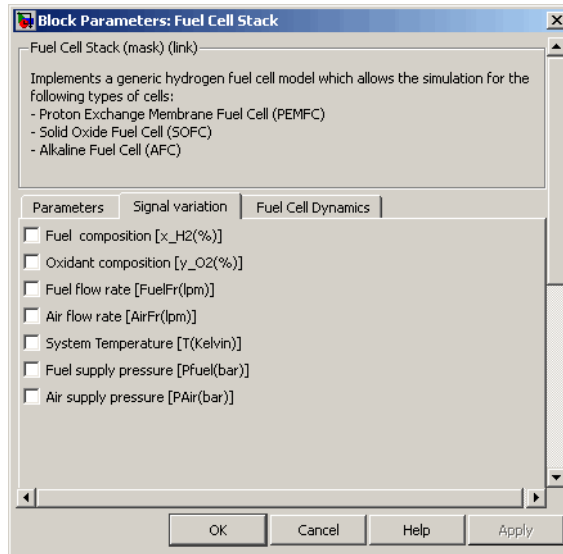
## **View cell parameters**

Presents the overall parameters of the stack. This check box is available only for a detailed model. Select the check box to view the parameters. The dialog box is shown below for a particular stack.



# Fuel Cell Stack

## Signal Variation Tab (Detailed Model Only)



The **Signal variation** pane provides a list of parameters that can be varied. Select a check box for a variable to input a corresponding signal to the block. The following signals can be input to the block:

### Fuel composition

Percentage of hydrogen in the fuel.

### Oxidant composition

Percentage of oxygen in the oxidant.

### Fuel flow rate

Fuel flow rate in liter per minutes.

### Air flow rate

Air flow rate in liter per minutes.

### System Temperature

Temperature of operation in kelvin.

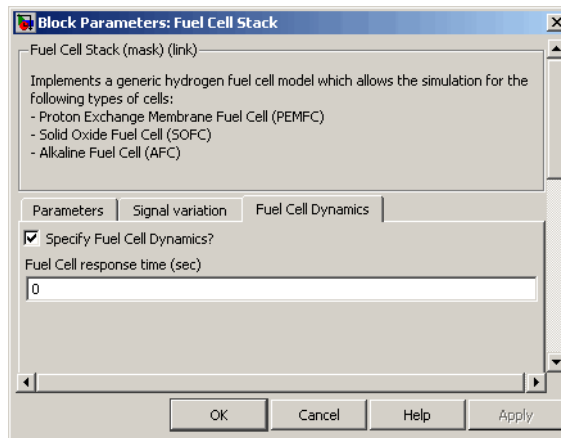
## Fuel supply pressure

Fuel supply pressure in bars.

## Air supply pressure

Air supply pressure in bars.

## Fuel Cell Dynamics Tab



## Specify Fuel Cell Dynamics?

Asks whether you want to specify the fuel cell dynamics. Select the check box to enter the fuel cell response time in seconds.

## Fuel Cell response time (sec)

Enter the response time of the cell (at 95% of the final value).

This parameter becomes visible only when the **Specify Fuel Cell Dynamics?** check box is selected.

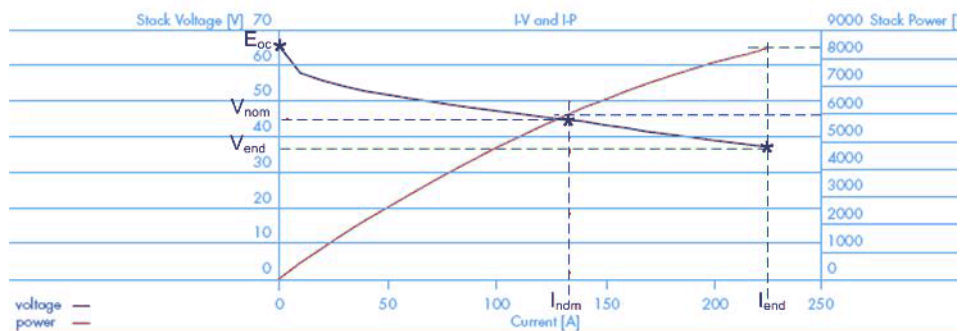
# Fuel Cell Stack

## How to Extract Parameters from Datasheet

Here is the procedure to extract parameters from fuel cell stack manufacturer's data sheet. This example uses the NedStack PS6 data sheet from NedStack.

Type	6 kW fuel cell system	NedStack PS6
Performance	Net Rated Electrical Peak Power	7 kW (DC)
	Net Rated Electrical Nominal Power	5 kW (AC)
	Output voltage	60–32 V (DC)
	Operating current range	0–225 A (DC)
	Typical Beginning of Life Voltage Range	42 V at nominal
	Efficiency – LHV	55 % (stack) 50 % (system)
	Time from off model to idle	Within 3 min.
	Time from 10% to full power	Approx. 10 s
	Expected Life	20,000 h (stack)
	Maintenance routine	2,000 h (system)
Fuel	Operational ambient temperature	-20 – +40 °C
	Fuel	H <sub>2</sub> or Reformat
	Purity	99.999 % H <sub>2</sub> or Reformat (<50 ppm CO)
	Supply pressure	0.5 – 5 bar
	Stack Operating Pressure	ambient
	Maximum Consumption	12.5 slpm/kW
Air delivery system	Flow rate	Max. 500 l/min
	Supply pressure	Ambient
Physical	Dimensions	400 × 600 × 1600 mm
	Mass	Approx. 80 kg
Emissions	Water collected	75 l/min.
	NO <sub>x</sub> , SO <sub>x</sub>	0
Cooling system requirements	Heat Rejection to Coolant at Maximum Power	10 kW
	Maximum Ambient Temperature	45 °C
	FCPM Operating Temperature	65 °C
	Cooling method	Radiator Fan

JV-curve NedStack P8/PS6





The rated power of the stack is 6 kW and the nominal voltage is 45 V. The following detailed parameters are deduced from the data sheet.

- Open circuit voltage ( $E_{oc}$ ) = 65 V
- Nominal operating point [ $I_{nom}$ ,  $V_{nom}$ ] = [133.3, 45]
- Maximum operating point [ $I_{end}$ ,  $V_{end}$ ] = [225, 37]
- Nominal stack efficiency ( $\eta_{nom}$ ) = 55 %
- Operating temperature = 65 °C
- Nominal supply pressure [H<sub>2</sub>, Air] = [1.5 1]

If the pressure given is relative to the atmospheric pressure, add 1 bar to get the absolute pressure.

- Nominal composition (%) [H<sub>2</sub>, O<sub>2</sub>, H<sub>2</sub>O(Air)] = [99.999, 21, 1]

If air is used as oxidant, assume 21% of O<sub>2</sub> and 1% of H<sub>2</sub>O in case their percentages are not specified.

- Number of cells

If not specified, estimate it from the formulas below:

$$N = \frac{2 \times 96485 \cdot V_{nom}}{241.83 \times 10^3 \cdot \eta_{nom}}$$

In this case,

$$N = \frac{2 \times 96485 \cdot 45}{241.83 \times 10^3 \cdot 0.55} = 65.28 = 65 \text{ cells}$$

- Nominal air flow rate

If the maximum air flow rate is given, the nominal flow rate can be calculated assuming a constant oxygen utilization at any load. The current drawn by the cell is linearly dependent on air flow rate and the nominal flow rate is given by:

# Fuel Cell Stack

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$$V_{lpm(air)_{nom}} = \frac{I_{nom} \times V_{lpm(air)_{max}}}{I_{end}}$$

In this case,

$$V_{lpm(air)_{nom}} = \frac{133.3 \times 500}{225} = 297 \text{ liters/min}$$

In case no information is given, assume the rate of conversion of oxygen to be 50% (as it is usually the case for most fuel cell stacks) and use the formulas below to determine the nominal air flow rate.

$$V_{lpm(air)_{nom}} = \frac{60000RT_{nom}NI_{nom}}{2zFP_{air_{nom}}0.5 \times 0.21}$$

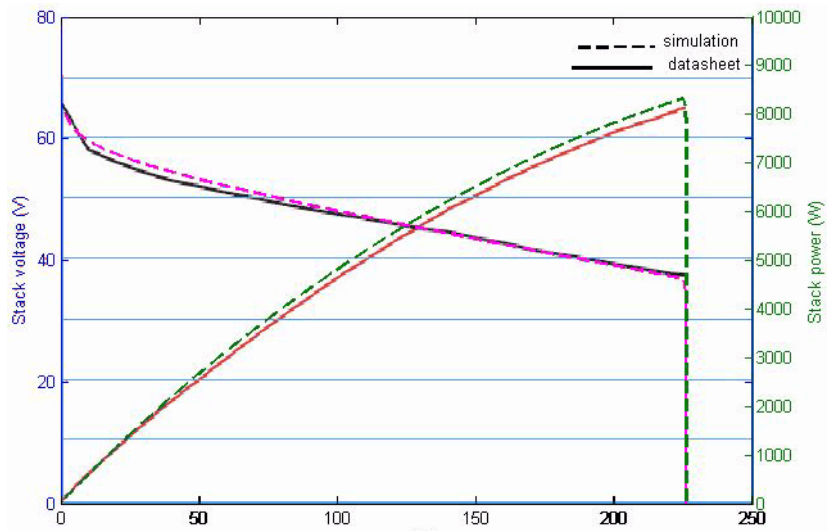
Fuel cell response time = 10 s

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**Note** The parameters  $E_{oc}$ ,  $[I_{nom}, V_{nom}]$ , and  $[I_{end}, V_{end}]$  are approximate and depend on the precision of the points obtained from the polarization curve. The higher the accuracy of these parameters, the closer the simulated stack voltage will be to the data sheet curve.

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With the above parameters, the polarization curve of the stack operating at fixed nominal rate of conversion of gases is close to the data sheet curves as shown below. The orange dotted line shows the simulated stack voltage and green dotted line shows the simulated stack power.



Above the maximum current, the flow rate of gases entering the stack is maximum and the stack voltage decreases abruptly as more current is drawn.

## Block Inputs and Outputs

m

The Simulink output of the block is a vector containing 11 signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

Signal Definition	Units	Symbol
1 Voltage	V	$V_{fc}$
2 Current	I	$I_{fc}$
3 Stack Efficiency	%	$\eta$
4 Stack consumption [Air, Fuel]	slpm	$V_{slpm}$
5 Flow Rate [Air, Fuel]	lpm	$Fr_{lpm}$
6 Stack consumption [Air, Fuel]	lpm	$V_{lpm}$

# Fuel Cell Stack

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	<b>Signal Definition</b>	<b>Units</b>	<b>Symbol</b>
7	Utilization [Oxygen, Hydrogen]	%	$U_f$
8	Slope of Tafel curve		A
9	Exchange current	A	$i_0$
10	Nernst voltage	V	$E_n$
11	Open circuit voltage	V	$E_{oc}$

V+, V-

The two electrical terminals of the fuel cell stack.

## Model Assumptions

- The gases are ideal.
- The stack is fed with hydrogen and air.
- The stack is equipped with a cooling system that maintains the temperature at the cathode and anode exits stable and equal to the stack temperature.
- The stack is equipped with a water management system to maintain the humidity inside the cell at appropriate level at any load.
- For output current less than 1 A, the output voltage is closed to the open circuit voltage.

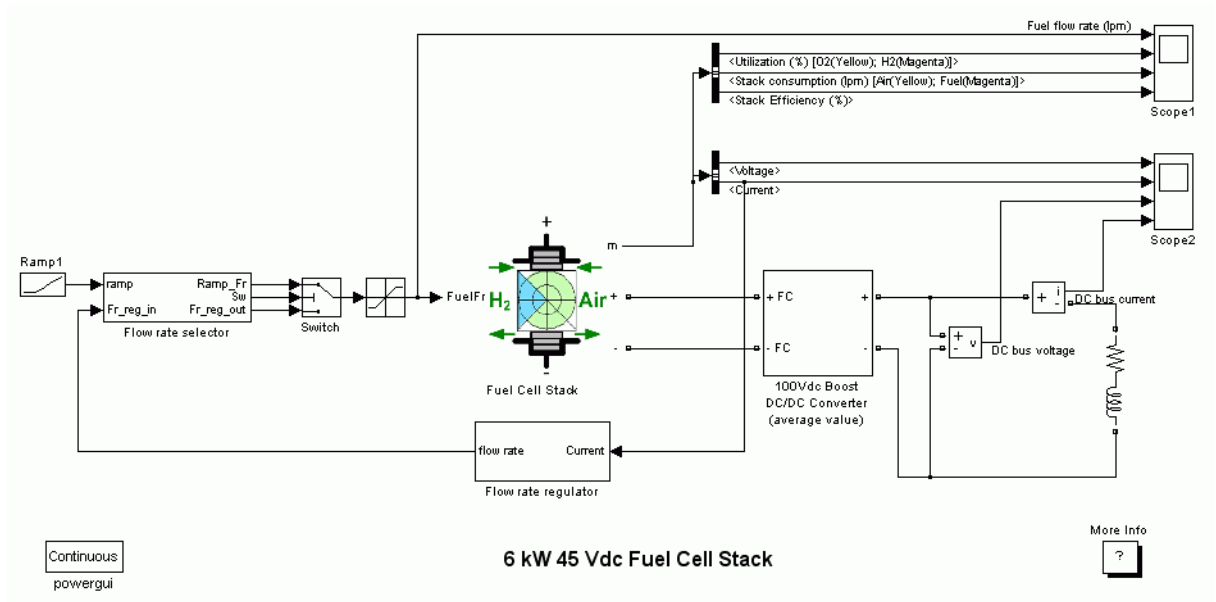
## Model Limitations

- Chemical reaction dynamics caused by partial pressure changes of chemical species inside the cell are not considered.
- The stack output power is limited by the fuel and air flow rates supplied.
- The effect of temperature and humidity of the membrane on the internal resistance is not considered.

## Example

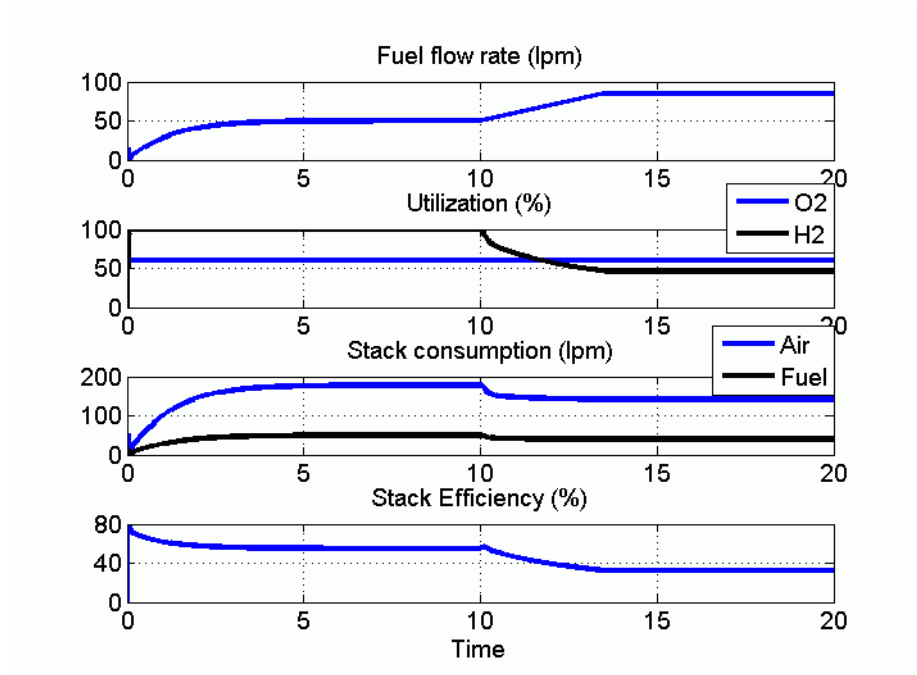
The `power_fuel_cell` demo illustrates a model of a 6 kW, 45 V proton exchange membrane (PEM) fuel cell stack feeding an average value 100 Vdc DC/DC converter.

The converter is loaded by an RL element of 6 kW with a time constant of 1 s. During the first 10 s, the utilization of the hydrogen is constant to the nominal value ( $U_{f\_H2} = 99.56\%$ ) using a fuel flow rate regulator. After 10 s, the flow rate regulator is bypassed and the rate of fuel is increased to the maximum value of 85 lpm to observe the variation in the stack voltage. This will affect the stack efficiency, the fuel consumption, and the air consumption.

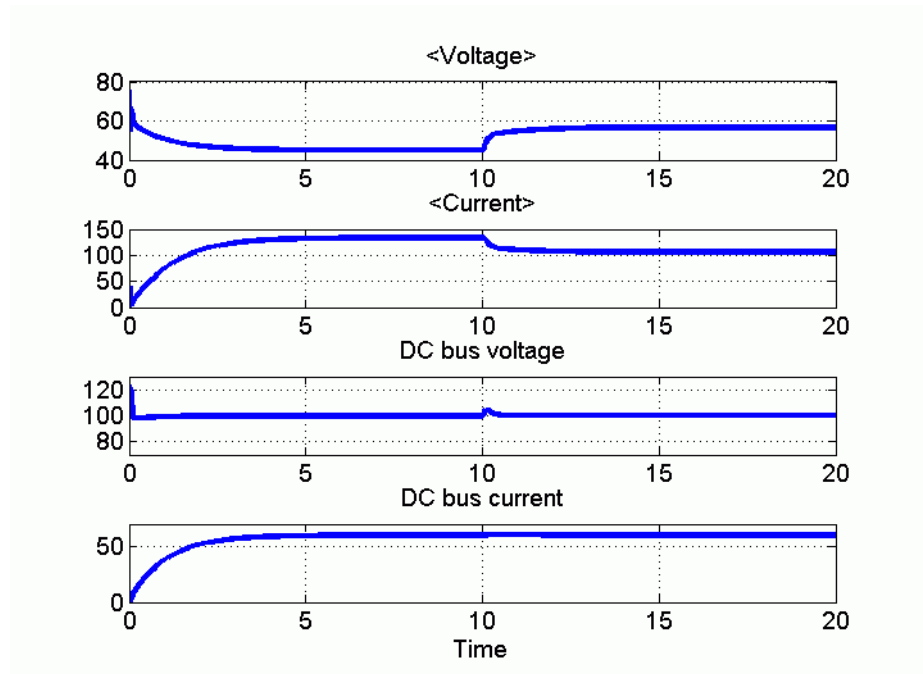


The simulation produces the followings results.

# Fuel Cell Stack



Results for Scope 1



## Results for Scope 2

At  $t = 0$  s, the DC/DC converter applies 100 Vdc to the RL load (the initial current of the load is 0 A). The fuel utilization is set to the nominal value of 99.56%. The current increases until the value of 133 A. The flow rate is automatically set to maintain the nominal fuel utilization. Observe the DC bus voltage (Scope2), which is very well regulated by the converter. The peak voltage of 122 Vdc at the beginning of the simulation is caused by the transient state of the voltage regulator.

At  $t = 10$  s, the fuel flow rate is increased from 50 liters per minute (lpm) to 85 lpm during 3.5 s, reducing by doing so the hydrogen utilization. This causes an increase of the Nernst voltage so the fuel cell current will decrease. Therefore, the stack consumption and the efficiency will decrease (Scope1).

# Generic Power System Stabilizer

**Purpose** Implement generic power system stabilizer for synchronous machine

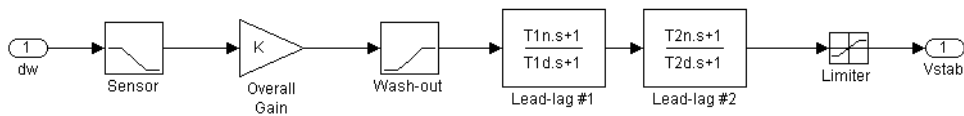
**Library** Machines

## Description



The Generic Power System Stabilizer (PSS) block can be used to add damping to the rotor oscillations of the synchronous machine by controlling its excitation. The disturbances occurring in a power system induce electromechanical oscillations of the electrical generators. These oscillations, also called power swings, must be effectively damped to maintain the system stability. The output signal of the PSS is used as an additional input (*vstab*) to the Excitation System block. The PSS input signal can be either the machine speed deviation,  $dw$ , or its acceleration power,  $P_a = P_m - P_e$  (difference between the mechanical power and the electrical power).

The Generic Power System Stabilizer is modeled by the following nonlinear system:



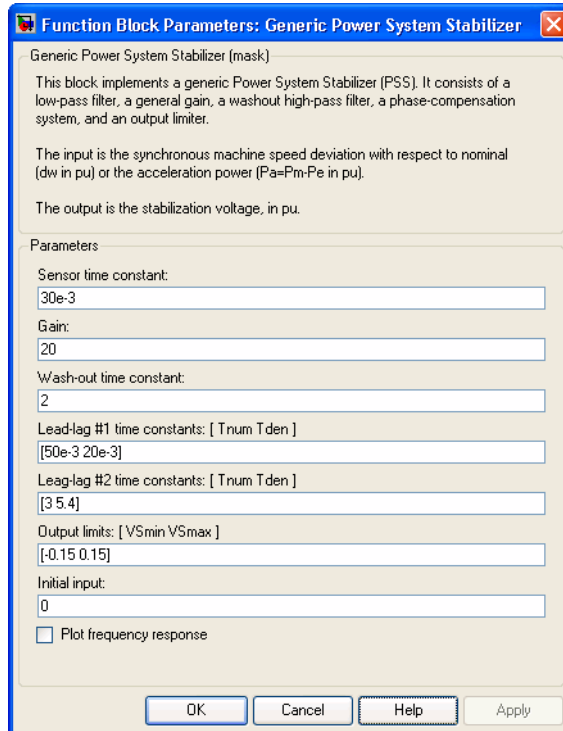
To ensure a robust damping, the PSS should provide a moderate phase advance at frequencies of interest in order to compensate for the inherent lag between the field excitation and the electrical torque induced by the PSS action.

The model consists of a low-pass filter, a general gain, a washout high-pass filter, a phase-compensation system, and an output limiter. The general gain  $K$  determines the amount of damping produced by the stabilizer. The washout high-pass filter eliminates low frequencies that are present in the  $dw$  signal and allows the PSS to respond only to speed changes. The phase-compensation system is represented by a cascade of two first-order lead-lag transfer functions used to compensate



the phase lag between the excitation voltage and the electrical torque of the synchronous machine.

## Dialog Box and Parameters



### Sensor time constant

The time constant, in seconds (s), of the first-order low-pass filter used to filter the block's input signal.

### Gain

The overall gain  $K$  of the generic power system stabilizer.

### Wash-out time constant

The time constant, in seconds (s), of the first-order high-pass filter used by the washout system of the model.

# Generic Power System Stabilizer

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## Lead-lag #1 time constants: [Tnum Tden]

The numerator time constant T1n and denominator time constant T1d, in seconds (s), of the first lead-lag transfer function.

## Lead-lag #2 time constants: [Tnum Tden]

The numerator time constant T2n and denominator time constant T2d, in seconds (s), of the second lead-lag transfer function.

## Output limits: [Vsmin Vsmax]

The limits VSmin and VSmax, in pu, imposed on the output of the stabilizer.

## Initial input

The initial DC voltage, in pu, of the block's input signal. Specification of this parameter is required to initialize all states and start the simulation in steady state with vstab set to zero.

## Plot frequency response

If selected, a plot of the frequency response of the stabilizer is displayed when you click the **Apply** button.

## Magnitude in dB

The **Magnitude in dB** parameter is not visible if the **Plot frequency response** is not selected. If selected, the magnitude of the frequency response is plotted in dB.

## Frequency range

The **Frequency range** parameter is not visible in the dialog box if the **Plot frequency response** is not selected. Specify the frequency range used to plot the frequency response of the stabilizer.

## Inputs and Outputs

In

Two types of signals can be used at the input In:

- The synchronous machine speed deviation dw signal (in pu)
- The synchronous machine acceleration power  $P_a = P_m - P_{eo}$  (difference between the machine mechanical power and output electrical power (in pu))

## Vstab

The output is the stabilization voltage (in pu) to connect to the Vstab input of the Excitation System block used to control the terminal voltage of the synchronous machine.

## Example

See the help text of the power\_PSS demo model.

## References

[1] Kundur, P., *Power System Stability and Control*, McGraw-Hill, 1994, Section 12.5.

## See Also

Multiband Power System Stabilizer

# Ground

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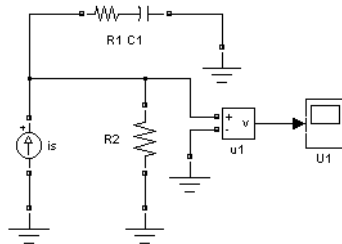
**Purpose** Provide connection to ground

**Library** Elements

**Description** The Ground block implements a connection to the ground.



**Example** The power\_ground demo shows an application of the Ground block.



**See Also** Neutral

# Grounding Transformer

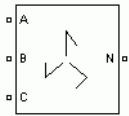
## Purpose

Implement three-phase grounding transformer providing a neutral in three-wire system

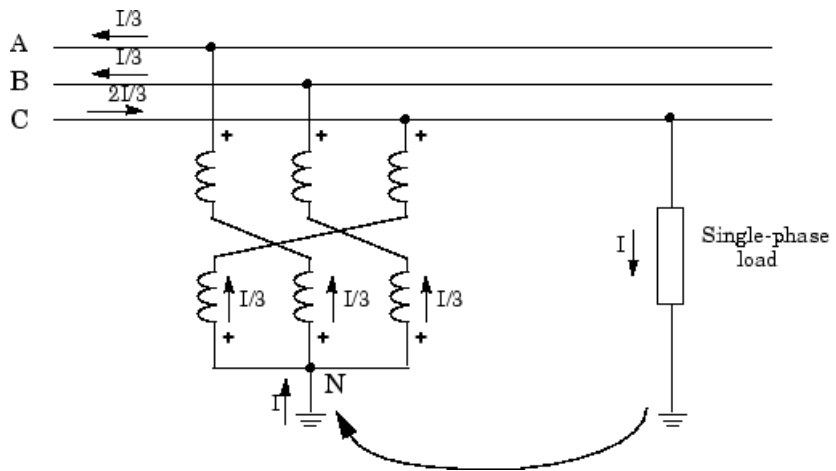
## Library

Elements

## Description



Grounding transformers are used in utility distribution networks and in some power electronic converters in order to provide a neutral point in a three-wire system. This transformer is a three-phase two-winding transformer with winding 1 and winding 2 connected in zig zag as shown in the figure below.



The figure shows a single-phase load connected between phase C and ground in a three-wire system. The current  $I$  absorbed by the load returns to the source through the ground and the neutral of the grounding transformer. Because of the zig zag connection and the opposite winding polarities of upper and lower windings, the grounding transformer offers a low impedance in zero-sequence while keeping a very high impedance to positive-sequence. In other words, only a zero-sequence current can flow through the three windings. By definition, a zero-sequence current is a set of three-phase currents having same magnitude and phase. Therefore, the neutral current  $I$  shares into three equal currents  $I/3$ . Because the three currents

# Grounding Transformer

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flowing in the grounding transformer are equal, the neutral point stays fixed and the line-to-neutral voltages remain balanced.

The grounding transformer is modeled by three two-winding transformers having a 1:1 voltage ratio. Assume six identical windings with:

$R$  = winding resistances

$X$  = winding leakage reactances

$R_{mag}, X_{mag}$  = parallel resistance and reactance of the magnetizing branch

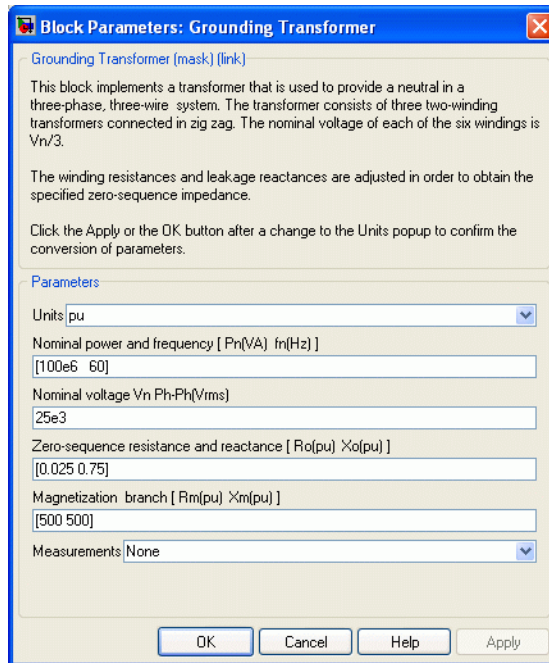
The positive-sequence impedance  $Z_1$  and the zero-sequence impedance  $Z_0$  of the grounding transformer are given by:

$$Z_1 = R_1 + jX_1 = 3 \frac{jR_{mag}X_{mag}}{(R_{mag} + jX_{mag})}$$

$$Z_0 = R_o + jX_0 = 2(R + jX)$$

The zero-sequence reactance  $X_0$  is the most important parameter of the grounding transformer. In order to minimize voltage unbalance, reactance  $X_0$  should be kept as low as possible.

## Dialog Box and Parameters



### Units

Specify the units used to enter the parameters of the Grounding Transformer block. Select **pu** to use per unit. Select **SI** to use SI units. Changing the **Units** parameter from **pu** to **SI**, or from **SI** to **pu**, will automatically convert the parameters displayed in the mask of the block.

### Nominal power and frequency

The nominal power rating, in volt-amperes (VA), and nominal frequency, in hertz (Hz), of the transformer.

### Nominal voltage

The nominal phase-to-phase voltage  $V_n$  of the Grounding Transformer, in volts RMS (Vrms).

# Grounding Transformer

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## Zero-sequence resistance and reactance

The zero-sequence resistance  $R_0$  and the zero-sequence reactance  $X_0$  in pu or in ohms.

## Magnetization branch

The shunt resistance  $R_m$  modeling the transformer core losses and the magnetizing reactance  $X_m$  modeling the magnetization current, in pu or ohms.

These values define the active power losses  $P$  and the reactive power losses  $Q$  required for magnetizing the grounding transformer.

$$P = \frac{V_n^2}{R_m}$$

$$Q = \frac{V_n^2}{X_m}$$

As the nominal voltage across each of the six windings is the nominal line-to-line voltage divided by 3 ( $V_n/3$ ), the three impedances effectively connected across one of the two windings on each leg are  $R_{mag}=R_m/3$  and  $X_{mag}=X_m/3$ .

## Measurements

Select **Voltages** to measure the line-to-neutral voltages at the terminals of the Grounding Transformer block.

Select **Currents** to measure the currents flowing into the three terminals of the Grounding Transformer block.

Select **All voltages and currents** to measure voltages and currents.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available**



**Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name.

Measurement	Label
line-to-neutral voltages	Uan Ubn Ucn
currents	Ian Ibn Icn

## Limitations

Saturation of the grounding transformer is not modeled.

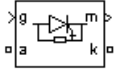
## See Also

Linear Transformer, Multimeter, Three-Phase Transformer (Two Windings), Three-Phase Transformer (Three Windings)

**Purpose** Implement gate turn off (GTO) thyristor model

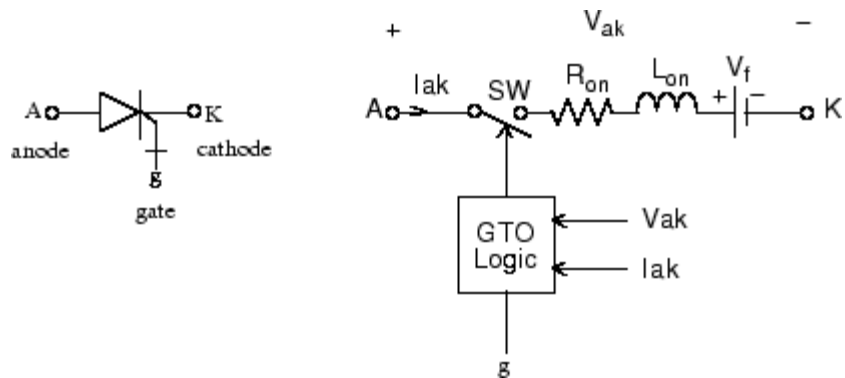
**Library** Power Electronics

## Description



The gate turnoff (GTO) thyristor is a semiconductor device that can be turned on and off via a gate signal. Like a conventional thyristor, the GTO thyristor can be turned on by a positive gate signal ( $g > 0$ ). However, unlike the thyristor, which can be turned off only at a zero crossing of current, the GTO can be turned off at any time by the application of a gate signal equal to 0.

The GTO thyristor is simulated as a resistor  $R_{on}$ , an inductor  $L_{on}$ , and a DC voltage source  $V_f$  connected in series with a switch. The switch is controlled by a logical signal depending on the voltage  $V_{ak}$ , the current  $I_{ak}$ , and the gate signal  $g$ .

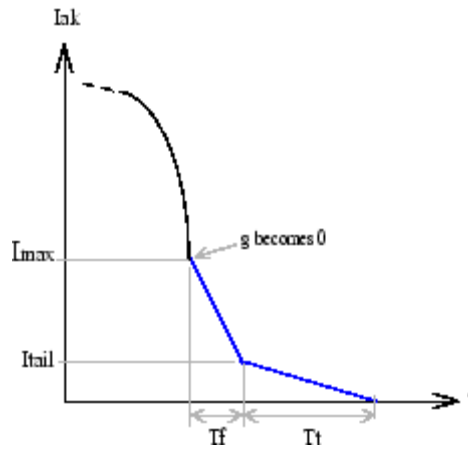


The  $V_f$ ,  $R_{on}$ , and  $L_{on}$  parameters are the forward voltage drop while in conduction, the forward conducting resistance, and the inductance of the device. The GTO block also contains a series  $R_s$ - $C_s$  snubber circuit that can be connected in parallel with the GTO device (between terminal ports A and K).

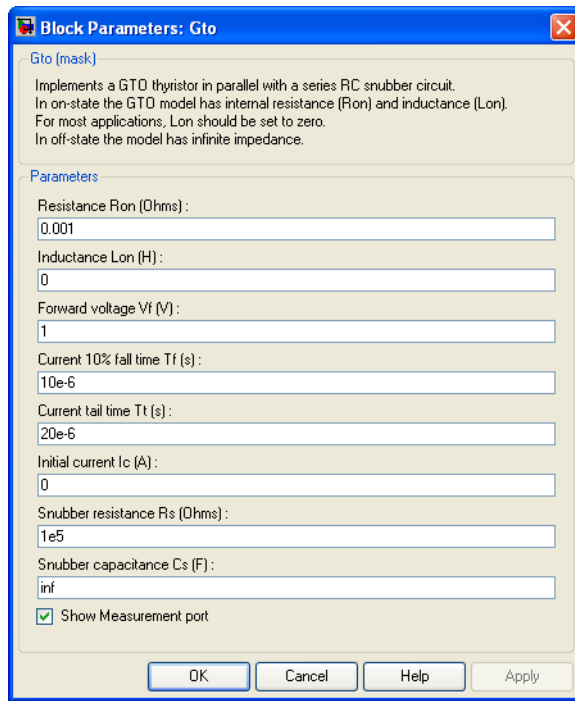
The GTO thyristor turns on when the anode-cathode voltage is greater than  $V_f$  and a positive pulse signal is present at the gate input ( $g > 0$ ).

When the gate signal is set to 0, the GTO thyristor starts to block but its current does not stop instantaneously.

Because the current extinction process of a GTO thyristor contributes significantly to the turnoff losses, the turnoff characteristic is built into the model. The current decrease is approximated by two segments. When the gate signal becomes 0, the current  $I_{ak}$  first decreases from the value  $I_{max}$  (value of  $I_{ak}$  when the GTO thyristor starts to open) to  $I_{max}/10$ , during the fall time ( $T_f$ ), and then from  $I_{max}/10$  to 0 during the tail time ( $T_t$ ). The GTO thyristor turns off when the current  $I_{ak}$  becomes 0. The latching and holding currents are not considered.



## Dialog Box and Parameters



### Resistance Ron

The internal resistance Ron, in ohms ( $\Omega$ ).

### Inductance Lon

The internal inductance Lon, in henries (H). The **Inductance Lon** parameter cannot be set to 0.

### Forward voltage Vf

The forward voltage of the GTO thyristor device, in volts (V).

### Current 10% fall time

The current fall time Tf, in seconds (s).

### Current tail time

The current tail time Tt, in seconds (s).

**Initial current  $I_c$** 

You can specify an initial current flowing in the GTO thyristor. It is usually set to 0 in order to start the simulation with the device blocked.

If the **Initial Current IC** parameter is set to a value greater than 0, the steady-state calculation considers the initial status of the GTO as closed. Initializing all states of a power electronic converter is a complex task. Therefore, this option is useful only with simple circuits.

**Snubber resistance  $R_s$** 

The snubber resistance, in ohms ( $\Omega$ ). Set the **Snubber resistance  $R_s$**  parameter to `inf` to eliminate the snubber from the model.

**Snubber capacitance  $C_s$** 

The snubber capacitance, in farads (F). Set the **Snubber capacitance  $C_s$**  parameter to 0 to eliminate the snubber, or to `inf` to get a resistive snubber.

**Show measurement port**

If selected, add a Simulink output to the block returning the GTO current and voltage.

**Inputs and Outputs**

g

Simulink signal to control the gate of the GTO.

m

The Simulink output of the block is a vector containing two signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

Signal	Definition	Units
1	GTO current	A
2	GTO voltage	V

## Assumptions and Limitations

The GTO block implements a macro model of a real GTO thyristor. It does not take into account either the geometry of the device or the underlying physical processes of the device [1].

The GTO block requires a continuous application of the gate signal ( $g > 0$ ) in order to be in the on state (with  $I_{ak} > 0$ ). The latching current and the holding current are not considered. The critical value of the derivative of the reapplied anode-cathode voltage is not considered.

Depending on the value of the inductance  $L_{on}$ , the GTO is modeled either as a current source ( $L_{on} > 0$ ) or as a variable topology circuit ( $L_{on} = 0$ ). The GTO block cannot be connected in series with an inductor, a current source, or an open circuit, unless its snubber circuit is in use. See Improving Simulation Performance for more details on this topic.

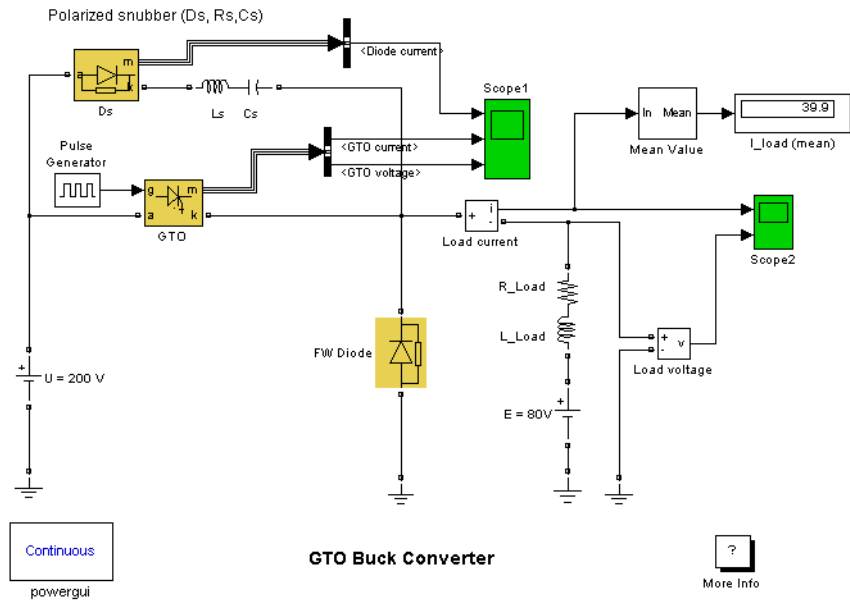
Use the Powergui block to specify either continuous simulation or discretization of your electrical circuit containing GTO blocks. When using a continuous model, the ode23tb solver with a relative tolerance of  $1e-4$  is recommended for best accuracy and simulation speed.

The inductance  $L_{on}$  is forced to 0 if you choose to discretize your circuit.

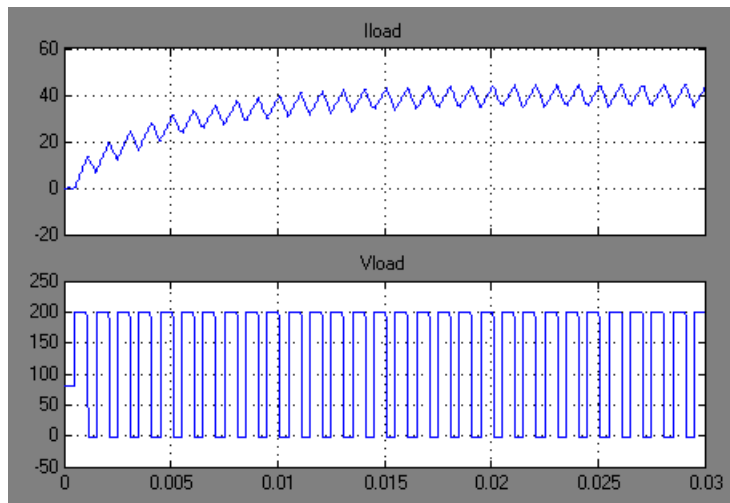
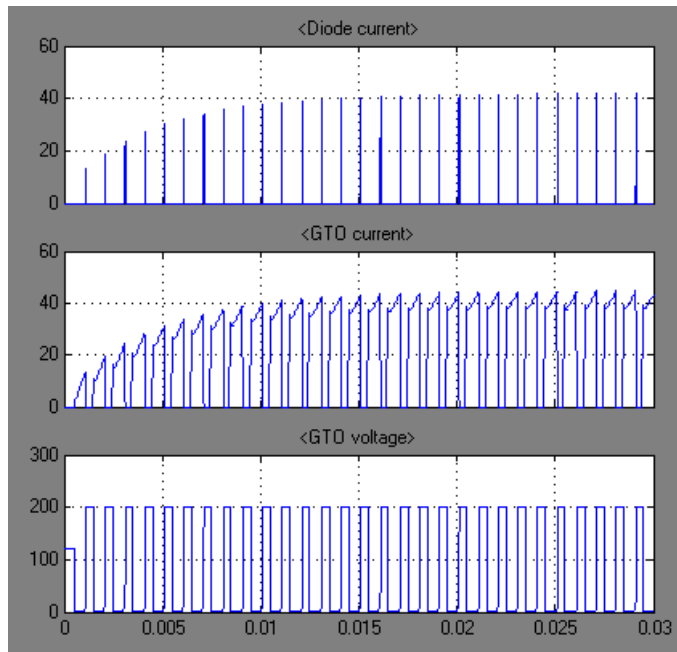
## Example

The power\_buckconv demo illustrates the use of the GTO block in a buck converter topology. The basic polarized snubber circuit is connected across the GTO block. The snubber circuit consists of a capacitor  $C_s$ , a resistor  $R_s$ , and a diode  $D_s$ . The parasitic inductance  $L_s$  of the snubber circuit is also taken into consideration.

The parameters of the GTO block are those found in the dialog box section, except for the internal snubber, which is not used ( $R_s = \text{inf}$ ;  $C_s = 0$ ). The switching frequency is 1000 Hz and the pulse width is 216 degrees (duty cycle: 60%).



Run the simulation. Observe the GTO voltage and current as well as the load voltage and current.





**References**

[1] Mohan, N., T.M. Undeland, and W.P. Robbins, *Power Electronics: Converters, Applications, and Design*, John Wiley & Sons, Inc., New York, 1995.

**See Also**

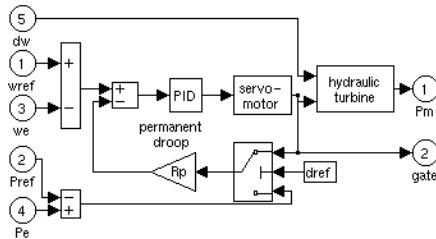
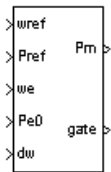
IGBT, MOSFET, Three-Level Bridge, Thyristor, Universal Bridge

# Hydraulic Turbine and Governor

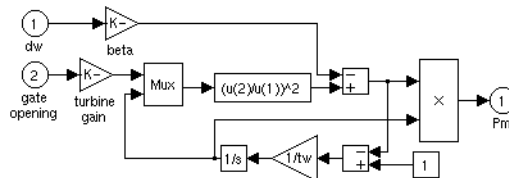
**Purpose** Model hydraulic turbine and proportional-integral-derivative (PID) governor system

**Library** Machines

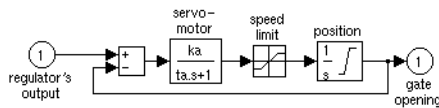
**Description** The Hydraulic Turbine and Governor block implements a nonlinear hydraulic turbine model, a PID governor system, and a servomotor [1].



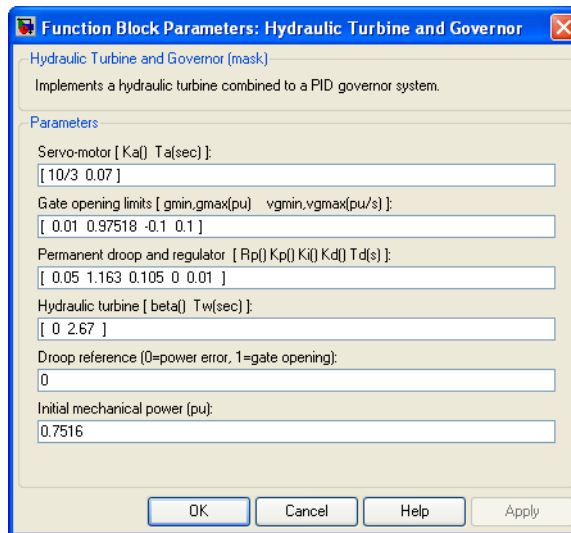
The hydraulic turbine is modeled by the following nonlinear system.



The gate servomotor is modeled by a second-order system.



## Dialog Box and Parameters



### Servo-motor

The gain  $K_a$  and time constant  $T_a$ , in seconds (s), of the first-order system representing the servomotor.

### Gate opening limits

The limits  $g_{min}$  and  $g_{max}$  (pu) imposed on the gate opening, and  $vg_{min}$  and  $vg_{max}$  (pu/s) imposed on gate speed.

### Permanent droop and regulator

The static gain of the governor is equal to the inverse of the permanent droop  $R_p$  in the feedback loop. The PID regulator has a proportional gain  $K_p$ , an integral gain  $K_i$ , and a derivative gain  $K_d$ . The high-frequency gain of the PID is limited by a first-order low-pass filter with time constant  $T_d$  (s).

### Hydraulic turbine

The speed deviation damping coefficient  $\beta$  and water starting time  $T_w$  (s).

# Hydraulic Turbine and Governor

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## **Droop reference**

Specifies the input of the feedback loop: gate position (set to 1) or electrical power deviation (set to 0).

## **Initial mechanical power**

The initial mechanical power  $P_{m0}$  (pu) at the machine's shaft. This value is automatically updated by the load flow utility of the Powergui block.

## **Inputs and Outputs**

wref

Reference speed, in pu.

Pref

Reference mechanical power in pu. This input can be left unconnected if you want to use the gate position as input to the feedback loop instead of the power deviation.

we

Machine actual speed, in pu.

Pe0

Machine actual electrical power in pu. This input can be left unconnected if you want to use the gate position as input to the feedback loop instead of the power deviation.

dw

Speed deviation, in pu.

Pm

Mechanical power  $P_m$  for the Synchronous Machine block, in pu.

gate

Gate opening, in pu.

## **Example**

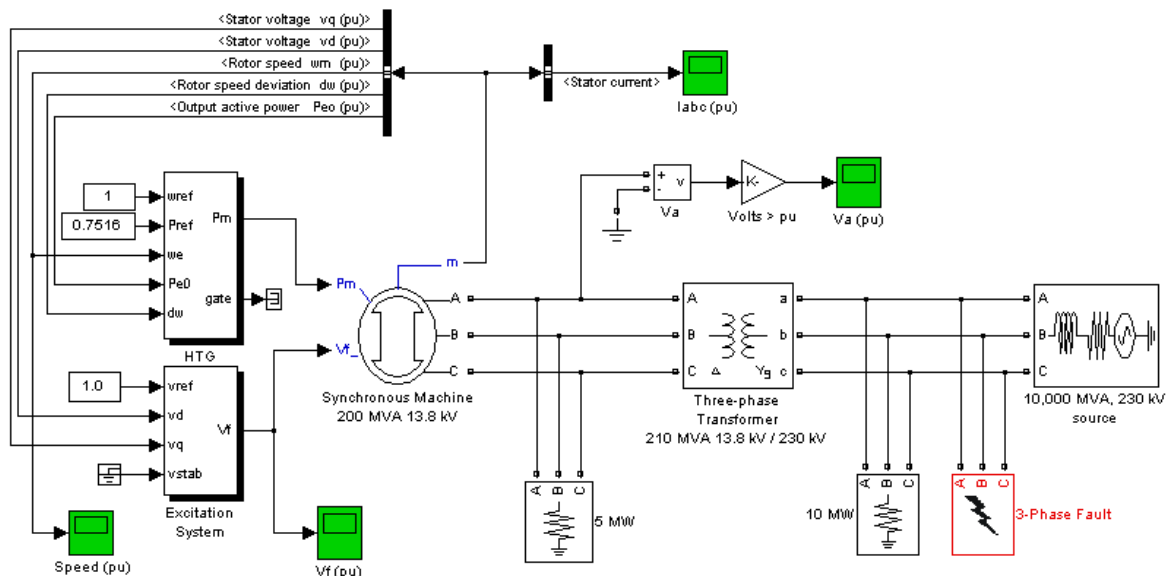
This power\_turbine demo illustrates the use of the Synchronous Machine associated with the Hydraulic Turbine and Governor (HTG) and Excitation System blocks. It also demonstrates the use of the load flow tool of the Powergui block to initialize machine currents and initial mechanical power of the HTG block. A three-phase generator rated 200 MVA, 13.8 kV, 112.5 rpm is connected to a 230 kV network through

# Hydraulic Turbine and Governor

a Delta-Y 210 MVA transformer. The system starts in steady state with the generator supplying 150 MW of active power. At  $t = 0.1$  s, a three-phase to ground fault occurs on the 230 kV bus of the transformer. The fault is cleared after six cycles ( $t = 0.2$  s).

In order to start the simulation in steady state, you must initialize the Synchronous Machine block for the desired load flow. Open the Powergui and select **Load flow and machine initialization**. The machine **Bus type** should be already initialized as PV generator, indicating that the load flow is performed with the machine controlling the active power and its terminal voltage. Specify the desired values by entering the following parameters:

- Terminal voltage  $U_{AB}$  ( $V_{rms}$ ) = 13800
- Active power (watts) = 150e6



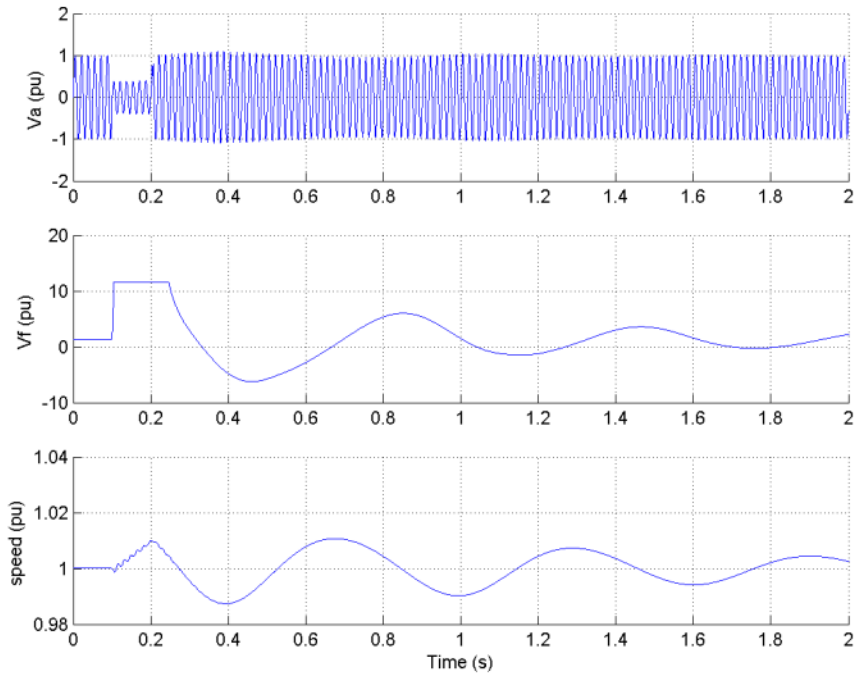
# Hydraulic Turbine and Governor

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Then click the **Update Load Flow** button. Once the load flow has been solved, the line-to-line machine voltages as well as the phase currents flowing out of the machine. The machine reactive power, mechanical power, and field voltage requested to supply the electrical power should also be displayed:

- $Q = 3.4$  Mvar
- $P_{mec} = 150.32$  MW (0.7516 pu)
- Field voltage  $V_f = 1.291$  pu

The load flow also initializes the HTG and Excitation System blocks. Open the HTG block menu and notice that the initial mechanical power is set to 0.5007 pu (100.14 MW). Then open the Excitation System block menu and note that the initial terminal voltage and field voltage are set respectively to 1.0 and 1.291 pu. Open the four scopes and start the simulation. The simulation starts in steady state.



Observe that the terminal voltage  $V_a$  is 1.0 pu at the beginning of the simulation. It falls to about 0.4 pu during the fault and returns to nominal quickly after the fault is cleared. This quick response in terminal voltage is due to the fact that the Excitation System output  $V_f$  can go as high as 11.5 pu, which it does during the fault. The speed of the machine increases to 1.01 pu during the fault, then it oscillates around 1 pu as the governor system regulates it. The speed takes much longer than the terminal voltage to stabilize, mainly because the rate of valve opening/closing in the governor system is limited to 0.1 pu/s.

## References

[1] IEEE Working Group on Prime Mover and Energy Supply Models for System Dynamic Performance Studies, "Hydraulic Turbine and Turbine Control Models for Dynamic Studies," *IEEE Transactions on Power Systems*, Vol. 7, No. 1, February, 1992, pp. 167-179.

# Hydraulic Turbine and Governor

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## **See Also**

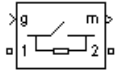
Excitation System, Steam Turbine and Governor, Synchronous Machine



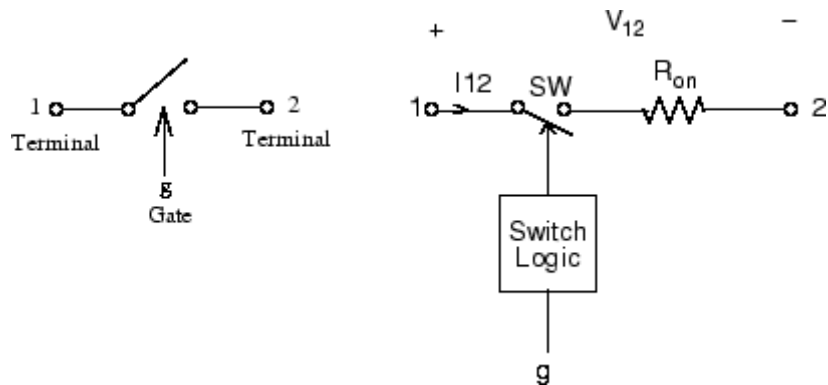
**Purpose** Implement ideal switch device

**Library** Power Electronics

## Description



The Ideal Switch block does not correspond to a particular physical device. When used with appropriate switching logic, it can be used to model simplified semiconductor devices such as a GTO or a MOSFET, or even a power circuit breaker with current chopping. The switch is simulated as a resistor  $R_{on}$  in series with a switch controlled by a logical gate signal  $g$ .



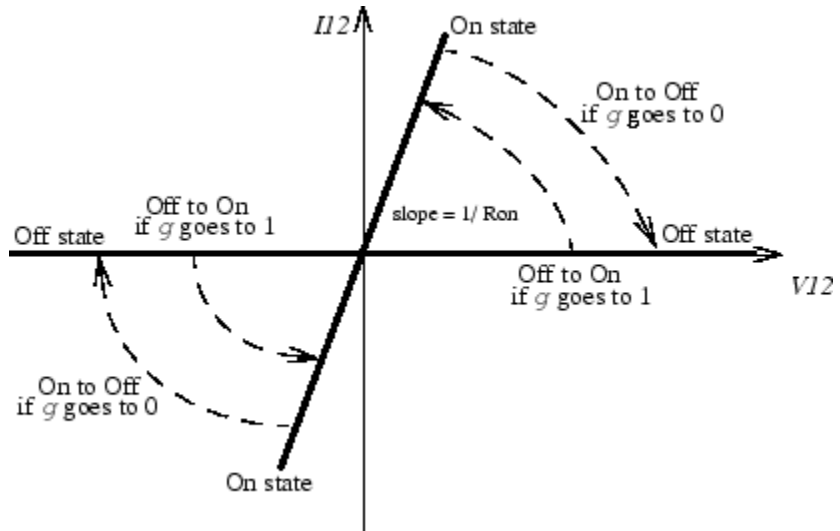
The Ideal Switch block is fully controlled by the gate signal ( $g > 0$  or  $g = 0$ ). It has the following characteristics:

- Blocks any forward or reverse applied voltage with 0 current flow when  $g = 0$
- Conducts any bidirectional current with quasi-zero voltage drop when  $g > 0$
- Switches instantaneously between on and off states when triggered

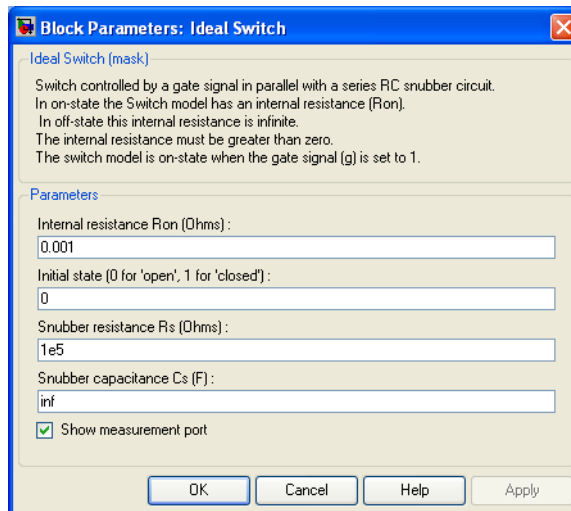
The Ideal Switch block turns on when a positive signal is present at the gate input ( $g > 0$ ). It turns off when the gate signal equals 0 ( $g = 0$ ).

# Ideal Switch

The Ideal Switch block also contains a series Rs-Cs snubber circuit that can be connected in parallel with the ideal switch (between nodes 1 and 2).



## Dialog Box and Parameters



### Internal resistance Ron

The internal resistance of the switch device, in ohms ( $\Omega$ ). The **Internal resistance Ron** parameter cannot be set to 0.

### Initial state

The initial state of the Ideal Switch block. The initial status of the Ideal Switch block is taken into account in the steady-state calculation.

### Snubber resistance Rs

The snubber resistance, in ohms ( $\Omega$ ). Set the **Snubber resistance Rs** parameter to `inf` to eliminate the snubber from the model.

### Snubber capacitance Cs

The snubber capacitance in farads (F). Set the **Snubber capacitance Cs** parameter to 0 to eliminate the snubber, or to `inf` to get a resistive snubber.

### Show measurement port

If selected, add a Simulink output to the block returning the ideal switch current and voltage.

# Ideal Switch

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## Inputs and Outputs

g Simulink signal to control the opening and closing of the switch.

m The Simulink output of the block is a vector containing two signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

Signal	Definition	Units
1	Ideal switch current	A
2	Ideal switch voltage	V

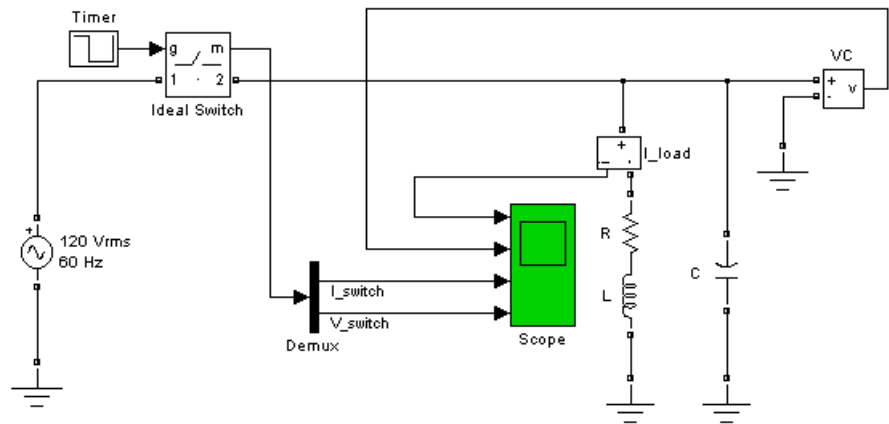
## Assumptions and Limitations

The Ideal Switch block is modeled as a current source. It cannot be connected in series with an inductor, a current source, or an open circuit, unless its snubber circuit is in use. See *Improving Simulation Performance* for more details on this topic.

Use the Powergui block to specify either continuous simulation or discretization of your electrical circuit containing ideal switches. When using a continuous model, the ode23tb solver with a relative tolerance of 1e-4 is recommended for best accuracy and simulation speed.

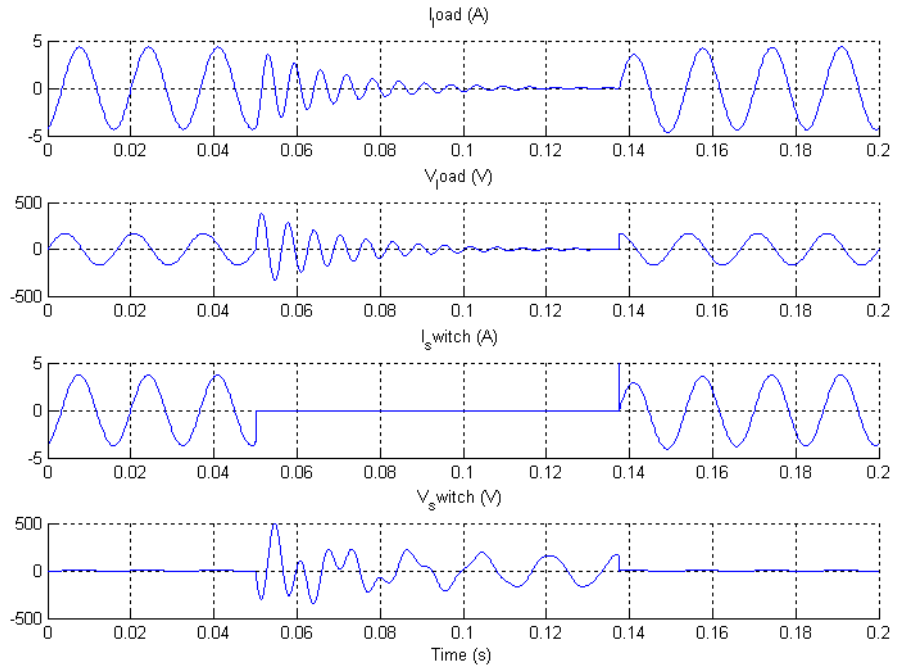
## Example

The power\_switch demo uses the Ideal Switch block to switch an RLC circuit on an AC source (60 Hz). The switch, which is initially closed, is first opened at  $t = 50$  ms (3 cycles) and then reclosed at  $t = 138$  ms (8.25 cycles). The Ideal Switch block has 0.01 ohms resistance and no snubber is used.



Run the simulation and observe the inductor current, the switch current, and the capacitor voltage. Notice the high-frequency overvoltage produced by inductive current chopping. Note also the high switch current spike when the switch is reclosed on the capacitor at maximum source voltage.

# Ideal Switch



## References

[1] Mohan, N., T.M. Undeland, and W.P. Robbins, *Power Electronics: Converters, Applications, and Design*, John Wiley & Sons, Inc., New York, 1995.

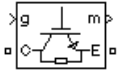
## See Also

Breaker

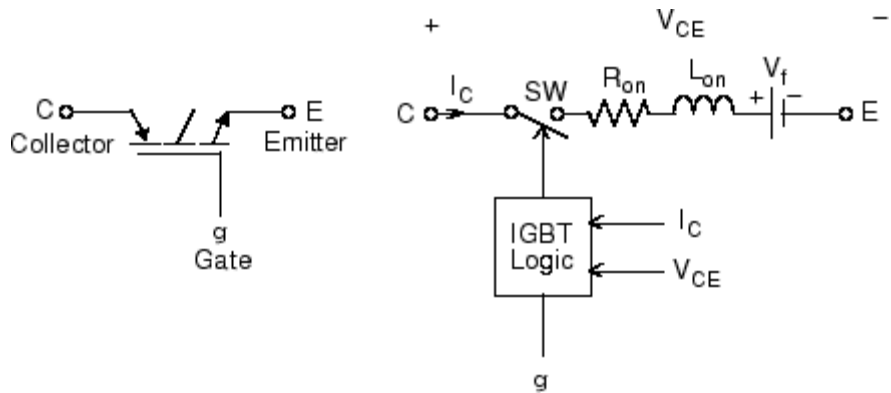
**Purpose** Implement insulated gate bipolar transistor (IGBT)

**Library** Power Electronics

**Description**



The IGBT block implements a semiconductor device controllable by the gate signal. The IGBT is simulated as a series combination of a resistor  $R_{on}$ , inductor  $L_{on}$ , and a DC voltage source  $V_f$  in series with a switch controlled by a logical signal ( $g > 0$  or  $g = 0$ )

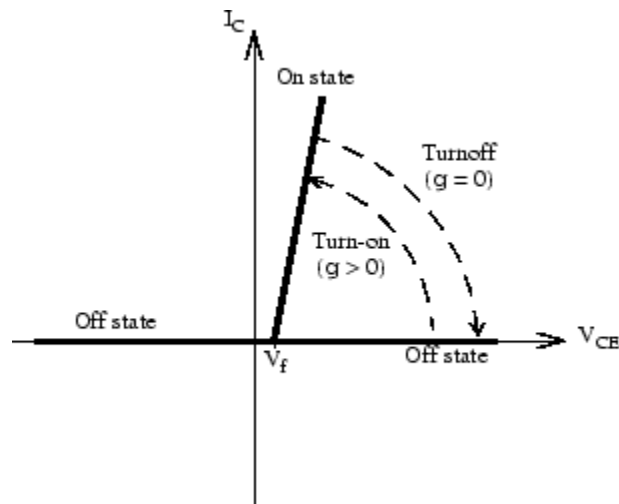


The IGBT turns on when the collector-emitter voltage is positive and greater than  $V_f$  and a positive signal is applied at the gate input ( $g > 0$ ). It turns off when the collector-emitter voltage is positive and a 0 signal is applied at the gate input ( $g = 0$ ).

The IGBT device is in the off state when the collector-emitter voltage is negative. Note that many commercial IGBTs do not have the reverse blocking capability. Therefore, they are usually used with an antiparallel diode.

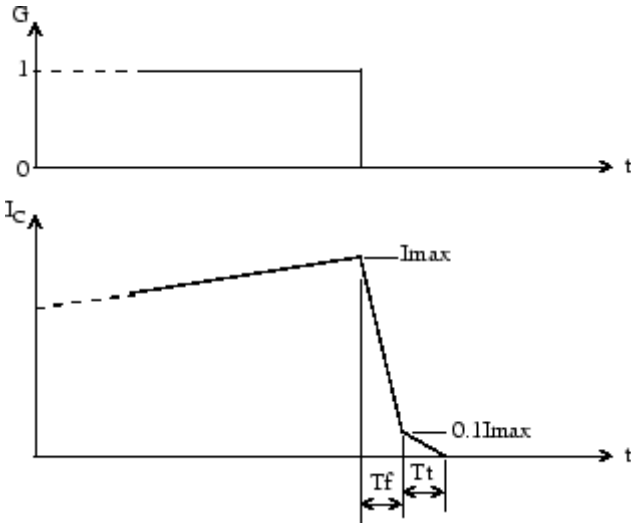
The IGBT block contains a series  $R_s$ - $C_s$  snubber circuit, which is connected in parallel with the IGBT device (between terminals C and E).

# IGBT

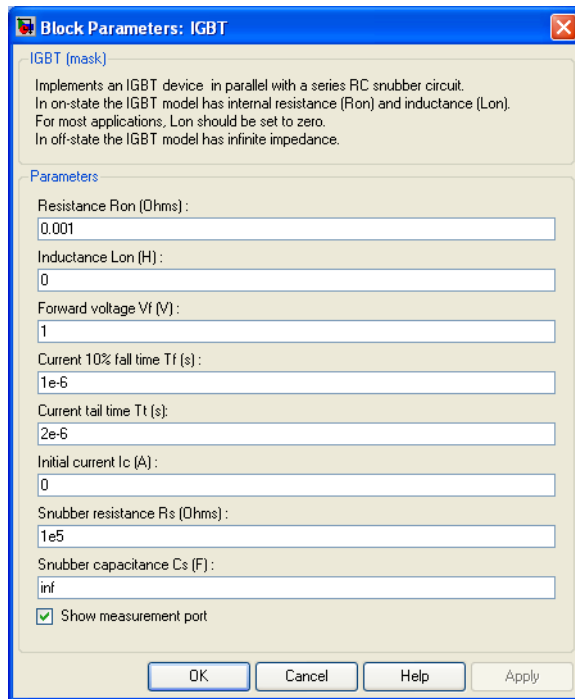


The turnoff characteristic of the IGBT model is approximated by two segments. When the gate signal falls to 0, the collector current decreases from  $I_{max}$  to  $0.1 I_{max}$  during the fall time ( $T_f$ ), and then from  $0.1 I_{max}$  to 0 during the tail time ( $T_t$ ).





## Dialog Box and Parameters



### Resistance Ron

The internal resistance Ron, in ohms ( $\Omega$ ).

### Inductance Lon

The internal inductance Lon, in henries (H). The **Inductance Lon** parameter cannot be set to 0.

### Forward voltage Vf

The forward voltage of the IGBT device, in volts (V).

### Current 10% fall time

The current fall time Tf, in seconds (s).

### Current tail time

The current tail time Tt, in seconds (s).

**Initial current Ic**

You can specify an initial current flowing in the IGBT. It is usually set to 0 in order to start the simulation with the device blocked.

If the **Initial Current IC** parameter is set to a value greater than 0, the steady-state calculation considers the initial status of the IGBT as closed. Initializing all states of a power electronic converter is a complex task. Therefore, this option is useful only with simple circuits.

**Snubber resistance Rs**

The snubber resistance, in ohms ( $\Omega$ ). Set the **Snubber resistance Rs** parameter to `inf` to eliminate the snubber from the model.

**Snubber capacitance Cs**

The snubber capacitance in farads (F). Set the **Snubber capacitance Cs** parameter to 0 to eliminate the snubber, or to `inf` to get a resistive snubber.

**Show measurement port**

If selected, add a Simulink output to the block returning the diode IGBT current and voltage.

**Inputs and Outputs**

g

Simulink signal to control the opening and closing of the IGBT.

m

The Simulink output of the block is a vector containing two signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

Signal	Definition	Units
1	IGBT current	A
2	IGBT voltage	V

## Assumptions and Limitations

The IGBT block implements a macro model of the real IGBT device. It does not take into account either the geometry of the device or the complex physical processes [1].

Depending on the value of the inductance  $L_{on}$ , the IGBT is modeled either as a current source ( $L_{on} > 0$ ) or as a variable topology circuit ( $L_{on} = 0$ ). The IGBT block cannot be connected in series with an inductor, a current source, or an open circuit, unless its snubber circuit is in use. See Improving Simulation Performance for more details on this topic.

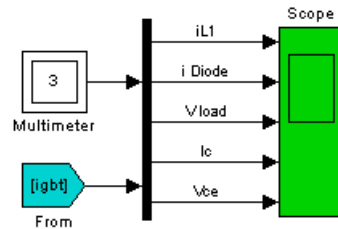
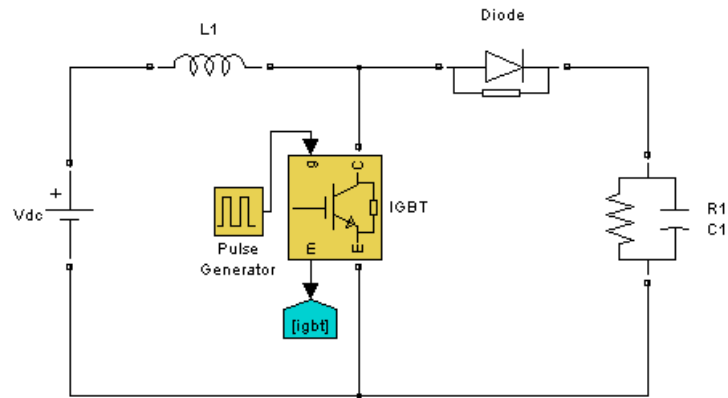
Use the Powergui block to specify either continuous simulation or discretization of your electrical circuit containing IGBT blocks. When using a continuous model, the ode23tb solver with a relative tolerance of  $1e-4$  is recommended for best accuracy and simulation speed.

The inductance  $L_{on}$  is forced to 0 if you choose to discretize your circuit.

## Example

The power\_igbtconv demo illustrates the use of the IGBT block in a boost DC-DC converter. The IGBT is switched on and off at a frequency of 10 kHz to transfer energy from the DC source to the load (RC). The average output voltage ( $V_R$ ) is a function of the duty cycle ( $\alpha$ ) of the IGBT switch:

$$V_R = \frac{1}{1-\alpha} V_{dc}$$

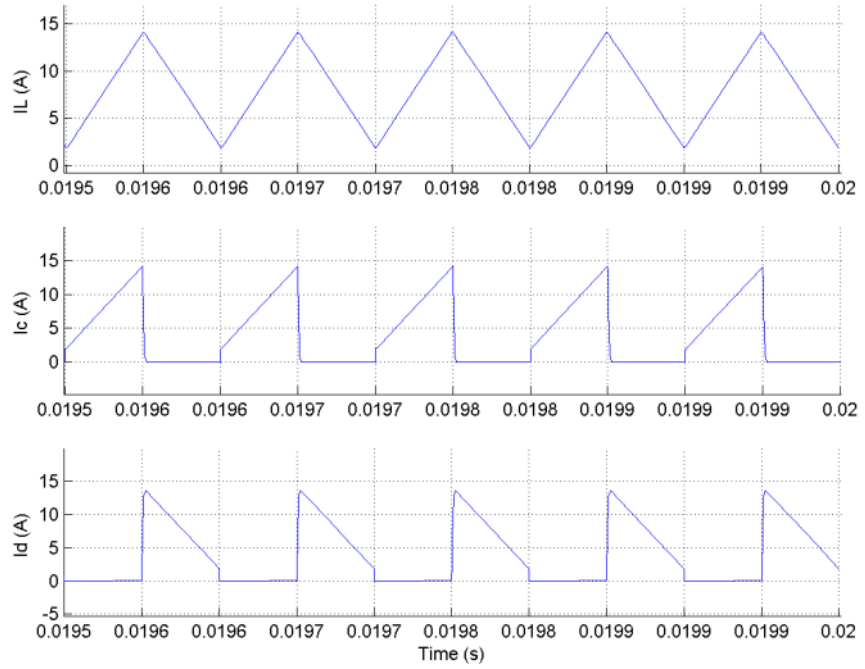


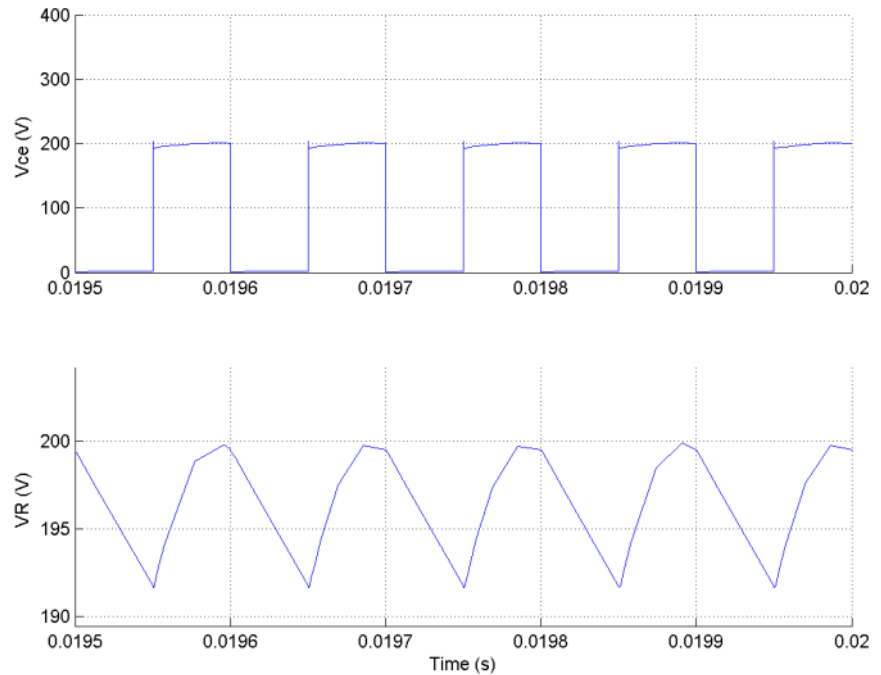
In our example,  $\alpha = 0.5$  so that the theoretical value of  $V_R$  is 200 V, assuming no voltage drop across the diode and the IGBT.

Run the simulation and observe the inductor current ( $I_L$ ), the IGBT collector current ( $I_C$ ), the diode current ( $I_D$ ), the IGBT device collector-emitter voltage ( $V_{CE}$ ), and the load voltage ( $V_R$ ).

The load voltage (197 V) is slightly lower than the theoretical value (200 V) mainly because of the forward voltage ( $V_f$ ) of the diode (0.8 V) and of the IGBT ( $V_f = 1$  V).

# IGBT





## References

[1] Mohan, N., T.M. Undeland, and W.P. Robbins, *Power Electronics: Converters, Applications, and Design*, John Wiley & Sons, Inc., New York, 1995.

## See Also

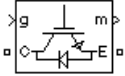
GTO, MOSFET, Three-Level Bridge, Thyristor

# IGBT/Diode

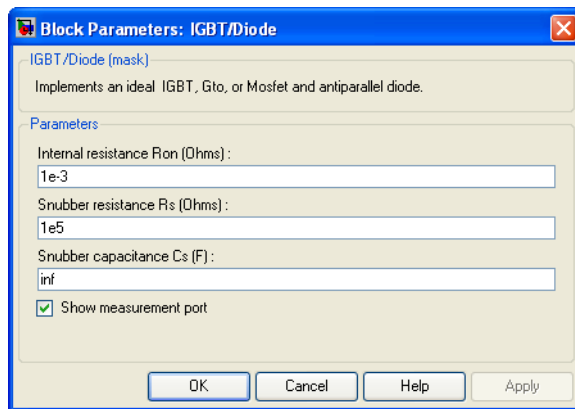
**Purpose** Implements ideal IGBT, GTO, or MOSFET and antiparallel diode

**Library** Power Electronics

**Description** The IGBT/Diode block is a simplified mode of an IGBT (or GTO or MOSFET)/Diode pair where the forward voltages of the forced-commutated device and diode are ignored.



## Dialog Box and Parameters



### Internal resistance $R_{on}$

The internal resistance  $R_{on}$  of the IGBT device, in ohms ( $\Omega$ ).

### Snubber resistance $R_s$

The snubber resistance, in ohms ( $\Omega$ ). Set the **Snubber resistance  $R_s$**  parameter to `inf` to eliminate the snubber from the model.

### Snubber capacitance $C_s$

The snubber capacitance in farads (F). Set the **Snubber capacitance  $C_s$**  parameter to 0 to eliminate the snubber, or to `inf` to get a resistive snubber.

### Show measurement port

If selected, add a Simulink output to the block returning the diode IGBT current and voltage.



## Inputs and Outputs

g

Simulink signal to control the opening and closing of the IGBT.

m

The Simulink output of the block is a vector containing two signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

Signal	Definition	Units
1	IGBT/Diode current	A
2	IGBT/diode voltage	V

## Assumptions and Limitations

The IGBT/Diode block implements a macro model of the real IGBT and Diode devices. It does not take into account either the geometry of the devices or the complex physical processes [1].

The IGBT/Diode block cannot be connected in series with an inductor, a current source, or an open circuit, unless its snubber circuit is in use. See *Improving Simulation Performance* for more details on this topic.

Use the Powergui block to specify either continuous simulation or discretization of your electrical circuit containing IGBT/Diode blocks. When using a continuous model, the `ode23tb` solver with a relative tolerance of  $1e-4$  is recommended for best accuracy and simulation speed.

## Example

The `power_1phPWM_IGBT` demo illustrates use of the IGBT/Diode block in voltage-sourced converters. The system consists of two independent circuits illustrating single-phase PWM voltage-sourced converters (VSC):

- 1 Half-bridge converter
- 2 Full-bridge converter

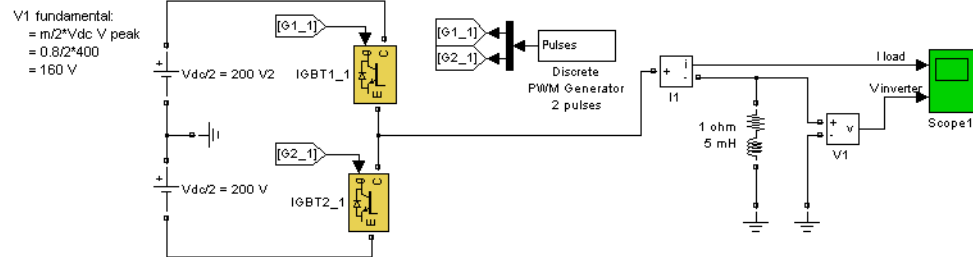
# IGBT/Diode

The converters are built with the IGBT/Diode block which is the basic building block of all VSCs. You may replace these blocks by individual IGBT and diode blocks for a more detailed representation.

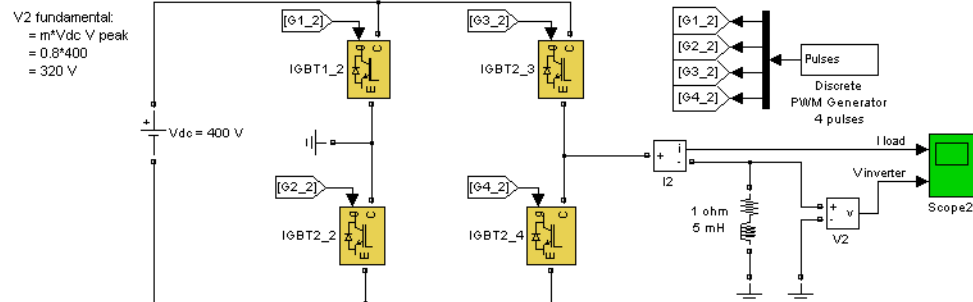
VSCs are controlled in open loop with the Discrete PWM Generator block available in the Extras/Discrete Control Blocks library.

The two circuits use the same DC voltage of 400 Volts, carrier frequency of 1080 Hz and modulation index of 0.8.

## DC/AC Half-bridge Inverter



## DC/AC Full-bridge Inverter



Run the simulation and observe the current into the load (trace 1) and the voltage generated by the PWM inverter (trace 2) on the Scope blocks.

**See Also**

IGBT, Diode

**Purpose** Measure impedance of circuit as function of frequency

**Library** Measurements

## Description



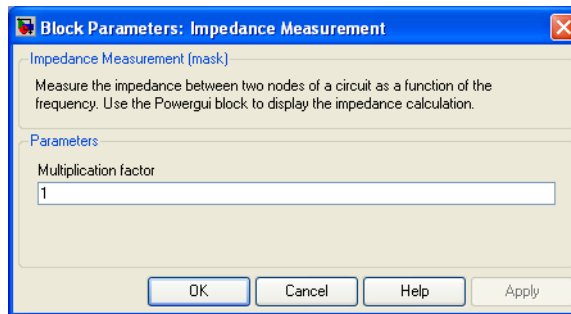
The Impedance Measurement block measures the impedance between two nodes of a linear circuit as a function of the frequency. It consists of a current source  $I_z$ , connected between inputs one and two of the Impedance Measurement block, and a voltage measurement  $V_z$ , connected across the terminals of the current source. The network impedance is calculated as the transfer function  $H(s)$  from the current input to the voltage output of the state-space model.

$$H(s) = \frac{V_z(s)}{I_z(s)}$$

The impedance (magnitude and phase) as function of frequency is displayed by using the Impedance vs Frequency Measurement tool of the Powergui block.

The measurement takes into account the initial states of the Breaker and Ideal Switch blocks. It also allows impedance measurements with Distributed Parameter Line blocks in your circuit.

## Dialog Box and Parameter



### Multiplication factor

If you use the Impedance Measurement block in a three-phase circuit, you can use the **Multiplication factor** parameter to

# Impedance Measurement

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rescale the measured impedance. For example, measuring the impedance between two phases of a three-phase circuit gives two times the positive-sequence impedance. Therefore you must apply a multiplication factor of 1/2 to the impedance in order to obtain the correct positive-sequence impedance value.

Similarly, to measure the zero-sequence impedance of a balanced three-phase circuit, you can connect the Impedance Measurement block between ground or neutral and the three phases connected together.

In that case, you are measuring one third of the zero-sequence impedance and you must apply a multiplication factor of 3 to obtain the correct zero-sequence value.

## Limitations

The only nonlinear blocks that are taken into account during the impedance measurement are the Breaker, Three-Phase Breaker, Three-Phase Fault, Ideal Switch, and Distributed Parameter Line blocks. All other nonlinear blocks, such as machines and power electronic devices, are not considered, and they are disconnected during the measurement.

If you plan to connect the Impedance Measurement block in series with an inductance, a current source, or any nonlinear element, you must add a large resistor across the terminals of the block, because the Impedance Measurement block is simulated as a current source block.

## Example

See the Powergui block reference page for an example using the Impedance Measurement block.

## See Also

Powergui

## Purpose

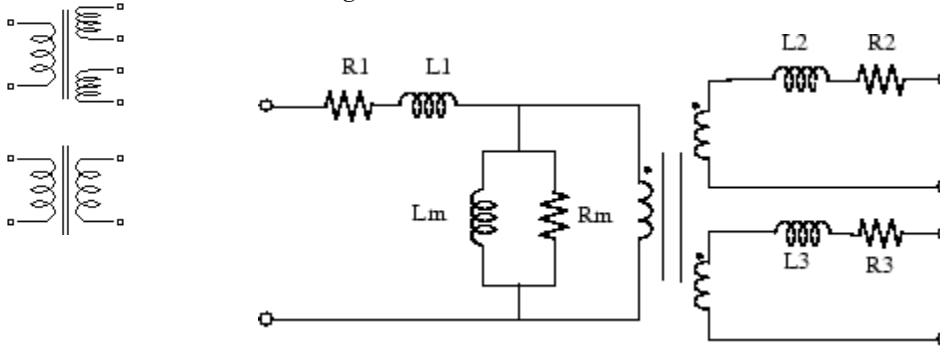
Implement two- or three-winding linear transformer

## Library

Elements

## Description

The Linear Transformer block model shown consists of three coupled windings wound on the same core.



The model takes into account the winding resistances ( $R_1$   $R_2$   $R_3$ ) and the leakage inductances ( $L_1$   $L_2$   $L_3$ ), as well as the magnetizing characteristics of the core, which is modeled by a linear ( $R_m$   $L_m$ ) branch.

## The Per Unit Conversion

In order to comply with industry, you must specify the resistance and inductance of the windings in per unit (pu). The values are based on the transformer rated power  $P_n$ , in VA, nominal frequency  $f_n$ , in Hz, and nominal voltage  $V_n$ , in  $V_{rms}$ , of the corresponding winding. For each winding, the per unit resistance and inductance are defined as

$$R(\text{p.u.}) = \frac{R(\Omega)}{R_{base}}$$

$$L(\text{p.u.}) = \frac{L(H)}{L_{base}}$$

The base resistance and base inductance used for each winding are

# Linear Transformer

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$$R_{base} = \frac{(V_n)^2}{P_n}$$

$$L_{base} = \frac{R_{base}}{2\pi f_n}$$

For the magnetization resistance  $R_m$  and inductance  $L_m$ , the pu values are based on the transformer rated power and on the nominal voltage of winding 1.

For example, the default parameters of winding 1 specified in the dialog box section give the following bases:

$$R_{base} = \frac{(735e3/(\sqrt{3}))^2}{250e6} = 720.3\Omega \quad L_{base} = \frac{720.3}{2\pi 60} = 1.91H$$

Suppose that the winding 1 parameters are  $R_1 = 1.44\Omega$  and  $L_1 = 0.1528H$ ; the corresponding values to be entered in the dialog box are

$$R_1 = \frac{1.44\Omega}{720.3\Omega} = 0.002 \text{ p.u.}$$

$$L_1 = \frac{0.1528H}{1.91H} = 0.08 \text{ p.u.}$$

To specify a magnetizing current of 0.2% (resistive and inductive) based on nominal current, you must enter per unit values of  $1/0.002 = 500$  pu for the resistance and the inductance of the magnetizing branch. Using the base values calculated previously, these per unit values correspond to  $R_m = 3.6e5$  ohms and  $L_m = 955$  henries.

## Modeling an Ideal Transformer

To implement an ideal transformer model, set the winding resistances and inductances to 0, and the magnetization resistance and inductance ( $R_m$   $L_m$ ) to  $\text{inf}$ .

## Dialog Box and Parameters

**Block Parameters: Linear Transformer**

Linear Transformer (mask)  
Implements a three windings linear transformer.  
Click the Apply or the OK button after a change to the Units popup to confirm the conversion of parameters.

**Parameters**

Units: pu

Nominal power and frequency [Pn(VA) fn(Hz)]:  
[ 250e6 60 ]

Winding 1 parameters [V1(Vrms) R1(pu) L1(pu)]:  
[ 735e3 0.002 0.08 ]

Winding 2 parameters [V2(Vrms) R2(pu) L2(pu)]:  
[ 315e3 0.002 0.08 ]

Three windings transformer

Winding 3 parameters [V3(Vrms) R3(pu) L3(pu)]:  
[ 315e3 0.002 0.08 ]

Magnetization resistance and reactance [Rm(pu) Lm(pu)]:  
[ 500 500 ]

Measurements: None

OK Cancel Help Apply

### Units

Specify the units used to enter the parameters of the Linear Transformer block. Select pu to use per unit. Select SI to use SI units. Changing the **Units** parameter from pu to SI, or from SI to pu, will automatically convert the parameters displayed in the mask of the block.

### Nominal power and frequency

The nominal power rating Pn in volt-amperes (VA) and frequency fn, in hertz (Hz), of the transformer.

### Winding 1 parameters

The nominal voltage V, in volts RMS, resistance, in pu or ohms, and leakage inductance, in pu or henries. The pu values are based on the nominal power Pn and on V1. Set the winding resistances and inductances to 0 to implement an ideal winding.

# Linear Transformer

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## **Winding 2 parameters**

The nominal voltage  $V_2$  in volts RMS, resistance, in pu or ohms, and leakage inductance, in pu or henries. The pu values are based on the nominal power  $P_n$  and on  $V_2$ . Set the winding resistances and inductances to 0 to implement an ideal winding.

## **Three windings transformer**

If selected, implements a linear transformer with three windings; otherwise, it implements a two-windings transformer.

## **Winding 3 parameters**

The **Winding 3 parameters** parameter is not available if the **Three windings transformer** parameter is not selected.

The nominal voltage in volts RMS ( $V_{rms}$ ), resistance, in pu or ohms, and leakage inductance in pu or henries. The pu values are based on the nominal power  $P_n$  and on  $V_3$ . Set the winding resistances and inductances to 0 to implement an ideal winding.

## **Magnetization resistance and reactance**

The resistance and inductance simulating the core active and reactive losses. When selected, the pu values are based on the nominal power  $P_n$  and on  $V_1$ . For example, to specify 0.2% of active and reactive core losses, at nominal voltage, use  $R_m = 500$  pu and  $L_m = 500$  pu.

$R_m$  must have a finite value when the inductance of winding 1 is greater than zero.

## **Measurements**

Select **Winding voltages** to measure the voltage across the winding terminals of the Linear Transformer block.

Select **Winding currents** to measure the current flowing through the windings of the Linear Transformer block.

Select **Magnetization current** to measure the magnetization current of the Linear Transformer block.



Select All voltages and currents to measure the winding voltages and currents plus the magnetization current.

Place a Multimeter block in your model to display the selected measurements during the simulation.

In the **Available Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name.

Measurement	Label
Winding voltages	Uw1: , Uw2: , Uw3:
Winding currents	Iw1: , Iw2: , Iw3:
Magnetization current	Imag:

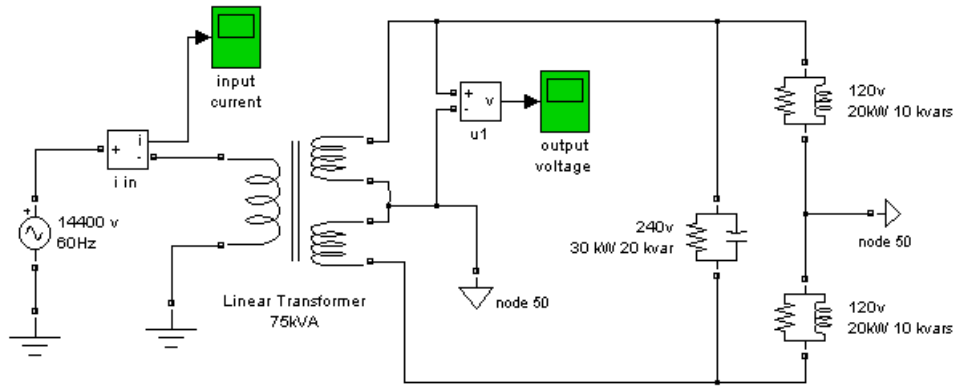
## Limitations

Windings can be left floating (that is, not connected to the rest of the circuit). However, an internal resistor is automatically added between the floating winding and the main circuit. This internal connection does not affect voltage and current measurements.

## Example

The power\_transformer demo shows a typical residential distribution transformer network feeding line-to-neutral and line-to-line loads.

# Linear Transformer



## See Also

Mutual Inductance, Saturable Transformer, Three-Phase Transformer (Two Windings), Three-Phase Transformer (Three Windings)

# Machine Measurement Demux

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**Purpose** Split measurement signal of machine models into separate signals

**Library** Machines

**Description**

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**Note** This block is now obsolete. We strongly recommend to use the Bus Selector block from Simulink library to demux the measurement signals of the machine blocks.

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# Mechanical Shaft

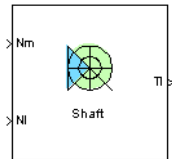
## Purpose

Implement mechanical shaft

## Library

Electric Drives/Shafts and Speed Reducers

## Description

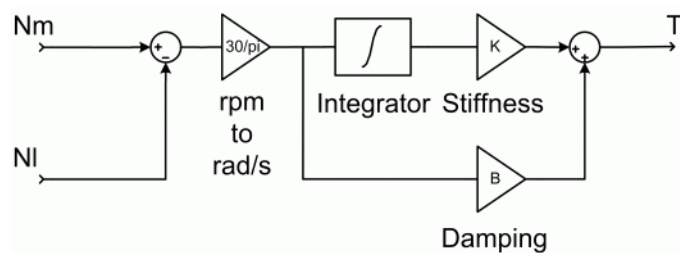


The model outputs the transmitted torque through the shaft regarding the speed difference between the driving side and the loaded side of the shaft.

The transmitted torque  $T_l$  is given by the following equation:

$$T_l = K \int (\omega_m - \omega_l) dt + B (\omega_m - \omega_l)$$

where  $K$  (N.m) is the shaft stiffness,  $B$  (N.m.s) is the internal damping, and  $\omega_m$  and  $\omega_l$  are the speeds (rad/s) of the driving side and the loaded side, respectively. The following figure shows the internal schematic of the model. In this model the speeds are converted from rpm to rad/s.



### Mechanical Shaft Model Schematic

The stiffness is defined as

$$K = \frac{T}{\theta}$$

where  $T$  is the torsional torque applied to the shaft and  $\theta$  the resulting angular deflection (rad).

The stiffness can also be determined by

$$K = \frac{G \cdot J}{l}$$

where  $G$  is the shear modulus,  $J$  the polar moment of inertia, and  $l$  the length of the shaft.

For steel, the shear modulus  $G$  is usually equal to about 80 GPa, and the polar moment of inertia  $J$  of a shaft with a circular section of diameter  $D$  is given by

$$J = \frac{\pi \cdot D^4}{32}$$

Mechanical shafts have very small angular deflections to avoid bearing problems. As an example, the following table gives the corresponding stiffness for angular deflections of 0.1 degrees at maximum torque with respect to the power and speed of electrical motors connected to the driving end of the shaft. The maximum torque is here assumed to be 1.5 times bigger than the nominal torque.

### Shaft Stiffness K

<b>P (HP)</b>	<b>N (rpm)</b>	<b>T (N.m)</b>	<b>Tmax (N.m) (=1.5 T)</b>	<b>K (N.m)</b>
5	1750	20	30	17190
200	1750	815	1223	700730
200	1200	1190	1785	1022730

The damping factor  $B$  represents internal friction. This factor increases with the shaft stiffness. As an example, the following table gives some values of  $B$  for the stiffness of the preceding table.

### Shaft Internal Damping B

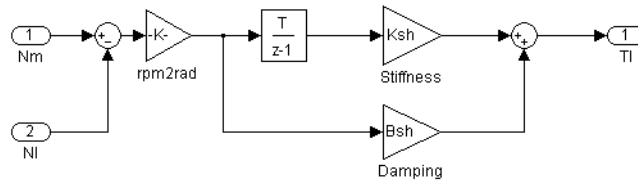
<b>K (N.m)</b>	<b>B (N.m.s)</b>
17190	600

# Mechanical Shaft

## Shaft Internal Damping B (Continued)

K (N.m)	B (N.m.s)
700730	24460
1022730	35700

### Simulink Schematic



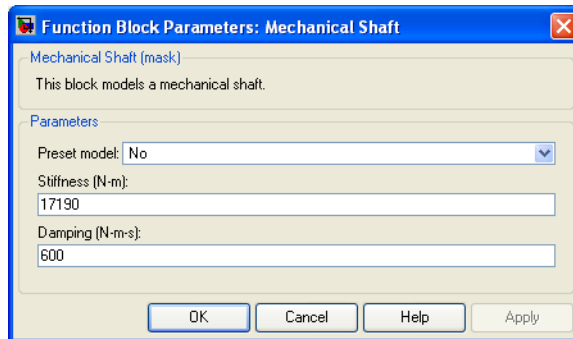
### Remarks

The stiffness must be high enough to avoid large angular deflections that could cause misalignment inside the bearings and damage.

For proper simulation results, the internal damping must be high enough to avoid undesired transient speed and torque oscillations.

The model is discrete. Good simulation results have been obtained with a 10  $\mu$ s time step.

### Dialog Box



## Preset Model

This pop-up menu allows you to choose preset model parameters.

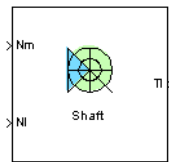
## Stiffness

The stiffness of the shaft (N.m).

## Damping

The internal damping of the shaft (N.m.s).

## Block Inputs and Outputs



## Inputs

The block has two inputs: Nm and Nl.

The first input, Nm, is the speed (rpm) of the driving end of the shaft.

The second input, Nl, is the speed (rpm) of the load connected to the second end of the shaft.

## Outputs

The block has one output: Tl.

The Tl output is the torque transmitted from the driving end of the shaft to the load.

## Model Specifications

The library contains three preset models. The nominal torques of these mechanical shaft models are shown in the following table:

### Preset Mechanical Shaft Models

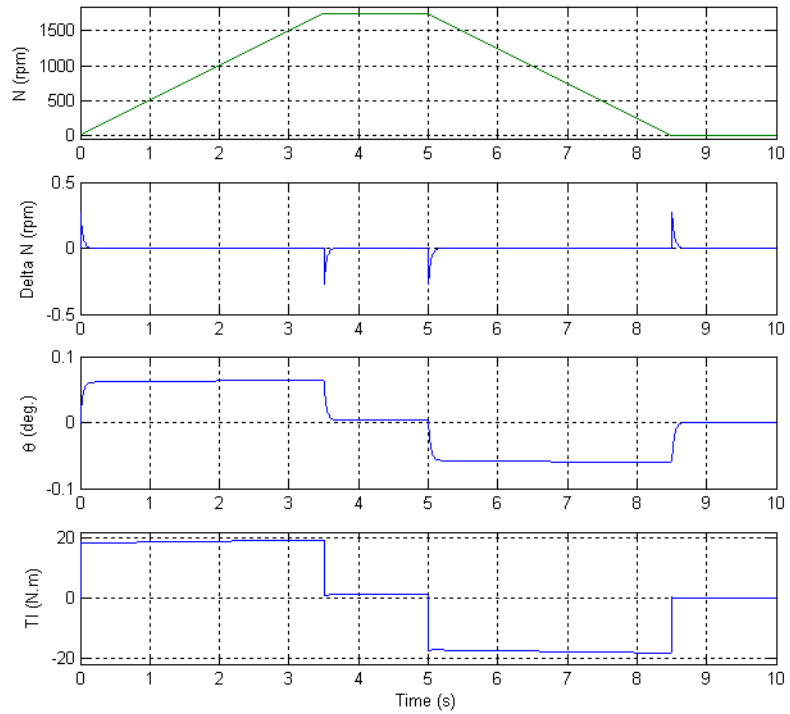
	1st	2nd	3rd
Nominal torque (N.m)	20	815	1190

The preset models have been designed in order to present 0.1 degrees of angular deflection at maximum torque (supposed to be 1.5 times the nominal torque).

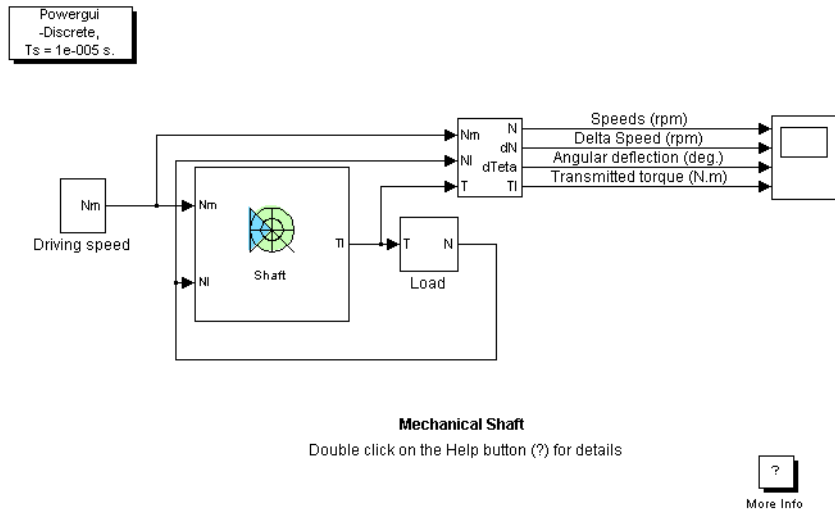
# Mechanical Shaft

## Example

The `shaft_example` demo illustrates the mechanical shaft model.







The shaft is driven by a variable speed source and is connected to a load. The load has an inertia of 0.35 kg.m<sup>2</sup> and a viscous friction term of 0.006 N.m.s.

The shaft has a stiffness of 17190 N.m and an internal damping factor of 600 N.m.s. This shaft is designed to have 0.1 degree of angular deflection for a 30 N.m load torque.

At  $t = 0$  s, the driving speed starts climbing to 1750 rpm with a 500 rpm/s acceleration ramp. The angular deflection jumps to about 0.06 degree and the shaft transmits about 18.5 N.m to the load in order to accelerate it. At  $t = 0.2$  s, the driving and load speeds tend to equalize. During the acceleration phase, the angular deflection increases slowly in order to transmit a higher torque to compensate the viscous friction increase.

At  $t = 3.5$  s, the driving speed settles at 1750 rpm. This reduces the angular deflection and also the transmitted torque, which settles around 1.1 N.m to compensate the viscous friction of the load.

# Mechanical Shaft

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At  $t = 5$  s, the driving speed lowers towards 0 rpm with a -500 rpm/s deceleration ramp. The angular deflection becomes negative and thus the transmitted torque in order to decelerate the load. During the deceleration phase, the angular deflection increases in order to transmit a higher deceleration torque to compensate the reduction of viscous friction.

At  $t = 8.5$  s, the driving speed stabilizes at 0 rpm. This causes the angular deflection to decrease to 0 degree, the transmitted torque becomes null, and the load stops.

The following figure shows the speeds of the driving and loaded sides, the speed difference between both sides, the angular deflection, and the transmitted torque.

## References

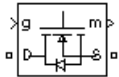
[1] Norton, Robert L., *Machine Design*, Prentice Hall, 1998.

[2] Nise, Norman S., *Control Systems Engineering*, Addison-Wesley Publishing Company, 1995.

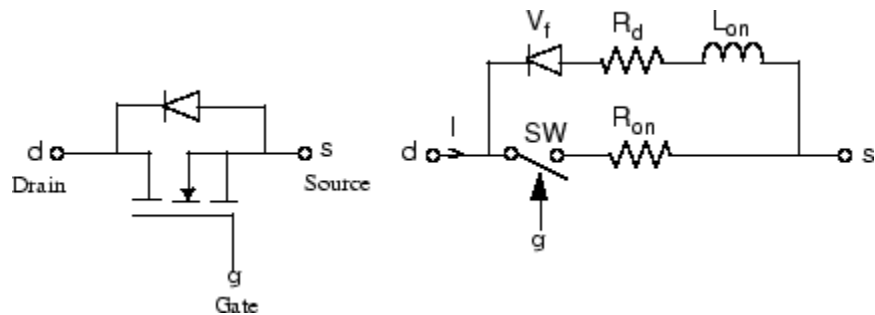
**Purpose** Implement MOSFET model

**Library** Power Electronics

## Description



The metal-oxide semiconductor field-effect transistor (MOSFET) is a semiconductor device controllable by the gate signal ( $g > 0$ ). The MOSFET device is connected in parallel with an internal diode that turns on when the MOSFET device is reverse biased ( $V_{ds} < 0$ ) and no gate signal is applied ( $g=0$ ). The model is simulated by an ideal switch controlled by a logical signal ( $g > 0$  or  $g = 0$ ), with a diode connected in parallel.



The MOSFET device turns on when a positive signal is applied at the gate input ( $g > 0$ ) whether the drain-source voltage is positive or negative. If no signal is applied at the gate input ( $g=0$ ), only the internal diode conducts when voltage exceeds its forward voltage  $V_f$ .

With a positive or negative current flowing through the device, the MOSFET turns off when the gate input becomes 0. If the current  $I$  is negative and flowing in the internal diode (no gate signal or  $g = 0$ ), the switch turns off when the current  $I$  becomes 0.

The on state voltage  $V_{ds}$  varies

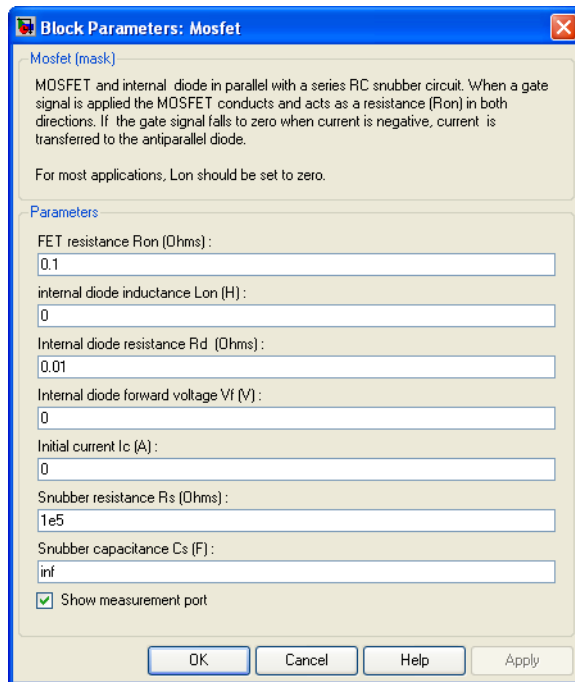
- $V_{ds} = R_{on} \cdot I$  when a positive signal is applied at the gate input.
- $V_{ds} = R_d \cdot I - V_f + L_{on} \cdot dI/dt$  when the antiparallel diode is conducting (no gate signal).

# MOSFET

The Lon diode inductance is available only with the continuous model. For most applications, Lon should be set to zero for both continuous and discrete models.

The MOSFET block also contains a series Rs-Cs snubber circuit that can be connected in parallel with the MOSFET (between nodes d and s).

## Dialog Box and Parameters



### FET Resistance Ron

The internal resistance Ron, in ohms ( $\Omega$ ).

### Internal diode inductance Lon

The internal inductance Lon, in henries (H). The **Inductance Lon** parameter cannot be set to 0.

### Internal diode resistance Rd

The internal resistance of the internal diode, in ohms ( $\Omega$ ).

## Internal diode forward voltage Vf

The forward voltage of the internal diode, in volts (V).

## Initial current Ic

You can specify an initial current flowing in the MOSFET device. It is usually set to 0 in order to start the simulation with the device blocked.

If the **Initial current IC** parameter is set to a value greater than 0, the steady-state calculation considers the initial status of the MOSFET as closed. Initializing all states of a power electronic converter is a complex task. Therefore, this option is useful only with simple circuits.

## Snubber resistance Rs

The snubber resistance, in ohms ( $\Omega$ ). Set the **Snubber resistance Rs** parameter to `inf` to eliminate the snubber from the model.

## Snubber capacitance Cs

The snubber capacitance, in farads (F). Set the **Snubber capacitance Cs** parameter to 0 to eliminate the snubber, or to `inf` to get a resistive snubber.

## Show measurement port

If selected, add a Simulink output to the block returning the MOSFET current and voltage.

## Inputs and Outputs

g

Simulink signal to control the opening and closing of the MOSFET.

m

The Simulink output of the block is a vector containing 2 signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

Signal	Definition	Units
1	MOSFET current	A
2	MOSFET voltage	V

## Assumptions and Limitations

The MOSFET block implements a macro model of the real MOSFET device. It does not take into account either the geometry of the device or the complex physical processes [1].

Depending on the value of the inductance  $L_{on}$ , the MOSFET is modeled either as a current source ( $L_{on} > 0$ ) or as a variable topology circuit ( $L_{on} = 0$ ). The MOSFET block cannot be connected in series with an inductor, a current source, or an open circuit, unless its snubber circuit is in use. See *Improving Simulation Performance* for more details on this topic.

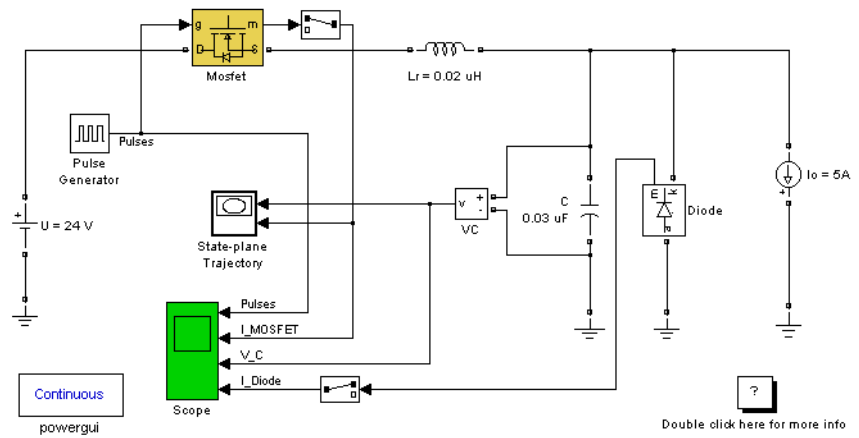
Use the Powergui block to specify either continuous simulation or discretization of your electrical circuit containing MOSFET blocks. When using a continuous model, the ode23tb solver with a relative tolerance of  $1e-4$  is recommended for best accuracy and simulation speed.

The inductance  $L_{on}$  is forced to 0 if you choose to discretize your circuit.

## Example

The power\_mosconv demo illustrates the use of the MOSFET block in a zero-current quasi-resonant switch converter. In such a converter, the current produced by the Lr-Cr resonant circuit flows through the MOSFET and internal diode. The negative current flows through the internal diode that turns off at 0 current [1]. The switching frequency is 2 MHz and the pulse width is 72 degrees (duty cycle: 20%).

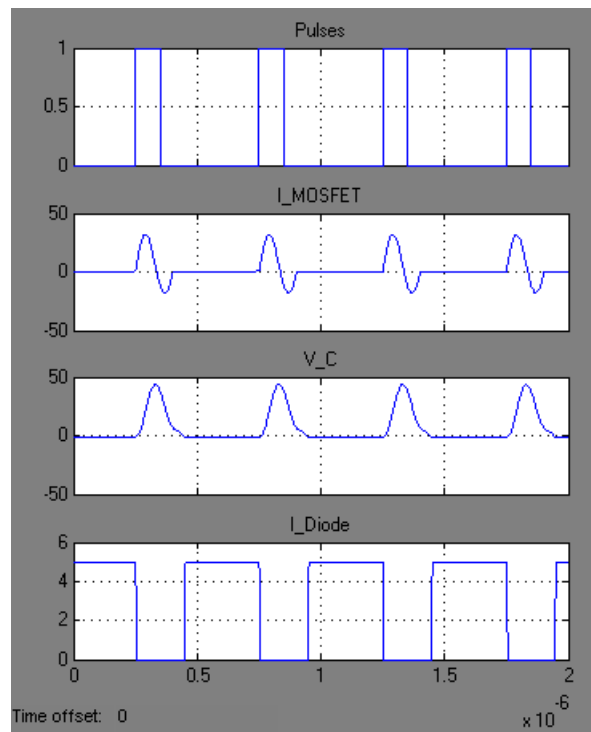
## MOSFET Converter



Run the simulation and observe the gate pulse signal, the MOSFET current, the capacitor voltage, and the diode current on the four-trace Scope block.

# MOSFET

---



## References

[1] Mohan, N., T.M. Undeland, and W.P. Robbins, *Power Electronics: Converters, Applications, and Design*, John Wiley & Sons, Inc., New York, 1995.

## See Also

Diode, GTO, Ideal Switch, Three-Level Bridge, Thyristor, Universal Bridge



# Multiband Power System Stabilizer

## Purpose

Implement multiband power system stabilizer

## Library

Machines

## Description



The disturbances occurring in a power system induce electromechanical oscillations of the electrical generators. These oscillations, also called power swings, must be effectively damped to maintain the system's stability. Electromechanical oscillations can be classified in four main categories:

- Local oscillations: between a unit and the rest of the generating station and between the latter and the rest of the power system. Their frequencies typically range from 0.8 to 4.0 Hz.
- Interplant oscillations: between two electrically close generation plants. Frequencies can vary from 1 to 2 Hz.
- Interarea oscillations: between two major groups of generation plants. Frequencies are typically in a range of 0.2 to 0.8 Hz.
- Global oscillation: characterized by a common in-phase oscillation of all generators as found on an isolated system. The frequency of such a global mode is typically under 0.2 Hz.

The need for effective damping of such a wide range, almost two decades, of electromechanical oscillations motivated the concept of the multiband power system stabilizer (MB-PSS).

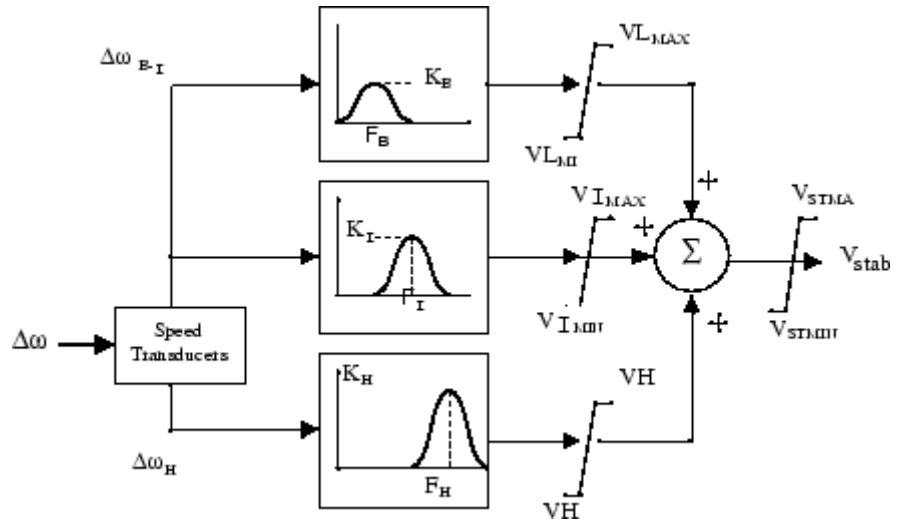
As its name reveals, the MB-PSS structure is based on multiple working bands. Three separate bands are used, respectively dedicated to the low-, intermediate-, and high-frequency modes of oscillations: the low band is typically associated with the power system global mode, the intermediate with the interarea modes, and the high with the local modes.

Each of the three bands is made of a differential bandpass filter, a gain, and a limiter (see the figure called Conceptual Representation on page 2-302). The outputs of the three bands are summed and passed through a final limiter producing the stabilizer output  $V_{stab}$ . This signal

# Multiband Power System Stabilizer

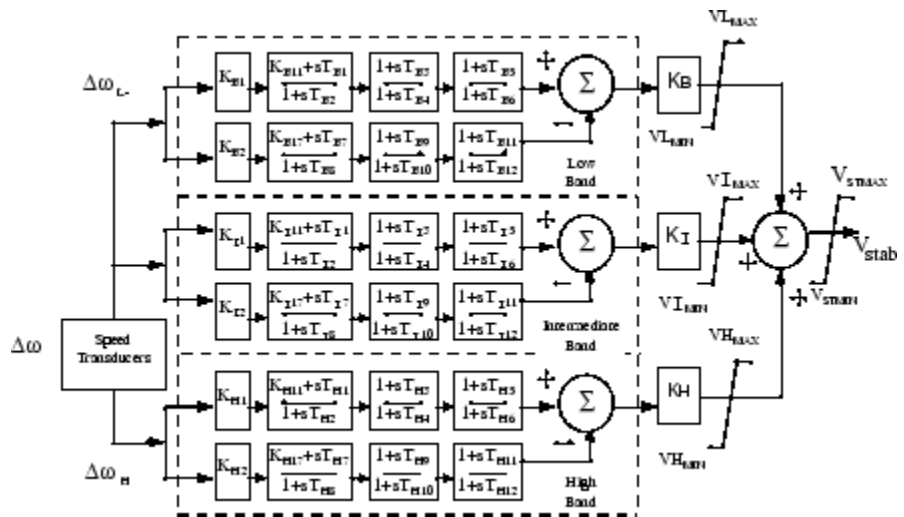
then modulates the set point of the generator voltage regulator so as to improve the damping of the electromechanical oscillations.

To ensure robust damping, the MB-PSS should include a moderate phase advance at all frequencies of interest to compensate for the inherent lag between the field excitation and the electrical torque induced by the MB-PSS action.



**Conceptual Representation**

# Multiband Power System Stabilizer



## Internal Specifications

The MB-PSS is represented by the IEEE St. 421.5 PSS 4B type model [2], illustrated in the figure called Internal Specifications on page 2-303, with built-in speed transducers whose parameters are fixed according to manufacturer's specifications.

Generally, only a few of the lead-lag blocks in this figure should be used in a given PSS application. Two different approaches are available to configure the settings in order to facilitate the tuning process:

### 1 Simplified settings:

Only the first lead-lag block of each frequency band is used to tune the Multiband Power System Stabilizer block. The differential filters are assumed to be symmetrical bandpass filters respectively tuned at the center frequency  $F_L$ ,  $F_I$ , and  $F_H$ . The peak magnitude of the frequency responses (see the figure called Conceptual Representation on page 2-302) can be adjusted independently through the three gains  $K_L$ ,  $K_I$ , and  $K_H$ . Only six parameters are therefore required for a simplified tuning of the MB-PSS.

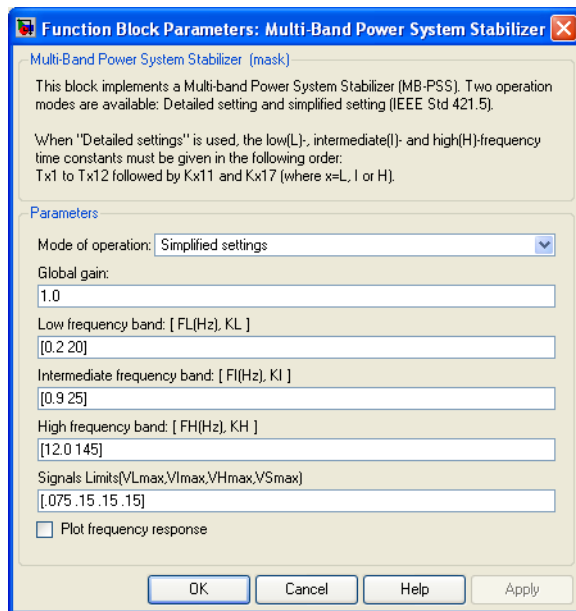
# Multiband Power System Stabilizer

## 2 Detailed settings:

The designer is free to use all the flexibility built into the MB-PSS structure to achieve nontrivial controller schemes and to tackle even the most constrained problem (for example, multi unit plant including an intermachine mode, in addition to a local mode and multiple interarea modes). In this case, all the time constants and gains appearing in the figure called Internal Specifications on page 2-303 have to be specified in the dialog box.

## Dialog Box and Parameters

### Simplified Settings Mode



### Global gain

The overall gain  $K$  of the multiband power system stabilizer.

# Multiband Power System Stabilizer

---

**Low frequency band: [FL KL]**

The center frequency, in hertz, and peak gain of the low-frequency bandpass filter.

**Intermediate frequency band: [FI KI]**

The center frequency, in hertz, and peak gain of the intermediate-frequency bandpass filter.

**High frequency band: [FH KH]**

The center frequency, in hertz, and peak gain of the high-frequency bandpass filter.

**Signal limits [VLmax VImax VHmax VSmax]**

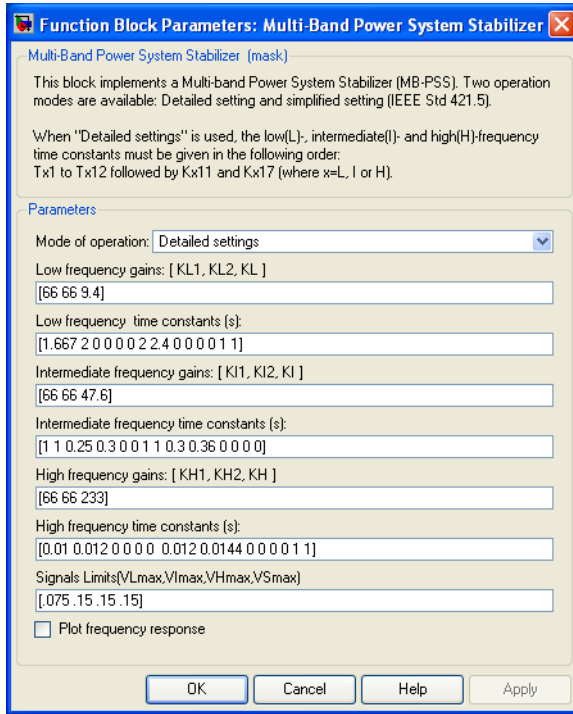
The limits imposed on the output of the low-, intermediate-, and high-frequency bands and the limit VSmax imposed on the output of the stabilizer, all in pu.

**Plot frequency response**

If selected, a plot of the frequency response of the stabilizer is displayed when you click the **Apply** button.

# Multiband Power System Stabilizer

## Detailed Settings Mode



### Low frequency gains: [KL1 KL2 KL]

The gains of the positive and negative branches of the differential filter in the low-frequency band and the overall gain  $K_L$  of the low-frequency band, in pu.

### Low frequency time constants

The time constants, in seconds, of the lead-lag blocks in the positive and negative branches of the low-frequency filter. You need to specify the following twelve time constants and two gains:

$$[T_{B1} T_{B2} T_{B3} T_{B4} T_{B5} T_{B6} T_{B7} T_{B8} T_{B9} T_{B10} T_{B11} T_{B12} K_{B11} K_{B17}]$$

# Multiband Power System Stabilizer

---

Set  $K_{B11}$  to 0 in order to make the first block of the positive filter branch a washout block. Set  $K_{B11}$  to 1 in order to make the block a lead-lag block.

Set  $K_{B17}$  to 0 in order to make the first block of the negative filter branch a washout block. Set  $K_{B17}$  to 1 in order to make the block a lead-lag block.

## **Intermediate frequency gains: [KI1 KI2 KI]**

The gains of the positive and negative branches of the differential filter in the intermediate-frequency band and the overall gain  $K_I$  of the intermediate-frequency band, in pu.

## **Intermediate frequency time constants**

The time constants, in seconds, of the lead-lag blocks in the positive and negative branches of the intermediate-frequency filter. You need to specify the following twelve time constants and two gains:

[ $T_{I1}$   $T_{I2}$   $T_{I3}$   $T_{I4}$   $T_{I5}$   $T_{I6}$   $T_{I7}$   $T_{I8}$   $T_{I9}$   $T_{I10}$   $T_{I11}$   $T_{I12}$   $K_{I11}$   $K_{I17}$ ]

Set  $K_{I11}$  to 0 in order to make the first block of the positive filter branch a washout block. Set  $K_{I11}$  to 1 in order to make the block a lead-lag block.

Set  $K_{I17}$  to 0 in order to make the first block of the negative filter branch a washout block. Set  $K_{I17}$  to 1 in order to make the block a lead-lag block.

## **High frequency gains: [KH1 KH2 KH]**

The gains of the positive and negative branches of the differential filter in the high-frequency band and the overall gain  $K_I$  of the high-frequency band, in pu.

## **High frequency time constants**

The time constants, in seconds, of the lead-lag blocks in the positive and negative branches of the high-frequency filter. You need to specify the following twelve time constants and two gains:

# Multiband Power System Stabilizer

---

[ $T_{H1}$   $T_{H2}$   $T_{H3}$   $T_{H4}$   $T_{H5}$   $T_{H6}$   $T_{H7}$   $T_{H8}$   $T_{H9}$   $T_{H10}$   $T_{H11}$   $T_{H12}$   $K_{H11}$   $K_{H17}$ ]

Set  $K_{H11}$  to 0 in order to make the first block of the positive filter branch a washout block. Set  $K_{H11}$  to 1 in order to make the block a lead-lag block.

Set  $K_{H17}$  to 0 in order to make the first block of the negative filter branch a washout block. Set  $K_{H17}$  to 1 in order to make the block a lead-lag block.

## Signal limits [VLmax VImax VHmax VSmax]

The limits imposed on the output of the low-, intermediate-, and high-frequency bands and the limit VSmax imposed on the output of the stabilizer, all in pu.

## Plot frequency response

If selected, a plot of the frequency response of the stabilizer is displayed when you click the **Apply** button.

## Input and Output

dw

Connect to the first input the synchronous machine speed deviation *dw* signal (in pu).

Vstab

The output is the stabilization voltage, in pu, to connect to the vstab input of the Excitation System block used to control the terminal voltage of the block.

## Example

See the help text of the power\_PSS demo model.

## References

[1] Grondin, R., I. Kamwa, L. Soulieres, J. Potvin, and R. Champagne, "An approach to PSS design for transient stability improvement through supplementary damping of the common low frequency," *IEEE Transactions on Power Systems*, 8(3), August 1993, pp. 954-963.

[2] IEEE recommended practice for excitation system models for power system stability studies: *IEEE St. 421.5-2002*(Section 9).



# Multiband Power System Stabilizer

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**See Also**      Generic Power System Stabilizer

# Multimeter

**Purpose** Measure voltages and currents specified in dialog boxes of SimPowerSystems blocks

**Library** Measurements

**Description** The Multimeter block is used to measure voltages and currents of the measurements described by the dialog boxes of SimPowerSystems blocks.



The **powerlib** blocks listed in the following table have a special parameter (**Measurements**) that allows you to measure voltages or currents related to the block. Choosing voltages or currents through this measurement parameter is equivalent to connecting an internal voltage or current measurement block inside your blocks. The measured signals can be observed through a Multimeter block placed in your circuit.

Drag the Multimeter block into the top-level system of your circuit and double-click the icon to open the dialog box.

Block Name	Block Name
AC Current Source	PI Section Line
AC Voltage Source	Saturable Transformer
Breaker	Series RLC Branch
Controlled Current Source	Series RLC Load
Controlled Voltage Source	Surge Arrester
DC Voltage Source	Three-Level Bridge
Distributed Parameter Line	Three-Phase Harmonic Filter
Linear Transformer	Three-Phase Load (Series and Parallel)
Multi-Winding Transformer	Three-Phase Branch (Series and Parallel)

Block Name	Block Name
Mutual Inductance	Three-Phase Transformer (Two and Three Windings)
Parallel RLC Branch	Universal Bridge
Parallel RLC Load	Zigzag Phase-Shifting Transformer

## Sign Conventions for Voltages and Currents

When you measure a current using a Current Measurement block, the positive direction of current is indicated on the block icon (positive current flowing from + terminal to – terminal). Similarly, when you measure a voltage using a Voltage Measurement block, the measured voltage is the voltage of the + terminal with respect to the – terminal. However, when voltages and currents of blocks from the Elements library are measured using the Multimeter block, the voltage and current polarities are not immediately obvious because blocks might have been rotated and there are no signs indicating polarities on the block icons.

Unlike Simulink signal lines and input and output ports, the Physical Modeling connection lines and terminal ports  $\square$  lack intrinsic directionality. The voltage and current polarities are determined, not by line direction, but instead by block orientation. To find out a block orientation, first click the block to select it. Then enter the following command:

```
get_param(gcf, 'Orientation')
```

The following table indicates the polarities of the currents and voltages measured with the Multimeter block for single-phase and three-phase RLC elements (branches or loads), surge arresters, and single-phase and three-phase breakers. The table also indicates the polarities of their state variables (inductor currents and capacitor voltages).

# Multimeter

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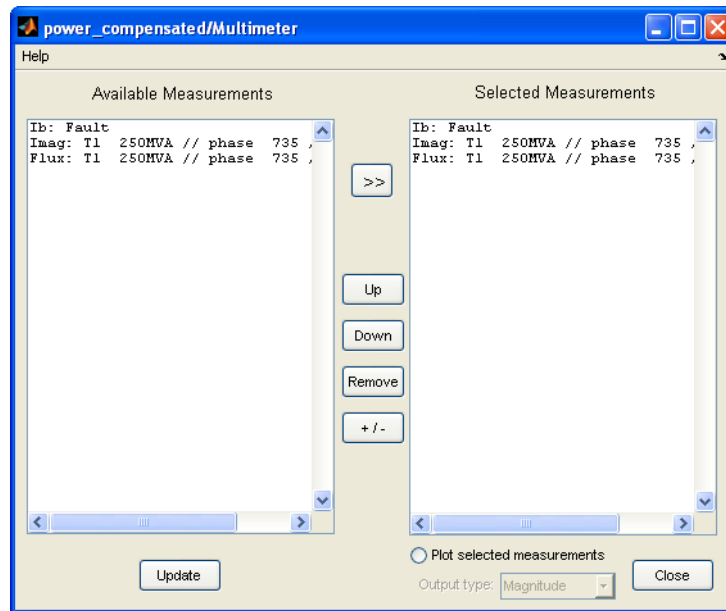
<b>Block Orientation</b>	<b>Positive Current Direction</b>	<b>Measured Voltage</b>
right	left → right	$V_{\text{left}} - V_{\text{right}}$
left	right → left	$V_{\text{right}} - V_{\text{left}}$
down	top → bottom	$V_{\text{top}} - V_{\text{bottom}}$
up	bottom → top	$V_{\text{bottom}} - V_{\text{top}}$

The natural orientation of the blocks (that is, their orientation in the Element library) is *right* for horizontal blocks and *down* for vertical blocks.

For single-phase transformers (linear or saturable), with the winding connectors appearing on the left and right sides, the winding voltages are the voltages of the top connector with respect to the bottom connector whatever the block orientation (*right* or *left*). The winding currents are the currents entering the top connector.

For three-phase transformers, the voltage polarities and positive current directions are indicated by the signal labels used in the Multimeter block. For example,  $U_{\text{an\_w2}}$  = phase A-to-neutral voltage of the Y connected winding #2,  $I_{\text{ab\_w1}}$  = winding current flowing from A to B in the delta-connected winding #1.

## Dialog Box and Parameters



### Available Measurements

The **Available Measurements** list box shows the measurements in the Multimeter block. Use the >> button to select measurements from the **Available Measurements** list box. Click the **Update** button to refresh the list of available measurements in the Multimeter block.

The measurements in the list box are identified by the name of the block where the measurement is done. The type of measurement (voltage measurement, current measurement, or flux) is defined by a label preceding the block name. See the reference sections of blocks listed in the previous table for a description of these measurements.

### Selected Measurements

The **Selected Measurements** list box shows the measurements sent to the output of the block. You can reorder the measurements

# Multimeter

---

by using the **Up**, **Down**, and **Remove** buttons. The **+/-** button allows you to reverse the polarity of any selected measurement.

## Plot selected measurements

If selected, displays a plot of selected measurements using a MATLAB® figure window. The plot is generated when the simulation stops.

## Output type

Specifies the format of the output signals when the block is used in a phasor simulation. The **Output signal** parameter is disabled when the block is not used in a phasor simulation. The phasor simulation is activated by a Powergui block placed in the model.

Set to **Complex** to output the selected measurements as complex values. The outputs are complex signals.

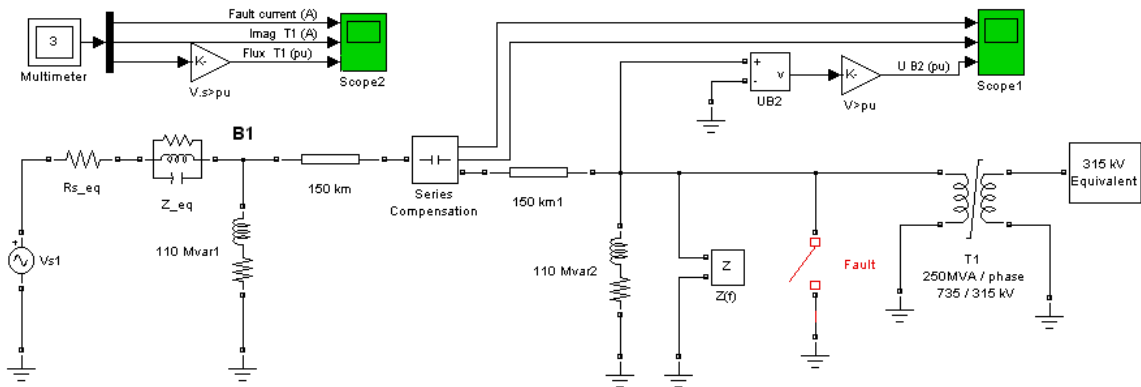
Set to **Real-Imag** to output the real and imaginary parts of the measurements. For each selected measurement, the multimeter outputs the real and imaginary parts.

Set to **Magnitude-Angle** to output the magnitude and angle of the selected measurements. For each selected measurement, the multimeter outputs the magnitude and angle values.

Set to **Magnitude** to output the magnitude of the selected measurements.

## Example

The `power_compensated` demo uses a Multimeter block to measure the voltage across the secondary winding of a Saturable Transformer block and the currents flowing through two Series RLC Load blocks.



A Multimeter block is dragged into the model. In the dialog box of the 250 MVA block, set the **Measurements** parameter to All measurements (V, I, flux). In the 110 Mvar1 block, set it to Branch voltage and in the 110 Mvar2 block, set it to Branch voltage and current.

The output of the Multimeter block is connected to a Scope block in order to display the measurements during the simulation. In addition, you can select the **Plot selected measurements** parameter to display a plot of selected measurements when simulation stops.

Open the Multimeter block dialog box and select the signals you want to observe, as shown on the Dialog Box and Parameters section. Notice the labels used to define the available measurements in the Multimeter block. See the reference section of the Saturable Transformer block and Series RLC Load block for a description of these labels.

Start the simulation. After 0.4 seconds, the simulation stops and a MATLAB figure window opens to display the selected measurements in the Multimeter block.

## See Also

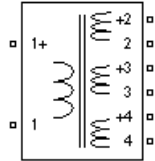
Current Measurement, Voltage Measurement

# Multi-Winding Transformer

**Purpose** Implement multi-winding transformer with taps

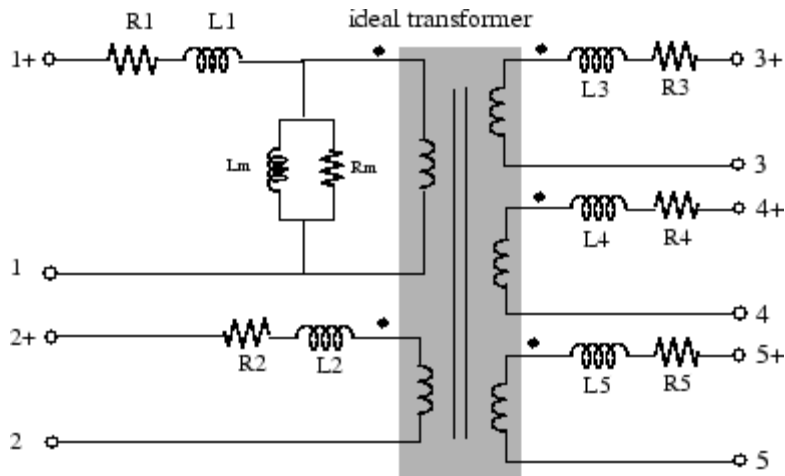
**Library** Elements

**Description** The Multi-Winding Transformer block implements a transformer where the number of windings can be specified for both the primary (left side windings) and the secondary (right side windings).



The equivalent circuit of the Multi-Winding Transformer block is similar to the one of the Linear Transformer block and the saturation characteristic of the core can be specified or not. See the Saturable Transformer block reference pages for more details on how the saturation and the hysteresis characteristic are implemented.

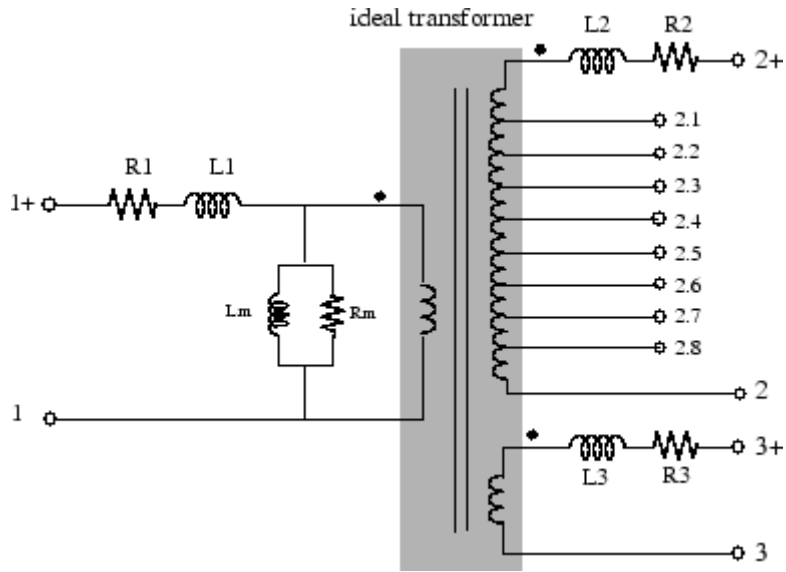
The equivalent circuit of a Multi-Windings Transformer block with two primary windings and three secondary windings is shown in the next figure.



You can add equally spaced taps to the first primary winding (the upper-left winding) or to the first secondary winding (the upper-right winding). The equivalent circuit of a Multi-Winding Transformer block with one primary winding and eight taps on the first of the two secondary windings is shown in the next figure.



# Multi-Winding Transformer



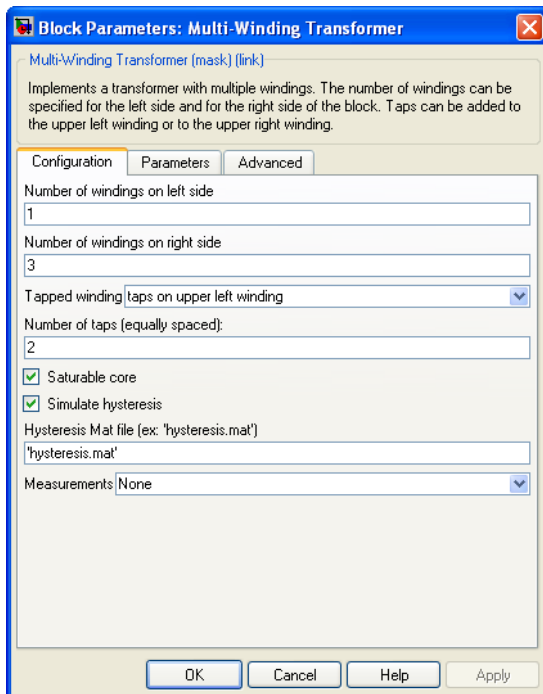
The winding terminals are identified by the corresponding winding number. The first winding is the first one on the primary side (upper-left side) and the last winding is the last one on the secondary side (bottom-right side). The polarity of the windings are defined by a plus sign.

The tap terminals are identified by their winding number followed by a dot character and the tap number. Taps are equally spaced so that voltage appearing at no load between two consecutive taps is equal to the total voltage of the winding divided by (number of taps +1). The total winding resistance and leakage inductance of a tapped winding is equally distributed along the taps.

# Multi-Winding Transformer

## Dialog Box and Parameters

### Configuration Tab



#### Number of windings on left side

Specifies the number of windings on the primary side (left side) of the transformer.

#### Number of windings on right side

Specifies the number of windings on the secondary side (right side) of the transformer.

#### Tapped winding

Select no taps if you don't want to add taps to the transformer. Select taps on upper left winding to add taps to the first winding on the primary side of the transformer. Select taps on upper right winding to add taps to the secondary winding on

the right side of the transformer. The number of taps is specified by the **Number of taps (equally spaced)** parameter.

### **Number of taps (equally spaced)**

This parameter is not visible if the **Tapped winding** parameter is set to no taps.

If the **Tapped winding** parameter is set to taps on upper left winding, you specify the number of taps to add to the first winding on the left side.

If the **Tapped winding** parameter is set to taps on upper right windings, you specify the number of taps to add to the first winding on the right side.

### **Saturable core**

If selected, implements a saturable transformer. See also the **Saturation characteristic** parameter on the Parameters tab.

### **Simulate hysteresis**

Select to model hysteresis saturation characteristic instead of a single-valued saturation curve. This parameter is visible only if the **Saturable core** parameter is selected.

### **Hysteresis Mat file**

The **Hysteresis Mat file** parameter is visible only if the **Simulate hysteresis** parameter is selected.

Specify a **.mat** file containing the data to be used for the hysteresis model. When you open the **Hysteresis Design Tool** of the Powergui, the default hysteresis loop and parameters saved in the **hysteresis.mat** file are displayed. Use the **Load** button of the Hysteresis Design tool to load another **.mat** file. Use the **Save** button of the Hysteresis Design tool to save your model in a new **.mat** file.

### **Measurements**

Select **Winding voltages** to measure the voltage across the winding terminals of the Saturable Transformer block.

# Multi-Winding Transformer

---

Select **Winding currents** to measure the current flowing through the windings of the Saturable Transformer block.

Select **Flux and excitation current ( $I_m + I_{Rm}$ )** to measure the flux linkage, in volt seconds (V.s), and the total excitation current including iron losses modeled by  $R_m$ .

Select **Flux and magnetization current ( $I_m$ )** to measure the flux linkage, in volt seconds (V.s), and the magnetization current, in amperes (A), not including iron losses modeled by  $R_m$ .

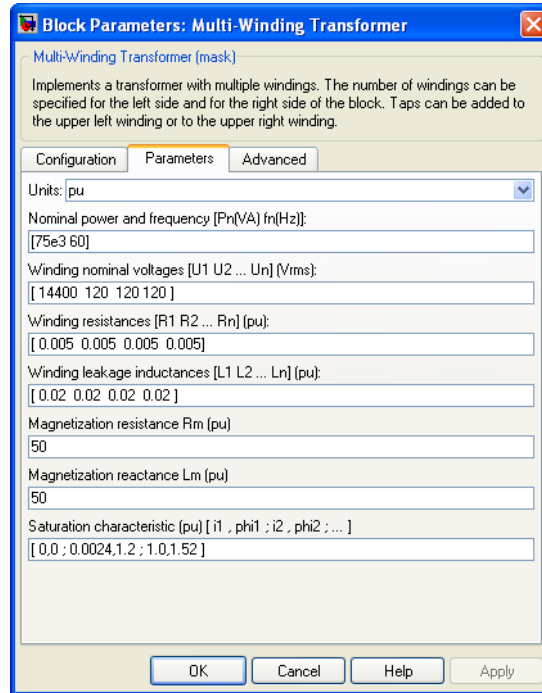
Select **All measurement (V, I, Flux)** to measure the winding voltages, currents, magnetization currents, and the flux linkage.

Place a Multimeter block in your model to display the selected measurements during the simulation.

In the **Available Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name.

<b>Measurement</b>	<b>Label</b>
Winding voltages	U_LeftWinding_1:, U_TapWinding_2.1:, U_RightWinding_1:, etc.
Winding currents	I_LeftWinding_1:, I_TapWinding_2.1:, I_RightWinding_1:, etc.
Excitation current	Iexc:
Magnetization current	Imag:
Flux linkage	Flux:

## Parameters Tab



### Units

Specify the units used to enter the parameters of the Multi-Winding Transformer block. Select pu to use per unit. Select SI to use SI units. Changing the **Units** parameter from pu to SI, or from SI to pu, will automatically convert the parameters displayed in the mask of the block.

### Nominal power and frequency

The nominal power rating, in volt-amperes (VA), and nominal frequency, in hertz (Hz), of the transformer.

# Multi-Winding Transformer

---

## Winding nominal voltages

Specify a vector containing the nominal RMS voltages, in  $V_{rms}$ , of the windings on the left side, followed by the nominal RMS voltages of the windings on the right side. You don't have to specify the individual tap nominal voltages.

## Winding resistances

Specify a vector containing the resistance values of the windings on the left side, followed by the resistance values of the windings on the right side. You don't have to specify the individual tap resistances.

## Winding leakage inductances

Specify a vector containing the leakage inductance values of the windings on the left side, followed by the leakage inductance values of windings on the right side. You don't have to specify the individual tap leakage inductances.

## Magnetization resistance $R_m$

The magnetization resistance  $R_m$ , in ohms or in pu.

## Magnetization reactance $L_m$

The **Magnetization reactance  $L_m$**  parameter is not accessible if the **Saturable core** parameter on the Configuration tab is selected.

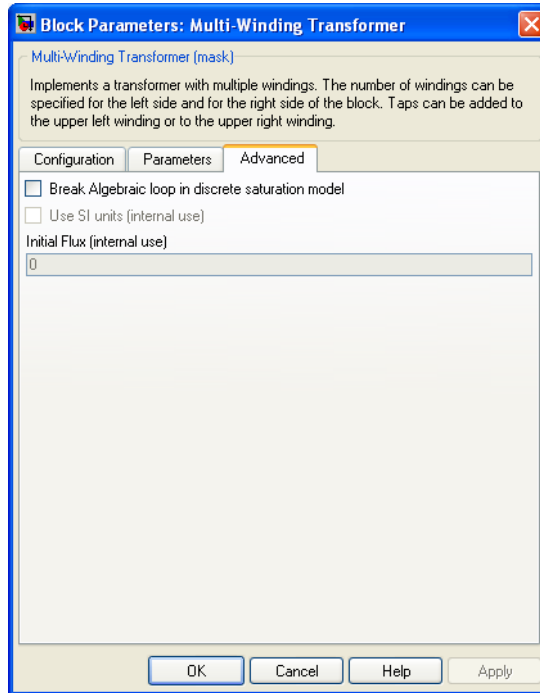
The magnetization inductance  $L_m$ , in Henry or in pu, for a nonsaturable core.

## Saturation characteristic

This parameter is accessible only if the **Saturable core** parameter on the Configuration tab is selected.

The saturation characteristic for the saturable core. Specify a series of current/ flux pairs (in pu) starting with the pair (0,0).

## Advanced Tab



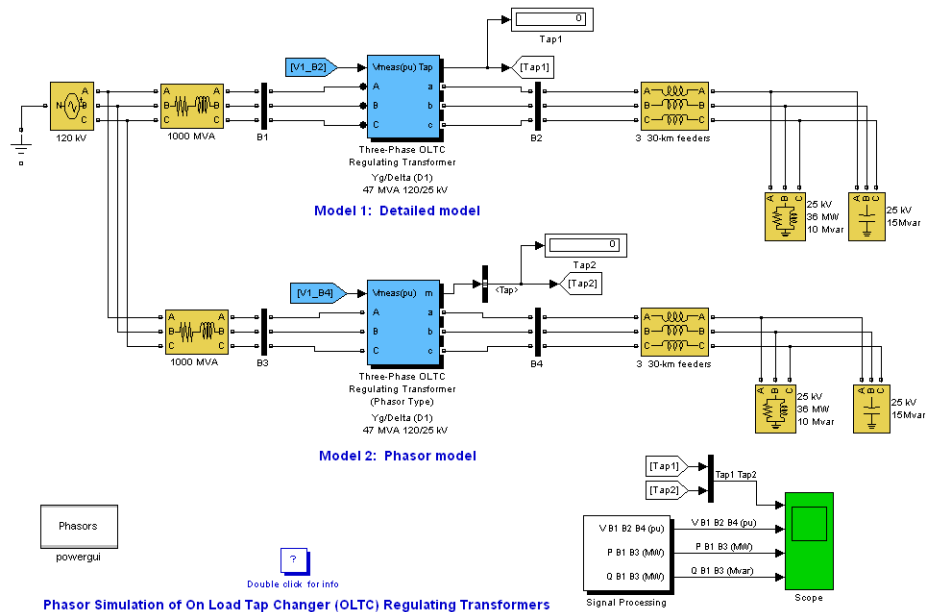
### Break Algebraic loop in discrete saturation model

When you use the block in a discrete system, you will get an algebraic loop. This algebraic loop, which is required in most cases to get an accurate solution, tends to slow down the simulation. However, to speed up the simulation, in some circumstances, you can disable the algebraic loop by selecting **Break Algebraic loop in discrete saturation model**. You should be aware that disabling the algebraic loop introduces a one-simulation-step time delay in the model. This can cause numerical oscillations if the sample time is too large.

# Multi-Winding Transformer

## Example

The power\_OLTCregtransformer demo uses three Multi-Winding Transformer blocks to implement a three-phase On Load Tap Changer (OLTC) transformer. Because of long simulation times required for illustrating operation of the tap changer (simulation time is set to 120 s), the demo uses the Phasor simulation method.



## Phasor Simulation of On Load Tap Changer (OLTC) Regulating Transformers

A 25 kV distribution network consisting of three 30-km distribution feeders connected in parallel supplies power to a 36 MW /10 Mvar load (0.964 PF lagging) from a 120 kV, 1000 MVA system and a 120kV/25 kV OLTC regulating transformer. The OLTC transformer is used to regulate system voltage at the 25 kV bus.

The same circuit is duplicated to compare the performance of two different models of OLTC transformers:



- Model 1 is a detailed model where all OLTC switches and transformer windings are represented. This model uses three Multi-Winding Transformer blocks to implement a three-phase regulating transformer, with the OLTC connected on the high voltage side (120 kV). This model can be used with either continuous or discrete solvers to get detailed waveshapes or with the phasor simulation method (as in the present demo) to observe variations of phasor voltages and currents.
- Model 2 is a simplified phasor model where the transformer and OLTC are simulated by current sources. This model can be used only with the phasor solution method. It is faster to execute and it should be the preferred model for transient stability studies, when several such devices are used in the same system.

Both OLTC transformer models implement a three-phase regulating transformer rated 47 MVA, 120 kV/25 kV, Y/ Delta, with the OLTC connected on the high voltage side (120 kV).

Select the Model 1 transformer block and use the **Edit/Look\_under mask** menu to see how the regulating transformer is implemented. The OLTC transformer model is built from three Multi-Winding Transformer blocks. Each phase consists of two main windings (winding 2 = 120 kV and winding 3 = 25 kV) and one regulation winding (tapped winding 1). The seven taps of the regulation winding allow eight steps of voltage variation either in positive or negative direction. Three OLTC subsystems contain switches performing tap selection and reversal of the regulation winding.

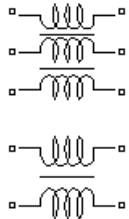
Run the demo. Double-click the Double click for info block to get details.

# Mutual Inductance

**Purpose** Implement inductances with mutual coupling

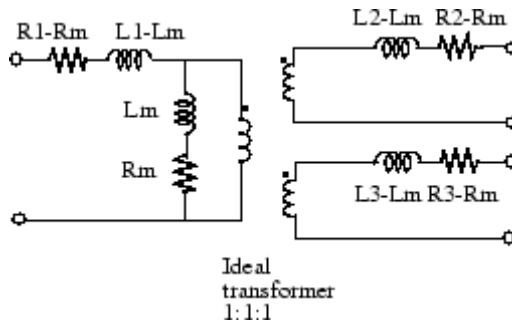
**Library** Elements

## Description



The Mutual Inductance block can be used to model two- or three-windings inductances with equal mutual coupling, or to model a generalized multi-windings mutual inductance with balanced or unbalanced mutual coupling.

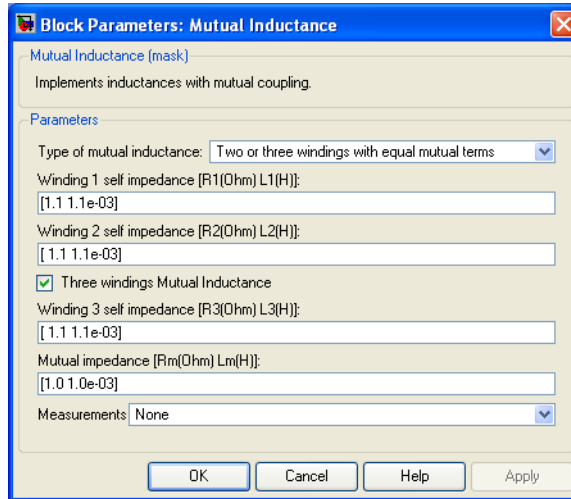
If you choose to model two- or three-windings inductances with equal mutual coupling, you specify the self-resistance and inductance of each winding plus the mutual resistance and inductance. The electrical model for this block in this case is given below:



If you choose to model a general mutual inductance, you need to specify the number of self windings (not just limited to 2 or 3 windings) plus the Resistance and Inductance matrices that define the mutual coupling relationship between the windings (balanced or not).

## Dialog Box and Parameters

### Two or three windings inductances with equal mutual coupling:



#### Type of mutual inductance

Set to **Two or Three windings with equal mutual terms** to implement a three-phase mutual inductance with equal mutual coupling between the windings

#### Winding 1 self impedance

The self-resistance and inductance for winding 1, in ohms ( $\Omega$ ) and henries (H).

#### Winding 2 self impedance

The self-resistance and inductance for winding 2, in ohms ( $\Omega$ ) and henries (H).

#### Three windings Mutual Inductance

If selected, implements three coupled windings; otherwise, it implements two coupled windings.

# Mutual Inductance

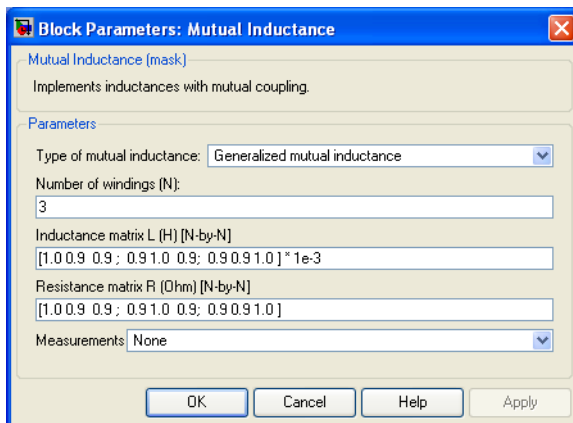
## Winding 3 self impedance

The **Winding 3 self impedance** parameter is not available if the **Three windings Mutual Inductance** parameter is not selected. The self-resistance and inductance in ohms ( $\Omega$ ) and henries (H) for winding 3.

## Mutual impedance

The mutual resistance and inductance between windings, in ohms ( $\Omega$ ) and henries (H). The mutual resistance and inductance corresponds to the magnetizing resistance and inductance on the standard transformer circuit diagram. If the mutual resistance and reactance are set to [0 0], the block implements three separate inductances with no mutual coupling.

## Generalized mutual inductance:



## Type of mutual inductance

Set to **Generalized mutual inductance** to implement a multi windings mutual inductance with mutual coupling defined by an inductance and a resistance matrix.

## Number of windings

The number of self inductances.

## Inductance matrix **L**

The inductance matrix, in Henrys, that define the mutual coupling relationship between the self windings. It must be a N-by-N symmetrical matrix.

## Resistance matrix **R**

The resistance matrix, in ohms, that define the mutual coupling relationship between the self windings. It must be a N-by-N symmetrical matrix.

## Measurements

Select Winding voltages to measure the voltage across the winding terminals.

Select Winding currents to measure the current flowing through the windings.

Select Winding voltages and currents to measure the winding voltages and currents.

Place a Multimeter block in your model to display the selected measurements during the simulation.

In the **Available Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name.

Measurement	Label
Winding voltages	Uw1 : , Uw2 : , Uw3 :
Winding currents	Iw1 : , Iw2 : , Iw3 :

## Limitations

If you choose to model two or three windings inductances with equal mutual coupling , the following restrictions apply:

$$R_1, R_2, \dots, R_N \neq R_m$$

$$L_1, L_2, \dots, L_N \neq L_m$$

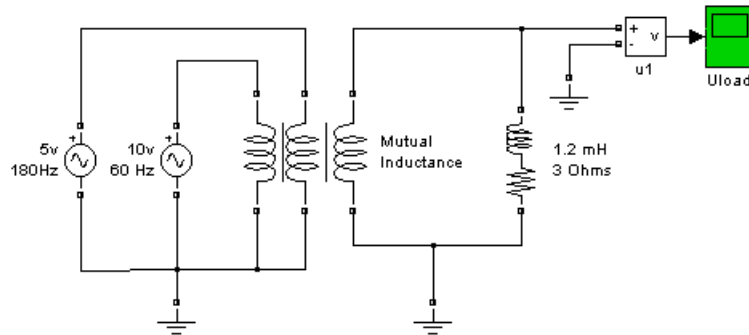
# Mutual Inductance

Negative values are allowed for the self- and mutual inductances as long as the self-inductances are different from the mutual inductance.

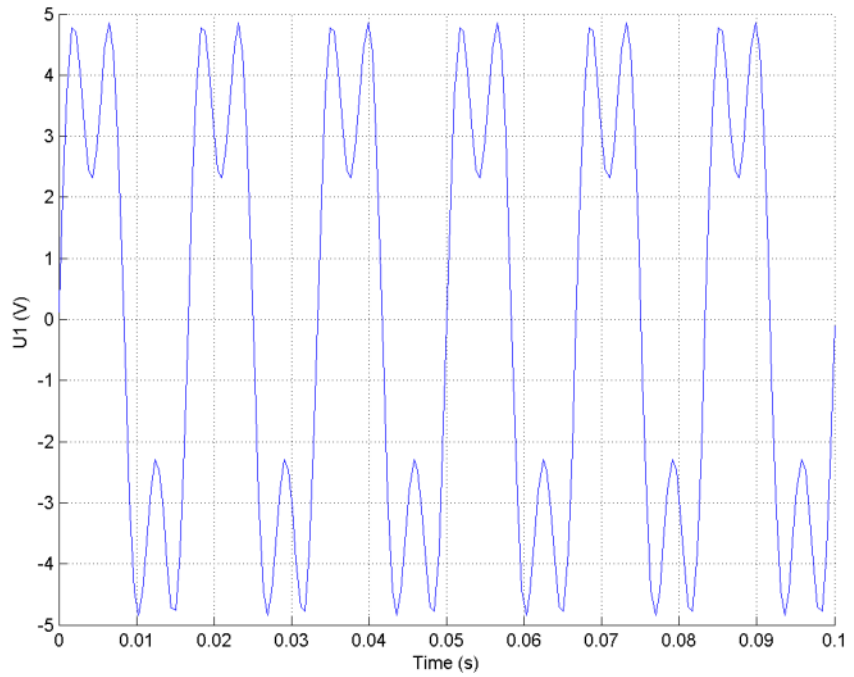
Windings can be left floating (not connected by an impedance to the rest of the circuit). However an internal resistor between the floating winding and the main circuit is automatically added. This internal connection does not affect voltage and current measurements.

## Example

The power\_mutual demo uses three coupled windings to inject a third harmonic voltage into a circuit fed at 60 Hz.



Simulation produces the following load voltage waveform:



## See Also

Linear Transformer, Saturable Transformer, Three-Phase Mutual Inductance Z1-Z0

# Neutral

---

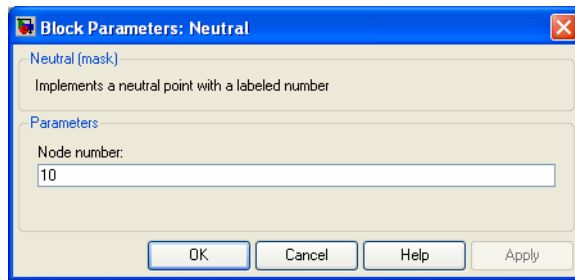
**Purpose** Implement common node in circuit

**Library** Elements

**Description** The Neutral block implements a common node with a specific node number. You can use this block to create a floating neutral or to interconnect two points without drawing a connection line.



## Dialog Box and Parameters

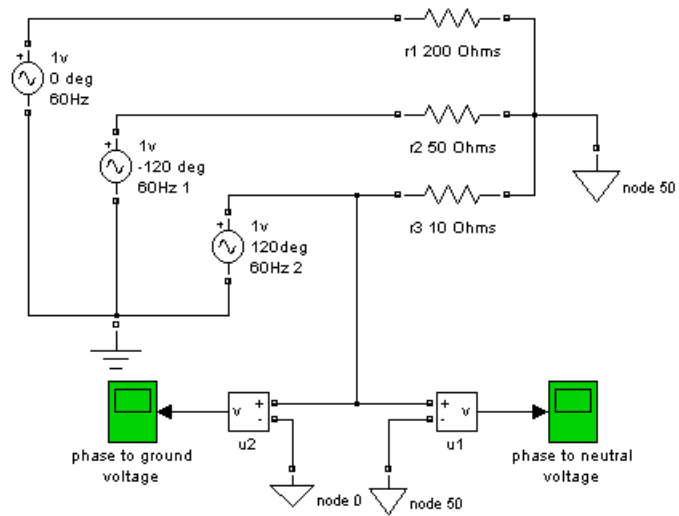


### Node number

Specify a number of the neutral node. If the **Node number** parameter is set to 0, the Neutral block makes a connection to ground. The node number is displayed next to the block icon.

**Example** The power\_neutral demo uses three Neutral blocks. One Neutral block is used to refer a Voltage Measurement block to the ground (node 0).





**See Also** Ground

# One-Quadrant Chopper DC Drive

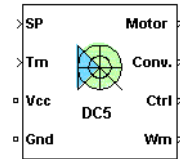
## Purpose

Implement one-quadrant chopper (buck converter topology) DC drive

## Library

Electric Drives/DC drives

## Description



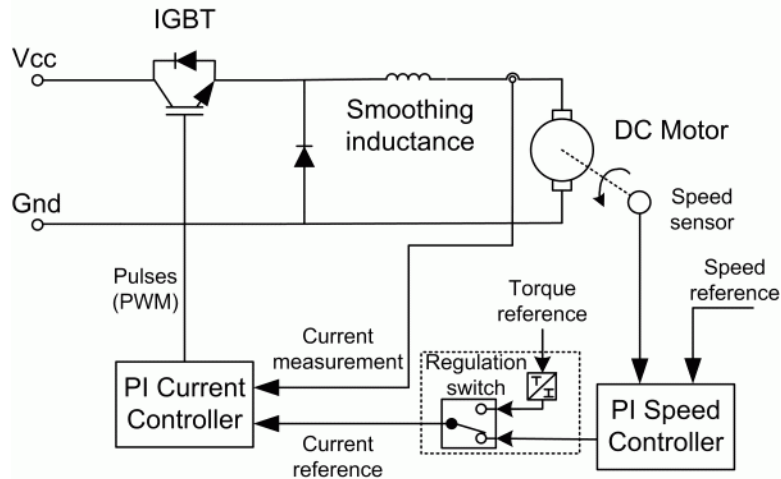
The high-level schematic shown below is built from four main blocks. The DC motor and the IGBT/Diode device (within the Universal Bridge block) are provided with the SimPowerSystems library. More details are available in the reference pages for these blocks. The two other blocks are specific to the Electric Drives library. These blocks are the speed controller and the current controller. They allow speed or torque regulation. A “regulation switch” block allows you to toggle from one type of regulation to the other. During torque regulation the speed controller is disabled. It is possible to use a simplified version of the drive containing an average-value model of the one-quadrant chopper and allowing faster simulation.

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**Note** In SimPowerSystems software, the One-Quadrant Chopper DC Drive block is commonly called the DC5 motor drive.

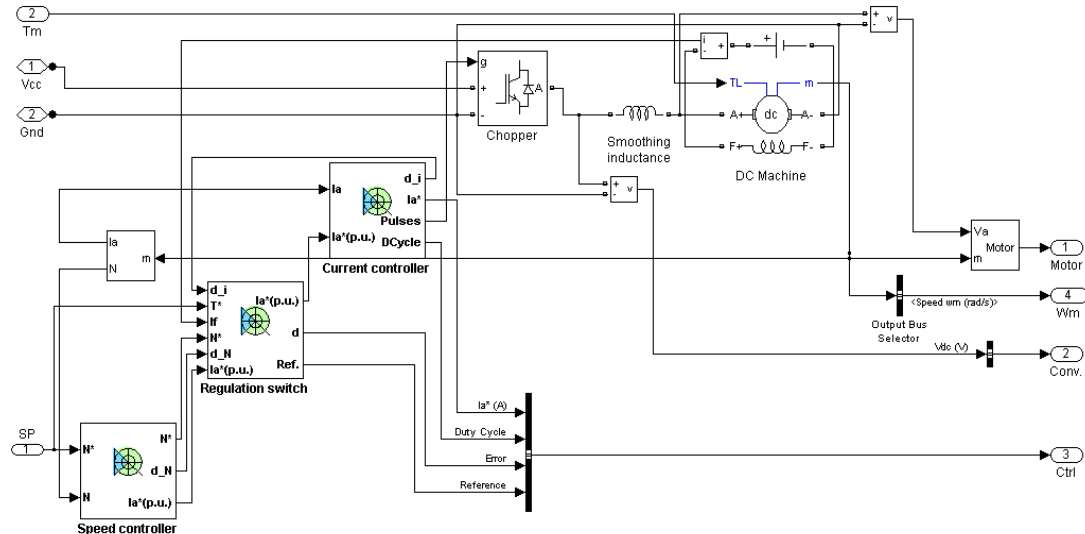
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## High-Level Schematic



# One-Quadrant Chopper DC Drive

## Simulink Schematic



## Speed Controller

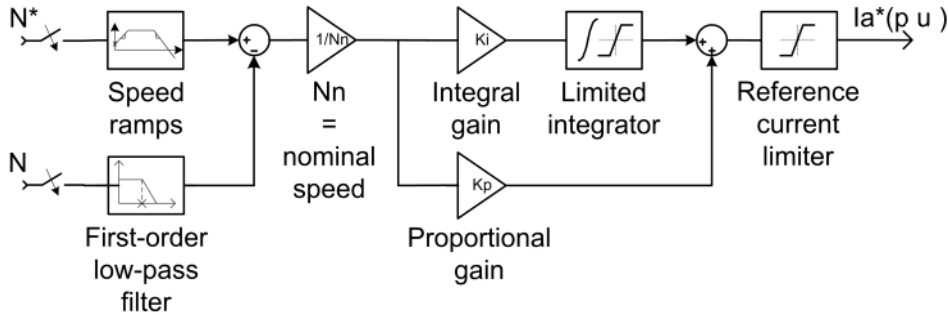
The speed regulator shown below uses a PI controller. The controller outputs the armature current reference (in pu) used by the current controller in order to obtain the electromagnetic torque needed to reach the desired speed. During torque regulation, the speed controller is disabled.

The controller takes the speed reference (in rpm) and the rotor speed of the DC machine as inputs. The speed reference change rate will follow user-defined acceleration and deceleration ramps in order to avoid sudden reference changes that could cause armature over-current and destabilize the system. In order to avoid negative speeds that could induce conduction of the free-wheeling diode, the speed reference has a lower limit of 0 rpm.

The speed measurement is filtered by a first-order low-pass filter.

# One-Quadrant Chopper DC Drive

The current reference output is limited between 0 pu and an upper limit defined by the user.



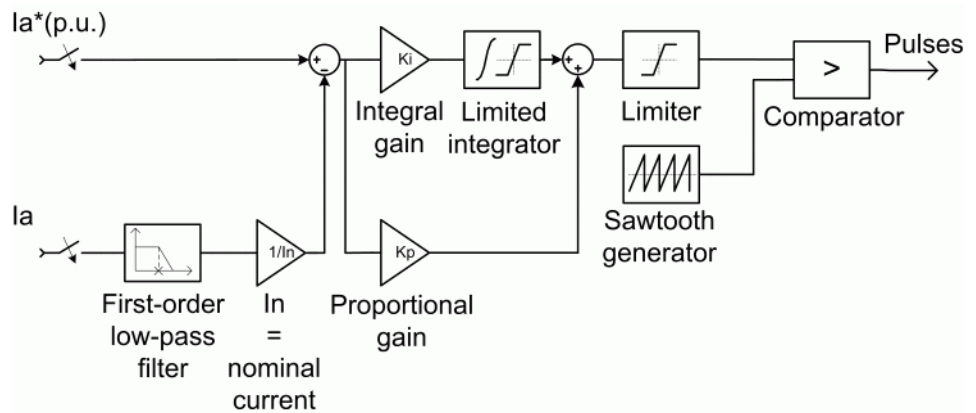
## Current Controller

The armature current regulator shown below is based on a second PI controller. The regulator controls the armature current by computing the appropriate duty ratio of the IGBT fixed frequency pulses (Pulse Width Modulation). This generates the average armature voltage needed to obtain the desired armature current and thus the desired electromagnetic torque.

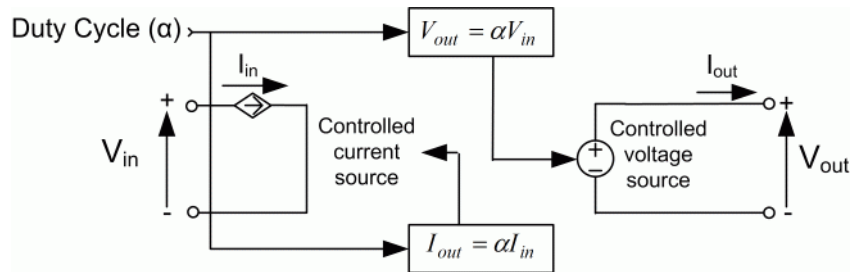
The controller takes the current reference (in pu) and the armature current flowing through the motor as inputs. The current reference is either provided by the speed controller during speed regulation or computed from the torque reference provided by the user during torque regulation. This is managed by the “regulation switch” block. The armature current input is filtered by a first-order low-pass filter.

The pulse width modulation is obtained by comparison of the PI output and a fixed frequency sawtooth carrier signal (see the figure called Pulse Width Modulation (PWM) on page 2-339).

# One-Quadrant Chopper DC Drive



**Average-Value One-Quadrant Chopper** The average-value converter is shown in the following figure.



It is composed of one controlled current source on the DC source side and one controlled voltage source on the motor side. The current source allows the representation of the average input current value following the next equations:

$$I_{in} = \alpha I_{out} \text{ when } I_{out} > 0$$

$$I_{in} = I_{out} \text{ when } I_{out} \leq 0$$

with  $\alpha$  being the firing angle value and  $I_{out}$  the armature current value. The voltage source on the motor side represents the average voltage value following the next equations :

# One-Quadrant Chopper DC Drive

---

$$V_{out} = \alpha V_{in} \text{ when } I_{out} > 0$$

$$V_{out} = V_{in} \text{ when } I_{out} \leq 0$$

with  $V_{in}$  being the input voltage.

## Remarks

The machine is separately excited with a constant DC field voltage source. There is thus no field voltage control. By default, the field current is set to its steady-state value when a simulation is started.

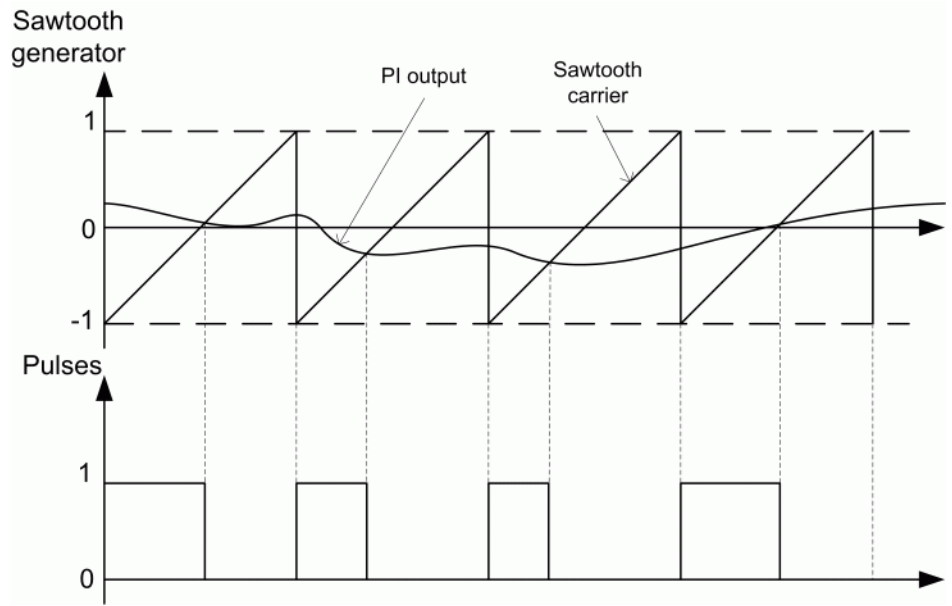
The armature voltage is provided by an IGBT buck converter controlled by two PI regulators. The buck converter is fed by a constant DC voltage source. Armature current oscillations are reduced by a smoothing inductance connected in series with the armature circuit.

The model is discrete. Good simulation results have been obtained with a 1  $\mu$ s time step. In order to simulate a digital controller device, the control system has two different sampling times:

- The speed controller sampling time
- The current controller sampling time

The speed controller sampling time has to be a multiple of the current sampling time. The latter sampling time has to be a multiple of the simulation time step.

# One-Quadrant Chopper DC Drive



**Pulse Width Modulation (PWM)**

# One-Quadrant Chopper DC Drive

## Dialog Box

### DC Machine Tab

The screenshot shows a dialog box titled "1-Quadrant Chopper DC Motor Drive". It has three tabs: "DC Machine", "Converter", and "Controller". The "DC Machine" tab is selected. The dialog contains the following fields and controls:

- Electrical parameters:**
  - Mutual inductance (H): 1.234
  - Armature:**
    - Resistance (ohm): 0.78
    - Inductance (H): 0.016
  - Field:**
    - Resistance (ohm): 150
    - Inductance (H): 112.5
- Mechanical parameters:**
  - Inertia (kg\*m<sup>2</sup>): 0.05
  - Viscous friction coefficient (N-m-s): 0.01
  - Coulomb friction torque (N-m): 0
  - Initial speed (rad/s): 0
- Model detail level: Detailed (dropdown)
- Mechanical input: Torque Tm (dropdown)
- Parameters file options: Load, Save (buttons)
- OK, Cancel, Help, Apply (buttons)

The DC Machine tab displays the parameters of the DC machine block of the powerlib library. Refer to the DC Machine for more information on the DC machine block parameters.

### Model detail level

Select between the detailed and the average-value inverter.

### Mechanical input

Allows you to select either the load torque or the motor speed as mechanical input. Note that if you select and apply a load torque, you will obtain as output the motor speed according to the following differential equation that describes the mechanical system dynamics:



$$T_e = J \frac{d}{dt} \omega_r + F \omega_r + T_m$$

This mechanical system is included in the motor model.

However, if you select the motor speed as mechanical input then you will get the electromagnetic torque as output, allowing you to represent externally the mechanical system dynamics. Note that the internal mechanical system is not used with this mechanical input selection and the inertia and viscous friction parameters are not displayed.

See for example “Mechanical Coupling of Two Motor Drives”.

# One-Quadrant Chopper DC Drive

## Converter Tab

1-Quadrant Chopper DC Motor Drive

1-Quadrant Chopper DC Motor Drive

The DC motor parameters are specified in the DC Machine tab. The converter parameters, smoothing inductance and field voltage values are specified in the Converter tab. The speed and current regulator parameters are specified in the Controller tab.

DC Machine Converter Controller

Smoothing inductance and excitation circuit

Smoothing inductance (H): 10e-3 Field DC source (V): 150

IGBT/Diode device

Snubbers

Resistance (ohm): 10e3

Capacitance (F): inf

IGBT/Diode

On-state resistance (ohm): 1e-3

IGBT

Forward voltage (V): 1.3

Current fall time (s): 0

Current tail time (s): 0

Diode

Forward voltage (V): 1.3

Model detail level: Detailed Mechanical input: Torque Tm

Parameters file options

Load Save

OK Cancel Help Apply

### IGBT/Diode Device section

The IGBT/Diode Device section of the Converter tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the Universal Bridge for more information on the Universal Bridge block parameters.

### Smoothing Inductance

The smoothing inductance value (H).

### Field DC Source

The DC motor field voltage value (V).

# One-Quadrant Chopper DC Drive

## Controller Tab

1-Quadrant Chopper DC Motor Drive

1-Quadrant Chopper DC Motor Drive

The DC motor parameters are specified in the DC Machine tab. The converter parameters, smoothing inductance and field voltage values are specified in the Converter tab. The speed and current regulator parameters are specified in the Controller tab.

DC Machine | Converter | **Controller**

Regulation type: Speed regulation

Speed Controller | Current Controller

Nominal speed (rpm): 1750 Initial speed reference (rpm): 0 Low-pass filter cutoff frequency (Hz): 40 Sampling time (s): 100e-6

PI regulator: Proportional gain: 50 Integral gain: 400 Speed ramps (rpm/s): Acceleration: 1000 Deceleration: -1000

Model detail level: Detailed Mechanical input: Torque Tm

Parameters file options:

### Schematic Button

When you press this button, a diagram illustrating the speed and current controllers schematics appears.

### Regulation Type

This pop-up menu allows you to choose between speed and torque regulation.

## Controller – Speed Controller Subtab

### Nominal Speed

The nominal speed value of the DC motor (rpm). This value is used to convert motor speed from rpm to pu (per unit).

# One-Quadrant Chopper DC Drive

---

## **Initial Speed Reference**

The initial speed reference value (rpm). This value allows the user to start a simulation with a speed reference other than 0 rpm.

## **Low-Pass Filter Cutoff Frequency**

Cutoff frequency of the low-pass filter used to filter the motor speed measurement (Hz).

## **Sampling Time**

The speed controller sampling time (s). This sampling time has to be a multiple of the current controller sampling time and of the simulation time step.

## **Proportional Gain**

The proportional gain of the PI speed controller.

## **Integral Gain**

The integral gain of the PI speed controller.

## **Acceleration**

The maximum change of speed allowed during motor acceleration (rpm/s). Too great a value can cause armature over-current.

## **Deceleration**

The maximum change of speed allowed during motor deceleration (rpm/s). Too great a value can cause armature over-current.

# One-Quadrant Chopper DC Drive

## Controller – Current Controller Subtab

1-Quadrant Chopper DC Motor Drive

1-Quadrant Chopper DC Motor Drive

The DC motor parameters are specified in the DC Machine tab. The converter parameters, smoothing inductance and field voltage values are specified in the Converter tab. The speed and current regulator parameters are specified in the Controller tab.

DC Machine | Converter | **Controller**

Regulation type: Speed regulation

Speed Controller | **Current Controller**

Low-pass filter cutoff frequency (Hz):	Reference limit (p.u.):	PWM switching frequency (Hz):	Sampling time (s):
500	1.5	5e3	20e-6

Nominal values		PI regulator	
Power (VA):	5746	Proportional gain:	2
Voltage (V):	240	Integral gain:	200

Model detail level: Detailed

Parameters file options

### Low-Pass Filter Cutoff Frequency

Cutoff frequency of the low-pass filter used to filter the armature current measurement (Hz).

### Reference Limit

Maximum current reference value (pu). 1.5 pu is a common value.

### PWM Switching Frequency

The switching frequency of the IGBT device (Hz).

# One-Quadrant Chopper DC Drive

---

## Block Inputs and Outputs

### Sampling Time

The current controller sampling time (s). This sampling time has to be a submultiple of the speed controller sampling time and a multiple of the simulation time step.

### Power and Voltage nominal values

The DC motor nominal power (W) and voltage (V) values. These values are used to convert armature current from amperes to pu (per unit).

### Proportional Gain

The proportional gain of the PI current controller.

### Integral Gain

The integral gain of the PI current controller.

### SP

The speed or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration / deceleration ramps. If the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

### Tm or Wm

The mechanical input: load torque (Tm) or motor speed (Wm).

### Vcc, Gnd

The DC voltage source electric connections. The voltage must be adequate for the motor size.

### Wm or Te

The mechanical output: motor speed (Wm) or electromagnetic torque (Te).

### Motor

The motor measurement vector. This vector is composed of two elements:

- The armature voltage

# One-Quadrant Chopper DC Drive

- The DC motor measurement vector (containing the speed, armature current, field current, and electromagnetic torque values). Note that the speed signal is converted from rad/s to rpm before output.

## Conv

The IGBT/Diode device measurement vector. This vector includes the converter output voltage. The output current is not included since it is equal to the DC motor armature current. Note that all current and voltage values of the converter can be visualized with the Multimeter block.

## Ctrl

The controller measurement vector. This vector contains:

- The armature current reference
- The duty cycle of the PWM pulses
- The speed or torque error (difference between the speed reference ramp and actual speed or between the torque reference and actual torque)
- The speed reference ramp or torque reference

## Model Specifications

The library contains a 5 hp drive parameter set. The specifications of the 5 hp drive are shown in the following table.

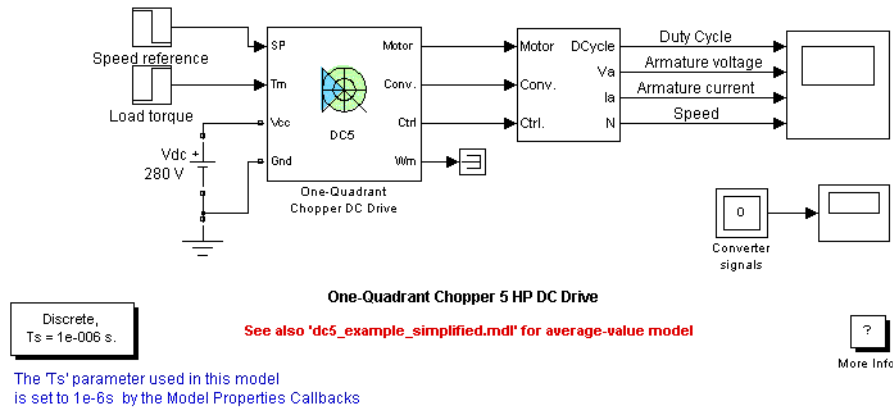
### 5 HP Drive Specifications

Drive Input Voltage		
	Amplitude	280 V
Motor Nominal Values		
	Power	5 hp
	Speed	1750 rpm
	Voltage	240 V

# One-Quadrant Chopper DC Drive

## Example

The dc5\_example demo illustrates the one-quadrant chopper drive used with the 5 hp drive parameter set during speed regulation.



The buck converter is fed by a 280 V DC voltage source and the IGBT switching frequency is 5 kHz.

The speed reference is set at 500 rpm at  $t = 0$  s. Initial load torque is 15 N.m.

Observe that the motor speed follows the reference ramp accurately (+250 rpm/s) and reaches steady state around  $t = 2.5$  s.

The armature current follows the current reference very well, with fast response time and small ripples. Notice that the current ripple frequency is 5 kHz.

At  $t = 2.5$  s, the load torque passes from 15 N.m to 20 N.m. The motor speed recovers fast and is back at 500 rpm at  $t = 3$  s. The current reference rises to about 16.7 A to generate a higher electromagnetic torque to maintain the speed reference. As observed before, the armature current follows its reference perfectly.

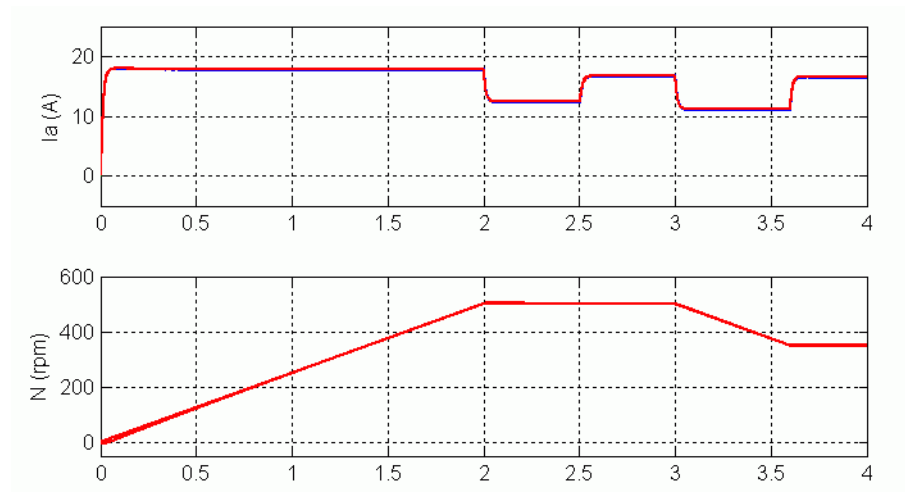


# One-Quadrant Chopper DC Drive

At  $t = 3$  s, the speed reference jumps down to 350 rpm. The armature current lowers in order for the speed to decrease following the negative speed slope (-250 rpm/s) with the help of the load torque.

At  $t = 4$  s, the speed stabilizes around its reference.

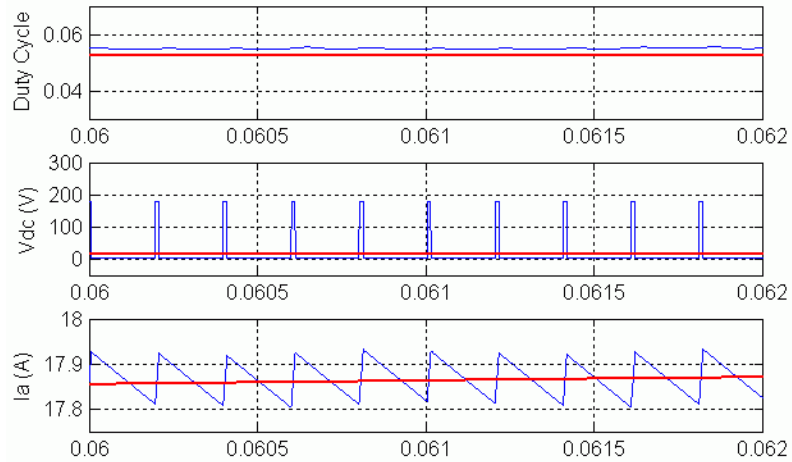
The following figure shows the armature current and speed waveforms.



## DC5 Example – Current and Speed Waveforms (Blue: Detailed Converter, Red: Average-Value Converter)

The next figure shows the duty cycle of the chopper pulses and the corresponding armature voltage and current waveforms during a time interval of 2 ms.

# One-Quadrant Chopper DC Drive



**DC5 Example – Duty Cycles, Armature Voltage, and Current Waveforms (Blue: Detailed Converter, Red: Average-Value Converter)**

## References

- [1] Boldea, Ion, and S.A. Nasar, *Electric Drives*, CRC Press LLC, 1999.
- [2] Séguier, Guy, *Electronique de puissance*, Dunod, 1999.

**Purpose** Implement parallel RLC branch

**Library** Elements

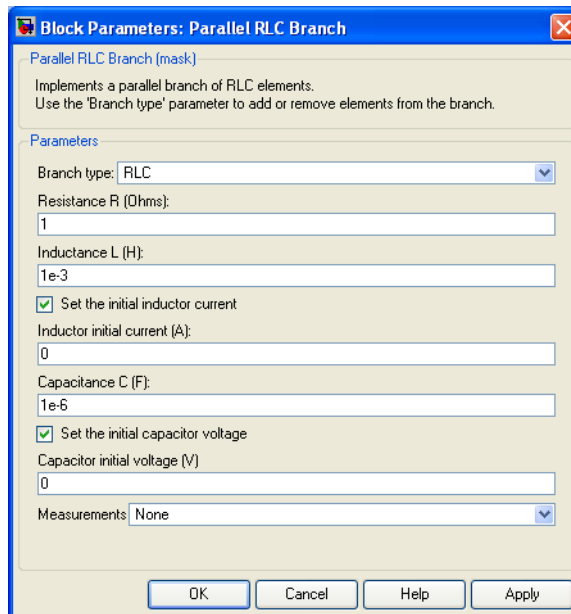
## Description



The Parallel RLC Branch block implements a single resistor, inductor, and capacitor or a parallel combination of these. Only existing elements are displayed in the block icon.

Negative values are allowed for resistance, inductance, and capacitance.

## Dialog Box and Parameters



## Branch type

Select the elements you want to include in the branch. The **R** letter defines the resistor, the **L** letter defines the inductor, and the **C** letter defines the inductor.

# Parallel RLC Branch

---

## **Resistance**

The branch resistance, in ohms ( $\Omega$ ). The **Resistance** parameter is not visible if the resistor element is not specified in the **Branch type** parameter.

## **Inductance L**

The branch inductance, in henries (H). The **Inductance** parameter is not visible if the inductor element is not specified in the **Branch type** parameter.

## **Set the initial inductor current**

If selected, the initial inductor current is defined by the **Inductor initial current** parameter. If not selected, the software calculates the initial inductor current in order to start the simulation steady-state.

The **Set the initial inductor current** parameter is not visible and have no effect on the block if the inductor element is not specified in the **Branch type** parameter.

## **Inductor initial current (A)**

The initial inductor current used at the start of the simulation. The **Inductor initial current** parameter is not visible and have no effect on the block if the inductor is not modeled and if the **Set the initial inductor current** parameter is not selected.

## **Capacitance C**

The branch capacitance, in farads (F). The **Capacitance** parameter is not visible if the capacitance element is not specified in the **Branch type** parameter.

## **Set the initial capacitor voltage**

If selected, the initial capacitor voltage is defined by the **Capacitor initial voltage** parameter. If not selected, the software calculates the initial capacitor voltage in order to start the simulation in steady-state.

The **Set the initial capacitor voltage** parameter is not visible and have no effect on the block if the capacitor element is not specified in the **Branch type** parameter.

## Capacitor initial voltage (V)

The initial capacitor voltage used at the start of the simulation. The **Capacitor initial voltage** parameter is not visible and have no effect on the block if the capacitor is not modeled and if the **Set the initial capacitor voltage** parameter is not selected.

## Measurements

Select **Branch voltage** to measure the voltage across the Parallel RLC Branch block terminals.

Select **Branch current** to measure the total current (sum of R, L, C currents) flowing through the Parallel RLC Branch block.

Select **Branch voltage** and **current** to measure the voltage and the current of the Parallel RLC Branch block.

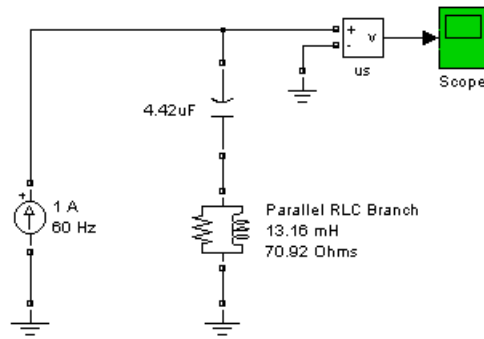
Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name.

Measurement	Label
Branch voltage	Ub:
Branch current	Ib:

## Example

The `power_paralbranch` demo is used to obtain the frequency response of an eleventh-harmonic filter (tuned frequency at 660 Hz) connected on a 60 Hz power system:

# Parallel RLC Branch



The network impedance in the Laplace domain is

$$Z(s) = \frac{V(s)}{I(s)} = \frac{RLCs^2 + Ls + R}{LCs^2 + RCs}$$

To obtain the frequency response of the impedance you have to get the state-space model (A B C D matrices) of the system.

This system is a one input ( $I_s$ ) and one output ( $V_s$ ) system.

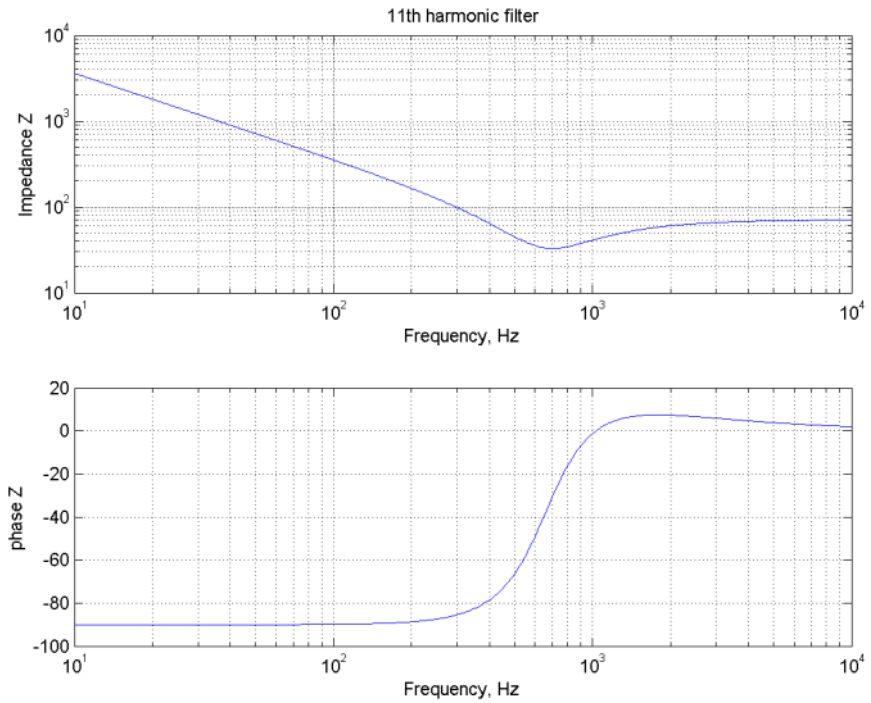
**Note** If you have Control System Toolbox™ software installed, you can get the transfer function  $Z(s)$  from the state-space matrices and the bode function.

```
[A,B,C,D] = power_analyze('power_paralbranch');
freq = logspace(1,4,500);
w = 2*pi*freq;
[Zmag,Zphase] = bode(A,B,C,D,1,w);
subplot(2,1,1)
loglog(freq,Zmag)
grid
title('11th harmonic filter')
xlabel('Frequency, Hz')
ylabel('Impedance Z')
subplot(2,1,2)
semilogx(freq,Zphase)
xlabel('Frequency, Hz')
ylabel('phase Z')
grid
```

You can also use the Impedance Measurement block and the Powergui block to plot the impedance as a function of frequency.

---

# Parallel RLC Branch



## See Also

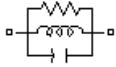
Multimeter, Parallel RLC Load, Powergui, Series RLC Branch, Series RLC Load



**Purpose** Implement linear parallel RLC load

**Library** Elements

## Description



The Parallel RLC Load block implements a linear load as a parallel combination of RLC elements. At the specified frequency, the load exhibits a constant impedance. The active and reactive powers absorbed by the load are proportional to the square of the applied voltage.

Only elements associated with nonzero powers are displayed in the block icon.

## Dialog Box and Parameters

**Block Parameters: Parallel RLC Load**

Parallel RLC Load (mask)  
Implements a parallel RLC load.

**Parameters**

Nominal voltage  $V_n$  (Vrms):  
1000

Nominal frequency  $f_n$  (Hz):  
60

Active power  $P$  (W):  
10e3

Inductive reactive Power  $Q_L$  (positive var):  
100

Capacitive reactive power  $Q_c$  (negative var):  
100

Set the initial capacitor voltage  
Capacitor initial voltage (V):  
0

Set the initial inductor current  
Inductor initial current (A):  
0

Measurements: None

OK Cancel Help Apply

### Nominal voltage $V_n$

The nominal voltage of the load, in volts RMS (Vrms).

# Parallel RLC Load

---

## **Nominal frequency $f_n$**

The nominal frequency, in hertz (Hz).

## **Active power $P$**

The active power of the load, in watts.

## **Inductive reactive power $Q_L$**

The inductive reactive power  $Q_L$ , in vars. Specify a positive value, or 0.

## **Capacitive reactive power $Q_C$**

The capacitive reactive power  $Q_C$ , in vars. Specify a positive value, or 0.

## **Set the initial capacitor voltage**

If selected, the initial capacitor voltage is defined by the **Capacitor initial voltage** parameter. If not selected, the software calculates the initial capacitor voltage in order to start the simulation in steady-state.

The **Set the initial capacitor voltage** parameter have no effect on the block if the capacitive reactive power is equal to zero.

## **Capacitor initial voltage (V)**

The initial capacitor voltage used at the start of the simulation. The **Capacitor initial voltage** parameter have no effect on the block if the capacitive reactive power is equal to zero and if the **Set the initial capacitor voltage** parameter is not selected.

## **Set the initial inductor current**

If selected, the initial inductor current is defined by the **Inductor initial current** parameter. If not selected, the software calculates the initial inductor current in order to start the simulation steady-state.

The **Set the initial inductor current** parameter have no effect on the block if the inductive reactive power is equal to zero.

## Inductor initial current (A)

The initial inductor current used at the start of the simulation.

The **Inductor initial current** parameter have no effect on the block if the inductive reactive power is equal to zero and if the **Set the initial inductor current** parameter is not selected.

## Measurements

Select **Branch voltage** to measure the voltage across the Parallel RLC Load block terminals.

Select **Branch current** to measure the current flowing through the Parallel RLC Load block.

Select **Branch voltage and current** to measure the voltage and the current of the Parallel RLC Load block.

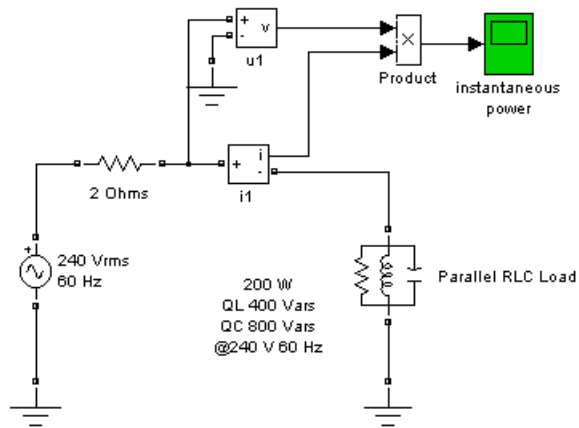
Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name.

Measurement	Label
Branch voltage	Ub:
Branch current	Ib:

## Example

The power\_parallelload demo uses a parallel RLC load block to implement a load.

# Parallel RLC Load



## See Also

Multimeter, Parallel RLC Branch, Series RLC Branch, Series RLC Load

# Permanent Magnet Synchronous Machine

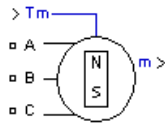
## Purpose

Model the dynamics of three-phase permanent magnet synchronous machine with sinusoidal or trapezoidal back electromotive force (back EMF)

## Library

Machines

## Description



The Permanent Magnet Synchronous Machine block operates in either generator or motor mode. The mode of operation is dictated by the sign of the mechanical torque (positive for motor mode, negative for generator mode). The electrical and mechanical parts of the machine are each represented by a second-order state-space model. The sinusoidal model assumes that the flux established by the permanent magnets in the stator is sinusoidal, which implies that the electromotive forces are sinusoidal. For the trapezoidal machine, the model assumes that the winding distribution and flux established by the permanent magnets produce three trapezoidal back EMF waveforms.

The block implements the following equations.

### Sinusoidal Model Electrical System

These equations are expressed in the rotor reference frame (qd frame).

$$\frac{d}{dt} i_d = \frac{1}{L_d} v_d - \frac{R}{L_d} i_d + \frac{L_q}{L_d} p \omega_r i_q$$

$$\frac{d}{dt} i_q = \frac{1}{L_q} v_q - \frac{R}{L_q} i_q - \frac{L_d}{L_q} p \omega_r i_d - \frac{\lambda p \omega_r}{L_q}$$

$$T_e = 1.5 p [\lambda i_q + (L_d - L_q) i_d i_q]$$

where (all quantities in the rotor reference frame are referred to the stator)

$L_q, L_d$       q and d axis inductances

$R$               Resistance of the stator windings

# Permanent Magnet Synchronous Machine

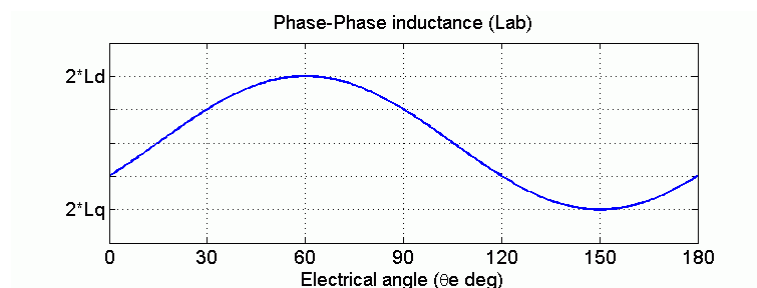
$i_q, i_d$	q and d axis currents
$v_q, v_d$	q and d axis voltages
$\omega_r$	Angular velocity of the rotor
$\lambda$	Amplitude of the flux induced by the permanent magnets of the rotor in the stator phases
$p$	Number of pole pairs
$T_e$	Electromagnetic torque

The  $L_q$  and  $L_d$  inductances represent the relation between the phase inductance and the rotor position due to the saliency of the rotor. For example, the inductance measured between phase a and b (phase c is left open) is given by:

$$L_{ab} = L_d + L_q + (L_q - L_d) \cos\left(2\theta_e + \frac{\pi}{3}\right)$$

where  $\theta_e$  represents the electrical angle.

The next figure shows the variation of the line-line inductance in function of the electrical angle of the rotor:



- For a round rotor, there is no variation in the phase inductance. Therefore,

# Permanent Magnet Synchronous Machine

$$L_d = L_q = \frac{L_{ab}}{2}$$

- For a salient round rotor, the dq inductances are given by:

$$L_d = \frac{\max(L_{ab})}{2}$$

and

$$L_q = \frac{\min(L_{ab})}{2}$$

## Trapezoidal Model Electrical System

These equations are expressed in the phase reference frame (abc frame). Note that the phase inductance  $L_s$  is assumed constant and does not vary with the rotor position.

$$\frac{d}{dt}i_a = \frac{1}{3L_s}[2v_{ab} + v_{bc} - 3R_s i_a + \lambda p \omega_r (-2\Phi'_a + \Phi'_b + \Phi'_c)]$$

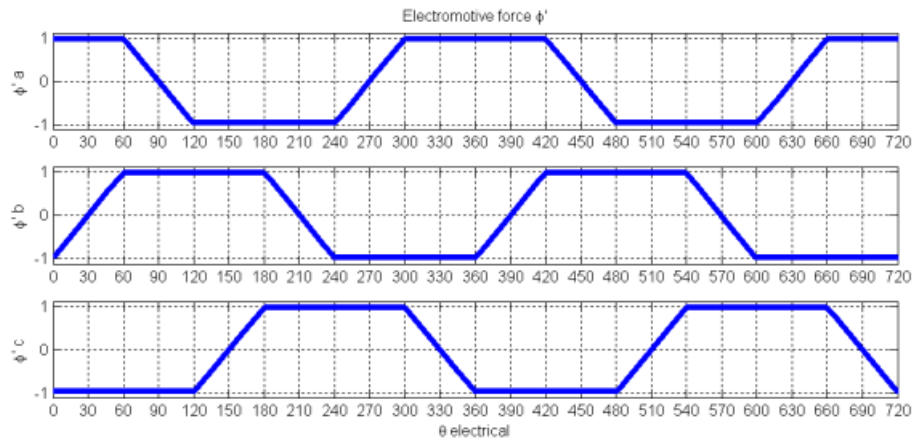
$$\frac{d}{dt}i_b = \frac{1}{3L_s}[-v_{ab} + v_{bc} - 3R_s i_b + \lambda p \omega_r (\Phi'_a - 2\Phi'_b + \Phi'_c)]$$

$$\frac{d}{dt}i_c = -\left(\frac{d}{dt}i_a + \frac{d}{dt}i_b\right)$$

$$T_e = p\lambda(\Phi'_a \cdot i_a + \Phi'_b \cdot i_b + \Phi'_c \cdot i_c)$$

where the electromotive force  $\Phi'$  is represented by

# Permanent Magnet Synchronous Machine



and

$L_s$	Inductance of the stator windings
$R$	Resistance of the stator windings
$i_a, i_b, i_c$	a, b and c phase currents
$\Phi'_a, \Phi'_b, \Phi'_c$	a, b and c phase electromotive forces
$v_{ab}, v_{bc}$	ab and bc phase to phase voltages
$\omega_r$	Angular velocity of the rotor
$\lambda$	Amplitude of the flux induced by the permanent magnets of the rotor in the stator phases
$p$	Number of pole pairs
$T_e$	Electromagnetic torque



# Permanent Magnet Synchronous Machine

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## Mechanical System (for both models)

$$\frac{d}{dt}\omega_r = \frac{1}{J}(T_e - F\omega_r - T_m)$$

$$\frac{d\theta}{dt} = \omega_r$$

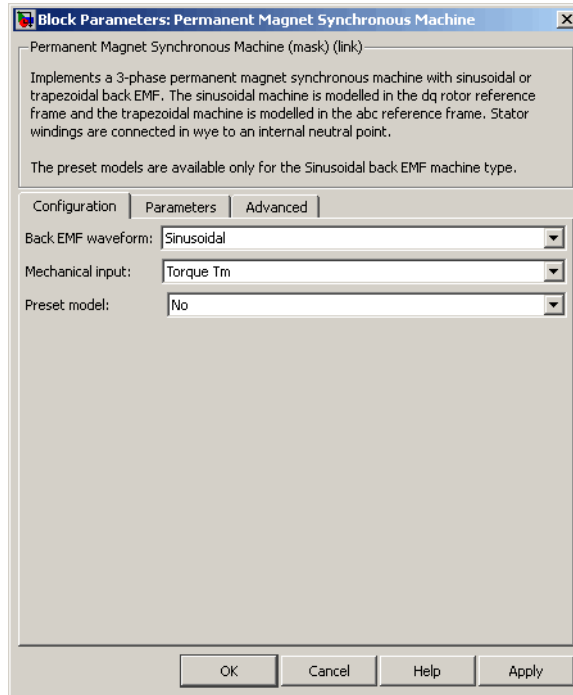
where

J	Combined inertia of rotor and load
F	Combined viscous friction of rotor and load
$\Theta$	Rotor angular position
$T_m$	Shaft mechanical torque

# Permanent Magnet Synchronous Machine

## Dialog Box and Parameters

### Configuration Tab



### Back EMF waveform

Allows to select between the sinusoidal and the trapezoidal electromotive force.

### Mechanical input

Allows you to select either the torque applied to the shaft or the rotor speed as the Simulink signal applied to the block's input.

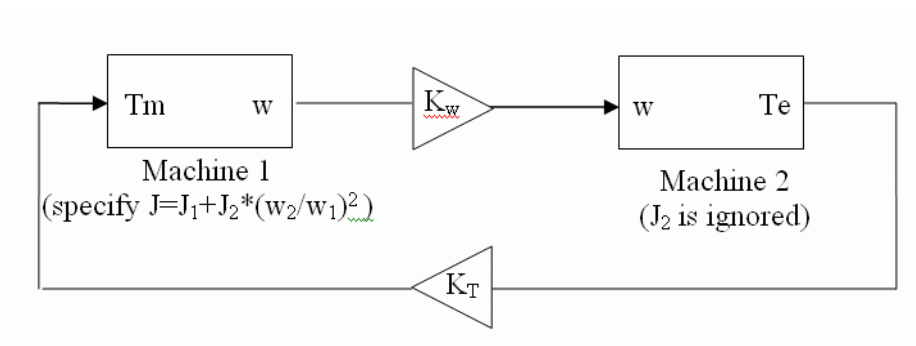
Select **Torque Tm** to specify a torque input, in N.m., and change labeling of the block's input to Tm. The machine speed is determined by the machine Inertia J and by the difference between the applied mechanical torque Tm and the internal

# Permanent Magnet Synchronous Machine

electromagnetic torque  $T_e$ . The sign convention for the mechanical torque is the following: when the speed is positive, a positive torque signal indicates motor mode and a negative signal indicates generator mode.

Select **Speed  $w$**  to specify a speed input, in rad/s, and change labeling of the block's input to  $w$ . The machine speed is imposed and the mechanical part of the model (Inertia  $J$ ) is ignored. Using the speed as the mechanical input allows modeling a mechanical coupling between two machines and interfacing with SimMechanics and SimDriveline models.

The next figure indicates how to model a stiff shaft interconnection in a motor-generator set when friction torque is ignored in machine 2. The speed output of machine 1 (motor) is connected to the speed input of machine 2 (generator), while machine 2 electromagnetic torque output  $T_e$  is applied to the mechanical torque input  $T_m$  of machine 1. The  $K_w$  factor takes into account speed units of both machines (pu or rad/s) and gear box ratio  $w_2/w_1$ . The  $K_T$  factor takes into account torque units of both machines (pu or N.m) and machine ratings. Also, as the inertia  $J_2$  is ignored in machine 2,  $J_2$  referred to machine 1 speed must be added to machine 1 inertia  $J_1$ .



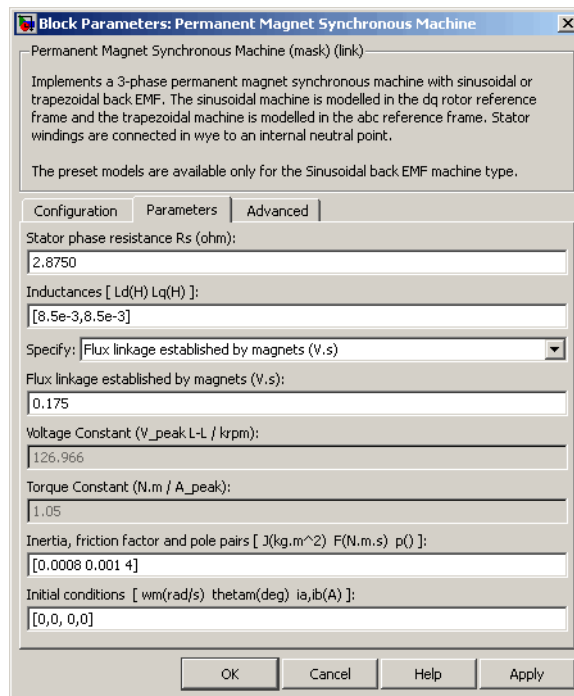
# Permanent Magnet Synchronous Machine

## Preset Model

Provides a set of predetermined electrical and mechanical parameters for various permanent magnet synchronous motor ratings of torque (N.m), DC bus voltage (V), rated speed (rpm), and continuous stall torque (N.m) . This parameter is available only for sinusoidal machine.

Select one of the preset models to load the corresponding electrical and mechanical parameters in the entries of the dialog box. Select No if you do not want to use a preset model.

## Parameters Tab



The screenshot shows a dialog box titled "Block Parameters: Permanent Magnet Synchronous Machine" with a close button (X) in the top right corner. The dialog contains a description of the machine type and a "Parameters" tab. The parameters are as follows:

- Stator phase resistance  $R_s$  (ohm): 2.8750
- Inductances [  $L_d(H)$   $L_q(H)$  ]: [8.5e-3, 8.5e-3]
- Specify: Flux linkage established by magnets (V.s) (dropdown menu)
- Flux linkage established by magnets (V.s): 0.175
- Voltage Constant ( $V_{peak}$  L-L / krpm): 126.966
- Torque Constant (N.m / A\_peak): 1.05
- Inertia, friction factor and pole pairs [  $J(kg.m^2)$   $F(N.m.s)$   $p()$  ]: [0.0008 0.001 4]
- Initial conditions [  $\omega_m(rad/s)$   $\theta_{tam(deg)}$   $i_a, i_b(A)$  ]: [0, 0, 0, 0]

Buttons at the bottom: OK, Cancel, Help, Apply.

## Stator phase resistance

The stator phase resistance  $R_s$  ( $\Omega$ ).

# Permanent Magnet Synchronous Machine

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## Stator inductances

- Sinusoidal model: The d-axis and q-axis stator inductances  $L_d$  (H) and  $L_q$  (H).
- Trapezoidal model: The stator phase inductance  $L_s$  (H).

## Specify a machine constant

Lets you select the machine constant that you wish to specify for block parameterization:

- Flux linkage established by magnets
- Voltage Constant
- Torque Constant

Once you select a constant, you can enter its value in the appropriate parameter field, while the other two parameters become inaccessible and are only shown for information.

## Flux linkage established by magnets

The constant flux  $\lambda$  (Wb) induced in the stator windings by the magnets.

## Voltage Constant

The peak line to line voltage per 1000 rpm. This voltage represents the peak open circuit voltage when the machine is driven as a generator at 1000 rpm.

## Torque Constant

The torque per ampere constant. This constant assumes that the machine is driven by an inverter which provides a perfect synchronization between the current and the Back-EMF.

- Sinusoidal model: A sine wave current is assumed (see `ac6_example_simplified.mdl` for more detail).
- Trapezoidal model: A square wave current is assumed (see `ac7_example_simplified.mdl` for more detail).

# Permanent Magnet Synchronous Machine

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## Back EMF flat top area

The width of the flat top for a half period of the electromotive force  $\Phi'$  (degrees) (only for trapezoidal machine).

## Inertia, friction factor and pole pairs

The combined machine and load inertia coefficient  $J$  ( $\text{kg}\cdot\text{m}^2$ ), combined viscous friction coefficient  $F$  ( $\text{N}\cdot\text{m}\cdot\text{s}$ ), and pole pairs  $p$ .

## Initial conditions

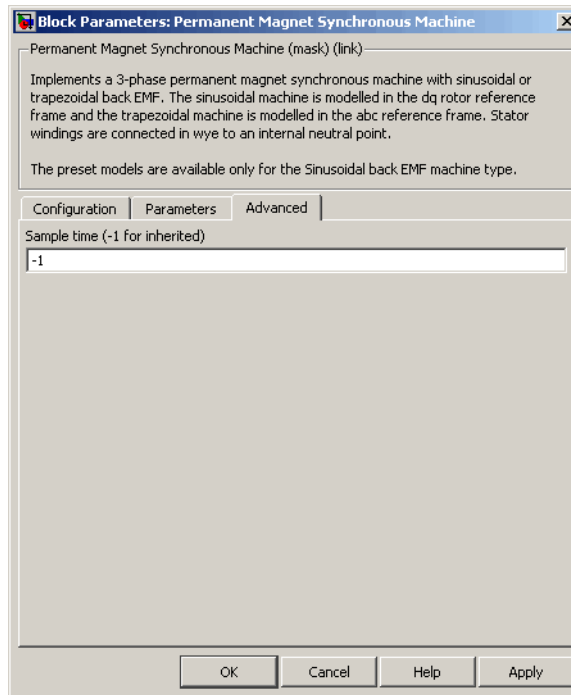
Specifies the mechanical speed ( $\text{rad/s}$ ), mechanical angle  $\Theta_m$  (degrees), and instantaneous stator current (A):

$[w_m, \Theta_m, i_a, i_b]$

Note that since the stator is wye-connected, the current  $i_c$  is given by  $i_c = -i_a - i_b$ .

# Permanent Magnet Synchronous Machine

## Advanced Tab



### Sample time (-1 for inherited)

Specifies the sample time used by the block. To inherit the sample time specified in the Powergui block, set this parameter to -1.

## Inputs and Outputs

$T_m$

The Simulink input is the mechanical torque at the machine's shaft. This input should normally be positive because the Permanent Magnet Synchronous Machine block is usually used as a motor. Nevertheless, you can apply a negative torque input if you choose to use the block in generator mode.

# Permanent Magnet Synchronous Machine

m

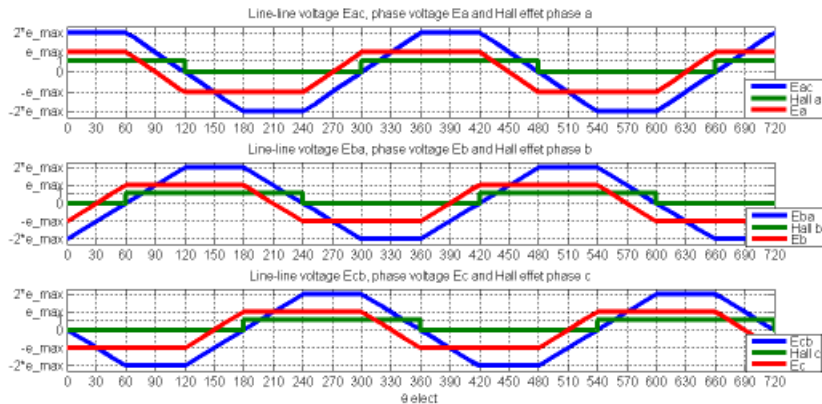
The Simulink output of the block is a vector containing 13 signals for the sinusoidal model and 12 signals for the trapezoidal model. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

Definition	Units	Symbol	Signal number	
			Sinusoidal model	Trapezoidal model
Stator current is_a	A	$i_a$	1	1
Stator current is_b	A	$i_b$	2	2
Stator current is_c	A	$i_c$	3	3
Stator current is_q	A	$i_q$	4	N/A
Stator current is_d	A	$i_d$	5	N/A
Stator voltage Vs_q	V	$v_q$	6	N/A
Stator voltage Vs_d	V	$v_d$	7	N/A
Phase back EMF e_a	V	$e_a$	N/A	4
Phase back EMF e_b	V	$e_b$	N/A	5
Phase back EMF e_c	V	$e_c$	N/A	6
Hall effect signal h_a*	logic 0-1	$h_a$	8	7
Hall effect signal h_b*	logic 0-1	$h_b$	9	8
Hall effect signal h_c*	logic 0-1	$h_c$	10	9
Rotor speed $\omega_r$	rad/s	$\omega_r$	11	10
Rotor angle $\theta_r$	rad	$\theta_r$	12	11
Electromagnetic torque $T_e$	N.m	$T_e$	13	12



# Permanent Magnet Synchronous Machine

The Hall effect signal provides a logical indication of the back EMF positioning. This signal is very useful to control directly the power switches. There is a change of state at each zero crossing of the phase to phase voltage. These signals must be decoded before being applied to the switches.



## Assumption

The Permanent Magnet Synchronous Machine block assumes a linear magnetic circuit with no saturation of the stator and rotor iron. This assumption can be made because of the large air gap usually found in permanent magnet synchronous machines.

## Limitations

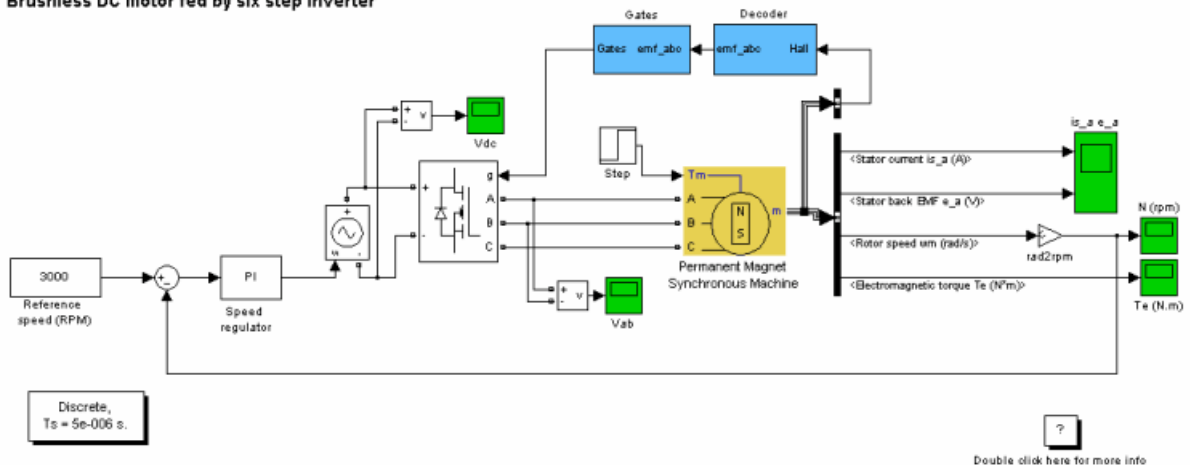
When you use Permanent Magnet Synchronous Machine blocks in discrete systems, you might have to use a small parasitic resistive load, connected at the machine terminals, in order to avoid numerical oscillations. Large sample times require larger loads. The minimum resistive load is proportional to the sample time. As a rule of thumb, remember that with a  $25 \mu\text{s}$  time step on a 60 Hz system, the minimum load is approximately 2.5% of the machine nominal power. For example, a 200 MVA PM synchronous machine in a power system discretized with a  $50 \mu\text{s}$  sample time requires approximately 5% of resistive load or 10 MW. If the sample time is reduced to  $20 \mu\text{s}$ , a resistive load of 4 MW should be sufficient.

# Permanent Magnet Synchronous Machine

## Example

The power\_brushlessDCmotor demo illustrates the use of the Permanent Magnet Synchronous Machine block in motoring mode with a closed-loop control system built entirely with Simulink blocks. The complete system includes a six step inverter block from the SimPowerSystems library. Two control loops are used; the inner loop synchronizes the pulses of the bridge with the electromotive forces, and the outer loop regulates the motor's speed, by varying the DC bus voltage. The mechanical torque applied at the motor's shaft is originally 0 N.m (no load) and steps to its nominal value (3 N.m) at  $t = 0.1$  second. The parameters of the machine are found in the dialog box section.

Brushless DC motor fed by six step inverter

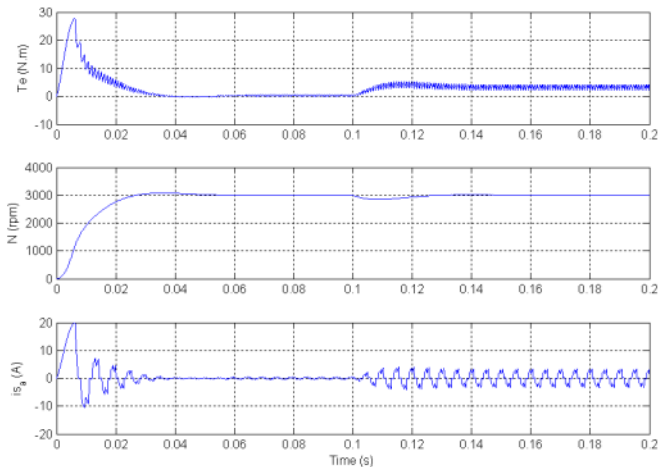


Set the simulation parameters as follows:

- Type: Fixed-step
- Integrator type: Runge-Kutta, ode4
- Sample time: 5e-6 (set automatically by the **Model properties**)
- Stop time: 0.2

# Permanent Magnet Synchronous Machine

Set the **Flux distribution** parameter to Trapezoidal and run the simulation to observe the motor's torque, speed, and currents. Change the **Back EMF flat top area parameter** of the trapezoidal model from 120 to 0 and observe the waveform of the electromotive force  $e_a$ .



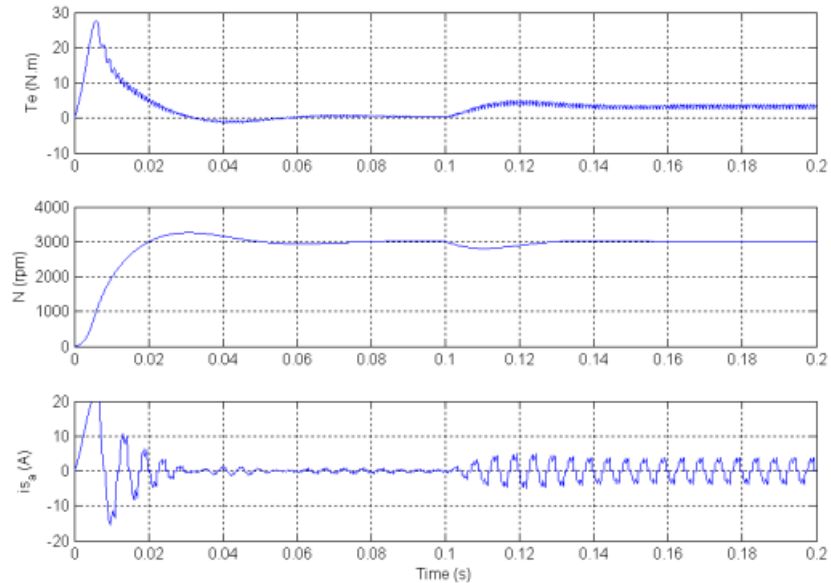
The torque climbs to nearly 28 N.m when the motor starts and stabilizes rapidly when the motor reaches the reference value. The nominal torque is applied at  $t = 0.1$  second and the controller reacts rapidly and increases the DC bus voltage to produce the required electric torque. Observe the saw tooth shape of the currents waveforms. This is caused by the six step controller, which applies a constant voltage value during 120 electrical degrees to the motor. The initial current is high and decreases during the acceleration to the nominal speed. When the nominal torque is applied, the stator current increases to maintain the nominal speed. The saw tooth waveform is also observed in the electromotive torque signal  $T_e$ . However, the motor's inertia prevents this noise from appearing in the motor's speed waveform.

When the **Back EMF flat top area** parameter of the trapezoidal model is changed from 120 to 0, the model reacts exactly like the sinusoidal model. The electromotive force  $e_a$  is purely sinusoidal and the torque ripple is less than the previous case. The sinusoidal model requires a

# Permanent Magnet Synchronous Machine

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larger current to produce the same torque. That's why the trapezoidal machine is used in high torque applications, and the sinusoidal machine in precision applications.



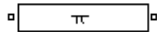
## References

- [1] Grenier, D., L.-A. Dessaint, O. Akhrif, Y. Bonnassieux, and B. LePioufle, "Experimental Nonlinear Torque Control of a Permanent Magnet Synchronous Motor Using Saliency," *IEEE Transactions on Industrial Electronics*, Vol. 44, No. 5, October 1997, pp. 680-687.

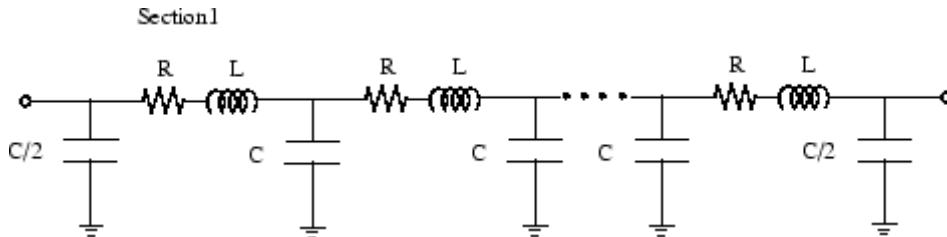
**Purpose** Implement single-phase transmission line with lumped parameters

**Library** Elements

**Description** The PI Section Line block implements a single-phase transmission line with parameters lumped in PI sections.



For a transmission line, the resistance, inductance, and capacitance are uniformly distributed along the line. An approximate model of the distributed parameter line is obtained by cascading several identical PI sections, as shown in the following figure.



Unlike the Distributed Parameter Line block, which has an infinite number of states, the PI section linear model has a finite number of states that permit you to compute a linear state-space model. The number of sections to be used depends on the frequency range to be represented.

A good approximation of the maximum frequency range represented by the PI line model is given by the following equation:

$$f_{max} = \frac{Nv}{8l}$$

where

- N      Number of PI sections
- v      Propagation speed in km/s =  $1/\sqrt{LC}$   $L$  in H/km,  $C$  in F/km
- l      Line length in km

# PI Section Line

---

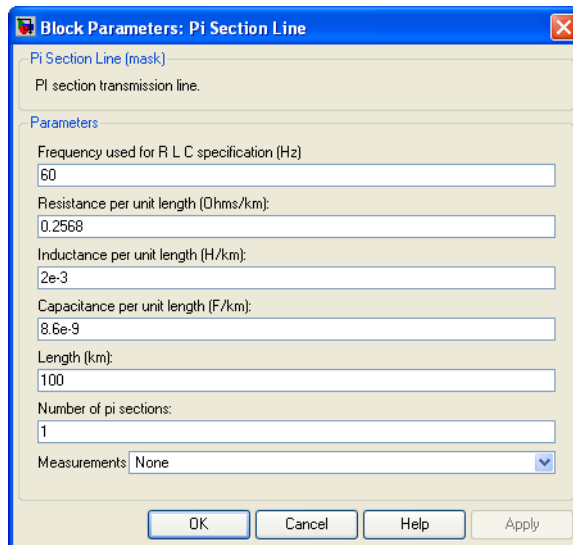
For example, for a 100 km aerial line having a propagation speed of 300,000 km/s, the maximum frequency range represented with a single PI section is approximately 375 Hz. For studying interactions between a power system and a control system, this simple model could be sufficient. However for switching surge studies involving high-frequency transients in the kHz range, much shorter PI sections should be used. In fact, you can obtain the most accurate results by using a distributed parameters line model.

---

**Note** The Powergui block provides a graphical tool for the calculation of the resistance, inductance, and capacitance per unit length based on the line geometry and the conductor characteristics.

---

## Dialog Box and Parameters



### Frequency used for RLC specifications

Frequency used to compute the line parameters, in hertz (Hz).

## Resistance per unit length

The resistance per unit length of the line, in ohms/km ( $\Omega$ ).

## Inductance per unit length

The inductance per unit length of the line, in henries/km (H/km).

## Capacitance per unit length

The capacitance per unit length of the line, in farads/km (F/km).

## Length

The line length in km.

## Number of pi sections

The number of PI sections. The minimum value is 1.

## Measurements

Select **Input** and **output voltages** to measure the sending end (input port) and receiving end (output port) voltages of the line model.

Select **Input** and **output currents** to measure the sending end and receiving end currents of the line model.

Select **All pi-section voltages** and **currents** to measure voltages and currents at the start and end of each pi-section.

Select **All voltages** and **currents** to measure the sending end and receiving end voltages and currents of the line model.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name.

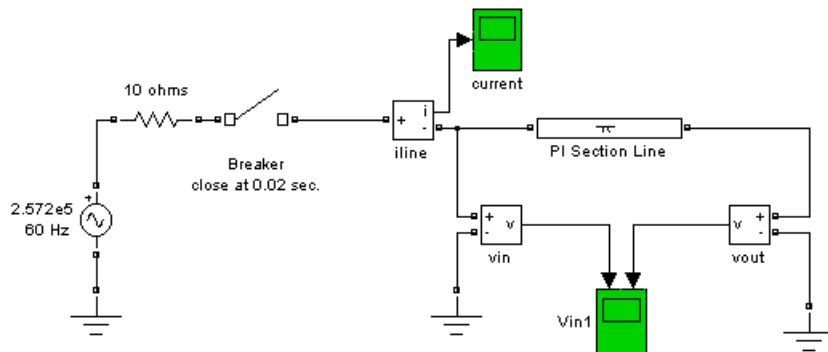
Measurement	Label
Sending end voltage (block input)	Us:
Receiving end voltage (block output)	Ur:

# PI Section Line

Measurement	Label
Sending end current (input current)	Is :
Receiving end current (output current)	Ir :

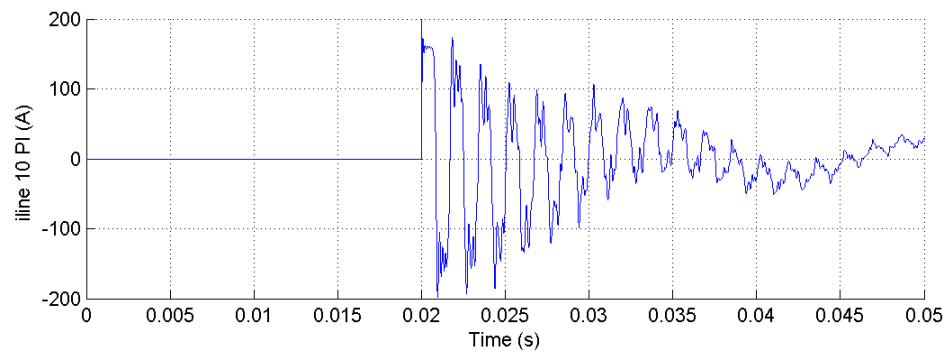
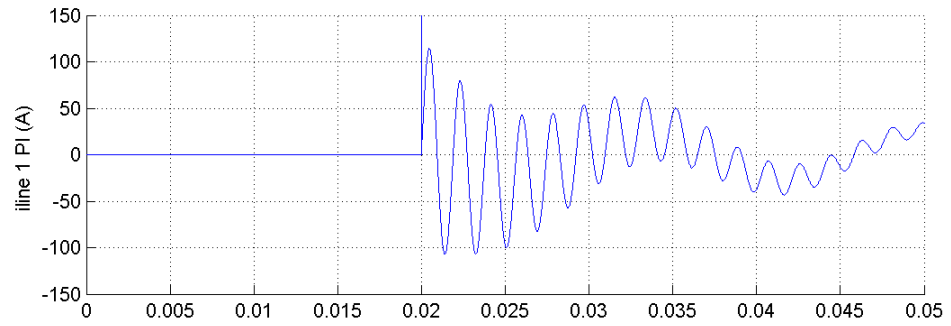
## Example

The power\_piline demo shows the line energization voltages and currents of a PI section line.



The results obtained with the line modeled by one PI section of 100 km and 10 PI sections of 10 km are shown.





**See Also**

Distributed Parameter Line

# PM Synchronous Motor Drive

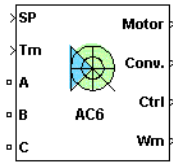
## Purpose

Implement Permanent Magnet Synchronous Motor (PMSM) vector control drive

## Library

Electric Drives/AC drives

## Description



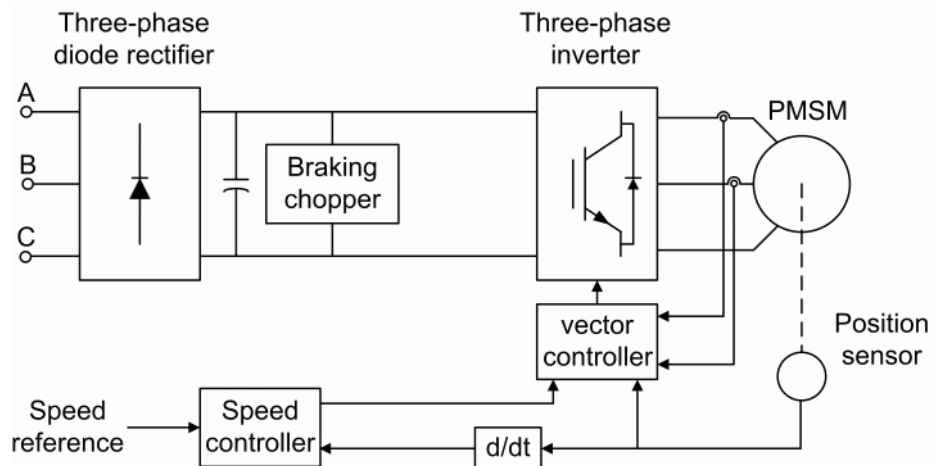
The high-level schematic shown below is built from six main blocks. The PMSM motor, the three-phase inverter, and the three-phase diode rectifier models are provided with the SimPowerSystems library. More details are available in the reference pages for these blocks. The speed controller, the braking chopper, and the vector controller models are specific to the drive library. It is possible to use a simplified version of the drive containing an average-value model of the inverter for faster simulation.

---

**Note** In SimPowerSystems software, the PM Synchronous Motor Drive block is commonly called the AC6 motor drive.

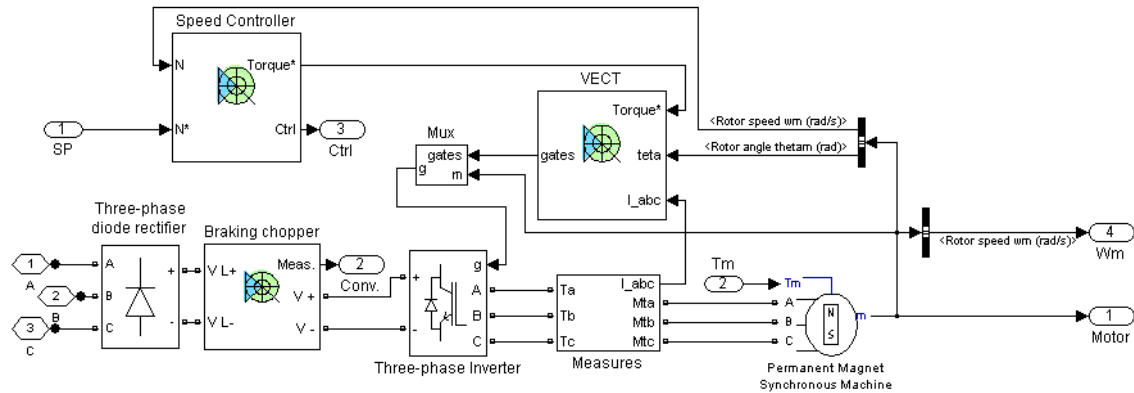
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## High-Level Schematic



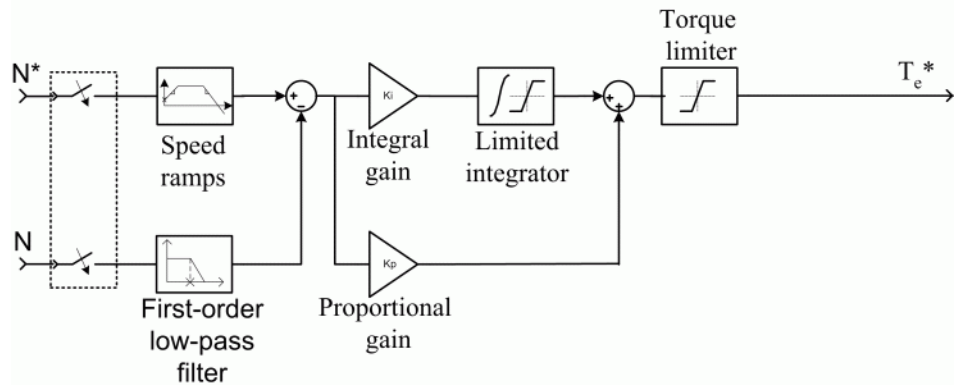
# PM Synchronous Motor Drive

## Simulink Schematic



## Speed Controller

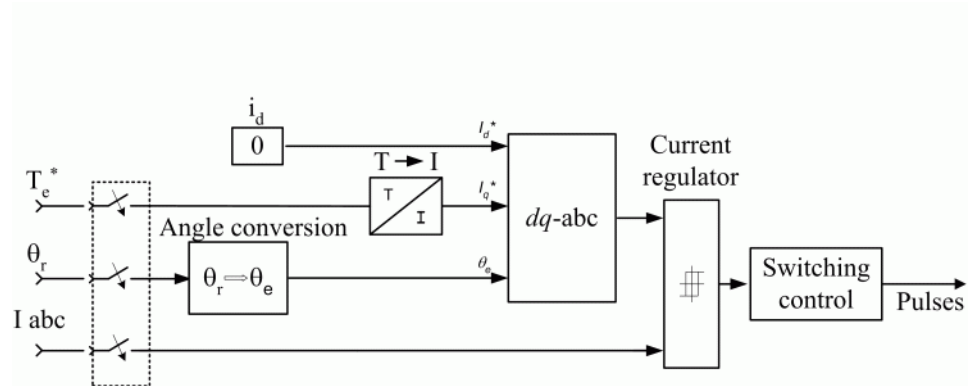
The speed controller is based on a PI regulator, shown below. The output of this regulator is a torque set point applied to the vector controller block.



# PM Synchronous Motor Drive

## Vector Controller

The vector controller contains four main blocks, shown below. These blocks are described below.



The *dq-abc* block performs the conversion of the *dq* current component in the rotor reference frame into *abc* phase variables.

The *current regulator* is a bang-bang current controller with adjustable hysteresis bandwidth.

The *angle conversion* block is used to compute the electrical rotor angle from the mechanical rotor angle.

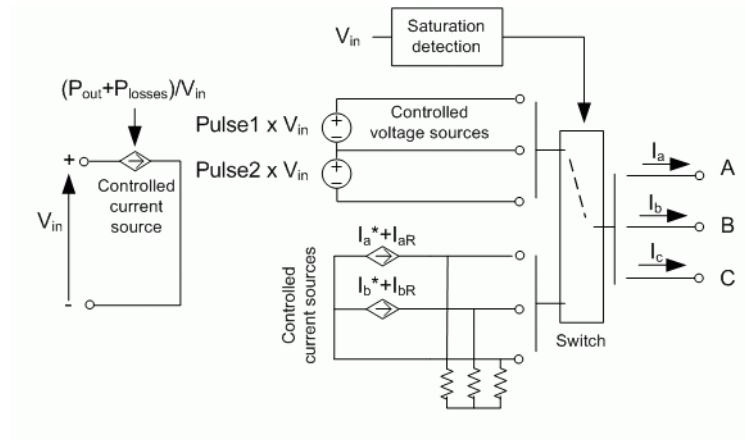
The *Switching control* block is used to limit the inverter commutation frequency to a maximum value specified by the user.

When using the average-value inverter, the *ab* current references are sent to the inverter, as well as switching pulses from a slightly modified *Switching control block*.

## Braking Chopper

The braking chopper block contains the DC bus capacitor and the dynamic braking chopper, which is used to absorb the energy produced by a motor deceleration.

**Average-Value Inverter** The average-value inverter is shown in the following figure.



It is composed of one controlled current source on the DC side and of two controlled current sources and two controlled voltage sources on the AC side. The DC current source allows the representation of the average DC bus current behavior following the next equation:

$$I_{dc} = (P_{out} + P_{losses})/V_{in}$$

with  $P_{out}$  being the output power,  $P_{losses}$  the losses in the power electronic devices, and  $V_{in}$  the DC bus voltage.

On the AC side, the current sources represent the average phase currents fed to the motor. The regulation being fast, the current values are set equal to the current references sent by the current regulator. A small current is injected to compensate for the current drawn by the three-phase load (needed because of the inverter current sources in series with inductive motor).

During loss of current tracking due to insufficient inverter voltage, the currents are fed by two controlled voltage sources. These voltage sources represent the square wave mode and allow good representation of the phase currents during inverter saturation. Each voltage source

# PM Synchronous Motor Drive

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outputs either  $V_{in}$  or 0, depending on the values of the pulses (1 or 0) sent by the current controller.

## Remarks

The model is discrete. Good simulation results have been obtained with a  $2 \mu\text{s}$  time step. To simulate a digital controller device, the control system has two different sampling times:

- Speed controller sampling time
- Vector controller sampling time

The speed controller sampling time has to be a multiple of the vector controller sampling time. The latter sampling time has to be a multiple of the simulation time step. The average-value inverter allows the use of bigger simulation time steps since it does not generate small time constants (due to the RC snubbers) inherent to the detailed converter. For a vector controller sampling time of  $75 \mu\text{s}$ , good simulation results have been obtained for a simulation time step of  $75 \mu\text{s}$ . The simulation time step can, of course, not be higher than the vector controller time step.

The stator current direct component  $i_d^*$  is set to zero inside the vector controller block because the rotor flux is supplied by the permanent magnets.

## Dialog Box

### PM Synchronous Machine Tab

The screenshot shows a dialog box titled "PM Synchronous Motor Drive" with a sub-tab "Permanent Magnet Synchronous Machine". The dialog is divided into several sections:

- Electrical parameters:**
  - Back electromotive force: Sinusoidal (dropdown)
  - Equivalent circuit parameters:
    - Resistance (ohm): 0.2
    - D-axis inductance (H): 8.5e-3
    - Q-axis inductance (H): 8.5e-3
  - Flux constant:
    - Specify: Flux linkage established by magnets (V.s) (dropdown)
    - Value: 0.175
  - Initial currents:
    - Phase A (A): 0
    - Phase B (A): 0
- Mechanical parameters:**
  - Rotor values:
    - Inertia (kg\*m<sup>2</sup>): 0.089
    - Friction (N-m-s): 0.005
    - Pole pairs: 4
  - Initial values:
    - Speed (rad/s): 0
    - Angle (deg): 0
- Model detail level:** Detailed (dropdown)
- Mechanical input:** Torque Tm (dropdown)
- Parameters file options:** Load, Save buttons
- Buttons:** OK, Cancel, Help, Apply

The PM synchronous machine tab displays the parameters of the PM synchronous machine block of the powerlib library. Refer to Permanent Magnet Synchronous Machine for more information on the PM synchronous machine parameters.

#### Model detail level

Select between the detailed and the average-value inverter.

#### Mechanical input

Allows you to select either the load torque or the motor speed as mechanical input. Note that if you select and apply a load torque, you will obtain as output the motor speed according to

# PM Synchronous Motor Drive

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the following differential equation that describes the mechanical system dynamics:

$$T_e = J \frac{d}{dt} \omega_r + F \omega_r + T_m$$

This mechanical system is included in the motor model.

However, if you select the motor speed as mechanical input then you will get the electromagnetic torque as output, allowing you to represent externally the mechanical system dynamics. Note that the internal mechanical system is not used with this mechanical input selection and the inertia and viscous friction parameters are not displayed.

See for example “Mechanical Coupling of Two Motor Drives”.



## Converters and DC Bus Tab

PM Synchronous Motor Drive

The PM synchronous motor parameters are specified in the PMSM tab. The braking chopper, the diode rectifier and the inverter switches parameters are specified in the Converters and DC bus tab. Vector controller and speed controller parameters are specified in the controller tab.

Permanent Magnet Synchronous Machine    Converters and DC bus    Controller

**Rectifier**

**Snubbers**

Resistance (ohm): 10e3

Capacitance (F): 20e-9

**Diodes**

On-state resistance (ohm): 1e-3

Forward voltage (V): 1.3

**DC Bus**

Capacitance (F): 2000e-6

**Braking chopper**

Resistance (ohm): 8

Chopper frequency (Hz): 4000

Activation voltage (V): 320

Shutdown voltage (V): 310

**Inverter**

**Switches**

Device type: IGBT / Diodes

On-state resistance (ohm): 1e-3

**Forward voltages (V)**

Main device: 0.8

Diode: 0.8

**Turn-off characteristics**

Fall time (s): 1e-6

Tail time (s): 2e-6

**Snubbers**

Resistance (ohm): 5000

Capacitance (F): inf

Model detail level: Detailed    Mechanical input: Torque Tm

Parameters file options

Load    Save

OK    Cancel    Help    Apply

### Rectifier section

The rectifier section of the Converters and DC bus tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the Universal Bridge for more information on the universal bridge parameters.

### Inverter section

The inverter section of the Converters and DC bus tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the Universal Bridge for more information on the universal bridge parameters.

# PM Synchronous Motor Drive

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The average-value inverter uses the following parameters.

## **Source frequency**

The frequency of the three-phase voltage source (Hz).

## **On-state resistance**

The on-state resistance of the inverter devices (ohms).

## **DC Bus Field — Capacitance**

The DC bus capacitance (F).

## **Braking Chopper Section**

### **Resistance**

The braking chopper resistance used to avoid bus over-voltage during motor deceleration or when the load torque tends to accelerate the motor (ohms).

### **Frequency**

The braking chopper frequency (Hz).

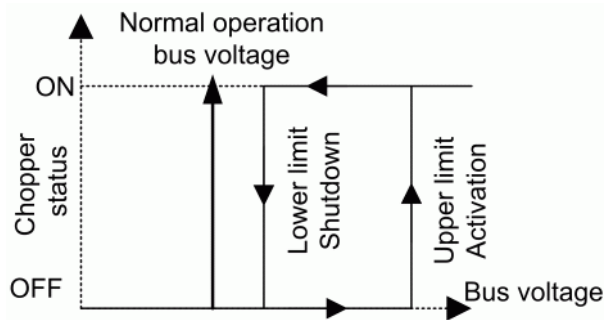
### **Activation Voltage**

The dynamic braking is activated when the bus voltage reaches the upper limit of the hysteresis band. The following figure illustrates the braking chopper hysteresis logic.

### **Deactivation Voltage**

The dynamic braking is shut down when the bus voltage reaches the lower limit of the hysteresis band. The chopper hysteresis logic is shown in the following figure.

# PM Synchronous Motor Drive



## Controller Tab

PM Synchronous Motor Drive

PM Synchronous Motor Drive

The PM synchronous motor parameters are specified in the PMSM tab. The braking chopper, the diode rectifier and the inverter switches parameters are specified in the Converters and DC bus tab. Vector controller and speed controller parameters are specified in the controller tab.

Permanent Magnet Synchronous Machine   Converters and DC bus   **Controller**

Regulation type:    Schematic

Speed controller

Speed ramps (rpm/s)

Acceleration:	Deceleration:	Speed cutoff frequency (Hz):	Speed controller sampling time (s):
<input type="text" value="1000"/>	<input type="text" value="-1000"/>	<input type="text" value="100"/>	<input type="text" value="7*20e-6"/>

PI regulator

Proportional gain:	Integral gain:	Torque output limits (N-m)	
<input type="text" value="5"/>	<input type="text" value="100"/>	Negative:	Positive:
		<input type="text" value="-17.8"/>	<input type="text" value="17.8"/>

Vector control

Sampling time (s):	Current controller hysteresis band (A):	Maximum switching frequency (Hz):
<input type="text" value="20e-6"/>	<input type="text" value="0.1"/>	<input type="text" value="20e3"/>

Model detail level:    Mechanical input:

Parameters file options

# PM Synchronous Motor Drive

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## **Regulation Type**

This pop-up menu allows you to choose between speed and torque regulation.

## **Schematic Button**

When you press this button, a diagram illustrating the speed and vector controllers schematics appears.

## **Speed Controller section**

### **Speed cutoff frequency**

The speed measurement first-order low-pass filter cutoff frequency (Hz). This parameter is used in speed regulation mode only.

### **Speed controller sampling time**

The speed controller sampling time (s). The sampling time must be a multiple of the simulation time step.

### **Speed Ramps — Acceleration**

The maximum change of speed allowed during motor acceleration (rpm/s). An excessively large positive value can cause DC bus under-voltage. This parameter is used in speed regulation mode only.

### **Speed Ramps — Deceleration**

The maximum change of speed allowed during motor deceleration (rpm/s). An excessively large negative value can cause DC bus overvoltage. This parameter is used in speed regulation mode only.

### **PI Regulator — Proportional Gain**

The speed controller proportional gain. This parameter is used in speed regulation mode only.

### **PI Regulator — Integral Gain**

The speed controller integral gain. This parameter is used in speed regulation mode only.

### **Torque output limits — Negative**

The maximum negative demanded torque applied to the motor by the current controller (N.m).

## Torque output limits — Positive

The maximum positive demanded torque applied to the motor by the current controller (N.m).

## Vector Controller Section

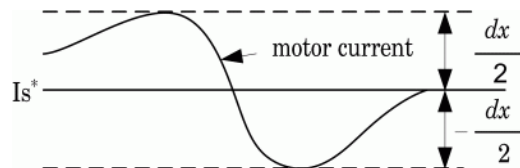
### Sampling Time

The vector controller sampling time (s). The sampling time must be a multiple of the simulation time step.

### Current controller hysteresis band

The current hysteresis bandwidth. This value is the total bandwidth distributed symmetrically around the current set point (A). The following figure illustrates a case where the current set point is  $I_s^*$  and the current hysteresis bandwidth is set to  $dx$ .

This parameter is not used when using the average-value inverter.



**Note** This bandwidth can be exceeded because a fixed-step simulation is used. A rate transition block is needed to transfer data between different sampling rates. This block causes a delay in the gate signals, so the current may exceed the hysteresis band.

### Maximum switching frequency

The maximum inverter switching frequency (Hz). This parameter is not used when using the average-value inverter.

# PM Synchronous Motor Drive

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## Block Inputs and Outputs

SP	The speed or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration / deceleration ramps. If the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.
Tm or Wm	The mechanical input: load torque (Tm) or motor speed (Wm).
A, B, C	The three phase terminals of the motor drive.
Wm or Te	The mechanical output: motor speed (Wm) or electromagnetic torque (Te).
Motor	The motor measurement vector. This vector allows you to observe the motor's variables using the Bus Selector block.
Conv	The three-phase converters measurement vector. This vector contains: <ul style="list-style-type: none"><li>• The DC bus voltage</li><li>• The rectifier output current</li><li>• The inverter input current</li></ul> Note that all current and voltage values of the bridges can be visualized with the Multimeter block.
Ctrl	The controller measurement vector. This vector contains: <ul style="list-style-type: none"><li>• The torque reference</li><li>• The speed error (difference between the speed reference ramp and actual speed)</li></ul>

# PM Synchronous Motor Drive

- The speed reference ramp or torque reference

## Model Specifications

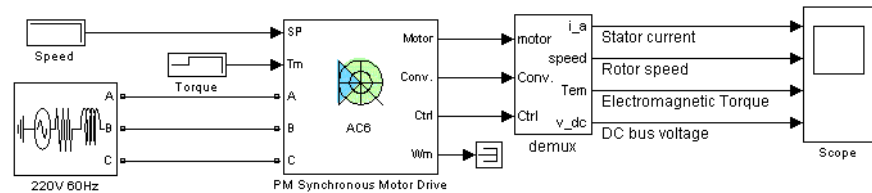
The library contains a 3 hp drive parameter set. The specifications of the 3 hp drive are shown in the following table

### 3 HP Drive Specifications

Drive Input Voltage		
Amplitude		220 V
Frequency		60 Hz
Motor Nominal Values		
Power		3 hp
Speed		1800
Voltage		300

## Example

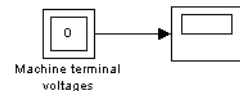
The `ac6_example` demo illustrates an AC6 motor drive simulation with standard load condition. At time  $t = 0$  s, the speed set point is 300 rpm.



Discrete,  
Ts = 2e-006 s.  
powergui

### PM Synchronous Motor Drive during speed regulation

See also '`ac6_example_simplified.mdl`' for average-value model

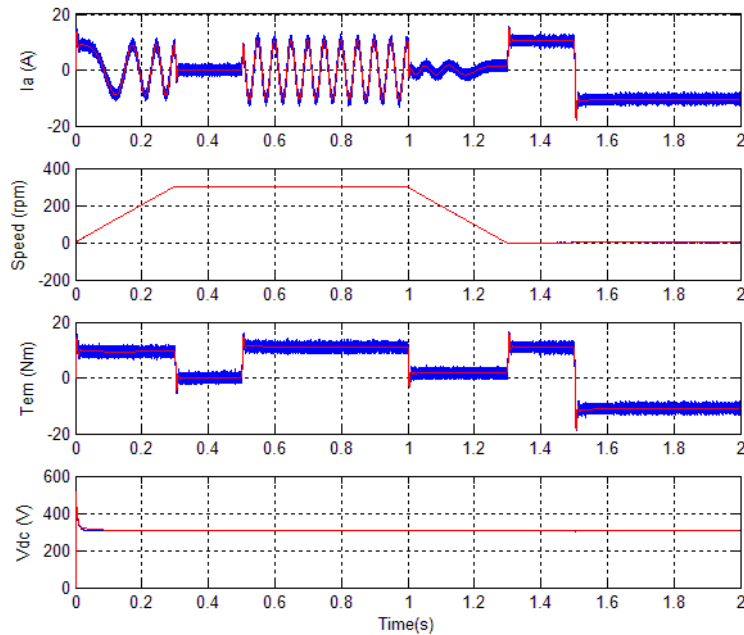


The 'Ts' parameter used in this model is set to 2e-6 by the Model Properties Callbacks

More Info

# PM Synchronous Motor Drive

As shown in the following figure, the speed precisely follows the acceleration ramp. At  $t = 0.5$  s, the nominal load torque is applied to the motor. At  $t = 1$  s, the speed set point is changed to 0 rpm. The speed decreases to 0 rpm. At  $t = 1.5$  s., the mechanical load passes from 11 N.m to -11 N.m. Average voltage, current, torque, and speed values are identical for both models. Notice that the higher frequency signal components are not represented with the average-value converter.



**AC6 Example Waveforms (Blue: Detailed Converter, Red: Average-Value Converter)**

## References

- [1] Bose, B. K., *Modern Power Electronics and AC Drives*, Prentice-Hall, N.J., 2002.
- [2] Krause, P. C., *Analysis of Electric Machinery*, McGraw-Hill, 1986.



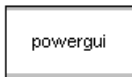
## Purpose

Graphical user interface for analysis of circuits and systems and environment block for SimPowerSystems models

## Library

powerlib

## Description



The Powergui block is necessary for simulation of any Simulink model containing SimPowerSystems blocks. It is used to store the equivalent Simulink circuit that represents the state-space equations of the model.

You must follow these rules when using this block in a model:

- Place the Powergui block at the top level of diagram for optimal performance. However, you can place it anywhere inside subsystems for your convenience; its functionality will not be affected.
- You can have a maximum of one Powergui block per model
- You must name the block `powergui`

## What the Powergui Block Does

The main purpose of the Powergui block is to provide useful graphical user interface (GUI) tools for the analysis of SimPowerSystems models. It allows you to choose one of the following methods to solve your circuit:

- Continuous method, which uses a variable step Simulink solver
- Discretization of the electrical system for a solution at fixed time steps
- Phasor solution method

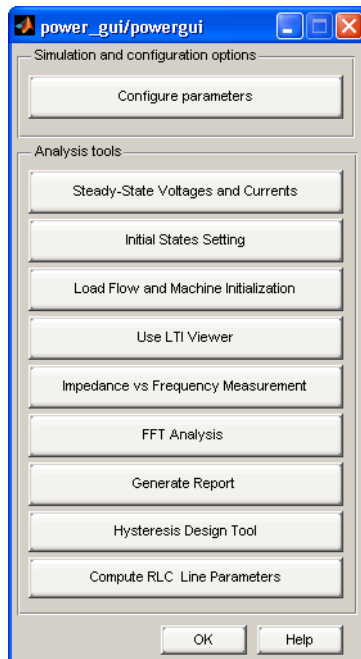
The Powergui block also allows you to

- Display steady-state values of measured current and voltages as well as all state variables (inductor currents and capacitor voltages) in a circuit.
- Modify the initial electrical states in order to start the simulation from any initial conditions. The names of the electrical state variables are the name of the block where the capacitor or the

inductor is found, preceded by the `Uc_` label for capacitor voltages and by the `IL_` label for the inductor currents.

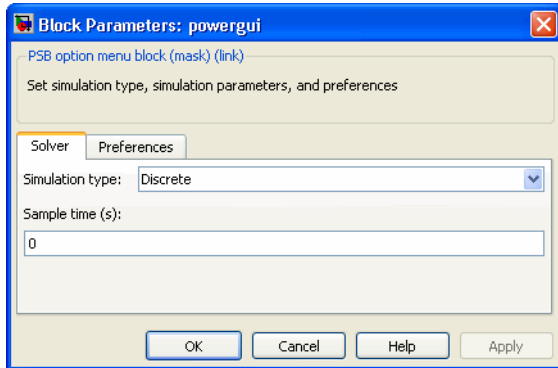
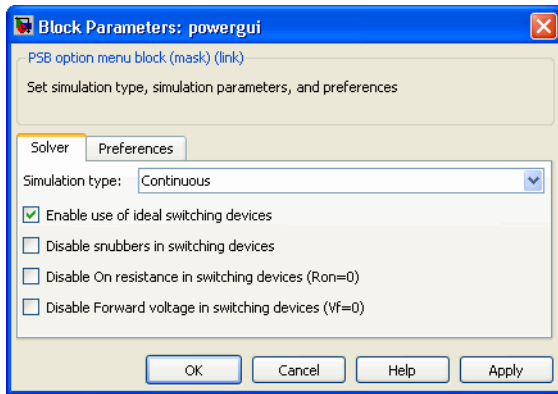
- Perform load flows and initialize three-phase networks containing three-phase machines so that the simulation starts in steady state. This option is available with circuits containing the following types of machines: Simplified Synchronous Machine, Synchronous Machine, or Asynchronous Machine (squirrel cage) blocks.
- Display impedance versus frequency plots when Impedance Measurement blocks are present in your circuit.
- Perform FFT analysis of the simulation results.
- Generate the state-space model (SS) of your system (if you have Control System Toolbox software installed) and automatically open the LTI Viewer interface for time and frequency domain responses.
- Generate a report containing steady-state values of the measurement blocks, the sources, the nonlinear models, and the states of your circuit. The report is saved in a file with the `.rep` extension.
- Model the hysteresis characteristic of the Saturable Transformer blocks.

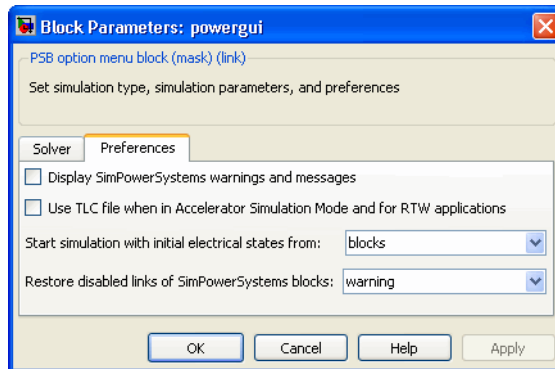
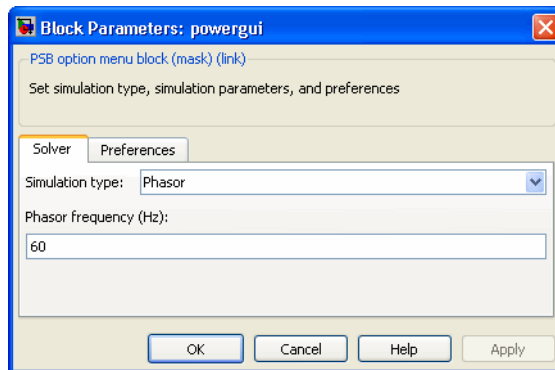
## Dialog Box and Parameters



## Simulation and Configuration Options

To specify the simulation type, parameters, and preferences, select **Configure parameters** in the Powergui dialog. This opens another dialog box with the Powergui block parameters. This dialog box contains two tabs, **Solver** and **Preferences**. The configuration of the **Solver** tab depends on the option selected from the **Simulation type** drop-down list.





## Simulation type

Select **Continuous** to perform a continuous solution of the model.

Select **Discrete** to perform a discretization of the model. The sample time is specified by the **Sample time** parameter.

Select **Phasor** to perform phasor simulation of the model, at the frequency specified by the **Phasor frequency** parameter.

## Enable use of ideal switching devices

If selected, the switches and power electronic blocks are modeled by an alternative method allowing ideal or quazi-ideal switches.

For more information, see “Using the Ideal Switching Device Method”. This parameter is visible only when the **Simulation type** parameter is set to Continuous.

### **Disable snubbers in switching devices**

If selected, the snubber devices of the power electronic and breaker blocks in your model are disabled and not modeled. This parameter is visible only if **Enable use of ideal switching devices** is selected.

### **Disable On resistance in switching devices (Ron=0)**

If selected, the internal resistance  $R_{on}$  of switches and power electronic devices is disabled and forced to zero ohms. This parameter is visible only if **Enable use of ideal switching devices** is selected.

### **Disable Forward voltage in switching devices (Vf=0)**

If selected, the internal forward voltage  $V_f$  of power electronic devices is disabled and forced to zero volts. This parameter is visible only if **Enable use of ideal switching devices** is selected.

### **Sample time (s)**

Specify the sample time used to discretize the electrical circuit. This parameter is visible only when the **Simulation type** parameter is set to Discrete.

The **Sample time** parameter must be set to a value greater than 0. The icon displays the value of the sample time.

### **Phasor frequency (Hz)**

Specify the frequency used by the software to perform the phasor simulation of the model. This parameter is visible only when the **Simulation type** parameter is set to Phasor.

### **Display SimPowerSystems warnings and messages**

If selected, the command line echo messages are enabled during the analysis and simulation of the model.

## **Use TLC file when in Accelerator Simulation Mode and for RTW applications**

If selected, TLS state-space S-function (`sfun_spsw_discc.tlc`) will be used in Accelerator mode and for code generation.

Clear this box if you notice a slowdown in performance when using Accelerator mode, compared to previous releases. This slowdown is observed if you have the `lcc` compiler installed as the default compiler for building external interface (`mex`).

## **Start simulation with initial electrical states from**

If `blocks` is selected, initial state values defined in blocks are used for the simulation.

If `steady` is selected, force all initial electrical state values to steady-state values.

If `zero` is selected, force all initial electrical state values to zero.

## **Restore disabled links of SimPowerSystems blocks**

If `yes` is selected, the Powergui block detects SimPowerSystems blocks that have a disabled link at the simulation start and restores the link automatically.

If `warning` is selected, the Powergui block detects SimPowerSystems blocks that have a disabled link at the simulation start and displays a warning.

If `no` is selected, SimPowerSystems blocks with disabled links will not be detected and relinked.

## **Analysis Tools**

### **Steady-State Voltages and Currents**

Open a window that displays the steady-state voltages and currents of the model.

### **Initial States Setting**

Open a window that allows you to display and modify initial capacitor voltages and inductor currents of the model.

## **Load Flow and Machine Initialization**

Open a window to perform load flow and machine initialization.

## **Use LTI Viewer**

Open a window to use the LTI Viewer, provided with Control System Toolbox software.

## **Impedance vs Frequency Measurement**

Open a window that allows you to display the impedance versus frequency measurements performed by the Impedance Measurement blocks of the model.

## **FFT Analysis**

Open a window to use the FFT analysis tool.

An example of using the FFT tool is described in “Performing Harmonic Analysis Using the FFT Tool”.

## **Generate Report**

Open a window and generate a report of the steady-state calculations.

## **Hysteresis Design Tool**

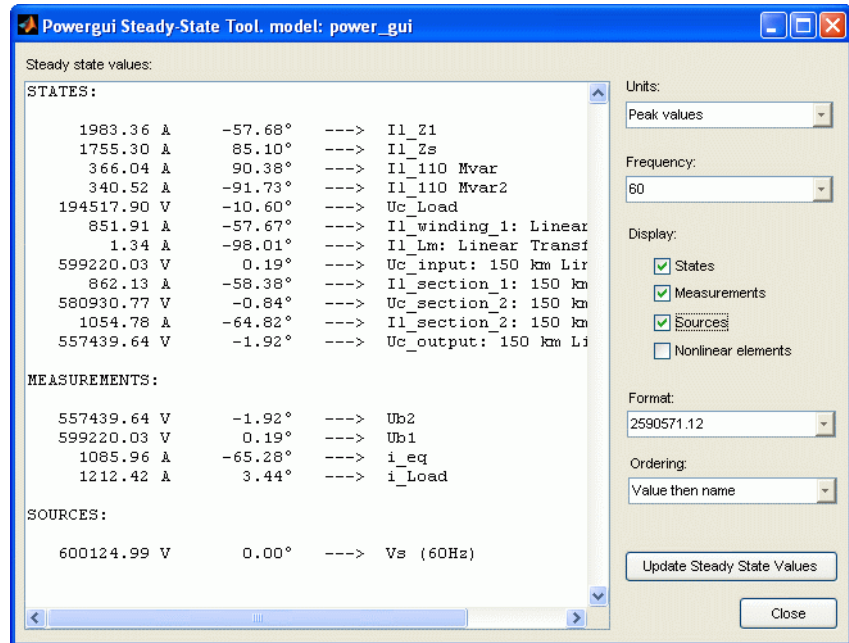
Open a window to design a hysteresis characteristic for the saturable core of the Saturable Transformer block and the Three-Phase Transformer blocks (two- and three-windings).

## **Compute RLC Line Parameters**

Open a window to compute RLC parameters of overhead transmission line from its conductor characteristics and tower geometry.



## Steady-State Voltages and Currents GUI



### Steady state values

Display measurements of steady-state voltages and currents in the model.

### Units

Set the **Units** parameter to **Peak** values to display the peak values of the selected values. Set the **Units** parameter to **RMS** to display the root-mean-square (RMS) values of the selected values.

### Frequency

Allows you to choose the frequency, in hertz (Hz), that you want for display of the voltage and current phasors. The **Frequency** parameter lists all the different frequencies of the electrical sources of the model.

## **States**

If selected, the window displays the steady-state phasors of the capacitor voltages and inductor currents of the circuit. The default is unselected.

## **Measurements**

If selected, the window displays the steady-state voltage and current phasors of the measurement blocks of the circuit. The default is selected.

## **Sources**

If selected, the window displays the steady-state voltage and current phasors of the electrical sources of the circuit. The default is unselected.

## **Nonlinear elements**

If selected, the window displays the steady-state voltages and currents of the nonlinear blocks of the circuit. The default is unselected.

## **Format**

In the pull-down menu, choose the format in which you want your measurements displayed. The `floating point` option is displayed in mantissa-exponent form with five significant figures. The `best of` option displays with four significant figures and uses mantissa-exponent form only for numbers larger than 9999. The final option is displayed in plain numbers with two figures to the right of the decimal point. The default is `floating point`.

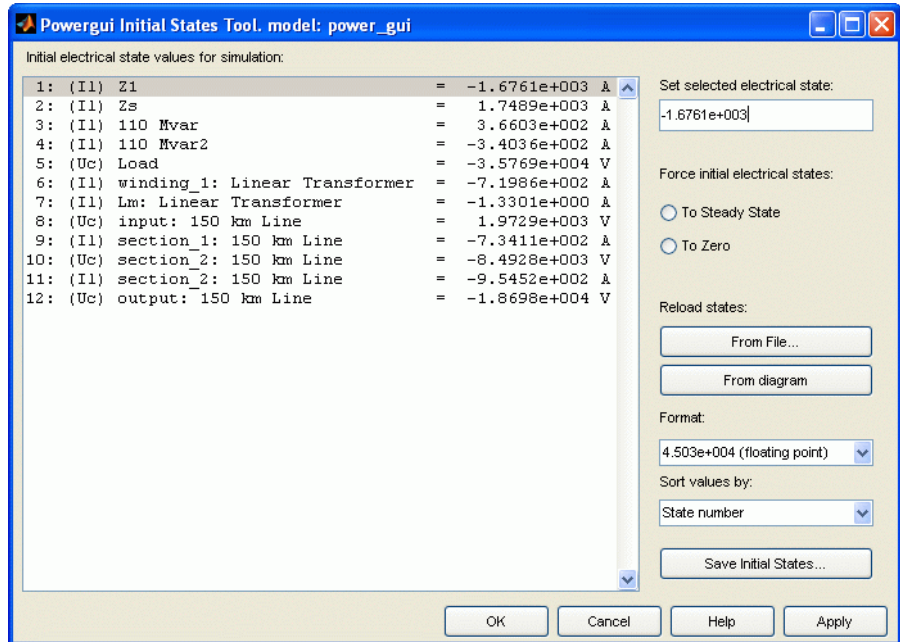
## **Ordering**

In the pull-down menu, choose the ordering in which you want your measurements displayed. The `Value then name` option displays the steady-state values in the first column followed by the names of the states variables. The `Name then value` option displays the name of the states variables in the first column followed by the steady-state values.

## **Update Steady State Values**

Recompute and display the steady-state measurements.

## Initial States Setting GUI



### Initial state values for simulation

Display names of model state variables and their initial values.

### Set selected state

Enter a value here to set the initial value of the variable selected in the **Initial state values for simulation** list.

### Force initial electrical states

If **To Steady State** is selected, force all initial electrical state values to steady-state values. When this option is selected, the **Set selected state** option is disabled, because all states are forced to steady-state values.

If **To Zero** is selected, force all initial electrical state values to zero. When this option is selected, the **Set selected state** option is disabled, because all states are forced to zero. If you want to set all states to zero, and then set one or several states to something else, do this by using the **Set selected state** option: first, select all states, enter 0, and click **Apply**; then select the states that you want to set to something else and modify their values individually.

If neither **To Steady State** nor **To Zero** is selected, initial state values defined in blocks are used for the simulation.

### Reload states

If **From File** is selected, allows you to choose a previously saved file storing the model's states. If **From Diagram** is selected, sets all initial state values to their current values (either steady state values or last modified values).

### Format

In the pull-down menu, choose the format in which you want your measurements displayed. The **floating point** option is displayed in mantissa-exponent form with five significant figures. The **best of** option displays with four significant figures and uses mantissa-exponent form only for numbers larger than 9999. The **final** option is displayed in plain numbers with two figures to the right of the decimal point. The default is **floating point**.

### Sort values by

Select order of displayed initial state values. Selecting **Default** order displays the value by block order in the diagram. Selecting **State number** displays the values according to the states' ordering in the state-space model. Selecting **Type** displays the values grouped by capacitors and inductors. The default is **Default order**.

### Save Initial States

Save the model's initial state settings in a file.

### Sign Conventions for Voltages and Currents

Unlike Simulink signal lines and input and output ports, the Physical Modeling connection lines and terminal ports  $\square$  lack intrinsic directionality. The voltage and current polarities are determined, not by line direction, but instead by block orientation. To find out a block orientation, first click on the block to select it. Then enter the following command:

```
get_param(gcf, 'Orientation')
```

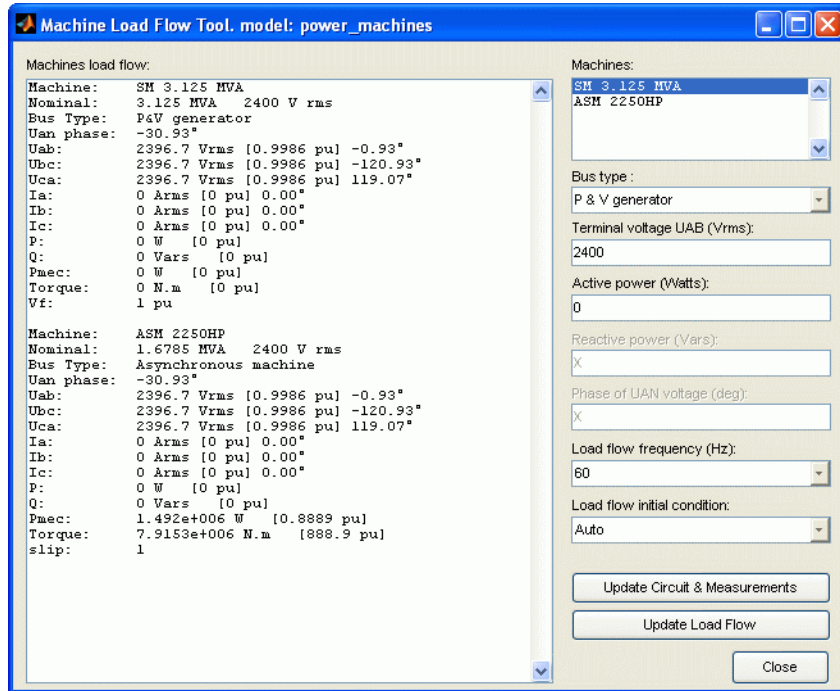
The following table indicates the polarities of the currents and voltages for single-phase and three-phase RLC elements (branches or loads), surge arresters, and single-phase and three-phase breakers. The table also indicates the polarities of their state variables (inductor currents and capacitor voltages).

Block Orientation	Positive Current Direction	Measured Voltage
right	left $\rightarrow$ right	$V_{\text{left}} - V_{\text{right}}$
left	right $\rightarrow$ left	$V_{\text{right}} - V_{\text{left}}$
down	top $\rightarrow$ bottom	$V_{\text{top}} - V_{\text{bottom}}$
up	bottom $\rightarrow$ top	$V_{\text{bottom}} - V_{\text{top}}$

The natural orientation of the blocks (that is, their orientation in the Element library) is *right* for horizontal blocks and *down* for vertical blocks.

For single-phase transformers (linear or saturable), with the winding connectors appearing on the left and right sides, the winding voltages are the voltages of the top connector with respect to the bottom connector whatever the block orientation (*right* or *left*). The winding currents are the currents entering the top connector. For three-phase transformers, the voltage polarities and positive current directions are indicated by the signal labels used in the Multimeter block.

## Load Flow and Machine Initialization GUI



### Machine load flow

Displays load flow characteristics of the machine selected in the **Machines** field.

### Machines

Display the names of the Simplified Synchronous Machines, the Synchronous Machines, the Asynchronous Machine, and the Three-Phase Dynamic Load blocks of your model. Select a machine or a load in the list box in order to set its parameters for the load flow.

## **Bus type**

If **Bus type** is set to P&V Generator, you can set the desired terminal voltage and active power of the machine. If **Bus type** is set to PQ generator, you can set the desired active and reactive powers. If **Bus type** is set to Swing Bus, you can set the desired terminal voltage, enter an active power guess, and specify the phase of the UAN terminal voltage of the machine.

If you select an Asynchronous Machine block machine, you only have to enter the desired mechanical power delivered by the machine. If you select a Three-Phase Dynamic Load block, you have to specify the active and reactive powers consumed by the load.

## **Terminal voltage UAB**

Specify the terminal line-to-line voltage of the selected machine.

## **Active power**

Specify the active power of the selected machine or load.

## **Active power guess**

Specify active power guess to start iterations when the specified machine bus type is Swing Bus.

## **Reactive power**

Specify the reactive power of the selected machine or load.

## **Phase of UAN voltage**

This parameter is activated only when the bus type is Swing Bus.

Specify the phase of the phase-to-neutral voltage of phase A of the selected machine.

## **Mechanical power**

In motor mode, specify the mechanical power developed by the squirrel cage induction machine. In generator mode, specify the mechanical power absorbed by the machine as a negative number.

## **Load flow frequency**

Specify the frequency to be used in the load flow calculations (normally 60 Hz or 50 Hz).

## **Load flow initial condition**

Normally, you should keep the default setting **Auto** to let the load flow automatically adjust the initial conditions before starting iterations. If you select **Start from previous solution**, the load flow starts with initial conditions corresponding to the previous solution. Try this option if the load flow fails to converge after a change has been made to the power and voltage settings of the machines or to the circuit parameters.

## **Update Circuit & Measurements**

Update the list of machines, voltage and current phasors, as well as the powers in the load flow window if you have made a change in your model while the load flow window is open. The new voltages and powers displayed in the load flow window are computed by using the machine currents obtained from the last load flow (the three currents stored in the **Initial conditions** parameter of the machine blocks).

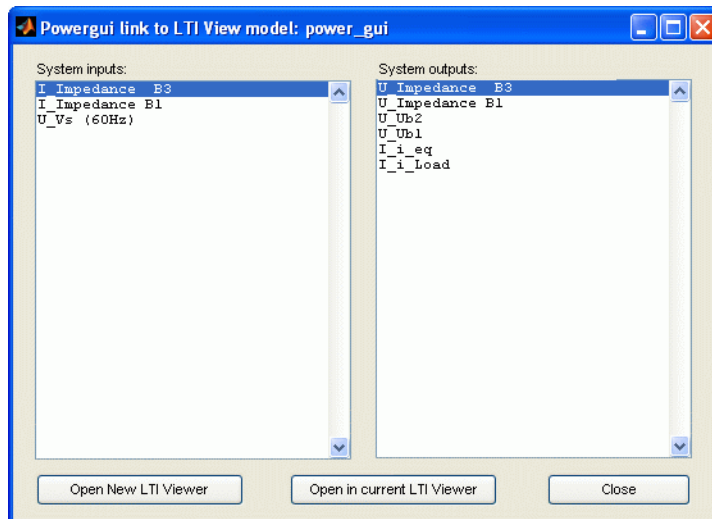
## **Update Load Flow**

Executes the load flow calculations for the given load flow parameters.

## **Use LTI Viewer GUI**

This tool can be used to create a state-space object (SS) of the linear part of the electrical circuit (ABCD state-space matrices representing the RLC devices in the model). All the nonlinear elements, such as the distributed parameter line blocks, will be considered as inputs and outputs to the SS object (because they are modeled as current source in feedback to the state-space system). You can analyze the time and frequency responses of this SS object with the LTI Viewer tools.





### System inputs

Lists the inputs of the state-space model of your circuit. Select the inputs to be used by the LTI Viewer.

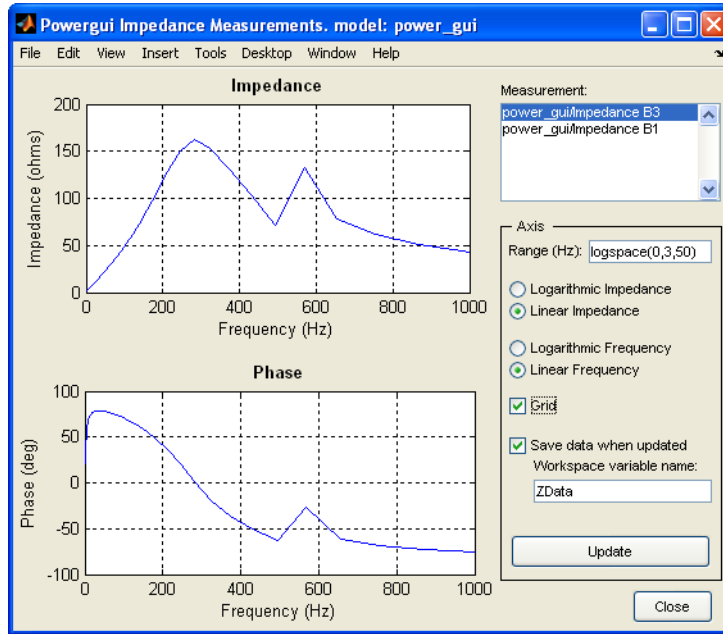
### System outputs

Lists the outputs of the state-space model of your circuit. Select the outputs to be used by the LTI Viewer.

### Open New LTI Viewer

Generate the state-space model of the circuit and opens the LTI viewer for the selected system inputs and outputs.

## Impedance vs Frequency Measurement GUI



### Measurement

Lists the Impedance Measurement blocks of the model. Select the blocks for which you want to obtain the frequency response. Use the **CTRL** key to select several impedances to be displayed on the same plot.

### Axis

#### Range (Hz)

Specify the frequency vector, in hertz (Hz). You can specify in that field any valid MATLAB expression defining a vector of frequencies; for example, `0:2:1000` or `linspace(0,1000,500)`. The default is `logspace(0,3,50)`.

#### Logarithmic Impedance/Linear Impedance

Choose logarithmic or linear scale for the vertical impedance scale.

## **Logarithmic Frequency/Linear Frequency**

Choose logarithmic or linear scale for the horizontal frequency scales.

## **Grid**

If selected, a grid is displayed for the two plots. Default is unselected.

## **Save data when updated**

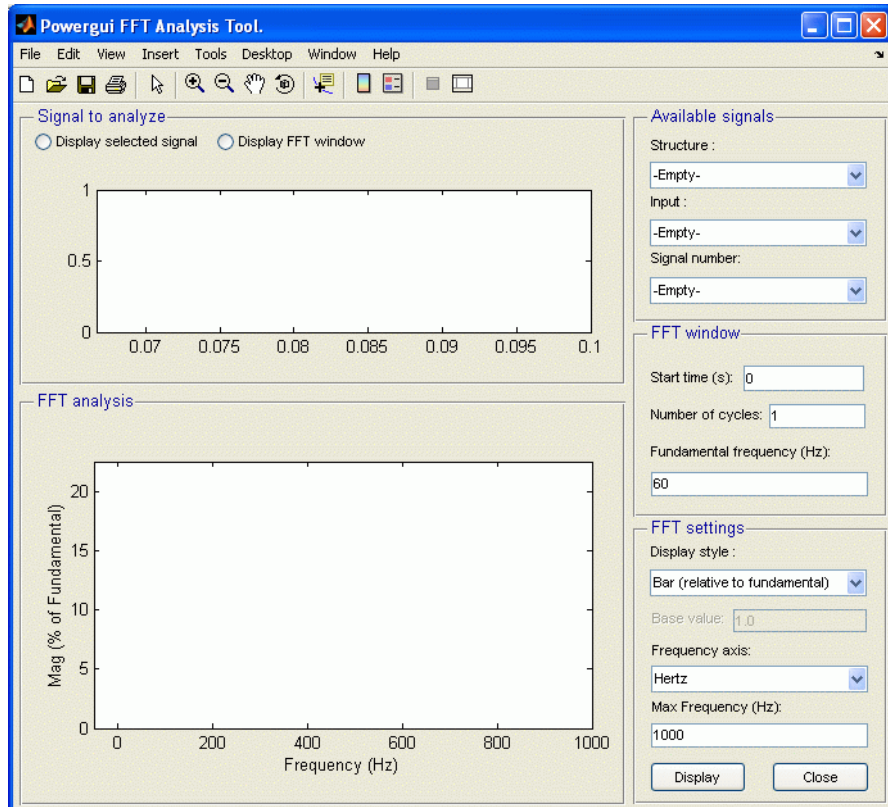
If selected, data are saved in a variable in the workspace. The name of the variable is defined by the **Workspace variable name** parameter. The complex impedances are saved in an array together with the corresponding frequencies. Frequency is saved in column 1 and impedances are saved in the next columns. Default is unselected.

## **Display/Save or Update**

Click to initially display the impedance versus frequency measurement and, if the **Save data when updated** check box is selected, save the data to your workspace.

Click to start the impedance versus frequency measurement again and display results after multiple runs of your model.

## FFT Analysis GUI



### Display selected signal

If selected, display in the upper plot the signal selected by the **Structure**, **Input**, and **Signal number** parameters.

### Display FFT window

If selected, display in the upper plot the portion of the selected signal where the FFT analysis is performed.

## Structure

Lists the structures with time variables that are present in your workspace. You first need to run a simulation of your model. These structures are generated by the Scope or To Workspace blocks in your model. The signals must be sampled at a fixed rate, by using the Scope block settings. Use the pull-down menu to select the variable you want to analyze.

## Input

Select the input signal of the selected structure with time variables specified in the **Structure** field. Structures with time variables with multiple inputs can be generated by a Scope block having multiple input ports.

## Signal Number

Specify the index of the selected input signal specified by the **Input** parameter. For example, the **Signal Number** parameter allows you to select the phase A signal of a three-phase signal connected to input 2 of a Scope block.

## Start time(s)

Specify the start times for the FFT analysis. The FFT analysis will be performed on the portion of the signal starting at the specified time and for the specified number of cycles.

## Number of cycles

Specify the number of cycles of the selected signal to analyze for the FFT analysis.

## Fundamental frequency

Specify the fundamental frequency, in hertz (Hz), as a reference frequency for the FFT analysis.

## Display style

In the pull-down menu, select **Bar (relative to fundamental)** to display the spectrum as a bar graph relative to the fundamental frequency. Select **Bar (relative to specified base)** to display the spectrum as a bar graph relative to the base defined by the **Base value** parameter.

Select **List (relative to fundamental)** to display the spectrum as a list in % relative to the fundamental or DC component. Select **List (relative to specified base)** to display the spectrum as a list in % relative to the base value defined by the **Base value** parameter.

**Base value**

Enter a base value for the display of harmonics.

**Frequency axis**

In the pull-down menu, select **Hertz** to display the spectrum frequency axis in hertz. Select **Harmonic order** to display the spectrum frequency axis in harmonic order relative to the fundamental frequency.

**Max Frequency**

Specify the maximum frequency, in hertz (Hz), for the FFT analysis.

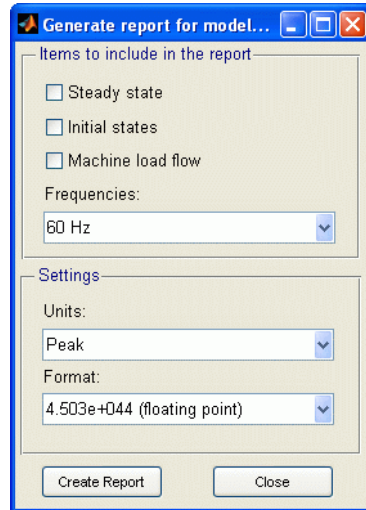
**Display**

Display in the lower plot the FFT analysis results for the selected measurement.

**Close**

Close the FFT analysis tool window.

## Generate Report GUI



### Items to include in the report

In the check boxes, select any combination of measurements to include in the generated report, **Steady state**, **Initial states**, and **Machine load flow**. The default is unselected for all three.

### Frequency to include in the report

Select the frequency or frequencies to include in the generated report, 60 Hz or All. The default is 60 Hz.

### Units

Set the **Units** parameter to **Peak** values to display the peak values of the selected values. Set the **Units** parameter to **RMS** to display the root-mean-square (RMS) values of the selected values.

### Format

In the pull-down menu, choose the format in which you want your measurements displayed. The **floating point** option is displayed in mantissa-exponent form with five significant figures. The **best of** option is displayed with four significant figures and

uses mantissa-exponent form only for numbers larger than 9999. The final option is displayed in plain numbers with two figures to the right of the decimal point. The default is floating point.

## **Create Report**

Generate a report and save it to a file.

## **Hysteresis Design Tool**

To learn more about hysteresis design tool, see the `power_hysteresis` reference page.

## **Compute RLC Line Parameters**

To learn more about computing RLC line parameters, see the `power_lineparam` reference page.

## **Example**

Open SimPowerSystems demos and double-click the Powergui block contained in the model. For each demo, you can use the tools of the Powergui to look at the initial values and steady-state values of the inductor currents and capacitor voltages. For demos containing machines, you can edit and perform a machine load flow analysis.

## **See Also**

Multimeter, Saturable Transformer, `power_init`



**Purpose** Generate pulses for carrier-based two-level pulse width modulator (PWM) in converter bridge

**Library** Extras/Control Blocks  
A discrete version of this block is available in the Extras/Discrete Control Blocks library.

## Description



The PWM Generator block generates pulses for carrier-based pulse width modulation (PWM) converters using two-level topology. The block can be used to fire the forced-commutated devices (FETs, GTOs, or IGBTs) of single-phase, two-phase, three-phase, two-level bridges or a combination of two three-phase bridges.

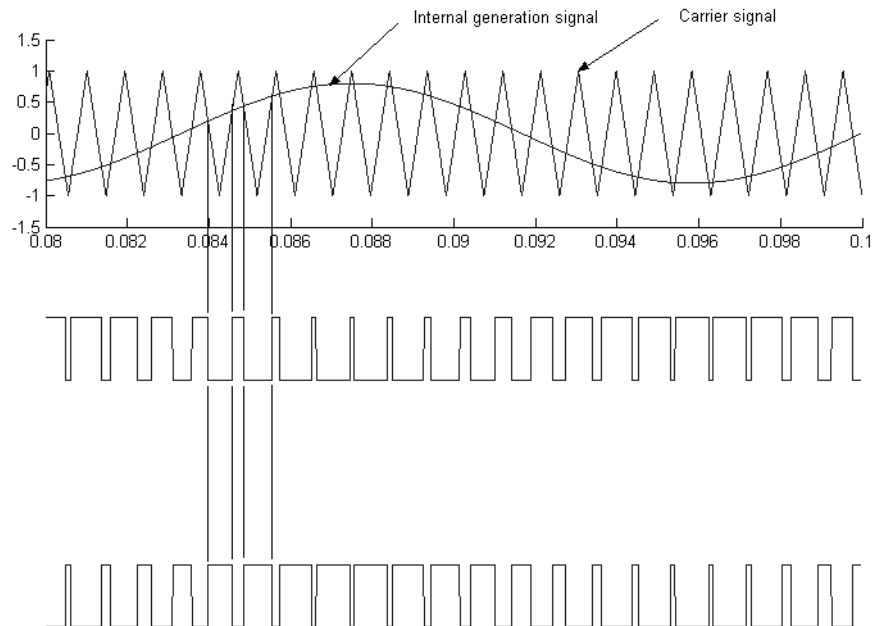
The pulses are generated by comparing a triangular carrier waveform to a reference modulating signal. The modulating signals can be generated by the PWM generator itself, or they can be a vector of external signals connected at the input of the block. One reference signal is needed to generate the pulses for a single- or a two-arm bridge, and three reference signals are needed to generate the pulses for a three-phase, single or double bridge.

The amplitude (modulation), phase, and frequency of the reference signals are set to control the output voltage (on the AC terminals) of the bridge connected to the PWM Generator block.

The two pulses firing the two devices of a given arm bridge are complementary. For example, pulse 4 is low (0) when pulse 3 is high (1). This is illustrated in the next two figures.

The following figure displays the two pulses generated by the PWM Generator block when it is programmed to control a one-arm bridge.

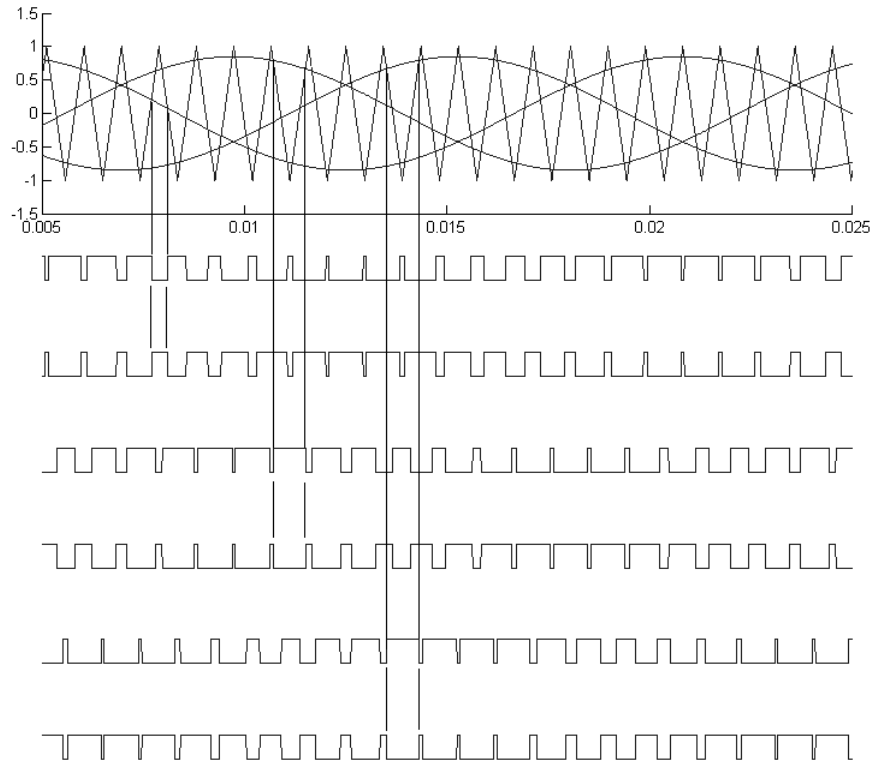
# PWM Generator



The triangular carrier signal is compared with the sinusoidal modulating signal. When the modulating signal is greater than the carrier pulse 1 is high (1) and pulse 2 is low (0).

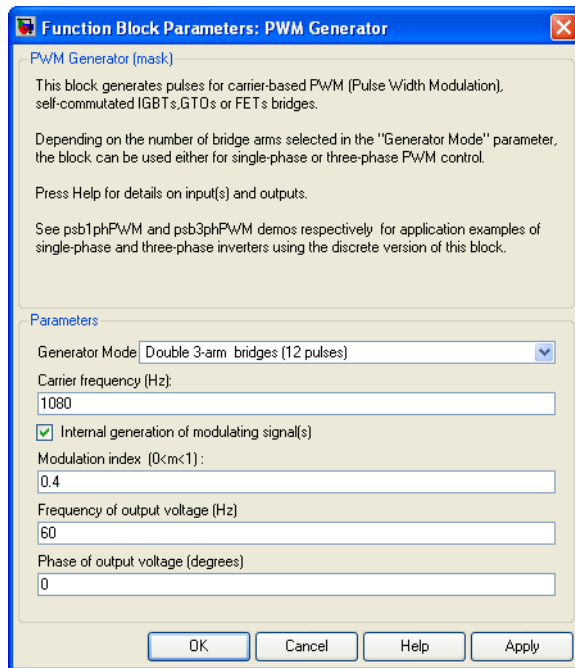
For a single-phase two-arm bridge the modulating signal used for arm 2 is the negative of modulating signal used for arm 1 (180 degrees phase shift). For a three-phase six-arm bridge the three modulating signals used for bridge 2 are the negative of the modulating signals applied to bridge 1.

The following figure displays the six pulses generated by the PWM Generator block when it is programmed to control a three-arm bridge.



# PWM Generator

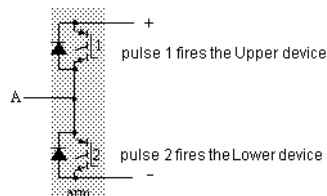
## Dialog Box and Parameters



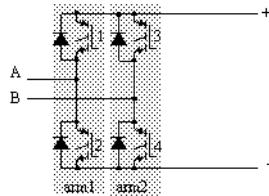
### Generator Mode

Specify the number of pulses to generate. The number of pulses is proportional to the number of bridge arms to fire.

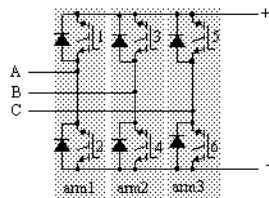
Select 1-arm bridge (2 pulses) to fire the self-commutated devices of a one-arm bridge. Pulse 1 fires the upper device and pulse 2 fires the lower device.



Select 2-arm bridge (4 pulses) to fire the self-commutated devices of a two-arm bridge. Four pulses are generated for a two-arm bridge. Pulses 1 and 3 fire the upper devices of the first and second arm. Pulses 2 and 4 fire the lower devices.



Select 3-arm bridge (6 pulses) to fire the self-commutated devices of a three-arm bridge. Pulses 1, 3, and 5 fire the upper devices of the first, second, and third arms. Pulses 2, 4, and 6 fire the lower devices.



Select Double 3-arm bridges (12 pulses) to fire the self-commutated devices of two six-pulse bridges connected in a twelve-pulse bridge configuration. The first six pulses (1 to 6) fire the six devices of the first three-arm bridge and the last six pulses (7 to 12) fire the six devices of the second three-arm bridge.

## Carrier frequency

The frequency, in hertz, of the carrier triangular signal.

# PWM Generator

---

## **Internal generation of modulating signal**

If selected, the modulating signal is generated by the block. Otherwise, external modulating signals are used for pulse generation.

## **Modulation index ( $0 < m < 1$ )**

The **Modulation index** parameter is visible only if the **Internal generation of modulating signal (s)** parameter is selected.

The amplitude of the internal sinusoidal modulating signal. The **Modulation index** must be greater than 0, and lower than or equal to 1. This parameter is used to control the amplitude of the fundamental component of the output voltage of the controlled bridge.

## **Frequency of output voltage**

The **Frequency of output voltage (Hz)** parameter is visible only if the **Internal generation of modulating signal (s)** parameter is selected.

The frequency, in hertz, of the internal modulating signals. This parameter is used to control the fundamental frequency of the output voltage of the controlled bridge.

## **Phase of output voltage**

The **Phase of output voltage** parameter is visible only if the **Internal generation of modulating signal (s)** parameter is selected.

The phase, in degrees, of the internal modulating signal. This parameter is used to control the phase of the fundamental component of the output voltage of the controlled bridge.

## **Inputs and Outputs**

### Signal(s)

The input is not visible when **Internal generation of modulating signal (s)** is selected.

The input is the vector of modulating signals when **Internal generation of modulating signal** is not selected. Connect this input to a single-phase sinusoidal signal when the block is used to control a single- or a two-arm bridge, or to a three-phase sinusoidal signal when the PWM Generator block is controlling one or two three-phase bridges.

## Pulses

The output contains the two, four, six, or twelve pulse signals used to fire the self-commutated devices (MOSFETs, GTOs, or IGBTs) of single-phase, two-phase, or three-phase bridges or a combination of two three-phase bridges.

## Example

See the `power_1phPWM` and `power_3phPWM` demos for examples of single-phase and three-phase two-level inverters.

## See Also

Universal Bridge

**Purpose** Measure root mean square (RMS) value of signal

**Library** Extras/Measurements

A discrete version of this block is available in the Extras/Discrete Measurements library.

## Description



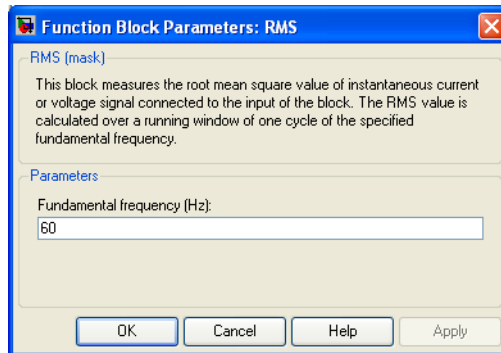
This block measures the root mean square value of an instantaneous current or voltage signal connected to the input of the block. The RMS value of the input signal is calculated over a running average window of one cycle of the specified fundamental frequency.

$$RMS(f(t)) = \sqrt{\frac{1}{T} \int_{(t-T)}^t f(t)^2 dt}$$

$f(t)$ : input signal,  $T = 1/\text{fundamental frequency}$

as this block uses a running average window, one cycle of simulation has to be completed before the output gives the correct value. The discrete version of this block allows you to specify the initial magnitude of inputs. For the first cycle of simulation the output is held to the RMS value of the specified initial input.

## Dialog Box and Parameters



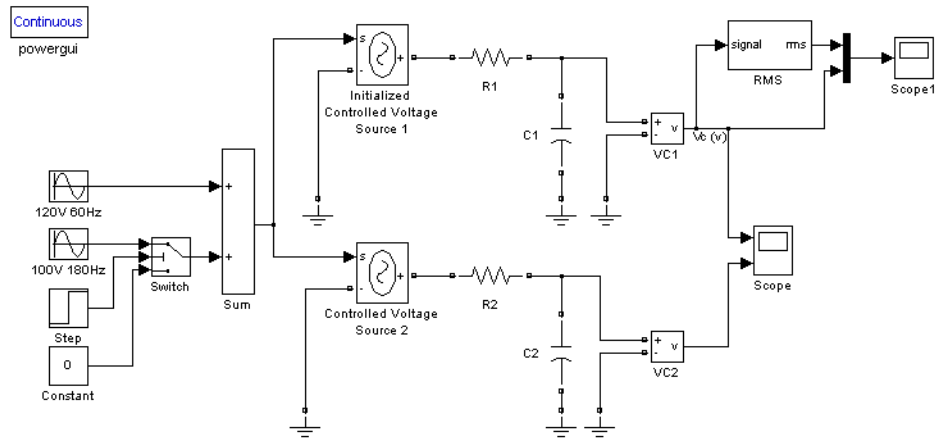


### Fundamental frequency

The fundamental frequency, in hertz, of the input signal.

### Example

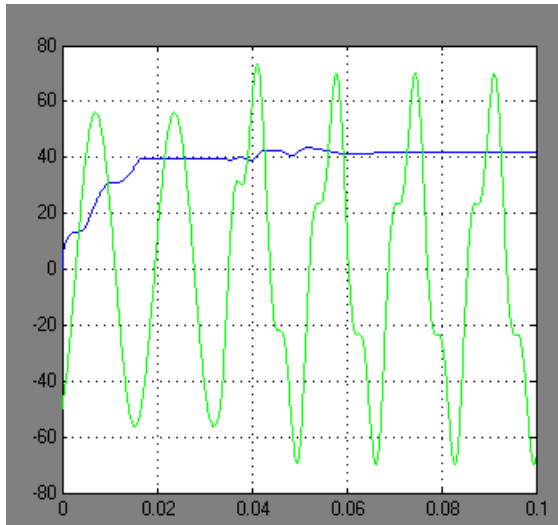
In the power\_controlvolt demo, you can add an RMS block as shown below to measure the RMS value of the capacitor voltage. The Controlled Voltage Source block introduces a third harmonic (180 Hz) in the voltage at  $t = 0.4$  seconds.



At the beginning of the simulation, the RMS block needs one cycle of the fundamental frequency (60Hz) to calculate the RMS value of the voltage. At  $t = 0.4$  seconds the RMS value slightly increases because of the addition of the third harmonic in the signal. Again, the RMS block needs one cycle of the fundamental signal to stabilize and give the correct result.

# RMS

---



## Purpose

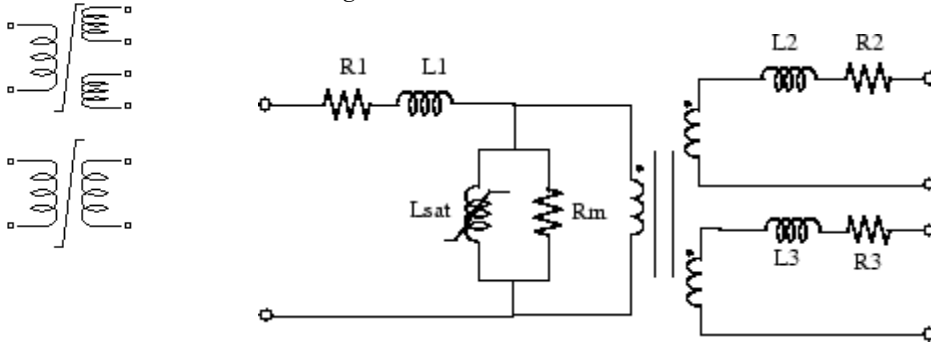
Implement two- or three-winding saturable transformer

## Library

Elements

## Description

The Saturable Transformer block model shown consists of three coupled windings wound on the same core.



The model takes into account the winding resistances ( $R_1$   $R_2$   $R_3$ ) and the leakage inductances ( $L_1$   $L_2$   $L_3$ ) as well as the magnetizing characteristics of the core, which is modeled by a resistance  $R_m$  simulating the core active losses and a saturable inductance  $L_{sat}$ .

You can choose one of the following two options for the modeling of the nonlinear flux-current characteristic

- 1 Model saturation without hysteresis. The total iron losses (eddy current + hysteresis) are modeled by a linear resistance,  $R_m$ .
- 2 Model hysteresis and saturation. Specification of the hysteresis is done by means of the **Hysteresis Design Tool** of the Powergui block. The eddy current losses in the core are modeled by a linear resistance,  $R_m$ .

# Saturable Transformer

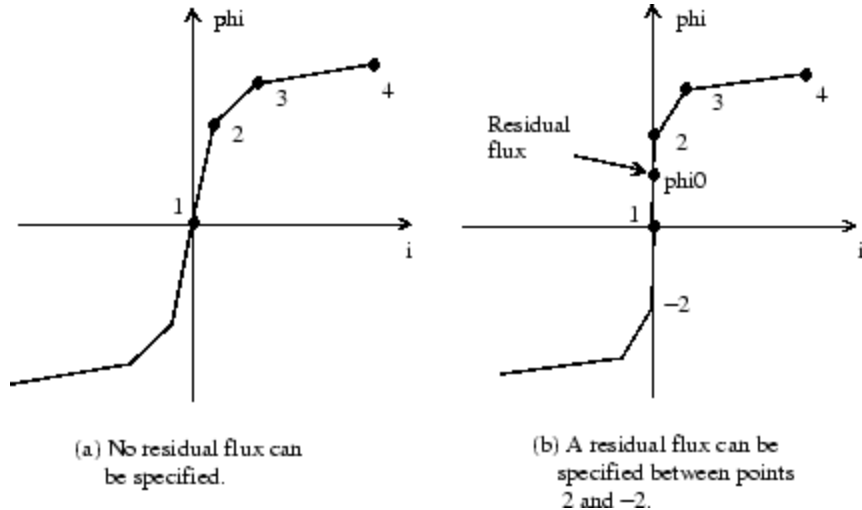
---

**Note** Modeling the hysteresis requires additional computation load and therefore slows down the simulation. The hysteresis model should be reserved for specific applications where this phenomenon is important.

---

## Saturation Characteristic Without Hysteresis

When the hysteresis is not modeled, the saturation characteristic of the Saturable Transformer block is defined by a piecewise linear relationship between the flux and the magnetization current.



Therefore, if you want to specify a residual flux,  $\phi_{i0}$ , the second point of the saturation characteristic should correspond to a null current, as shown in the figure (b).

The saturation characteristic is entered as  $(i, \phi)$  pair values in per units, starting with pair  $(0, 0)$ . The software converts the vector of fluxes  $\Phi_{pu}$  and the vector of currents  $I_{pu}$  into standard units to be used in the saturation model of the Saturable Transformer block:

$$\Phi = \Phi_{pu} \Phi_{base}$$
$$I = I_{pu} I_{base}$$

where the base flux linkage ( $\Phi_{base}$ ) and base current ( $I_{base}$ ) are the peak values obtained at nominal voltage power and frequency:

$$I_{base} = \frac{P_n}{V_1} \sqrt{2} \quad \Phi_{base} = \frac{V_1}{2\pi f_n} \sqrt{2} \text{ (Flux linkage in volts-seconds)}$$

The base flux is defined as the peak value of the sinusoidal flux (in webers) when winding 1 is connected to a 1 pu sinusoidal voltage source (nominal voltage). The  $\Phi_{base}$  value defined above represents the base flux linkage (in volt-seconds). It is related to the base flux by the following equation:

$$\Phi_{base} = \text{Base flux} \times \text{number of turns of winding 1}$$

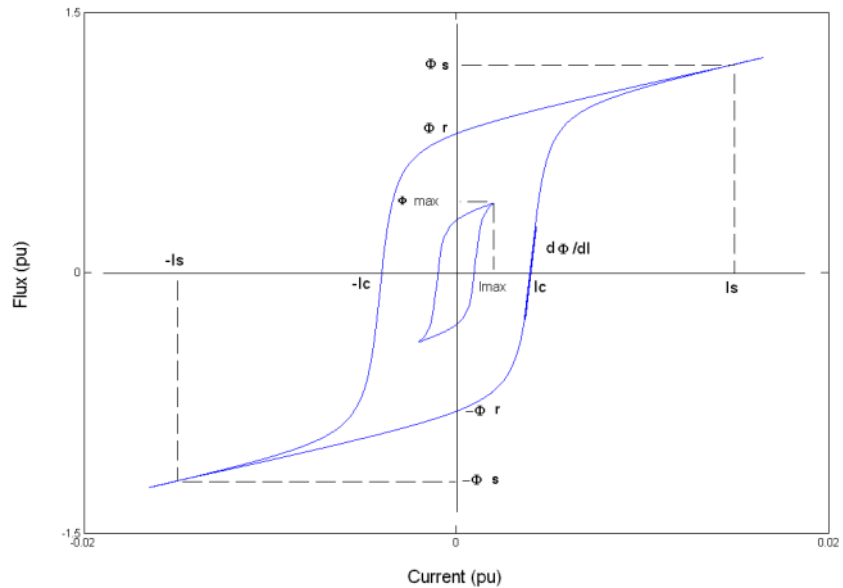
When they are expressed in pu, the flux and the flux linkage have the same value.

## Saturation Characteristic with Hysteresis

The magnetizing current  $I$  is computed from the flux  $\Phi$  obtained by integrating voltage across the magnetizing branch. The static model of hysteresis defines the relation between flux and the magnetization current evaluated in DC, when the eddy current losses are not present.

The hysteresis model is based on a semi empirical characteristic, using an arctangent analytical expression  $\Phi(I)$  and its inverse  $I(\Phi)$  to represent the operating point trajectories. The analytical expression parameters are obtained by curve fitting empirical data defining the major loop and the single-valued saturation characteristic. The **Hysteresis design tool** of the Powergui block is used to fit the hysteresis major loop of a particular core type to basic parameters. These parameters are defined by the remanent flux ( $\Phi_r$ ), the coercive current ( $I_c$ ), and the slope ( $d\Phi/dI$ ) at  $(0, I_c)$  point as shown in the next figure.

# Saturable Transformer



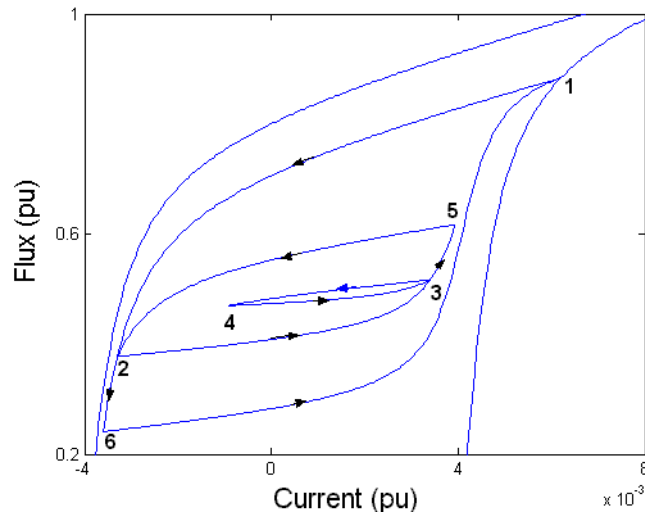
The major loop half cycle is defined by a series of N equidistant points connected by line segments. The value of N is defined in the **Hysteresis design tool** of the Powergui block. Using  $N = 256$  yields a smooth curve and usually gives satisfactory results.

The single-valued saturation characteristic is defined by a set of current-flux pairs defining a saturation curve which should be asymptotic to the air core inductance  $L_s$ .

The main characteristics of the hysteresis model are summarized below:

- 1 A symmetrical variation of the flux produces a symmetrical current variation between  $-I_{max}$  and  $+I_{max}$ , resulting in a symmetrical hysteresis loop whose shape and area depend on the value of  $\Phi_{max}$ . The major loop is produced when  $\Phi_{max}$  is equal to the saturation flux ( $\Phi_s$ ). Beyond that point the characteristic reduces to a single-valued saturation characteristic.

- 2 In transient conditions, an oscillating magnetizing current produces minor asymmetrical loops, as shown in the next figure, and all points of operation are assumed to be within the major loop. Loops once closed have no more influence on the subsequent evolution.



The trajectory starts from the initial (or residual) flux point, which must lie on the vertical axis inside the major loop. You can specify this initial flux value  $\phi_0$ , or it is automatically adjusted so that the simulation starts in steady state.

## The Per Unit Conversion

In order to comply with industry practice, you must specify the resistance and inductance of the windings in per unit (pu). The values are based on the transformer rated power  $P_n$  in VA, nominal frequency  $f_n$  in Hz, and nominal voltage  $V_n$ , in Vrms, of the corresponding winding. For each winding the per unit resistance and inductance are defined as

# Saturable Transformer

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$$R(\text{p.u.}) = \frac{R(\Omega)}{R_{base}}$$

$$L(\text{p.u.}) = \frac{L(H)}{L_{base}}$$

The base resistance and base inductance used for each winding are

$$R_{base} = \frac{(V_n)^2}{P_n}$$

$$L_{base} = \frac{R_{base}}{2\pi f_n}$$

For the magnetization resistance  $R_m$ , the pu values are based on the transformer rated power and on the nominal voltage of winding 1.

The default parameters of winding 1 specified in the dialog box section give the following base values:

$$R_{base} = \frac{(735e3/\sqrt{3})^2}{250e6} = 720.3\Omega \quad L_{base} = \frac{720.3}{2\pi 60} = 1.91H$$

For example, if winding 1 parameters are  $R_1 = 1.44 \Omega$  and  $L_1 = 0.1528 H$ , the corresponding values to enter in the dialog box are

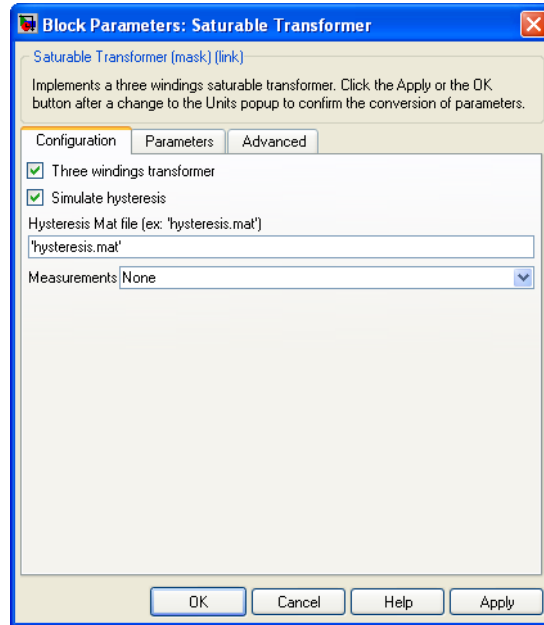
$$R_1 = \frac{1.44\Omega}{720.3\Omega} = 0.002 \text{ p.u.}$$

$$L_1 = \frac{0.1528H}{1.91H} = 0.08 \text{ p.u.}$$



## Dialog Box and Parameters

### Configuration Tab



### Three windings transformer

If selected, specify a saturable transformer with three windings; otherwise it implements a two windings transformer.

### Simulate hysteresis

Select to model hysteresis saturation characteristic instead of a single-valued saturation curve.

### Hysteresis Mat file

The **Hysteresis Mat file** parameter is visible only if the **Simulate hysteresis** parameter is selected.

Specify a **.mat** file containing the data to be used for the hysteresis model. When you open the **Hysteresis Design Tool** of the Powergui, the default hysteresis loop and parameters saved in

# Saturable Transformer

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the `hysteresis.mat` file are displayed. Use the **Load** button of the Hysteresis Design tool to load another `.mat` file. Use the **Save** button of the Hysteresis Design tool to save your model in a new `.mat` file.

## Measurements

Select **Winding voltages** to measure the voltage across the winding terminals of the Saturable Transformer block.

Select **Winding currents** to measure the current flowing through the windings of the Saturable Transformer block.

Select **Flux and excitation current ( $I_m + I_{Rm}$ )** to measure the flux linkage, in volt seconds (V.s), and the total excitation current including iron losses modeled by  $R_m$ .

Select **Flux and magnetization current ( $I_m$ )** to measure the flux linkage, in volt seconds (V.s), and the magnetization current, in amperes (A), not including iron losses modeled by  $R_m$ .

Select **All measurement (V, I, Flux)** to measure the winding voltages, currents, magnetization currents, and the flux linkage.

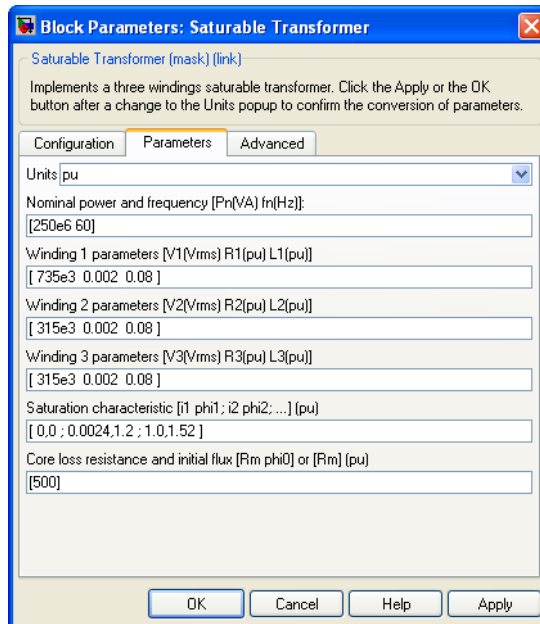
Place a Multimeter block in your model to display the selected measurements during the simulation.

In the **Available Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name.

Measurement	Label
Winding voltages	Uw1:, Uw2:, Uw3:
Winding currents	Iw1:, Iw2:, Iw3:
Excitation current	Iexc:

Measurement	Label
Magnetization current	Imag:
Flux linkage	Flux:

## Parameters Tab



## Units

Specify the units used to enter the parameters of the Saturable Transformer block. Select pu to use per unit. Select SI to use SI units. Changing the **Units** parameter from pu to SI, or from SI to pu, will automatically convert the parameters displayed in the mask of the block.

# Saturable Transformer

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## Nominal power and frequency

The nominal power rating,  $P_n$ , in volt-amperes (VA), and frequency, in hertz (Hz), of the transformer.

## Winding 1 parameters

The nominal voltage in volts RMS, resistance in pu or ohms, and leakage inductance in pu or Henrys for winding 1. Set the winding resistances and inductances to 0 to implement an ideal winding.

## Winding 2 parameters

The nominal voltage in volts RMS, resistance in pu or ohms, and leakage inductance in pu or Henrys for winding 2. Set the winding resistances and inductances to 0 to implement an ideal winding.

## Winding 3 parameters

The **Winding 3 parameters** are not available if the **Three windings transformer** parameter is not selected. The nominal voltage in volts RMS, resistance in pu or ohms, and leakage inductance in pu or Henrys for winding 3. Set the winding resistances and inductances to 0 to implement an ideal winding.

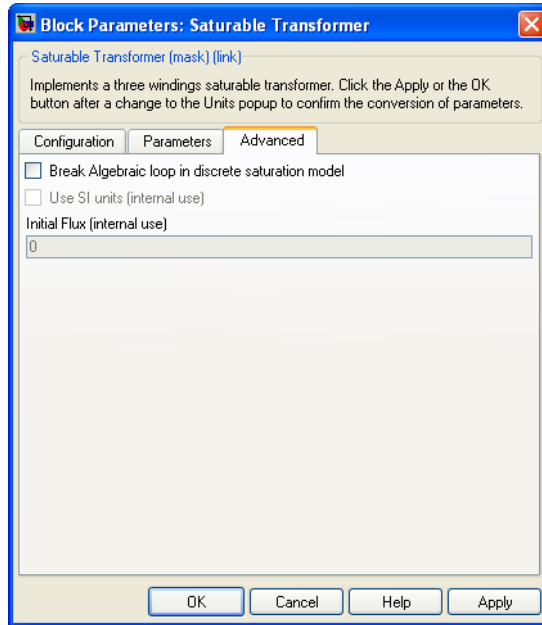
## Saturation characteristic

Specify a series of magnetizing current (pu) - flux (pu) pairs starting with (0,0).

## Core loss resistance and initial flux

Specify the active power dissipated in the core by entering the equivalent resistance  $R_m$  in pu. For example, to specify a 0.2% of active power core loss at nominal voltage, use  $R_m = 500$  pu. You can also specify the initial flux  $\phi_0$  (pu). This initial flux becomes particularly important when the transformer is energized. If  $\phi_0$  is not specified, the initial flux is automatically adjusted so that the simulation starts in steady state. When simulating hysteresis,  $R_m$  models the eddy current losses only.

## Advanced Tab



### Break Algebraic loop in discrete saturation model

When you use the block in a discrete system, you will get an algebraic loop. This algebraic loop, which is required in most cases to get an accurate solution, tends to slow down the simulation. However, to speed up the simulation, in some circumstances, you can disable the algebraic loop by selecting **Break Algebraic loop in discrete saturation model**. You should be aware that disabling the algebraic loop introduces a one-simulation-step time delay in the model. This can cause numerical oscillations if the sample time is too large.

### Limitations

Windings can be left floating (that is, not connected by an impedance to the rest of the circuit). However, the floating winding is connected

# Saturable Transformer

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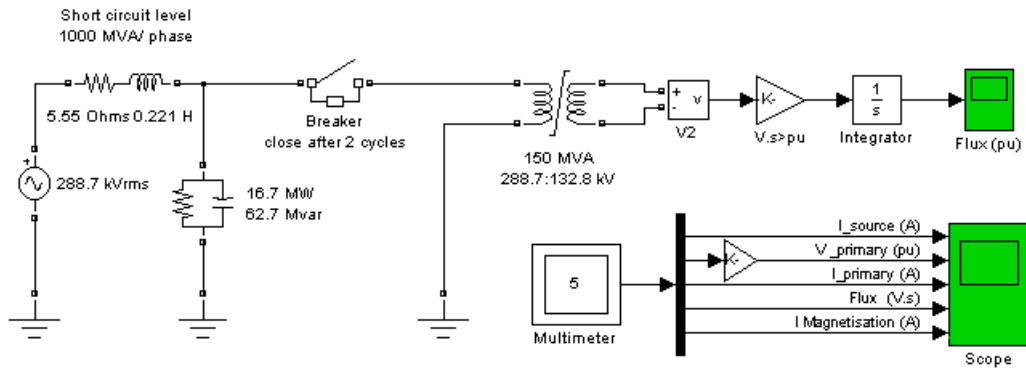
internally to the main circuit through a resistor. This invisible connection does not affect voltage and current measurements.

## Example

The power\_xfosaturable demo illustrates the energization of one phase of a three-phase 450 MVA, 500/230 kV transformer on a 3000 MVA source. The transformer parameters are

<b>Nominal power and frequency</b>	$P_n = 150e6 \text{ VA}$	$f_n = 60 \text{ Hz}$	
<b>Winding 1 parameters (primary)</b>	$V_1 = 500e3 \text{ V}_{\text{rms}/\sqrt{3}}$	$R_1 = 0.002 \text{ pu}$	$L_1 = 0.08 \text{ pu}$
<b>Winding 2 parameters (secondary)</b>	$V_2 = 230e3 \text{ V}_{\text{rms}/\sqrt{3}}$	$R_2 = 0.002 \text{ pu}$	$L_2 = 0.08 \text{ pu}$
<b>Saturation characteristic</b>	[0 0; 0.0 1.2; 1.0 1.52]		
<b>Core loss resistance and initial flux</b>	$R_m = 500 \text{ pu}$	$\phi_0 = 0.8 \text{ pu}$	

# Saturable Transformer



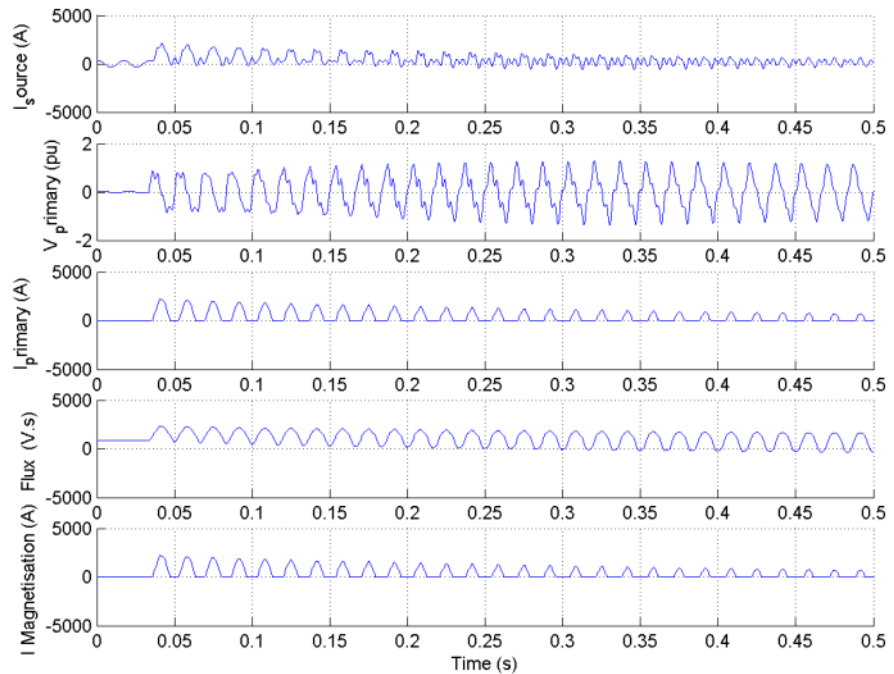
Simulation of this circuit illustrates the saturation effect on the transformer current and voltage.

As the source is resonant at the fourth harmonic, you can observe a high fourth- harmonic content in the secondary voltage. In this circuit, the flux is calculated in two ways:

- By integrating the secondary voltage
- By using the Multimeter block

The simulation results demonstrate these points:

# Saturable Transformer



## References

[1] Casoria, S., P. Brunelle, and G. Sybille, "Hysteresis Modeling in the MATLAB/Power System Blockset," *Electrimacs 2002*, École de technologie supérieure, Montreal, 2002.

[2] Frame, J.G., N. Mohan, and Tsu-huei Liu, "Hysteresis modeling in an Electro-Magnetic Transients Program," presented at the IEEE PES winter meeting, New York, January 31 to February 5, 1982.

## See Also

Linear Transformer, Multimeter, Mutual Inductance, Powergui, Three-Phase Transformer (Two Windings), Three-Phase Transformer (Three Windings)



# Self-Controlled Synchronous Motor Drive

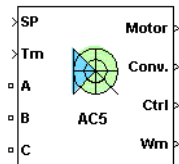
## Purpose

Implement Self-Controlled Synchronous Motor Drive

## Library

Electric Drives/AC drives

## Description



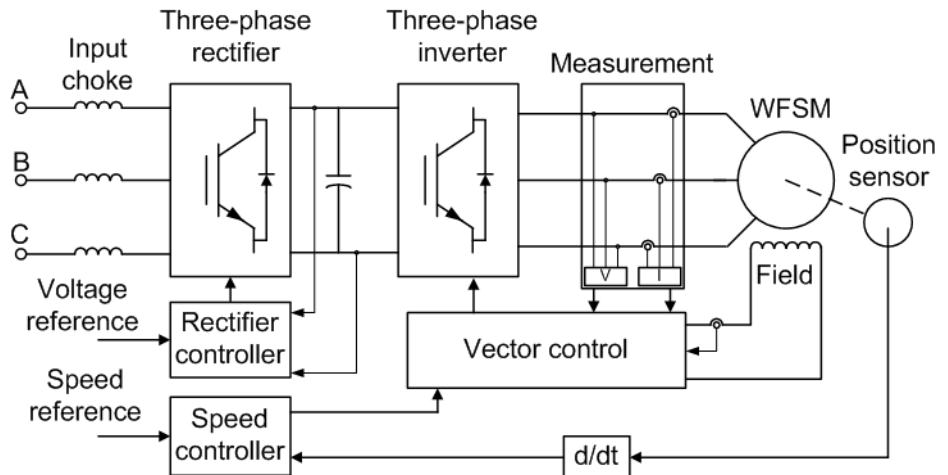
This block models a wound field synchronous motor (WFSM) vector control drive model. The high-level schematic shown below is built from six main blocks. The WFSM motor, the three-phase inverter, and the three-phase rectifier models are provided with the SimPowerSystems library. More details are available in the reference pages for these blocks. The speed controller, the rectifier controller, and the vector control models are specific to the drive library. It is possible to use a simplified version of the drive containing average-value models of the inverter and rectifier for faster simulation.

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**Note** In SimPowerSystems software, the Self-Controlled Synchronous Motor Drive block is commonly called the AC5 motor drive.

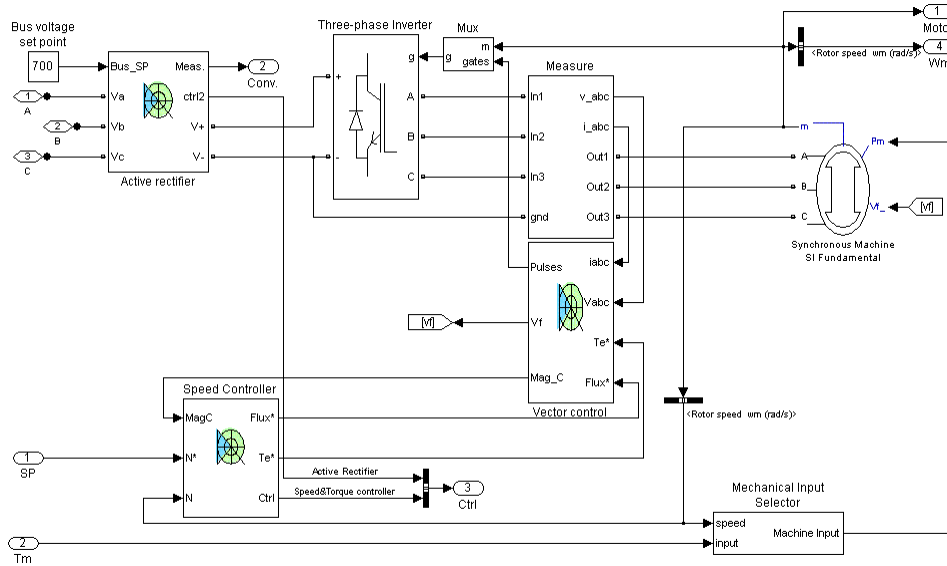
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## High-Level Schematic



# Self-Controlled Synchronous Motor Drive

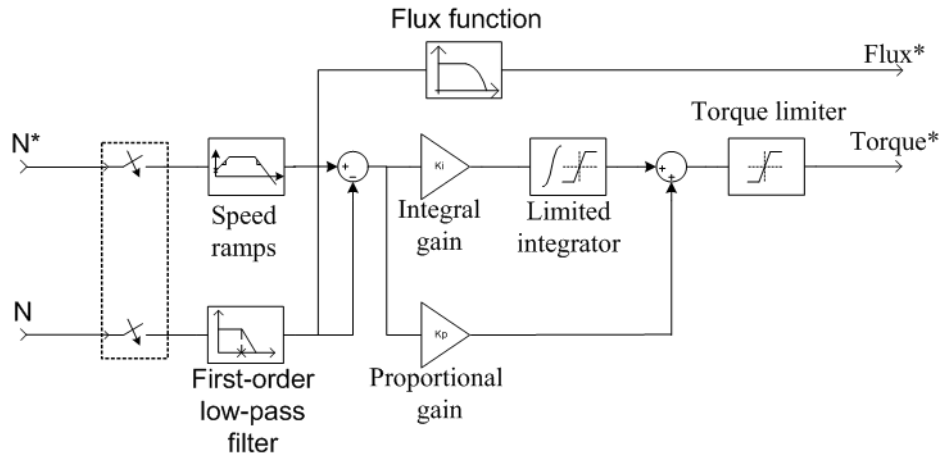
## Simulink Schematic



## Speed Controller

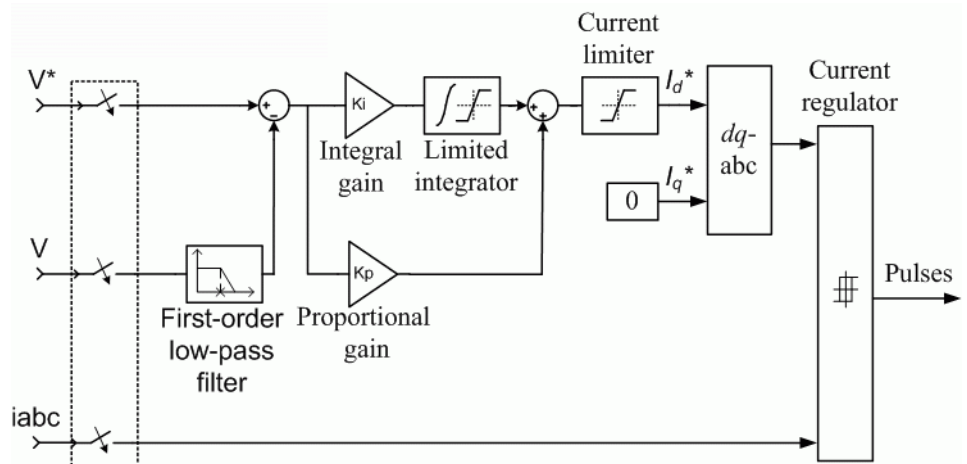
The speed controller is based on a PI regulator, shown below. The outputs of this regulator are set points for the torque and the flux applied to the vector control block.

# Self-Controlled Synchronous Motor Drive



## Rectifier Controller

The rectifier controller is based on a PI regulator of the DC bus voltage. The output of this regulator is the direct (active) component of the AC line current. The reactive component of the AC line current is set to zero in order to operate at unity power factor.



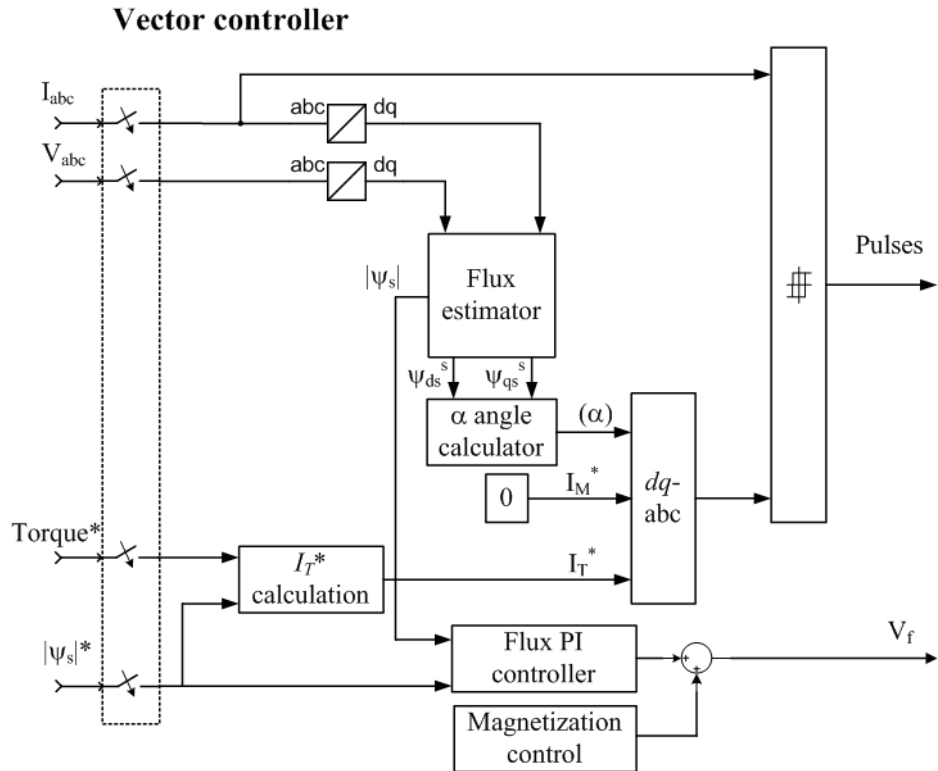
# Self-Controlled Synchronous Motor Drive

## Vector Controller

The *dq-abc* block performs the conversion of the *dq* current components into *abc* phase variables.

The *current regulator* is a bang-bang current controller with adjustable hysteresis bandwidth.

The vector control contains five main blocks shown in this figure. These blocks are described below.



The *flux estimator* block is used to estimate the motor stator flux  $\Psi_{dq}^s$ .

The *flux PI controller* is used to regulate the flux in the machine.

# Self-Controlled Synchronous Motor Drive

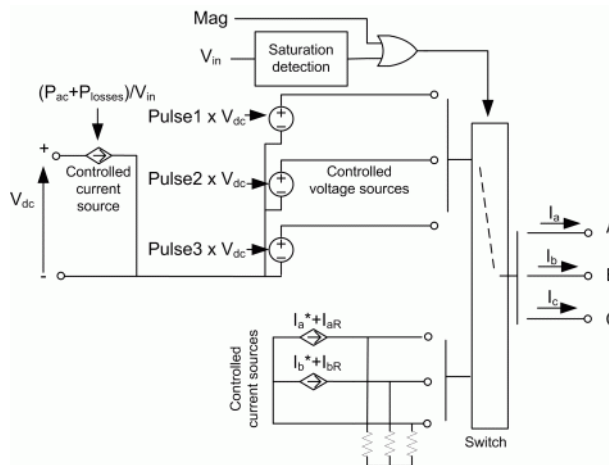
The  $dq2abc$  block performs the conversion of the  $dq$  current components into  $abc$  phase variables.

The *current regulator* is a bang-bang current controller with adjustable hysteresis bandwidth.

The *magnetization control* unit contains the logic used to switch between the magnetization and normal operation mode.

## Average-Value Inverter and Rectifier

The average-value inverter/rectifier internal architecture is shown in the following figure.



It is composed of one controlled current source on the DC side and of two controlled current sources and three controlled voltage sources on the AC side. The DC current source allows the representation of the average DC bus current behavior following the next equation:

$$I_{dc} = \frac{P_{ac} + P_{losses}}{V_{dc}}$$

with  $P_{ac}$  being the AC side instantaneous power,  $P_{losses}$  the losses in the power electronics devices and  $V_{in}$  the DC bus voltage.

# Self-Controlled Synchronous Motor Drive

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On the AC side, the current sources represent the average phase currents fed to the motor. The regulation being fast, the current values are set equal to the current references sent by the current regulator. A small current is injected to compensate for the current drawn by the three-phase load (needed because of the inverter current sources in series with the inductive motor).

During loss of current tracking due to insufficient inverter voltage, the currents are fed by three controlled voltage sources. These voltage sources represent the square wave mode and allow good representation of the phase currents during inverter saturation. Each voltage source outputs either  $V_{in}$  or 0, depending on the values of the pulses (1 or 0) sent by the current controller.

## Remarks

The model is discrete. Good simulation results have been obtained with a  $2 \mu\text{s}$  time step. To simulate a digital controller device, the control system has two different sampling times:

- Speed controller sampling time
- Active rectifier controller and vector controller sampling time

The speed controller sampling time has to be a multiple of the vector controller sampling time. The latter sampling time has to be a multiple of the simulation time step. The average-value inverter and rectifier allow the use of bigger simulation time steps since they do not generate small time constants (due to the RC snubbers) inherent to the detailed converters. For a vector controller and active rectifier controller sampling time of  $50 \mu\text{s}$ , good simulation results have been obtained for a simulation time step of  $50 \mu\text{s}$ . This time step can, of course, not be higher than the smallest controller sampling time.

The torque sign convention of the synchronous machine is different from the one of the asynchronous and PM synchronous machines. That is, the synchronous machine is in the motor operation mode when the electric torque is negative and in the generator operation mode when the electric torque is positive.

# Self-Controlled Synchronous Motor Drive

## Dialog Box

### Synchronous Machine Tab

The dialog box is titled "Self-Controlled Synchronous Motor Drive" and contains a text area with the following text: "The synchronous motor parameters are specified in the Machine tab. The input choke, the DC bus capacitance, the active rectifier and the inverter switches parameters are specified in the Converters tab. Vector controller, active rectifier controller and speed controller parameters are specified in the controller tab."

The dialog has three tabs: "Synchronous Machine" (selected), "Converters and DC Bus", and "Controller".

**Electrical parameters**

**Nominal values**

Power (VA):	Voltage (Vrms):	Frequency (Hz):	Field current (A):
149.2e3	460	60	1

**Equivalent circuit values**

	Resistance (ohm):	Leakage inductance (H):	Mutual inductance (H):
Stator:	2.01e-3	4.289e-4	
Field:	4.083e-4	0.429e-3	D-axis: 4.477e-3
D-axis dampers:	8.25e-3	0.685e-3	Q-axis: 1.354e-3
Q-axis dampers:	13.89e-3	1.44e-3	

**Initial conditions**

	Phase A current:	Phase B current:	Phase C current:	Field voltage (V):
Magnitude (A):	0	0	0	0
Phase (deg):	0	0	0	

**Mechanical parameters**

Inertia (kg·m <sup>2</sup> ):	15
Friction (N·m·s):	0.005
Pole pairs:	2

**Initial values**

Speed deviation (%):	-99.99
Angle (deg):	0

Model detail level: Detailed (dropdown menu)

Mechanical input: Torque Tm (dropdown menu)

Parameters file options: Load, Save

Buttons: OK, Cancel, Help, Apply

The synchronous machine tab displays the parameters of the synchronous machine block of the powerlib library. Refer to the Synchronous Machine for more information on the synchronous machine parameters.

### Model detail level

Select between the detailed and the average-value inverter.

# Self-Controlled Synchronous Motor Drive

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## Mechanical input

Allows you to select either the load torque or the motor speed as mechanical input. Note that if you select and apply a load torque, you will obtain as output the motor speed according to the following differential equation that describes the mechanical system dynamics:

$$T_e = J \frac{d}{dt} \omega_r + F \omega_r + T_m$$

This mechanical system is included in the motor model.

However, if you select the motor speed as mechanical input then you will get the electromagnetic torque as output, allowing you to represent externally the mechanical system dynamics. Note that the internal mechanical system is not used with this mechanical input selection and the inertia and viscous friction parameters are not displayed.

See for example “Mechanical Coupling of Two Motor Drives”.



# Self-Controlled Synchronous Motor Drive

## Converters and DC bus tab

Self-Controlled Synchronous Motor Drive

Self-Controlled Synchronous Motor Drive

The synchronous motor parameters are specified in the Machine tab. The input choke, the DC bus capacitance, the active rectifier and the inverter switches parameters are specified in the Converters tab. Vector controller, active rectifier controller and speed controller parameters are specified in the controller tab.

Synchronous Machine    Converters and DC Bus    Controller

**Rectifier**

Switches

Device type: IGBT / Diodes

On-state resistance (ohm): 1e-3

Forward voltages (V)

Main device: 1.2

Diode: 1.2

Turn-off characteristics

Fall time (s): 1e-6

Tail time (s): 2e-6

Snubbers

Resistance (ohm): 4e3

Capacitance (F): 40e-9

**DC Bus**

Capacitance (F): 7500e-6

Input choke

Resistance (ohm): 0.05

Inductance (H): 1e-3

**Inverter**

Switches

Device type: IGBT / Diodes

On-state resistance (ohm): 1e-3

Forward voltages (V)

Main device: 1.2

Diode: 1.2

Turn-off characteristics

Fall time (s): 1e-6

Tail time (s): 2e-6

Snubbers

Resistance (ohm): 10e3

Capacitance (F): 10e-9

Model detail level: Detailed

Mechanical input: Torque Tm

Parameters file options

Load    Save

OK    Cancel    Help    Apply

### Rectifier section

The rectifier section of the Converters and DC bus tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the Universal Bridge for more information on the universal bridge parameters.

### Inverter section

The inverter section of the Converters and DC bus tab displays the parameters of the Universal Bridge block of the powerlib

# Self-Controlled Synchronous Motor Drive

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library. Refer to the Universal Bridge for more information on the universal bridge parameters.

The average-value rectifier uses the three following parameters.

## **Source frequency**

The frequency of the three-phase voltage source (Hz).

## **Source Voltage**

The RMS line-to-line voltage of the three-phase voltage source (V).

## **On-state resistance**

The on-state resistance of the rectifier devices (ohms).

The average-value inverter uses the two following parameters:

## **On-state resistance**

The on-state resistance of the inverter devices (ohms).

## **Forward voltages [Device $V_f$ , Diode $V_{df}$ ]**

Forward voltages, in volts (V), of the forced-commutated devices and of the antiparallel diodes. These values are needed for startup and for square wave mode.

## **DC Bus Capacitance**

The DC bus capacitance value (F).

## **Input Choke section**

Input chokes reduce line current harmonics.

### **Resistance**

The input choke resistance value (ohms).

### **Inductance**

The input choke inductance value (H).

# Self-Controlled Synchronous Motor Drive

## Controller tab

The screenshot shows the 'Controller' tab of the 'Self-Controlled Synchronous Motor Drive' software. The window title is 'Self-Controlled Synchronous Motor Drive'. Below the title bar, there is a text area with the following text: 'The synchronous motor parameters are specified in the Machine tab. The input choke, the DC bus capacitance, the active rectifier and the inverter switches parameters are specified in the Converters tab. Vector controller, active rectifier controller and speed controller parameters are specified in the controller tab.'

The interface has three tabs: 'Synchronous Machine', 'Converters and DC Bus', and 'Controller'. The 'Controller' tab is active. Below the tabs, there is a 'Regulation type:' dropdown menu set to 'Speed regulation' and a 'Schematic' button.

Below the 'Regulation type' dropdown, there are three sub-tabs: 'Speed Controller', 'DC Bus Controller', and 'Vector Controller'. The 'Speed Controller' sub-tab is active.

The 'Speed Controller' sub-tab contains two main sections:

- Speed ramps (rpm/s):** This section has four input fields: 'Acceleration:' (100), 'Deceleration:' (-100), 'Negative:' (-1200), and 'Positive:' (1200).
- Torque output limits (N-m):** This section has two input fields: 'Negative:' (-1200) and 'Positive:' (1200).

Below these sections is a 'PI regulator' section with four input fields: 'Proportional gain:' (75), 'Integral gain:' (100), 'Speed cutoff frequency (Hz):' (5), and 'Speed controller sampling time (s):' ( $7 \times 10^{-6}$ ).

At the bottom of the window, there is a 'Model detail level:' dropdown menu set to 'Detailed' and a 'Mechanical input:' dropdown menu set to 'Torque Tm'. Below these are 'Parameters file options' with 'Load' and 'Save' buttons. At the very bottom are 'OK', 'Cancel', 'Help', and 'Apply' buttons.

### Regulation type

This drop-down menu allows you to choose between speed and torque regulation.

### Schematic

When you click this button, a diagram illustrating the speed, rectifier, and vector controllers schematics appears.

# Self-Controlled Synchronous Motor Drive

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## **Controller – Speed Controller Subtab**

### **Speed cutoff frequency**

The speed measurement first-order low-pass filter cutoff frequency (Hz).

### **Speed controller sampling time**

The speed controller sampling time (s). The sampling time must be a multiple of the simulation time step.

### **Speed ramps — Acceleration**

The maximum change of speed allowed during motor acceleration. An excessively large positive value can cause DC bus under-voltage (rpm/s).

### **Speed ramps — Deceleration**

The maximum change of speed allowed during motor deceleration. An excessively large negative value can cause DC bus over-voltage (rpm/s).

### **PI regulator — Proportional gain**

The speed controller proportional gain.

### **PI regulator — Integral gain**

The speed controller integral gain.

### **Torque output limits — Negative**

The maximum negative demanded torque applied to the motor by the vector controller (N.m).

### **Torque output limits — Positive**

The maximum positive demanded torque applied to the motor by the vector controller (N.m).

# Self-Controlled Synchronous Motor Drive

## Controller – DC Bus Controller Subtab

Self-Controlled Synchronous Motor Drive

Self-Controlled Synchronous Motor Drive

The synchronous motor parameters are specified in the Machine tab. The input choke, the DC bus capacitance, the active rectifier and the inverter switches parameters are specified in the Converters tab. Vector controller, active rectifier controller and speed controller parameters are specified in the controller tab.

Synchronous Machine   Converters and DC Bus   **Controller**

Regulation type: Speed regulation   Schematic

Speed Controller   **DC Bus Controller**   Vector Controller

PI regulator

Proportional gain: 10   Integral gain: 100

Line current d component limits (A)

Minimum (negative): -500   Maximum (positive): 500

Voltage measurement cutoff frequency (Hz): 100   Active rectifier sampling time (s): 20e-6   Current hysteresis bandwidth (A): 10

Model detail level: Detailed   Mechanical input: Torque Tm

Parameters file options

Load   Save

OK   Cancel   Help   Apply

### PI regulator — Proportional gain

The DC bus voltage controller proportional gain.

### PI regulator — Integral gain

The DC bus voltage controller integral gain.

### Line current d component limits — Minimum (negative)

The maximum current flowing from the DC bus capacitor towards the AC line (A).

# Self-Controlled Synchronous Motor Drive

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## Line current d component limits — Maximum (positive)

The maximum current flowing from the AC line towards the DC bus capacitor (A).

## Voltage measurement cutoff frequency

The bus voltage measurement low-pass filter cutoff frequency (Hz).

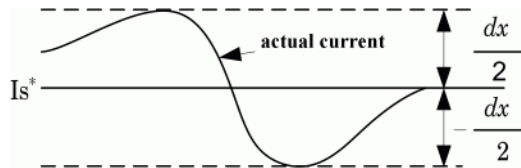
## Active rectifier sampling time

The DC bus voltage controller sampling time (s). The sampling time must be a multiple of the simulation time step.

## Current hysteresis bandwidth

The current hysteresis bandwidth. This value is the total bandwidth distributed symmetrically around the current set point (A). The following figure illustrates a case where the current set point is  $I_s^*$  and the current hysteresis bandwidth is set to  $dx$ .

This parameter is not used when using the average-value inverter.



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**Note** This bandwidth can be exceeded because a fixed-step simulation is used. A rate transition block is needed to transfer data between different sampling rates. This block causes a delay in the gate signals, so the current may exceed the hysteresis band.

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# Self-Controlled Synchronous Motor Drive

## Controller – Vector Controller Subtab

Self-Controlled Synchronous Motor Drive

Self-Controlled Synchronous Motor Drive

The synchronous motor parameters are specified in the Machine tab. The input choke, the DC bus capacitance, the active rectifier and the inverter switches parameters are specified in the Converters tab. Vector controller, active rectifier controller and speed controller parameters are specified in the controller tab.

Synchronous Machine   Converters and DC Bus   Controller

Regulation type: Speed regulation   Schematic

Speed Controller   DC Bus Controller   Vector Controller

Flux controller

PI regulator

Proportional gain: 1000   Integral gain: 1000

Voltage limits (V)

Minimum: -300   Maximum: 300

Flux estimation lowpass cutoff frequency (Hz): 2

Magnetization controller

Field magnetization voltage (V): 600   High voltage field magnetization time (s): 0.2   Field nominal voltage (V): 30   Total field magnetization time (s): 1

Controller sampling time (s): 20e-6   Machine nominal flux (Wb): 0.98   Current hysteresis bandwidth (A): 10

Model detail level: Detailed   Mechanical input: Torque Tm

Parameters file options

Load   Save

OK   Cancel   Help   Apply

### Controller sampling time

The vector controller sampling time (s). The sampling time must be a multiple of the simulation time step.

### Machine nominal flux

The motor stator nominal flux (Wb).

### Current hysteresis bandwidth

The current hysteresis bandwidth (for details, see the **DC Bus Controller** subtab).

# Self-Controlled Synchronous Motor Drive

---

## Flux Controller Section

### PI regulator — Proportional gain

The flux controller proportional gain.

### PI regulator — Integral gain

The flux controller integral gain.

### Voltage limits — Minimum

The minimum voltage applied to the motor excitation field (V).

### Voltage limits — Maximum

The maximum voltage applied to the motor excitation field (V).

### Flux estimation lowpass cutoff frequency

The flux estimation first-order filter cutoff frequency (Hz).

## Magnetization Controller Section

When you start the self-controlled synchronous motor, the magnetic flux of the motor must be first established before the motor is allowed to produce an electric torque. Since the motor field time constant is high, a field voltage much higher than nominal is applied in order to accelerate the building of the magnetic flux in the synchronous motor. After the period during which the high voltage is applied, the field voltage is lowered down to its nominal value during a second short period that adds to the latter period giving the total magnetization period. This procedure gives a smooth startup of the self-controlled synchronous motor.

### Field magnetization voltage

The field magnetization voltage applied in order to establish the stator flux (V).

### High voltage field magnetization time

The field magnetization high voltage application time (s).

### Field nominal voltage

The field nominal voltage (V).



# Self-Controlled Synchronous Motor Drive

## Block Inputs and Outputs

### Total field magnetization time

The total time before the drive is ready to produce a torque (s).

### SP

The speed or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration / deceleration ramps. If the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

### $T_m$ or $W_m$

The mechanical input: load torque ( $T_m$ ) or motor speed ( $W_m$ ).

### A, B, C

The three phase terminals of the motor drive.

### $W_m$ or $T_e$

The mechanical output: motor speed ( $W_m$ ) or electromagnetic torque ( $T_e$ ).

### Motor

The motor measurement vector. This vector allows you to observe the motor's variables using the Bus Selector block.

### Conv

The three-phase converters measurement vector. This vector contains:

- The DC bus voltage
- The rectifier output current
- The inverter input current

Note that all current and voltage values of the bridges can be visualized with the Multimeter block.

### Ctrl

The controller measurement vector. This vector contains the values for the active rectifier and for the inverter.

# Self-Controlled Synchronous Motor Drive

---

For the active rectifier:

- The active component of the current reference.
- The voltage error (difference between the DC bus voltage reference and actual DC bus voltage)
- The DC bus voltage reference

For the inverter:

- The torque reference
- The flux reference
- The speed error (difference between the speed reference ramp and actual speed)
- The speed reference ramp or torque reference

## Model Specifications

The library contains a 200 hp drive parameter set. The specifications of the 200 hp drive are shown in the following table

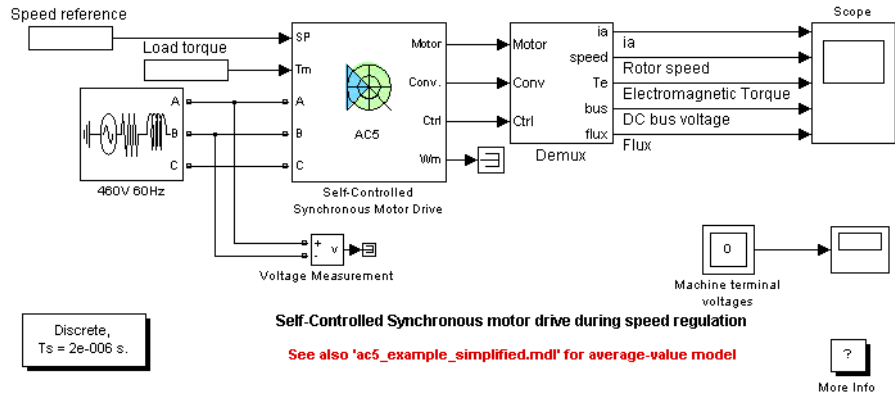
### 14 HP and 200 HP Drive Specifications

	14 HP Drive	200 HP Drive
<b>Drive Input Voltage</b>		
Amplitude	460 V	460 V
Frequency	60 Hz	60 Hz
<b>Motor Nominal Values</b>		
Power	14 hp	200 hp
Speed	1800 rpm	1800 rpm
Voltage	460 V	460 V

# Self-Controlled Synchronous Motor Drive

## Example

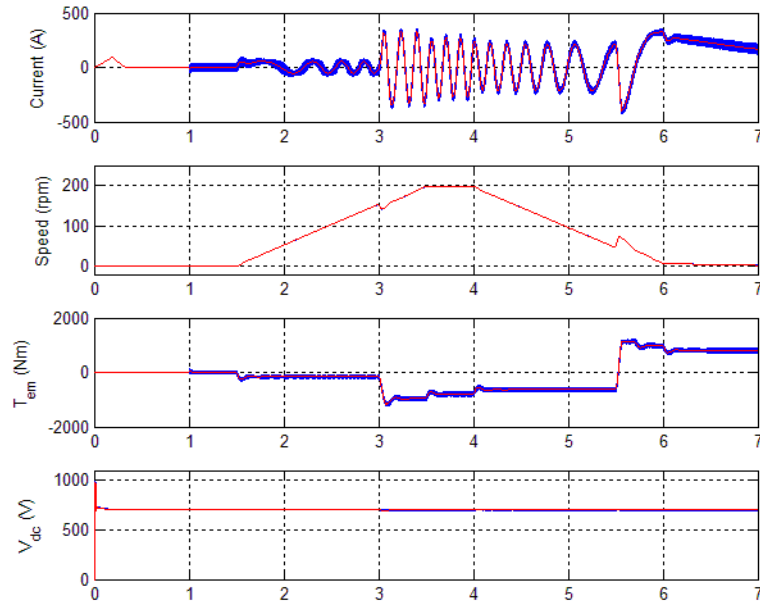
The `ac5_example` demo illustrates an AC5 motor drive simulation with standard load condition for the detailed and average-value models. At time  $t = 0$  s, the speed set point is 300 rpm.



The '`Ts`' parameter used in this model is set to `2e-6` by the Model Properties Callbacks

As shown below, the speed precisely follows the acceleration ramp. At  $t = 3$  s, the nominal load torque is applied to the motor. At  $t = 4$  s, the speed set point is changed to 0 rpm. The speed decreases along the prescribed deceleration ramp to 0 rpm. At  $t = 5.5$  s., the mechanical load passes from -792 N.m to 792 N.m. Notice that the results of the average-value model are similar to those of the detailed model except that the higher frequency signal components are not represented with the average-value converter.

# Self-Controlled Synchronous Motor Drive



**AC5 Example Waveforms (Blue : Detailed Converter, Red : Average-Value Converter)**

## References

- [1] Bose, B. K., *Modern Power Electronics and AC Drives*, Prentice-Hall, N.J., 2002.
- [2] Krause, P. C., *Analysis of Electric Machinery*, McGraw-Hill, 1986.

**Purpose** Implement series RLC branch

**Library** Elements

## Description



The Series RLC Branch block implements a single resistor, inductor, or capacitor, or a series combination of these. To eliminate either the resistance, inductance, or capacitance of the branch, the R, L, and C values must be set respectively to 0, 0, and infinity (inf). Only existing elements are displayed in the block icon.

Negative values are allowed for resistance, inductance, and capacitance.

## Dialog Box and Parameters

**Block Parameters: Series RLC Branch**

Series RLC Branch [mask]  
Implements a series branch of RLC elements.  
Use the 'Branch type' parameter to add or remove elements from the branch.

**Parameters**

Branch type: RLC

Resistance (Ohms): 1

Inductance (H): 1e-3

Set the initial inductor current

Inductor initial current (A): 0

Capacitance (F): 1e-6

Set the initial capacitor voltage

Capacitor initial voltage (V): 0

Measurements: None

OK Cancel Help Apply

## Branch type

Select the elements you want to include in the branch. The **R** letter defines the resistor, the **L** letter defines the inductor, and the **C** letter defines the inductor.

# Series RLC Branch

---

## Resistance

The branch resistance, in ohms ( $\Omega$ ). The **Resistance** parameter is not visible if the resistor element is not specified in the **Branch type** parameter.

## Inductance L

The branch inductance, in henries (H). The **Inductance** parameter is not visible if the inductor element is not specified in the **Branch type** parameter.

## Set the initial inductor current

If selected, the initial inductor current is defined by the **Inductor initial current** parameter. If not selected, the software calculates the initial inductor current in order to start the simulation steady-state.

The **Set the initial inductor current** parameter is not visible and have no effect on the block if the inductor element is not specified in the **Branch type** parameter.

## Inductor initial current (A)

The initial inductor current used at the start of the simulation. The **Inductor initial current** parameter is not visible and have no effect on the block if the inductor is not modeled and if the **Set the initial inductor current** parameter is not selected.

## Capacitance C

The branch capacitance, in farads (F). The **Capacitance** parameter is not visible if the capacitance element is not specified in the **Branch type** parameter.

## Set the initial capacitor voltage

If selected, the initial capacitor voltage is defined by the **Capacitor initial voltage** parameter. If not selected, the software calculates the initial capacitor voltage in order to start the simulation in steady-state.

The **Set the initial capacitor voltage** parameter is not visible and have no effect on the block if the capacitor element is not specified in the **Branch type** parameter.

### Capacitor initial voltage (V)

The initial capacitor voltage used at the start of the simulation. The **Capacitor initial voltage** parameter is not visible and have no effect on the block if the capacitor is not modeled and if the **Set the initial capacitor voltage** parameter is not selected.

### Measurements

Select **Branch voltage** to measure the voltage across the Series RLC Branch block terminals.

Select **Branch current** to measure the current flowing through the Series RLC Branch block.

Select **Branch voltage** and **current** to measure the voltage and the current of the Series RLC Branch block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name.

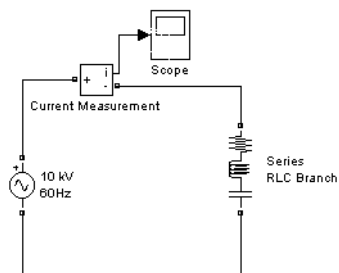
Measurement	Label
Branch voltage	Ub:
Branch current	Ib:

### Example

Obtain the frequency response of a fifth-harmonic filter (tuned frequency = 300 Hz) connected on a 60 Hz power system. This example is available in the `power_seriesbranch` model.

# Series RLC Branch

---



The network impedance in the Laplace domain is

$$Z(s) = \frac{V(s)}{I(s)} = \frac{LCs^2 + RCs + 1}{Cs}$$

To obtain the frequency response of the impedance you have to get the state-space model (A B C D matrices) of the system.

This system is a one-input ( $V_{source}$ ) and one-output (Current Measurement block) system.



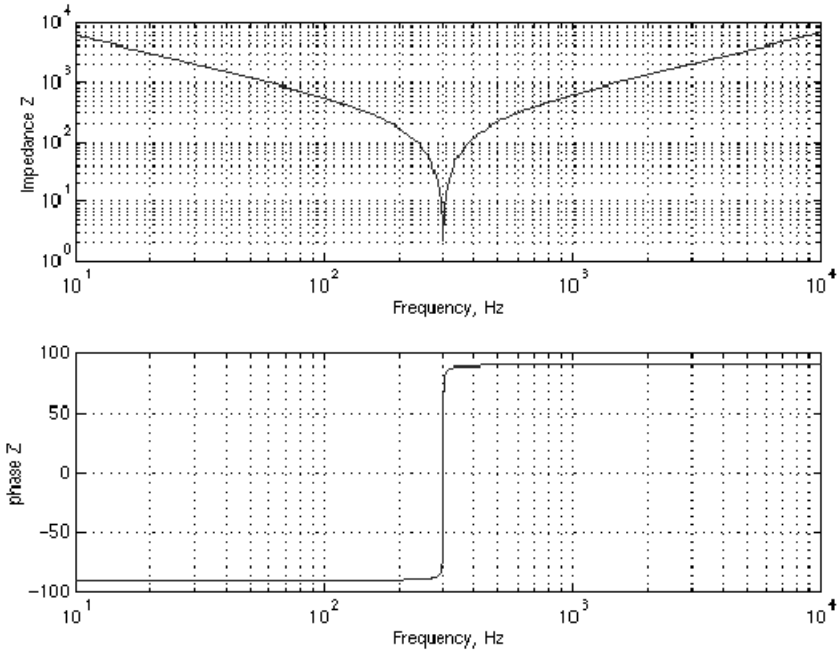
**Note** If you have Control System Toolbox software installed, you can use the `bode` function to get the transfer function  $Z(s)$  from the state-space matrices as follows:

```
[A,B,C,D] = power_analyze('power_seriesbranch');
freq = logspace(1,4,500);
w = 2*pi*freq;
[Ymag,Yphase] = bode(A,B,C,D,1,w);
% invert Y(s) to get Z(s)
Zmag = 1./Ymag;
Zphase = -Yphase;
subplot(2,1,1)
loglog(freq,Zphase)
grid
title('5th harmonic filter')
xlabel('Frequency, Hz')
ylabel('Impedance Zmag')
subplot(2,1,2)
semilogx(freq,Zphase)
xlabel('Frequency, Hz')
ylabel('phase Z')
grid
```

You can also use the Impedance Measurement block and the Powergui block to plot the impedance as a function of frequency. In order to measure the impedance you must disconnect the voltage source.

---

# Series RLC Branch



**See Also**

Multimeter, Parallel RLC Branch, Parallel RLC Load, Series RLC Load

**Purpose** Implement linear series RLC load

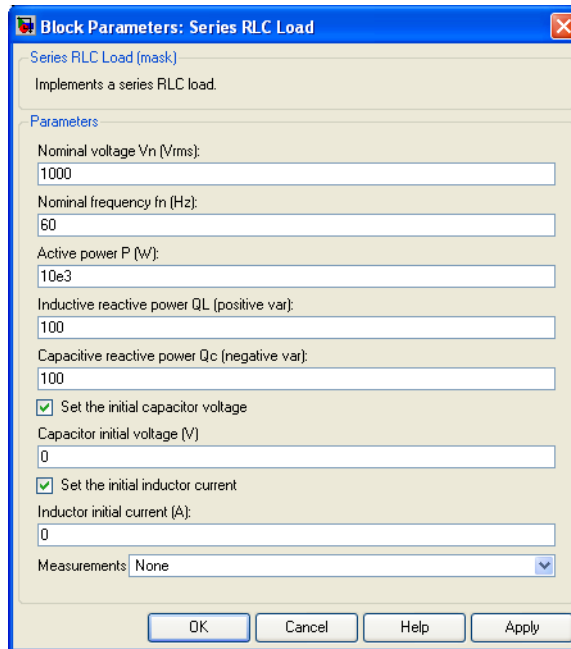
**Library** Elements

## Description



The Series RLC Load block implements a linear load as a series combination of R L C elements. At the specified frequency, the load exhibits a constant impedance. The active and reactive powers absorbed by the load are proportional to the square of the applied voltage. Only elements associated with nonzero powers are displayed in the block icon.

## Dialog Box and Parameters



### Nominal voltage $V_n$

The nominal voltage of the load, in volts RMS.

### Nominal frequency $f_n$

The nominal frequency, in hertz.

# Series RLC Load

---

## **Active power P**

The active power of the load, in watts.

## **Inductive reactive power QL**

The inductive reactive power QL, in vars. Specify a positive value, or 0.

## **Capacitive reactive power QC**

The capacitive reactive power QC, in vars. Specify a positive value, or 0.

## **Set the initial capacitor voltage**

If selected, the initial capacitor voltage is defined by the **Capacitor initial voltage** parameter. If not selected, the software calculates the initial capacitor voltage in order to start the simulation in steady-state.

The **Set the initial capacitor voltage** parameter have no effect on the block if the capacitive reactive power is equal to zero.

## **Capacitor initial voltage (V)**

The initial capacitor voltage used at the start of the simulation. The **Capacitor initial voltage** parameter have no effect on the block if the capacitive reactive power is equal to zero and if the **Set the initial capacitor voltage** parameter is not selected.

## **Set the initial inductor current**

If selected, the initial inductor current is defined by the **Inductor initial current** parameter. If not selected, the software calculates the initial inductor current in order to start the simulation steady-state.

The **Set the initial inductor current** parameter have no effect on the block if the inductive reactive power is equal to zero.

## **Inductor initial current (A)**

The initial inductor current used at the start of the simulation. The **Inductor initial current** parameter have no effect on the block if the inductive reactive power is equal to zero and if the **Set the initial inductor current** parameter is not selected.

## Measurements

Select **Branch voltage** to measure the voltage across the Series RLC Load block terminals.

Select **Branch current** to measure the current flowing through the Series RLC Load block.

Select **Branch voltage** and **current** to measure the voltage and the current of the Series RLC Load block.

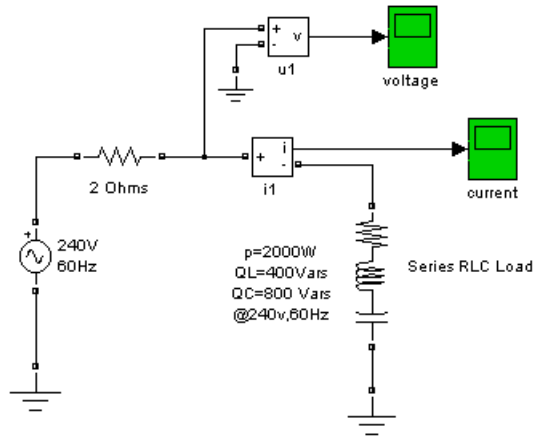
Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name:

Measurement	Label
Branch voltage	Ub:
Branch current	Ib:

## Example

The `power_seriesload` demo uses a Series RLC Load block to implement a simple load.

# Series RLC Load



## See Also

Multimeter, Parallel RLC Branch, Parallel RLC Load, Series RLC Branch

# Simplified Synchronous Machine

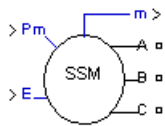
## Purpose

Model the dynamics of simplified three-phase synchronous machine

## Library

Machines

## Description



The Simplified Synchronous Machine block models both the electrical and mechanical characteristics of a simple synchronous machine.

The electrical system for each phase consists of a voltage source in series with an RL impedance, which implements the internal impedance of the machine. The value of R can be zero but the value of L must be positive.

The Simplified Synchronous Machine block implements the mechanical system described by

$$\Delta\omega(t) = \frac{1}{2H} \int_0^t (T_m - T_e) dt - Kd\Delta\omega(t)$$
$$\omega(t) = \Delta\omega(t) + \omega_0$$

where

$\Delta\omega$  = Speed variation with respect to speed of operation

$H$  = Constant of inertia

$T_m$  = Mechanical torque

$T_e$  = Electromagnetic torque

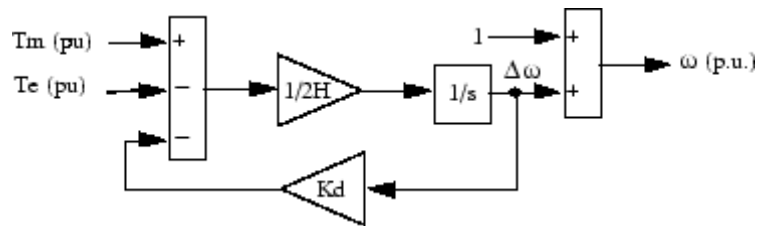
$Kd$  = Damping factor representing the effect of damper windings

$\omega(t)$  = Mechanical speed of the rotor

$\omega_0$  = Speed of operation (1 p.u.)

Although the parameters can be entered in either SI units or per unit in the dialog box, the internal calculations are done in per unit. The following block diagram illustrates how the mechanical part of the model is implemented. Notice that the model computes a deviation with respect to the speed of operation, and not the absolute speed itself.

# Simplified Synchronous Machine



The  $K_d$  damping coefficient simulates the effect of damper windings normally used in synchronous machines. When the machine is connected to an infinite network (zero impedance), the variation of machine power angle  $\delta$  resulting from a change of mechanical power ( $P_m$ ) can be approximated by the following second-order transfer function:

$$\delta/P_m = (\omega_s/2H)/(s^2 + 2\zeta\omega_n s + \omega_n^2)$$

where

$\delta$  Power angle delta: angle of internal voltage  $E$  with respect to terminal voltage, in radians

$P_m$  Mechanical power in pu

$\omega_n$  Frequency of electromechanical oscillations =  $\sqrt{\omega_s \cdot P_{max}/(2H)}$  in rad/s

$\zeta$  Damping ratio =  $(K_d/4)\sqrt{2/(\omega_s \cdot H \cdot P_{max})}$

$\omega_s$  Electrical frequency in rad/s

$P_{max}$  Maximum power in pu transmitted through reactance  $X$  at terminal voltage  $V_t$  and internal voltage  $E$ .  $P_{max} = V_t \cdot E/X$  (pu) where  $V_t$ ,  $E$ , and  $X$  are in pu

$H$  Inertia constant(s)

$K_d$  Damping factor (pu\_of\_torque / pu\_of\_speed)



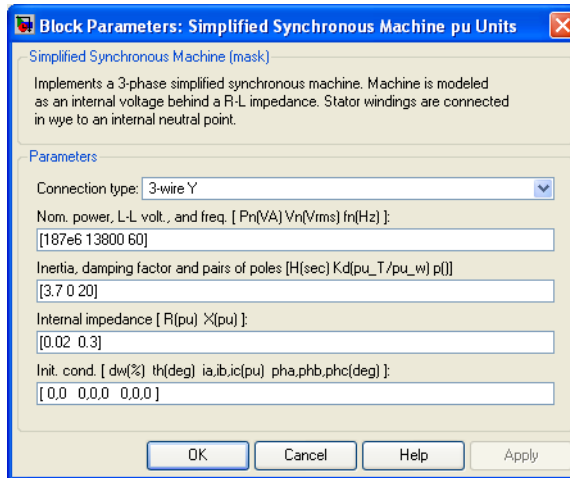
# Simplified Synchronous Machine

This approximate transfer function, which has been derived by assuming  $\sin(\delta) = \delta$ , is valid for small power angles ( $\delta < 30$  degrees). It follows from the above  $\zeta$  expression that the  $K_d$  value required to obtain a given  $\zeta$  damping ratio is

$$K_d = 4\zeta \sqrt{\omega_s \cdot H \cdot P_{max} / 2}$$

## Dialog Box and Parameters

In the **powerlib** library you can choose between the SI units or the pu units Simplified Synchronous Machine blocks to specify the electrical and mechanical parameters of the model.



### Connection type

Specify the number of wires used in three-phase Y connection: either three-wire (neutral not accessible) or four-wire (neutral is accessible).

### Nominal power, L-L voltage, and frequency

The nominal apparent power  $P_n$  (VA), frequency  $f_n$  (Hz), and RMS line-to-line voltage  $V_n$  (V). Used to compute nominal torque and convert SI units to pu.

# Simplified Synchronous Machine

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## **Inertia, friction factor and pairs of poles**

The inertia (J in  $\text{kg}\cdot\text{m}^2$  or H in seconds) damping factor (Kd) and number of pairs of poles (p). The damping factor should be specified in (pu of torque)/(pu of speed) in both machine dialog boxes (in pu and in SI).

## **Internal impedance**

The resistance R ( $\Omega$  or pu) and reactance L (H or pu) for each phase.

## **Initial conditions**

The initial speed deviation (% of nominal), rotor angle (degrees), line current magnitudes (A or pu), and phase angles (degrees). These values can be computed by the load flow utility of the Powergui block.

---

**Note** These two blocks simulate exactly the same simplified synchronous machine model; the only difference is the way of entering the parameter units.

---

## **Inputs and Outputs**

Pm

The mechanical power supplied to the machine. The input can be a constant signal or it can be connected to the output of the Hydraulic Turbine and Governor block. The frequency of the internal voltage sources depends on the mechanical speed of the machine.

E

The amplitude of the internal voltages of the block. It can be a constant signal or it can be connected to the output of a voltage regulator. If you use the SI units machine, these two inputs should be in watts and volts phase-to-phase RMS. If you use the pu units machine, both inputs should be in pu.

# Simplified Synchronous Machine

m

The Simulink output of the block is a vector containing 12 signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

Signal	Definition	Units	Symbol
1	Stator current is_a	A or pu	$i_{sa}$
2	Stator current is_b	A or pu	$i_{sb}$
3	Stator current is_c	A or pu	$i_{sc}$
4	Terminal voltage Va	V or pu	$v_a$
5	Terminal voltage Vb	V or pu	$v_b$
6	Terminal voltage Vc	V or pu	$v_c$
7	Internal voltage Ea	V or pu	$E_a$
8	Internal voltage Eb	V or pu	$E_b$
9	Internal voltage Ec	V or pu	$E_c$
10	Rotor angle theta	rad	$\Theta$
11	Rotor speed wm	rad/s	$\omega$
12	Electrical power Pe	W	$P_e$

## Assumptions

The electrical system of the Simplified Synchronous Machine block consists solely of a voltage source behind a synchronous reactance and resistance. All the other self- and magnetizing inductances of the armature, field, and damping windings are neglected. The effect of damper windings is approximated by the damping factor  $K_d$ . The three voltage sources and RL impedance branches are Y-connected (three wires or four wires). The load might or might not be balanced.

## Limitations

When you use Simplified Synchronous Machine blocks in discrete systems, you might have to use a small parasitic resistive load, connected at the machine terminals, in order to avoid numerical

# Simplified Synchronous Machine

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oscillations. Large sample times require larger loads. The minimum resistive load is proportional to the sample time. As a rule of thumb, remember that with a 25  $\mu\text{s}$  time step on a 60 Hz system, the minimum load is approximately 2.5% of the machine nominal power. For example, a 200 MVA simplified synchronous machine in a power system discretized with a 50  $\mu\text{s}$  sample time requires approximately 5% of resistive load or 10 MW. If the sample time is reduced to 20  $\mu\text{s}$ , a resistive load of 4 MW should be sufficient.

## Example

The power\_simplealt demo uses the Simplified Synchronous Machine block to represent a 1000 MVA, 315 kV, 60 Hz equivalent source connected to an infinite bus (Three-Phase Programmable Voltage Source block). The Simplified Synchronous Machine (SI Units) block is used as a synchronous generator. The internal resistance and reactance are set respectively to 0.02 pu (1.9845  $\Omega$ ) and 0.2 pu ( $X = 19.845 \Omega$ ;  $L = 0.0526$  H). The inertia of the machine is  $J = 168,870 \text{ kg}\cdot\text{m}^2$ , corresponding to an inertia constant  $H = 3$  s. The electrical frequency is  $\omega_s = 2\pi \cdot 60/2 = 377 \text{ rad/s}$ . The machine has two pairs of poles such that its synchronous speed is  $2\pi \cdot 60/2 = 188.5 \text{ rad/s}$  or 1800 rpm.

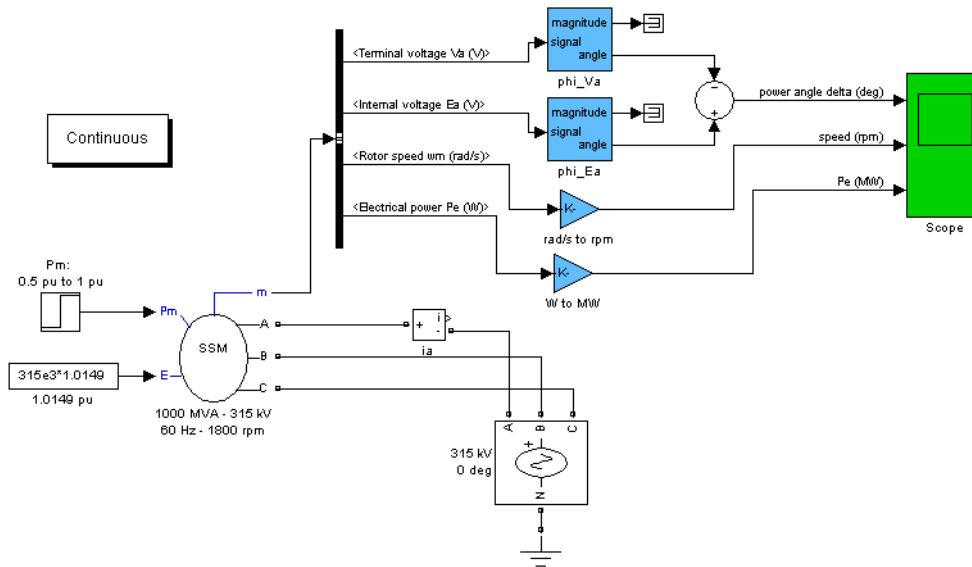
The **Load Flow** option of the Powergui has been used to initialize the machine in order to start simulation in steady state with the machine generating 500 MW. The required internal voltage computed by the load flow is 1.0149 pu. Therefore an internal voltage  $E = 315\text{e}3 \cdot 1.0149 = 319,690 \text{ Vrms}$  phase-to-phase is specified in the Constant block connected to the E input. The maximum power that can be delivered by the machine with a terminal voltage  $V_t = 1.0$  pu and an internal voltage  $E = 1.0149$  pu is  $P_{\max} = V_t \cdot E / X = 1.0149 / 0.2 = 5.0745$  pu.

The damping factor Kd is adjusted in order to obtain a damping ratio  $\zeta = 0.3$ . According to the formula given in the Description section, the required Kd value is

$$K_d = 4\zeta \sqrt{(\omega_s \cdot H \cdot P_{\max})/2} = 64.3$$

Two Fourier blocks are used to measure the power angle  $\delta$ . This angle is computed as the difference between the phase angle of phase A internal voltage and the phase angle of phase A terminal voltage.

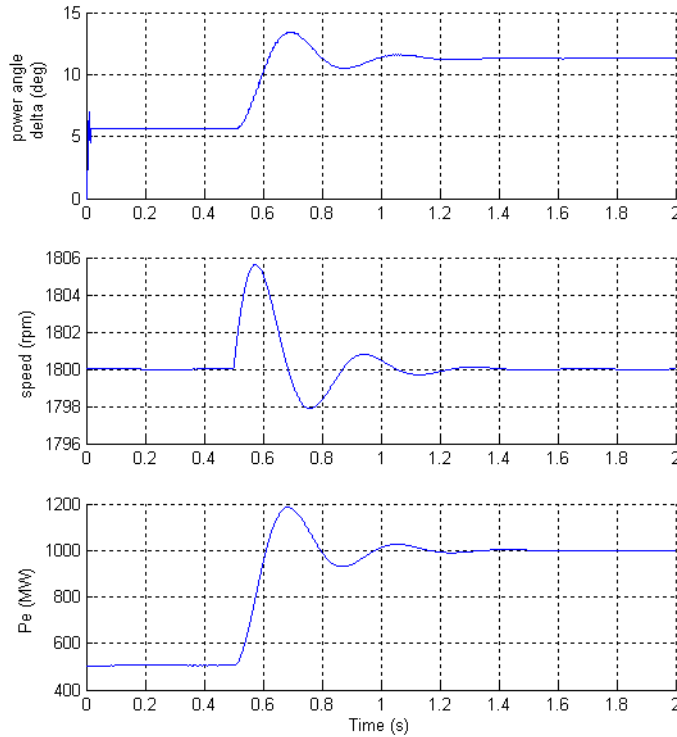
# Simplified Synchronous Machine



In this demo, a step is performed on the mechanical power applied to the shaft. The machine is initially running in steady state with a mechanical power of 505 MW (mechanical power required for an output electrical power of 500 MW, considering the resistive losses). At  $t = 0.5$  s the mechanical power is suddenly increased to 1000 MW.

Run the demo and observe the electromechanical transient on the Scope block displaying the power angle  $\delta$  in degrees, the machine speed in rpm, and the electrical power in MW. Simulation results are shown in the following figure.

# Simplified Synchronous Machine



For an initial electrical power  $P_e = 500$  MW (0.5 pu), the load angle  $\delta$  is 5.65 degrees, which corresponds to the expected value:

$$P_e = \frac{V_t \cdot E \cdot \sin \delta}{X} = \frac{1.0 \cdot 1.0149 \cdot \sin(5.65^\circ)}{0.2} = 0.5 \text{ p.u.}$$

As the mechanical power is stepped from 0.5 pu to 1.0 pu, the load angle increases and goes through a series of under damped oscillations (damping ratio  $\zeta = 0.3$ ) before stabilizing to its new value of 11.3 degrees. The frequency of the oscillations is given by

$$f_n = (1/2\pi) \cdot \sqrt{\omega_s \cdot P_{max} / (2H)} = 2.84 \text{ Hz}$$

**See Also**

Excitation System, Hydraulic Turbine and Governor, Powergui, Steam Turbine and Governor, Synchronous Machine

# Single Phase Asynchronous Machine

## Purpose

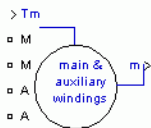
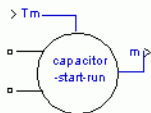
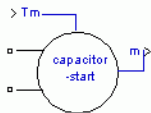
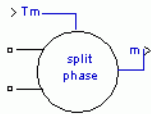
Model the dynamics of single phase asynchronous machine with squirrel-cage rotor

## Library

Machines

## Description

This machine has two windings: the main winding and the auxiliary winding. The model allows to simulate the split-phase, the capacitor-start, the capacitor-start-capacitor-run, and main & auxiliary windings operation modes.



The electrical part of the machine is represented by a fourth-order state-space model and the mechanical part by a second-order system. All electrical variables and parameters are referred to the stator. This is indicated by the prime signs in the machine equations given below. All stator and rotor quantities are in the stator reference frame (dq frame). The subscripts used are defined as follows:

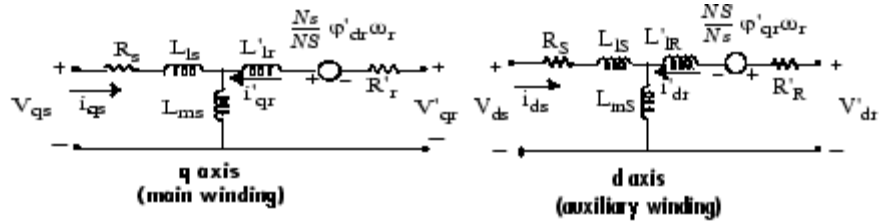
### Subscript Definition

d	d axis quantity
q	q axis quantity
r	Referred to the main winding rotor quantity
R	Referred to the auxiliary winding rotor quantity
s	Main winding stator quantity
S	Auxiliary winding stator quantity
l	Leakage inductance
m	Magnetizing inductance



# Single Phase Asynchronous Machine

## Electrical System



$$V_{qs} = R_s i_{qs} + \frac{d}{dt} \Phi_{qs}$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt} \Phi_{ds}$$

$$V'_{qr} = R'_r i'_{qr} + \frac{d}{dt} \Phi'_{qr} - \frac{N_s}{N_s} \omega_r \Phi'_{dr}$$

$$V'_{dr} = R'_R i'_{dr} + \frac{d}{dt} \Phi'_{dr} + \frac{N_s}{N_s} \omega_r \Phi'_{qr}$$

$$T_e = p \left( \frac{N_s}{N_s} \Phi'_{qr} i'_{dr} - \frac{N_s}{N_s} \Phi'_{dr} i'_{qr} \right)$$

$$\Phi_{qs} = L_{ss} i_{qs} + L_{ms} i'_{qr}$$

$$\Phi_{ds} = L_{SS} i_{ds} + L_{mS} i'_{dr}$$

$$\Phi'_{qr} = L'_{rr} i'_{qr} + L_{ms} i_{qs}$$

$$\Phi'_{dr} = L'_{RR} i'_{dr} + L_{mS} i_{ds}$$

$$L_{ss} = L_{ls} + L_{ms}$$

$$L_{SS} = L_{lS} + L_{mS}$$

$$L'_{rr} = L'_{lr} + L_{ms}$$

$$L'_{RR} = L'_{lR} + L_{mS}$$

where

## Mechanical System

$$\frac{d}{dt} \omega_m = \frac{1}{2H} (T_e - F \omega_m - T_m)$$

$$\frac{d}{dt} \theta_m = \omega_m$$

Reference frame

The reference frame fixed in the stator is used to convert voltages and currents to the dq frame.

The following relationships describe the ab-to-dq frame transformations applied to the single phase asynchronous machine.

# Single Phase Asynchronous Machine

$$\begin{bmatrix} f_{qs} \\ f_{ds} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} f_{as} \\ f_{bs} \end{bmatrix}$$

$$\begin{bmatrix} f_{qr} \\ f_{dr} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & -\sin\theta_r \\ -\sin\theta_r & -\cos\theta_r \end{bmatrix} \begin{bmatrix} f_{ar} \\ f_{br} \end{bmatrix}$$

The variable  $f$  can represent either voltage, currents or flux linkage.

The single phase asynchronous machine block parameters are defined as follows (all quantities are referred to the stator):

Parameter	Definition
$R_s, L_{ls}$	Main winding stator resistance and leakage inductance
$R_S, L_{lS}$	Auxiliary winding stator resistance and leakage inductance
$R'_r, L'_{lr}$	Main winding rotor resistance and leakage inductance
$R'_R, L'_{lR}$	Auxiliary winding rotor resistance and leakage inductance
$L_{ms}$	Main winding magnetizing inductance
$L_{mS}$	Auxiliary winding magnetizing inductance
$L_{ss}, L'_{rr}$	Total main winding stator and rotor inductances
$L_{SS}, L'_{RR}$	Total auxiliary winding stator and rotor inductances
$V_{as}, i_{as}$	Main winding stator voltage and current
$V_{bs}, i_{bs}$	Auxiliary winding stator voltage and current
$V_{qs}, i_{qs}$	q axis stator voltage and current
$V'_{qr}, i'_{qr}$	q axis rotor voltage and current
$V_{ds}, i_{ds}$	d axis stator voltage and current
$V'_{dr}, i'_{dr}$	d axis rotor voltage and current
$\Phi_{qs}, \Phi_{ds}$	Stator q and d axis fluxes

# Single Phase Asynchronous Machine

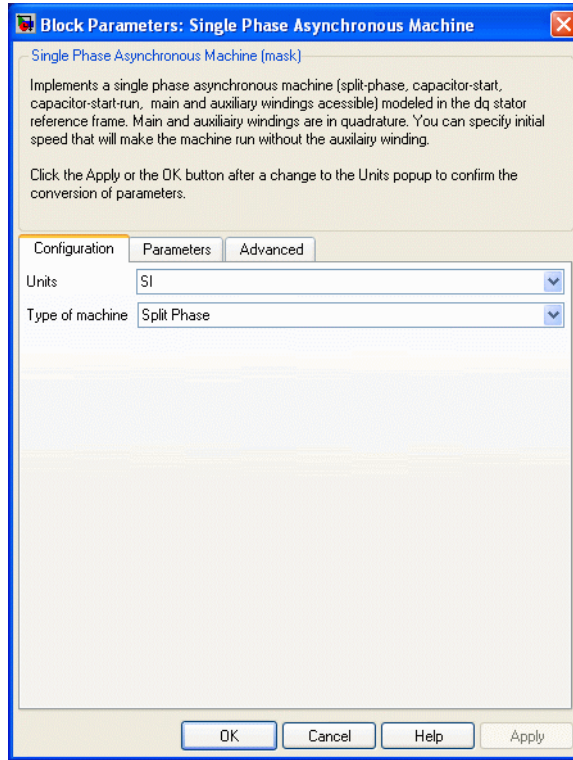
Parameter	Definition
$\phi'_{qr}, \phi'_{dr}$	Rotor q and d axis fluxes
$\omega_m$	Angular velocity of the rotor
$\Theta_m$	Rotor angular position
p	Number of pole pairs
$\omega_r$	Electrical angular velocity ( $\omega_m \times p$ )
$\Theta_r$	Electrical rotor angular position ( $\Theta_m \times p$ )
$T_e$	Electromagnetic torque
$T_m$	Shaft mechanical torque
J	Combined rotor and load inertia coefficient in (kg.m <sup>2</sup> ).
F	Set to infinite to simulate locked rotor. Combined rotor and load viscous friction coefficient
H	Combined rotor and load inertia constant in (s). Set to infinite to simulate locked rotor.
$N_s$	Number of main winding's effective turns
$N_S$	Number of auxiliary winding's effective turns
$R_{st}$	Capacitor-Start resistance
$C_s$	Capacitor-Start
$R_{run}$	Capacitor-Run resistance
$C_{run}$	Capacitor-Run
N	Ratio of number of auxiliary winding's effective turns and number of main winding's effective turns

## Dialog Box and Parameters

You can choose between two types of unit to specify the electrical and mechanical parameters of the model, the per unit dialog box and the SI dialog box. Both blocks are modeling the same machine. Depending on the dialog box you choose to use, the software automatically converts the parameters you enter into per unit parameters. The Simulink model of the single phase asynchronous machine block uses per unit parameters.

# Single Phase Asynchronous Machine

## Configuration Tab



### Units

Specify the per unit dialog box or the SI dialog box.

### Type of machine

Specify one of the four types of single phase asynchronous machine (the split-phase, the capacitor-start, the capacitor-start-capacitor-run, or the main & auxiliary windings).

# Single Phase Asynchronous Machine

## Parameters Tab

Block Parameters: Single Phase Asynchronous Machine

Single Phase Asynchronous Machine (mask)

Implements a single phase asynchronous machine (split-phase, capacitor-start, capacitor-start-run, main and auxiliary windings accessible) modeled in the dq stator reference frame. Main and auxiliary windings are in quadrature. You can specify initial speed that will make the machine run without the auxiliary winding.

Click the Apply or the OK button after a change to the Units popup to confirm the conversion of parameters.

Configuration Parameters Advanced

Nominal power, voltage, and frequency [ Pn(VA), Vn(Vrms), f(HZ) ]  
[ .25\*746 110 60 ]

Main winding stator [ Rs(ohm), Lls(H) ]  
[ 2.02 7.4e-3 ]

Main winding rotor [ Rr'(ohm), Llr'(H) ]  
[ 4.12 5.6e-3 ]

Main winding mutual inductance Lms(H)  
0.1772

Auxiliary winding stator [ RS(ohm), LIS(H) ]  
[ 7.14 8.5e-3 ]

Inertia, friction factor, pole pairs, turn ratio(aux/main) [ J(kg.m<sup>2</sup>), F(N.m.s), p, NS/Ns ]  
[ 0.0146 0 2 1.18 ]

Disconnection speed w0 (% synchronous speed)  
75

Initial speed w0 (% synchronous speed)  
0

OK Cancel Help Apply

### Nominal power, voltage, and frequency

The nominal apparent power  $P_n$  (VA), RMS  $V_n$  (V), and frequency  $f_n$  (Hz).

### Main winding stator

The stator resistance  $R_s$  ( $\Omega$  or pu) and leakage inductance  $L_{ls}$  (H or pu).

### Main winding rotor

The rotor resistance  $R_r'$  ( $\Omega$  or pu) and leakage inductance  $L_{lr}'$  (H or pu), both referred to the stator.

# Single Phase Asynchronous Machine

---

## **Main winding mutual inductance**

The magnetizing inductance  $L_{ms}$  (H or pu).

## **Auxiliary winding stator**

The stator resistance  $R_s$  ( $\Omega$  or pu) and leakage inductance  $L_{ls}$  (H or pu).

## **Inertia, friction factor, pole pairs, turn ratio (aux/main)**

For the **SI units** dialog box: the combined machine and load inertia coefficient  $J$  ( $\text{kg.m}^2$ ), combined viscous friction coefficient  $F$  (N.m.s), number of pole pairs  $p$  and ratio of number of auxiliary winding's effective turns and number of main winding's effective turns. **pu units** dialog box: the inertia constant  $H$  (s), combined viscous friction coefficient  $F$  (pu), and number of pole pairs  $p$ .

## **Capacitor-Start**

The start capacitance  $C_s$  (farad or pu) and capacitor series resistance  $R_{st}$  ( $\Omega$  or pu)

## **Capacitor-Run**

The run capacitance  $C_{run}$  (farad or pu) and series resistance  $R_{run}$  (farad or pu)

## **Disconnection speed**

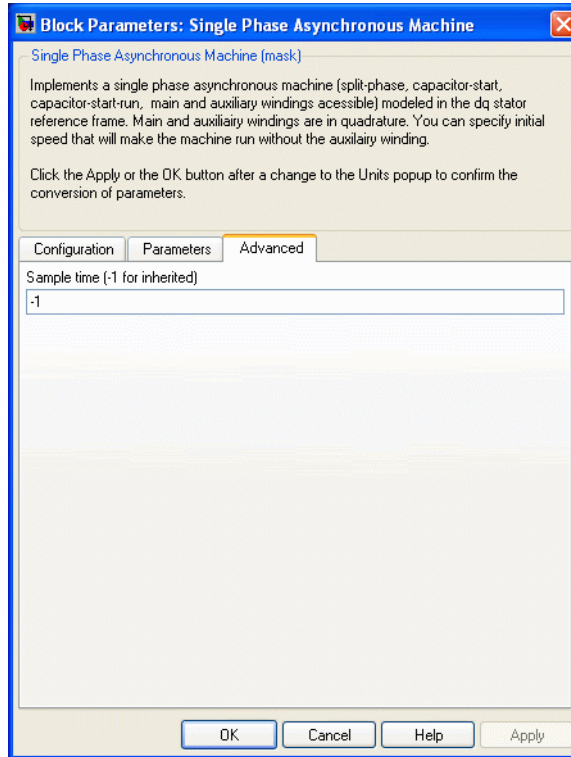
Specifies the speed (%) when the auxiliary winding may be disconnected.

## **Initial speed**

Specifies the initial speed (%).

# Single Phase Asynchronous Machine

## Advanced Tab



### Sample time (-1 for inherited)

Specifies the sample time used by the block. To inherit the sample time specified in the Powergui block, set this parameter to -1.

## Inputs and Outputs

### Tm

The Simulink input of the block is the mechanical torque at the machine's shaft. When you use the SI parameters mask, the input is a signal in N.m, otherwise it is in pu.

# Single Phase Asynchronous Machine

m

The Simulink output of the block is a vector containing 16 signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library. Depending on the type of mask you use, the units are in SI, or in pu.

Signal	Definition	Units	Symbol
1	Rotor current ir_a	A or pu	$i'_{ra}$
2	Rotor current ir_b	A or pu	$i'_{rb}$
3	Rotor current iq	A or pu	$i'_{qr}$
4	Rotor current id	A or pu	$i'_{dr}$
5	Rotor flux phir_q	V.s or pu	$\phi'_{qr}$
6	Rotor flux phir_d	V.s or pu	$\phi'_{dr}$
7	Rotor voltage Vr_q	V or pu	$v'_{qr}$
8	Rotor voltage Vr_d	V or pu	$v'_{dr}$
9	Main winding stator current ia	A or pu	$i_a$
10	Auxiliary winding stator current ib	A or pu	$i_b$
11	Voltage capacitor Vc	V or pu	$V_c$
12	Stator flux phis_q(V.s)	V.s or pu	$\phi_{qs}$
13	Stator flux phis_d(V.s)	V.s or pu	$\phi_{ds}$
14	Rotor speed	rad/s	$\omega_m$
15	Electromagnetic torque Te	N.m or pu	$T_e$
16	Rotor angle thetam	rad	$\Theta_m$

## Limitations

The single phase asynchronous machine block does not include a representation of iron losses and saturation.

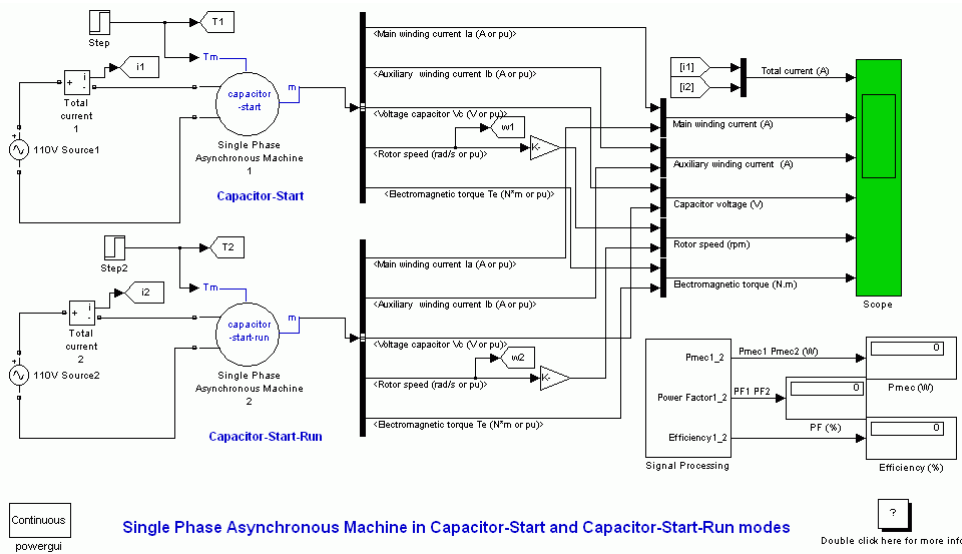


# Single Phase Asynchronous Machine

## Example

This example, available in the power\_singlephaseASM demo, illustrates the use of the Single Phase Asynchronous Machine block in two modes of operation.

It consists of a single phase asynchronous machine in an open-loop speed control system. The main and auxiliary windings are fed by a single phase power supply. The motor is started at no-load and a step of 1N.m is applied at 2 seconds.



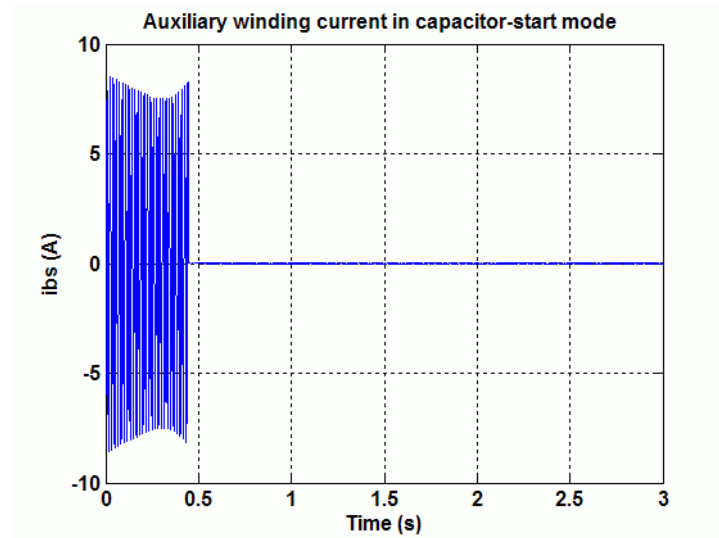
## Capacitor-Start Operation Mode

The next series of figures shows the capacitor-start operation where the auxiliary winding is tripped when the machine is speeded up to 75% of the rated speed.

The last figure in the series, Electromagnetic Torque in Capacitor-Start Operation Mode on page 2-496, shows the electromagnetic torque developed by the machine. Since there is a step load of 1 N.m, the average torque will be 1 N.m. The torque ripple amplitude is about

# Single Phase Asynchronous Machine

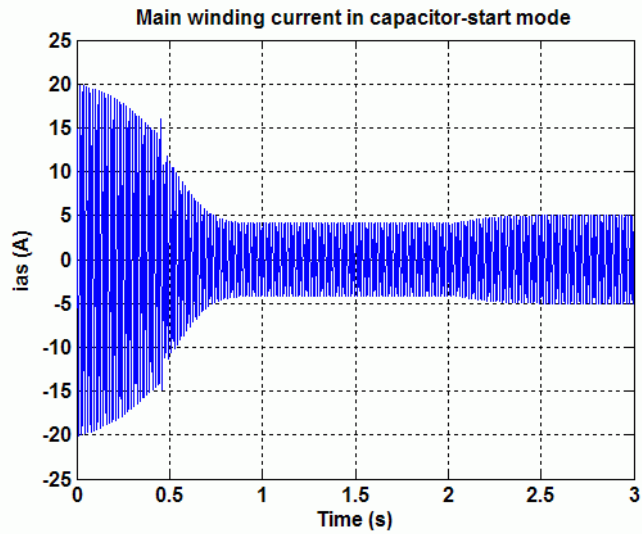
2.5 N.m, or 150% of the rated load. The torque pulsation affects the operation of the machine.



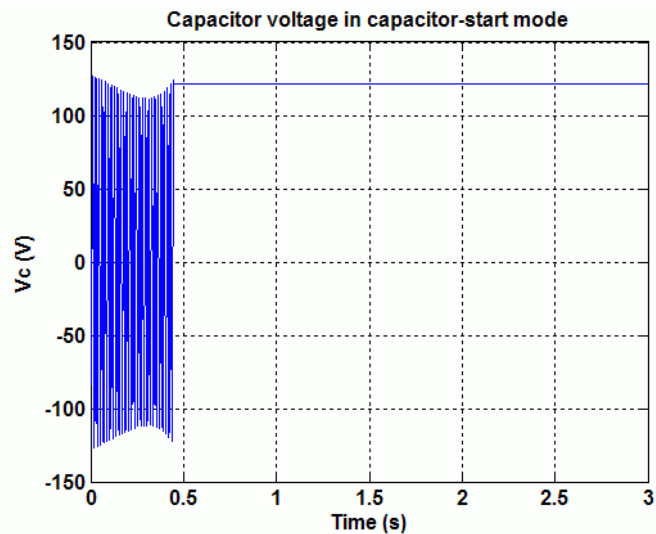
## Auxiliary Winding Current in Capacitor-Start Operation Mode

The auxiliary winding current is set to zero when the speed reaches 75% of the rated speed. The voltage across the start-capacitor remains at its maximum value, since current and voltage across a capacitor are in quadrature.

# Single Phase Asynchronous Machine

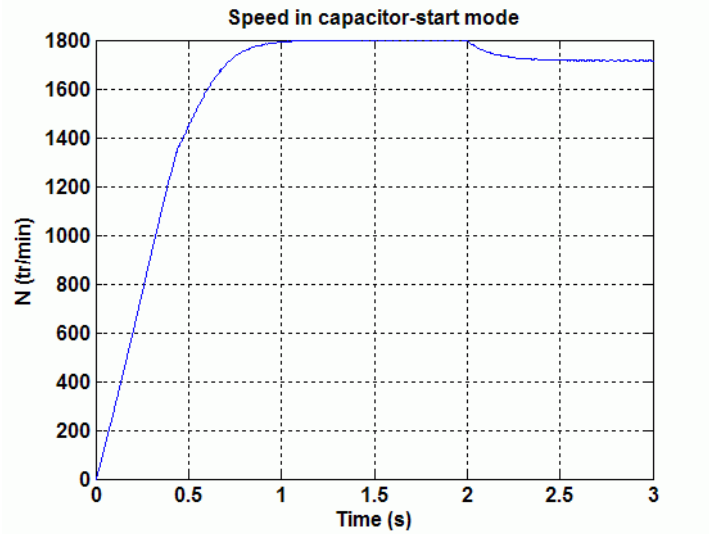


**Main Winding Current in Capacitor-Start Operation Mode**

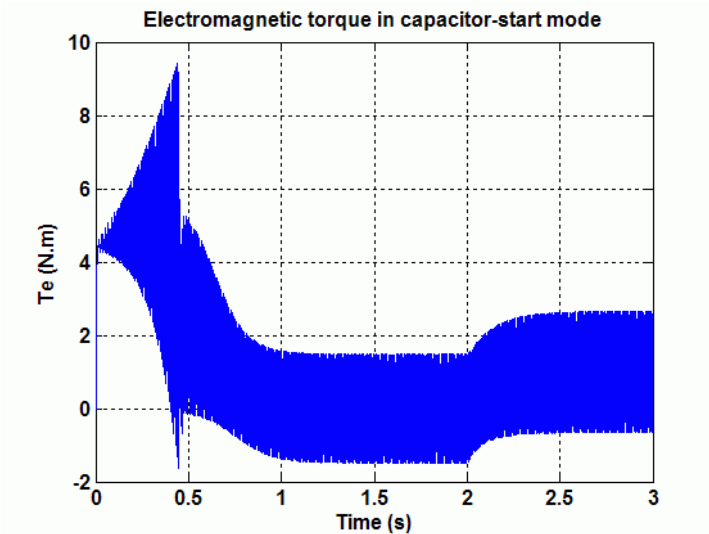


**Capacitor Voltage in Capacitor-Start Operation Mode**

# Single Phase Asynchronous Machine



**Speed in Capacitor-Start Operation Mode**



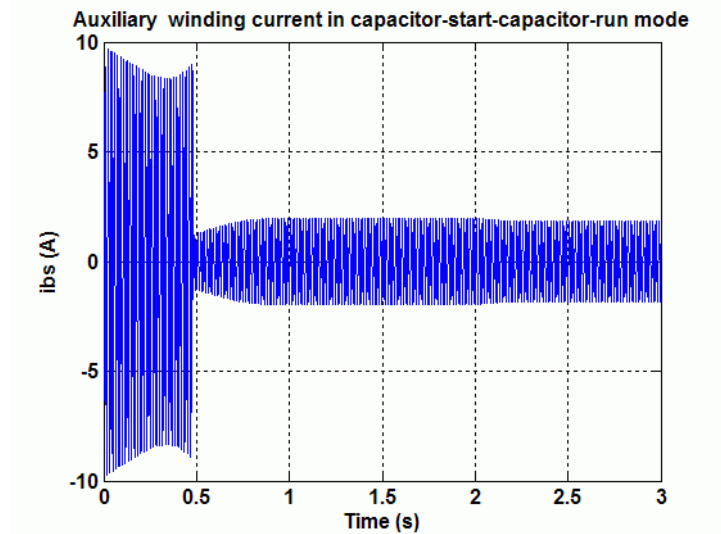
**Electromagnetic Torque in Capacitor-Start Operation Mode**

# Single Phase Asynchronous Machine

## Capacitor-Start-Run Operation Mode

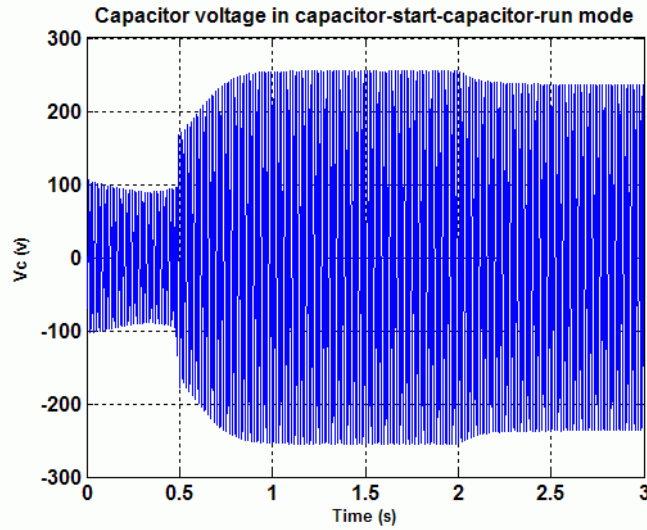
An improvement in the operation mode of the single phase asynchronous machine occurs when the auxiliary winding is still connected in series with a capacitor after starting.

The next figures show the simulation wave forms in the capacitor-start-run operation mode single phase asynchronous machine. The magnitude of the torque ripple at steady state is only about 3% of the load torque. It improves the operation of a single phase asynchronous machine by limiting the shaft's vibrations.

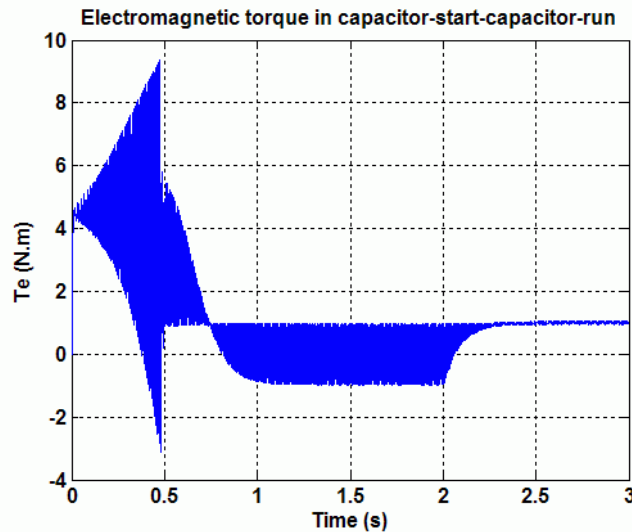


**Auxiliary Winding Current in Capacitor-Start-Run Operation Mode**

# Single Phase Asynchronous Machine

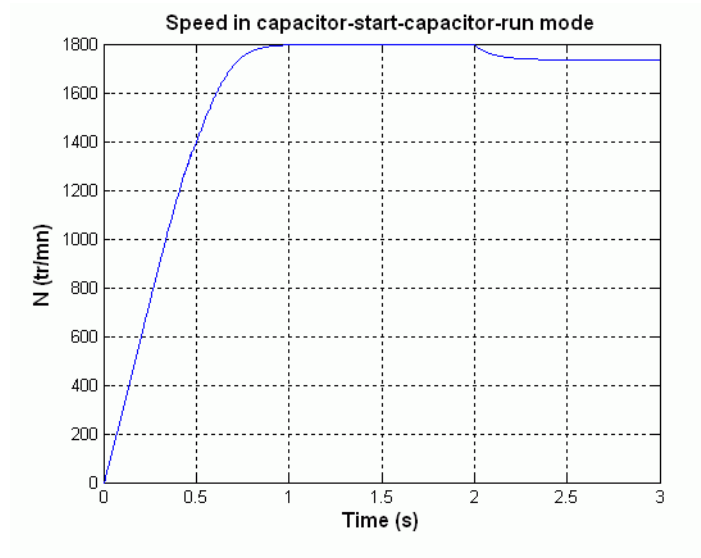


**Capacitor Voltage in Capacitor-Start-Run Operation Mode**



**Electromagnetic Torque in Capacitor-Start-Run Operation Mode**

# Single Phase Asynchronous Machine



## Speed in Capacitor-Start-Run Operation Mode

### References

- [1] Krause, P.C., O. Wasynczuk, and S.D. Sudhoff, *Analysis of Electric Machinery*, IEEE Press, 1995.

# Six-Step VSI Induction Motor Drive

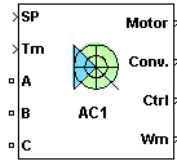
## Purpose

Implement six-step inverter fed Induction Motor Drive

## Library

Electric Drives/AC drives

## Description



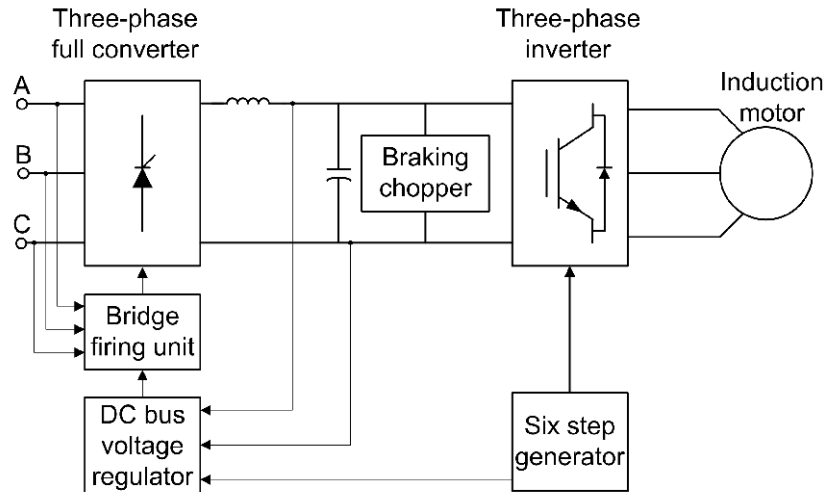
The high-level schematic shown below is built from seven main blocks. The induction motor, the three-phase inverter, the three-phase thyristor rectifier, and the bridge firing unit are provided with the SimPowerSystems library. More details are available in the reference pages for these blocks. The three other blocks are specific to the Electric Drives library. These blocks are the DC bus voltage regulator, the six-step generator, and the DC bus voltage filter.

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**Note** In SimPowerSystems software, the Six-Step VSI Induction Motor Drive block is commonly called the AC1 motor drive.

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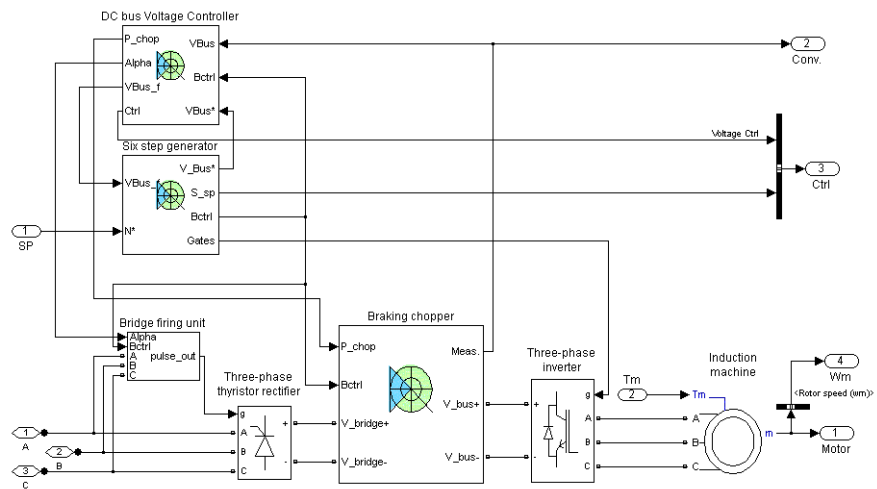
## High-Level Schematic





# Six-Step VSI Induction Motor Drive

## Simulink Schematic



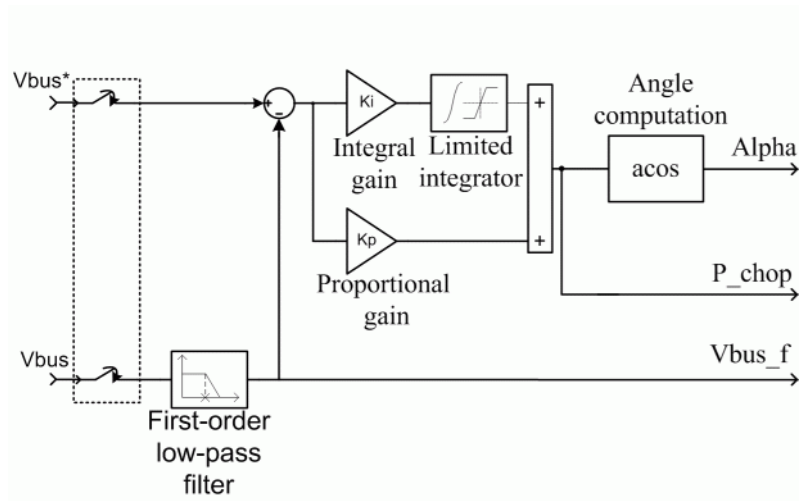
## Bridge Firing Unit

The bridge firing unit is used to convert the firing angle, provided by the DC bus voltage regulator, into pulses applied to the thyristor gates. The bridge firing unit block contains notch filters applied to the voltage measurement to remove harmonics. The discrete synchronized six-pulse generator block is used to generate the pulses. Refer to the Synchronized 6-Pulse Generator for more information on this block.

## DC Bus Voltage Regulator and Braking Chopper

The DC bus voltage regulator is based on a PI controller and a hysteresis chopper logic. When the bus voltage decreases, the PI controller reduces the firing angle. When the bus voltage increases, the PI controller increases the firing angle. The chopper logic is based on hysteresis control. If the voltage reaches the upper hysteresis limit, the DC voltage controller toggles to braking mode and the chopper is activated, whereas the thyristor bridge is shut off. In chopper mode, the proportional action remains active but the integral gain is set to zero because the chopper dynamics are very high and the integral gain is useless. When the bus voltage reaches the hysteresis lower limit, the braking chopper is shut down and the thyristor bridge is reactivated. The following figure illustrates the DC bus PI regulator.

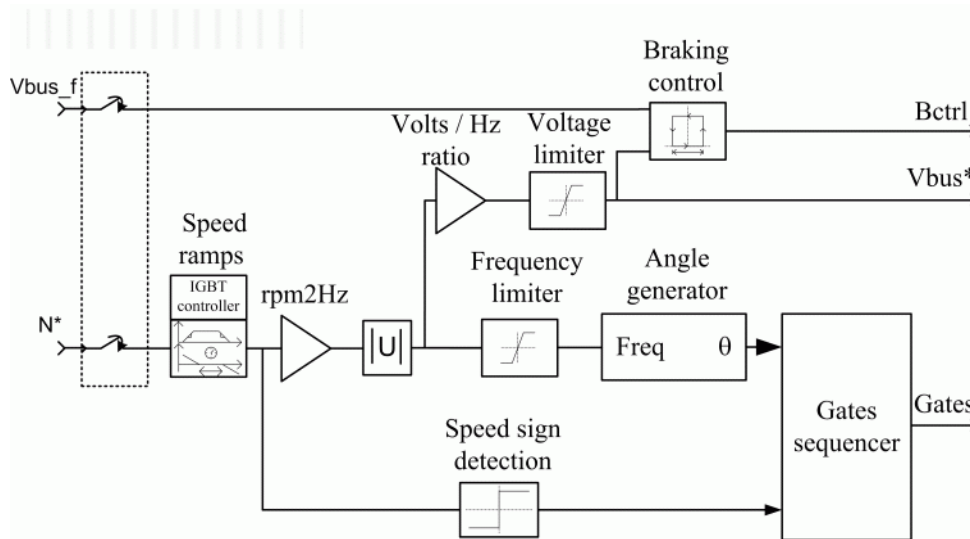
# Six-Step VSI Induction Motor Drive



## Six-Step Generator

The six-step generator illustrated in the following figure contains six comparators to produce the six-step switching waveforms. Some supplementary logic enables a speed reversal by inverting two phases.

# Six-Step VSI Induction Motor Drive



## Remarks

In the AC1 motor drive, the motor speed is not regulated in closed loop. Instead, the speed set point is used only to determine the motor voltage and frequency applied by the six-step inverter in order to maintain the (V/F) ratio (or the motor flux) constant from 0 to the nominal speed. Above nominal speed, the motor operates in the flux weakening mode; that is, the voltage is maintained constant at its nominal value while the frequency is increased proportionally to the speed set point.

When reversing speed, a short delay is required at the zero speed crossing so that air gap flux decays to zero.

# Six-Step VSI Induction Motor Drive

## Dialog Box

## Asynchronous Machine Tab

The screenshot shows a software dialog box titled "Six-Step VSI Induction Motor Drive". It has three tabs: "Asynchronous Machine", "Converters and DC bus", and "Controller". The "Asynchronous Machine" tab is selected. The dialog contains several sections for parameter input:

- Reference frame:** A dropdown menu set to "Stationary".
- Nominal values:** Three input fields for "Power (VA)" (2238), "Voltage (Vrms)" (220), and "Frequency (Hz)" (60).
- Equivalent circuit values:** A table for resistance, leakage inductance, and mutual inductance for both stator and rotor.

	Resistance (ohm)	Leakage inductance (H)	Mutual inductance (H)
Stator:	0.435	0.002	69.31e-3
Rotor:	0.816	0.002	
- Initial currents:** A table for magnitude and phase for three phases (A, B, C).

	Phase A:	Phase B:	Phase C:
Magnitude (A):	0	0	0
Phase (deg):	0	0	0
- Mechanical parameters:** Input fields for "Rotor values": Inertia (kg\*m<sup>2</sup>): 0.089, Friction (N-m-s): 0.005, Pole pairs: 2. An "Initial values" section has "Slip": 1 and "Angle (deg)": 0.
- Mechanical input:** A dropdown menu set to "Torque Tm".
- Parameters file options:** "Load" and "Save" buttons.
- Buttons:** "OK", "Cancel", "Help", and "Apply" at the bottom.

The asynchronous machine tab displays the parameters of the asynchronous machine block of the powerlib library. Refer to the Asynchronous Machine for more information on the asynchronous machine parameters.

### Mechanical input

Allows you to select either the load torque or the motor speed as mechanical input. Note that if you select and apply a load torque, you will obtain as output the motor speed according to

the following differential equation that describes the mechanical system dynamics:

$$T_e = J \frac{d}{dt} \omega_r + F \omega_r + T_m$$

This mechanical system is included in the motor model.

However, if you select the motor speed as mechanical input then you will get the electromagnetic torque as output, allowing you to represent externally the mechanical system dynamics. Note that the internal mechanical system is not used with this mechanical input selection and the inertia and viscous friction parameters are not displayed.

See for example “Mechanical Coupling of Two Motor Drives”.

# Six-Step VSI Induction Motor Drive

## Converters and DC Bus Tab

The screenshot shows the 'Converters and DC bus' tab of the 'Six-Step VSI Induction Motor Drive' software. The window title is 'Six-Step VSI Induction Motor Drive'. Below the title bar, there is a text area stating: 'The AC motor parameters are specified in the AC Machine tab. The DC bus LC filter, the thyristor rectifier and the inverter switches parameters are specified in the Converter and DC bus tab. DC bus regulator and six step generator parameters are specified in the Controller Tab.' Below this text are three tabs: 'Asynchronous Machine', 'Converters and DC bus' (selected), and 'Controller'.

The 'Converters and DC bus' tab is divided into several sections:

- Rectifier**
  - Snubbers**: Resistance (ohm): 5e3, Capacitance (F): 100e-9
  - Thyristors**: On-state resistance (ohm): 1e-3, Forward voltage (V): 1.3
- Dc Bus**
  - Inductance (H)**: 1e-3
  - Capacitance (F)**: 4000e-6
  - Braking chopper**: Resistance (ohm): 8, Chopper frequency (Hz): 4000
- Inverter**
  - Switches**: Device type: IGBT / Diodes, On-state resistance (ohm): 1e-3, Forward voltages (V): Main device: 1.7, Diode: 1.7, Turn-off characteristics: Fall time (s): 1e-6, Tail time (s): 2e-6
  - Snubbers**: Resistance (ohm): 1e3, Capacitance (F): 20e-9

At the bottom of the tab, there is a 'Mechanical input' dropdown menu set to 'Torque Trn'. Below this is a 'Parameters file options' section with 'Load' and 'Save' buttons. At the very bottom of the window are 'OK', 'Cancel', 'Help', and 'Apply' buttons.

### Rectifier section

The rectifier section of the Converters and DC bus tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the Universal Bridge for more information on the universal bridge parameters.

### Inverter section

The inverter section of the Converters and DC bus tab displays the parameters of the Universal Brige block of the powerlib

library. Refer to the Universal Bridge for more information on the universal bridge parameters.

**DC Bus Filter — Inductance**

The low-pass DC bus filter inductance (H).

**DC Bus Filter — Capacitance**

The low-pass DC bus filter capacitance (F).

**Braking Chopper section**

**Resistance**

The braking chopper resistance used to avoid bus over-voltage during motor deceleration or when the load torque tends to accelerate the motor ( $\Omega$ ).

**Frequency**

The braking chopper frequency (Hz).

# Six-Step VSI Induction Motor Drive

## Controller Tab

The screenshot shows a software window titled "Six-Step VSI Induction Motor Drive" with a "Controller" tab selected. The window contains several sections for parameter configuration:

- DC bus control:** Includes input fields for Voltage sensor cutoff frequency (Hz) set to 30, Network frequency (Hz) set to 60, DC bus negative deviation (V) set to 20, and DC bus positive deviation (V) set to 20.
- PI regulator:** Includes input fields for Proportional gain set to 0.01 and Integral gain set to 0.1.
- Bus voltage limits (V):** Includes input fields for Minimum set to 30 and Maximum set to 280.
- Six step generator:** Includes a "Speed ramps (rpm/s)" section with Acceleration set to 2000 and Deceleration set to -2000, and an "Output frequency limits (Hz)" section with Minimum set to 0 and Maximum set to 120.
- Other parameters:** Includes "Volts / Hertz ratio" set to 5 and "Zero speed crossing time (s)" set to 0.5.
- Mechanical input:** A dropdown menu currently set to "Torque Trn".
- Parameters file options:** Includes "Load" and "Save" buttons.
- Bottom buttons:** Includes "OK", "Cancel", "Help", and "Apply" buttons.

## Schematic Button

When you press this button, a diagram illustrating the speed and current controllers schematics appears.

## DC Bus Control section

### Voltage Sensor Cutoff Frequency

The DC bus voltage measurement first-order filter cutoff frequency (Hz).



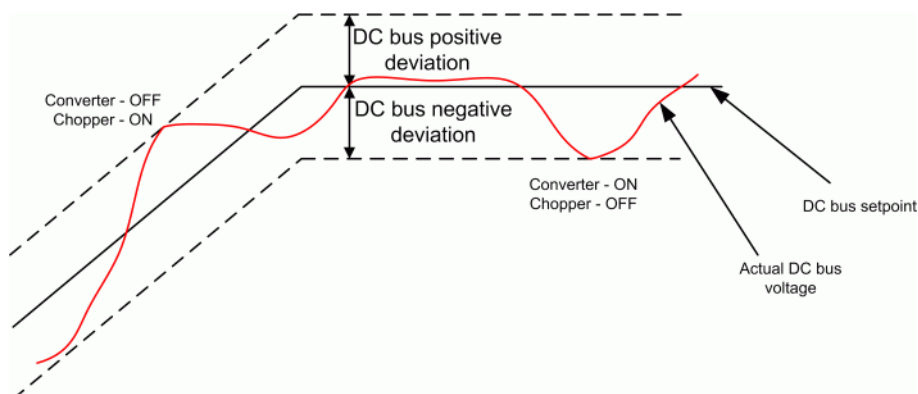
# Six-Step VSI Induction Motor Drive

## DC Bus Negative Deviation

The maximum deviation of the actual bus voltage under the DC bus set point. Refer to the figure shown in the DC Bus Positive Deviation parameter section.

## DC Bus Positive Deviation

The maximum deviation of the actual bus voltage over the DC bus set point.



## Proportional Gain

The proportional gain of the DC bus PI controller.

## Integral Gain

The integral gain of the DC bus PI controller.

## Voltage limits — Minimum

The minimum DC bus voltage (V).

## Voltage limits — Maximum

The maximum DC bus voltage (V).

## Six-Step Generator section

### Volts / Hertz Ratio

The proportionality constant between the stator line-to-line RMS voltage and frequency (V / Hz).

# Six-Step VSI Induction Motor Drive

---

## **Zero Speed Crossing Time**

The delay at zero speed to eliminate the motor air gap residual flux (s).

## **Speed Ramps — Acceleration**

The maximum change of speed allowed during motor acceleration. An excessively large positive value can cause DC bus under-voltage and undesirable harmonics on the line side voltages (rpm/s).

## **Speed Ramps — Deceleration**

The maximum change of speed allowed during motor deceleration. An excessively large negative value can cause DC bus over-voltage (rpm/s).

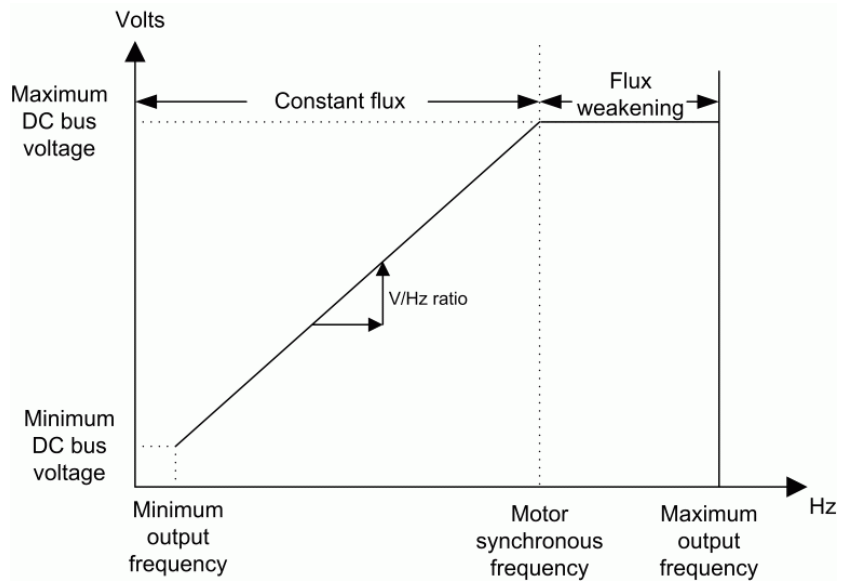
## **Frequency Limits — Minimum**

The six-step generator minimum output frequency (Hz).

## **Frequency Limits — Maximum**

The six-step generator maximum output frequency (Hz).

# Six-Step VSI Induction Motor Drive



**Graphical Representation of the Six-Step Generator Limits**

## Block Inputs and Outputs

SP

The speed or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration / deceleration ramps. If the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

$T_m$  or  $W_m$

The mechanical input: load torque ( $T_m$ ) or motor speed ( $W_m$ ).

A, B, C

The three phase terminals of the motor drive.

$W_m$  or  $T_e$

The mechanical output: motor speed ( $W_m$ ) or electromagnetic torque ( $T_e$ ).

# Six-Step VSI Induction Motor Drive

---

## Motor

The motor measurement vector. This vector allows you to observe the motor's variables using the Bus Selector block.

## Conv

The three-phase converters measurement vector. This vector contains:

- The rectifier output voltage
- The inverter output voltage
- The rectifier input current
- The inverter output current

Note that all current and voltage values of the bridges can be visualized with the Multimeter block.

## Ctrl

The controller measurement vector. This vector contains:

- The firing angle computed by the current controller
- The speed error (difference between the speed reference ramp and actual speed)
- The speed reference ramp

## Model Specifications

The library contains a 3 hp and a 500 hp drive parameter set. The specifications of these two drives are shown in the following table.

### 3 HP and 500 HP Drive Specifications

	3 HP Drive	500 HP Drive
<b>Drive Input Voltage</b>		
Amplitude	220 V	2300 V
Frequency	60 Hz	60 Hz

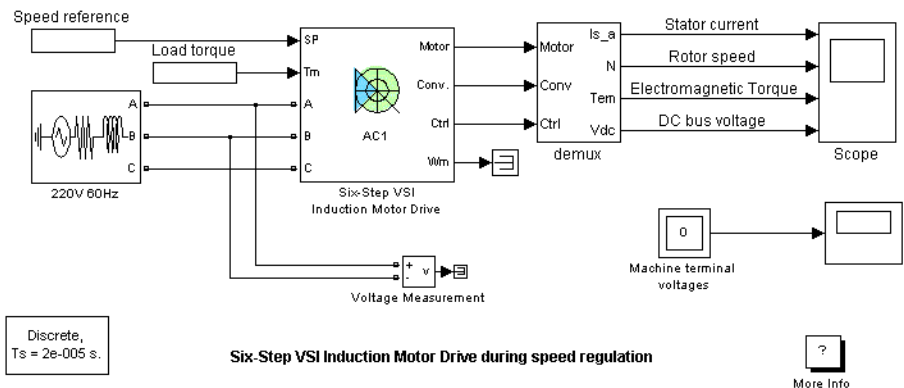
# Six-Step VSI Induction Motor Drive

## 3 HP and 500 HP Drive Specifications (Continued)

	3 HP Drive	500 HP Drive
<b>Drive Input Voltage</b>		
<b>Motor Nominal Values</b>		
Power	3 hp	500 hp
Speed	1705 rpm	1773 rpm
Voltage	220 V	2300 V

### Example

The ac1\_example demo illustrates a typical operation of the AC1 motor drive. A speed reference step from zero to 1800 rpm is applied at  $t = 0$ .



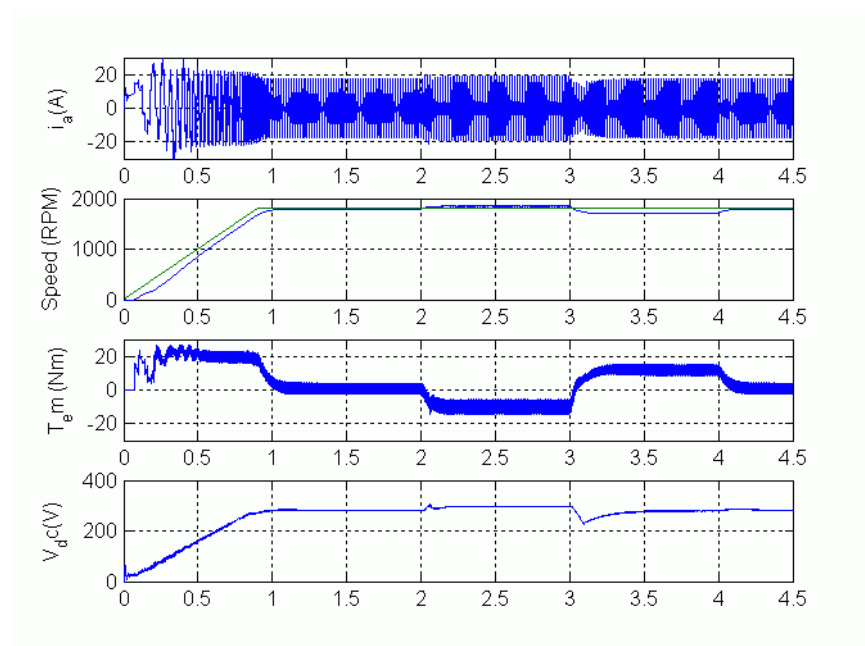
The 'Ts' parameter used in this model is set to 20e-6 by the Model Properties Callbacks

More Info

As shown in the following figure, the speed set point doesn't go instantaneously to 1800 rpm but follows the acceleration ramp (2000 rpm/s). The motor reaches steady state at  $t = 1.3$  s. At  $t = 2$  s, an accelerating torque is applied on the motor's shaft. You can observe a speed increase. Because the rotor speed is higher than the synchronous speed, the motor is working in the generator mode. The braking energy

# Six-Step VSI Induction Motor Drive

is transferred to the DC link and the bus voltage tends to increase. However, the over-voltage activates the braking chopper, which causes the voltage to decrease. In this example, the braking resistance is not big enough to avoid a voltage increase but the bus is maintained within tolerable limits. At  $t = 3$  s, the torque applied to the motor's shaft steps from  $-11$  N.m to  $+11$  N.m. You can observe a DC voltage and speed drop at this point. The DC bus controller switches from braking to motoring mode. At  $t = 4$  s, the load torque is removed completely.



## References

- [1] Bose, B. K., *Modern Power Electronics and AC Drives*, Prentice-Hall, N.J., 2002.
- [2] Harunur, M. R., *Power Electronics*, Prentice-Hall, 1988.

# Space Vector PWM VSI Induction Motor Drive

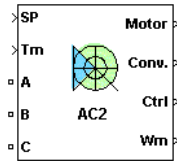
## Purpose

Implement space vector PWM VSI induction motor drive

## Library

Electric Drives/AC drives

## Description



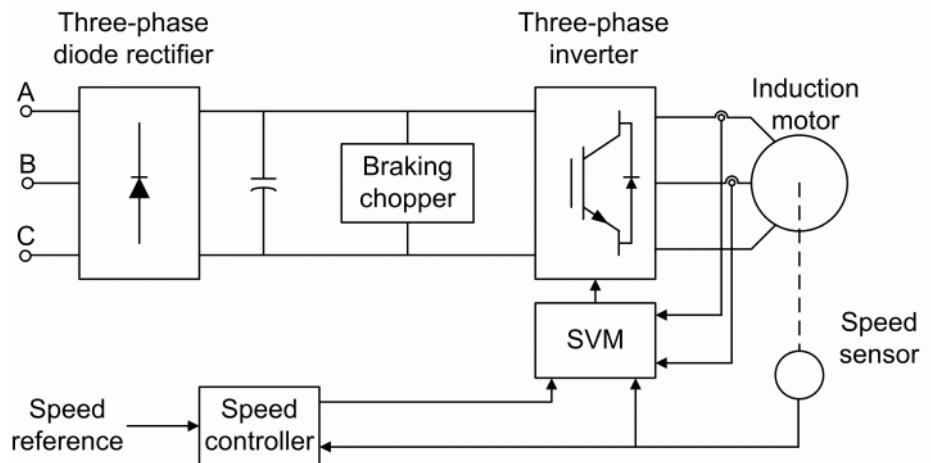
The high-level schematic shown below is built from six main blocks. The induction motor, the three-phase inverter, and the three-phase diode rectifier models are provided with the SimPowerSystems library. The speed controller, the braking chopper, and the space vector modulator models are specific to the drive library. It is possible to use a simplified version of the drive containing an average-value model of the inverter for faster simulation.

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**Note** In SimPowerSystems software, the Space Vector PWM VSI Induction Motor Drive block is commonly called the AC2 motor drive.

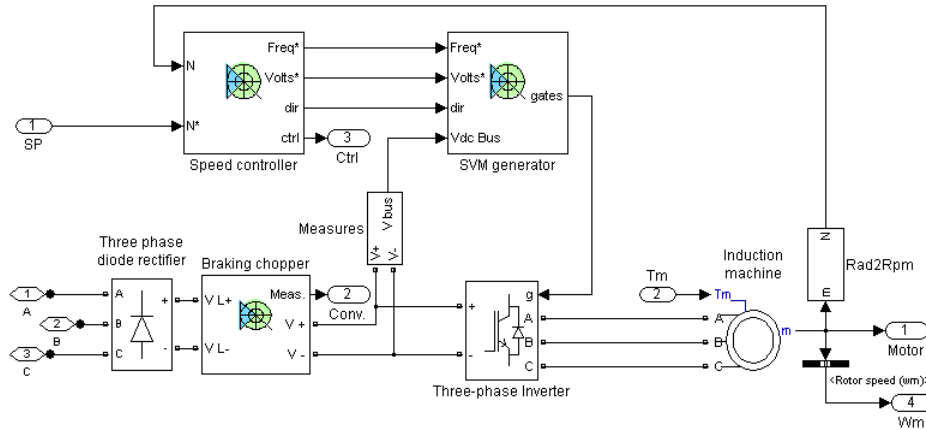
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## High-Level Schematic



# Space Vector PWM VSI Induction Motor Drive

## Simulink Schematic

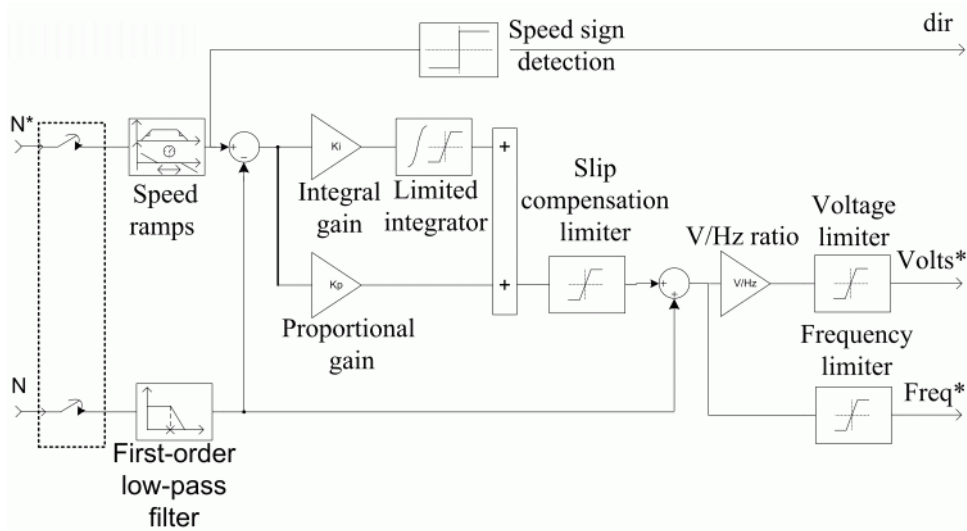


## Speed Controller

The speed controller is based on a PI regulator that controls the motor slip. As shown in the following figure, the slip value computed by the PI regulator is added to the motor speed in order to produce the demanded inverter frequency. The latter frequency is also used to generate the demanded inverter voltage in order to maintain the motor V/F ratio constant.



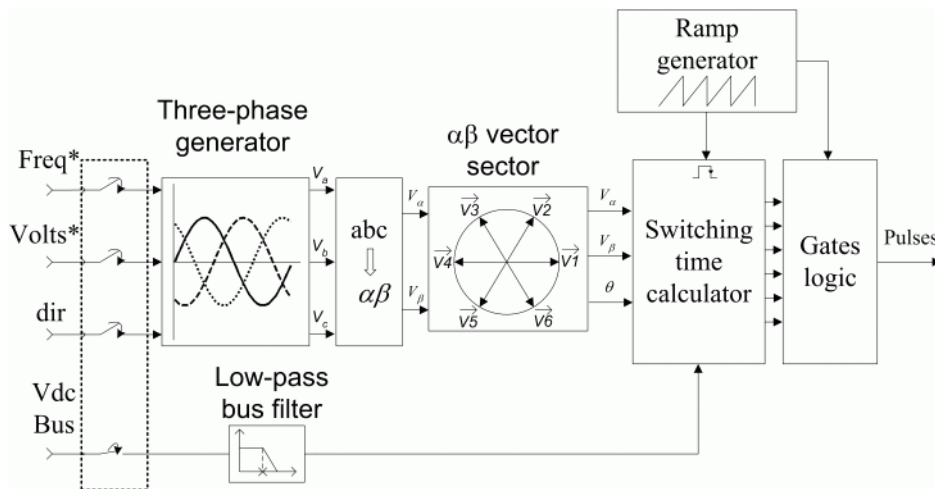
# Space Vector PWM VSI Induction Motor Drive



## Space Vector Modulator

The space vector modulator (SVM) contains seven blocks, shown in the following figure. These blocks are described below.

# Space Vector PWM VSI Induction Motor Drive



The *three-phase generator* is used to produce three sine waves with variable frequency and amplitude. The three signals are out of phase with each other by 120 degrees. The inverter demanded frequency and voltage are two of the block inputs.

The *low-pass bus filter* is used to remove fast transients from the DC bus voltage measurement. This measure is used to compute the voltage vector applied to the motor.

The *alpha beta transformation* converts variables from the three-phase system to the two-phase  $\alpha\beta$  system.

The *alpha beta vector sector* is used to find the sector of the  $\alpha\beta$  plane in which the voltage vector lies. The  $\alpha\beta$  plane is divided into six different sectors spaced by 60 degrees.

The *ramp generator* is used to produce a unitary ramp at the PWM switching frequency. This ramp is used as a time base for the switching sequence.

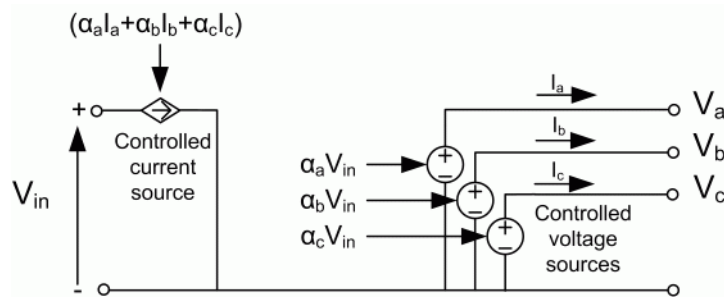
The *switching time calculator* is used to calculate the timing of the voltage vector applied to the motor. The block input is the sector in which the voltage vector lies.

# Space Vector PWM VSI Induction Motor Drive

The *gates logic* receives the timing sequence from the *switching time calculator* and the ramp from the *ramp generator*. This block compares the ramp and the gate timing signals to activate the inverter switches at the proper time.

When using the average-value inverter, the *gates logic* block is disabled and the inverter leg PWM duty cycles are issued by the *switching time calculator* to control the average-value inverter.

**Average-Value Inverter** The average-value inverter is shown in the following figure.



It is composed of one controlled current source on the DC side and three controlled voltage sources on the AC side. The DC current source allows the representation of the average DC bus current behavior, following the next equation:

$$I_{dc} = \alpha_a I_a + \alpha_b I_b + \alpha_c I_c$$

with  $\alpha_a$ ,  $\alpha_b$ ,  $\alpha_c$  being the PWM duty cycles of the inverter legs A, B, and C respectively, and  $I_a$ ,  $I_b$ ,  $I_c$  the corresponding three-phase currents. The three AC voltage sources represent the average voltage values of the three-phase inverter voltages  $V_a$ ,  $V_b$ ,  $V_c$ , following the next equation:

$$V_a = \alpha_a V_{in}$$

$$V_b = \alpha_b V_{in}$$

# Space Vector PWM VSI Induction Motor Drive

---

$$V_c = \alpha_c V_{in}$$

with  $V_{in}$  being the input DC bus voltage value.

## Braking Chopper

The braking chopper block contains the DC bus capacitor and the dynamic braking chopper, which is used to absorb the energy produced by a motor deceleration.

## Remarks

The model is discrete. Good simulation results have been obtained with a  $2 \mu\text{s}$  time step. In order to simulate a digital controller device, the control system has two different sampling times:

- The speed controller sampling time
- The SVM controller sampling time

The speed controller sampling time has to be a multiple of the SVM sampling time. The latter sampling time has to be a multiple of the simulation time step.

The simulation step size must be chosen in accordance with the inverter's switching frequency. A rule of thumb is to choose a simulation step size 100 times smaller than the switching period. If the simulation step size is set too high, the simulation results can be erroneous. The average-value inverter allows the use of bigger simulation time steps since it does not generate small time constants (due to the RC snubbers) inherent to the detailed converter. For a controller sampling time of  $20 \mu\text{s}$ , good simulation results have been obtained for a simulation time step of  $20 \mu\text{s}$ . This time step can, of course, not be higher than the controller time step.

In the AC2 motor drive, the motor speed is regulated by controlling the motor slip. The motor current or torque is not regulated, however, so the speed response tends to be sluggish at low speed because of torque ripple.

When reversing speed, a short delay is required at the zero speed crossing so that air gap flux decays to zero.

# Space Vector PWM VSI Induction Motor Drive

## Dialog Box

### Asynchronous Machine Tab

The dialog box is titled "Space Vector PWM VSI Induction Motor Drive" and contains the following sections:

- Reference frame:** Stationary (dropdown)
- Nominal values:**
  - Power (VA): 2238
  - Voltage (Vrms): 220
  - Frequency (Hz): 60
- Equivalent circuit values:**
  - Resistance (ohm): Stator: 0.435, Rotor: 0.816
  - Leakage inductance (H): Stator: 0.002, Rotor: 0.002
  - Mutual inductance (H): 69.31e-3
- Initial currents:**
  - Phase A: Magnitude (A): 0, Phase (deg): 0
  - Phase B: Magnitude (A): 0, Phase (deg): 0
  - Phase C: Magnitude (A): 0, Phase (deg): 0
- Mechanical parameters:**
  - Rotor values:
    - Inertia (kg\*m<sup>2</sup>): 0.089
    - Friction (N-m-s): 0.005
    - Pole pairs: 2
  - Initial values:
    - Slip: 1
    - Angle (deg): 0
- Model detail level:** Detailed (dropdown)
- Mechanical input:** Torque Tm (dropdown)
- Parameters file options:** Load, Save buttons
- Buttons:** OK, Cancel, Help, Apply

The asynchronous machine tab displays the parameters of the asynchronous machine block of the powerlib library. Refer to Asynchronous Machine for more information on the asynchronous machine parameters.

#### Model detail level

Select between the detailed and the average-value inverter.

#### Mechanical input

Allows you to select either the load torque or the motor speed as mechanical input. Note that if you select and apply a load

# Space Vector PWM VSI Induction Motor Drive

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torque, you will obtain as output the motor speed according to the following differential equation that describes the mechanical system dynamics:

$$T_e = J \frac{d}{dt} \omega_r + F \omega_r + T_m$$

This mechanical system is included in the motor model.

However, if you select the motor speed as mechanical input then you will get the electromagnetic torque as output, allowing you to represent externally the mechanical system dynamics. Note that the internal mechanical system is not used with this mechanical input selection and the inertia and viscous friction parameters are not displayed.

See for example “Mechanical Coupling of Two Motor Drives”.

# Space Vector PWM VSI Induction Motor Drive

## Converters and DC Bus Tab

Space Vector PWM VSI Induction Motor Drive

Space Vector PWM VSI Induction Motor Drive

The AC motor parameters are specified in the AC Machine tab. The braking chopper, the diode rectifier and the inverter switches parameters are specified in the Converter and DC bus tab. Speed regulator and drive limits are specified in the Controller Tab.

Asynchronous Machine    Converters and DC bus    Controller

**Rectifier**

Snubbers

Resistance (ohm): 10e3

Capacitance (F): 20e-9

Diodes

On-state resistance (ohm): 1e-3

Forward voltage (V): 1.3

**DC Bus**

Capacitance (F): 3400e-6

**Braking chopper**

Resistance (ohm): 8

Chopper frequency (Hz): 4000

Activation voltage (V): 340

Shutdown voltage (V): 320

**Inverter**

Switches

Device type: IGBT / Diodes

On-state resistance (ohm): 1e-3

Forward voltages (V)

Main device: 1.2

Diode: 1.2

Turn-off characteristics

Fall time (s): 1e-6

Tail time (s): 2e-6

Snubbers

Resistance (ohm): 500

Capacitance (F): 1e-9

Model detail level: Detailed    Mechanical input: Torque Tm

Parameters file options

Load    Save

OK    Cancel    Help    Apply

### Rectifier section

The rectifier section of the Converters and DC bus tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the Universal Bridge for more information on the universal bridge parameters.

### Inverter section

The inverter section of the Converters and DC bus tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the Universal Bridge for more information on the

# Space Vector PWM VSI Induction Motor Drive

universal bridge parameters. This parameter is not used when using the average-value inverter.

## Braking Chopper section

### Capacitance

The DC bus capacitance (F).

### Resistance

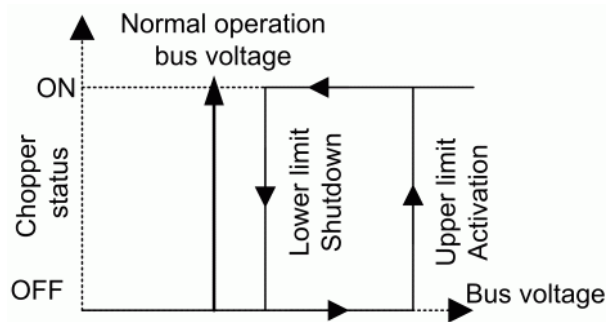
The braking chopper resistance used to avoid bus over-voltage during motor deceleration or when the load torque tends to accelerate the motor ( $\Omega$ ).

### Frequency

The braking chopper frequency (Hz).

### Activation and Shutdown Voltage

The dynamic braking is activated when the bus voltage reaches the upper limit of the hysteresis band. The dynamic braking is shut down when the bus voltage reaches the lower limit of the hysteresis band. The following figure illustrates the braking hysteresis logic.





# Space Vector PWM VSI Induction Motor Drive

## Controller Tab

The screenshot shows a software window titled "Space Vector PWM VSI Induction Motor Drive". It features a tabbed interface with three tabs: "Asynchronous Machine", "Converters and DC bus", and "Controller". The "Controller" tab is active. Below the tabs is a "Schematic" button. The main area is divided into several sections:

- Speed controller:**
  - Speed ramps (rpm/s):** Acceleration: 1800, Deceleration: -1800.
  - PI regulator:** Proportional gain: 9, Integral gain: 10.
  - Output limits:** Controller: Minimum: -30, Maximum: 30; Frequency (Hz): 0.05, 120; Voltage (V): 10, 180.
  - Other parameters:** Sampling time (s): 100e-6, Sensor cutoff frequency (Hz): 100, Voltz / Hertz ratio: 3.2, Zero speed crossing time (s): 0.4.
- SVM generator:**
  - SVM switching frequency (Hz): 4500
  - DC bus voltage sensor cutoff frequency (Hz): 50
  - Sampling time (s): 20e-6
- Model detail level:** Detailed (dropdown)
- Mechanical input:** Torque Tm (dropdown)
- Parameters file options:** Load, Save buttons.

At the bottom of the window are buttons for "OK", "Cancel", "Help", and "Apply".

## Schematic Button

When you press this button, a diagram illustrating the speed and current controllers schematics appears.

## Speed Controller section

### Speed Ramps — Acceleration

The maximum change of speed allowed during motor acceleration. An excessively large positive value can cause DC bus under-voltage (rpm/s).

# Space Vector PWM VSI Induction Motor Drive

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## **Speed Ramps — Deceleration**

The maximum change of speed allowed during motor deceleration. An excessively large negative value can cause DC bus over-voltage (rpm/s).

## **Proportional Gain**

The speed controller proportional gain.

## **Integral Gain**

The speed controller integral gain.

## **Output Negative Saturation**

The maximum negative slip compensation computed by the slip regulator (Hz).

## **Output Positive Saturation**

The maximum positive slip compensation computed by the slip regulator (Hz).

## **Minimum Frequency**

The minimum demanded inverter frequency applied to the motor (Hz).

## **Maximum Frequency**

The maximum demanded inverter frequency applied to the motor (Hz).

## **Minimum Output Voltage**

The minimum demanded inverter output voltage (V). If this parameter is set to zero, the zero speed cannot be reached under several load conditions.

## **Maximum Output Voltage**

The maximum demanded inverter output voltage (V). This parameter must be set in accordance with the motor rating. If this parameter is set too high, you will observe over-modulation in the current and voltage waveforms.

## **Volts / Hertz Ratio**

The proportionality constant between the stator line-to-line RMS voltage and frequency (V / Hz).

# Space Vector PWM VSI Induction Motor Drive

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## Zero Speed Crossing Time

The delay at zero speed to eliminate the motor air gap residual flux (s).

## Speed Sensor Cutoff Frequency

The speed measurement first-order low-pass filter cutoff frequency (Hz).

## Sampling Time

The speed controller sampling time(s). The sampling time must be a multiple of the simulation time step.

## SVM Generator section

### Switching Frequency

The inverter switching frequency (Hz).

### Voltage Sensor Cutoff Frequency

The cutoff frequency of the first-order low-pass filter applied to the DC bus voltage measurement.(Hz).

### Sampling Time

The SVM generator sampling time (s). The sampling time must be a multiple of the simulation time step.

## Block Inputs and Outputs

SP

The speed or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration / deceleration ramps. If the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

T<sub>m</sub> or W<sub>m</sub>

The mechanical input: load torque (T<sub>m</sub>) or motor speed (W<sub>m</sub>).

A, B, C

The three phase terminals of the motor drive.

W<sub>m</sub> or T<sub>e</sub>

The mechanical output: motor speed (W<sub>m</sub>) or electromagnetic torque (T<sub>e</sub>).

# Space Vector PWM VSI Induction Motor Drive

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## Motor

The motor measurement vector. This vector allows you to observe the motor's variables using the Bus Selector block.

## Conv

The three-phase converters measurement vector. This vector contains:

- The DC bus voltage
- The rectifier output current
- The inverter input current

Note that all current and voltage values of the bridges can be visualized with the Multimeter block.

## Ctrl

The controller measurement vector. This vector contains:

- The slip compensation
- The speed error (difference between the speed reference ramp and actual speed)
- The speed reference ramp

## Model Specifications

The library contains a 3 hp and a 200 hp drive parameter set. The specifications of these two drives are shown in the following table.

### 3 HP and 200 HP Drive Specifications

	<b>3 HP Drive</b>	<b>200 HP Drive</b>
<b>Drive Input Voltage</b>		
Amplitude	220 V	575 V
Frequency	60 Hz	60 Hz

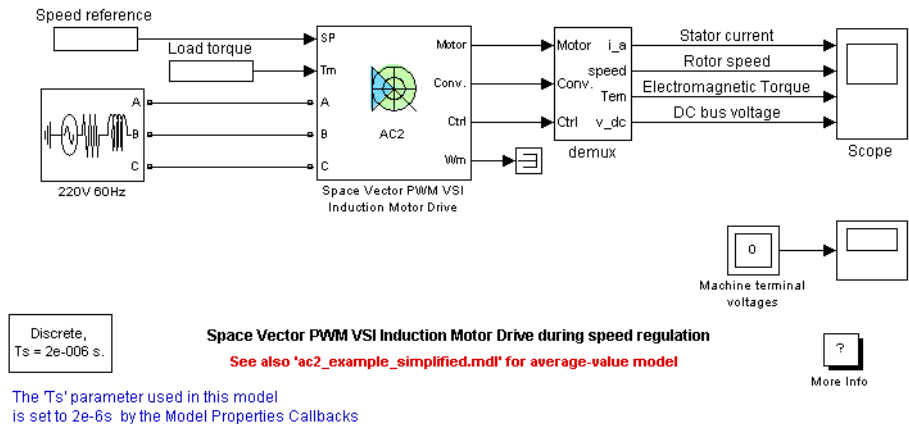
# Space Vector PWM VSI Induction Motor Drive

## 3 HP and 200 HP Drive Specifications (Continued)

	3 HP Drive	200 HP Drive
<b>Drive Input Voltage</b>		
<b>Motor Nominal Values</b>		
Power	3 hp	200 hp
Speed	1705 rpm	1785 rpm
Voltage	220 V	575 V

### Example

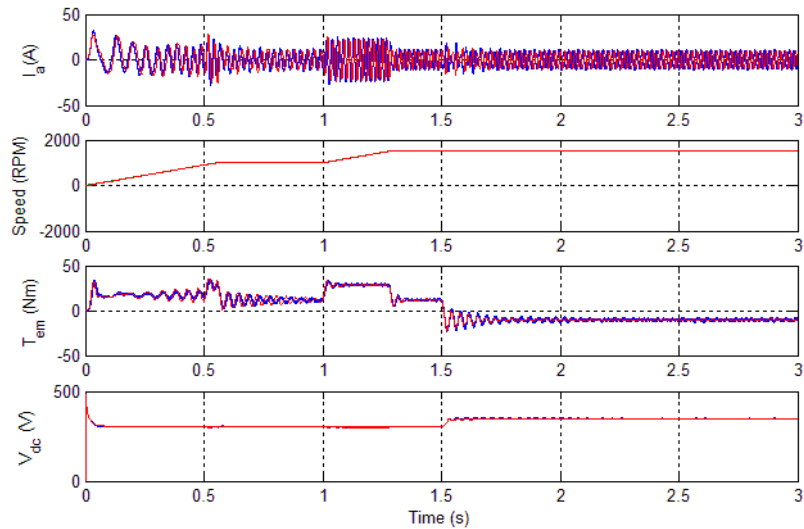
The ac2\_example demo illustrates an AC2 induction motor drive simulation with standard load conditions. At time  $t = 0$  s, the speed set point is 1000 rpm.



As shown in the following figure, the speed precisely follows the acceleration ramp. At  $t = 0.5$  s, the nominal load torque is applied to the motor. At  $t = 1$  s, the speed set point is changed to 1500 rpm. The speed increases to 1500 rpm. At  $t = 1.5$  s, the mechanical load passes

# Space Vector PWM VSI Induction Motor Drive

from 11 N.m to -11 N.m. The figure illustrates the results obtained respectively with the detailed and the average-value inverter. Average voltage, current, torque, and speed values are identical for both models. The higher frequency signal components are not represented with the average-value converter.



**AC2 Example Waveforms (Blue : Detailed Converter, Red : Average-Value Converter)**

## References

- [1] Bose, B. K., *Modern Power Electronics and AC Drives*, Prentice-Hall, N.J., 2002.
- [2] Grelet, G., and G. Clerc, *Actionneurs électriques*, Éditions, Eyrolles, Paris, 1997.
- [3] Krause, P. C., *Analysis of Electric Machinery*, McGraw-Hill, 1986.

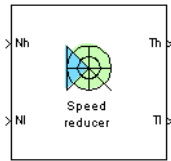
## Purpose

Implement speed reducer

## Library

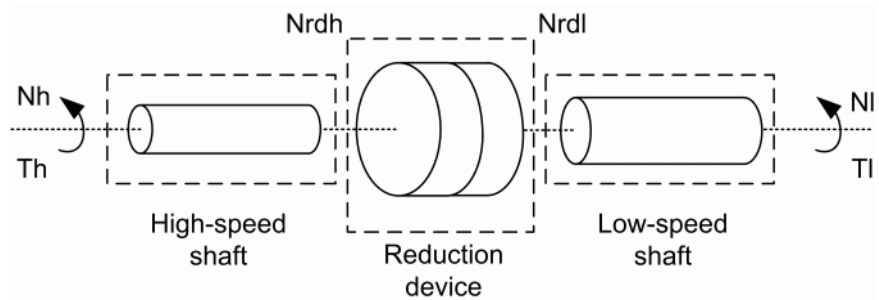
Electric Drives/Shafts and Speed Reducers

## Description



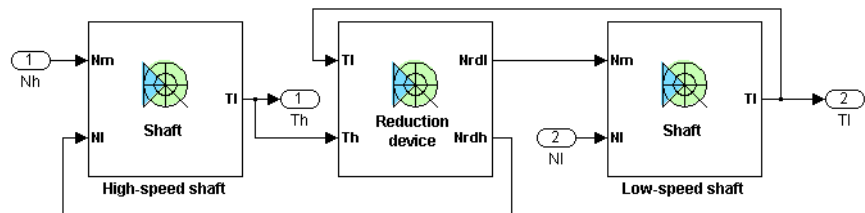
The high-level schematic shown below is built from three main blocks: a high-speed shaft, a reduction device, and a low-speed shaft. More details on the shaft model are included in the Mechanical Shaft reference pages.

## High-Level Schematic



## Simulink Schematic

The next figure shows the Simulink schematic of the speed reducer model.



# Speed Reducer

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## Reduction Device

The reduction device dynamics are governed by the following equation:

$$J_{rdh} \cdot \ddot{\theta}_{rdh} = T_h - \frac{T_l}{(\eta \cdot i)}$$

where  $J_{rdh}$  is the inertia of the reduction device with respect to the high-speed side,  $\ddot{\theta}_{rdh}$  is the acceleration of the high-speed side of the reduction device,  $T_h$  is the torque transmitted by the high-speed shaft to the input of the reduction device,  $T_l$  is the torque transmitted by the low-speed shaft from the output of the reduction device,  $\eta$  is the efficiency of the reduction device, and  $i$  is the reduction ratio ( $i \geq 1$ ).

For reduction devices composed of gears, the efficiency varies according to the type of gears, the number of stages (thus the reduction ratio), the lubricant, etc. For small reduction ratios, the efficiency can climb up to 95%. For higher reduction ratios, the efficiency can be as low as 75%. However, most commercial speed reducers now have high efficiencies of 90% to 95%.

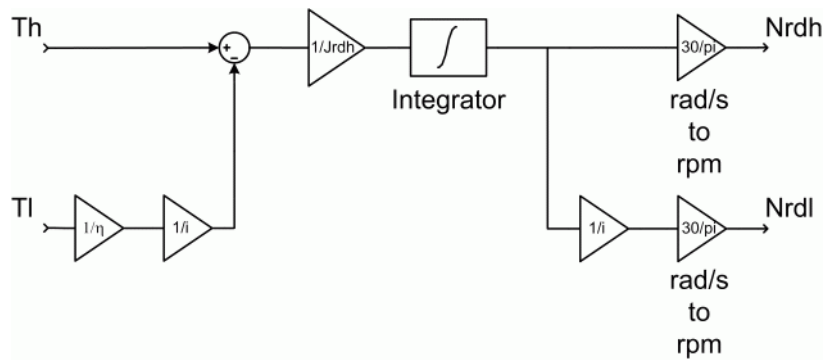
The output speed  $N_{rdl}$  (the speed of the driving side of the low-speed shaft) of the reduction device is given by the following equation:

$$N_{rdl} = \frac{N_{rdh}}{i}$$

where  $N_{rdh}$  is the input speed of the reduction device (the speed of the loaded side of the high-speed shaft).

The following figure shows the reduction device schematic.





## Remarks

The stiffness of the shafts must be high enough to avoid large angular deflections that could cause misalignment inside the bearings and damage.

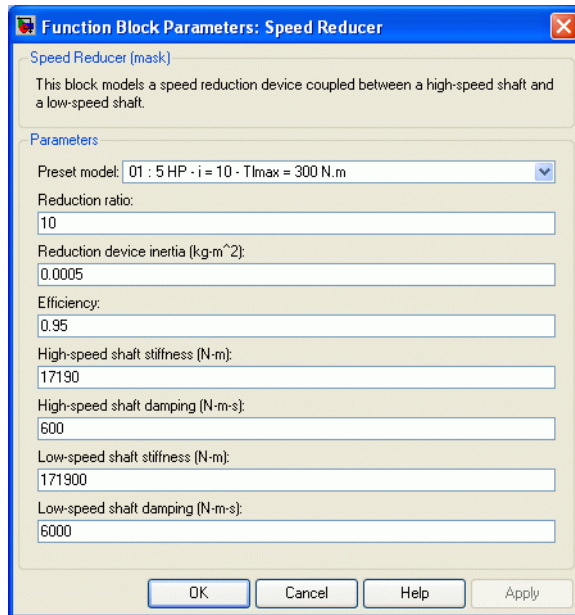
Keep in mind that the low-speed shaft will have a higher stiffness and a higher damping factor than the high-speed shaft, the torque on the low-speed shaft being a lot bigger. For proper simulation results, the damping factor of both shafts must be high enough to avoid undesired transient speed and torque oscillations.

Too high stiffness and damping factor values or too low gearbox inertias can cause simulation errors.

The model is discrete. Good simulation results have been obtained with a  $1 \mu\text{s}$  time step.

# Speed Reducer

## Dialog Box



### Preset Model

This pop-up menu allows you to choose preset model parameters.

### Reduction Ratio

The reduction ratio of the speed reducer ( $i \geq 1$ ).

### Reduction Device Inertia

The inertia of the reduction device with respect to the high-speed side (kg.m<sup>2</sup>).

### Efficiency

The efficiency of the reduction device.

### High-Speed Shaft Stiffness

The stiffness of the high-speed shaft (N.m).

### High-Speed Shaft Damping

The internal damping of the high-speed shaft (N.m.s).

## Low-Speed Shaft Stiffness

The stiffness of the low-speed shaft (N.m).

## Low-Speed Shaft Damping

The internal damping of the low-speed shaft (N.m.s).

## Block Inputs and Outputs

### Inputs

The block has two inputs:  $N_h$  and  $N_l$ .

The first input,  $N_h$ , is the speed (rpm) of the driving end of the high-speed shaft.

The second input,  $N_l$ , is the speed (rpm) of the loaded end of the low-speed shaft.

### Outputs

The block has two outputs:  $T_h$  and  $T_l$ .

The  $T_h$  output is the torque transmitted by the high-speed shaft to the reduction device.

The  $T_l$  output is the torque transmitted by the low-speed shaft to the load.

## Model Specifications

The library contains four preset models. The specifications of these speed reducer models are shown in the following table.

### Preset Speed Reducer Models

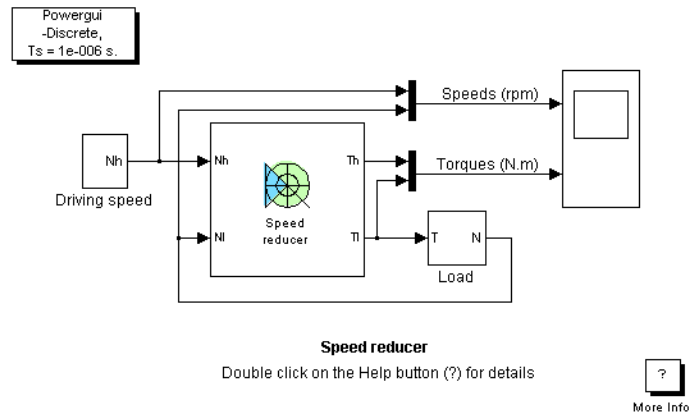
	1st	2nd	3rd	4th
Power (hp)	5	5	200	200
Reduction ratio	10	100	10	100
Max. output torque (N.m)	300	3000	12200	122000

# Speed Reducer

The high-speed and low-speed shafts of the preset models have been designed in order to present 0.1 degrees of angular deflection at maximum torque.

## Example

The reducer\_example demo illustrates the speed reducer model.



The speed reducer is driven by a variable-speed source and is connected to a load. The load has an inertia of 30 kg.m<sup>2</sup> and a viscous friction term of 0.5 N.m.s.

The speed reducer has a reduction ratio of 10, and the inertia of the reduction device with respect to the high-speed side is 0.0005 kg.m<sup>2</sup>. The reduction ratio being quite low, the efficiency is high and worth 0.95.

The high-speed shaft has a stiffness of 17190 N.m and an internal damping factor of 600 N.m.s. This shaft is designed to have 0.1 degree of angular deflection for a 30 N.m load torque. The low-speed shaft, having a higher torque to transmit, has a stiffness of 171900 N.m and an internal damping factor of 6000 N.m.s. This shaft is designed to have 0.1 degree of angular deflection for a 300 N.m load torque.

At  $t = 0$  s, the driving speed starts climbing to 1750 rpm with a 500 rpm/s acceleration ramp. This causes the transmitted torque of the

high-speed shaft to jump to about 18 N.m. Because of the reduction device, the torque transmitted to the load by the low-speed shaft is a lot bigger and is worth about 170 N.m.

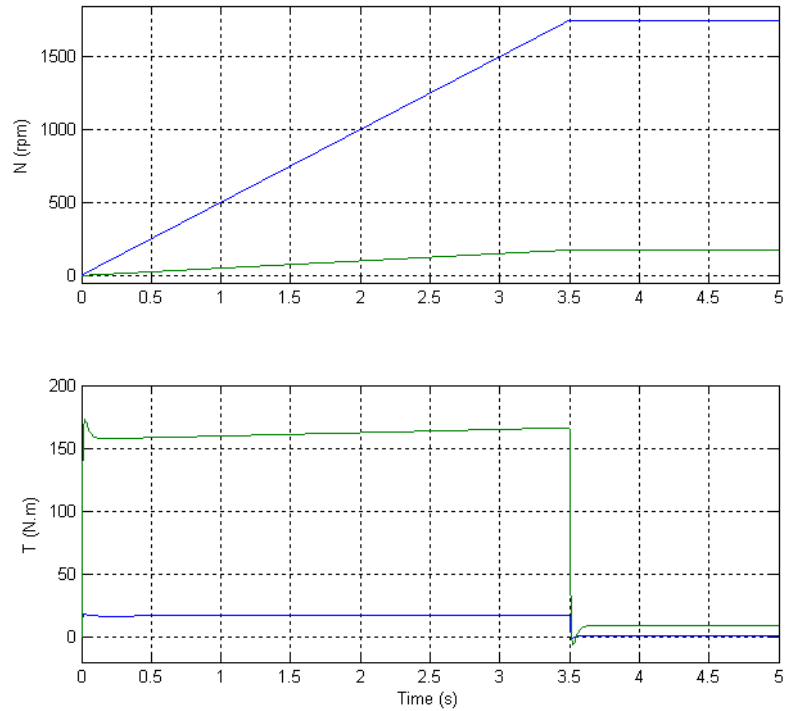
During the accelerating phase, both torques keep increasing in order to compensate the viscous friction of the load. Notice that the load accelerates with a ramp of +50 rpm/s because of the reduction ratio of the gearbox.

At  $t = 3.5$  s, the driving speed settles at 1750 rpm. Since no more accelerating torque is needed, the input and output torques decrease and stabilize respectively to 0.965 N.m and 9.16 N.m at  $t = 4$  s. The load speed is now equal to 175 rpm.

The following figure shows the speed reducer input and output speeds and torques.

# Speed Reducer

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## References

- [1] Norton, Robert L., *Machine Design*, Prentice Hall, 1998.
- [2] Nise, Norman S., *Control Systems Engineering*, Addison-Wesley Publishing Company, 1995.

# Static Synchronous Compensator (Phasor Type)

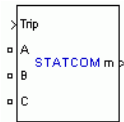
## Purpose

Implement phasor model of three-phase static synchronous compensator

## Library

Flexible AC Transmission Systems (FACTS)/Power-Electronics Based FACTS

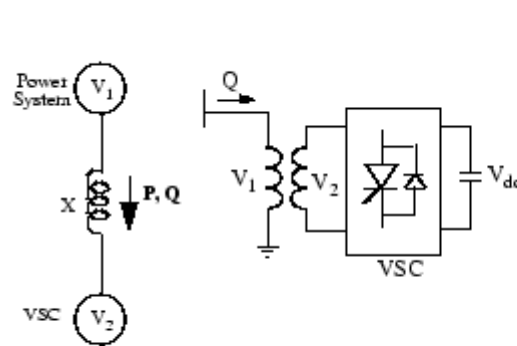
## Description



The Static Synchronous Compensator (STATCOM) is a shunt device of the Flexible AC Transmission Systems (FACTS) family using power electronics to control power flow and improve transient stability on power grids [1]. The STATCOM regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the STATCOM generates reactive power (STATCOM capacitive). When system voltage is high, it absorbs reactive power (STATCOM inductive).

The variation of reactive power is performed by means of a Voltage-Sourced Converter (VSC) connected on the secondary side of a coupling transformer. The VSC uses forced-commutated power electronic devices (GTOs, IGBTs or IGCTs) to synthesize a voltage  $V_2$  from a DC voltage source. The principle of operation of the STATCOM is explained on the figure below showing the active and reactive power transfer between a source  $V_1$  and a source  $V_2$ . In this figure,  $V_1$  represents the system voltage to be controlled and  $V_2$  is the voltage generated by the VSC.

# Static Synchronous Compensator (Phasor Type)



$$P = \frac{V_1 V_2 \sin \delta}{X}$$

$$Q = \frac{V_1 (V_1 - V_2 \cos \delta)}{X}$$

where:

$V_1$  = line to line voltage of source  $V_1$

$V_2$  = line to line voltage  $V_2$

$X$  = Reactance of interconnection transformer and filters

$\delta$  = angle of  $V_1$  with respect to  $V_2$

## Operating Principle of the STATCOM

In steady state operation, the voltage  $V_2$  generated by the VSC is in phase with  $V_1$  ( $\delta=0$ ), so that only reactive power is flowing ( $P=0$ ). If  $V_2$  is lower than  $V_1$ ,  $Q$  is flowing from  $V_1$  to  $V_2$  (STATCOM is absorbing reactive power). On the reverse, if  $V_2$  is higher than  $V_1$ ,  $Q$  is flowing from  $V_2$  to  $V_1$  (STATCOM is generating reactive power). The amount of reactive power is given by

$$Q = \frac{V_1 (V_1 - V_2)}{X}$$

A capacitor connected on the DC side of the VSC acts as a DC voltage source. In steady state the voltage  $V_2$  has to be phase shifted slightly behind  $V_1$  in order to compensate for transformer and VSC losses and to keep the capacitor charged. Two VSC technologies can be used for the VSC:

- VSC using GTO-based square-wave inverters and special interconnection transformers. Typically four three-level inverters are used to build a 48-step voltage waveform. Special interconnection transformers are used to neutralize harmonics contained in the square waves generated by individual inverters. In this type of VSC, the fundamental component of voltage  $V_2$  is proportional to



# Static Synchronous Compensator (Phasor Type)

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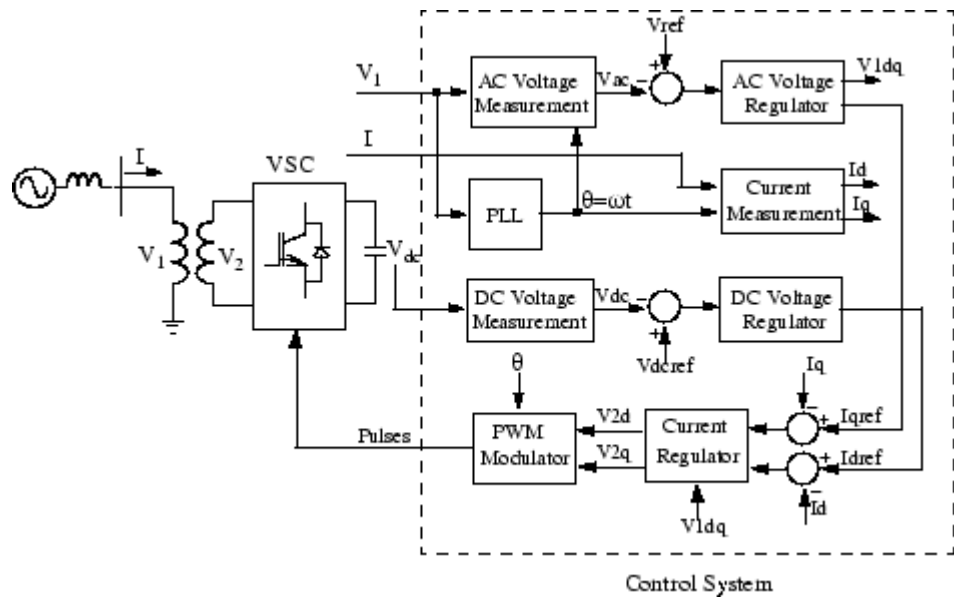
the voltage  $V_{dc}$ . Therefore  $V_{dc}$  has to be varied for controlling the reactive power.

- VSC using IGBT-based PWM inverters. This type of inverter uses Pulse-Width Modulation (PWM) technique to synthesize a sinusoidal waveform from a DC voltage source with a typical chopping frequency of a few kilohertz. Harmonic voltages are cancelled by connecting filters at the AC side of the VSC. This type of VSC uses a fixed DC voltage  $V_{dc}$ . Voltage  $V_2$  is varied by changing the modulation index of the PWM modulator.

The STATCOM (Phasor Type) block models an IGBT-based STATCOM (fixed DC voltage). However, as details of the inverter and harmonics are not represented, it can be also used to model a GTO-based STATCOM in transient stability studies. A detailed model of a GTO-based STATCOM is provided in the FACTS demo library (`power_statcom_gto48p` demo).

The figure below shows a single-line diagram of the STATCOM and a simplified block diagram of its control system.

# Static Synchronous Compensator (Phasor Type)



## Single-line Diagram of a STATCOM and Its Control System Block Diagram

The control system consists of:

- A phase-locked loop (PLL) which synchronizes on the positive-sequence component of the three-phase primary voltage  $V_1$ . The output of the PLL (angle  $\theta = \omega t$ ) is used to compute the direct-axis and quadrature-axis components of the AC three-phase voltage and currents (labeled as  $V_d$ ,  $V_q$  or  $I_d$ ,  $I_q$  on the diagram).
- Measurement systems measuring the d and q components of AC positive-sequence voltage and currents to be controlled as well as the DC voltage  $V_{dc}$ .
- An outer regulation loop consisting of an AC voltage regulator and a DC voltage regulator. The output of the AC voltage regulator is the reference current  $I_{qref}$  for the current regulator ( $I_q$  = current in quadrature with voltage which controls reactive power flow). The output of the DC voltage regulator is the reference current  $I_{dref}$ .

# Static Synchronous Compensator (Phasor Type)

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for the current regulator ( $I_d$  = current in phase with voltage which controls active power flow).

- An inner current regulation loop consisting of a current regulator. The current regulator controls the magnitude and phase of the voltage generated by the PWM converter ( $V_{2d}$   $V_{2q}$ ) from the  $I_{dref}$  and  $I_{qref}$  reference currents produced respectively by the DC voltage regulator and the AC voltage regulator (in voltage control mode). The current regulator is assisted by a feed forward type regulator which predicts the  $V_2$  voltage output ( $V_{2d}$   $V_{2q}$ ) from the  $V_1$  measurement ( $V_{1d}$   $V_{1q}$ ) and the transformer leakage reactance.

The STATCOM block is a phasor model which does not include detailed representations of the power electronics. You must use it with the phasor simulation method, activated with the Powergui block. It can be used in three-phase power systems together with synchronous generators, motors, dynamic loads and other FACTS and DR systems to perform transient stability studies and observe impact of the STATCOM on electromechanical oscillations and transmission capacity at fundamental frequency.

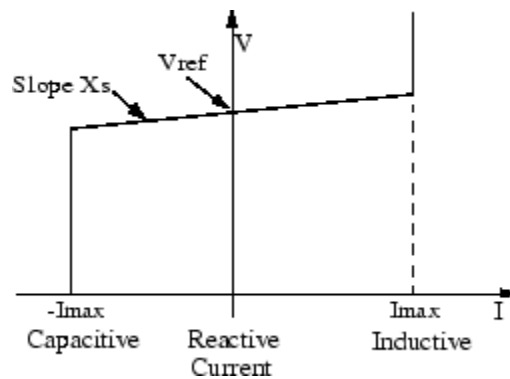
## STATCOM V-I Characteristic

The STATCOM can be operated in two different modes:

- In voltage regulation mode (the voltage is regulated within limits as explained below)
- In var control mode (the STATCOM reactive power output is kept constant)

When the STATCOM is operated in voltage regulation mode, it implements the following V-I characteristic.

# Static Synchronous Compensator (Phasor Type)



## STATCOM V-I characteristic

As long as the reactive current stays within the minimum and maximum current values ( $-I_{max}$ ,  $I_{max}$ ) imposed by the converter rating, the voltage is regulated at the reference voltage  $V_{ref}$ . However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output), and the V-I characteristic has the slope indicated in the figure. In the voltage regulation mode, the V-I characteristic is described by the following equation:

$$V = V_{ref} + X_s \cdot I$$

where

V	Positive sequence voltage (pu)
I	Reactive current (pu/Pnom) ( $I > 0$ indicates an inductive current)
$X_s$	Slope or droop reactance (pu/Pnom)
Pnom	Three-phase nominal power of the converter specified in the block dialog box

# Static Synchronous Compensator (Phasor Type)

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## **STATCOM vs SVC**

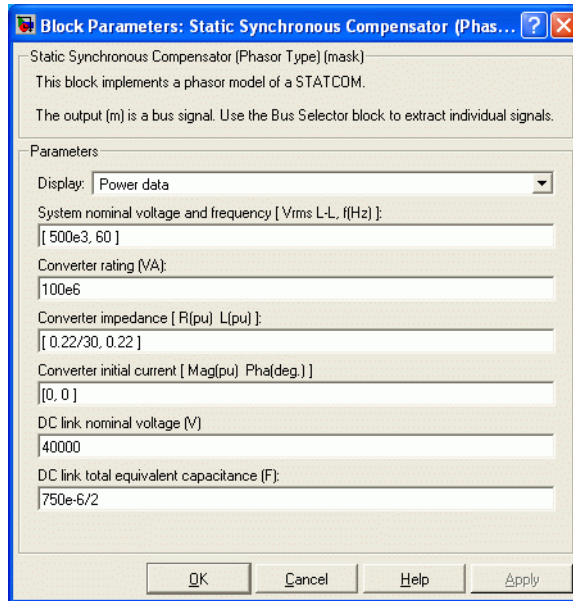
The STATCOM performs the same function as the SVC. However at voltages lower than the normal voltage regulation range, the STATCOM can generate more reactive power than the SVC. This is due to the fact that the maximum capacitive power generated by a SVC is proportional to the square of the system voltage (constant susceptance) while the maximum capacitive power generated by a STATCOM decreases linearly with voltage (constant current). This ability to provide more capacitive reactive power during a fault is one important advantage of the STATCOM over the SVC. In addition, the STATCOM will normally exhibit a faster response than the SVC because with the VSC, the STATCOM has no delay associated with the thyristor firing (in the order of 4 ms for a SVC).

# Static Synchronous Compensator (Phasor Type)

## Dialog Box and Parameters

The STATCOM parameters are grouped in two categories: Power data and Control parameters. Use the **Display** listbox to select which group of parameters you want to visualize.

### Power Data Parameters



### System nominal voltage and frequency [Vrms f]

The nominal line-to-line voltage in Vrms and the nominal system frequency in hertz.

### Converter rating $S_{nom}$

The nominal power of the converter in VA.

### Converter impedance [R L]

The positive-sequence resistance and inductance of the converter, in pu based on the nominal power and voltage ratings. R and L represent the resistance and leakage inductance of the coupling transformer and the resistance and inductance of the series filtering inductors connected at the VSC output.

# Static Synchronous Compensator (Phasor Type)

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## Converter initial current [Mag Phase]

The initial value of the positive-sequence current phasor (Magnitude in pu and Phase in degrees). If you know the initial value of the current corresponding to the STATCOM operating point you may specify it in order to start simulation in steady state. If you don't know this value, you can leave [0 0]. The system will reach steady-state after a short transient.

## DC link nominal voltage

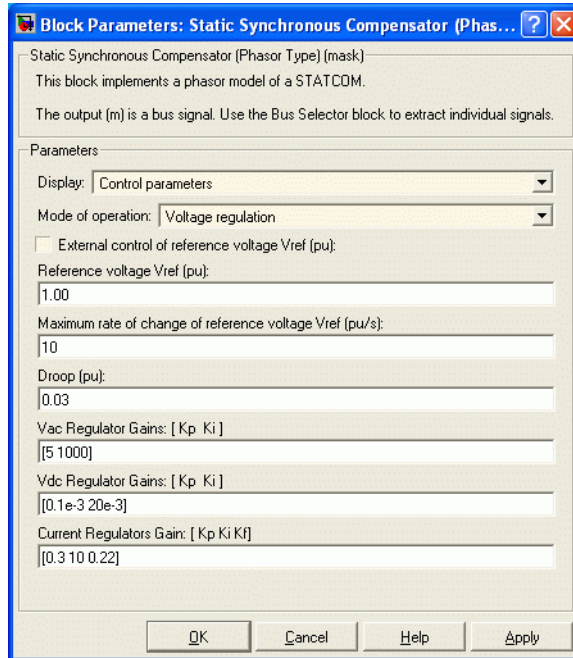
The nominal voltage of the DC link in volts.

## DC link total equivalent capacitance

The total capacitance of the DC link in farads. This capacitance value is related to the STATCOM rating and to the DC link nominal voltage. The energy stored in the capacitance (in joules) divided by the STATCOM rating (in VA) is a time duration which is usually a fraction of a cycle at nominal frequency. For example, for the default parameters, ( $C=375 \mu\text{F}$ ,  $V_{dc}=40\,000 \text{ V}$ ,  $S_{nom}=100 \text{ MVA}$ ) this ratio  $(1/2 \times C \times V_{dc}^2) / (S_{nom})$  is 3.0 ms, which represents 0.18 cycle for a 60 Hz frequency. If you change the default values of the nominal power rating and DC voltage, you should change the capacitance value accordingly.

# Static Synchronous Compensator (Phasor Type)

## Control Parameters



### Mode of operation

Specifies the STATCOM mode of operation. Select either Voltage regulation or Var Control.

### External control of reference voltage Vref

If this parameter is checked, a Simulink input named Vref appears on the block, allowing to control the reference voltage from an external signal (in pu). Otherwise a fixed reference voltage is used, as specified by the parameter below.

### Reference voltage Vref

This parameter is not visible when the **Mode of operation** parameter is set to Var Control or when the **External control of reference voltage Vref** parameter is checked.



# Static Synchronous Compensator (Phasor Type)

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Reference voltage, in pu, used by the voltage regulator.

## **Maximum rate of change of reference voltage Vref**

This parameter is not visible when the **Mode of operation** parameter is set to Var Control.

Maximum rate of change of the reference voltage, in pu/s, when an external reference voltage is used.

## **Droop (pu):**

This parameter is not visible when the **Mode of operation** parameter is set to Var Control.

Droop reactance, in pu/converter rating  $S_{nom}$ , defining the slope of the V-I characteristic.

## **Vac Regulator Gains: [Kp Ki]**

This parameter is not visible when the **Mode of operation** parameter is set to Var Control.

Gains of the AC voltage PI regulator. Specify proportional gain  $K_p$  in (pu of I)/(pu of V), and integral gain  $K_i$ , in (pu of I)/(pu of V)/s, where V is the AC voltage error and I is the output of the voltage regulator.

## **Reactive power setpoint Qref**

This parameter is not visible when the **Mode of operation** parameter is set to Voltage Control.

Reference reactive power, in pu, when the STATCOM is in Var Control.

## **Maximum rate of change of reactive power setpoint Qref**

This parameter is not visible when the **Mode of operation** parameter is set to Voltage Control.

Maximum rate of change of the reference reactive power, in pu/s.

# Static Synchronous Compensator (Phasor Type)

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## Vdc Regulator Gains: [Kp Ki]

Gains of the DC voltage PI regulator which controls the voltage across the DC bus capacitor. Specify proportional gain  $K_p$  in (pu of I)/Vdc, and integral gain  $K_i$ , in (pu of I)/Vdc/s, where Vdc is the DC voltage error and I is the output of the voltage regulator.

## Current Regulators Gains: [Kp Ki Kf]

Gains of the inner current regulation loop.

Specify proportional gain  $K_p$  in (pu of V)/(pu of I), integral gain  $K_i$ , in (pu of V)/(pu of I)/s, and feed forward gain  $K_f$  in (pu of V)/(pu of I), where V is the output  $V_{2d}$  or  $V_{2q}$  of the current regulator and I is the  $I_d$  or  $I_q$  current error.

For optimal performance, the feed forward gain should be set to the converter reactance (in pu) given by parameter L in the **Converter impedance [R L]** parameters.

## Inputs and Outputs

A B C

The three terminals of the STATCOM.

Trip

Apply a simulink logical signal (0 or 1) to this input. When this input is high the STATCOM is disconnected and its control system is disabled. Use this input to implement a simplified version of the protection system.

Vref

Simulink input of the external reference voltage signal.

This input is visible only the **External control of reference voltage Vref** parameter is checked.

m

Simulink output vector containing 16 STATCOM internal signals. These signals are either voltage and current phasors (complex signals) or control signals. They can be individually accessed by using the Bus Selector block. They are, in order:

# Static Synchronous Compensator (Phasor Type)

	<b>Signal Group</b>	<b>Signal Names</b>	<b>Definition</b>
1-3	Power Vabc (cmplx)	Va_prim (pu) Vb_prim (pu) Vc_prim (pu)	Phasor voltages (phase to ground) Va, Vb, Vc at the STATCOM primary terminals (pu)
4-6	Power Iabc (cmplx)	Ia_prim (pu) Ib_prim (pu) Ic_prim (pu)	Phasor currents Ia, Ib, Ic flowing into the STATCOM (pu)
7	Power	Vdc (V)	DC voltage (V)
8	Control	Vm (pu)	Positive-sequence value of the measured voltage (pu)
9	Control	Vref (pu)	Reference voltage (pu)
10	Control	Qm (pu)	STATCOM reactive power. A positive value indicates inductive operation.
11	Control	Qref (pu)	Reference reactive power (pu)
12	Control	Id (pu)	Direct-axis component of current (active current) flowing into STATCOM (pu). A positive value indicates active power flowing into STATCOM.

# Static Synchronous Compensator (Phasor Type)

Signal Group	Signal Names	Definition
13 Control	Iq (pu)	Quadrature-axis component of current (reactive current) flowing into STATCOM (pu). A positive value indicates capacitive operation.
14 Control	Idref (pu)	Reference value of direct-axis component of current flowing into STATCOM (pu)
15 Control	Iqref (pu)	Reference value of quadrature-axis component of current flowing into STATCOM (pu)
16 Control	modindex	The modulation index $m$ of the PWM modulator. A positive number $0 < m < 1$ . $m=1$ corresponds to the maximum voltage $V_2$ which can be generated by the VSC without overmodulation.

## Example

See the `power_statcom` demo which illustrates the steady-state and dynamic performance of a STATCOM regulating voltage on a 500 kV, 60 Hz, system. The demo also compares the performance of the STACOM with an SVC having the same rating.

# Static Synchronous Compensator (Phasor Type)

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## References

[1] N. G. Hingorani, L. Gyugyi, "Understanding FACTS; Concepts and Technology of Flexible AC Transmission Systems," *IEEE Press book*, 2000.

## See Also

Static Var Compensator (Phasor Type), Unified Power Flow Controller (Phasor Type)

# Static Synchronous Series Compensator (Phasor Type)

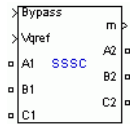
## Purpose

Implement phasor model of three-phase static synchronous series compensator

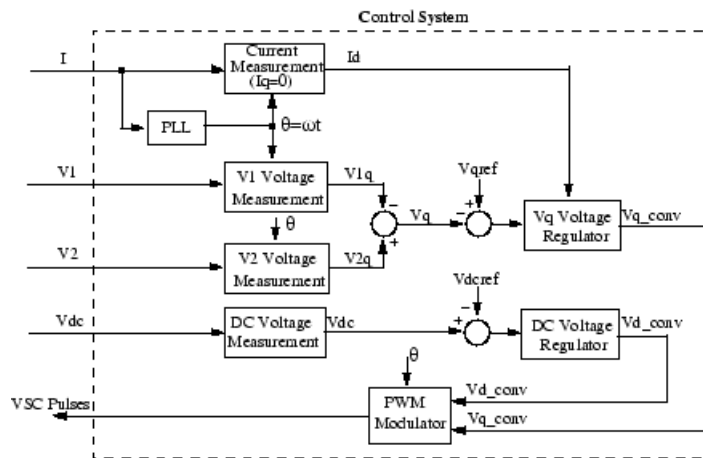
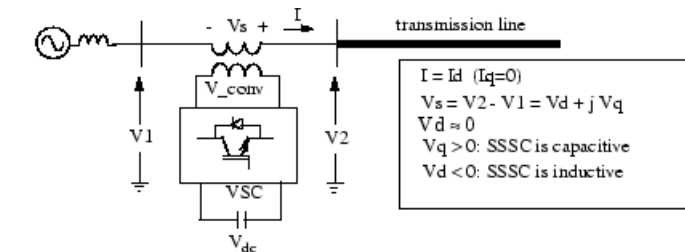
## Library

Flexible AC Transmission Systems (FACTS)/Power-Electronics Based FACTS

## Description



The Static Synchronous Series Compensator (SSSC) is a series device of the Flexible AC Transmission Systems (FACTS) family using power electronics to control power flow and improve power oscillation damping on power grids [1]. The SSSC injects a voltage  $V_s$  in series with the transmission line where it is connected.



**Single-line Diagram of a SSSC and Its Control System Block Diagram**

# Static Synchronous Series Compensator (Phasor Type)

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As the SSSC does not use any active power source, the injected voltage must stay in quadrature with line current. By varying the magnitude  $V_q$  of the injected voltage in quadrature with current, the SSSC performs the function of a variable reactance compensator, either capacitive or inductive.

The variation of injected voltage is performed by means of a Voltage-Sourced Converter (VSC) connected on the secondary side of a coupling transformer. The VSC uses forced-commutated power electronic devices (GTOs, IGBTs or IGCTs) to synthesize a voltage  $V_{conv}$  from a DC voltage source.

A capacitor connected on the DC side of the VSC acts as a DC voltage source. A small active power is drawn from the line to keep the capacitor charged and to provide transformer and VSC losses, so that the injected voltage  $V_s$  is practically 90 degrees out of phase with current  $I$ . In the control system block diagram  $V_d_{conv}$  and  $V_q_{conv}$  designate the components of converter voltage  $V_{conv}$  which are respectively in phase and in quadrature with current. Two VSC technologies can be used for the VSC:

- VSC using GTO-based square-wave inverters and special interconnection transformers. Typically four three-level inverters are used to build a 48-step voltage waveform. Special interconnection transformers are used to neutralize harmonics contained in the square waves generated by individual inverters. In this type of VSC, the fundamental component of voltage  $V_{conv}$  is proportional to the voltage  $V_{dc}$ . Therefore  $V_{dc}$  has to varied for controlling the injected voltage.
- VSC using IGBT-based PWM inverters. This type of inverter uses Pulse-Width Modulation (PWM) technique to synthesize a sinusoidal waveform from a DC voltage with a typical chopping frequency of a few kilohertz. Harmonics are cancelled by connecting filters at the AC side of the VSC. This type of VSC uses a fixed DC voltage  $V_{dc}$ . Voltage  $V_{conv}$  is varied by changing the modulation index of the PWM modulator.

# Static Synchronous Series Compensator (Phasor Type)

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The SSSC (Phasor Type) block models an IGBT-based SSSC (fixed DC voltage). However, as details of the inverter and harmonics are not represented, it can be also used to model a GTO-based SSSC in transient stability studies.

The control system consists of:

- A phase-locked loop (PLL) which synchronizes on the positive-sequence component of the current  $I$ . The output of the PLL (angle  $\Theta = \omega t$ ) is used to compute the direct-axis and quadrature-axis components of the AC three-phase voltages and currents (labeled as  $V_d$ ,  $V_q$  or  $I_d$ ,  $I_q$  on the diagram).
- Measurement systems measuring the  $q$  components of AC positive-sequence of voltages  $V_1$  and  $V_2$  ( $V_{1q}$  and  $V_{2q}$ ) as well as the DC voltage  $V_{dc}$ .
- AC and DC voltage regulators which compute the two components of the converter voltage ( $V_{d\_conv}$  and  $V_{q\_conv}$ ) required to obtain the desired DC voltage ( $V_{dcref}$ ) and the injected voltage ( $V_{qref}$ ). The  $V_q$  voltage regulator is assisted by a feed forward type regulator which predicts the  $V_{conv}$  voltage from the  $I_d$  current measurement.

The SSSC block is a phasor model which does not include detailed representations of the power electronics. You must use it with the phasor simulation method, activated with the Powergui block. It can be used in three-phase power systems together with synchronous generators, motors, dynamic loads and other FACTS and DR systems to perform transient stability studies and observe impact of the SSSC on electromechanical oscillations and transmission capacity at fundamental frequency.

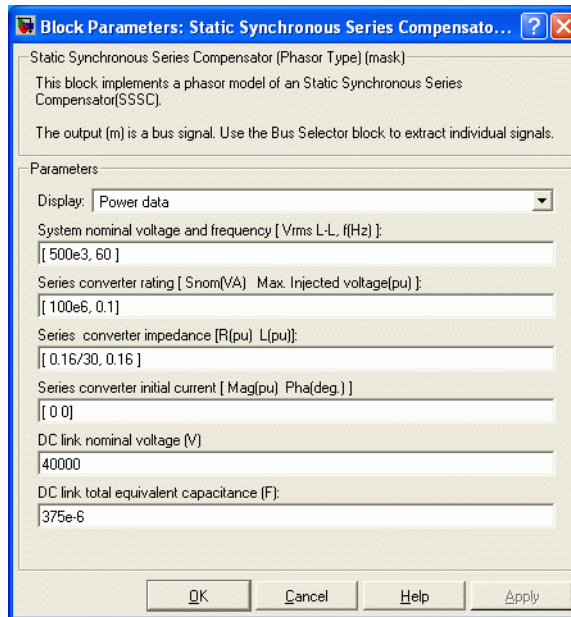


# Static Synchronous Series Compensator (Phasor Type)

## Dialog Box and Parameters

The SSSC parameters are grouped in two categories: Power data and Control parameters. Use the **Display** listbox to select which group of parameters you want to visualize.

### Power Data Parameters



### System nominal voltage and frequency [Vrms f]

The nominal line-to-line voltage in Vrms and the nominal system frequency in hertz.

### Series converter rating [Snom, Max. Injected voltage]

The nominal rating of the series converter in VA and the maximum value of the injected voltage  $V_{conv}$  on the VSC side of the transformer (see single line diagram), in pu of nominal phase-to-ground voltage.

# Static Synchronous Series Compensator (Phasor Type)

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## Series converter impedance [R L]

The positive-sequence resistance and inductance of the converter, in pu based on the nominal converter rating and nominal voltage. R and L represent the resistance and leakage inductance of the coupling transformer plus the resistance and inductance of the series filtering inductors connected at the VSC output.

## Series converter initial current [Mag Phase]

The initial value of the positive-sequence current phasor (Magnitude in pu and Phase in degrees). If you know the initial value of the current corresponding to the SSSC operating point you may specify it in order to start simulation in steady state. If you don't know this value, you can leave [0 0]. The system will reach steady-state after a short transient.

## DC link nominal voltage

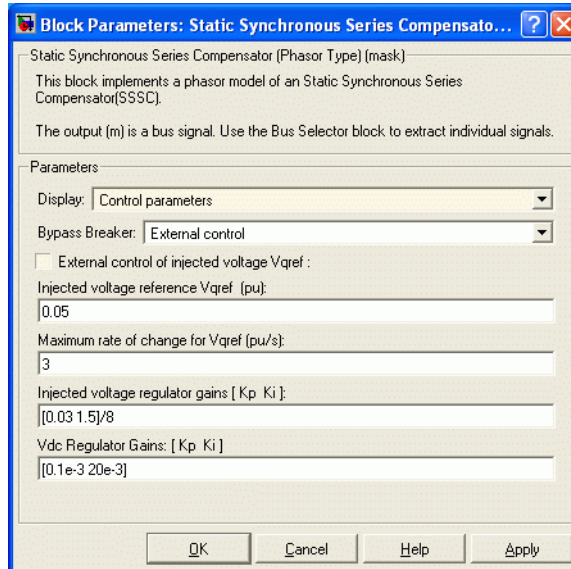
The nominal voltage of the DC link in volts.

## DC link total equivalent capacitance

The total capacitance of the DC link in farads. This capacitance value is related to the SSSC converter rating and to the DC link nominal voltage. The energy stored in the capacitance (in joules) divided by the converter rating (in VA) is a time duration which is usually a fraction of a cycle at nominal frequency. For example, for the default parameters, ( $C=375 \mu\text{F}$ ,  $V_{dc}=40\,000 \text{ V}$ ,  $S_{nom}=100 \text{ MVA}$ ) this ratio  $(1/2 \times C \cdot V_{dc}^2) / (S_{nom})$  is 3.0 ms, which represents 0.18 cycle for a 60 Hz frequency. If you change the default values of the nominal power rating and DC voltage, you should change the capacitance value accordingly.

# Static Synchronous Series Compensator (Phasor Type)

## Control Parameters



### Bypass Breaker

Specifies the status of the bypass breaker connected inside the block across terminals A1, B1, C1 and A2, B2, C2. Select either **External Control**, **Open** or **Closed**. If the bypass breaker is in external control, a Simulink input named **Bypass** appears on the block, allowing to control the status of the bypass breaker from an external signal (0 or 1).

### External control of injected voltage Vqref

If this parameter is checked, a Simulink input named **Vqref** appears on the block, allowing to control the injected voltage from an external signal (in pu). Otherwise a fixed reference voltage is used, as specified by the parameter below.

### Injected voltage reference Vqref

This parameter is not visible when the **External control of injected voltage Vqref** parameter is checked.

# Static Synchronous Series Compensator (Phasor Type)

Specify the quadrature-axis component of the voltage injected on the VSC side of the series transformer, in pu.

## Maximum rate of change for Vqref

Maximum rate of change of the Vqref voltage, in pu/s.

## Injected voltage regulator gains: [Kp Ki]

Gains of the PI regulator which controls the injected voltage. Specify proportional gain Kp in (pu of Vq\_conv)/(pu of V), and integral gain Ki, in (pu of Vq\_conv)/(pu of V)/s, where V is the Vq voltage error and Vq\_conv is the quadrature-axis component of the voltage generated by the VSC.

The feed forward gain is computed from the **Series converter impedance [R L]** parameters.

## Vdc regulator gains: [Kp Ki]

Gains of the DC voltage PI regulator which controls the voltage across the DC bus capacitor. Specify proportional gain Kp in (pu of Vd\_conv)/Vdc, and integral gain Ki, in (pu of Vd\_conv)/Vdc/s, where Vdc is the DC voltage error and Vd\_conv is the direct-axis component of the voltage generated by the converter.

## Inputs and Outputs

A1 B1 C1

The three input terminals of the SSSC.

A2 B2 C2

The three output terminals of the SSSC.

Bypass

This input is visible only when the **Bypass Breaker** parameter is set to **External Control**.

Apply a simulink logical signal (0 or 1) to this input. When this input is high the bypass breaker is closed.

Vqref

This input is visible only when the **External control of injected voltage Vqref** parameter is checked.

# Static Synchronous Series Compensator (Phasor Type)

Apply a simulink signal specifying the reference voltage, in pu.

m

Simulink output vector containing 17 SSSC internal signals. These signals are either voltage and current phasors (complex signals) or control signals. They can be individually accessed by using the Bus Selector block. They are, in order:

Signal	Signal Group	Signal Names	Definition
1-3	Power Vabc1 (cmlx)	Va1 (pu) Vb1 (pu) Vc1 (pu)	Phasor voltages (phase to ground) Va, Vb, Vc at the SSSC input terminals A1, B1, C1 (pu)
4	Power	Vdc (V)	DC voltage (V)
5-7	Power Vabc2 (cmlx)	Va2 (pu) Vb2 (pu) Vc2 (pu)	Phasor voltages (phase to ground) Va, Vb, Vc at the SSSC output terminals A2, B2, C2 (pu)
8-10	Power Vabc_Inj (cmlx)	Va_Inj (pu) Vb_Inj (pu) Vc_Inj (pu)	Phasors of injected voltages $V_s = V_2 - V_1$ (pu)
11-13	Power Iabc (cmlx)	Ia (pu) Ib (pu) Ic (pu)	Phasor currents Ia, Ib, Ic flowing out of terminals A2, B2, C2 (pu)
14	Control	Vqref (pu)	Reference value of quadrature-axis injected voltage (pu)
15	Control	Vqinj (pu)	Measured injected voltage in quadrature-axis (pu)

# Static Synchronous Series Compensator (Phasor Type)

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Signal	Signal Group	Signal Names	Definition
16	Control	Id(pu)	Measured current (pu)
17	Control	modindex	The modulation index $m$ of the PWM modulator. A positive number $0 < m < 1$ . $m=1$ corresponds to the maximum voltage $V_{conv}$ which can be generated by the series converter without overmodulation.

## Example

See the `power_sssc` demo which illustrates the use of a SSSC for damping power oscillations on a 500 kV, 60 Hz, system.

## References

[1] N. G. Hingorani, L. Gyugyi, "Understanding FACTS; Concepts and Technology of Flexible AC Transmission Systems," *IEEE Press book*, 2000

## See Also

Unified Power Flow Controller (Phasor Type)

# Static Var Compensator (Phasor Type)

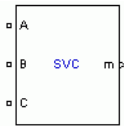
## Purpose

Implement phasor model of three-phase static var compensator

## Library

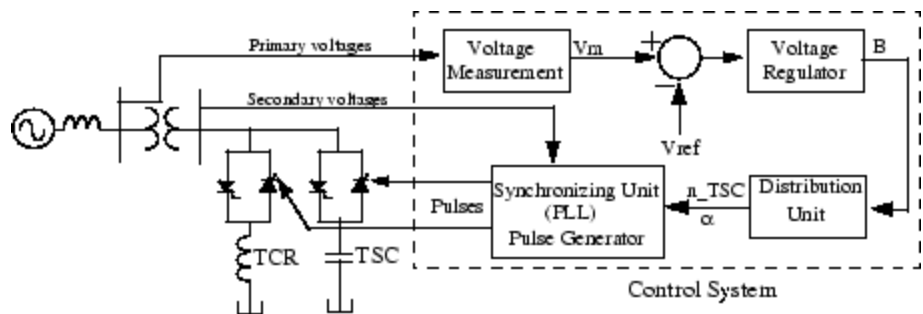
Flexible AC Transmission Systems (FACTS)/Power-Electronics Based FACTS

## Description



The Static Var Compensator (SVC) is a shunt device of the Flexible AC Transmission Systems (FACTS) family using power electronics to control power flow and improve transient stability on power grids [1]. The SVC regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the SVC generates reactive power (SVC capacitive). When system voltage is high, it absorbs reactive power (SVC inductive). The variation of reactive power is performed by switching three-phase capacitor banks and inductor banks connected on the secondary side of a coupling transformer. Each capacitor bank is switched on and off by three thyristor switches (Thyristor Switched Capacitor or TSC). Reactors are either switched on-off (Thyristor Switched Reactor or TSR) or phase-controlled (Thyristor Controlled Reactor or TCR).

The figure below shows a single-line diagram of a static var compensator and a simplified block diagram of its control system.



### Single-line Diagram of an SVC and Its Control System Block Diagram

The control system consists of

# Static Var Compensator (Phasor Type)

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- A measurement system measuring the positive-sequence voltage to be controlled. A Fourier-based measurement system using a one-cycle running average is used.
- A voltage regulator that uses the voltage error (difference between the measured voltage  $V_m$  and the reference voltage  $V_{ref}$ ) to determine the SVC susceptance  $B$  needed to keep the system voltage constant
- A distribution unit that determines the TSCs (and eventually TSRs) that must be switched in and out, and computes the firing angle  $\alpha$  of TCRs
- A synchronizing system using a phase-locked loop (PLL) synchronized on the secondary voltages and a pulse generator that send appropriate pulses to the thyristors

The SVC (Phasor Type) block is a phasor model, and you must use it with the phasor simulation method, activated with the Powergui block. It can be used in three-phase power systems together with synchronous generators, motors, and dynamic loads to perform transient stability studies and observe impact of the SVC on electromechanical oscillations and transmission capacity. This model does not include detailed representations of the power electronics, the measurement system, or the synchronization system. These systems are approximated rather by simple transfer functions that yield a correct representation at the system's fundamental frequency.

A detailed model of a SVC using three TSCs and one TCR is provided in the `power_svc_1tcr3tsc` demo.

## SVC V-I Characteristic

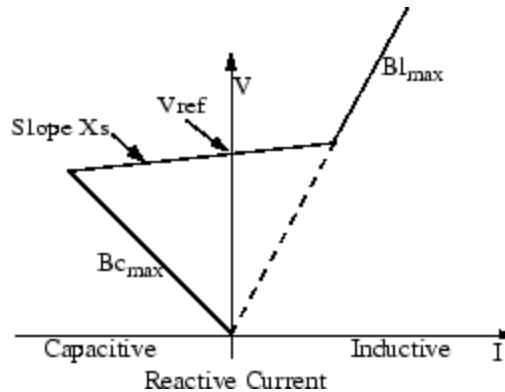
The SVC can be operated in two different modes:

- In voltage regulation mode (the voltage is regulated within limits as explained below)
- In var control mode (the SVC susceptance is kept constant)



# Static Var Compensator (Phasor Type)

When the SVC is operated in voltage regulation mode, it implements the following V-I characteristic.



## SVC V-I characteristic

As long as the SVC susceptance  $B$  stays within the maximum and minimum susceptance values imposed by the total reactive power of capacitor banks ( $B_{c_{max}}$ ) and reactor banks ( $B_{l_{max}}$ ), the voltage is regulated at the reference voltage  $V_{ref}$ . However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output), and the V-I characteristic has the slope indicated in the figure. The V-I characteristic is described by the following three equations:

$$V = V_{ref} + X_s \cdot I \quad \text{SVC is in regulation range } (-B_{c_{max}} < B < B_{l_{max}})$$

$$V = -\frac{I}{B_{c_{max}}} \quad \text{SVC is fully capacitive } (B = B_{c_{max}})$$

$$V = \frac{I}{B_{l_{max}}} \quad \text{SVC is fully inductive } (B = B_{l_{max}})$$

where

$V$  Positive sequence voltage (pu)

$I$  Reactive current (pu/Pbase) ( $I > 0$  indicates an inductive current)

# Static Var Compensator (Phasor Type)

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Xs	Slope or droop reactance (pu/Pbase)
Bmax	Maximum capacitive susceptance (pu/Pbase) with all TSCs in service, no TSR or TCR
Blmax	Maximum inductive susceptance (pu/Pbase) with all TSRs in service or TCRs at full conduction, no TSC
Pbase	Three-phase base power specified in the block dialog box

## SVC Dynamic Response

When the SVC is operating in voltage regulation mode, its response speed to a change of system voltage depends on the voltage regulator gains (proportional gain  $K_p$  and integral gain  $K_i$ ), the droop reactance  $X_s$ , and the system strength (short-circuit level).

For an integral-type voltage regulator ( $K_p = 0$ ), if the voltage measurement time constant  $T_m$  and the average time delay  $T_d$  due to valve firing are neglected, the closed-loop system consisting of the SVC and the power system can be approximated by a first-order system having the following closed-loop time constant:

$$T_c = \frac{1}{K_i \cdot (X_s + X_n)}$$

where

Tc	Closed loop time constant
Ki	Proportional gain of the voltage regulator (pu_B/pu_V/s)
Xs	Slope reactance pu/Pbase
Xn	Equivalent power system reactance (pu/Pbase)

This equation demonstrates that you obtain a faster response speed when the regulator gain is increased or when the system short-circuit

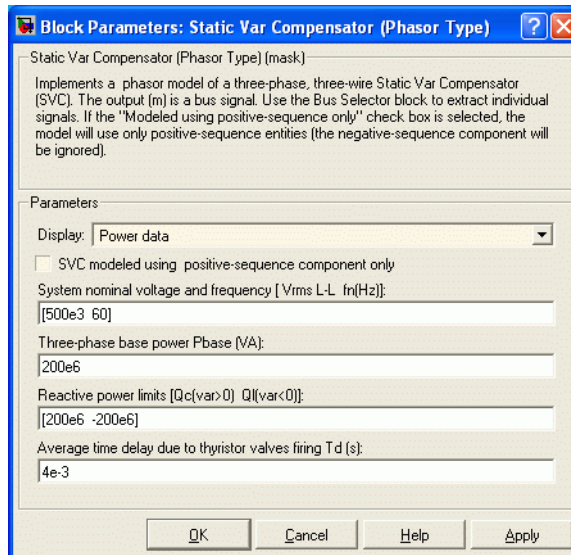
# Static Var Compensator (Phasor Type)

level decreases (higher  $X_n$  values). If you take into account the time delays due to voltage measurement system and valve firing, you obtain an oscillatory response and, eventually, an instability with too weak a system or too large a regulator gain.

## Dialog Box and Parameters

The SVC parameters are grouped in two categories: Power Data and Control Parameters. Use the **Display** listbox to select which group of parameters you want to visualize.

### Power Data Parameters



### SVC modeled using positive-sequence only

The SVC is modeled by a three-wire system using two current sources. The SVC does not generate any zero-sequence current, but it can generate negative-sequence currents during unbalanced system operation. The negative-sequence susceptance of the SVC is assumed to be identical to its positive-sequence value, as determined by the B value computed by the voltage regulator.

# Static Var Compensator (Phasor Type)

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Check this box to ignore negative-sequence current.

## **System nominal voltage and frequency [Vrms f]**

The nominal line-to-line voltage in Vrms and the nominal system frequency in hertz.

## **Three-phase base power Pbase**

Three-phase base power, in VA, used to specify the following parameters in pu: droop reactance  $X_s$ , gains  $K_p$  and  $K_i$  of the voltage PI regulator, and reference susceptance  $B_{ref}$ . This base power is also used to normalize the output B susceptance signal.

## **Reactive power limits [Qc Ql]**

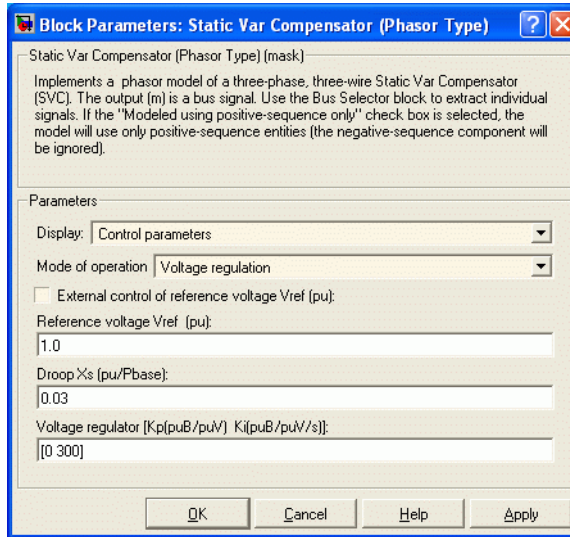
The maximum SVC reactive powers at 1 pu voltage, in vars. Enter a positive value for the capacitive reactive power  $Q_c$  (vars generated by the SVC) and a negative value for the inductive reactive power  $Q_l$  (vars absorbed by the SVC).

## **Average time delay due to thyristor valves firing Td**

Average time delay simulating the non instantaneous variation of thyristor fundamental current when the distribution unit sends a switching order to the pulse generator. Because pulses have to be synchronized with thyristor commutation voltages, this delay normally varies between 0 and 1/2 cycle. The suggested average value is 4 ms.

# Static Var Compensator (Phasor Type)

## Control Parameters



### Mode of operation

Specifies the SVC mode of operation. Select either Voltage regulation or Var control (Fixed susceptance Bref).

### External control of reference voltage Vref

If this parameter is checked, a Simulink input named Vref appears on the block, allowing to control the reference voltage from an external signal (in pu). Otherwise a fixed reference voltage is used, as specified by the parameter below.

### Reference voltage Vref

This parameter is not visible when the **Mode of operation** parameter is set to Var Control or when the **External control of reference voltage Vref** parameter is checked

Reference voltage, in pu, used by the voltage regulator.

# Static Var Compensator (Phasor Type)

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## **Droop Xs**

This parameter is not visible when the **Mode of operation** parameter is set to Var Control.

Droop reactance, in pu/Pbase, defining the slope of the V-I characteristic.

## **Voltage regulator [Kp Ki]**

This parameter is not visible when the **Mode of operation** parameter is set to Var Control.

Proportional gain, in (pu of B)/(pu of V), and integral gain, in pu\_B/pu\_V/s, of the voltage regulator.

## **Bref for var control mode**

This parameter is not visible when the **Mode of operation** parameter is set to Voltage regulation.

Reference susceptance, in pu/Pbase, when the SVC is operating in var control mode.

## **Inputs and Outputs**

A B C

The three terminals of the SVC.

Vref

Simulink input of the reference voltage signal.

This input is visible only when the **External control of reference voltage Vref** parameter is checked.

m

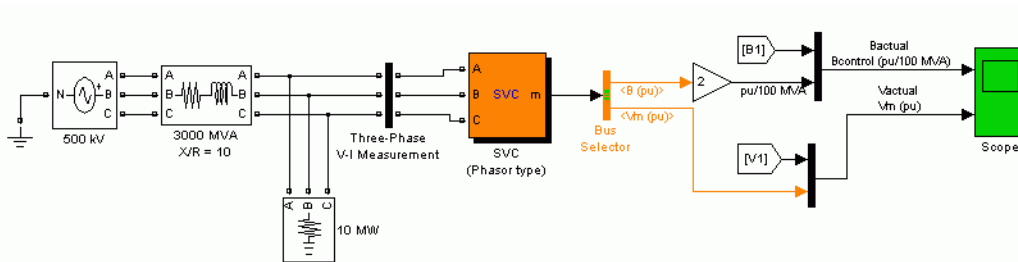
Simulink output vector containing six SVC internal signals. These signals are either voltage and current phasors (complex signals) or control signals. They can be individually accessed by using the Bus Selector block. They are, in order:

# Static Var Compensator (Phasor Type)

	Signal Group	Signal Names	Definition
1-3	Power Iabc (cmplx)	Ia(pu) Ib(pu) Ic(pu)	Phasor currents Ia, Ib, Ic flowing into the SVC (pu)
4	Control	Vm (pu)	Positive-sequence value of measured voltage (pu)
5	Control	B (pu)	SVC susceptance output of the voltage regulator (pu). A positive value indicates that the SVC is capacitive.
6	Control	Q (pu)	SVC reactive power output (pu). A positive value indicates inductive operation.

## Example

The power\_svc demo illustrates the steady-state and dynamic performance of a +200 Mvar/- 100 Mvar SVC regulating voltage on a 500 kV, 60 Hz, system.



Open the SVC block menu and look at its parameters. The SVC is set to Voltage regulation mode with a reference voltage  $V_{ref} = 1.0$  pu. The voltage droop reactance is  $0.03$  pu/200 MVA, so that the voltage varies from  $0.97$  pu to  $1.015$  pu when the SVC current goes from fully

## Static Var Compensator (Phasor Type)

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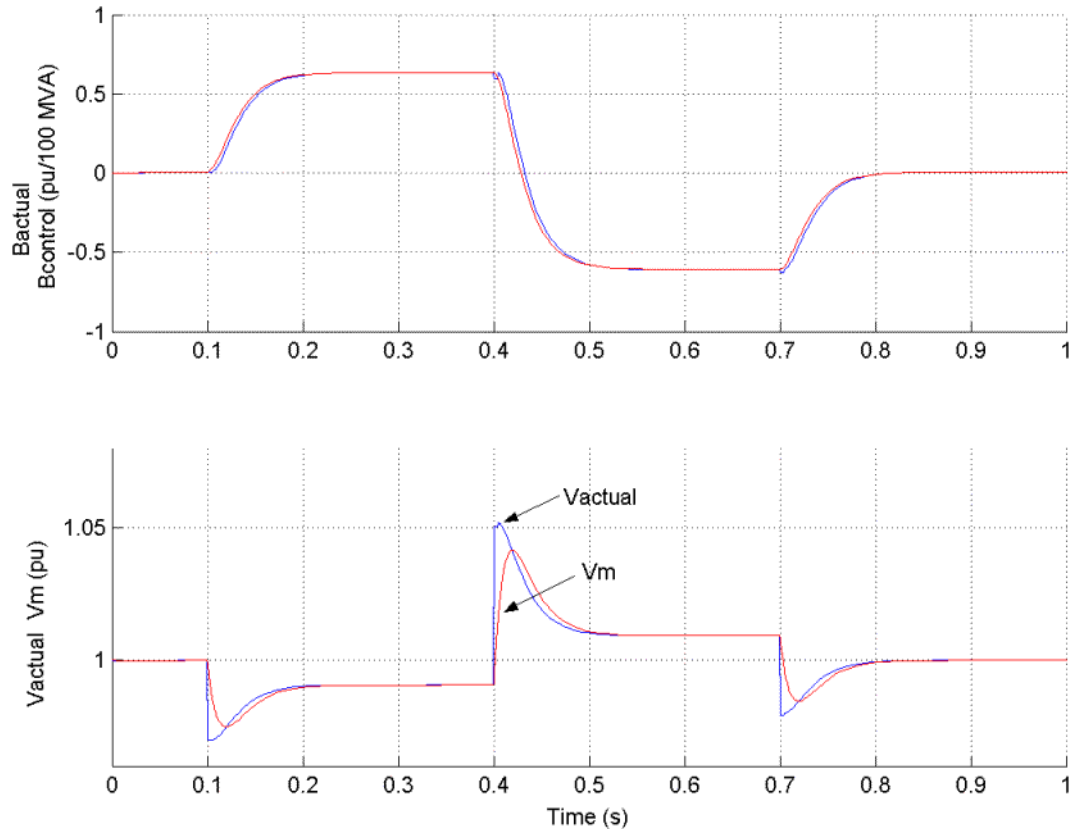
capacitive to fully inductive. Double-click the blue block to display the SVC V-I characteristic.

The Three-Phase Programmable Voltage Source is used to vary the system voltage and observe the SVC performance. Initially the source is generating its nominal voltage (500 kV). Then, voltage is successively decreased (0.97 pu at  $t = 0.1$  s), increased (1.03 pu at  $t = 0.4$  s) and finally returned to nominal voltage (1 pu at  $t = 0.7$  s).

Start the simulation and observe the SVC dynamic response to voltage steps on the Scope. Waveforms are reproduced on the figure below. Trace 1 shows the actual positive-sequence susceptance B1 and control signal output B of the voltage regulator. Trace 2 shows the actual system positive-sequence voltage V1 and output Vm of the SVC measurement system.



# Static Var Compensator (Phasor Type)



The SVC response speed depends on the voltage regulator integral gain  $K_i$  (proportional gain  $K_p$  is set to zero), system strength (reactance  $X_n$ ), and droop (reactance  $X_s$ ).

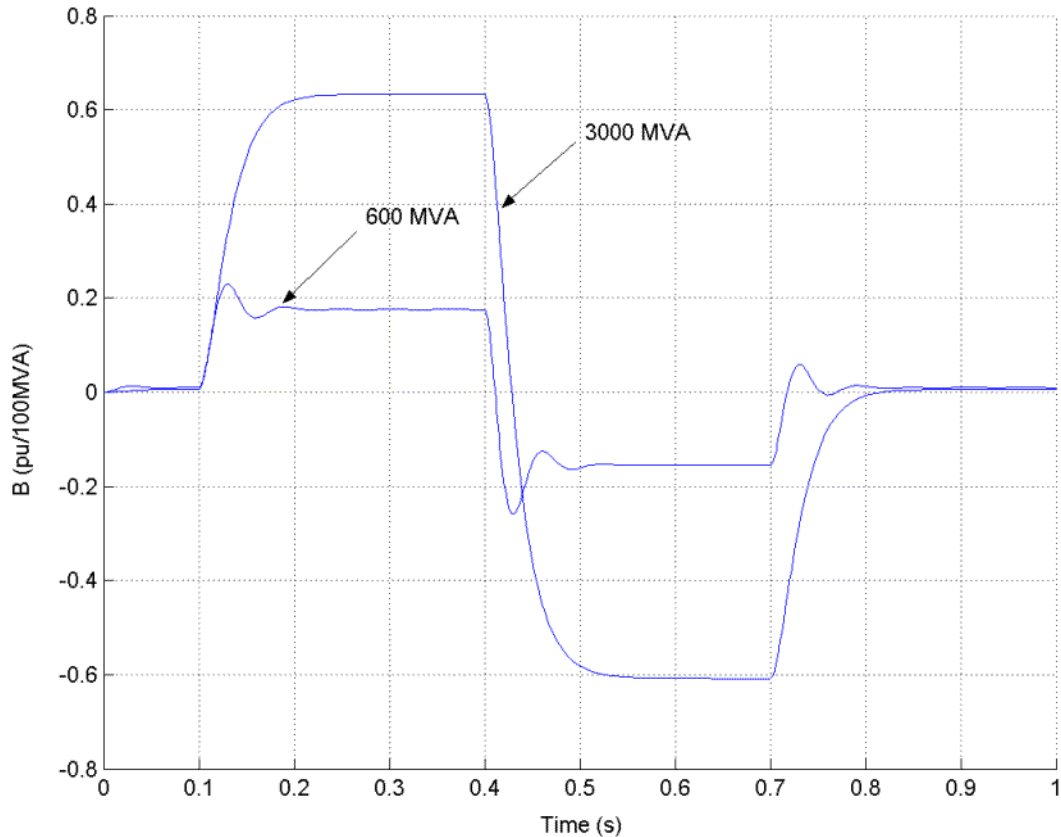
As mentioned above, neglecting the voltage measurement time constant  $T_m$  and the average time delay  $T_d$  due to valve firing, the system can be approximated by a first-order system having a closed-loop time constant:

$$T_c = \frac{1}{K_i \cdot (X_s + X_n)}$$

# Static Var Compensator (Phasor Type)

With given system parameters ( $K_i = 300$ ;  $X_n = 0.0667$  pu/200 MVA;  $X_s = 0.03$  pu/200 MVA), the closed-loop time constant is  $T_c = 0.0345$  s.

If you increase the regulator gain or decrease the system strength,  $T_m$  and  $T_d$  are no longer negligible, and you instead observe an oscillatory response and eventually instability. The figure below compares the SVC susceptance ( $B$  output of the voltage regulator) for two different short-circuit levels: 3000 VA and 600 MVA.



# Static Var Compensator (Phasor Type)

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## References

[1] N. G. Hingorani, L. Gyugyi, "Understanding FACTS; Concepts and Technology of Flexible AC Transmission Systems," *IEEE Press book*, 2000

## See Also

Static Synchronous Compensator (Phasor Type)

# Steam Turbine and Governor

## Purpose

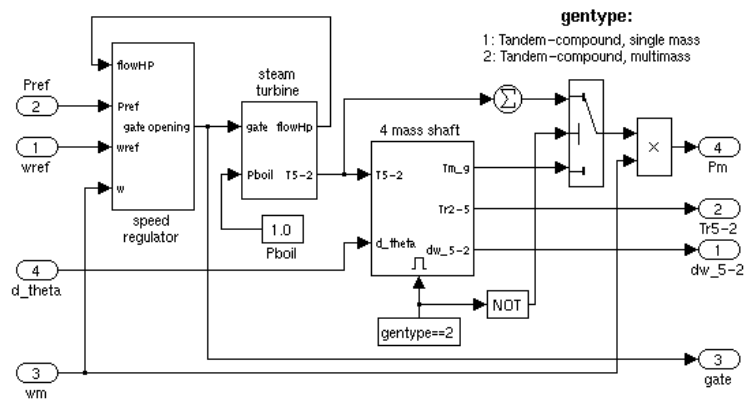
Model the dynamics of speed governing system, steam turbine, and multimass shaft

## Library

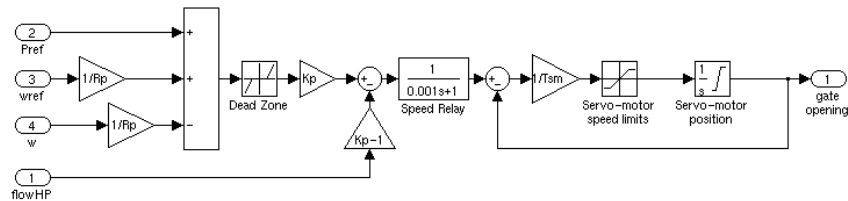
Machines

## Description

The Steam Turbine and Governor block implements a complete tandem-compound steam prime mover, including a speed governing system, a four-stage steam turbine, and a shaft with up to four masses.



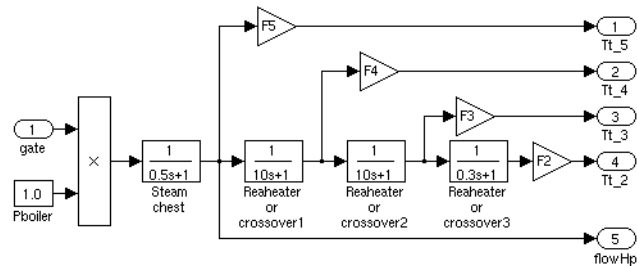
The speed governing system consists of a proportional regulator, a speed relay, and a servomotor controlling the gate opening. It is similar to one of the models proposed in [1].



The steam turbine has four stages, each modeled by a first-order transfer function. The first stage represents the steam chest while the

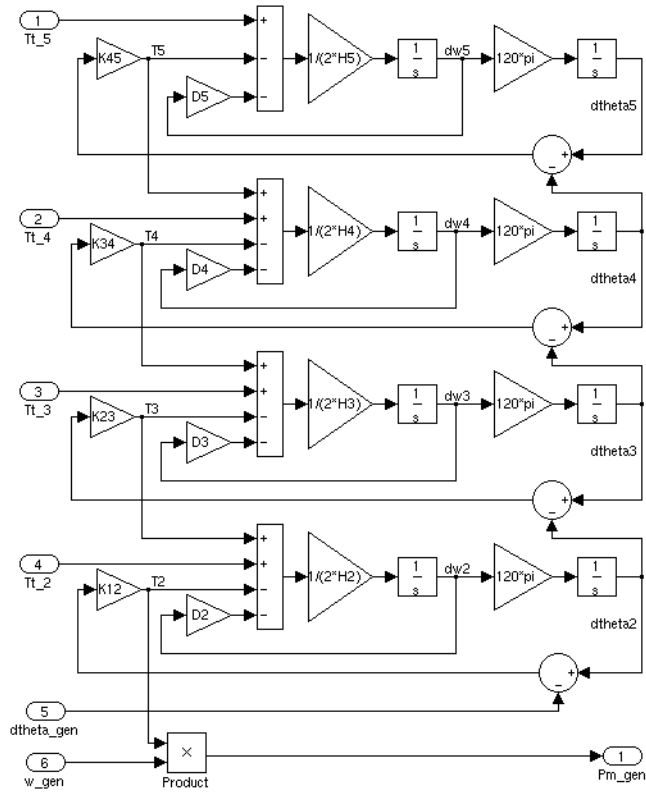
# Steam Turbine and Governor

three other stages represent either reheaters or crossover piping. The boiler is not modeled and boiler pressure is constant at 1.0 pu. Fractions F2 to F5 are used to distribute the turbine power to the various shaft stages:

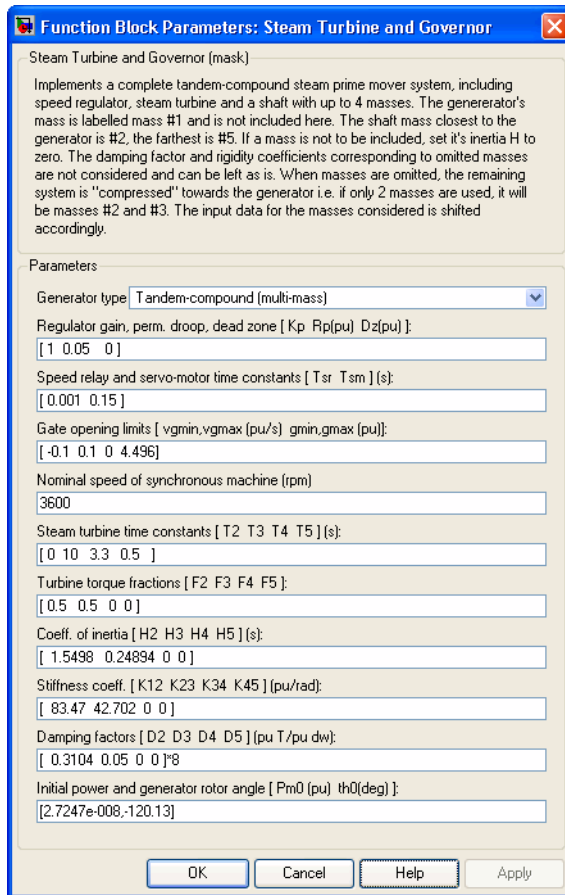


The shaft models a four-mass system, which is coupled to the mass in the Synchronous Machine model for a total of five masses. The machine's mass is labeled mass #1. The mass in the Steam Turbine and Governor block, which is closest to the machine's mass, is mass #2, while the mass farthest from the machine is mass #5. The shaft is characterized by mass inertias  $H$ , damping factors  $D$ , and rigidity coefficients  $K$ . If you choose to simulate a single-mass shaft, the entire four-mass shaft subsystem in the Steam Turbine and Governor block is disabled and all the torque from the turbine is added together and applied to the machine's mass:

# Steam Turbine and Governor



## Dialog Box and Parameters



**Function Block Parameters: Steam Turbine and Governor**

Steam Turbine and Governor (mask)

Implements a complete tandem-compound steam prime mover system, including speed regulator, steam turbine and a shaft with up to 4 masses. The generator's mass is labelled mass #1 and is not included here. The shaft mass closest to the generator is #2, the farthest is #5. If a mass is not to be included, set its inertia H to zero. The damping factor and rigidity coefficients corresponding to omitted masses are not considered and can be left as is. When masses are omitted, the remaining system is "compressed" towards the generator i.e. if only 2 masses are used, it will be masses #2 and #3. The input data for the masses considered is shifted accordingly.

Parameters

Generator type: Tandem-compound (multi-mass)

Regulator gain, perm. droop, dead zone [ Kp Rp(pu) Dz(pu) ]:  
[ 1 0.05 0 ]

Speed relay and servo-motor time constants [ Tsr Tsm ] (s):  
[ 0.001 0.15 ]

Gate opening limits [ vgmin,vgmax (pu/s) gmin,gmax (pu) ]:  
[ -0.1 0.1 0 4.496 ]

Nominal speed of synchronous machine (rpm)  
3600

Steam turbine time constants [ T2 T3 T4 T5 ] (s):  
[ 0 10 3.3 0.5 ]

Turbine torque fractions [ F2 F3 F4 F5 ]:  
[ 0.5 0.5 0 0 ]

Coeff. of inertia [ H2 H3 H4 H5 ] (s):  
[ 1.5498 0.24894 0 0 ]

Stiffness coeff. [ K12 K23 K34 K45 ] (pu/rad):  
[ 83.47 42.702 0 0 ]

Damping factors [ D2 D3 D4 D5 ] (pu T/pu dw):  
[ 0.3104 0.05 0 0 ]\*8

Initial power and generator rotor angle [ Pm0 (pu) th0(deg) ]:  
[ 2.7247e-008;-120.13 ]

OK Cancel Help Apply

### Generator type

Specifies rotor type: single mass or multimass tandem-compound. If you choose a single-mass system, the multimass shaft subsystem in the Steam Turbine and Governor block is disabled and the turbine's output torques are summed together and applied to the single mass in the Synchronous Machine block.

# Steam Turbine and Governor

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## **Regulator gain, permanent droop, dead zone**

The gain  $K_p$ , permanent droop  $R_p$  (pu), and dead-zone width  $D_z$  (pu). Set gain to 3 if you want to use the steam flow feedback loop. Otherwise, set gain to 1.

## **Speed relay and servo-motor time constants**

The speed relay and gate servomotor time constants  $T_{sr}$  (s) and  $T_{sm}$  (s).

## **Gate opening limits**

The minimum and maximum gate opening speed  $v_{gmin}$  and  $v_{gmax}$  (both in pu/s), and minimum and maximum gate opening  $g_{min}$  and  $g_{max}$  (both in pu).

## **Nominal speed of synchronous machine**

The synchronous speed of the generator driven by the steam turbine (rpm).

## **Steam turbine time constants**

The turbine time constants  $T_2$  to  $T_5$  (s). Numbered consistently with turbine torque fractions and mass numbers; i.e.,  $T_5$  is the time constant of the first turbine stage, which models the steam chest.

## **Turbine torque fractions**

The turbine torque fractions  $F_2$  to  $F_5$ . Must total 1, otherwise an error message appears. Fraction numbers correspond to mass numbers; i.e.,  $F_2$  is the fraction of torque to be applied to mass #2 of the multimass shaft.

## **Coefficient of inertia; Stiffness coefficient; Damping factors**

Only visible if generator type is `multimass`. Coefficients of inertia  $H_2$  to  $H_5$  (s), stiffness coefficients  $K_{12}$  to  $K_{45}$  (pu/rad), and damping factors  $D_2$  to  $D_5$  (pu torque / pu speed deviation) are associated with the masses of the multimass shaft.  $K_{12}$  corresponds to the rigidity coefficient between masses #1 and #2, and so on.



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**Note** If you do not want to simulate all four masses in the multimass shaft, simply set the inertia of unwanted masses to 0. The rigidity coefficient and damping factor corresponding to omitted masses are not considered. When masses are not simulated, the remaining system is “compressed” toward the generator; i.e., if only two masses are used (excluding the generator), they are masses #2 and #3. The input data for the masses considered are shifted accordingly. In any case, inertias must be consistent with torque fractions. You cannot set an inertia to 0 and set the corresponding torque fraction to a nonzero value. However, you can set a torque fraction to 0 and set the corresponding mass inertia to a nonzero value.

---

## Initial power and generator rotor angle

If the shaft is multimass, enter the initial mechanical power  $P_{m0}$  (pu) and initial generator angle  $\Theta_{e0}$  (degrees). If the shaft is single mass, enter only initial mechanical power.

Initial mechanical power is automatically updated by the load flow utility of the Powergui block. Initial angle is also computed by the load flow utility and is written in the associated Synchronous Machine block dialog box.

## Inputs and Outputs

wref

The speed reference, in pu. It is normally connected to a Constant block with the value set to 1.0 pu.

Pref

The electrical power reference, in pu. It is set to a constant value corresponding to the initial active power drawn from the Synchronous Machine block connected to the Steam Turbine and Governor block.

wm

The generator’s speed, in pu. This is one of the signals in the last output of the Synchronous Machine model (internal variables).

# Steam Turbine and Governor

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`d_theta`

The generator's power angle deviation. It is also one of the signals in the last output of the Synchronous Machine model (internal variables).

`dw_5-2`

Output a vector containing the speed deviations, in pu, of masses 5, 4, 3, and 2.

`Tr5-2`

Output a vector containing the torques, in pu, transmitted by masses 5, 4, 3, and 2.

`gate`

Gate opening in pu.

`Pm`

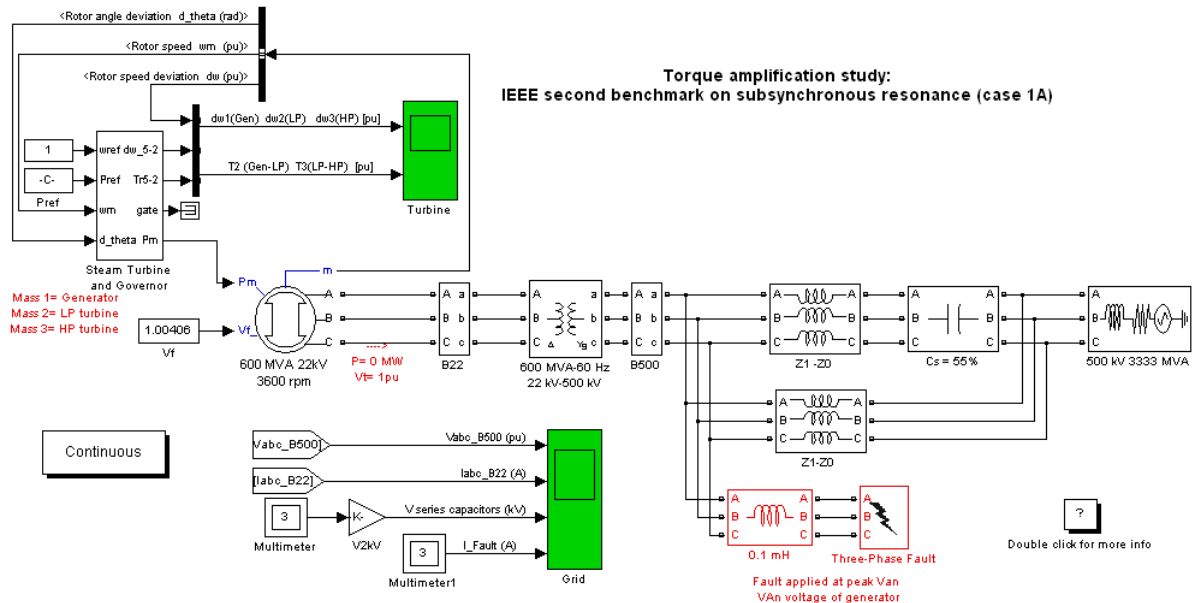
The mechanical power, in pu, that you connect to the first input of a Synchronous Machine block.

## Example

The `power_thermal` demo illustrates the use of the Steam Turbine and Governor block. This system is an IEEE benchmark used to study subsynchronous resonance and particularly torque amplification after a fault on a series-compensated power system [2]. It consists in a single generator connected to an infinite bus via two transmission lines, one of which is series compensated. The subsynchronous mode introduced by the compensation capacitor after a fault has been applied and cleared excites the oscillatory torsional modes of the multimass shaft and the torque amplification phenomenon can be observed. Open the Simulink diagram by typing `power_thermal`.

This system is slightly different from the one presented in [2]. Since we are using the Synchronous Machine mass as the first mass, we cannot model the exciter's mass as is done in [2]. Therefore, our system has only three masses, representing the generator's rotor (mass #1) and the turbine's low and high pressure stages (masses #2 and #3, respectively).

# Steam Turbine and Governor

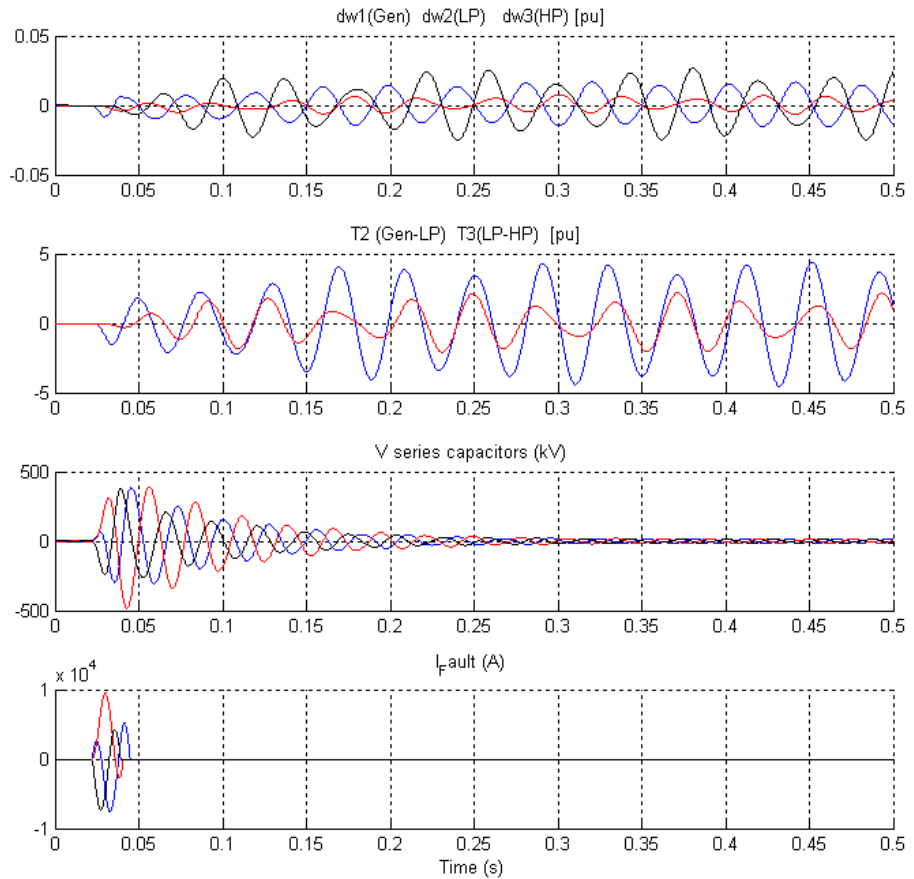


In order to start the simulation in steady state, you must first initialize the synchronous machine and steam turbine by using the **Load Flow and Machine Initialization** utility of the Powergui. Set the generator as a PV generator with zero active power to simulate an initially unloaded generator.

This test is performed without regulators. The machine's excitation voltage is also set to a constant value (1.00406 pu), which is computed by the load flow.

Run the simulation. Once the simulation is completed, observe the mass speed deviations, torques, series capacitor voltages and fault currents.

# Steam Turbine and Governor



The peak values of all these signals correspond within 3% to those given in Table 5, case 1A, of [2]. The torque amplification is clearly observed on all masses of the shaft system. The high-pressure turbine (mass #3) transmits a peak torque exceeding 2 pu to the low-pressure turbine (mass #2), while the low-pressure turbine transmits a peak torque exceeding 4 pu to the generator's rotor (mass #1).

## References

[1] IEEE committee report, "Dynamic models for steam and hydro turbines in power system studies," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-92, No. 6, 1973, pp. 1904-1915.

[2] IEEE Subsynchronous resonance working group, "Second benchmark model for computer simulation of subsynchronous resonance," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-104, No. 5, 1985, pp. 1057-1066.

## See Also

Excitation System, Hydraulic Turbine and Governor, Powergui, Synchronous Machine

# Stepper Motor

## Purpose

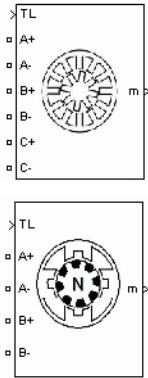
Implement stepper motor model

## Library

Machines

## Description

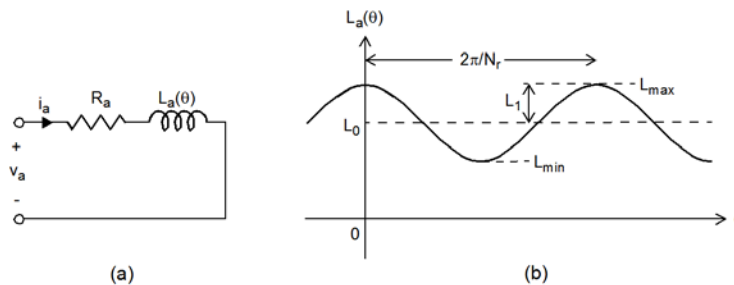
The Stepper Motor (STM) block implements a generic model that represents two most popular families of stepper motors:



- Variable-reluctance stepper motors
- Permanent-magnet or hybrid stepper motors

The Stepper Motor model consists of electrical and mechanical sections. The electrical section is represented by an equivalent circuit, configuration of which depends on the motor type. The equivalent circuits have been built with the supposition that the magnetic circuit is linear (no saturation) and the mutual inductance between phases is negligible. The mechanical section is represented by a state-space model based on inertia moment and viscous friction coefficient.

For a variable-reluctance stepper motor, the equivalent circuit for one phase is shown in the following figure.



In this model,  $R_a$  and  $L_a(\theta)$  represent respectively the resistance and the inductance of phase A winding. The winding inductance varies as a function of the rotor position:

$$L_a(\theta) = L_0 + L_1 \cos(N_r \theta)$$

where  $L_0$  is the average inductance,  $L_1$  is the maximum inductance variation and  $N_r$  is the rotor teeth number.

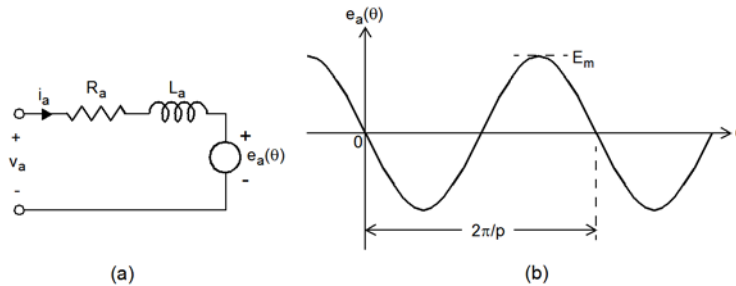
Note that at the reference position ( $\theta = 0$ ), the rotor tooth is fully aligned with A-axis pole so that the A-phase winding inductance is then maximum.

The total electromagnetic torque produced by the motor is the sum of the torques produced by the motor phases:

$$T_e = \sum_{x=1}^m 0.5 i_x^2 \frac{dL_x}{d\theta}$$

where  $m$  is the phase number,  $i_x$  is the winding current in phase  $x$  and  $L_x$  is the inductance function of phase  $x$  winding.

For a permanent-magnet (PM) or hybrid stepper motor, the equivalent circuit for one phase is shown in the following figure.



In this model,  $R_a$  and  $L_a$  represent respectively the resistance and inductance of A-phase winding. Due to the large value of the air gap introduced by the magnets, the winding inductance of the permanent-magnet or hybrid stepper motor can be considered to be independent of the rotor position. The voltage source  $e_a(\theta)$  represents the motor back EMF (electromotive force) which is a sinusoidal function of the rotor position:

$$e_a(\theta) = -p \psi_m \sin(p\theta) \frac{d\theta}{dt}$$

# Stepper Motor

---

where  $p$  is the number of pole pairs and  $\psi_m$  is the motor maximum magnetic flux.

Note that at the reference position ( $\theta = 0$ ), the North pole on the rotor is fully aligned with A-axis pole so that the A-phase back EMF is then zero.

The electromagnetic torque produced by a two-phase PM or hybrid stepper motor is equal to the sum of the torque resulting from the interaction of the phase currents and magnetic fluxes created by the magnets and the detent torque, which results from the saliency of the rotor:

$$T_e = -p\psi_m i_a \sin(p\theta) - p\psi_m i_b \sin\left(p\theta - \frac{\pi}{2}\right) - T_{dm} \sin(2p\theta)$$



## Dialog Box and Parameters

**Block Parameters: Stepper Motor**

Stepper Motor (mask)

Depending on the motor configuration specified by the Motor type parameter, this block models:

- a two or four phases permanent-magnet / hybrid stepper motor,
- a three, four, or five phases variable reluctance stepper motor.

Parameters

Motor type Variable reluctance

Number of phases 3

Maximum winding inductance (H)  
10e-3

Minimum winding inductance  
2e-3

Winding resistance (Ohm)  
1.2

Step angle (degree)  
30

Total inertia (kg.m.m)  
1e-4/5

Total friction (kg.m/s)  
1e-3

Initial speed (rad/s)  
0

Initial position (degrees)  
0

OK Cancel Help Apply

### Motor type

Select Variable reluctance to implement a variable-reluctance stepper motor.

### Number of phases

You can select 3, 4 or 5 phases.

### Maximum winding inductance

The maximum inductance  $L_{\max}$  (Henry) of each phase winding.

### Minimum winding inductance

The minimum inductance  $L_{\min}$  (Henry) of each phase winding.

# Stepper Motor

---

**Winding resistance**

The resistance  $R_a$  (ohm) of each phase winding.

**Step angle**

The step angle (degrees) of the rotor movement.

**Total inertia**

The total inertia momentum  $J$  ( $\text{kg}\cdot\text{m}^2$ ) of the motor and the load.

**Total friction**

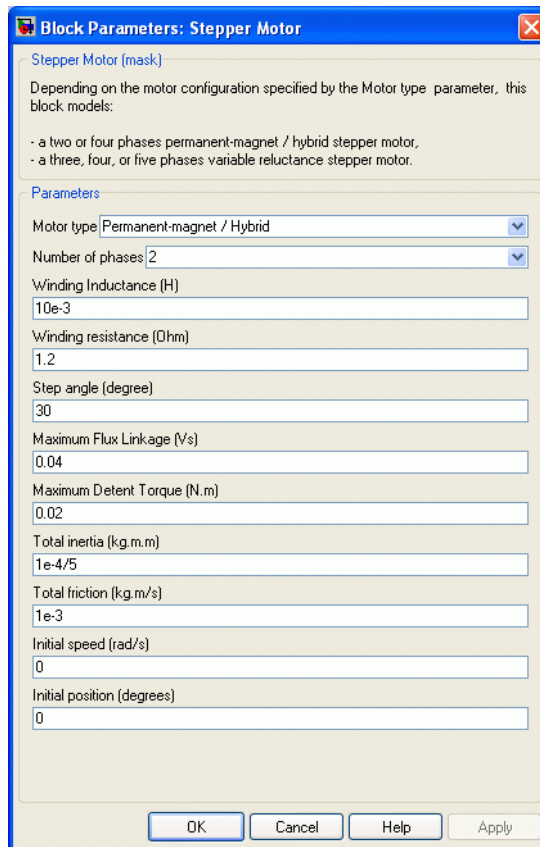
The total viscous friction coefficient  $B$  (N.m.s) of the motor and the load.

**Initial speed**

The initial rotation speed  $\omega_0$  (rad/s).

**Initial position**

The initial rotor position  $\Theta_0$  (degrees).



## Motor type

Select Permanent-magnet/Hybrid to implement a permanent-magnet or hybrid stepper motor.

## Number of phases

You can select 2 or 4 phases.

## Winding inductance

The inductance  $L_a$  (Henry) of each phase winding.

# Stepper Motor

---

## Winding resistance

The resistance  $R_a$  (ohm) of each phase winding.

## Step angle

The step angle (degrees) of the rotor movement.

## Maximum flux linkage

The maximum flux linkage  $\psi_m$  (V.s) produced by the magnets.

## Maximum detent torque

The maximum detent torque  $T_{dm}$  (N.m) resulting from the saliency of the rotor.

## Total inertia

The total inertia momentum  $J$  (kg.m<sup>2</sup>) of the motor and the load.

## Total friction

The total viscous friction coefficient  $B$  (N.m.s) of the motor and the load.

## Initial speed

The initial rotation speed  $\omega_0$  (rad/s).

## Initial position

The initial rotor position  $\Theta_0$  (degrees).

## Inputs and Outputs

### TL

The mechanical load torque (in N.m). TL is positive in motor operation and negative in generator operation.

### m

The Simulink output of the block is a vector containing 5 signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

Signal	Definition	Units	Symbol
1	Phase voltage	V	$V_{ph}$
2	Phase current	A	$I_{ph}$

Signal	Definition	Units	Symbol
3	Electromagnetic torque	N.m	$T_e$
4	Rotor speed	rad/s	w
5	Rotor position	rad	Theta

## How to Get Stepper Motor Parameters

The parameters used in the stepper model are usually obtained from the manufacturer data sheets. In the case where the parameters are not available, they can be determined from experimental measurements.

### Variable-Reluctance Stepper Motor Parameters

The parameters provided by manufacturer data sheets are usually: number of phases, holding torque, step angle, voltage per phase, current per phase, winding resistance ( $R_a$ ), maximum inductance ( $L_{max}$ ), average inductance ( $L_0$ ), and rotor inertia (J).

### Permanent-Magnet/Hybrid Stepper Motor Parameters

The parameters provided by manufacturer data sheets are usually: number of phases, holding torque, step angle, voltage per phase, current per phase, winding resistance ( $R_a$ ), winding inductance ( $L_a$ ), and rotor inertia (J).

The maximum detent torque ( $T_{dm}$ ) is not always specified. This parameter can be assumed to be equal to 1-10% of the maximum holding torque.

The maximum flux linkage ( $\psi_m$ ) is not always specified. This parameter can be obtained experimentally by driving the motor to a constant speed N (rpm) and by measuring the maximum open-circuit winding voltage  $E_m$  (V).

The parameter  $\psi_m$  is then computed by the following relation:

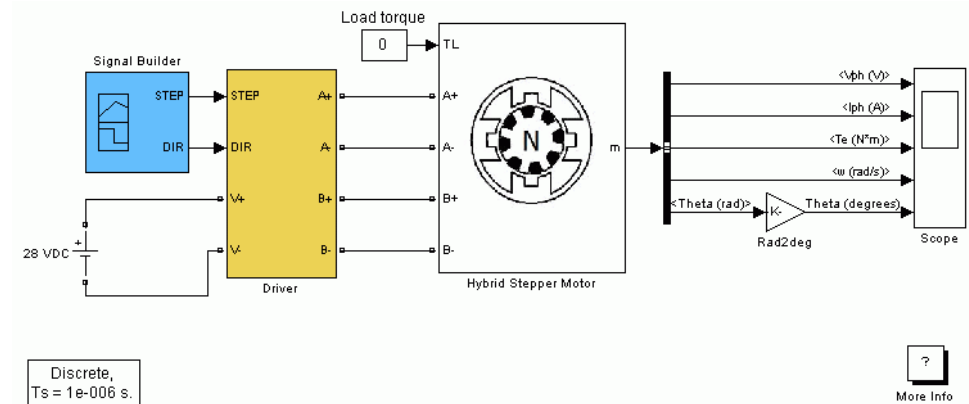
$$\psi_m = (30/p\pi)(E_m/N)$$

# Stepper Motor

where  $p$  is the number of pole pairs given by  $p = \frac{360}{2m \times \text{step}}$  ( $m =$  phase number,  $\text{step} =$  step angle in degrees).

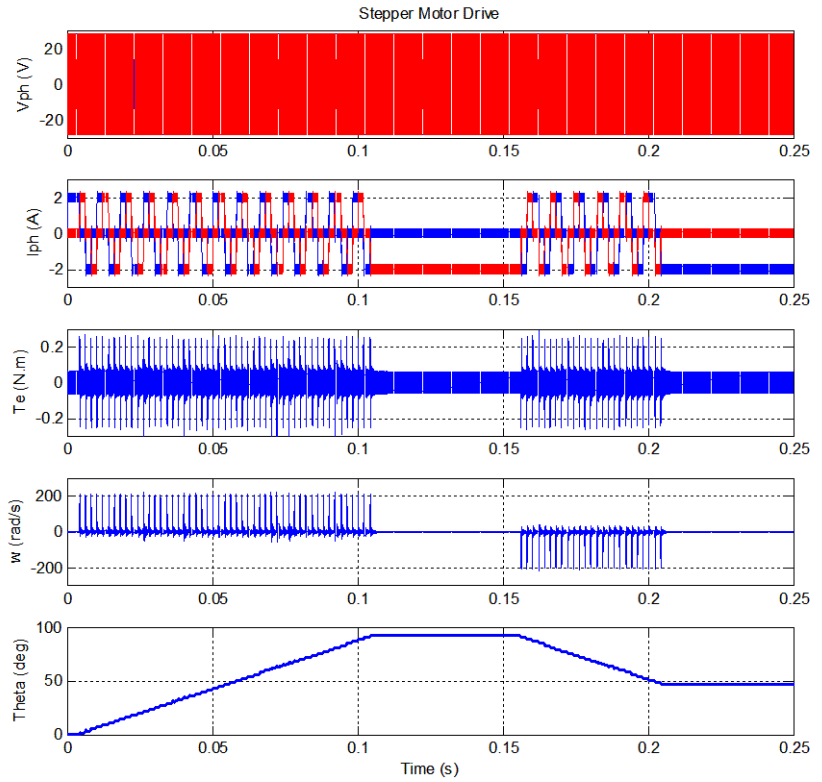
## Example

The power\_steppermotor demo illustrates the operation of a stepper motor drive using a two-phase hybrid stepper motor model.



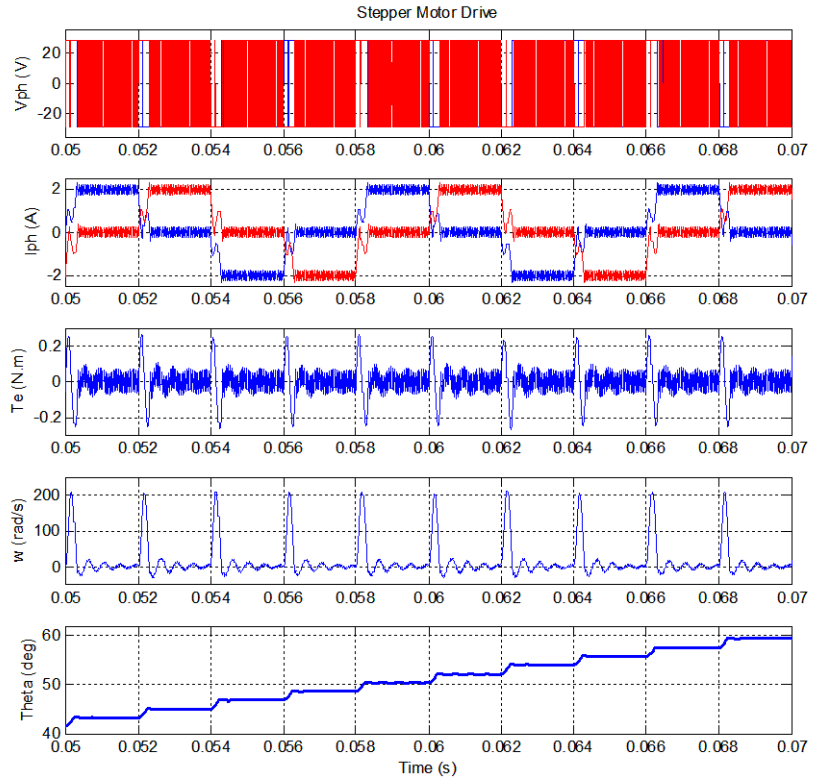
The motor phases are fed by two H-bridge MOSFET PWM converters connected to a 28 V DC voltage source. The motor phase currents are independently controlled by two hysteresis-based controllers which generate the MOSFET drive signals by comparing the measured currents with their references. Square-wave current references are generated using the current amplitude and the step frequency parameters specified in the dialog window. The movement of the stepper drive is controlled by the STEP and DIR signals received from external sources.

The following waveforms are obtained from a simulation of 0.25 sec operation of the stepper motor drive during which the stepper rotates during 0.1 sec in the positive direction, stops for 0.05 sec, rotates in the reverse direction for 0.05 sec and stops.



Detailed waveforms are shown in the following figure.

# Stepper Motor



## References

- [1] T. Kenjo, A. Sugawara, *Stepping Motors and Their Microprocessor Controls*, 2nd Edition, Oxford University Press, Oxford, 2003.
- [2] P. Acarnley, *Stepping Motors - A guide to theory and practice*, 4th Edition, The Institution of Electrical Engineers, London, 2002.



**Purpose** Implement metal-oxide surge arrester

**Library** Elements

**Description**

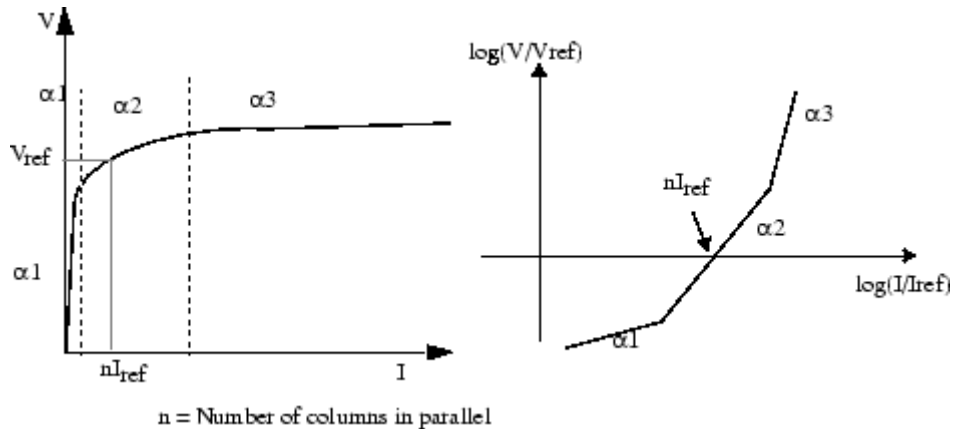


The Surge Arrester block implements a highly nonlinear resistor used to protect power equipment against overvoltages. For applications requiring high power dissipation, several columns of metal-oxide discs are connected in parallel inside the same porcelain housing. The nonlinear V-I characteristic of each column of the surge arrester is modeled by a combination of three exponential functions of the form

$$\frac{V}{V_{ref}} = k_i \left( \frac{I}{I_{ref}} \right)^{1/\alpha_i}$$

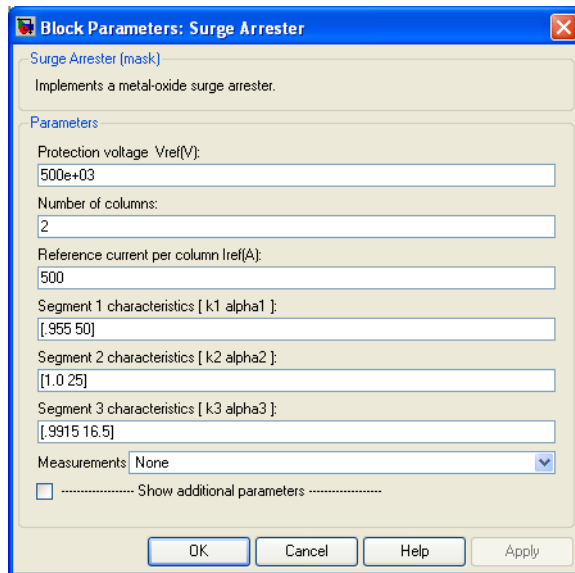
The protection voltage obtained with a single column is specified at a reference current (usually 500 A or 1 kA). Default parameters k and  $\alpha$  given in the dialog box fit the average V-I characteristic provided by the main metal-oxide arrester manufacturers and they do not change with the protection voltage. The required protection voltage is obtained by adding discs of zinc oxide in series in each column.

This V-I characteristic is graphically represented as follows (on a linear scale and on a logarithmic scale).



# Surge Arrester

## Dialog Box and Parameters



### Protection voltage $V_{ref}$

The protection voltage of the Surge Arrester block, in volts (V).

### Number of columns

The number of metal-oxide disc columns. The minimum is one.

### Reference current per column $I_{ref}$

The reference current of one column used to specify the protection voltage, in amperes (A).

### Segment 1 characteristics

The  $k$  and  $\alpha$  parameters of segment 1.

### Segment 2 characteristics

The  $k$  and  $\alpha$  parameters of segment 2.

### Segment 3 characteristics

The  $k$  and  $\alpha$  characteristics of segment 3.

## Measurements

Select **Branch voltage** to measure the voltage across the Surge Arrester block terminals.

Select **Branch current** to measure the current flowing through the Surge Arrester block.

Select **Branch voltage** and **current** to measure the surge arrester voltage and current.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name.

Measurement	Label
Branch voltage	Ub :
Branch current	Ib :

## Limitations

The Surge Arrester block is modeled as a current source driven by the voltage appearing across its terminals. Therefore, it cannot be connected in series with an inductor or another current source. As the Surge Arrester block is highly nonlinear, a stiff integrator algorithm must be used to simulate the circuit. `de23t` with default parameters usually gives the best simulation speed. For continuous simulation, in order to avoid an algebraic loop, the voltage applied to the nonlinear resistance is filtered by a first-order filter with a time constant of 0.01 microseconds. This very fast time constant does not significantly affect the result accuracy.

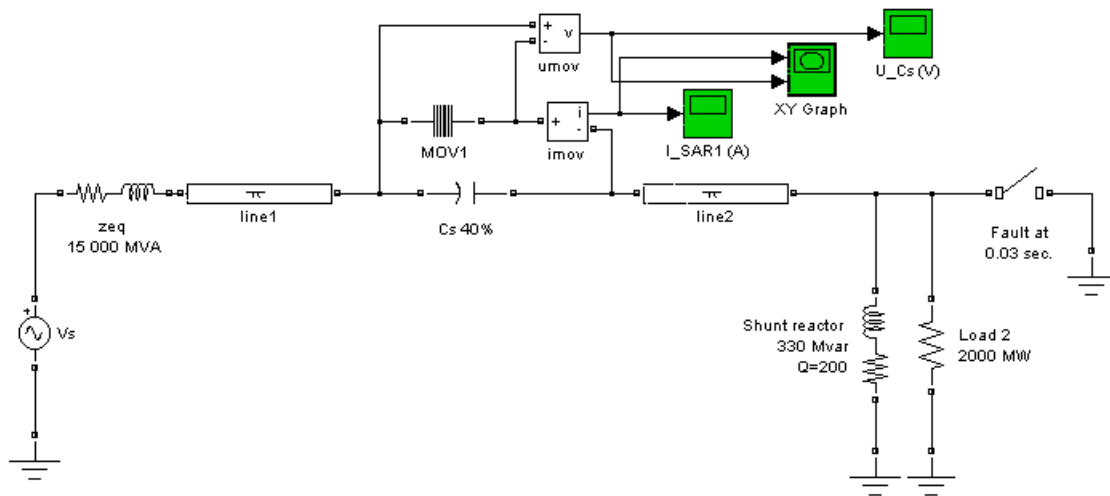
When you use the Surge Arrester block in a discrete system, you will get an algebraic loop. This algebraic loop, which is required in most cases to get an accurate solution, tends to slow down the simulation. However, to speed up the simulation, in some circumstances, you can disable the algebraic loop by selecting **Show additional parameters**

# Surge Arrester

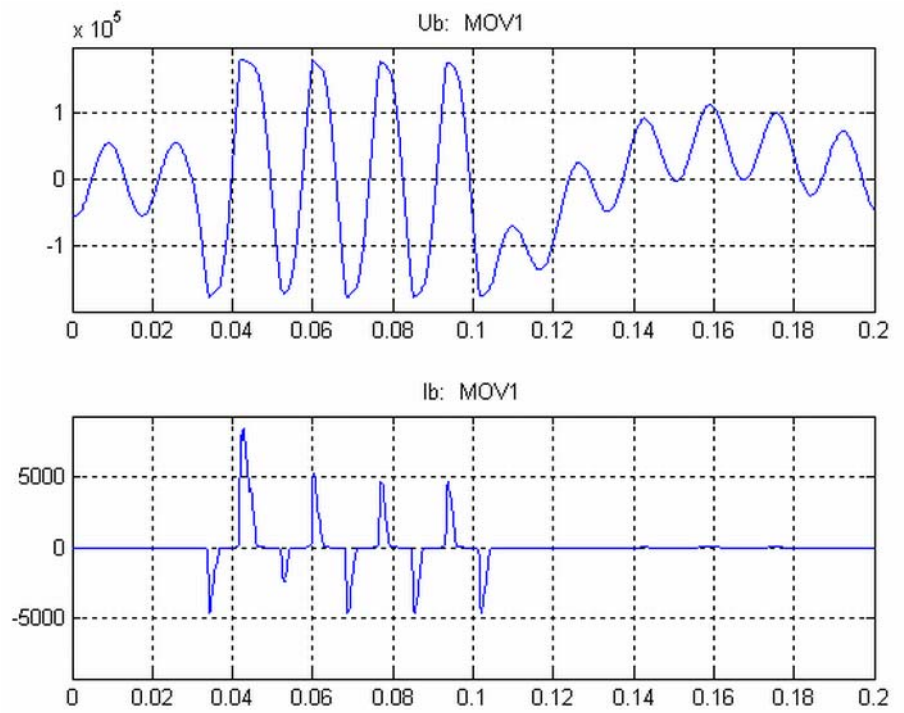
and then **Break algebraic loop in discrete model**. You should be aware that disabling the algebraic loop introduces a one-simulation-step time delay in the model. This can cause numerical oscillations if the sample time is too large.

## Example

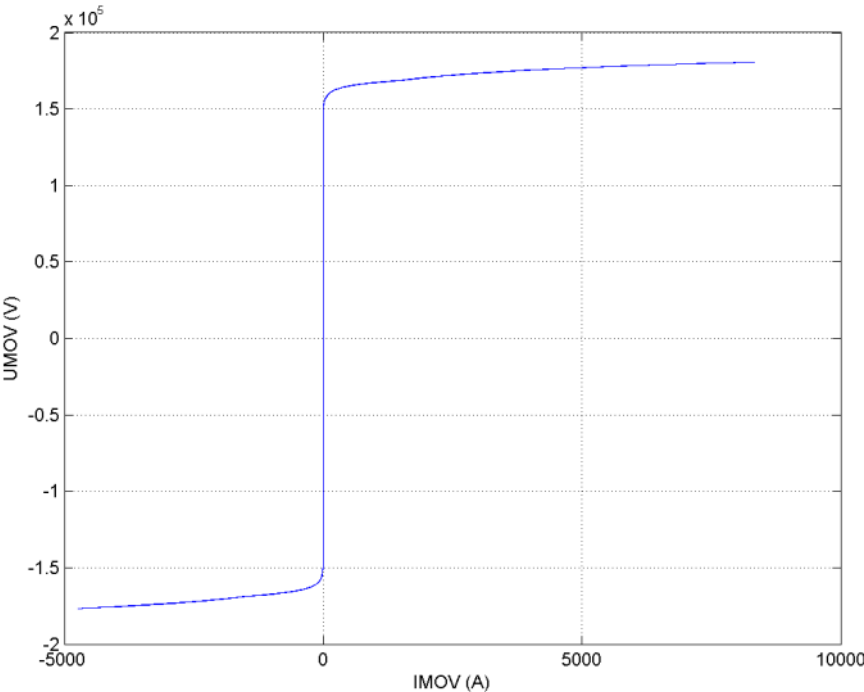
The power\_arrester demo illustrates the use of metal-oxide varistors (MOV) on a 735 kV series-compensated network. Only one phase of the network is represented. The capacitor connected in series with the line is protected by a 30 column arrester. At  $t = 0.03$  seconds, a fault is applied at the load terminals. The current increases in the series capacitor and produces an overvoltage that is limited by the Surge Arrester block. Then the fault is cleared at  $t = 0.1$  seconds.



At fault application, the resulting overvoltage makes the MOV conduct. The waveforms displayed by  $U_{mov}$  and  $I_{mov}$  measurements as well as the V-I characteristic plotted by the X-Y scope are shown below:



# Surge Arrester



**See Also**      Multimeter

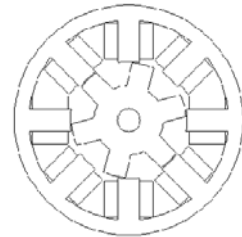
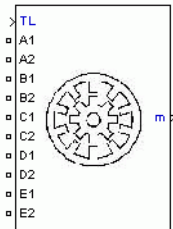
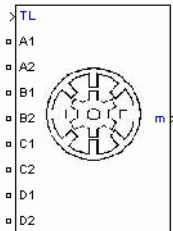
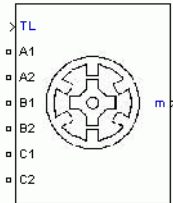
## Purpose

Model the dynamics of switched reluctance motor

## Library

Machines

## Description

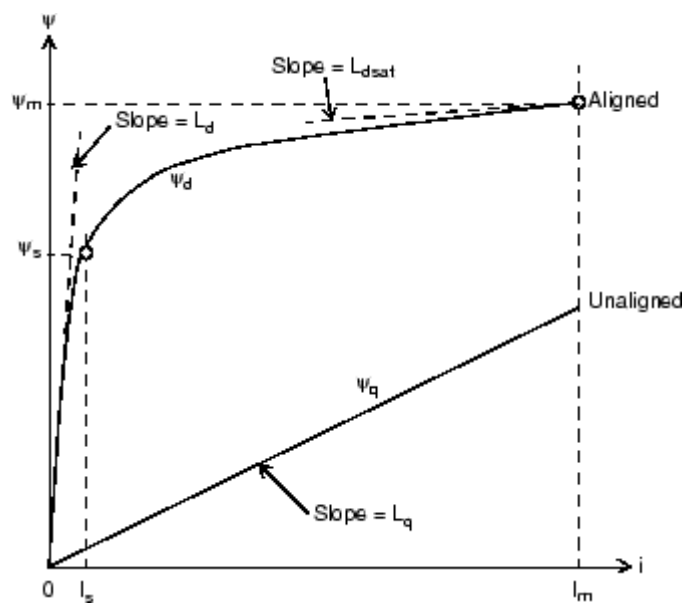


The Switched Reluctance Motor (SRM) block represents three most common switched reluctance motors: three-phase 6/4 SRM, four-phase 8/6 SRM, five-phase 10/8 SRM, as shown in the following figure.

The electric part of the motor is represented by a nonlinear model based on the magnetization characteristic composed of several magnetizing curves and on the torque characteristic computed from the magnetization curves. The mechanic part is represented by a state-space model based on inertia moment and viscous friction coefficient.

To be versatile, two models are implemented for the SRM block: specific and generic models. In the specific SRM model, the magnetization characteristic of the motor is provided in a lookup table. The values are obtained by experimental measurement or calculated by finite-element analysis. In the generic model, the magnetization characteristic is calculated using nonlinear functions and readily available parameters.

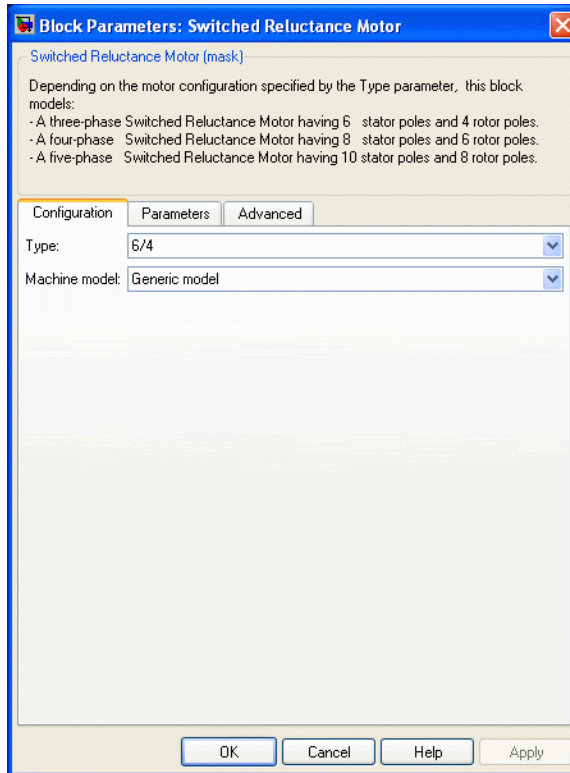
# Switched Reluctance Motor





## Dialog Box and Parameters

### Configuration Tab



### Type

Specifies a three-phase 6/4 motor, four-phase 8/6 motor, or a five-phase 10/8 motor.

### Machine model

Select **Generic model** or **Specific model**. The **Parameters** tab is modified accordingly.

# Switched Reluctance Motor

## Parameters Tab: Generic Model

The screenshot shows a software dialog box titled "Block Parameters: Switched Reluctance Motor". It has three tabs: "Configuration", "Parameters" (which is selected), and "Advanced". The "Parameters" tab contains several input fields with the following values:

- Stator resistance (Ohm): 0.01
- Inertia (kg.m.m): 0.0082
- Friction (N.m.s): 0.01
- Initial speed and position [wo (rad/s) Theta0 (rad)]: [0 0]
- Unaligned inductance (H): 0.67e-3
- Aligned inductance (H): 23.6e-3
- Saturated aligned inductance (H): 0.15e-3
- Maximum current (A): 450
- Maximum flux linkage (V.s): 0.486

At the bottom of the dialog are buttons for "OK", "Cancel", "Help", and "Apply".

### Stator resistance

The resistance  $R_s$  ( $\Omega$ ) of each stator phase winding.

### Inertia

The inertia momentum  $J$  ( $\text{kg.m}^2$ ).

### Friction

The friction coefficient  $B$  ( $\text{N.m.s}$ ).

**Initial speed and position**

The initial rotation speed  $\omega_0$  (rad/s) and initial rotor position  $\theta_0$  (rad).

**Unaligned inductance**

The stator inductance when the rotor is in unaligned position  $L_q$  (H).

**Aligned inductance**

The unsaturated stator inductance when the rotor is in aligned position  $L_d$  (H).

**Saturated aligned inductance**

The saturated stator inductance when the rotor is in aligned position  $L_{dsat}$  (H).

**Maximum current**

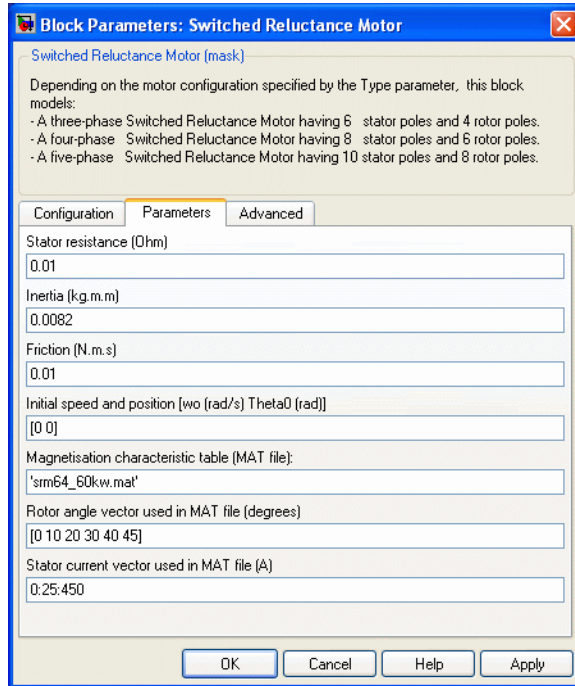
The stator maximum current  $I_m$  (A).

**Maximum flux linkage**

The maximum flux linkage  $\psi_m$  (Wb or V.s) corresponding to  $I_m$ .

# Switched Reluctance Motor

## Parameters Tab: Specific Model



### Stator resistance

The resistance  $R_s$  ( $\Omega$ ) of each stator phase winding.

### Inertia

The inertia momentum  $J$  ( $\text{kg.m}^2$ ).

### Friction

The friction coefficient  $B$  ( $\text{N.m.s}$ ).

### Initial speed

The initial rotation speed  $w_0$  ( $\text{rad/s}$ ) and initial rotor position  $\text{Theta}_0$  ( $\text{rad}$ ).

## Rotor angle vector

The rotor position  $\Theta$  (deg) for which the flux linkage is specified.

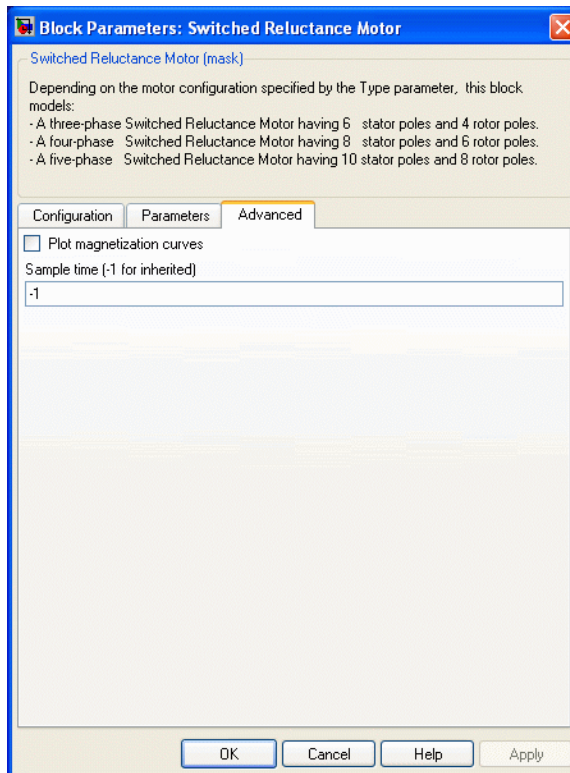
## Stator current vector

The stator current  $I_s$  (A) for which the flux linkage is specified.

## Magnetization characteristic

The 2-D lookup table containing the flux linkage as a function of stator current and rotor position.

## Advanced Tab



# Switched Reluctance Motor

---

## Plot magnetization curves

If selected, the mask plots the magnetization curves corresponding to the lookup table provided. The magnetization curves represent the machine flux linkage versus the stator current with the rotor position as a parameter.

## Sample time (-1 for inherited)

Specifies the sample time used by the block. To inherit the sample time specified in the Powergui block, set this parameter to -1.

## Inputs and Outputs

The Simulink input  $T_L$  is the mechanical load torque (In N.m).  $T_L$  is positive in motor mode and negative in generation mode.

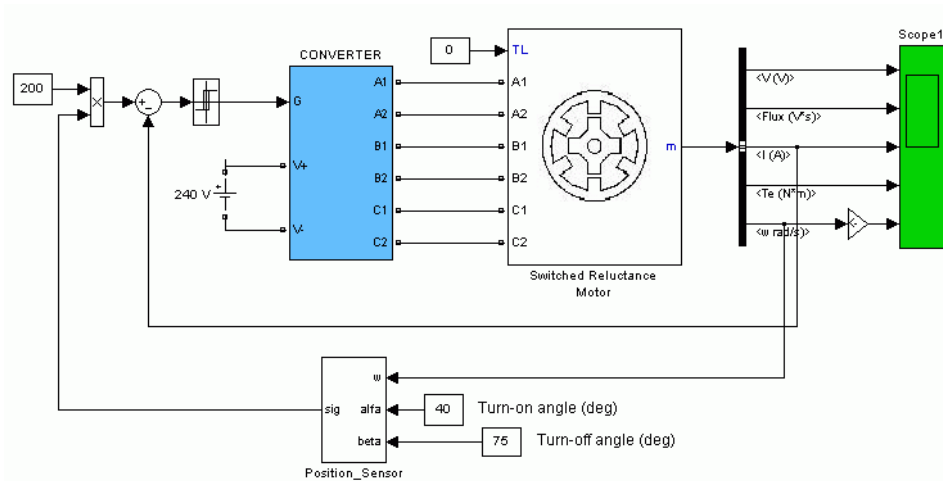
The block output  $m$  is a vector containing several signals. You can demultiplex these signals by using the Bus Selector block from Simulink library.

Signal	Definition	Units
V	Stator voltages	V
flux	Flux linkage	V.s
I	Stator currents	A
Te	Electromagnetic torque	N.m
w	Rotor speed	rad/s
teta	Rotor position	rad

## Example

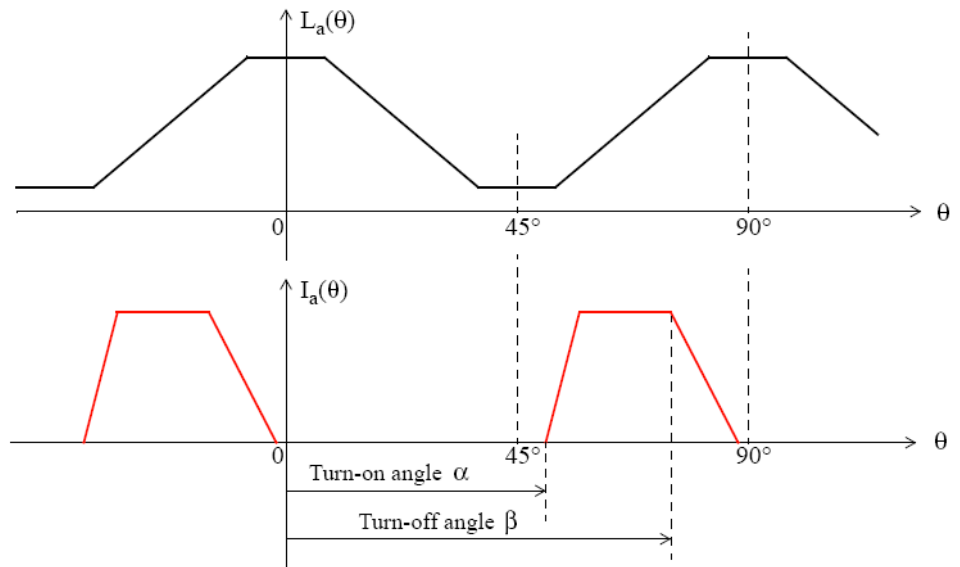
The power\_SwitchedReluctanceMotor demo illustrates the simulation of the Switched Reluctance Motor.

# Switched Reluctance Motor



To develop positive torque, the currents in the phases of a SRM must be synchronized to the rotor position. The following figure shows the ideal waveforms (Phase A inductance and current) in a 6/4 SRM. Turn-on and turn-off angles refer to the rotor position where the converter's power switch is turned on and turned off, respectively.

# Switched Reluctance Motor



## References

- [1] T.J.E. Miller, *Switched Reluctance Motors and Their Control*, Clarendon Press, Oxford, 1993.
- [2] R. Krishnan, *Switched Reluctance Motor Drives*, CRC Press, 2001.
- [3] D.A. Torrey, X.M. Niu, E.J. Unkauf, "Analytical modelling of variable-reluctance machine magnetisation characteristics," IEE Proceedings - Electric Power Applications, Vol. 142, No. 1, January 1995, pp. 14-22.
- [4] H. Le-Huy, P. Brunelle, "Design and Implementation of a Switched Reluctance Motor Generic Model for Simulink SimPowerSystems," Electrimacs2005 Conference.



# Synchronized 6-Pulse Generator

## Purpose

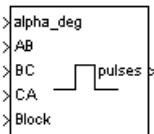
Implement synchronized pulse generator to fire thyristors of six-pulse converter

## Library

Extras/Control Blocks

A discrete version of this block is available in the Extras/Discrete Control Blocks library.

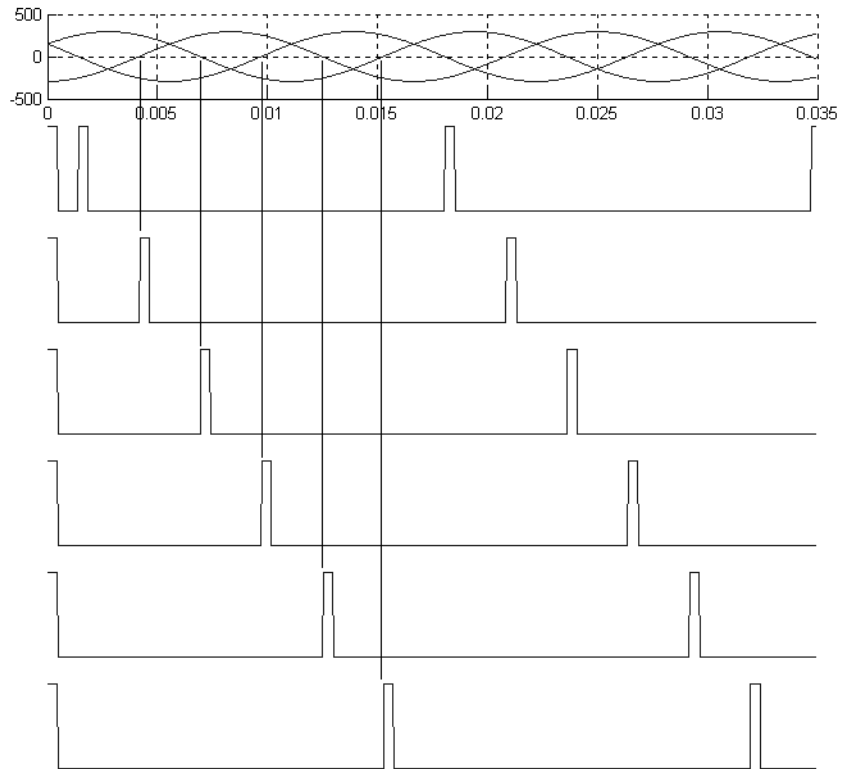
## Description



The Synchronized 6-Pulse Generator block can be used to fire the six thyristors of a six-pulse converter. The output of the block is a vector of six pulses individually synchronized on the six thyristor voltages. The pulses are generated alpha degrees after the increasing zero crossings of the thyristor commutation voltages.

The figures below display the synchronization of the six pulses for an alpha angle of 0 degrees. The pulses are generated exactly at the zero crossings of the three line-to-line synchronization voltages.

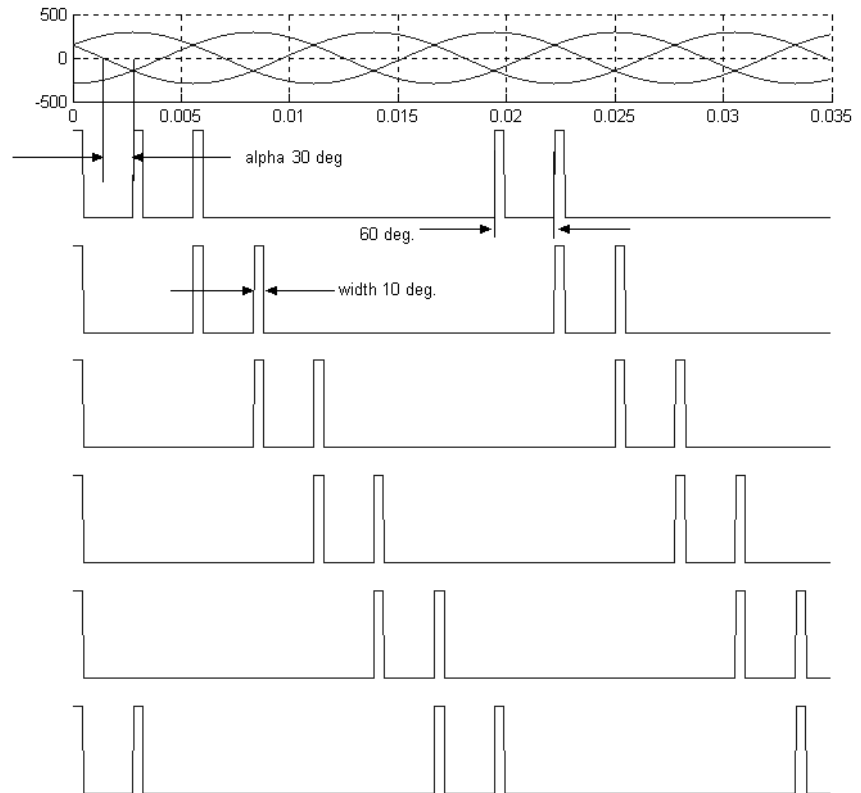
# Synchronized 6-Pulse Generator



The Synchronized 6-Pulse Generator block can be configured to work in double-pulsing mode. In this mode two pulses are sent to each thyristor: a first pulse when the alpha angle is reached, then a second pulse 60 degrees later, when the next thyristor is fired.

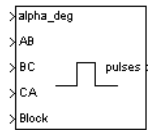
The figures below display the synchronization of the six pulses for an alpha angle of 30 degrees and with double-pulsing mode. Notice that the pulses are generated 30 degrees after the zero crossings of the line-to-line.

# Synchronized 6-Pulse Generator



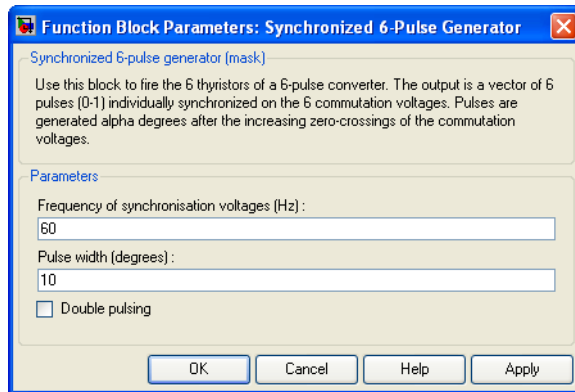
The pulse ordering at the output of the block corresponds to the natural order of commutation of a three-phase thyristor bridge. When you connect the Synchronized 6-Pulse Generator block to the pulses input of the Universal Bridge block (with the thyristors as the power electronic device), the pulses are sent to the thyristors in the following order:

# Synchronized 6-Pulse Generator



When you build your own three-phase thyristor bridge with single thyristor blocks, you need to connect the pulse signals of the Synchronized 6-Pulse Generator block to the gate inputs of the corresponding thyristors.

## Dialog Box and Parameters



### Frequency of synchronization voltages

The frequency, in hertz, of the synchronization voltages. It usually corresponds to the frequency of the network.

### Pulse width

The width of the pulses, in degrees.

### Double pulsing

If selected, the generator sends to each thyristor a first pulse when the alpha angle is reached, and then a second pulse 60 degrees later when the next thyristor in the sequence is fired.

# Synchronized 6-Pulse Generator

---

## Inputs and Outputs

### alpha\_deg

Input 1 is the alpha firing signal, in degrees. This input can be connected to a Constant block, or it can be connected to a controller system to control the pulses of the generator.

### AB, BC, CA

Inputs 2, 3, and 4 are the phase-to-phase synchronization voltages  $V_{ab}$ ,  $V_{bc}$ , and  $V_{ca}$ . The synchronization voltages should be in phase with the three phase-phase voltages at the converter AC terminals. Synchronization voltages are normally derived at the primary windings of the converter transformer. If the converter is connected to the delta winding of a Wye/Delta transformer, the synchronization voltages should be the phase-to-ground voltages of the primary windings.

### Freq

Available only with the discrete version of the Synchronized 6-Pulse Generator. This input should be connected to a constant block containing the fundamental frequency, in hertz, or to a PLL tracking the frequency of the system.

### block

Input 5 allows you to block the operation of the generator. The pulses are disabled when the applied signal is greater than zero.

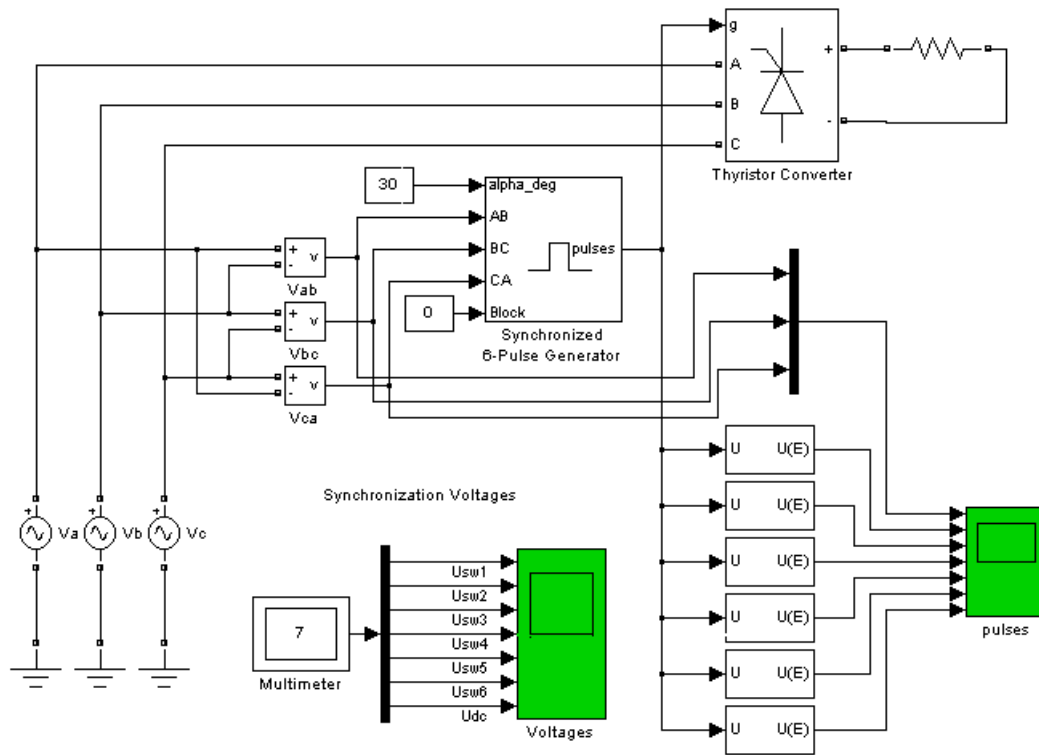
### pulses

The output contains the six pulse signals.

## Example

The `power_sixpulses` demo uses a Synchronized 6-Pulse Generator block to fire the thyristors of a six-pulse thyristor bridge. The bridge is fed by a three-phase voltage source (200 V peak line-to-ground or 245 V RMS line-to-line) and it is connected to a resistive load.

# Synchronized 6-Pulse Generator

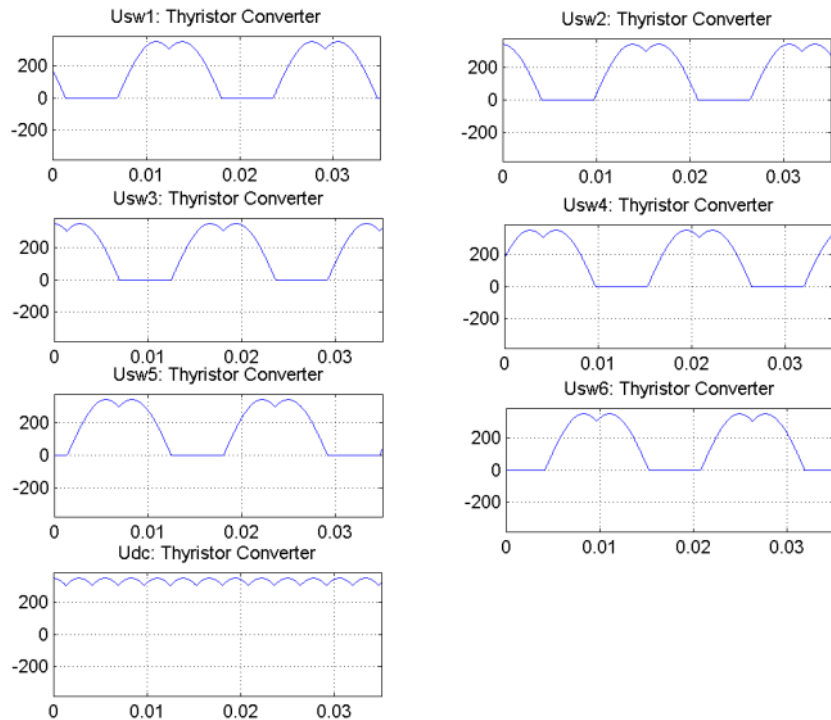


A first simulation is performed with an alpha angle of 0 degrees. Open the Constant block connected at input 1 of the Synchronized 6-Pulse Generator block and set its value to 0. Start the simulation. The average voltage is

$$V_{dc} = \frac{3\sqrt{2}}{\pi} E = \frac{3\sqrt{2}}{\pi} 245 = 331 \text{ volts}$$

The six thyristor voltages are displayed in the next figure. The resulting DC voltage at the output of the rectifier is also displayed (average value of 331 V).

# Synchronized 6-Pulse Generator

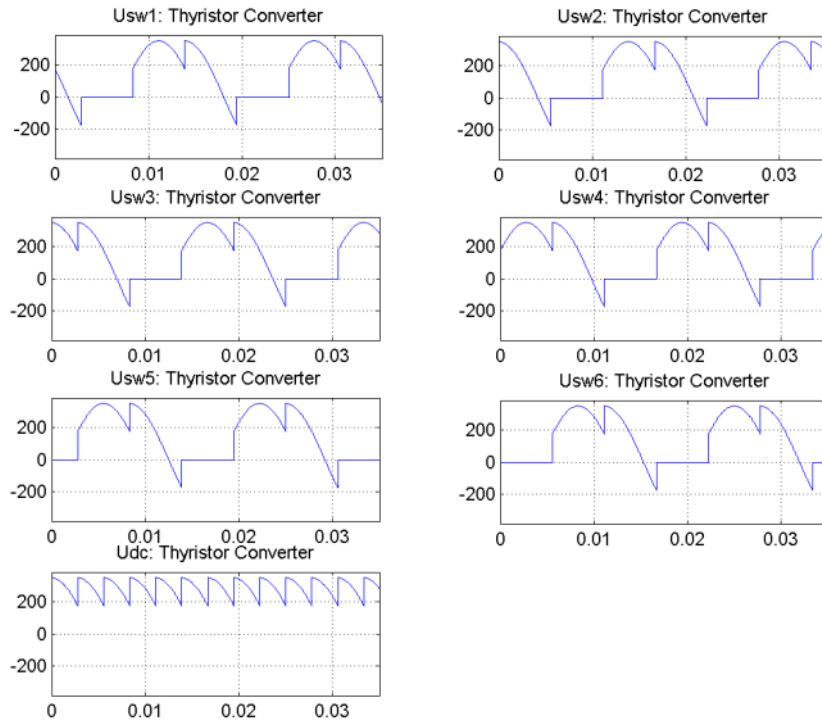


Now change the value of the alpha angle to 30 degrees and start the simulation. Notice that the waveforms of the thyristor voltages look different from the previous case. The thyristors start conducting 30 degrees after their commutation voltage becomes positive and the resulting DC voltage at the output of the rectifier is lower. Its average value is now

$$V_{dc} = \frac{3\sqrt{2}}{\pi} E \cos(\alpha) = \frac{3\sqrt{2}}{\pi} 245 \cos(30^\circ) = 286 \text{ volts}$$

The thyristor voltages and DC voltage for alpha = 30 degrees are

# Synchronized 6-Pulse Generator



The figures show that the mean value of the DC voltage can be controlled by the alpha angle applied to the Synchronized 6-Pulse Generator block.

## See Also

The `power_hvdc` demo illustrates the use of the Discrete Synchronized 6-Pulse Generator block.

Synchronized 12-Pulse Generator



# Synchronized 12-Pulse Generator

## Purpose

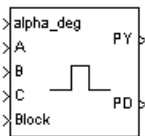
Implement synchronized pulse generator to fire thyristors of twelve-pulse converter

## Library

Extras/Control Blocks

A discrete version of this block is available in the Extras/Discrete Control Blocks library.

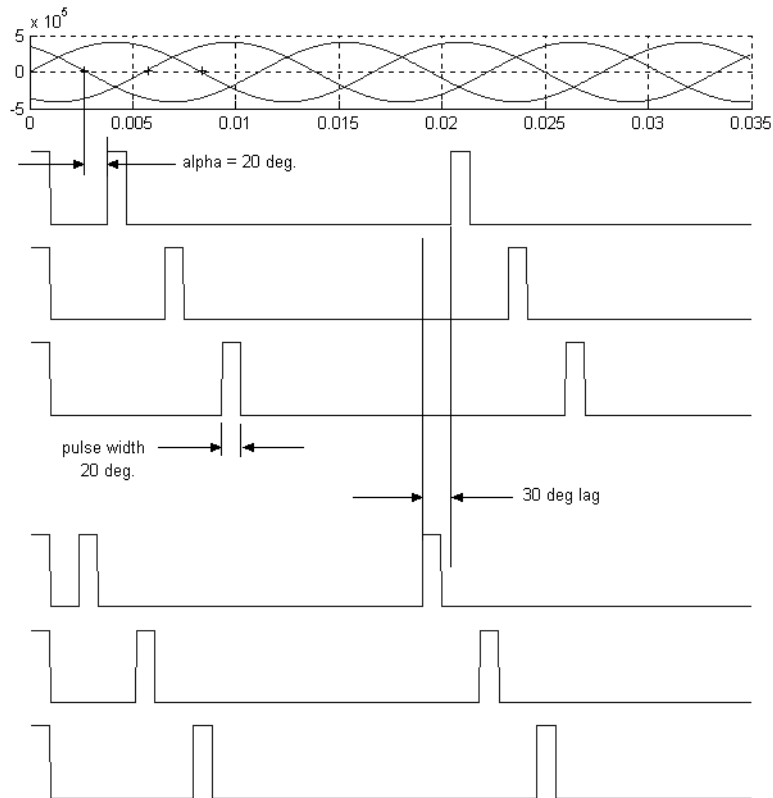
## Description



The Synchronized 12-Pulse Generator block generates two vectors of six pulses synchronized on the twelve thyristor commutation voltages. The first set of pulses, denoted PY, is sent to the six-pulse bridge connected to the wye secondary winding of the Y/Y/Delta converter transformer. It is generated alpha degrees after the zero crossing of the phase-to-phase synchronization voltages. The second set of pulses, denoted PD, is sent to the six-pulse bridge connected to the delta secondary winding of the converter transformer. It lags the PY pulses by 30 degrees.

The figure below shows the three synchronization voltages and the first three pulses of the two output vectors. The synchronization voltages are the three phase-to-ground voltages  $V_a$ ,  $V_b$ ,  $V_c$  measured on the primary side (Y) of the Y/Y/Delta converter transformer.

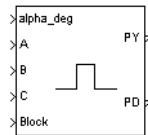
# Synchronized 12-Pulse Generator



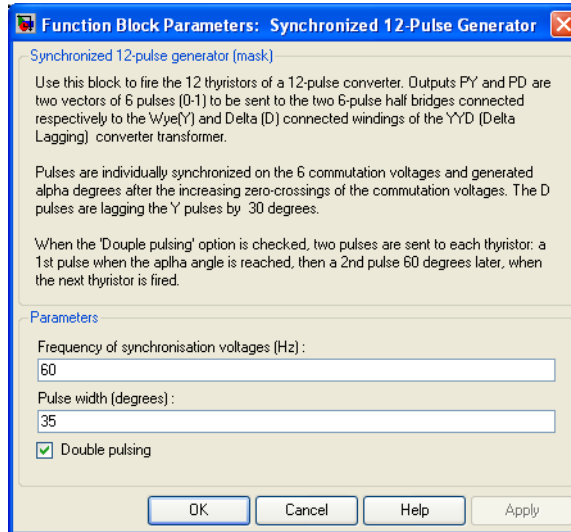
The phase-to-ground A,B, and C voltages are provided to the generator, and the two sets of phase-to-phase synchronization voltages required by the two six-pulse bridges are generated internally.

The ordering of the pulses in the two outputs of the block corresponds to the natural order of commutation of a three-phase thyristor bridge. When you connect the Synchronized 12-Pulse Generator block outputs to the pulse inputs of the Universal Bridge blocks (with the thyristor device), the pulses are sent to the thyristors in the following way:

# Synchronized 12-Pulse Generator



## Dialog Box and Parameters



### Frequency of synchronization voltages

The frequency, in hertz, of the synchronization voltages. It usually corresponds to the frequency of the network.

### Pulse width

The width of the pulses, in degrees.

### Double pulsing

If selected, the generator sends to each thyristor a first pulse when the alpha angle is reached, and then a second pulse 60 degrees later when the next thyristor in the sequence is fired. The double pulsing is applied separately on the two vectors of pulses.

# Synchronized 12-Pulse Generator

---

## Inputs and Outputs

alpha\_deg

Input 1 is the alpha firing signal, in degrees. This input can be connected to a Constant block, or it can be connected to a controller system to control the pulses of the generator.

A, B, C

Inputs 2, 3, and 4 are the phase-to-ground synchronization voltages  $V_a$ ,  $V_b$ , and  $V_c$ . The synchronization voltages should be measured at the primary side of the converter transformer.

Freq

Available only with the discrete version of the Synchronized 6-Pulse Generator. This input should be connected to a constant block containing the fundamental frequency, in hertz, or to a PLL tracking the frequency of the system.

block

Input 5 allows you to block the operation of the generator. The pulses are disabled when the applied signal is greater than zero.

PY

Output 1 contains the six-pulse signals to be sent to the six-pulse thyristor converter connected to the Y secondary winding of the converter transformer.

PD

Output 2 contains the six-pulse signals to be sent to the six-pulse thyristor converter connected to the Delta (D) secondary winding of the converter transformer.

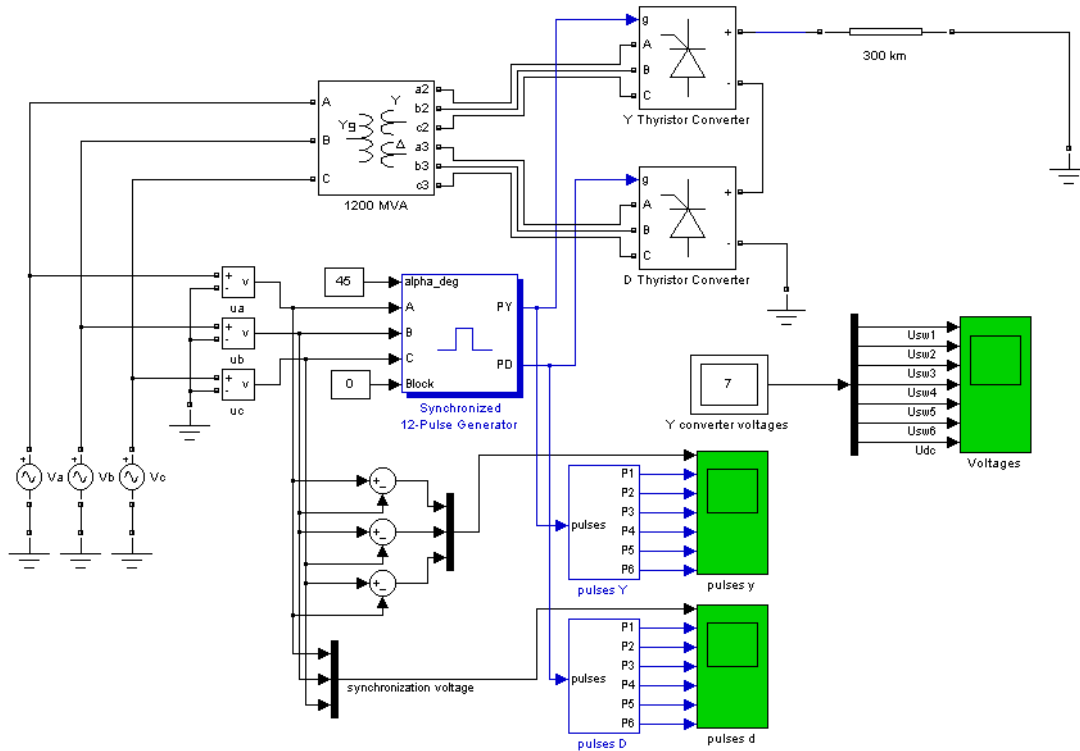
## Example

In the `power_twelvepulses` demo a Synchronized 12-Pulse Generator block is used to fire the thyristors of a twelve-pulse thyristor bridge built with two six-pulse bridges. The bridge is fed by a three-winding three-phase transformer (500 kV / 200 kV / 200 kV). The Y-connected secondary feeds the first six-pulse bridge. The Delta secondary feeds the second bridge. The transformer is assumed to be ideal (no leakage reactances, no resistance). The expected DC voltage obtained for  $\alpha = 0$  is

# Synchronized 12-Pulse Generator

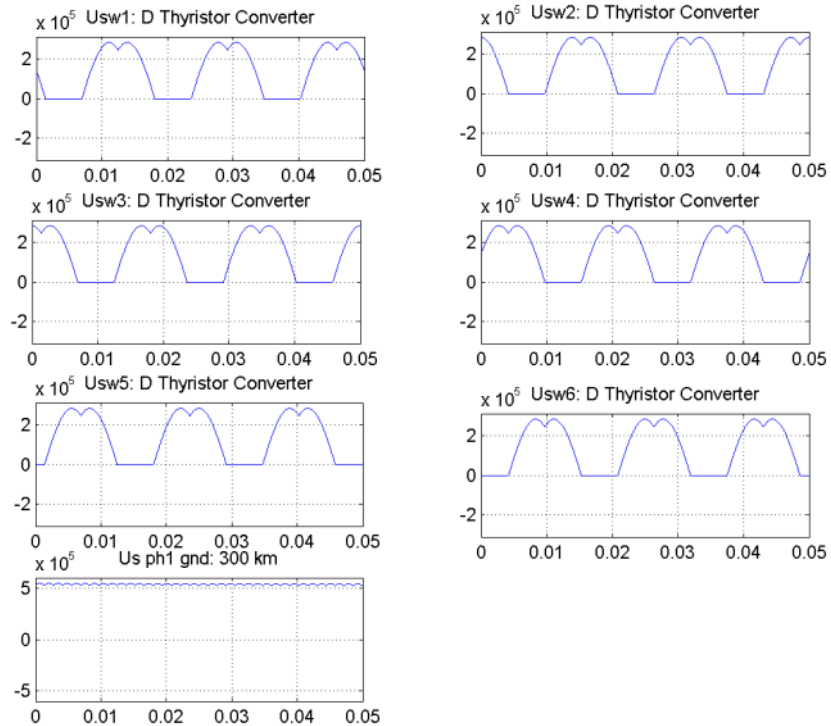
$$V_{dc} = 2 \frac{3\sqrt{2}}{\pi} 200 \text{ kV} = 540 \text{ kV}$$

The two bridge rectifiers are connected in series and a 300 km DC line is connected to the rectifier.



A first simulation is performed with an alpha angle of 0 degrees. Open the Constant block connected at input 1 of the Synchronized 12-Pulse Generator block and set its value to 0. Start the simulation. The voltages of the thyristors of the D thyristor Converter block are displayed in the next figure. The resulting DC voltage at the input terminal of the transmission line is also displayed (average value = 540 kV).

# Synchronized 12-Pulse Generator



Compare the DC voltage generated by the Synchronized 12-Pulse Generator with the DC voltage you obtained with the Synchronized 6-Pulse Generator. Notice that the ripple in the DC voltage waveform is lower. The rectifier voltage contains the harmonics  $12 \cdot k$  ( $k = 1, 2, \dots$ ).

## See Also

The `power_hvdc12pulse` demo illustrates the use of the Discrete Synchronized 12-Pulse Generator block.

Synchronized 6-Pulse Generator

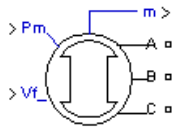
## Purpose

Model the dynamics of three-phase round-rotor or salient-pole synchronous machine

## Library

Machines

## Description

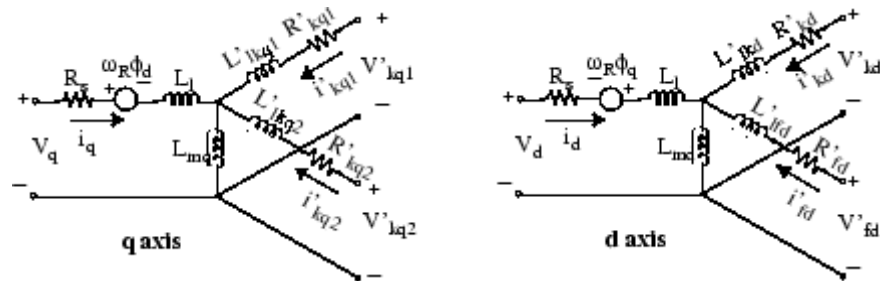


The Synchronous Machine block operates in generator or motor modes. The operating mode is dictated by the sign of the mechanical power (positive for generator mode, negative for motor mode). The electrical part of the machine is represented by a sixth-order state-space model and the mechanical part is the same as in the Simplified Synchronous Machine block.

The model takes into account the dynamics of the stator, field, and damper windings. The equivalent circuit of the model is represented in the rotor reference frame (qd frame). All rotor parameters and electrical quantities are viewed from the stator. They are identified by primed variables. The subscripts used are defined as follows:

- $d, q$ : d and q axis quantity
- $R, s$ : Rotor and stator quantity
- $l, m$ : Leakage and magnetizing inductance
- $f, k$ : Field and damper winding quantity

The electrical model of the machine is



with the following equations.

# Synchronous Machine

---

$$\begin{aligned}
 V_d &= R_s i_d + \frac{d}{dt} \Phi_d - \omega_R \Phi_q \\
 V_q &= R_s i_q + \frac{d}{dt} \Phi_q + \omega_R \Phi_d & \Phi_d &= L_d i_d + L_{md} (i'_{fd} + i'_{kd}) \\
 V'_{fd} &= R'_{fd} i'_{fd} + \frac{d}{dt} \Phi'_{fd} & \Phi_q &= L_q i_q + L_{mq} i'_{kq} \\
 V'_{kd} &= R'_{kd} i'_{kd} + \frac{d}{dt} \Phi'_{kd} & \Phi'_{fd} &= L'_{fd} i'_{fd} + L_{md} (i_d + i'_{kd}) \\
 V'_{kq1} &= R'_{kq1} i'_{kq1} + \frac{d}{dt} \Phi'_{kq1} & \Phi'_{kd} &= L'_{kd} i'_{kd} + L_{md} (i_d + i'_{fd}) \\
 V'_{kq2} &= R'_{kq2} i'_{kq2} + \frac{d}{dt} \Phi'_{kq2} & \Phi'_{kq1} &= L'_{kq1} i'_{kq1} + L_{mq} i_q \\
 & & \Phi'_{kq2} &= L'_{kq2} i'_{kq2} + L_{mq} i_q
 \end{aligned}$$

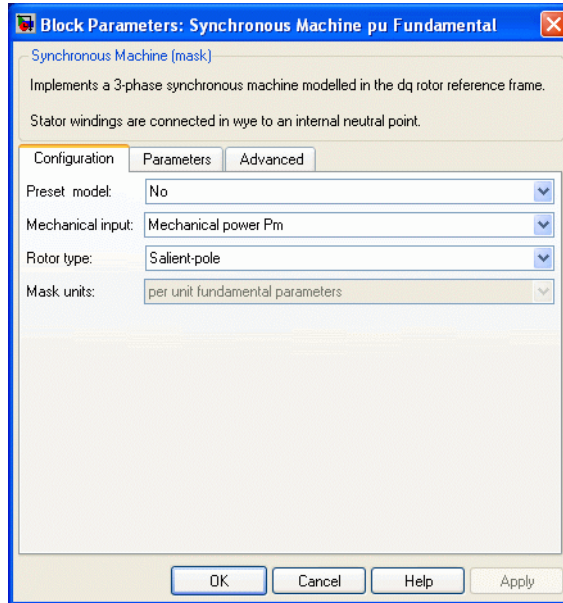
Note that this model assumes currents flowing into the stator windings. The measured stator currents returned by the Synchronous Machine block (Ia, Ib, Ic, Id, Iq) are the currents flowing out of the machine.

## Dialog Box and Parameters

In the **powerlib** library you can choose between three Synchronous Machine blocks to specify the parameters of the model. They simulate exactly the same synchronous machine model; the only difference is the way of entering the parameter units in the Parameters tab.



## Configuration Tab



### Preset model

Provides a set of predetermined electrical and mechanical parameters for various synchronous machine ratings of power (kVA), phase-to-phase voltage (V), frequency (Hz), and rated speed (rpm).

Select one of the preset models to load the corresponding electrical and mechanical parameters in the entries of the dialog box. Select No if you do not want to use a preset model.

### Mechanical input

Allows you to select either the torque applied to the shaft or the rotor speed as the Simulink signal applied to the block's input.

# Synchronous Machine

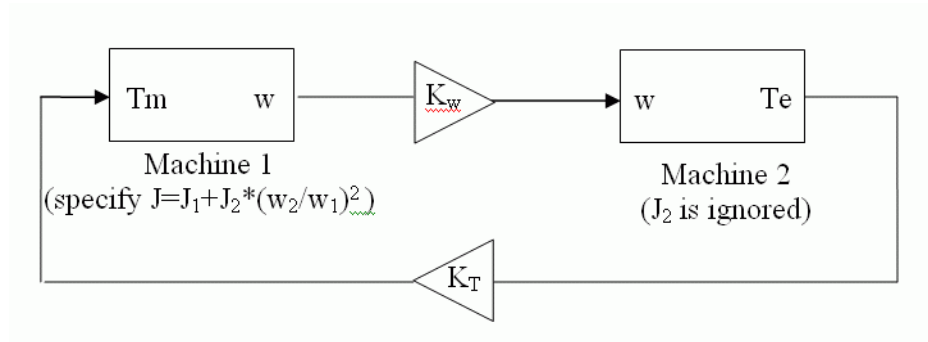
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Select **Mechanical power  $P_m$**  to specify a mechanical power input, in W or in pu, and change labeling of the block's input to  $P_m$ . The machine speed is determined by the machine Inertia  $J$  (or inertia constant  $H$  for the pu machine) and by the difference between the mechanical torque  $T_m$ , resulting from the the applied mechanical power  $P_m$ , and the internal electromagnetic torque  $T_e$ . The sign convention for the mechanical power is the following: when the speed is positive, a positive mechanical power signal indicates generator mode and a negative signal indicates motor mode.

Select **Speed  $w$**  to specify a speed input, in rad/s or in pu, and change labeling of the block's input to  $w$ . The machine speed is imposed and the mechanical part of the model (inertia constant  $H$ ) is ignored. Using the speed as the mechanical input allows modeling a mechanical coupling between two machines and interfacing with SimMechanics and SimDriveline models.

The next figure indicates how to model a stiff shaft interconnection in a motor-generator set, where both machines are synchronous machines.

The speed output of machine 1 (motor) is connected to the speed input of machine 2 (generator). In this figure friction torque is ignored in machine 2. Therefore, its electromagnetic torque output  $T_e$  corresponds to the mechanical torque  $T_m$  applied to the shaft of machine 1. The corresponding mechanical input power of machine 1 is computed as  $P_m = T_m * w$ . The  $K_w$  factor takes into account speed units of both machines (pu or rad/s) and gear box ratio  $w_2/w_1$ . The  $K_T$  factor takes into account torque units of both machines (pu or N.m) and machine ratings. Also, as the inertia  $J_2$  is ignored in machine 2,  $J_2$  referred to machine 1 speed must be added to machine 1 inertia  $J_1$ .



### Rotor type

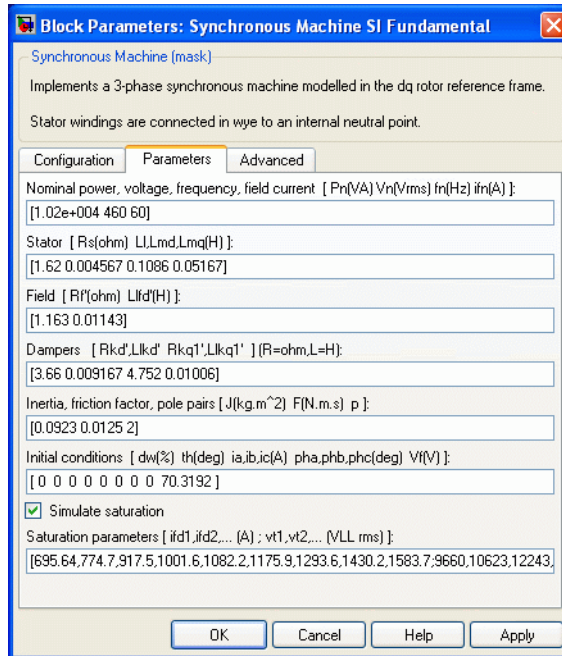
Specify rotor type: Salient-pole or Round (cylindrical). This choice affects the number of rotor circuits in the q-axis (damper windings).

### Mask units

Specifies the units of the electrical and mechanical parameters of the model. This parameter is not modifiable; it is provided for information purposes only.

# Synchronous Machine

## Parameters Tab for Synchronous Machine SI Fundamental



### Nominal power, voltage, frequency, field current

The total three-phase apparent power  $P_n$  (VA), RMS line-to-line voltage  $V_n$  (V), frequency  $f_n$  (Hz), and field current  $i_{fn}$  (A).

The nominal field current is the current that produces nominal terminal voltage under no-load conditions. This model was developed with all quantities viewed from the stator. The nominal field current makes it possible to compute the transformation ratio of the machine, which allows you to apply the field voltage viewed from the rotor, as in real life. This also allows the field current, which is a variable in the output vector of the model, to be viewed from the rotor. If the value of the nominal field current is not known, you must enter 0 or leave it blank. Since

the transformation ratio cannot be determined in this case, you have to apply the field voltage as viewed from the stator and the field current in the output vector is also viewed from the stator.

## **Stator**

The resistance  $R_s$  ( $\Omega$ ), leakage inductance  $L_{ls}$  (H), and d-axis and q-axis magnetizing inductances  $L_{md}$  (H) and  $L_{mq}$  (H).

## **Field**

The field resistance  $R_f$  ( $\Omega$ ) and leakage inductance  $L_{lfd}$  (H), both referred to the stator.

## **Dampers**

The d-axis resistance  $R_{kd}$  ( $\Omega$ ) and leakage inductance  $L_{lkd}$  (H), the q-axis resistance  $R_{kq1}$  ( $\Omega$ ) and leakage inductance  $L_{lkq1}$  (H), and (only if round rotor) the q-axis resistance  $R_{kq2}$  ( $\Omega$ ) and leakage inductance  $L_{lkq2}$  (H). All these values are referred to the stator.

## **Inertia, friction factor, pole pairs**

The inertia coefficient  $J$  ( $\text{kg}\cdot\text{m}^2$ ), friction factor  $F$  (N.m.s), and number of pole pairs  $p$ . The friction torque  $T_f$  is proportional to the rotor speed  $\omega$  ( $T_f = F\cdot\omega$ , where  $T_f$  is expressed in N.m,  $F$  in N.m.s, and  $\omega$  in rad/s).

## **Initial conditions**

The initial speed deviation  $\Delta\omega$  (% of nominal speed), electrical angle of the rotor  $\Theta_e$  (degrees), line current magnitudes  $i_a$ ,  $i_b$ ,  $i_c$  (A) and phase angles  $\text{pha}$ ,  $\text{phb}$ ,  $\text{phc}$  (degrees), and the initial field voltage  $V_f$  (V).

You can specify the initial field voltage in one of two ways. If you know the nominal field current (first line, last parameter), enter in the dialog box the initial field voltage in volts DC referred to the rotor. Otherwise, enter a zero as nominal field current, as explained earlier, and specify the initial field voltage in volts DC referred to the stator. You can determine the nominal field voltage viewed from the stator by selecting the **Display Vfd**

# Synchronous Machine

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which produces a nominal  $V_t$  check box at the bottom of the dialog box.

## **Simulate saturation**

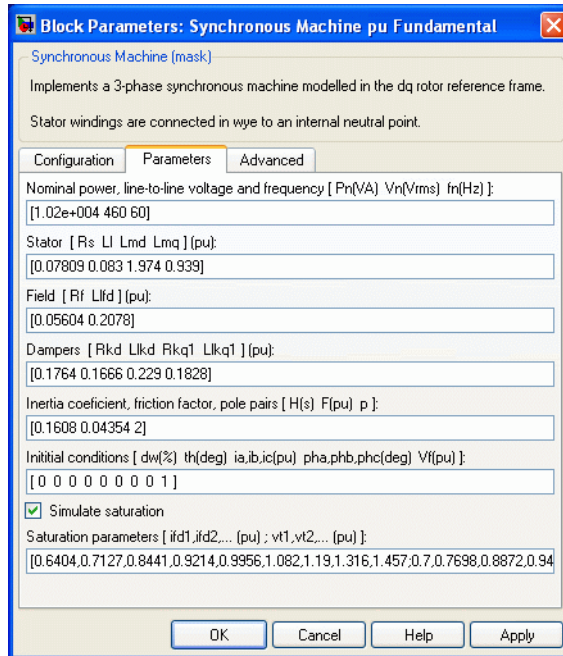
Specifies whether magnetic saturation of rotor and stator iron is to be simulated or not.

## **Saturation parameters**

The no-load saturation curve parameters. Magnetic saturation of stator and rotor iron is modeled by a nonlinear function (in this case a polynomial) using points on the no-load saturation curve. You must enter a 2-by-n matrix, where n is the number of points taken from the saturation curve. The first row of this matrix contains the values of field currents, while the second row contains values of corresponding terminal voltages. The first point (first column of the matrix) must correspond to the point where the effect of saturation begins.

You must select the **Simulate saturation** check box to simulate saturation. This check box allows you to enter the matrix of parameters for simulating the saturation. If you do not want to model saturation in your simulation, do not select the **Simulate saturation** check box. In this case the relationship between  $i_{fd}$  and  $V_t$  obtained is linear (no saturation).

## Parameters Tab for Synchronous Machine pu Fundamental



### Nominal power, line-to-line voltage, and frequency

Total three-phase apparent power (VA), RMS line-to-line voltage (V), frequency (Hz), and field current (A).

This line is identical to the first line of the fundamental parameters in SI dialog box, except that you do not specify a nominal field current. This value is not required here because we do not need the transformation ratio. Since rotor quantities are viewed from the stator, they are converted to pu using the stator base quantities derived from the preceding three nominal parameters.

# Synchronous Machine

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## **Stator; Field; Dampers**

Contain exactly the same parameters as in the previous dialog box, but they are expressed here in pu instead of SI units.

## **Inertia coefficient, friction factor, pole pairs**

The inertia constant  $H$  (s), where  $H$  is the ratio of energy stored in the rotor at nominal speed over the nominal power of the machine, the friction factor  $F$  (pu torque/pu speed), and the number of pole pairs  $p$ . The friction torque  $T_f$  is proportional to the rotor speed  $\omega$  ( $T_f = F \cdot \omega$ , where all quantities are expressed in pu).

## **Initial conditions; Simulate saturation; Saturation parameters**

The same initial conditions and saturation parameters as in the SI units dialog box, but all values are expressed in pu instead of SI units. For saturation, the nominal field current multiplied by the d-axis magnetizing inductance and nominal RMS line-to-line voltage are the base values for the field current and terminal voltage, respectively.



## Parameters Tab for Synchronous Machine pu Standard

The screenshot shows a software dialog box titled "Block Parameters: Synchronous Machine pu Standard". It has three tabs: "Configuration", "Parameters" (which is selected), and "Advanced". The dialog contains several input fields and dropdown menus for defining machine parameters. The "Parameters" tab includes fields for nominal power, voltage, and frequency; reactances; time constants (with dropdowns for "Short-circuit" or "Open-circuit"); stator resistance; inertia coefficient; and saturation parameters. A "Simulate saturation" checkbox is checked. The dialog also includes "OK", "Cancel", "Help", and "Apply" buttons at the bottom.

Synchronous Machine (mask)  
Implements a 3-phase synchronous machine modelled in the dq rotor reference frame.  
Stator windings are connected in wye to an internal neutral point.

Configuration Parameters Advanced

Nominal power, line-to-line voltage, frequency [ Pn(VA) Vn(Vrms) fn(Hz) ]:  
[1.02e+004 460 60]

Reactances [Xd Xd' Xd'' Xq Xq' Xl] (pu):  
[2.057 0.21 0.132 1.022 0.236 0.083]

d axis time constants: Short-circuit

q axis time constants: Short-circuit

Time constants [ Td' Td'' Tq'' ] (s):  
[0.012 0.003 0.003]

Stator resistance Rs (pu):  
0.003

Inertia coefficient, friction factor, pole pairs [ H(s) F(pu) p ]:  
[0.1608 0.04354 2]

Initial conditions [ dw(%) th(deg) ia,ib,ic(pu) pha,phb,phc(deg) Vf(pu) ]:  
[ 0 0 0 0 0 0 0 0 1 ]

Simulate saturation

Saturation parameters [ ifd1,ifd2,... (pu) ; vt1,vt2,... (pu) ]:  
[0.6404,0.7127,0.8441,0.9214,0.9956,1.082,1.19,1.316,1.457,0.7,0.7698,0.8872,0.94]

OK Cancel Help Apply

### Nominal power, line-to-line voltage, and frequency

The same parameters as in the pu Fundamental dialog box.

### Reactances

The d-axis synchronous reactance  $X_d$ , transient reactance  $X_d'$ , and subtransient reactance  $X_d''$ , the q-axis synchronous reactance  $X_q$ , transient reactance  $X_q'$  (only if round rotor), and subtransient reactance  $X_q''$ , and finally the leakage reactance  $X_l$  (all in pu).

### d-axis time constants; q-axis time constant(s)

Specify the time constants you supply for each axis: either open-circuit or short-circuit.

# Synchronous Machine

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## Time constants

The d-axis and q-axis time constants (all in s). These values must be consistent with choices made on the two previous lines: d-axis transient open-circuit ( $T_{do}'$ ) or short-circuit ( $T_d'$ ) time constant, d-axis subtransient open-circuit ( $T_{do}''$ ) or short-circuit ( $T_d''$ ) time constant, q-axis transient open-circuit ( $T_{qo}'$ ) or short-circuit ( $T_q'$ ) time constant (only if round rotor), q-axis subtransient open-circuit ( $T_{qo}''$ ) or short-circuit ( $T_q''$ ) time constant.

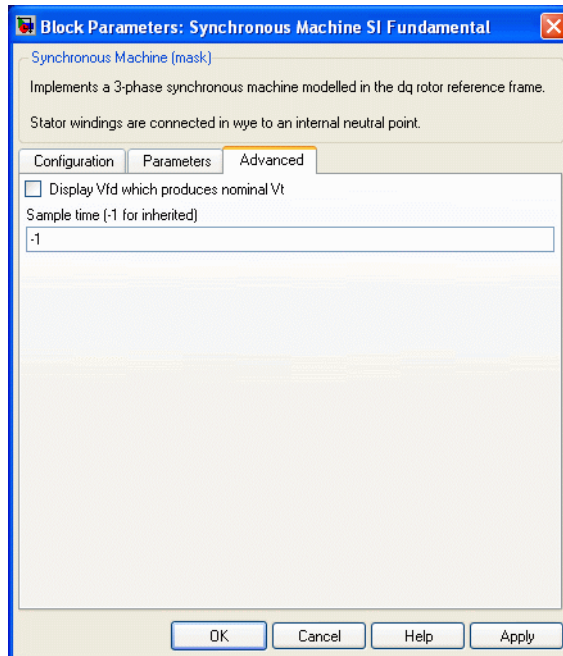
## Stator resistance

The stator resistance  $R_s$  (pu).

## Inertia coefficient, friction factor, pole pairs; Initial conditions; Simulate saturation; Saturation parameters

The same parameters as in the pu Fundamental dialog box.

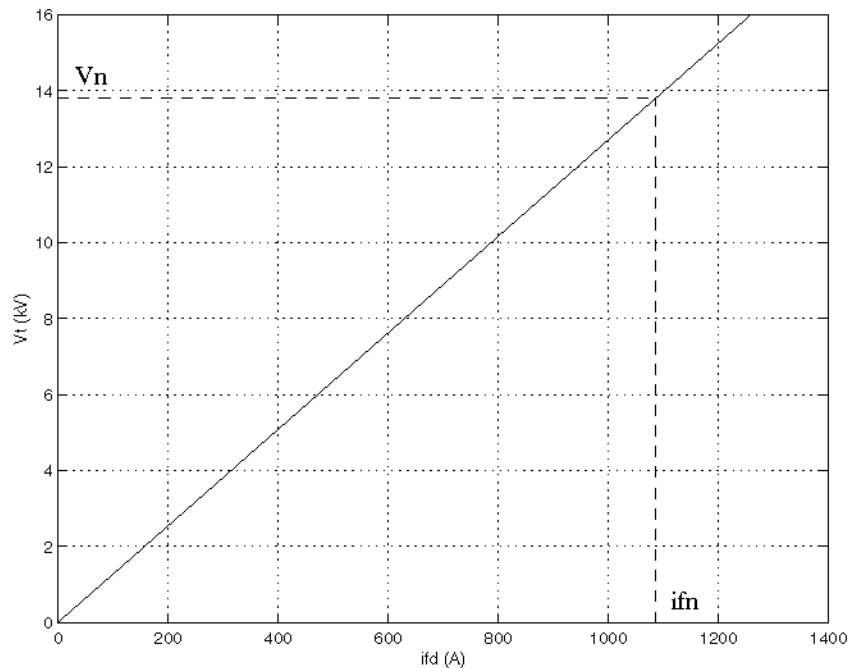
## Advanced Tab



## Display Vfd which produces a nominal Vt

Select to determine the nominal field voltage viewed from the stator. This parameter is visible only for the Synchronous Machine SI Fundamental block.

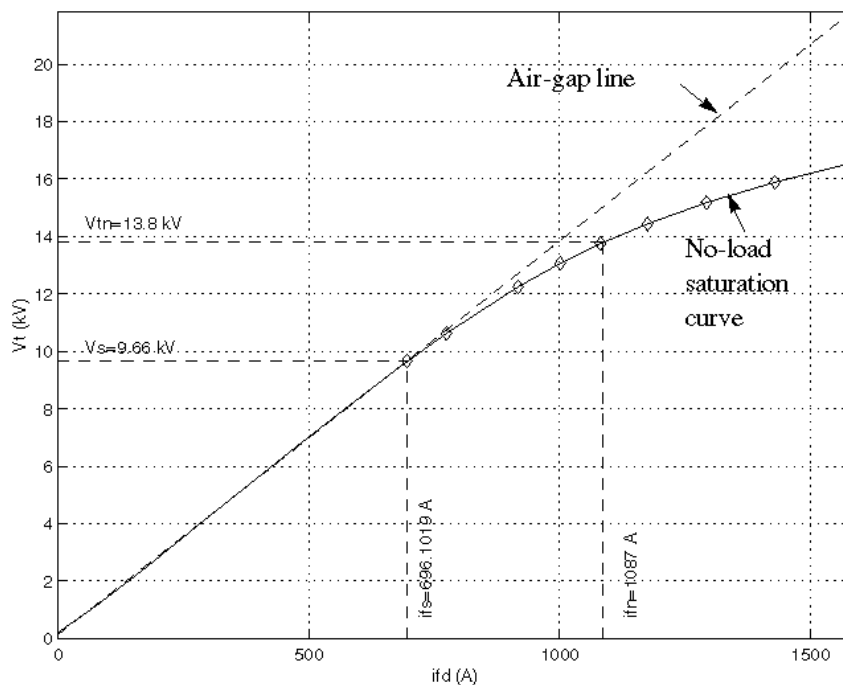
As an example, without saturation, a typical curve might be as shown below. Here  $if_n$  is 1087 A and  $V_n$  is 13800 V RMS line-to-line, which is also 11268 V peak line-to-neutral.



Saturation is modeled by fitting a polynomial to the curve corresponding to the matrix of points you enter. The more points you enter, the better the fit to the original curve.

# Synchronous Machine

The next figure illustrates the good fit graphically (the diamonds are the actual points entered in the dialog box).



In this particular case, the following values were used:

$i_{fn}$  1087 A  
 $i_{fd}$  [695.64, 774.7, 917.5, 1001.6, 1082.2, 1175.9, 1293.6, 1430.2, 1583.7] A  
 $V_t$  [9660, 10623, 12243, 13063, 13757, 14437, 15180, 15890, 16567] V

## Sample time (-1 for inherited)

Specifies the sample time used by the block. To inherit the sample time specified in the Powergui block, set this parameter to -1.

## Inputs and Outputs

The units of inputs and outputs vary according to which dialog box was used to enter the block parameters. If the fundamental parameters in SI units is used, the inputs and outputs are in SI units (except for  $d\omega$  in the vector of internal variables, which is always in pu, and angle  $\Theta$ , which is always in rad). Otherwise, the inputs and outputs are in pu.

$P_m$

The first Simulink input is the mechanical power at the machine's shaft. In generating mode, this input can be a positive constant or function or the output of a prime mover block (see the Hydraulic Turbine and Governor or Steam Turbine and Governor blocks). In motoring mode, this input is usually a negative constant or function.

$V_f$

The second Simulink input of the block is the field voltage. This voltage can be supplied by a voltage regulator in generator mode (see the Excitation System block). It is usually a constant in motor mode.

If you use the model in SI fundamental units, the field voltage  $V_f$  should be entered in volts DC if nominal field current  $I_{fn}$  is specified or in volts referred to stator if  $I_{fn}$  is not specified. To obtain the  $V_{fd}$  producing nominal voltage, select the last check box of the dialog box. If you use the model in pu Standard or in pu Fundamental units,  $V_f$  should be entered in pu (1 pu of field voltage producing 1 pu of terminal voltage at no load).

$m$

The Simulink output of the block is a vector containing 22 signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

# Synchronous Machine

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Signal	Definition	Units
1	Stator current is_a	A or pu
2	Stator current is_b	A or pu
3	Stator current is_c	A or pu
4	Stator current is_q	A or pu
5	Stator current is_d	A or pu
6	Field current ifd	A or pu
7	Damper winding current ikq1	A or pu
8	Damper winding current ikq2	A or pu
9	Damper winding current ikd	A or pu
10	Mutual flux phimq	V.s or pu
11	Mutual flux phimd	V.s or pu
12	Stator voltage vq	V or pu
13	Stator voltage vd	V or pu
14	Rotor angle deviation d_theta	rad
15	Rotor speed wm	rad/s.
16	Electrical power Pe	VA or pu
17	Rotor speed deviation dw	rad/s
18	Rotor mechanical angle theta	rad
19	Electromagnetic torque Te	N.m or pu
20	Load angle delta	N.m or pu
21	Output active power Peo	rad
22	Output reactive power Qeo	rad

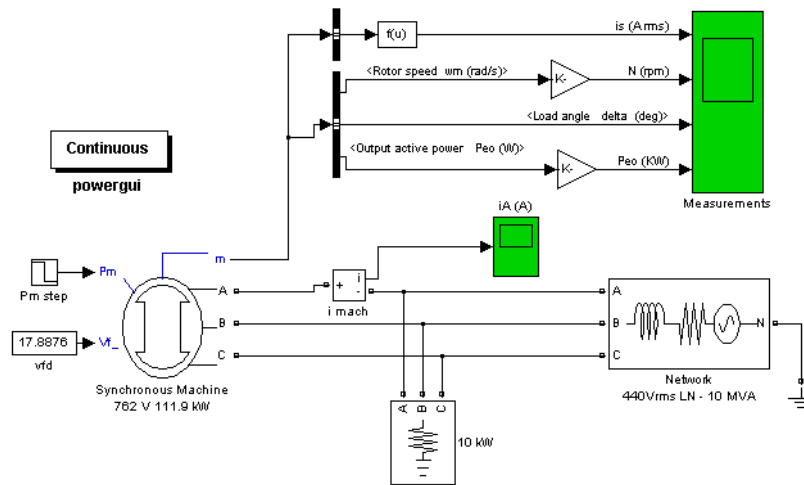
## Limitations

When you use Synchronous Machine blocks in discrete systems, you might have to use a small parasitic resistive load, connected at the machine terminals, in order to avoid numerical oscillations. Large sample times require larger loads. The minimum resistive load is proportional to the sample time. As a rule of thumb, remember that with a 25  $\mu\text{s}$  time step on a 60 Hz system, the minimum load is approximately 2.5% of the machine nominal power. For example, a 200 MVA synchronous machine in a power system discretized with a 50  $\mu\text{s}$  sample time requires approximately 5% of resistive load or 10 MW. If the sample time is reduced to 20  $\mu\text{s}$ , a resistive load of 4 MW should be sufficient.

## Example

The `power_syncmachine` demo illustrates the use of the Synchronous Machine block in motor mode. The simulated system consists of an industrial grade synchronous motor (150 HP (112 kVA), 762 V) connected to a network with a 10 MVA short-circuit level. In order to start simulation in steady state, the machine is initialized using the **Load Flow and Machine Initialization** option of the Powergui. The machine is initialized for an output electrical power of -50 kW (negative value for motor mode), corresponding to a mechanical power of -48.9 kW. The corresponding values of mechanical power and field voltage have been automatically entered by the **Load Flow** analysis into the Pm Step block and in the Vf Constant block. The Pm Step block has been programmed in order to apply a sudden increase of mechanical power from -48.9 kW to -60 kW at time  $t = 0.1$  s.

# Synchronous Machine



Run the simulation and observe the RMS current, RMS voltage, speed, load angle  $\delta$ , and output electrical power of the motor.

Since this is a four-pole machine, the nominal speed is 1800 rpm. The initial speed is 1800 rpm as prescribed. After the load has increased from 48.9 kW to 100 kW at  $t = 0.1$  s, the machine speed oscillates before stabilizing to 1800 rpm. The load angle (angle between terminal voltage and internal voltage) increases from -21 degrees to -53 degrees.

## References

[1] Krause, P.C., *Analysis of Electric Machinery*, McGraw-Hill, 1986, Section 12.5.

[2] Kamwa, I., et al., "Experience with Computer-Aided Graphical Analysis of Sudden-Short-Circuit Oscillograms of Large Synchronous Machines," *IEEE Transactions on Energy Conversion*, Vol. 10, No. 3, September 1995.

## See Also

Excitation System, Hydraulic Turbine and Governor, Powergui, Simplified Synchronous Machine, Steam Turbine and Governor



# Three-Level Bridge

## Purpose

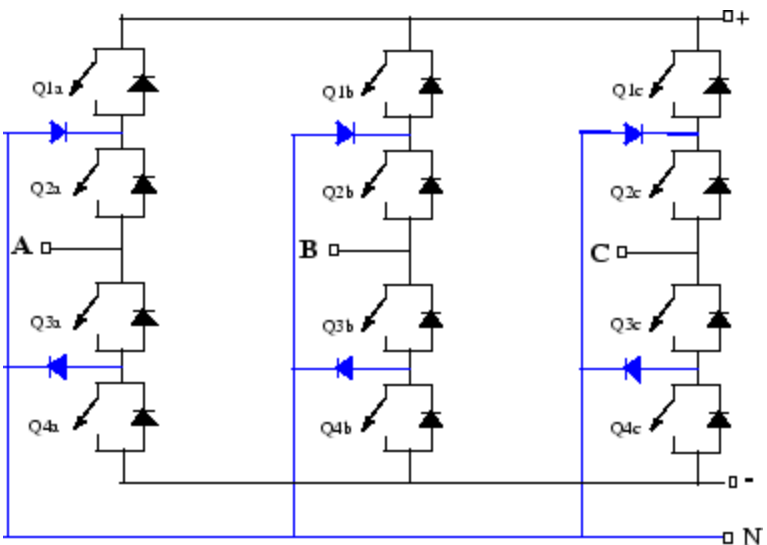
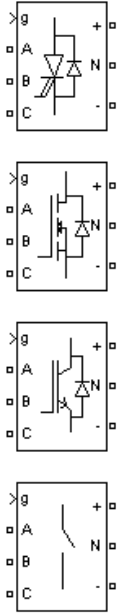
Implement three-level neutral point clamped (NPC) power converter with selectable topologies and power switching devices

## Library

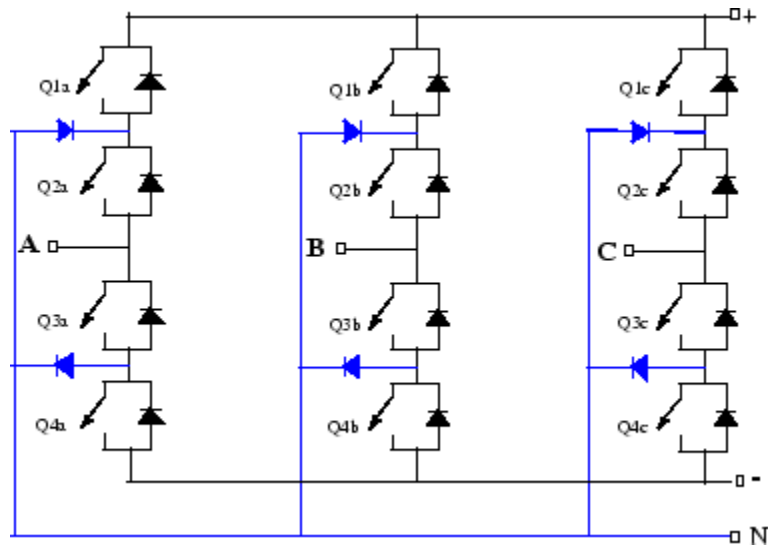
Power Electronics

## Description

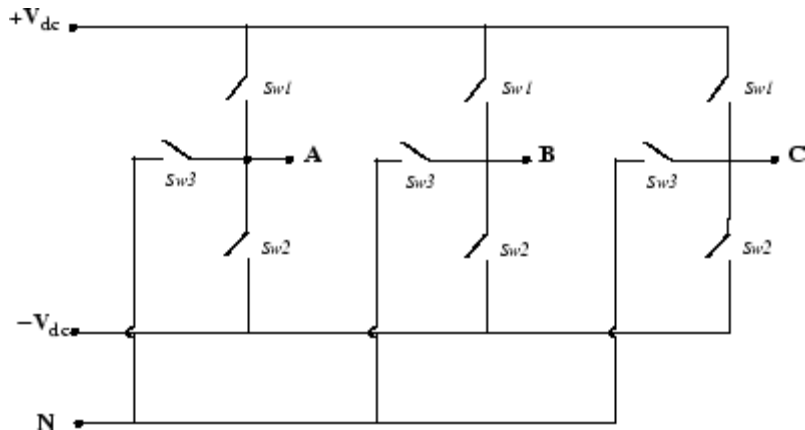
The Three-Level Bridge block implements a three-level power converter that consists of one, two, or three arms of power switching devices. Each arm consists of four switching devices along with their antiparallel diodes and two neutral clamping diodes as shown in the figure below.



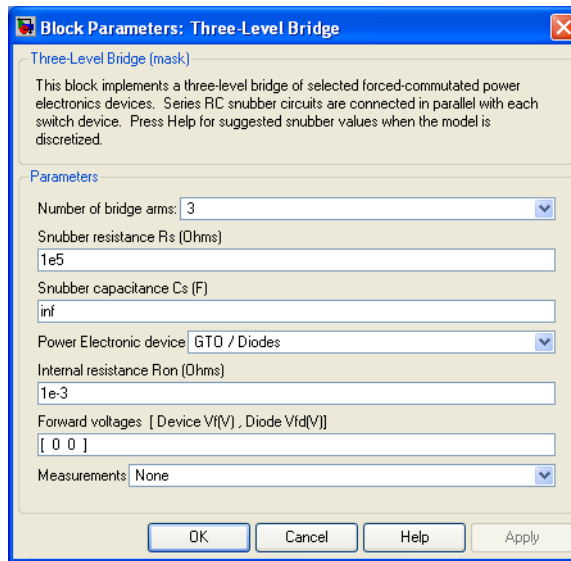
# Three-Level Bridge



The type of power switching device (IGBT, GTO, MOSFET, or ideal switch) and the number of arms (one, two, or three) are selectable from the dialog box. When the ideal switch is used as the switching device, the Three-Level Bridge block implements an ideal switch bridge having a three-level topology as shown.



## Dialog Box and Parameters



### Number of bridge arms

Determine the bridge topology: one, two, or three arms.

### Snubber resistance $R_s$

The snubber resistance, in ohms ( $\Omega$ ). Set the **Snubber resistance  $R_s$**  parameter to `inf` to eliminate the snubbers from the model.

### Snubber capacitance $C_s$

The snubber capacitance, in farads (F). Set the **Snubber capacitance  $C_s$**  parameter to 0 to eliminate the snubbers, or to `inf` to get a resistive snubber.

For forced-commutated devices (GTO, IGBT, or MOSFET) the Three-Level Bridge block operates satisfactorily with resistive snubbers as long as the firing pulses are sent to the switching devices.

If the firing pulses to forced-commutated devices are blocked, the bridge operates as a diode rectifier. In this condition, you must

# Three-Level Bridge

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use appropriate values of  $R_s$  and  $C_s$ . If the model is discretized, you can use the following formulas to compute approximate values of  $R_s$  and  $C_s$ :

$$R_s > 2 \frac{T_s}{C_s}$$

$$C_s < \frac{P_n}{1000(2\pi f)V_n^2}$$

where

$P_n$  = Nominal power of single- or three-phase converter (VA)

$V_n$  = Nominal line-to-line AC voltage (V<sub>rms</sub>)

$f$  = Fundamental frequency (Hz)

$T_s$  = Sample Time (s)

These  $R_s$  and  $C_s$  values are derived from the following two criteria:

- The snubber leakage current at fundamental frequency is less than 0.1% of nominal current when power electronic devices are not conducting.
- The RC time constant of snubbers is higher than two times the sample time  $T_s$ .

Note that the  $R_s$  and  $C_s$  values that guarantee numerical stability of the discretized bridge can be different from actual values used in the physical circuit.

## **Power electronic device**

Select the type of power electronic device to use in the bridge.

## **Internal resistance $R_{on}$**

Internal resistance of the selected devices and diodes, in ohms ( $\Omega$ ).

## Forward voltages [Device Vf, Diode Vfd]

The forward voltage of the selected devices (for GTO or IGBT only) and of the antiparallel and clamping diodes, in volts.

## Measurements

Select **All Device currents** to measure the current flowing through all the components (switching devices and diodes). If the snubber devices are defined, the measured currents are those flowing through the power electronic devices only.

Select **Phase-to-neutral** and **DC voltages** to measure the terminal voltages (AC and DC) of the Three-Level Bridge block.

Select **All voltages** and **currents** to measure all voltages and currents defined for the Three-Level Bridge block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurement** list box of the Multimeter block, the measurement is identified by a label followed by the block name.

Measurement	Label (for GTO, IGBT, MOSFET Devices)
Device currents	IQ1a, IQ2a, IQ3a, IQ4a, IQ1b, IQ2b, IQ3b, IQ4b, IQ1c, IQ2c, IQ3c, IQ4c, ID1a, ID2a, ID3a, ID4a, ID5a, ID6a, ID1b, ID2b, ID3b, ID4b, ID5b, ID6b, ID1c, ID2c, ID3c, ID4c, ID5c, ID6c
Terminal voltages	Uan:, Ubn:, Ucn:, Udc+:, Udc-:

# Three-Level Bridge

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Measurement	Label (for Ideal Switch Device)
Device currents	Isw1a, Isw2a, Isw3a, Isw1b, Isw2b, Isw3b, Isw1c, Isw2c, Isw3c
Terminal voltages	Uan:, Ubn:, Ucn:, Udc+:, Udc-:

## Inputs and Outputs

The input *g* is a vectorized gating signal containing pulses to control the power electronic devices of the bridge. The length of the input vector depends on the number of arm you specified for the bridge topology.

Topology	Pulse Vector of Input <i>g</i>
One arm	[Q1a, Q2a, Q3a, Q4a]
Two arms	[Q1a, Q2a, Q3a, Q4a, Q1b, Q2b, Q3b, Q4b]
Three arms	[Q1a, Q2a, Q3a, Q4a, Q1b, Q2b, Q3b, Q4b, Q1c, Q2c, Q3c, Q4c]

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**Note** In the case of the ideal switch converter, the Q1 pulse is sent to Sw1, the Q4 pulse to Sw2, and a logical AND operation is performed on the Q2 and Q3 pulses and the result sent to Sw3.

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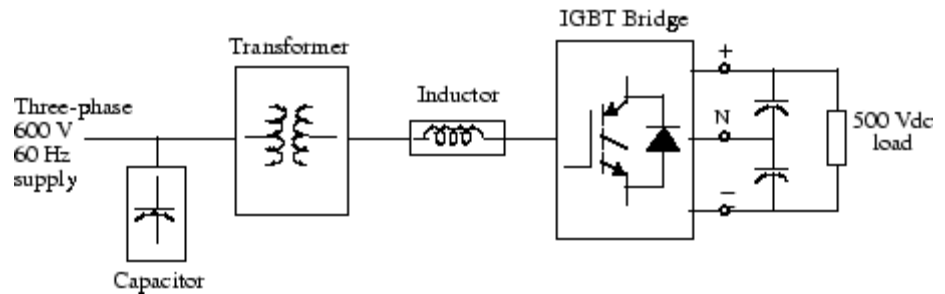
## Assumptions and Limitations

Turn-on and turn-off times (Fall time, Tail time) of power switching devices are not modeled in the Three-Level Bridge block.

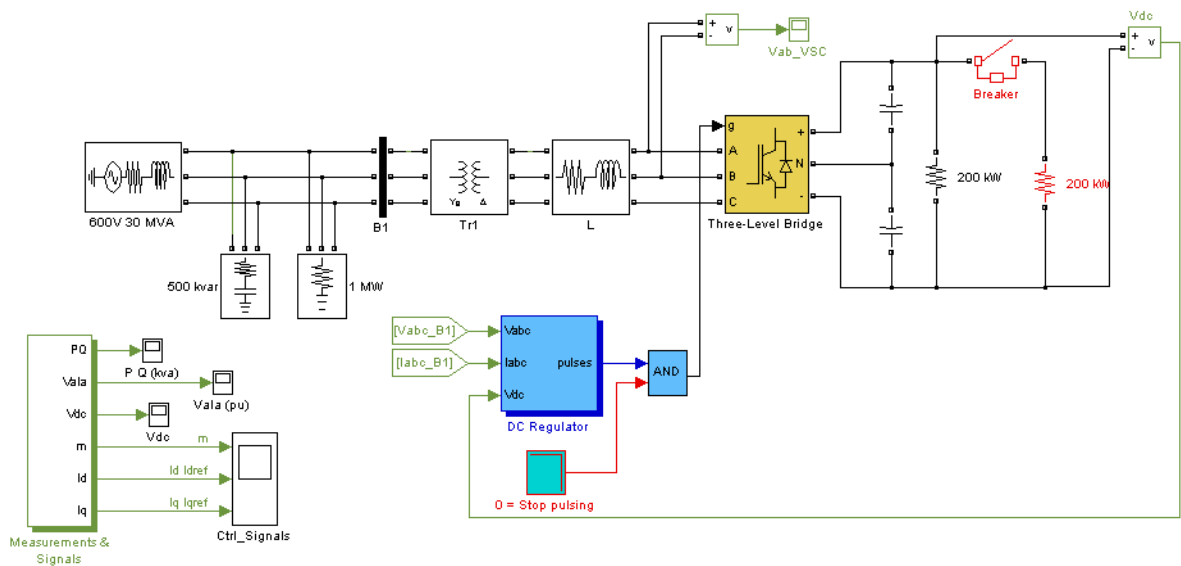
## Example

The power\_3levelVSC demo illustrates the use of the Three-Level Bridge block in an AC-DC converter consisting of a three-phase IGBT-based voltage sourced converter (VSC). The converter is pulse-width modulated (PWM) to produce a 500 V DC voltage (+/- 250 V). In this example, the converter chopping frequency is 1620 Hz and the power system frequency is 60 Hz.

# Three-Level Bridge



The VSC is controlled in a closed loop by two PI regulators in order to maintain a DC voltage of 500 V at the load while maintaining a unity input power factor for the AC supply.



The initial conditions for a steady-state simulation are generated by running an initial simulation to steady state for an integer number of cycles of 60 Hz. The final states (both SimPowerSystems and Simulink controller states) are saved in a vector called `xInitial`. This vector, as

## Three-Level Bridge

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well as the sample times ( $Ts\_Power$  and  $Ts\_Control$ ) are saved in the `power_3levelVSC_xinit.mat` file.

When you open this model, the initial condition vector `xInitial` and the sample times saved in the MAT file are automatically loaded in the workspace. Start the simulation. The monitored signals start in steady state.

Observe the following signals:

- The DC voltage (Vdc Scope block)
- The primary voltage and current of phase A of the AC supply (VaIa Scope block)
- The device currents of leg A of the IGBT bridge (Ia\_Devices Scope block inside the Measurements & Signals subsystem)
- The line-to-line terminal voltage of the VSC (Vab\_VSC Scope block)

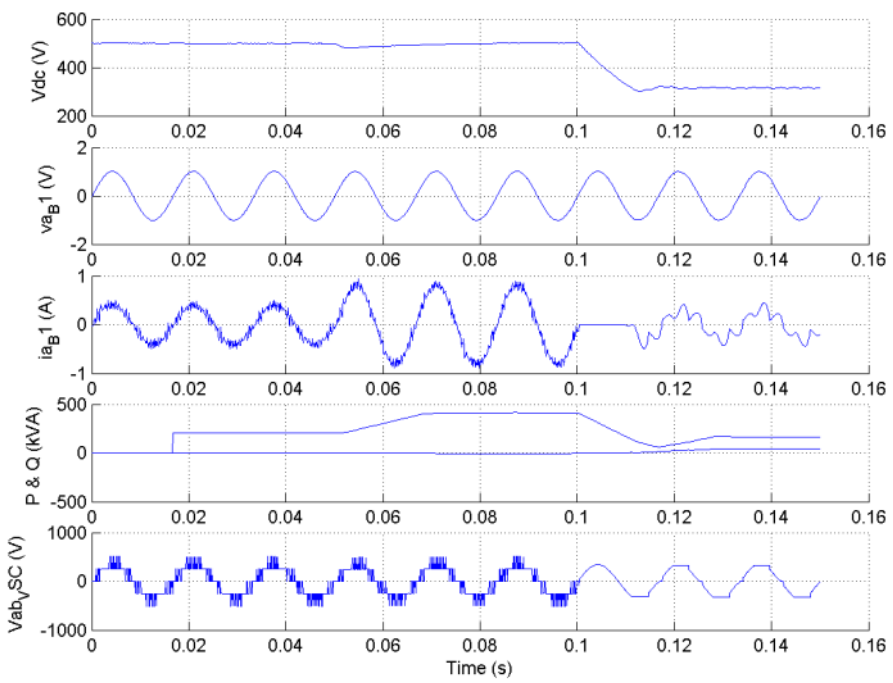
At 50 ms, a 200 kW load is switched in. You can see that the dynamic response of the DC regulator to the sudden load variation from 200 kW to 400 kW is satisfactory. The DC voltage reverts to 500 V within 2 cycles and the unity power factor on the AC side is maintained.

At 100 ms, a *stop-pulsing* signal is activated and the pulses normally sent to the converter are blocked. You can see that the DC voltage drops to 315 V. A drastic change in the primary current waveform can also be observed. When the pulses are blocked, the Three-Level Bridge block operation becomes similar to a three-phase diode bridge.

The following two figures summarize the results of the simulation. The first figure shows the operation of the AC-DC converter during the load variation and when the pulses are blocked.

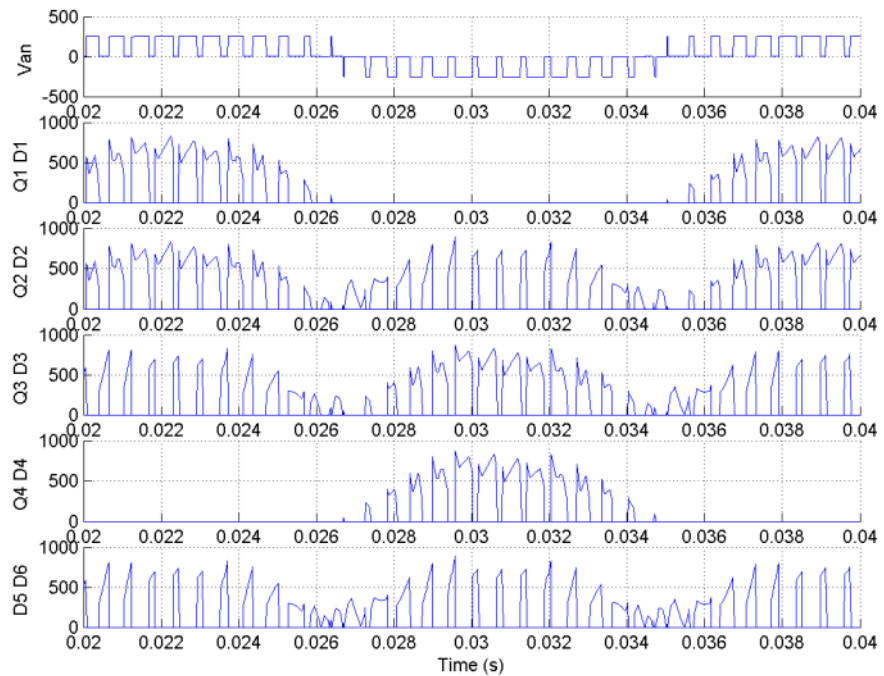


# Three-Level Bridge



The second figure shows the current flowing in the various devices of the IGBT bridge when the converter is feeding 500 Vdc to a 200-kW load.

# Three-Level Bridge



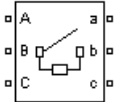
**See Also**

Multimeter

**Purpose** Implement three-phase circuit breaker opening at current zero crossing

**Library** Elements

## Description



The Three-Phase Breaker block implements a three-phase circuit breaker where the opening and closing times can be controlled either from an external Simulink signal (external control mode), or from an internal control timer (internal control mode).

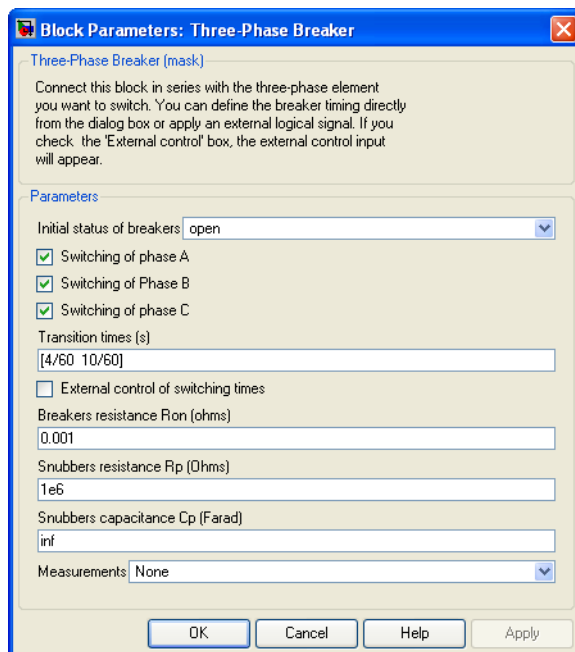
The Three-Phase Breaker block uses three Breaker blocks connected between the inputs and the outputs of the block. You can use this block in series with the three-phase element you want to switch. See the Breaker block reference pages for details on the modeling of the single-phase breakers.

If the Three-Phase Breaker block is set in external control mode, a control input appears in the block icon. The control signal connected to this input must be either 0 or 1, 0 to open the breakers, 1 to close them. If the Three-Phase Breaker block is set in internal control mode, the switching times are specified in the dialog box of the block. The three individual breakers are controlled with the same signal.

Series Rs-Cs snubber circuit are included in the model. They can be optionally connected to the three individual breakers. If the Three-Phase Breaker block happens to be in series with an inductive circuit, an open circuit or a current source, you must use the snubbers.

# Three-Phase Breaker

## Dialog Box and Parameters



### Initial status of breakers

The initial status of the breakers. The initial status is the same for the three breakers. Depending on the initial status, the icon shows a closed contact or an open contact.

### Switching of phase A

If selected, the switching of phase A is activated. If not selected, the breaker of phase A stays in its initial status specified in the **Initial status of breakers** parameter.

### Switching of Phase B

If selected, the switching of phase B is activated. If not selected, the breaker of phase B stays in its initial status specified in the **Initial status of breakers** parameter.

## Switching of phase C

If selected, the switching of phase C is activated. If not selected, the breaker of phase C stays in its initial status specified in the **Initial status of breakers** parameter.

## Transition times(s)

The **Transition times(s)** parameter is not visible in the dialog box if the **External control of switching times** parameter is selected.

Specify the vector of switching times when using the Three-Phase Breaker block in internal control mode. At each transition time the selected breakers opens or closes depending to their initial state.

## External control of switching times

If selected, adds a fourth input port to the Three-Phase Breaker block for an external control of the switching times of the breakers. The switching times are defined by a Simulink signal (0-1 sequence).

## Breakers resistance **Ron**

The internal breaker resistances, in ohms ( $\Omega$ ). The **Breaker resistance **Ron**** parameter cannot be set to 0.

## Snubbers resistance **Rp**

The snubber resistances, in ohms ( $\Omega$ ). Set the **Snubber resistance **Rp**** parameter to `inf` to eliminate the snubbers from the model.

## Snubbers capacitance **Cp**

The snubber capacitances, in farads (F). Set the **Snubber capacitance **Cp**** parameter to 0 to eliminate the snubbers, or to `inf` to get resistive snubbers.

## Measurements

Select **Breaker voltages** to measure the voltage across the three internal breaker terminals.

# Three-Phase Breaker

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Select **Breaker currents** to measure the current flowing through the three internal breakers. If the snubber devices are connected, the measured currents are the ones flowing through the breakers contacts only.

Select **Breaker voltages and currents** to measure the breaker voltages and the breaker currents.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurements is identified by a label followed by the block name and the phase:

Measurement Label	
Breaker voltages	Ub <block name> /Breaker A: Ub <block name> /Breaker B: Ub <block name> /Breaker C.
Breaker currents	Ib <block name> /Breaker A: Ib <block name> /Breaker B: Ib <block name> Breaker C.

## Inputs and Outputs

If the Three-Phase Breaker block is set in external control mode, a Simulink input is added to the block to control the opening and closing of the three internal breakers.

## Example

See the `power_3ph1inereclose` and `power_3phseriescomp` demos for circuits using the Three-Phase Breaker block.

## See Also

Breaker, Multimeter, Three-Phase Fault

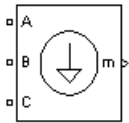
## Purpose

Implement three-phase dynamic load with active power and reactive power as function of voltage or controlled from external input

## Library

Elements

## Description



The Three-Phase Dynamic Load block implements a three-phase, three-wire dynamic load whose active power  $P$  and reactive power  $Q$  vary as function of positive-sequence voltage. Negative- and zero-sequence currents are not simulated. The three load currents are therefore balanced, even under unbalanced load voltage conditions.

The load impedance is kept constant if the terminal voltage  $V$  of the load is lower than a specified value  $V_{min}$ . When the terminal voltage is greater than the  $V_{min}$  value, the active power  $P$  and reactive power  $Q$  of the load vary as follows:

$$P(s) = P_o \left( \frac{V}{V_o} \right)^{n_p} \frac{(1 + T_{p1}s)}{(1 + T_{p2}s)}$$

$$Q(s) = Q_o \left( \frac{V}{V_o} \right)^{n_q} \frac{(1 + T_{q1}s)}{(1 + T_{q2}s)}$$

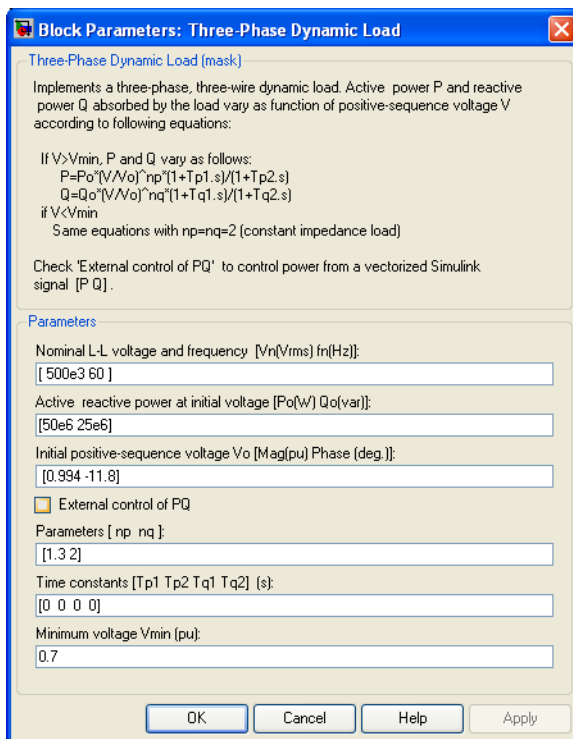
where

- $V_o$  is the initial positive sequence voltage.
- $P_o$  and  $Q_o$  are the initial active and reactive powers at the initial voltage  $V_o$ .
- $V$  is the positive-sequence voltage.
- $n_p$  and  $n_q$  are exponents (usually between 1 and 3) controlling the nature of the load.
- $T_{p1}$  and  $T_{p2}$  are time constants controlling the dynamics of the active power  $P$ .
- $T_{q1}$  and  $T_{q2}$  are time constants controlling the dynamics of the reactive power  $Q$ .

# Three-Phase Dynamic Load

For a constant current load, for example, you set  $n_p$  to 1 and  $n_q$  to 1, and for constant impedance load you set  $n_p$  to 2 and  $n_q$  to 2.

## Dialog Box and Parameters



### Nominal L-L voltage and frequency

Specifies the nominal phase-to-phase voltage, in volts RMS, and nominal frequency, in hertz, of the load.

### Active and reactive power at initial voltage

Specifies the initial active power  $P_0$ , in watts, and initial reactive power  $Q_0$ , in vars, at the initial voltage  $V_0$ . If the load flow utility of the Powergui is used to initialize the dynamic load and start simulation in steady state, these parameters are automatically updated according to  $P$  and  $Q$  set points specified for the load.



## Initial positive-sequence voltage $V_o$

Specifies the magnitude and phase of the initial positive-sequence voltage of the load. If the load flow utility of the Powergui is used to initialize the dynamic load and start simulation in steady state, these two parameters are automatically updated according to values computed by the load flow.

## External control of PQ

If selected, the active power and reactive power of the load are defined by an external Simulink vector of two signals.

## Parameters [np nq]

Specifies the **np** and **nq** parameters that define the nature of the load.

## Time constants [Tp1 Tp2 Tq1 Tq2]

Specifies the time constants controlling the dynamics of the active power and the reactive power.

## Minimum voltage $V_{min}$

Specifies the minimum voltage at which the load dynamics commences. The load impedance is constant below this value.

## Inputs and Outputs

If **External control of PQ** is selected, a Simulink input, labeled PQ, appears. This input is used to control the active and reactive powers of the load from a vector of two signals [P, Q].

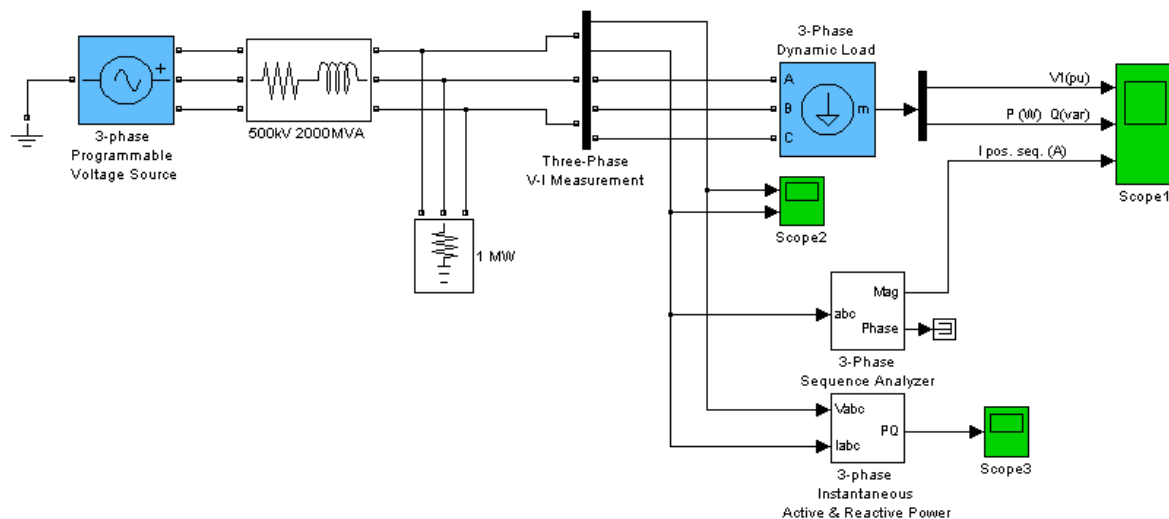
The m output is a vector containing the following three signals: positive-sequence voltage (pu); active power P (W); and reactive power Q (vars).

## Example

The power\_dynamicload model uses a Three-Phase Dynamic Load block connected on a 500 kV, 60 Hz power network. The network is simulated by its Thevenin equivalent (voltage source behind a R-L impedance corresponding to a three-phase short-circuit level of 2000 MVA). The source internal voltage is modulated in order to simulate voltage variation during a power swing. As the dynamic load is a nonlinear model simulated by current sources, it cannot be connected to

# Three-Phase Dynamic Load

an inductive network (R-L in series). Therefore, a small resistive load (1 MW) has been added in parallel with the dynamic load.



In order to start the simulation in steady state, you must specify the correct initial positive-sequence voltage  $V_0$  (magnitude and phase) corresponding to the desired  $P_0$  and  $Q_0$  values. You use the load flow utility to find this voltage and initialize the dynamic load. Open the Powergui and select **Load Flow and Machine Initialization**. Specify the desired active power and reactive powers for the dynamic load (50 MW, 25 Mvar):

$$\text{Active Power} = 50e6; \text{Reactive Power} = 25e6$$

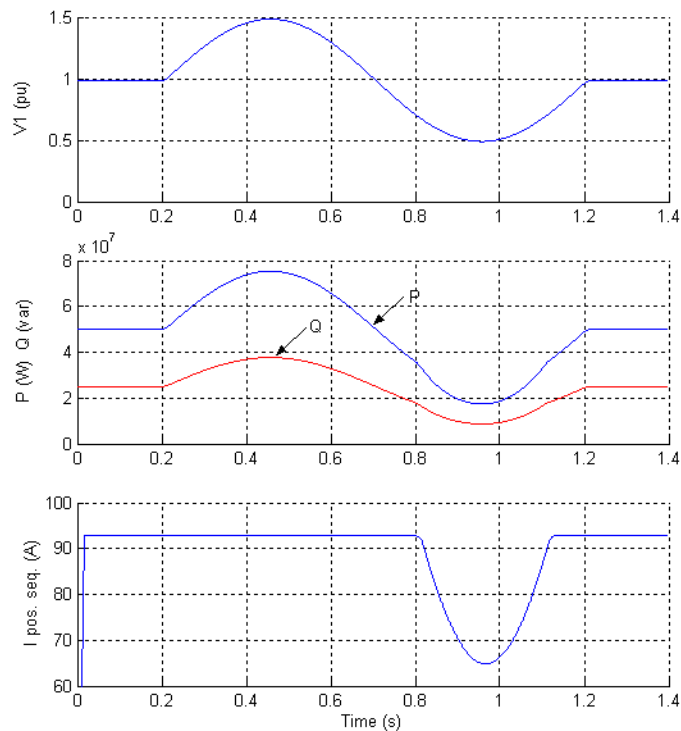
Then press the **Update Load Flow** button. Once the load flow has been solved the three phase-to-phase voltages of the dynamic load (0.9844 pu) as well as its line currents are displayed. The phase angle of the phase-to-neutral load voltage  $U_{an}$  is also displayed (-1.41 degrees). This angle corresponds to the angle of the positive-sequence voltage. If you now open the Three-Phase Dynamic Load dialog box, notice that the values of  $P_0$ ,  $Q_0$ , and  $V_0$  have been updated.

# Three-Phase Dynamic Load

Start the simulation and observe load voltage, P&Q powers, and current on Scope1. Observe that simulation starts in steady state. At  $t = 0.2$  s, when voltage modulation is initiated, P and Q start to increase (trace 2), but, as  $n_p$  and  $n_q$  are set to 1, the load current (trace 3) stays constant. When voltage falls below 0.7 pu the load behaves as a constant impedance. Therefore load current follows this voltage variation.

Observe on Scope2 variations of instantaneous voltages and currents. Also, notice that computed P and Q displayed on Scope3 are the same as P and Q internal signals returned by the Dynamic Load measurement output.

The signals displayed on the Scope1 block are shown below.



# Three-Phase Fault

## Purpose

Implement programmable phase-to-phase and phase-to-ground fault breaker system

## Library

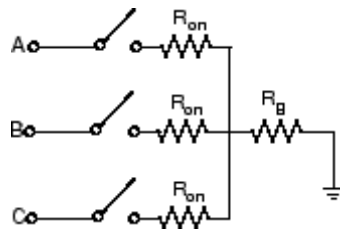
Elements

## Description



The Three-Phase Fault block implements a three-phase circuit breaker where the opening and closing times can be controlled either from an external Simulink signal (external control mode), or from an internal control timer (internal control mode).

The Three-Phase Fault block uses three Breaker blocks that can be individually switched on and off to program phase-to-phase faults, phase-to-ground faults, or a combination of phase-to-phase and ground faults.



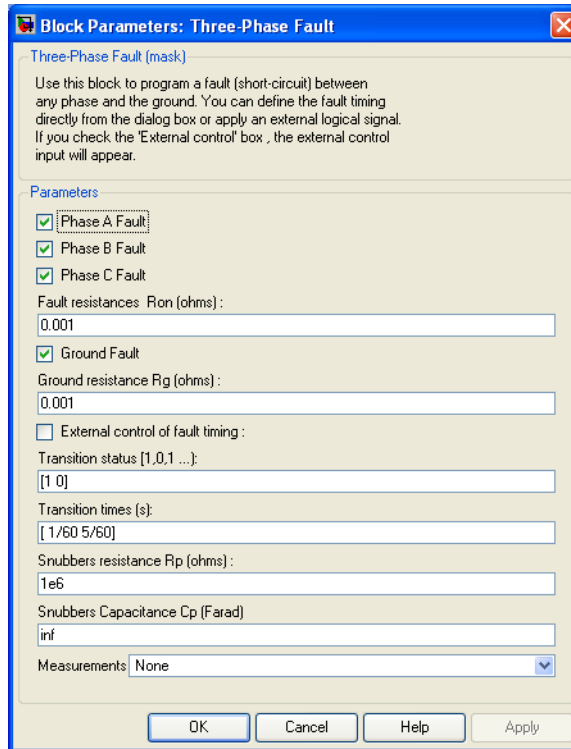
The ground resistance  $R_g$  is automatically set to  $10^6$  ohms when the ground fault option is not programmed. For example, to program a fault between the phases A and B you need to select the **Phase A Fault** and **Phase B Fault** block parameters only. To program a fault between the phase A and the ground, you need to select the **Phase A Fault** and **Ground Fault** parameters and specify a small value for the ground resistance.

If the Three-Phase Fault block is set in external control mode, a control input appears in the block icon. The control signal connected to the fourth input must be either 0 or 1, 0 to open the breakers, 1 to close them. If the Three-Phase Fault block is set in internal control mode, the switching times and status are specified in the dialog box of the block.

Series Rp-Cp snubber circuits are included in the model. They can be optionally connected to the fault breakers. If the Three-Phase Fault

block is in series with an inductive circuit, an open circuit or a current source, you must use the snubbers.

## Dialog Box and Parameters



### Phase A Fault

If selected, the fault switching of phase A is activated. If not selected, the breaker of phase A stays in its initial status. The initial status of the phase A breaker corresponds to the complement of the first value specified in the vector of **Transition status**. The initial status of the fault breaker is usually 0 (open). However, it is possible to start a simulation in steady state with the fault initially applied on the system. For example, if the first value in the **Transition status** vector is 0, the phase A

# Three-Phase Fault

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breaker is initially closed. It opens at the first time specified in the **Transition time(s)** vector.

## Phase B Fault

If selected, the fault switching of phase B is activated. If not selected, the breaker of phase B stays in its initial status. The initial status of the phase B breaker corresponds to the complement of the first value specified in the vector of **Transition status**.

## Phase C Fault

If selected, the fault switching of phase C is activated. If not selected, the breaker of phase C stays in its initial status. The initial status of the phase C breaker corresponds to the complement of the first value specified in the vector of **Transition status**.

## Fault resistances **Ron**

The internal resistance, in ohms ( $\Omega$ ), of the phase fault breakers. The **Fault resistances Ron** parameter cannot be set to 0.

## Ground Fault

If selected, the fault switching to the ground is activated. A fault to the ground can be programmed for the activated phases. For example, if the **Phase C Fault** and **Ground Fault** parameters are selected, a fault to the ground is applied to the phase C. The ground resistance is set internally to  $1e6$  ohms when the **Ground Fault** parameter is not selected.

## Ground resistance **Rg**

The **Ground resistance Rg (ohms)** parameter is not visible if the **Ground Fault** parameter is not selected. The ground resistance, in ohms ( $\Omega$ ). The **Ground resistance Rg (ohms)** parameter cannot be set to 0.

## External control of fault timing

If selected, adds a fourth input port to the Three-Phase Fault block for an external control of the switching times of the fault breakers. The switching times are defined by a Simulink signal (0 or 1) connected to the fourth input port of the block.

## Transition status

Specify the vector of switching status when using the Three-Phase Breaker block in internal control mode. The selected fault breakers open (0) or close (1) at each transition time according to the **Transition status** parameter values.

The initial status of the breakers corresponds to the complement of the first value specified in the vector of switching status.

## Transition times(s)

Specify the vector of switching times when using the Three-Phase Breaker block in internal control mode. At each transition time the selected fault breakers opens or closes depending to the initial state. The **Transition times (s)** parameter is not visible in the dialog box if the **External control of switching times** parameter is selected.

## Snubbers resistance Rp

The snubber resistances, in ohms ( $\Omega$ ). Set the **Snubbers resistance Rp** parameter to `inf` to eliminate the snubbers from the model.

## Snubbers capacitance Cp

The snubber capacitances, in farads (F). Set the **Snubbers capacitance Cp** parameter to `0` to eliminate the snubbers, or to `inf` to get resistive snubbers.

## Measurements

Select `Fault voltages` to measure the voltage across the three internal fault breaker terminals.

Select `Fault currents` to measure the current flowing through the three internal breakers. If the snubber devices are connected, the measured currents are the ones flowing through the breakers contacts only.

Select `Fault voltages` and `currents` to measure the breaker voltages and the breaker currents.

# Three-Phase Fault

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Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name and the phase:

Measurement Label	
Fault voltages	Ub <block name> /Fault A: Ub <block name> /Fault B: Ub <block name> /Fault C.
Fault currents	Ib <block name> /Fault A: Ib <block name> /Fault B: Ib <block name> /Fault C.

## Inputs and Outputs

The three fault breakers are connected in wye between terminals A, B and C and the internal ground resistor. If the Three-Phase Fault block is set to external control mode, a Simulink input is added to the block to control the opening and closing of the three internal breakers.

## Example

See the `power_3phseriescomp` demo for a circuit using the Three-Phase Fault block.

## See Also

Breaker, Multimeter, and Three-Phase Breaker



# Three-Phase Harmonic Filter

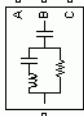
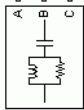
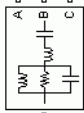
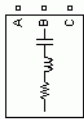
## Purpose

Implement four types of three-phase harmonic filters using RLC components

## Library

Elements

## Description



Three-phase harmonic filters are shunt elements that are used in power systems for decreasing voltage distortion and for power factor correction. Nonlinear elements such as power electronic converters generate harmonic currents or harmonic voltages, which are injected into power system. The resulting distorted currents flowing through system impedance produce harmonic voltage distortion. Harmonic filters reduce distortion by diverting harmonic currents in low impedance paths. Harmonic filters are designed to be capacitive at fundamental frequency, so that they are also used for producing reactive power required by converters and for power factor correction.

In order to achieve an acceptable distortion, several banks of filters of different types are usually connected in parallel. The most commonly used filter types are

- Band-pass filters, which are used to filter lowest order harmonics such as 5th, 7th, 11th, 13th, etc. Band-pass filters can be tuned at a single frequency (single-tuned filter) or at two frequencies (double-tuned filter).
- High-pass filters, which are used to filter high-order harmonics and cover a wide range of frequencies. A special type of high-pass filter, the C-type high-pass filter, is used to provide reactive power and avoid parallel resonances. It also allows filtering low order harmonics (such as 3rd), while keeping zero losses at fundamental frequency.

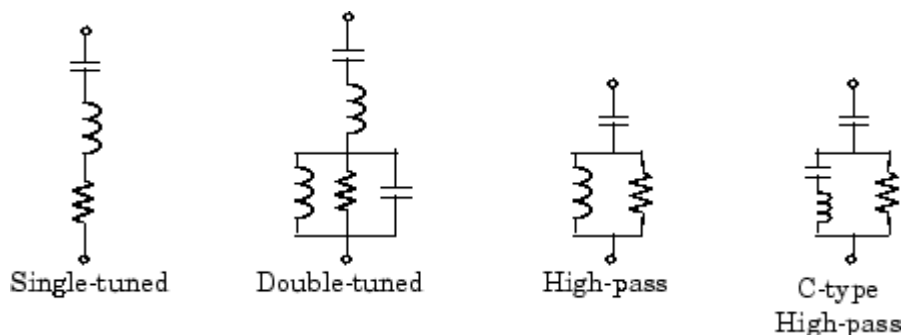
The Three-Phase Harmonic Filter is built of RLC elements. The resistance, inductance, and capacitance values are determined from the filter type and from the following parameters:

- Reactive power at nominal voltage
- Tuning frequencies

# Three-Phase Harmonic Filter

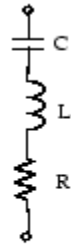
- Quality factor. The quality factor is a measure of the sharpness of the tuning frequency. It is determined by the resistance value.

The four types of filters that can be modeled with the Three-Phase Harmonic Filter block are shown below:



The simplest filter type is the single-tuned filter. The following figure gives the definition of the quality factor  $Q$  and practical formulae for computing the reactive power  $Q_C$  and losses (active power  $P$ ). The quality factor  $Q$  of the filter is the quality factor of the reactance at the tuning frequency  $Q = (nX_L)/R$ . The quality factor determines the bandwidth  $B$ , which is a measure of the sharpness of the tuning frequency as shown in the figure.

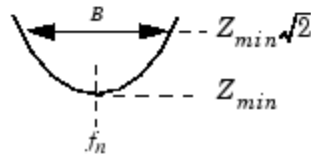
# Three-Phase Harmonic Filter



$$\text{Tuned harmonic order } n = \frac{f_n}{f_1} = \sqrt{\frac{X_C}{X_L}}$$

$$\text{Quality factor } Q = \frac{n \cdot X_L}{R} = \frac{X_C}{n \cdot R}$$

$$\text{Bandwidth } B = \frac{f_n}{Q}$$



$$\text{Reactive power at } f_1 \quad Q_C = \frac{V^2}{X_C} \cdot \frac{n^2}{(n^2 - 1)}$$

$$\text{Active power at } f_1 \text{ (losses)} \quad P \cong Q_C \cdot \frac{n}{n^2 - 1} \cdot \frac{1}{Q}$$

where:

$f_1$  = fundamental frequency

$\omega = 2\pi f_1$  = angular frequency

$f_n$  = tuning frequency

$n$  = harmonic order  $f_n / f_1$

$V$  = nominal line-line voltage

$X_L$  = inductor reactance at fundamental frequency =  $L\omega$

$X_C$  = capacitor reactance at fundamental frequency =  $1 / C\omega$

The double-tuned filter performs the same function as two single-tuned filters although it has certain advantages: its losses are much lower and the impedance magnitude at the frequency of the parallel resonance that arises between the two tuning frequencies is lower.

The double-tuned filter consists of a series LC circuit and a parallel RLC circuit. If  $f_1$  and  $f_2$  are the two tuning frequencies, both the series circuit and the parallel circuit are tuned to approximately the mean geometric frequency  $f_m = \sqrt{f_1 f_2}$ .

# Three-Phase Harmonic Filter

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The quality factor  $Q$  of the double-tuned filter is defined as the quality factor of the parallel  $L$ ,  $R$  elements at the mean frequency  $f_m$ :

$$Q = \frac{R}{L \times 2\pi f_m}$$

The high-pass filter is a single-tuned filter where the  $L$  and  $R$  elements are connected in parallel instead of series. This connection results in a wide-band filter having an impedance at high frequencies limited by the resistance  $R$ .

The quality factor of the high-pass filter is the quality factor of the

parallel  $RL$  circuit at the tuning frequency:  $Q = \frac{R}{L \times 2\pi f_n}$

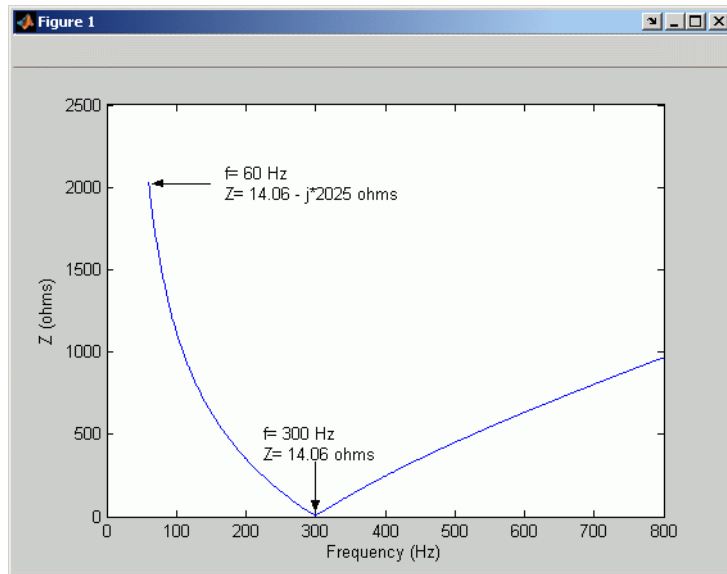
The C-type high-pass filter is a variation of the high-pass filter, where the inductance  $L$  is replaced with a series  $LC$  circuit tuned at the fundamental frequency. At fundamental frequency, the resistance is, therefore, bypassed by the resonant  $LC$  circuit and losses are null.

The quality factor of the C-type filter is still given by the ratio:

$$Q = \frac{R}{L \times 2\pi f_n}$$

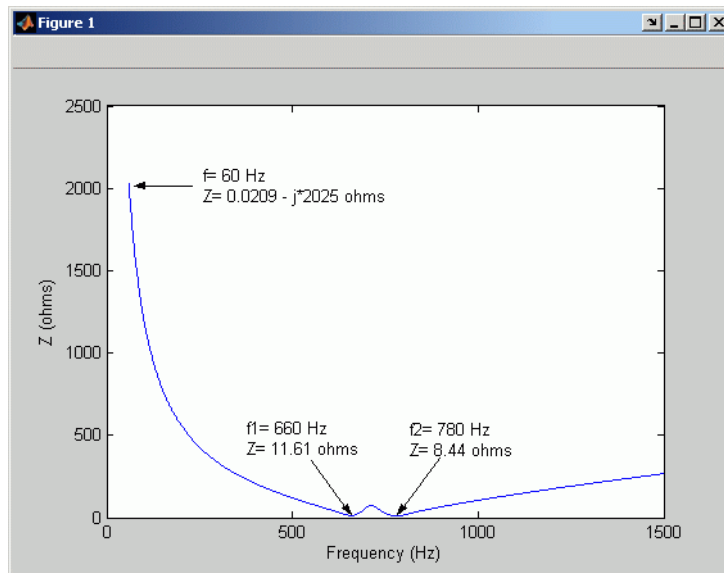
The following figures give  $R$ ,  $L$ ,  $C$  values and typical impedance versus frequency curves obtained for the four types of filters applied on a 60 Hz network. Each filter is rated 315 kV, 49 Mvar.

# Three-Phase Harmonic Filter



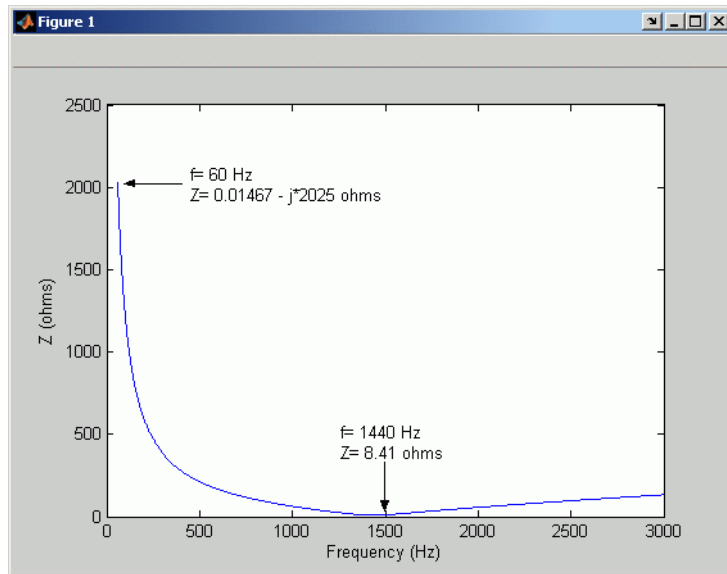
Single-Tuned, 315 kV, 49 Mvar, 5th Harmonic Filter;  $Q = 30$

# Three-Phase Harmonic Filter



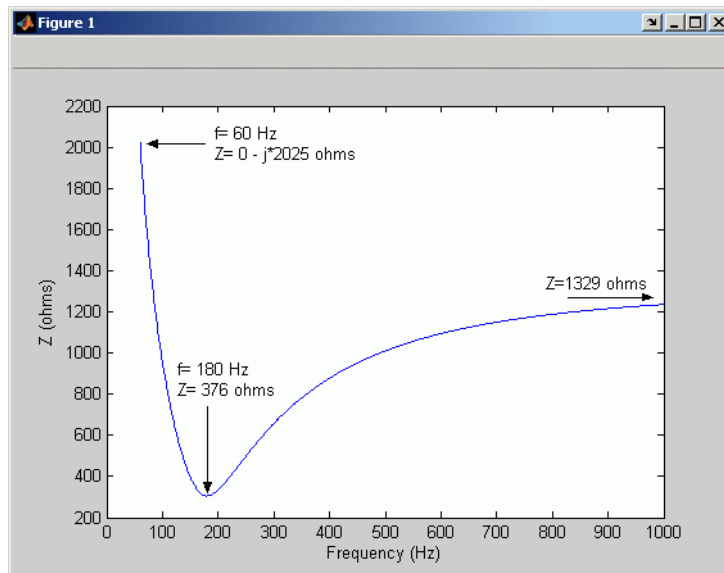
Double-Tuned, 315 kV, 49 Mvar, 11th and 13th Harmonics Filter;  $Q = 16$

# Three-Phase Harmonic Filter



High-Pass, 315 kV, 49 Mvar, 24th Harmonic Filter;  $Q = 10$

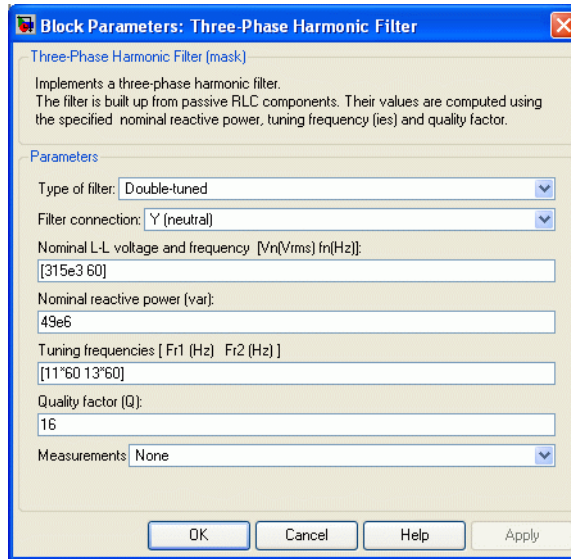
# Three-Phase Harmonic Filter



C-Type High-Pass, 315 kV, 49 Mvar, 3rd Harmonic Filter;  $Q = 1.75$



## Dialog Box and Parameters



### Type of filter

Select one of the four filter types: Single-tuned, Double-tuned, High-pass or C-type high-pass.

### Filter connection

Select the connection of the three filter branches.

- |             |  |
|-------------|--|
| Y(grounded) | Neutral is grounded.                                   |
| Y(floating) | Neutral is not accessible.                             |
| Y(neutral)  | Neutral is made accessible through a fourth connector. |
| Delta       | Three phases connected in delta.                       |

### Nominal L-L voltage and frequency

The nominal phase-to-phase voltage of the filter, in volts RMS (Vrms) and the nominal frequency, in hertz (Hz).

# Three-Phase Harmonic Filter

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## Nominal reactive power

The three-phase capacitive reactive power  $Q_C$ , in vars. Specify a positive value.

## Tuning frequency or Tuning frequencies

The tuning frequency of the single frequency filter (single-tuned, high-pass or C-type high-pass), or the two frequencies of the double-tuned filter, in hertz (Hz).

## Quality factor (Q)

The quality factor  $Q$  of the filter defined as explained in the above Description section. Dimensionless positive number.

## Measurements

Select **Branch voltages** to measure the three voltages across each phase of the Three-Phase Harmonic Filter block terminals. For a Y connection, these voltages are the phase-to-ground or phase-to-neutral voltages. For a delta connection, these voltages are the phase-to-phase voltages.

Select **Branch currents** to measure the three currents flowing through each phase of the filter. For a delta connection, these currents are the currents flowing in each branch of the delta.

Select **Branch voltages and currents** to measure the three voltages and the three currents of the Three-Phase Harmonic Filter block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name.

Measurement	Label
Branch voltages	Y(grounded): $U_{ag}$ , $U_{bg}$ , $U_{cg}$ $U_{ag}$ , $U_{bg}$ , $U_{cg}$

# Three-Phase Harmonic Filter

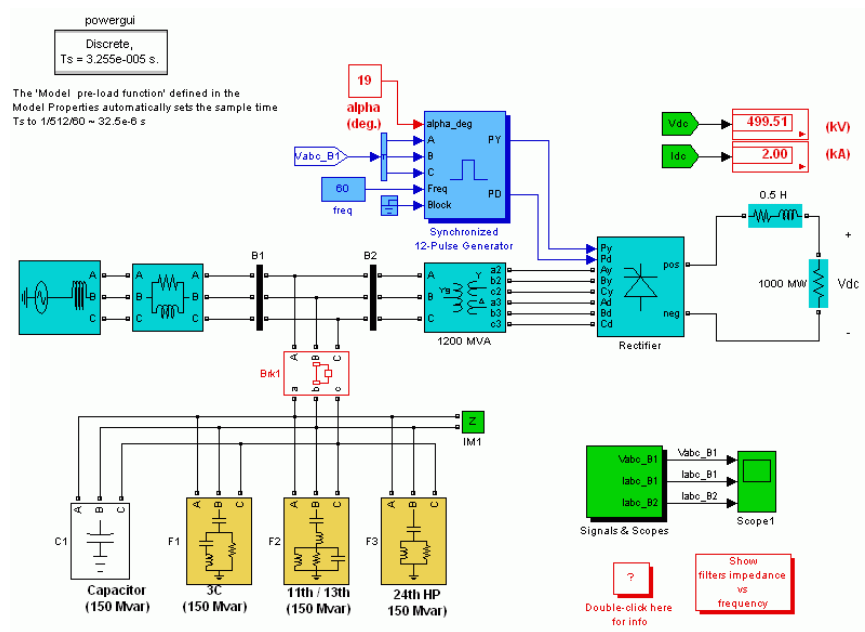
Measurement	Label	
Y(floating): Uan, Ubn, Ucn	Uan: , Ubn: , Ucn:	
Y(neutral): Uan, Ubn, Ucn	Uan: , Ubn: , Ucn:	
Delta: Uab, Ubc, Uca	Uab: , Ubc: , Uca:	
Branch currents	Y(grounded): Ia, Ib, Ic	Iag: , Ibg: , Icg:
	Y(floating): Ia, Ib, Ic	Ian: , Ibn: , Icn:
	Y(neutral): Ia, Ib, Ic	Ian: , Ibn: , Icn:
	Delta: Iab, Ibc, Ica	Iab: , Ibc: , Ica:

## Example

The `power_harmonicfilter` demo illustrates the use of the Three-Phase Harmonic Filter block to filter harmonic currents generated by a 12-pulse, 1000 MW, AC/DC converter in a 500 kV, 60 Hz system. The filter set is made of the following four components providing a total of 600 Mvar:

- One 150 Mvar C-type high-pass filter tuned to the 3rd harmonic (F1)
- One 150 Mvar double-tuned filter tuned to the 11/13th (F2)
- One 150 Mvar high-pass filter tuned to the 24th (F3)
- One 150 Mvar capacitor bank

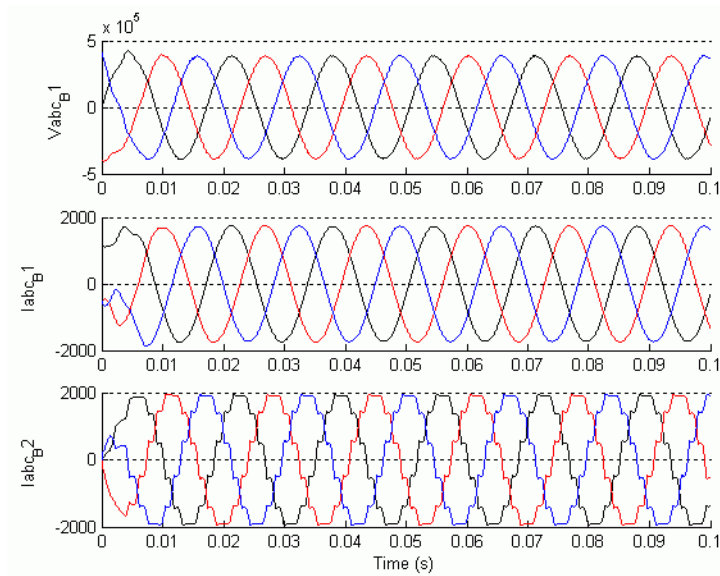
# Three-Phase Harmonic Filter



## Time-domain simulation

Run the simulation with an alpha firing angle of 19 degrees. You should get a DC voltage level of 500 kV. Now, look inside Scope1. Compare the currents flowing into Bus B1 (Iabc\_B1, axis 2) with those flowing into Bus B2 (Iabc\_B2, axis 3). You can see that the harmonic filters almost eliminate the harmonics generated by the converter. If you use the FFT tool of the Powergui, you will find that the harmonic filters reduce the THD of the current injected in the system from 9% to 0.7%.

# Three-Phase Harmonic Filter

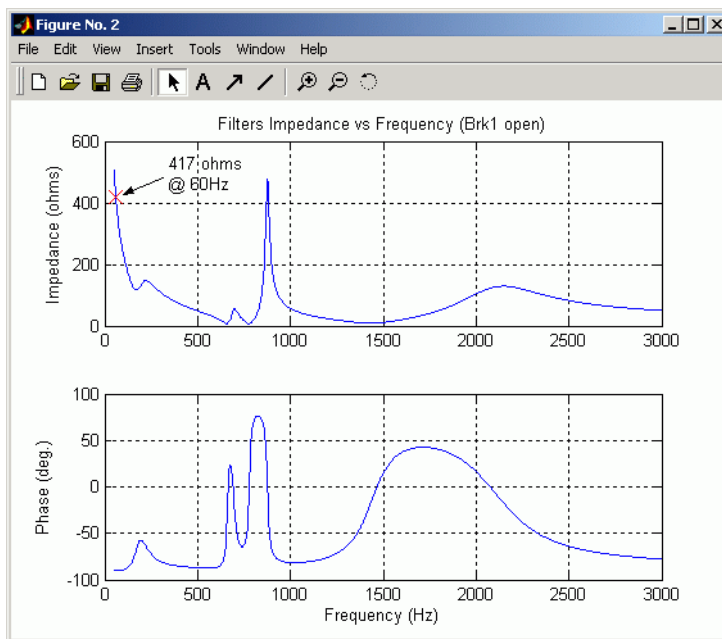


## Frequency-Domain Response

You will now plot the impedance vs. frequency of the harmonic filters:

- 1** Disconnect the filters from the AC bus. To do so, double-click on the breaker Brk1, select **open** for initial status of breakers, and click **OK**.
- 2** Open the Powergui and select **Impedance vs Frequency Measurement**.
- 3** Click the **Display/Save** button. The software computes and displays the filter's frequency response.
- 4** Double-click the block Show filters impedance vs frequency. A second figure appears, showing the precomputed filters frequency response. The impedance data of the two figures should be identical to the one shown below.

# Three-Phase Harmonic Filter



If you zoom the figure (using the **Tool** menu), you should find an impedance of 417 ohms capacitive (-90deg.) at 60 Hz. This value confirms that the total reactive power of the filters at 60 Hz is

$$Q_c = \frac{V^2}{X_c} = \frac{(500 \times 10^3)^2}{417} = 600 \text{ Mvar}$$

# Three-Phase Mutual Inductance Z1-Z0

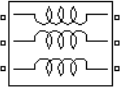
## Purpose

Implement three-phase impedance with mutual coupling among phases

## Library

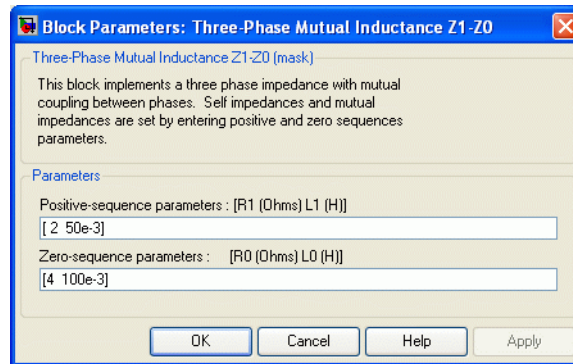
Elements

## Description



The Three-Phase Mutual Inductance Z1-Z0 block implements a three-phase balanced inductive and resistive impedance with mutual coupling between phases. This block performs the same function as the three-winding Mutual Inductance block. For three-phase balanced power systems, it provides a more convenient way of entering system parameters in terms of positive- and zero-sequence resistances and inductances than the self- and mutual resistances and inductances.

## Dialog Box and Parameters



### Positive-sequence parameters

The positive-sequence resistance  $R1$ , in ohms ( $\Omega$ ), and the positive-sequence inductance  $L1$ , in henries (H).

### Zero-sequence parameters

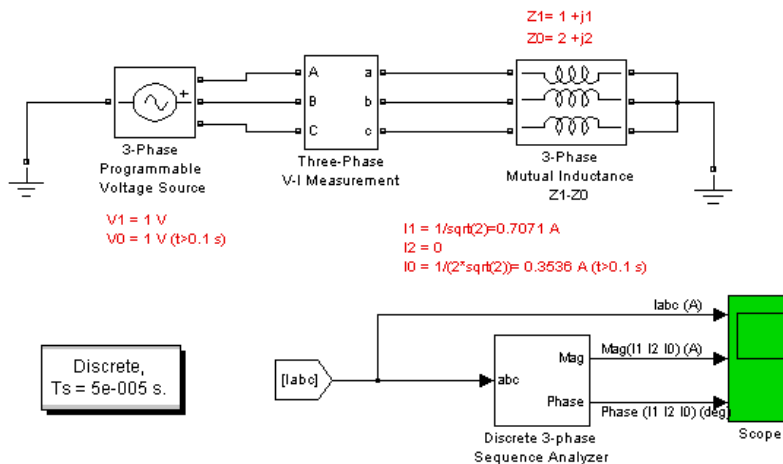
The zero-sequence resistance  $R0$ , in ohms ( $\Omega$ ), and the zero-sequence inductance  $L0$ , in henries (H).

## Example

The power\_3phmutseq10 demo illustrates the use of the Three-Phase Mutual Inductance Z1-Z0 block to build a three-phase inductive source with different values for the positive-sequence impedance  $Z1$  and the zero-sequence impedance  $Z0$ . The programmed impedance values are

# Three-Phase Mutual Inductance Z1-Z0

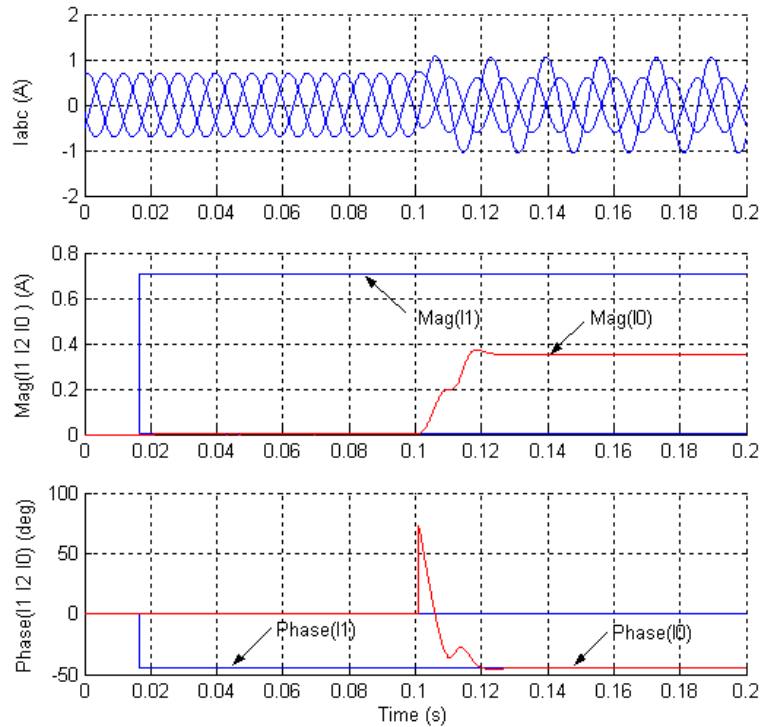
$Z1 = 1 + j1 \Omega$  and  $Z0 = 2 + j2 \Omega$ . The Three-Phase Programmable Voltage Source block is used to generate a 1-volt, 0-degree, positive-sequence internal voltage. At  $t = 0.1$  s, a 1-volt, 0-degree, zero-sequence voltage is added to the positive-sequence voltage. The three source terminals are short-circuited to ground and the resulting positive-, negative-, and zero-sequence currents are measured using the Discrete 3-Phase Sequence Analyzer block.



The current waveforms and their sequence components (magnitude and phase) are displayed on the Scope block. The resulting waveforms are shown on the following figure.



# Three-Phase Mutual Inductance Z1-Z0



The polar impedance values are  $Z1 = \sqrt{2} \angle 45^\circ \Omega$  and  $Z0 = 2\sqrt{2} \angle 45^\circ \Omega$

Therefore, the positive- and zero-sequence currents displayed on the scope are

$$I1 = V1/Z1 = 1/(\sqrt{2} \angle 45^\circ) = 0.7071 \text{ A} \angle -45^\circ$$

$$I0 = V0/Z0 = 1/(2\sqrt{2} \angle 45^\circ) = 0.3536 \text{ A} \angle -45^\circ$$

The transients observed on the magnitude and the phase angle of the zero-sequence current when the zero-sequence voltage is added (at  $t = 0.1$  s) are due to the Fourier measurement technique used by the Discrete 3-Phase Sequence Analyzer block. As the Fourier analysis

# Three-Phase Mutual Inductance Z1-Z0

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uses a running average window of one cycle, it takes one cycle for the magnitude and phase to stabilize.

## **See Also**

Mutual Inductance

# Three-Phase OLTC Phase Shifting Transformer Delta-Hexagonal (Phasor Type)

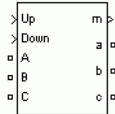
## Purpose

Implement phasor model of three-phase OLTC phase-shifting transformer using delta hexagonal connection

## Library

Flexible AC Transmission Systems (FACTS)/Transformers

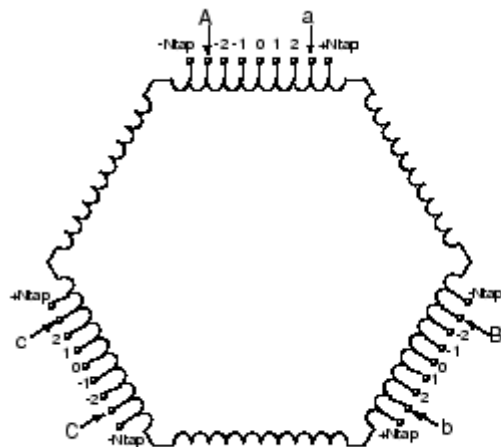
## Description



This block is used to model a phase-shifting transformer using on-load tap changers (OLTC) for introducing a phase shift between three-phase voltages at two buses in a transmission system. Controlling phase-shift on a transmission system will affect primarily flow of active power. Although the phase-shifting transformer does not provide as much flexibility and speed as power-electronics based FACTS, it can be considered as a basic power flow controller. This is why it has been included in the facts library. The dynamic performance of the phase-shifting transformer can be enhanced by using a thyristor-based tap changer instead of a mechanical tap changer. As this model is a phasor model which does not implement the details of current transfer from one tap to the next tap, you can use it to model a thyristor-based phase-shifter. You can also use this block together with the Three-phase OLTC Regulating Transformer (Phasor Type) block for building phasor models of more complex transformer-based FACTS topologies.

The delta hexagonal connection consists of three pairs of windings interconnected in a hexagonal configuration as shown on the figure below.

# Three-Phase OLTC Phase Shifting Transformer Delta-Hexagonal (Phasor Type)



$$\psi = 2 \times \text{atan} \left( \frac{-k}{\sqrt{3}} \right)$$

where:

$\psi$  = phase shift of abc output voltages  
with respect to ABC input voltages

$k$  = relative tap position =  $N/N_{\text{tap}}$   
 $N$  = tap position

$$-N_{\text{tap}} \leq N \leq N_{\text{tap}}$$

$$-1 \leq k \leq 1$$

$$-60^\circ \leq \psi \leq 60^\circ$$

## Delta-Hexagonal Phase-Shifting Transformer Connections

Each phase consists of two coupled windings drawn in parallel on the figure: one tapped winding with two OLTCs and one winding without taps. All windings have the same number of turns. The two OLTCs vary phase shift by moving transformer input terminals (A, B, C) and outputs terminals (a, b, c) symmetrically with respect to center tap 0. This delta hexagonal connection has the advantage of keeping a 1:1 voltage ratio while the phase shift is varied.

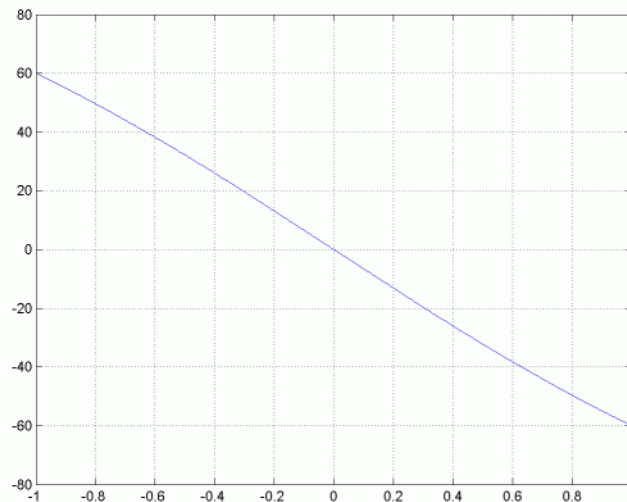
When the two OLTCs move taps from the center position (0) to the winding end (position  $N_{\text{tap}}$ ), the phase shift between inputs (ABC) and outputs (abc) varies from 0 to 60 degrees. When ABC are at position  $-N_{\text{tap}}$  and abc are at position  $+N_{\text{tap}}$ , the output voltages abc are lagging input voltages ABC by 60 degrees. On the other end, when ABC are at position  $+N_{\text{tap}}$  and abc are at position  $-N_{\text{tap}}$ , the output voltages abc are leading input voltages ABC by 60 degrees. For intermediate positions the phase shift  $\psi$  is given by the equation on the figure. This equation assumes that all tap are evenly spaced.

# Three-Phase OLTC Phase Shifting Transformer Delta-Hexagonal (Phasor Type)

For example, if each half tapped winding consists of 10 taps (total of 21 taps/ winding including center tap 0) and if ABC and abc terminals are respectively at tap -7 and tap +7, then,  $k=7/10=0.7$

Therefore, abc voltages are lagging ABC voltages by 44 degrees.

The phase angle varies almost linearly as function of tap position as shown on the figure below.



## Variation of phase shift as function of tap position

You control tap positions, and therefore phase shift, by sending pulses to one of the two block inputs labeled Up and Down. Applying a pulse to the Up (or Down) input will move the tap position upward (or downward) when the signal is changing from 0 to 1.

Mechanical tap changers are relatively slow devices. The time required to move from one tap position to the next one is usually comprised between 3 and 10 seconds. You specify this mechanical time delay in the block menu.

# Three-Phase OLTC Phase Shifting Transformer Delta-Hexagonal (Phasor Type)

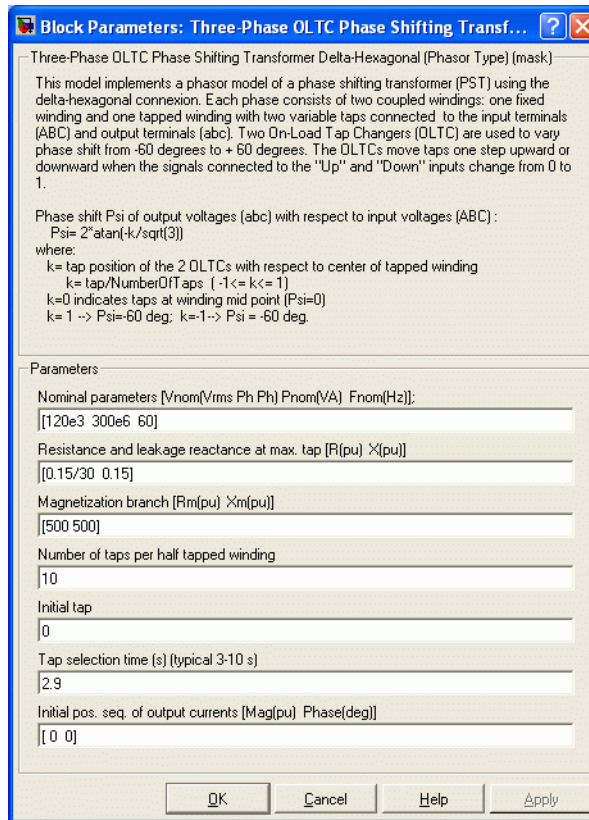
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**Note** OLTCs use additional switches and resistors (or inductors) to transfer current from the outgoing tap to the ongoing tap without interrupting load current. During the transfer, taps are temporarily short circuited through resistors or inductors. The transfer time (typically from 40 ms to 60 ms) is fast as compared to the tap selection process (3s to 10 s). As this block implements a phasor model for study of transient stability of power systems in the range of seconds to minutes, the tap transfer process is not modelled and an instantaneous tap transfer is assumed. A detailed delta-hexagonal phase-shifting transformer model is provided in the `power_PSTdeltahex` demo.

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# Three-Phase OLTC Phase Shifting Transformer Delta-Hexagonal (Phasor Type)



## Dialog Box and Parameters

### Nominal parameters [Vnom Pnom Fnom]

The nominal line to line voltage, in volts rms, the three-phase nominal power, in VA and the nominal frequency, in hertz.

### Resistance and leakage reactance at max. tap [R X]

The transformer short circuit impedance due to winding resistances and leakage reactances, at maximum phase shift (input and output taps at -Ntap and +Ntap positions). Specify resistance and reactance, in pu.

# Three-Phase OLTC Phase Shifting Transformer Delta-Hexagonal (Phasor Type)

---

The transformer positive-sequence impedance  $Z_1$ , in pu, and zero-sequence  $Z_0$ , in pu, vary with relative tap position  $k$  as follows:

$$Z_1 = (R + jX) \times \frac{|k|(-3k^2 + 2|k| + 9)}{2(k^2 + 3)}$$

$$Z_0 = \frac{R_m \times jX_m}{R_m + jX_m} \times k^2$$

where:  $R$ ,  $X$  are the transformer resistance and reactance defined in the parameter **Resistance and leakage reactance at max. tap** ( $k=1$  or  $k=-1$ ) and  **$R_m$ ,  $X_m$  are the transformer magnetizing** resistance and reactance defined in the **Magnetizing branch** parameter described below.

Note that these impedances keep the same value for positive and negative values of  $k$ . For  $k=0$ , impedances are zero because the transformer input terminals are short-circuited with output terminals.

## **Magnetizing branch [ $R_m$ $X_m$ ]**

The resistance, in pu, and the reactance, in pu of the parallel  $R_m$ ,  $X_m$  branch modelling respectively iron losses and reactive magnetizing currents. Saturation is not modelled.

## **Number of taps per half winding (Ntap)**

The number of taps per half winding. The total number of taps per winding, including center tap 0, is therefore  $2 \cdot Ntap + 1$ .

## **Initial tap**

Specify an integer (Tapinit) corresponding the initial tap position of output terminals abc. The initial tap position of input terminals ABC is therefore  $-Tapinit$ .

## **Tap selection time**

The mechanical time delay, in seconds, required for the OLTCs to move the taps by one position. Typical values are in the 3s-10s range.



# Three-Phase OLTC Phase Shifting Transformer Delta-Hexagonal (Phasor Type)

## Initial pos. seq. output currents [Mag Phase]

The initial value of the positive-sequence current phasor (Magnitude in pu and Phase in degrees) flowing out of terminals abc. If you know the initial value of currents you may specify it in order to start simulation in steady state. If you don't know these values, you can leave [0 0]. The system will reach steady-state after a short transient.

## Inputs and Outputs

A B C

The three transformer input terminals

a b c

The three transformer output terminals

Up

Simulink input for controlling tap position. Applying a pulse to this input will initiate upward tap changing when the pulse is changing from 0 to 1.

Down

Simulink input for controlling tap position. Applying a pulse to this input will initiate downward tap changing when the pulse is changing from 0 to 1.

m

Simulink output vector containing 17 internal signals. These signals are either complex signals (voltage phasors, current phasors or impedances) or control signals. They can be individually accessed by using the Bus Selector block. They are, in order:

Signal	Signal Group	Signal Names	Definition
1-3	VABC (cmplx)	VA (pu) VB (pu) VC (pu)	Phasor voltages (phase to ground) at the transformer input terminals A, B, C (pu)

# Three-Phase OLTC Phase Shifting Transformer Delta-Hexagonal (Phasor Type)

Signal	Signal Group	Signal Names	Definition
4-6	Vabc (cmplx)	Va (pu) Vb (pu) Vc (pu)	Phasor voltages (phase to ground) at the transformer output terminals a, b, c (pu)
7-9	IABC (cmplx)	IA (pu) IB (pu) IC (pu)	Phasor currents flowing into the input terminals A, B, C
10-12	Iabc (cmplx)	Ia (pu) Ib (pu) Ic (pu)	Phasor currents flowing out of the output terminals a, b, c
13-14	Z (cmplx)	Z1 (pu) Z0 (pu)	Positive- and zero-sequence complex impedances (R+jX)
15	Psi (degrees)	Psi (degrees)	Phase shift of abc output voltages with respect to ABC input voltages
16	Tap	Tap	Tap position
17	Ready	Ready	Logical signal generated by the tap changer controller. The Ready signal becomes (1) after the tap selection has been completed, thus enabling a new tap change. The Up and Down pulses to the OLTC are blocked as long as the Ready signal is (0).

## Example

See the power\_PSTdeltahex demo which illustrates the use of the Three-Phase OLTC Phase Shifting Transformer Delta-Hexagonal (Phasor Type) block to control power transfer between two equivalent sources in a 120 kV transmission. The phasor model is compared with a detailed model of phase shifting transformer. Look under the masked

# Three-Phase OLTC Phase Shifting Transformer Delta-Hexagonal (Phasor Type)

---

blocks to see how both models are implemented. The detailed model uses switches and three Multi-Winding Transformer blocks, whereas the phasor model uses current sources.

## **See Also**

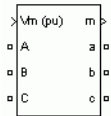
Three-Phase OLTC Regulating Transformer (Phasor Type)

# Three-Phase OLTC Regulating Transformer (Phasor Type)

**Purpose** Implement phasor model of three-phase OLTC regulating transformer

**Library** Flexible AC Transmission Systems (FACTS)/Transformers

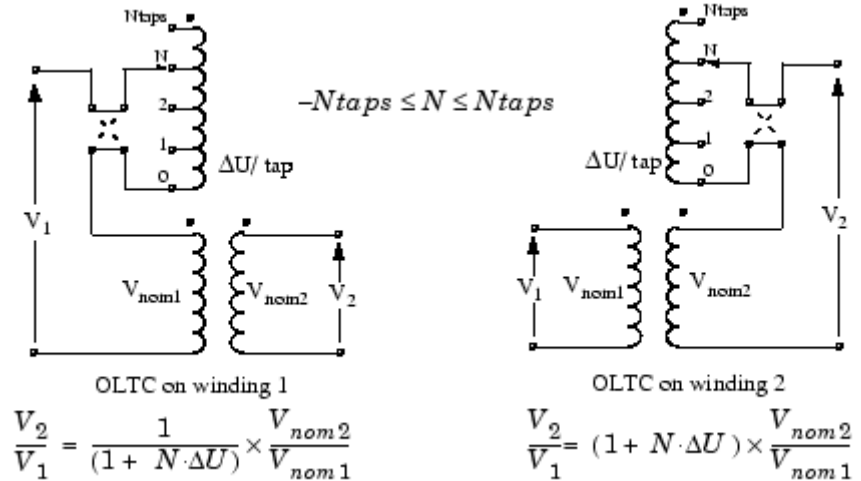
## Description



This block is used to model a three-phase two-winding transformer or autotransformer using a on-load tap changer (OLTC) for regulating voltage on a transmission or distribution system. Controlling voltage on a transmission system will affect primarily flow of reactive power, which, in turn, will affect the power transfer limits. Although the regulating transformer does not provide as much flexibility and speed as power-electronics based FACTS, it can be considered as a basic power flow controller. This is why it has been included in the facts library. The dynamic performance of the regulating transformer can be enhanced by using a thyristor-based tap changer instead of a mechanical tap changer. As this model is a phasor model which does not implement the details of current commutation from one tap to the next tap, you can use it to model a thyristor-based tap changer and implement your own control system by selecting **External control of OLTC** in the block menu. You can also use this block together with the Three-phase OLTC Phase-Shifting Transformer Delta-Hexagonal (Phasor Type) block for building phasor models of more complex transformer-based FACTS topologies.

The figure below shows one phase of the three-phase regulating transformer. Each phase consists of main windings 1 and 2 and of a tapped regulation winding.

# Three-Phase OLTC Regulating Transformer (Phasor Type)



## One Phase of the Regulating Transformer

Voltage regulation is performed by varying the transformer ratio  $V_2/V_1$  by means of the OLTC. The OLTC can be connected either on winding 1 (left diagram) or on winding 2 (right diagram). The OLTC can select any tap from position 0 (no voltage correction) to maximum tap (position  $N_{tap}$ ) yielding maximum voltage correction. The OLTC is also equipped with a reversing switch which allows connecting the regulation winding either in additive or subtractive polarity. The factor multiplying  $V_{nom2}/V_{nom1}$  on the figure is the voltage correction factor. It is given by:

$$\begin{aligned} & 1/(1 + N \cdot \Delta U) \quad \text{for OLTC on winding 1} \\ & (1 + N \cdot \Delta U) \quad \text{for OLTC on winding 2} \end{aligned}$$

where:  $N$  = tap position

$\Delta U$  = voltage per tap in pu of nominal voltage  
of winding 1 or winding 2

Negative values of  $N$  correspond to the reversing switch position shown in dashed lines (regulation winding in subtractive polarity).

# Three-Phase OLTC Regulating Transformer (Phasor Type)

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The transformer resistance and leakage reactance also vary with the tap position.

Mechanical tap changers are relatively slow devices. The time required to move from one tap position to the next one is usually comprised between 3 and 10 seconds. You specify this mechanical time delay in the block menu.

---

**Note** OLTCs use additional switches and resistors (or inductors) to transfer current from the outgoing tap to the ongoing tap without interrupting load current. During the transfer, taps are temporarily short circuited through resistors or inductors. The transfer time (typically from 40 ms to 60 ms) is fast as compared to the tap selection process (3s to 10 s). As this block implements a phasor model for study of transient stability of power systems in the range of seconds to minutes, the tap transfer process is not modelled and an instantaneous tap transfer is assumed. A detailed regulating transformer model is provided in the `power_OLTCregtransformer` demo.

---

## Automatic voltage control

The regulating transformer is usually associated with a control system which regulates voltage at the transformer terminals (side 1 or side 2) or at a remote bus. Such a control system is provided in the Three-Phase OLTC Regulating Transformer (Phasor Type) block. You must then connect at the `Vm` input of the block a simulink signal which is usually the magnitude of the positive-sequence voltage (in pu) to be controlled, but it can be any signal. The control system will adjust automatically the tap position until the measured voltage `Vm` is equal to the reference voltage `Vref` specified in the block menu.

The voltage regulator is a hysteresis type regulator. Each time a tap change is required, the regulator sends a pulse either to the Up or Down input of the Tap Changer Controller. Look under the block mask to see how these control blocks are built. The regulator will ask for a tap change if

# Three-Phase OLTC Regulating Transformer (Phasor Type)

---

$abs(V_m - V_{ref}) > DeadBand/2$  during a time  $t > Delay$

where  $V_{ref}$ ,  $Deadband$  and  $Delay$  are parameters of the voltage regulator.

## External control of OLTC

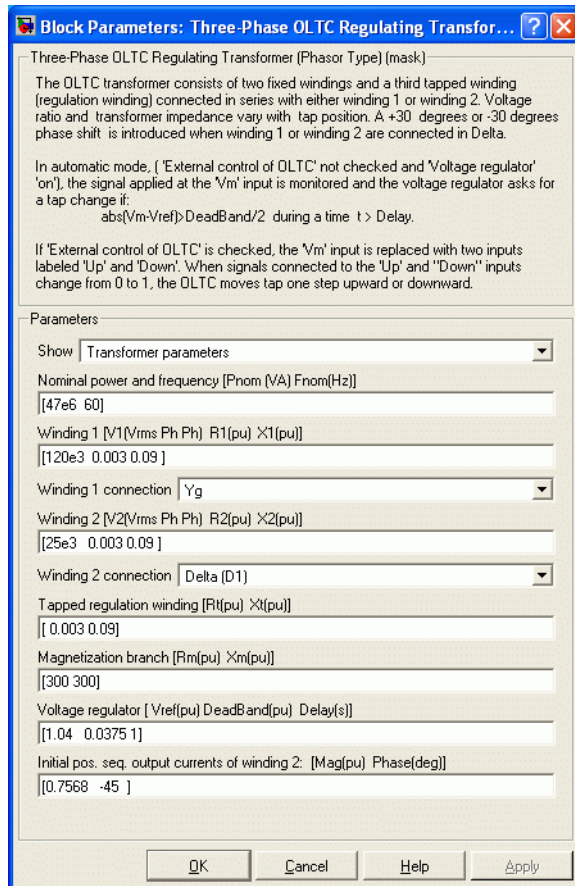
If you want to implement your own control system or manually control the tap position, you select **External control of OLTC**. The  $V_m$  input will then be replaced by two inputs labeled Up and Down. Applying a pulse to the Up or Down input will move the tap position upward or downward when the signal is changing from 0 to 1.

## Dialog Box and Parameters

The transformer and OLTC parameters are grouped in two categories: Transformer parameters and OLTC and Voltage Regulator parameters. Use the **Show** listbox to select which group of parameters you want to visualize.

Transformer Parameters

# Three-Phase OLTC Regulating Transformer (Phasor Type)



## Nominal Power and frequency [Pnom Fnom]

The three-phase nominal power, in VA and the nominal frequency, in hertz.

## Winding 1 [V1 R1 X1]

The nominal line to line voltage of winding 1, in volts rms, winding resistance, in pu, and leakage reactance, in pu.



# Three-Phase OLTC Regulating Transformer (Phasor Type)

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## Winding 1 connection

The connection of the three windings 1. Select either, Y (ungrounded wye), Yg (wye grounded), Delta(D1) (Delta connection introducing a -30 degrees phase-shift) or Delta(D11) (Delta connection introducing a +30 degrees phase-shift). See the Three-Phase Transformer (Two-Windings) block documentation for an explanation of the phase shifts introduced by D1 and D11 connections. The zero-sequence impedance will vary according to the connection. Zero-sequence impedance is computed assuming that the three-phase transformer bank is built with three single-phase, two-winding units.

## Winding 2 [V2 R2 X2]

The nominal line to line voltage of winding 2, in volts rms, winding resistance in pu, and leakage reactance, in pu.

## Winding 2 connection

The connection of the three windings 2. Select either, Y (ungrounded wye), Yg (wye grounded), Delta(D1) (Delta connection introducing a -30 degrees phase-shift) or Delta(D11) (Delta connection introducing a +30 degrees phase-shift). The zero-sequence impedance will vary according to the connection.

## Tapped regulation winding [Rt Xt]

The resistance and the leakage reactance of the tapped winding depend on the tap position. Enter the resistance, in pu, and the leakage reactance, in pu, corresponding to the maximum tap position.

## Magnetizing branch [Rm Xm]

The resistance, in pu and the reactance, in pu, of the parallel Rm, Xm branch modelling respectively iron losses and reactive magnetizing currents. Saturation is not modelled.

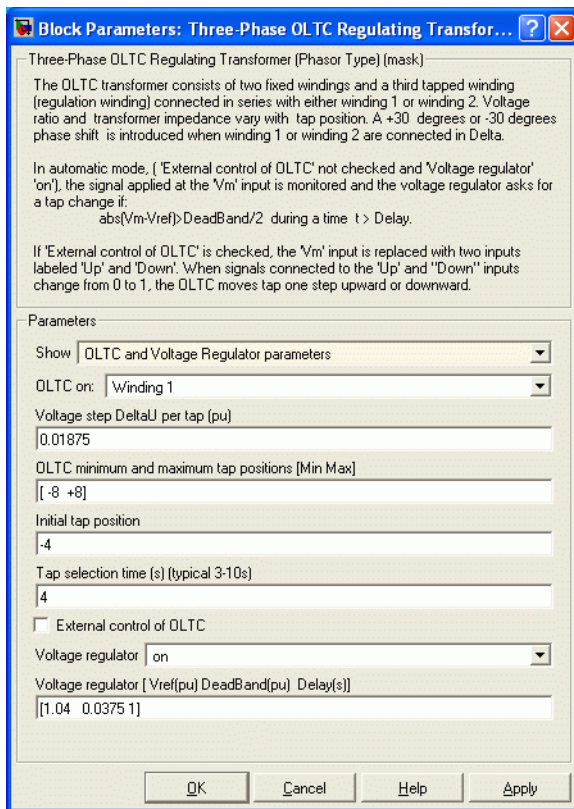
## Initial pos. seq. output currents of winding 2 [Mag Phase]

The initial value of the positive-sequence current phasor (Magnitude in pu and Phase in degrees) flowing out of winding 2. The currents flowing into winding 1 will be computed accordingly. If you know the initial value of currents you may specify it in

# Three-Phase OLTC Regulating Transformer (Phasor Type)

order to start simulation in steady state. If you don't know these values, you can leave [0 0]. The system will reach steady-state after a short transient.

## OLTC and Voltage Regulation Parameters



### OLTC on

Select either Winding 1 or Winding 2.

# Three-Phase OLTC Regulating Transformer (Phasor Type)

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## Voltage Step DeltaU per tap

The voltage step per tap, in pu of the nominal voltage of winding 1 or winding 2.

## OLTC minimum and maximum tap [MinTap MaxTap]

You normally specify a negative integer corresponding to maximum tap position with the regulation winding connected in subtractive polarity, followed by a positive integer corresponding to maximum tap position with the regulation winding connected in additive polarity. These two integers specify the number of taps and their absolute values are usually the same. However, if you want to limit tap excursion, you may specify two different values.

## Initial tap position

Specify an integer  $N$  corresponding to initial tap position with  $MinTap \leq N \leq MaxTap$ .

## Tap selection time

The mechanical time delay, in seconds, required for the OLTC to move the taps by one position. Typical values are in the 3s-10s range.

## External control of OLTC

The OLTC is usually controlled by the voltage regulator. Check this parameter if you want to implement your own control system or manually control the tap position. The  $V_m$  input will then be replaced by two inputs labeled Up and Down. Applying a pulse to the Up or Down input will move the tap position upward or downward when the signal is changing from 0 to 1.

## Voltage regulator

This parameter is not visible when the **External control of OLTC** parameter is checked.

Select on for enabling the voltage regulator. If you select off the OLTC is frozen at the position specified by the **Initial tap position** parameter.

# Three-Phase OLTC Regulating Transformer (Phasor Type)

## Voltage regulator [Vref DeadBand Delay]

This parameter is not visible when the **External control of OLTC** parameter is checked.

Specify the reference voltage Vref, in pu, the dead band of the hysteresis regulator, in pu, and the time delay, in seconds, during which the voltage error must exceed half the dead band for the OLTC to move tap position upward or downward. The dead band is normally adjusted at two times the voltage step specified in the **Voltage step DeltaU per tap** parameter.

## Inputs and Outputs

A B C

The three input terminals connected windings 1.

a b c

The three output terminals connected to windings 2.

Vm

This input is visible only when the **External control of OLTC** parameter is not checked.

Connect to this input the measured voltage to be controlled by the voltage regulator. This signal is usually the magnitude, in pu, of the positive-sequence voltage measured at the transformer terminals (side 1 or side 2) or at a remote bus.

Up

This input is visible only when the **External control of OLTC** parameter is checked.

Simulink input for controlling tap position. Applying a pulse to this input will initiate upward tap changing when the pulse is changing from 0 to 1.

Down

This input is visible only when the **External control of OLTC** parameter is checked.

# Three-Phase OLTC Regulating Transformer (Phasor Type)

Simulink input for controlling tap position. Applying a pulse to this input will initiate downward tap changing when the pulse is changing from 0 to 1.

m

Simulink output vector containing 16 internal signals. These signals are either complex signals (voltage phasors, current phasors or impedances) or control signals. They can be individually accessed by using the Bus Selector block. They are, in order:

Signal	Signal Group	Signal Names	Definition
1-3	VABC (cmplx)	VA (pu) VB (pu) VC (pu)	Phasor voltages (phase to ground) at the transformer input terminals A, B, C (pu)
4-6	Vabc (cmplx)	Va (pu) Vb (pu) Vc (pu)	Phasor voltages (phase to ground) at the transformer output terminals a, b, c (pu)
7-9	IABC (cmplx)	IA (pu) IB (pu) IC (pu)	Phasor currents flowing into the input terminals A, B, C
10-12	Iabc (cmplx)	Ia (pu) Ib (pu) Ic (pu)	Phasor currents flowing out of the output terminals a, b, c
13-14	Z (cmplx)	Z1 (pu) Z0 (pu)	Positive- and zero-sequence complex impedances (R+jX)

# Three-Phase OLTC Regulating Transformer (Phasor Type)

Signal	Signal Group	Signal Names	Definition
15	Tap	Tap	Tap position
16	Ready	Ready	Logical signal generated by the tap changer controller. This signal is used to enable voltage controller action. The Ready signal becomes (1) after the tap selection has been completed, thus enabling a new tap change. The Up and Down pulses to the OLTC are blocked as long as the Ready signal is (0).

## Example

See the `power_OLTCregtransformer` demo which illustrates the use of the Three-Phase OLTC Regulator Transformer (Phasor Type) block to regulate voltage on a 25 kV distribution feeder. The phasor model is compared with a detailed model of regulating transformer. Look under the masked blocks to see how both models are implemented. The detailed model uses switches and three Multi-Winding Transformer blocks, whereas the phasor model uses current sources.

## See Also

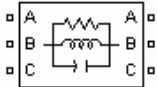
Three-Phase OLTC Phase Shifting Transformer Delta-Hexagonal (Phasor Type)

# Three-Phase Parallel RLC Branch

**Purpose** Implement three-phase parallel RLC branch

**Library** Elements

## Description



The Three-Phase Parallel RLC Branch block implements three balanced branches consisting each of a resistor, an inductor, a capacitor, or a parallel combination of these. To eliminate either the resistance, inductance, or capacitance of each branch, the R, L, and C values must be set respectively to infinity (inf), infinity (inf), and 0. Only existing elements are displayed in the block icon.

Negative values are allowed for resistance, inductance, and capacitance.

## Dialog Box and Parameters

### Branch type

Select the elements you want to include in the branch. The **R** letter defines the resistor, the **L** letter defines the inductor, and the **C** letter defines the inductor.

### Resistance R

The branch resistances, in ohms ( $\Omega$ ).

# Three-Phase Parallel RLC Branch

---

## Inductance L

The branch inductances, in henries (H).

## Capacitance C

The branch capacitances, in farads (F).

## Measurements

Select **Branch voltages** to measure the three voltages across the Three-Phase Parallel RLC Branch block terminals.

Select **Branch currents** to measure the three total currents (sum of R, L, C currents) flowing through the Three-Phase Parallel RLC Branch block.

Select **Branch voltages** and **currents** to measure the three voltages and the three currents of the Three-Phase Parallel RLC Branch block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name.

Measurement	Label
Branch voltages of phases A, B, and C	Ua: , Ub: , Uc:
Branch currents of phases A, B, and C	Ia: , Ib: , Ic:

## See Also

Multimeter, Three-Phase Parallel RLC Load, Three-Phase Series RLC Branch, Three-Phase Series RLC Load

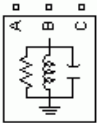


# Three-Phase Parallel RLC Load

**Purpose** Implement three-phase parallel RLC load with selectable connection

**Library** Elements

## Description



The Three-Phase Parallel RLC Load block implements a three-phase balanced load as a parallel combination of RLC elements. At the specified frequency, the load exhibits a constant impedance. The active and reactive powers absorbed by the load are proportional to the square of the applied voltage.

Only elements associated with nonzero powers are displayed in the block icon.

## Dialog Box and Parameters

## Configuration

The connection of the three phases. Select one of the following four connections:

# Three-Phase Parallel RLC Load

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Y(grounded)	Neutral is grounded.
Y(floating)	Neutral is not accessible.
Y(neutral)	Neutral is made accessible through a fourth connector.
Delta	Three phases connected in delta

The block icon is updated according to the load connection.

## **Nominal phase-to-phase voltage $V_n$**

The nominal phase-to-phase voltage of the load, in volts RMS ( $V_{rms}$ ).

## **Nominal frequency $f_n$**

The nominal frequency, in hertz (Hz).

## **Active power $P$**

The three-phase active power of the load, in watts (W).

## **Inductive reactive power $Q_L$**

The three-phase inductive reactive power  $Q_L$ , in vars. Specify a positive value, or 0.

## **Capacitive reactive power $Q_C$**

The three-phase capacitive reactive power  $Q_C$ , in vars. Specify a positive value, or 0.

## **Measurements**

Select **Branch voltages** to measure the three voltages across each phase of the Three-Phase Parallel RLC Load block terminals. For a Y connection, these voltages are the phase-to-ground or phase-to-neutral voltages. For a delta connection, these voltages are the phase-to-phase voltages.

Select **Branch currents** to measure the three total currents (sum of R, L, C currents) flowing through each phase of the Three-Phase Parallel RLC Load block. For a delta connection, these currents are the currents flowing in each branch of the delta.

# Three-Phase Parallel RLC Load

Select **Branch voltages and currents** to measure the three voltages and the three currents of the Three-Phase Parallel RLC Load block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name.

Measurement		Label
Branch voltages	Y(grounded): Uag, Ubg, Ucg	Uag: , Ubg: , Ucg:
	Y(floating): Uan, Ubn, Ucn	Uan: , Ubn: , Ucn:
	Y(neutral): Uan, Ubn, Ucn	Uan: , Ubn: , Ucn:
	Delta: Uab, Ubc, Uca	Uab: , Ubc: , Uca:
Branch currents	Y(grounded): Ia, Ib, Ic	Iag: , Ibg: , Icg:
	Y(floating): Ia, Ib, Ic	Ian: , Ibn: , Icn:
	Y(neutral): Ia, Ib, Ic	Ian: , Ibn: , Icn:
	Delta: Iab, Ibc, Ica	Iab: , Ibc: , Ica:

## See Also

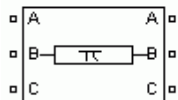
Multimeter, Three-Phase Dynamic Load, Three-Phase Parallel RLC Branch, Three-Phase Series RLC Branch, Three-Phase Series RLC Load

# Three-Phase PI Section Line

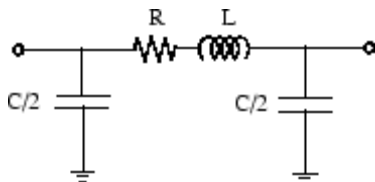
**Purpose** Implement three-phase transmission line section with lumped parameters

**Library** Elements

**Description** The Three-Phase PI Section Line block implements a balanced three-phase transmission line model with parameters lumped in a PI section.



Contrary to the Distributed Parameter Line model where the resistance, inductance, and capacitance are uniformly distributed along the line, the Three-Phase PI Section Line block lumps the line parameters in a single PI section as shown in the figure below where only one phase is represented.

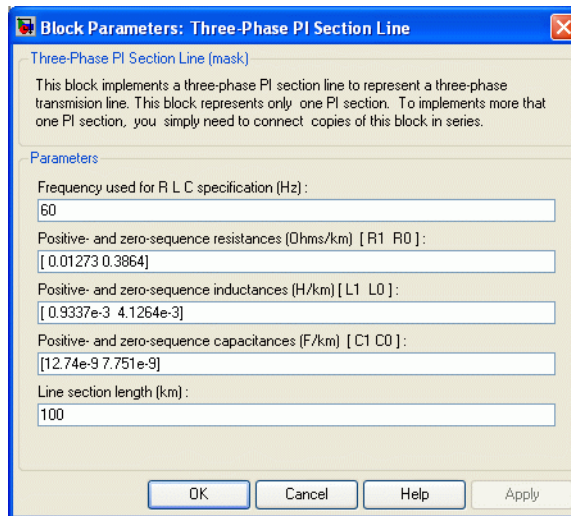


The line parameters  $R$ ,  $L$ , and  $C$  are specified as positive- and zero-sequence parameters that take into account the inductive and capacitive couplings between the three phase conductors as well as the ground parameters. This method of specifying line parameters assumes that the three phases are balanced.

Using a single PI section model is appropriate for modeling short transmission lines or when the frequency range of interest is limited around the fundamental frequency. You can obtain a more accurate model by cascading several identical blocks. See the PI Section Line for explanations of the maximum frequency range that can be achieved by a PI line model.

**Note** The Powergui block provides a graphical tool for the calculation of the resistance, inductance, and capacitance per unit length based on the line geometry and the conductor characteristics. See the Powergui to learn on how to use this tool.

## Dialog Box and Parameters



### Frequency used for R L C specification

The frequency used for specification of line parameters, in hertz (Hz). This is usually the nominal system frequency (50 Hz or 60 Hz).

### Positive- and zero-sequence resistances

The positive- and zero-sequence resistances in ohms/kilometer ( $\Omega/\text{km}$ ).

### Positive- and zero-sequence inductances

The positive- and zero-sequence inductances in henries/kilometer (H/km).

# Three-Phase PI Section Line

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## **Positive- and zero-sequence capacitances**

The positive- and zero-sequence capacitances in farads/kilometer (F/km).

## **Line section length**

The line section length in kilometers (km).

## **Example**

The `power_triphaseline` demo illustrates voltage transients at the receiving end of a 200 km line when only phase A is energized. Voltages obtained with two line models are compared: 1) the Distributed Parameters Line block and 2) a PI line model using two Three-Phase PI Section Line blocks.

## **See Also**

Distributed Parameter Line, PI Section Line

# Three-Phase Programmable Voltage Source

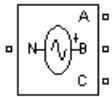
## Purpose

Implement three-phase voltage source with programmable time variation of amplitude, phase, frequency, and harmonics

## Library

Electrical Sources

## Description



Use this block to generate a three-phase sinusoidal voltage with time-varying parameters. You can program the time variation for the amplitude, phase, or frequency of the fundamental component of the source. In addition, two harmonics can be programmed and superimposed on the fundamental signal.

## Dialog Box and Parameters

**Block Parameters: Three-Phase Programmable Voltage Source**

Three-Phase Programmable Voltage Source (mask) (link)

This block implements a three-phase zero-impedance voltage source. The common node (neutral) of the three sources is accessible via input 1 (N) of the block. Time variation for the amplitude, phase and frequency of the fundamental can be pre-programmed. In addition, two harmonics can be superimposed on the fundamental.

Note: For "Phasor simulation", frequency variation and harmonic injection are not allowed. Specify Order=1 and Seq=1,2 or 0 to inject additional fundamental components A and B in any sequence.

Parameters

Positive-sequence: [ Amplitude(Vrms Ph-Ph) Phase(deg.) Freq. (Hz) ]  
[100 0 60]

Time variation of: Amplitude

Type of variation: Step

Step magnitude (pu, deg. or Hz):  
0.5

Variation timing (s) : [ Start End ]  
[1 2]

Fundamental and/or Harmonic generation:

A: [ Order(n) Amplitude(pu) Phase(degrees) Seq(0, 1 or 2) ]  
[3 0.2 -25 0]

B: [ Order(n) Amplitude(pu) Phase(degrees) Seq(0, 1 or 2) ]  
[2 0.15 35 2]

Timing (s) : [ Start End ]  
[0.05 3]

OK Cancel Help Apply

# Three-Phase Programmable Voltage Source

---

## **Positive-sequence**

The amplitude in volts RMS phase-to-phase, the phase in degrees, and the frequency in hertz of the positive-sequence component of the three voltages.

## **Time variation of**

Specify the parameter for which you want to program the time variation. Select **None** if you do not want to program the time variation of the source parameters. Select **Amplitude** if you want to program the time variation of the amplitude. Select **Phase** if you want to program the time variation of the phase. Select **Frequency** if you want to program the time variation of the frequency.

Note that the time variation applies on the three phases of the source except when the **Type of variation** parameter is set to **Table of amplitude-pairs**, in which case you can apply a variation on phase A only.

## **Type of variation**

Specify the type of variation that is applied on the parameter specified by the **Time variation of** parameter. Select **Step** to program a step variation. Select **Ramp** to program a ramp variation. Select **Modulation** to program a modulated variation. Select **Table of amplitude-pairs** to program a series of step changes of amplitudes at specific times.

## **Step magnitude**

This parameter is only visible if the **Type of Variation** parameter is set to **Step**.

Specify the amplitude of the step change. The variation of amplitude is specified in pu of the positive-sequence amplitude.

## **Rate of change**

This parameter is only visible if the **Type of Variation** parameter is set to **Ramp**.



# Three-Phase Programmable Voltage Source

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Specify the rate of change, in volt/seconds. The rate of change of voltage is specified in (pu of the positive-sequence voltage)/second.

## **Amplitude of the modulation**

This parameter is only visible if the **Type of variation** parameter is set to Modulation.

Specify the amplitude of the modulation for the source parameter specified in the **Time variation of** parameter. When the varying quantity is the voltage amplitude, the amplitude of the modulation is specified in pu of the positive-sequence amplitude.

## **Frequency of the modulation**

This parameter is only visible if the **Type of variation** parameter is set to Modulation.

Specify the frequency of the modulation for the source parameter specified in the **Time variation of** parameter.

## **Variation timing(s)**

Specify the time, in seconds, when the programmed time variation takes effect and the time when it stops.

## **Fundamental and/or Harmonic generation**

If selected, two harmonics can be programmed to be superimposed on the fundamental voltage of the source.

## **A: [Order Amplitude Phase Seq]**

This parameter is only visible if the **Fundamental and/or Harmonic generation** check box is selected.

Specify the order, amplitude, phase, and the type of sequence (1 = positive-sequence; 2 = negative-sequence; 0 = zero-sequence) of the first harmonic to be superimposed on the fundamental signal. The voltage of the harmonic is specified in pu of the positive-sequence voltage.

Specify 1 for the harmonic order and 0 or 2 for the sequence to produce a voltage imbalance without harmonics.

# Three-Phase Programmable Voltage Source

---

## **B: [Order Amplitude Phase Seq]**

This parameter is only visible if the **Fundamental and/or Harmonic generation** check box is selected.

Specify the order, amplitude, phase, and the type of sequence (0 = zero sequence, 1 = positive sequence, 2 = negative sequence) of the second harmonic to be superimposed on the fundamental signal. The voltage of the harmonic is specified in pu of the positive-sequence voltage.

Specify 1 for the harmonic order and 0 or 2 for the sequence to produce a voltage unbalance without harmonics.

## **Variation Timing(s)**

This parameter is only visible if the **Fundamental and/or Harmonic generation** check box is selected.

Specify the time, in seconds, when the harmonic generation is superimposed on the fundamental signal and the time when it stops.

## **Example**

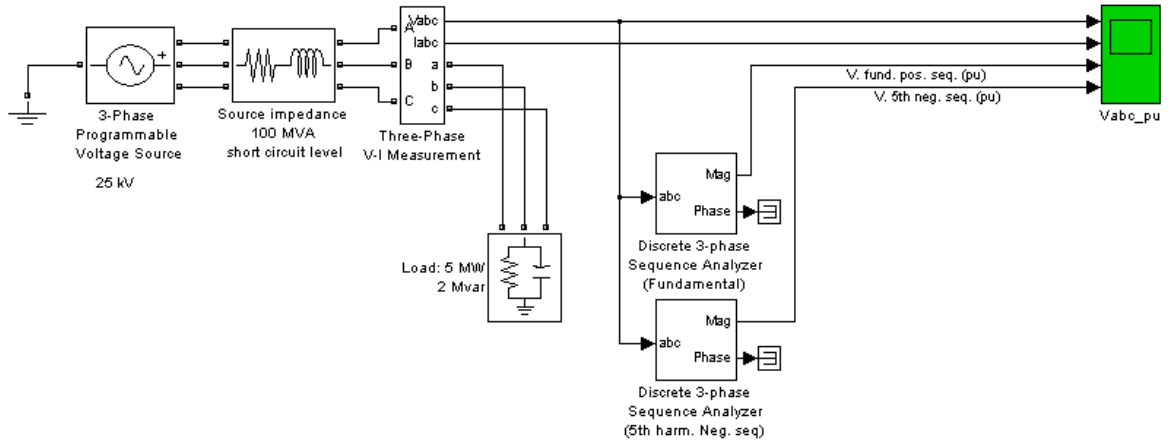
The power\_3phsignalseq circuit illustrates the use of the Three-Phase Programmable Voltage Source block to produce a step variation of the positive-sequence voltage and to inject harmonics into the circuit.

A 25 kV, 100 MVA short-circuit level, equivalent network feeds a 5 MW, 2 Mvar capacitive load. The internal voltage of the source is controlled by the Discrete 3-phase Programmable Voltage Source block.

A positive sequence of 1.0 pu, 0 degrees is specified for the fundamental signal. At  $t = 0.05$  s a step of 0.5 pu is applied on the positive-sequence voltage magnitude, then at  $t = 0.1$  s, 0.08 pu of fifth harmonic in negative sequence is added to the 1.5 pu voltage.

The three-phase voltage and current are measured at the output of the source impedance. Two Discrete Sequence Analyzer blocks are used to measure the positive-sequence fundamental component and the negative-sequence fifth harmonic of the three-phase voltage.

# Three-Phase Programmable Voltage Source



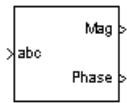
**See Also**      Three-Phase Source

# Three-Phase Sequence Analyzer

**Purpose** Measure positive-, negative-, and zero-sequence components of three-phase signal

**Library** Extras/Measurements  
A discrete version of this block is available in the Extras/Discrete Measurements library

## Description



The Three-Phase Sequence Analyzer block outputs the magnitude and phase of the positive- (denoted by the index 1), negative- (index 2), and zero-sequence (index 0) components of a set of three balanced or unbalanced signals. The signals can contain harmonics or not. The three sequence components of a three-phase signal (voltages  $V_1$   $V_2$   $V_0$  or currents  $I_1$   $I_2$   $I_0$ ) are computed as follows:

$$V_1 = \frac{1}{3}(V_a + a \cdot V_b + a^2 \cdot V_c)$$

$$V_2 = \frac{1}{3}(V_a + a^2 \cdot V_b + a \cdot V_c)$$

$$V_0 = \frac{1}{3}(V_a + V_b + V_c)$$

where

$V_a, V_b, V_c$  = three voltage phasors at specified frequency

$$a = e^{j2\pi/3} = 1\angle 120\text{degree complex operator}$$

A Fourier analysis over a sliding window of one cycle of the specified frequency is first applied to the three input signals. It evaluates the phasor values  $V_a$ ,  $V_b$ , and  $V_c$  at the specified fundamental or harmonic frequency. Then the transformation is applied to obtain the positive sequence, negative sequence, and zero sequence.

The Three-Phase Sequence Analyzer block is not sensitive to harmonics or imbalances. However, as this block uses a running average window to perform the Fourier analysis, one cycle of simulation has to be

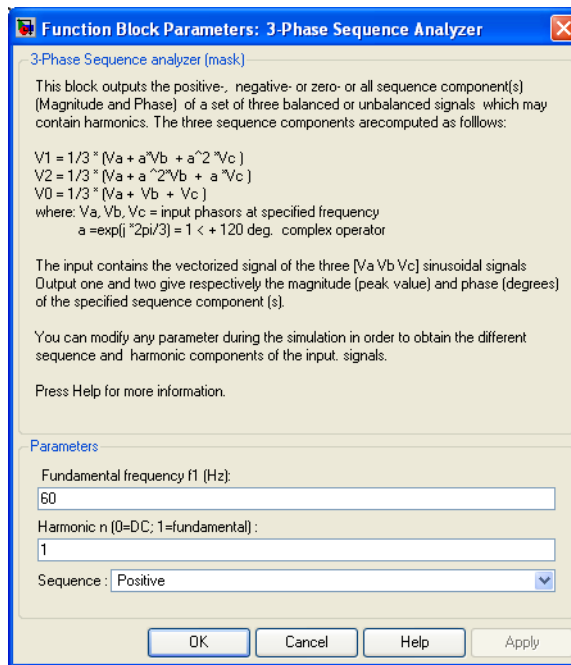
# Three-Phase Sequence Analyzer

completed before the outputs give the correct magnitude and angle. For example, its response to a step change of  $V_1$  is a one-cycle ramp.

The discrete version of this block allows you to specify the initial magnitude and phase of the output signal. For the first cycle of simulation the outputs are held to the values specified by the initial input parameter.

You can modify any parameter during the simulation in order to obtain the different sequence and harmonic components of the input signals.

## Dialog Box and Parameters



### Fundamental frequency f1

The fundamental frequency, in hertz, of the three-phase input signal.

# Three-Phase Sequence Analyzer

---

## Harmonic n

Specify the harmonic component from which you want to evaluate the sequences. For DC, enter 0. For fundamental, enter 1.

## Sequence

Specify which sequence component the block outputs. Select **Positive** to calculate the positive sequence, select **Negative** to calculate the negative sequence, select **0** to compute the zero sequence of the fundamental or specified harmonic of the three-phase input signal. Select **Positive Negative Zero** to get all the sequences.

## Inputs and Outputs

abc

Connect to the input the vectorized signal of the three [a b c] sinusoidal signals.

Mag

The first output gives the magnitude (peak value) of the specified sequence component.

Phase

The second output gives the phase in degrees of the specified component(s).

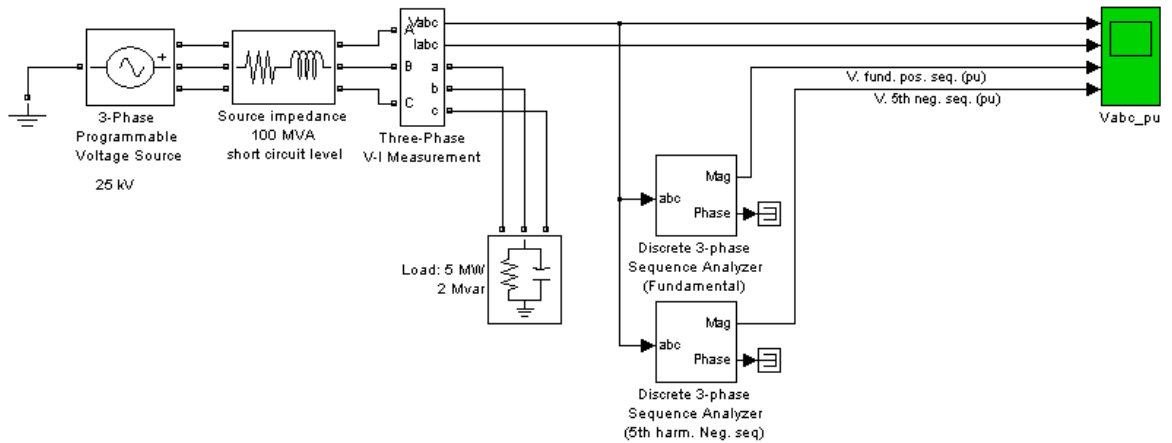
## Example

The power\_3phsignalseq demo illustrates the use of the Discrete Sequence Analyzer block to measure the fundamental and harmonic components of a three-phase voltage. A 25kV, 100 MVA short-circuit level, equivalent network feeds a 5 MW, 2 Mvar capacitive load. The internal voltage of the source is controlled by the Discrete 3-phase Programmable Voltage Source block.

A positive sequence of 1.0 pu, 0 degrees is specified for the fundamental signal. At  $t = 0.05$  s a step of 0.5 pu is applied on the positive-sequence voltage magnitude, then at  $t = 0.1$  s, 0.08 pu of fifth harmonic in negative sequence is added to the 1.5 pu voltage.

Two Discrete Three-Phase Sequence Analyzer blocks are used to measure the positive-sequence fundamental component and the negative-sequence fifth harmonic of the three-phase voltage.

# Three-Phase Sequence Analyzer



As the Three-Phase Sequence Analyzer blocks use Fourier analysis, their response time is delayed by one cycle of the fundamental frequency.

# Three-Phase Series RLC Branch

**Purpose** Implement three-phase series RLC branch

**Library** Elements

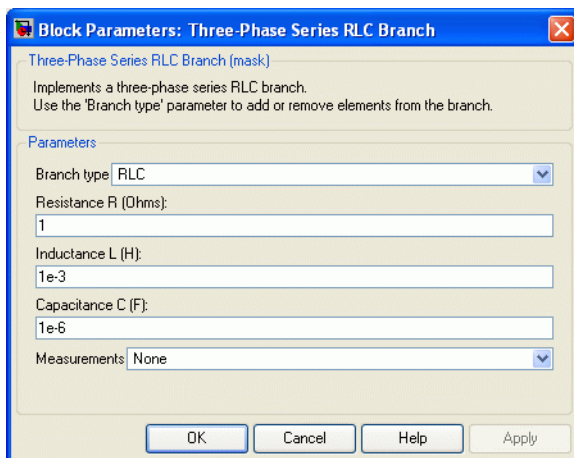
## Description



The Three-Phase Series RLC Branch block implements three balanced branches consisting each of a resistor, an inductor, or a capacitor or a series combination of these. To eliminate either the resistance, inductance, or capacitance of each branch, the R, L, and C values must be set respectively to 0, 0, and infinity (inf). Only existing elements are displayed in the block icon.

Negative values are allowed for resistance, inductance, and capacitance.

## Dialog Box and Parameters



### Branch Type

Select the elements you want to include in the branch. The **R** letter defines the resistor, the **L** letter defines the inductor, and the **C** letter defines the inductor.

### Resistance R

The branch resistances, in ohms ( $\Omega$ ).



# Three-Phase Series RLC Branch

---

## Inductance L

The branch inductances, in henries (H).

## Capacitance C

The branch capacitances, in farads (F).

## Measurements

Select **Branch voltages** to measure the three voltages across the Three-Phase Series RLC Branch block terminals.

Select **Branch currents** to measure the three currents flowing through the Three-Phase Series RLC Branch block.

Select **Branch voltages and currents** to measure the three voltages and the three currents of the Three-Phase Series RLC Branch block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name.

Measurement	Label
Branch voltages of phases A, B, and C	Ua: , Ub: , Uc:
Branch currents of phases A, B, and C	Ia: , Ib: , Ic:

## See Also

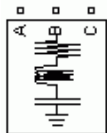
Multimeter, Three-Phase Parallel RLC Branch, Three-Phase Parallel RLC Load, Three-Phase Series RLC Load

# Three-Phase Series RLC Load

**Purpose** Implement three-phase series RLC load with selectable connection

**Library** Elements

## Description



The Three-Phase Series RLC Load block implements a three-phase balanced load as a series combination of RLC elements. At the specified frequency, the load exhibits a constant impedance. The active and reactive powers absorbed by the load are proportional to the square of the applied voltage.

Only elements associated with nonzero powers are displayed in the block icon.

## Dialog Box and Parameters

## Configuration

The connection of the three phases. Select one of the following four connections:

# Three-Phase Series RLC Load

---

Y(grounded)	Neutral is grounded.
Y(floating)	Neutral is not accessible.
Y(neutral)	Neutral is made accessible through a fourth connector.
Delta	Three phases connected in delta

The block icon is updated according to the load connection.

## **Nominal phase-to-phase voltage $V_n$**

The nominal phase-to-phase voltage of the load, in volts RMS ( $V_{rms}$ ).

## **Nominal frequency $f_n$**

The nominal frequency, in hertz (Hz).

## **Active power $P$**

The three-phase active power of the load, in watts (W).

## **Inductive reactive power $Q_L$**

The three-phase inductive reactive power  $Q_L$ , in vars. Specify a positive value, or 0.

## **Capacitive reactive power $Q_c$**

The three-phase capacitive reactive power  $Q_C$ , in vars. Specify a positive value, or 0.

## **Measurements**

Select **Branch voltages** to measure the three voltages across each phase of the Three-Phase Series RLC Load block terminals. For a Y connection, these voltages are the phase-to-ground or phase-to-neutral voltages. For a delta connection, these voltages are the phase-to-phase voltages.

Select **Branch currents** to measure the three total currents (sum of R, L, C currents) flowing through each phase of the Three-Phase Series RLC Load block. For a delta connection, these currents are the currents flowing in each branch of the delta.

# Three-Phase Series RLC Load

Select **Branch voltages** and **currents** to measure the three voltages and the three currents of the Three-Phase Series RLC Load block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name.

Measurement		Label
Branch voltages	Y(grounded): Uag, Ubg, Ucg	Uag: , Ubg: , Ucg:
	Y(floating): Uan, Ubn, Ucn	Uan: , Ubn: , Ucn:
	Y(neutral): Uan, Ubn, Ucn	Uan: , Ubn: , Ucn:
	Delta: Uab, Ubc, Uca	Uab: , Ubc: , Uca:
Branch currents	Y(grounded): Ia, Ib, Ic	Iag: , Ibg: , Icg:
	Y(floating): Ia, Ib, Ic	Ian: , Ibn: , Icn:
	Y(neutral): Ia, Ib, Ic	Ian: , Ibn: , Icn:
	Delta: Iab, Ibc, Ica	Iab: , Ibc: , Ica:

## See Also

Multimeter, Three-Phase Dynamic Load, Three-Phase Parallel RLC Branch, Three-Phase Parallel RLC Load, Three-Phase Series RLC Branch

**Purpose** Implement three-phase source with internal R-L impedance

**Library** Electrical Sources

## Description



The Three-Phase Source block implements a balanced three-phase voltage source with an internal R-L impedance. The three voltage sources are connected in Y with a neutral connection that can be internally grounded or made accessible. You can specify the source internal resistance and inductance either directly by entering R and L values or indirectly by specifying the source inductive short-circuit level and X/R ratio.

## Dialog Box and Parameters

**Block Parameters: Three-Phase Source**

Three-Phase Source (mask)  
Three-phase voltage source in series with RL branch.

Parameters

Phase-to-phase rms voltage (V):  
25e3

Phase angle of phase A (degrees):  
0

Frequency (Hz):  
60

Internal connection: Yg

Specify impedance using short-circuit level

3-phase short-circuit level at base voltage(VA):  
100e6

Base voltage (Vrms ph-ph):  
25e3

X/R ratio:  
7

OK Cancel Help Apply

### Phase-to-phase rms voltage

The internal phase-to-phase voltage in volts RMS (Vrms)

# Three-Phase Source

---

## Phase angle of phase A

The phase angle of the internal voltage generated by phase A, in degrees. The three voltages are generated in positive sequence. Thus, phase B and phase C internal voltages are lagging phase A respectively by 120 degrees and 240 degrees.

## Frequency

The source frequency in hertz (Hz).

## Internal connection

The internal connection of the three internal voltage sources. The block icon is updated according to the source connection.

Select one of the following three connections:

- Y      The three voltage sources are connected in Y to an internal floating neutral.
- Yn     The three voltage sources are connected in Y to a neutral connection which is made accessible through a fourth terminal.
- Yg     The three voltage sources are connected in Y to an internally grounded neutral.

## Specify impedance using short-circuit level

Select to specify internal impedance using the inductive short-circuit level and X/R ratio.

## 3-phase short-circuit level at base voltage

The three-phase inductive short-circuit power, in volts-amperes (VA), at specified base voltage, used to compute the internal inductance L. This parameter is available only if **Specify impedance using short-circuit level** is selected.

The internal inductance L (in H) is computed from the inductive three-phase short-circuit power Psc (in VA), base voltage Vbase (in Vrms phase-to-phase), and source frequency f (in Hz) as follows:

$$L = \frac{(V_{base})^2}{P_{sc}} \cdot \frac{1}{2\pi f}$$

## Base voltage

The phase-to-phase base voltage, in volts RMS, used to specify the three-phase short-circuit level. The base voltage is usually the nominal source voltage. This parameter is available only if **Specify impedance using short-circuit level** is selected.

## X/R ratio

The X/R ratio at nominal source frequency or quality factor of the internal source impedance. This parameter is available only if **Specify impedance using short-circuit level** is selected.

The internal resistance R (in  $\Omega$ ) is computed from the source reactance X (in  $\Omega$ ) at specified frequency, and X/R ratio as follows:

$$R = \frac{X}{(X/R)} = \frac{2\pi fL}{(X/R)}$$

## Source resistance

This parameter is available only if **Specify impedance using short-circuit level** is not selected.

The source internal resistance in ohms ( $\Omega$ ).

## Source inductance

This parameter is available only if **Specify impedance using short-circuit level** is not selected.

The source internal inductance in henries (H).

---

**Note** Either resistance or inductance of the source can be set to zero, but not both at the same time. The block icon is updated accordingly.

---

# Three-Phase Source

---

## **Example**

See the `power_3phseriescomp` demo, which uses a Three-Phase Source block to model a portion of a 735 kV system with a simplified R-L source. The source impedance is specified by using the three-phase short-circuit level (30,000 MVA) and X/R ratio ( $X/R = 10$ ).

## **See Also**

Three-Phase Programmable Voltage Source



# Three-Phase Transformer 12 Terminals

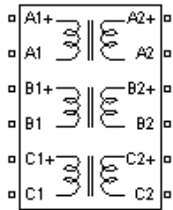
## Purpose

Implement three single-phase, two-winding transformers where all terminals are accessible

## Library

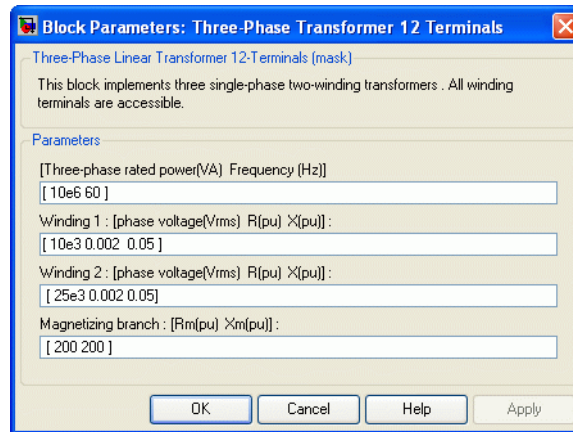
Elements

## Description



The Three-Phase Transformer 12 Terminals block implements three single-phase, two-winding linear transformers where all the twelve winding connectors are accessible. The block can be used in place of the Three-Phase Transformer (Two Windings) block to implement a three-phase transformer when primary and secondary are not necessarily connected in Y or Delta.

## Dialog Box and Parameters



### [Three-phase rated power Frequency]

The total nominal power of the three phases, in volt-amperes (VA), and the nominal frequency, in hertz (Hz).

### Winding 1: [phase voltage R X]

The nominal voltage of the three primary windings (labeled 1) in volts RMS ( $V_{rms}$ ), the winding resistances, in pu, and the winding leakage reactances, in pu.

# Three-Phase Transformer 12 Terminals

---

## **Winding 2: [phase voltage R X]**

The nominal voltage of the three secondary windings (labeled 2) in volts RMS ( $V_{rms}$ ), the winding resistances, in pu, and the winding leakage reactances, in pu.

## **Magnetizing branch: [Rm Xm]**

The resistance and reactance simulating the core active and reactive losses, both in pu. For example, to specify 0.2% of active and reactive core losses, at nominal voltage, use  $R_m = 500$  pu and  $L_m = 500$  pu.  $L_m$  can be set to `inf` (no reactive core losses), but  $R_m$  must have a finite value.

---

**Note** Refer to the Linear Transformer for explanations on the per unit system.

---

## **Example**

See the `power_3phPWM` demo for an example of use of the Three-Phase Transformer 12 Terminals block in a three-phase double-bridge voltage-sourced converter.

## **See Also**

Linear Transformer, Three-Phase Transformer (Two Windings)

# Three-Phase Transformer (Two Windings)

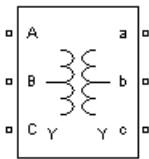
## Purpose

Implement three-phase transformer with configurable winding connections

## Library

Elements

## Description



The Three-Phase Transformer (Two Windings) block implements a three-phase transformer using three single-phase transformers. You can simulate the saturable core or not simply by setting the appropriate check box in the parameter menu of the block. See the Linear Transformer block and Saturable Transformer block sections for a detailed description of the electrical model of a single-phase transformer.

The two windings of the transformer can be connected in the following manner:

- Y
- Y with accessible neutral
- Grounded Y
- Delta (D1), delta lagging Y by 30 degrees
- Delta (D11), delta leading Y by 30 degrees

---

**Note** The D1 and D11 notations refer to the following clock convention. It assumes that the reference Y voltage phasor is at noon (12) on a clock display. D1 and D11 refer respectively to 1 PM (delta voltages lagging Y voltages by 30 degrees) and 11 AM (delta voltages leading Y voltages by 30 degrees).

---

The block takes into account the connection type you have selected, and the icon of the block is automatically updated. An input port labeled N is added to the block if you select the Y connection with accessible neutral for winding 1. If you ask for an accessible neutral on winding 2, an extra output port labeled n is generated.

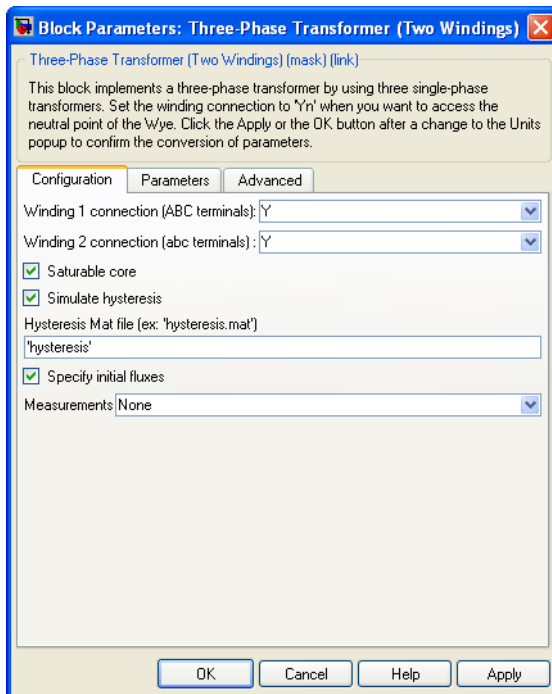
# Three-Phase Transformer (Two Windings)

The saturation characteristic, when activated, is the same as the one described for the Saturable Transformer block, and the icon of the block is automatically updated. If the fluxes are not specified, the initial values are automatically adjusted so that the simulation starts in steady state.

The leakage inductance and resistance of each winding are given in pu based on the transformer nominal power  $P_n$  and on the nominal voltage of the winding ( $V_1$  or  $V_2$ ). For an explanation of per units, refer to the Linear Transformer and to the Saturable Transformer.

## Dialog Box and Parameters

### Configuration Tab



# Three-Phase Transformer (Two Windings)

---

## **Winding 1 connection (ABC terminals)**

The winding connections for winding 1.

## **Winding 2 connection (abc terminals)**

The winding connections for winding 2.

## **Saturable core**

If selected, implements a saturable three-phase transformer. See also the **Saturation characteristic** parameter on the Parameters tab.

## **Simulate hysteresis**

Select to model a saturation characteristic including hysteresis instead of a single-valued saturation curve. This parameter is visible only if the **Saturable core** parameter is selected.

## **Hysteresis Mat file**

This parameter is visible only if the **Simulate hysteresis** parameter is selected.

Specify a `.mat` file containing the data to be used for the hysteresis model. When you open the **Hysteresis Design Tool** of the Powergui, the default hysteresis loop and parameters saved in the `hysteresis.mat` file are displayed. Use the **Load** button of the Hysteresis Design tool to load another `.mat` file. Use the **Save** button of the Hysteresis Design tool to save your model in a new `.mat` file.

## **Specify initial fluxes**

If selected, the initial fluxes are defined by the **Initial fluxes** parameter on the Parameters tab. The **Specify initial fluxes** parameter is visible only if the **Saturable core** parameter is selected.

## **Measurements**

Select **Winding voltages** to measure the voltage across the winding terminals of the Three-Phase Transformer block.

Select **Winding currents** to measure the current flowing through the windings of the Three-Phase Transformer block.

# Three-Phase Transformer (Two Windings)

---

Select **Fluxes** and excitation currents ( $I_m + I_{Rm}$ ) to measure the flux linkage, in volt seconds (V.s), and the total excitation current including iron losses modeled by  $R_m$  (for saturable transformers only).

Select **Fluxes** and magnetization currents ( $I_m$ ) to measure the flux linkage, in volt seconds (V.s), and the magnetization current, in amperes (A), not including iron losses modeled by  $R_m$  (for saturable transformers only).

Select **All measurements** (V, I, Flux) to measure the winding voltages, currents, magnetization currents, and the flux linkages.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name.

If the **Winding 1 connection (ABC terminals)** parameter is set to Y,  $Y_n$ , or  $Y_g$ , the labels are as follows).

Measurement	Label
Winding 1 voltages	$U_{an\_w1}$ : , $U_{bn\_w1}$ : , $U_{cn\_w1}$ : or $U_{ag\_w1}$ : , $U_{bg\_w1}$ : , $U_{cg\_w1}$ :
Winding 1 currents	$I_{an\_w1}$ : , $I_{bn\_w1}$ : , $I_{cn\_w1}$ : or $I_{ag\_w1}$ : , $I_{bg\_w1}$ : , $I_{cg\_w1}$ :
Fluxes	$Flux\_A$ : , $Flux\_B$ : , $Flux\_C$ :
Magnetization currents	$Imag\_A$ : , $Imag\_B$ : , $Imag\_C$ :
Excitation currents	$Iexc\_A$ : , $Iexc\_B$ : , $Iexc\_C$ :

# Three-Phase Transformer (Two Windings)

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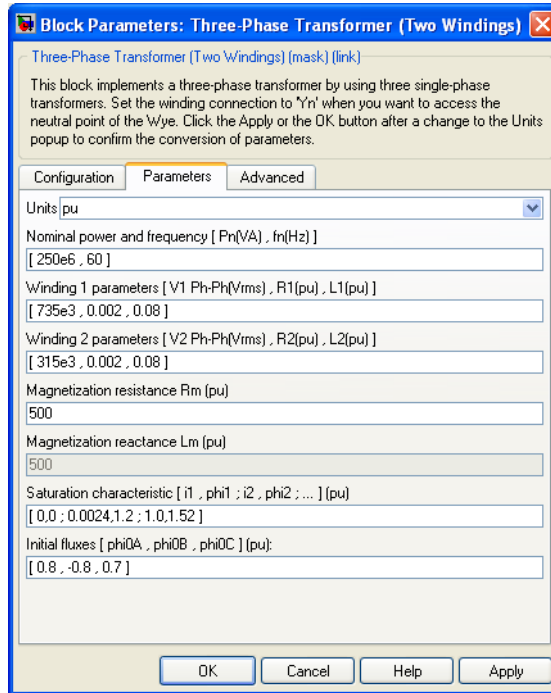
The same labels apply for winding 2, except that 1 is replaced by 2 in the labels.

If the **Winding 1 connection (ABC terminals)** parameter is set to Delta (D11) or Delta (D1), the labels are as follows.

Measurement	Label
Winding 1 voltages	Uab_w1:, Ubc_w1:, Uca_w1:
Winding 1 currents	Iab_w1:, Ibc_w1:, Ica_w1:
Flux linkages	Flux_A:, Flux_B:, Flux_C:
Magnetization currents	Imag_A:, Imag_B:, Imag_C:
Excitation currents	Iexc_A:, Iexc_B:, Iexc_C:

# Three-Phase Transformer (Two Windings)

## Parameters Tab



## Units

Specify the units used to enter the parameters of the Three Phase Transformer block. Select pu to use per unit. Select SI to use SI units. Changing the **Units** parameter from pu to SI, or from SI to pu, will automatically convert the parameters displayed in the mask of the block.

## Nominal power and frequency

The nominal power rating, in volt-amperes (VA), and nominal frequency, in hertz (Hz), of the transformer.



# Three-Phase Transformer (Two Windings)

---

## Winding 1 parameters

The phase-to-phase nominal voltage in volts RMS, resistance, and leakage inductance in pu for winding 1.

## Winding 2 parameters

The phase-to-phase nominal voltage in volts RMS, resistance, and leakage inductance in pu for winding 2.

## Magnetization resistance $R_m$

The magnetization resistance  $R_m$ , in pu.

## Magnetization reactance $L_m$

The **Magnetization reactance  $L_m$**  parameter is not accessible if the **Saturable core** parameter on the Configuration tab is selected.

The magnetization inductance  $L_m$ , in pu, for a nonsaturable core.

## Saturation characteristic

This parameter is accessible only if the **Saturable core** parameter on the Configuration tab is selected.

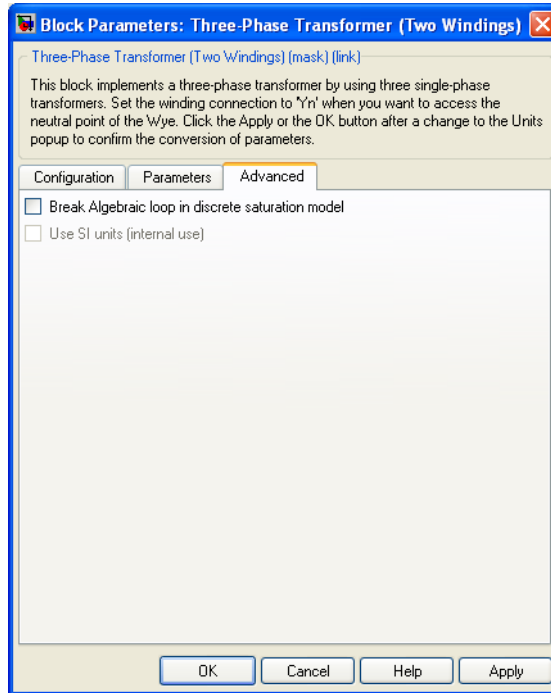
The saturation characteristic for the saturable core. Specify a series of current/ flux pairs (in pu) starting with the pair (0,0).

## Initial fluxes

Specify initial fluxes for each phase of the transformer. This parameter is accessible only if the **Specify initial fluxes** and **Saturable core** parameters on the Configuration tab are selected.

# Three-Phase Transformer (Two Windings)

## Advanced Tab



### Break Algebraic loop in discrete saturation model

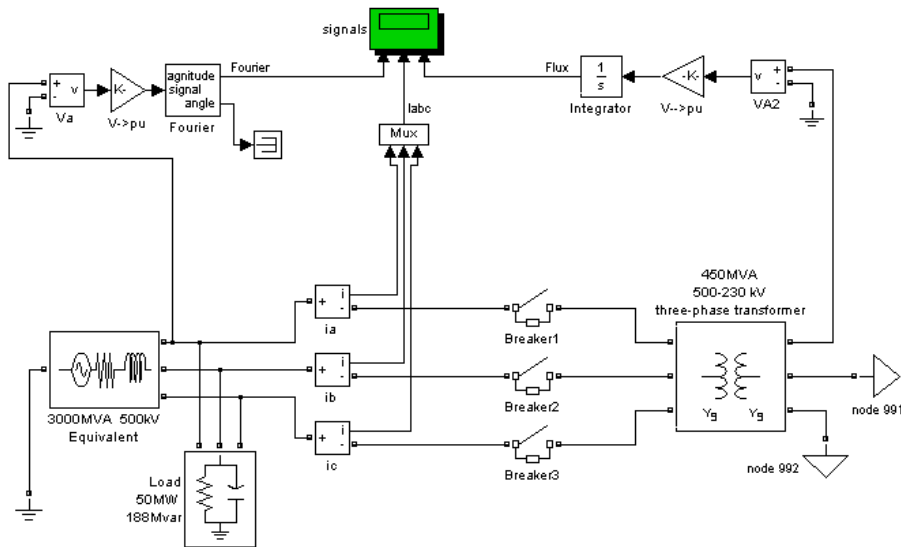
When you use the block in a discrete system, you will get an algebraic loop. This algebraic loop, which is required in most cases to get an accurate solution, tends to slow down the simulation. However, to speed up the simulation, in some circumstances, you can disable the algebraic loop by selecting **Break Algebraic loop in discrete saturation model**. You should be aware that disabling the algebraic loop introduces a one-simulation-step time delay in the model. This can cause numerical oscillations if the sample time is too large.

# Three-Phase Transformer (Two Windings)

## Example

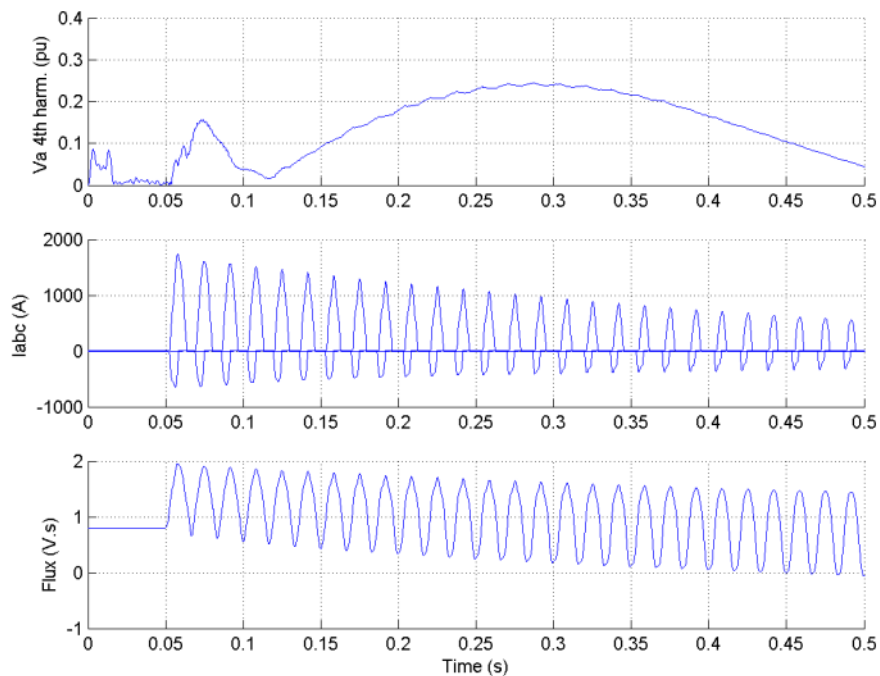
The power\_transfo3ph circuit uses the Three-Phase Transformer block where the saturable core is simulated. Both windings are connected in a Y grounded configuration. Note that the neutral points of the two windings are internally connected to the ground.

The 500 kV/ 230 kV saturable transformer is energized on the 500 kV system. Remanent fluxes of 0.8 pu, -0.4 pu, and 0.4 pu have been specified respectively for phases A, B, and C.



Run the simulation and observe inrush currents due to core saturation.

# Three-Phase Transformer (Two Windings)



## See Also

Linear Transformer, Multimeter, Saturable Transformer, Three-Phase Transformer (Three Windings), Three-Phase Transformer Inductance Matrix Type (Two Windings)

# Three-Phase Transformer (Three Windings)

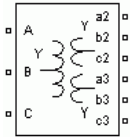
## Purpose

Implement three-phase transformer with configurable winding connections

## Library

Elements

## Description



This block implements a three-phase transformer by using three single-phase transformers with three windings. You can simulate the saturable core or not simply by setting the appropriate check box in the parameter menu of the block. See the Linear Transformer and Saturable Transformer block sections for a detailed description of the electrical model of a single-phase transformer.

The three windings of the transformer can be connected in the following manner:

- Y
- Y with accessible neutral (for windings 1 and 3 only)
- Grounded Y
- Delta (D1), delta lagging Y by 30 degrees
- Delta (D11), delta leading Y by 30 degrees

---

**Note** The D1 and D11 notations refer to the following clock convention. It assumes that the reference Y voltage phasor is at noon (12) on a clock display. D1 and D11 refer respectively to 1 PM (delta voltages lagging Y voltages by 30 degrees) and 11 AM (delta voltages leading Y voltages by 30 degrees).

---

The block takes into account the connection type you select, and the icon of the block is automatically updated. An input port labeled N is added to the block if you select the Y connection with accessible neutral for winding 1. If you ask for an accessible neutral on winding 3, an extra output port labeled n3 is generated.

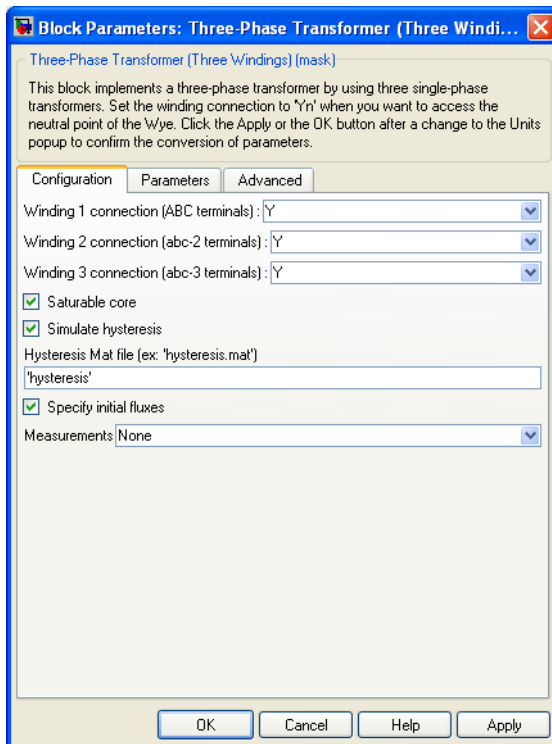
# Three-Phase Transformer (Three Windings)

The saturation characteristic, when activated, is the same as the one described for the Saturable Transformer block, and the icon of the block is automatically updated. If the fluxes are not specified, the initial values are automatically adjusted so that the simulation starts in steady state.

The leakage inductances and resistance of each winding are given in pu based on the transformer nominal power  $P_n$  and on the nominal voltage of the winding ( $V_1$ ,  $V_2$ , or  $V_3$ ). For an explanation of per units, refer to the Linear Transformer and to the Saturable Transformer.

## Dialog Box and Parameters

### Configuration Tab



# Three-Phase Transformer (Three Windings)

---

## **Winding 1 connection (ABC terminals)**

The winding connection for winding 1.

## **Winding 2 connection (abc-2 terminals)**

The winding connection for winding 2.

## **Winding 3 connection (abc-3 terminals)**

The winding connection for winding 3.

## **Saturable core**

If selected, implements a saturable three-phase transformer. See also the **Saturation characteristic** parameter on the Parameters tab.

## **Simulate hysteresis**

Select to model a saturation characteristic including hysteresis instead of a single-valued saturation curve. This parameter is visible only if the **Saturable core** parameter is selected.

## **Hysteresis Mat file**

This parameter is visible only if the **Simulate hysteresis** parameter is selected.

Specify a `.mat` file containing the data to be used for the hysteresis model. When you open the **Hysteresis Design Tool** of the Powergui, the default hysteresis loop and parameters saved in the `hysteresis.mat` file are displayed. Use the **Load** button of the Hysteresis Design tool to load another `.mat` file. Use the **Save** button of the Hysteresis Design tool to save your model in a new `.mat` file.

## **Specify initial fluxes**

If selected, the initial fluxes are defined by the **Initial fluxes** parameter on the Parameters tab. The **Specify initial fluxes** parameter is visible only if the **Saturable core** parameter is selected.

## **Measurements**

Select **Winding voltages** to measure the voltage across the winding terminals of the Three-Phase Transformer block.

# Three-Phase Transformer (Three Windings)

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Select **Winding currents** to measure the current flowing through the windings of the Three-Phase Transformer block.

Select **Fluxes** and excitation currents ( $I_m + I_{Rm}$ ) to measure the flux linkage, in volt seconds (V.s), and the total excitation current including iron losses modeled by  $R_m$  (for saturable transformers only).

Select **Fluxes** and magnetization currents ( $I_m$ ) to measure the flux linkage, in volt seconds (V.s), and the magnetization current, in amperes (A), not including iron losses modeled by  $R_m$  (for saturable transformers only).

Select **All measurements** (V, I, Flux) to measure the winding voltages, currents, magnetization currents, and the flux linkages.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name.

If the **Winding 1 connection (ABC terminals)** parameter is set to Y,  $Y_n$ , or  $Y_g$ , the labels are as follows.

Measurement	Label
Winding 1 voltages	$U_{an\_w1}$ :, $U_{bn\_w1}$ :, $U_{cn\_w1}$ :
	or
	$U_{ag\_w1}$ :, $U_{bg\_w1}$ :, $U_{cg\_w1}$ :
Winding 1 currents	$I_{an\_w1}$ :, $I_{bn\_w1}$ :, $I_{cn\_w1}$ :
	or
	$I_{ag\_w1}$ :, $I_{bg\_w1}$ :, $I_{cg\_w1}$ :
Flux linkages	$Flux_A$ :, $Flux_B$ :, $Flux_C$ :



# Three-Phase Transformer (Three Windings)

Measurement	Label
Magnetization currents	Imag_A:, Imag_B:, Imag_C:
Excitation currents	Iexc_A:, Iexc_B:, Iexc_C:

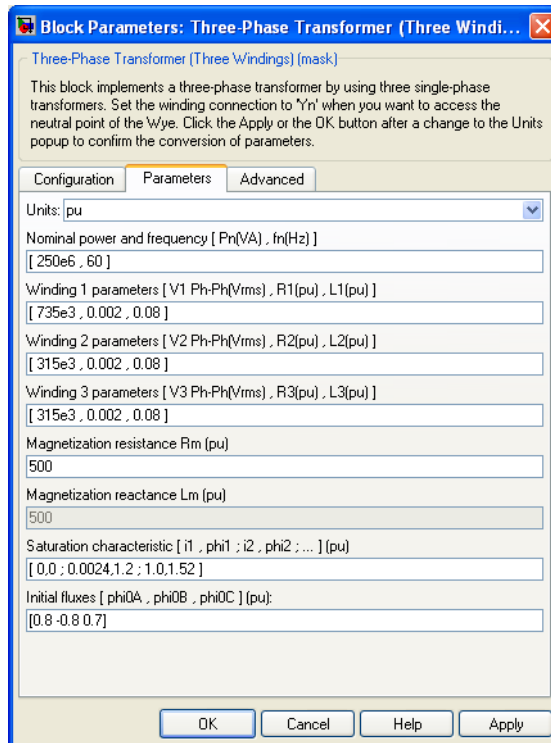
The same labels apply for winding 2 and winding 3, except that the 1 is replaced by 2 or by 3 in the labels.

If the **Winding 1 connection (ABC terminals)** parameter is set to Delta (D11) or Delta (D1), the labels are as follows.

Measurement	Label
Winding 1 voltages	Uab_w1:, Ubc_w1:, Uca_w1:
Winding 1 currents	Iab_w1:, Ibc_w1:, Ica_w1:
Flux linkages	Flux_A:, Flux_B:, Flux_C:
Magnetization currents	Imag_A:, Imag_B:, Imag_C:
Excitation currents	Iexc_A:, Iexc_B:, Iexc_C:

# Three-Phase Transformer (Three Windings)

## Parameters Tab



## Units

Specify the units used to enter the parameters of the Three Phase Transformer block. Select pu to use per unit. Select SI to use SI units. Changing the **Units** parameter from pu to SI, or from SI to pu, will automatically convert the parameters displayed in the mask of the block.

## Nominal power and frequency

The nominal power rating, in volt-amperes (VA), and nominal frequency, in hertz (Hz), of the transformer.

# Three-Phase Transformer (Three Windings)

---

## **Winding 1 parameters**

The phase-to-phase nominal voltage in volts RMS, resistance, and leakage inductance in pu for winding 1.

## **Winding 2 parameters**

The phase-to-phase nominal voltage in volts RMS, resistance, and leakage inductance in pu for winding 2.

## **Winding 3 parameters**

The phase-to-phase nominal voltage in volts RMS, resistance, and leakage inductance in pu for winding 3.

## **Magnetization resistance Rm**

The magnetization resistance Rm, in pu.

## **Magnetization reactance Lm**

The magnetization inductance Lm, in pu, for a nonsaturable core. The **Magnetization reactance Lm** parameter is not accessible if the **Saturable core** parameter is selected.

## **Saturation characteristic**

This parameter is accessible only if the **Saturable core** parameter is selected.

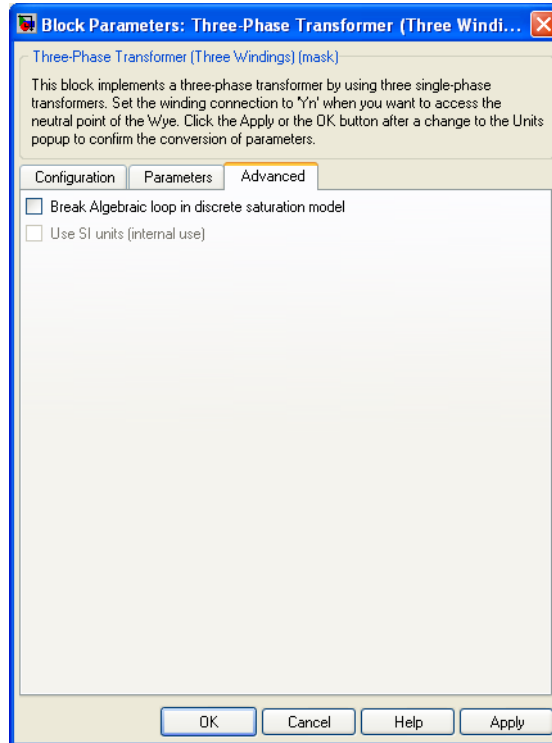
The saturation characteristic for the saturable core. Specify a series of current/ flux pairs (in pu) starting with the pair (0,0).

## **Initial fluxes**

Specifies initial fluxes for each phase of the transformer. This parameter is visible only if the **Specify initial fluxes** and **Saturable core** parameters are selected on the Configuration tab.

# Three-Phase Transformer (Three Windings)

## Advanced Tab



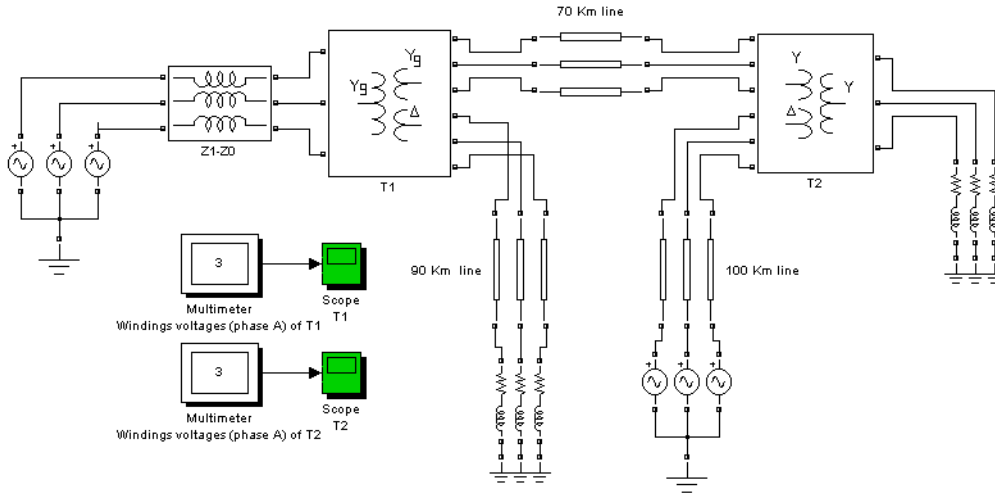
### Break Algebraic loop in discrete saturation model

When you use the block in a discrete system, you will get an algebraic loop. This algebraic loop, which is required in most cases to get an accurate solution, tends to slow down the simulation. However, to speed up the simulation, in some circumstances, you can disable the algebraic loop by selecting **Break Algebraic loop in discrete saturation model**. You should be aware that disabling the algebraic loop introduces a one-simulation-step time delay in the model. This can cause numerical oscillations if the sample time is too large.

# Three-Phase Transformer (Three Windings)

## Example

The power\_transfo3wdn circuit uses two Three-Phase Transformer blocks. Two Multimeter blocks are used to measure the phase A voltage (or AB for delta connections) of each winding



## See Also

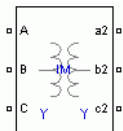
Linear Transformer, Multimeter, Saturable Transformer, Three-Phase Transformer (Two Windings), Three-Phase Transformer Inductance Matrix Type (Three Windings)

# Three-Phase Transformer Inductance Matrix Type (Two Windings)

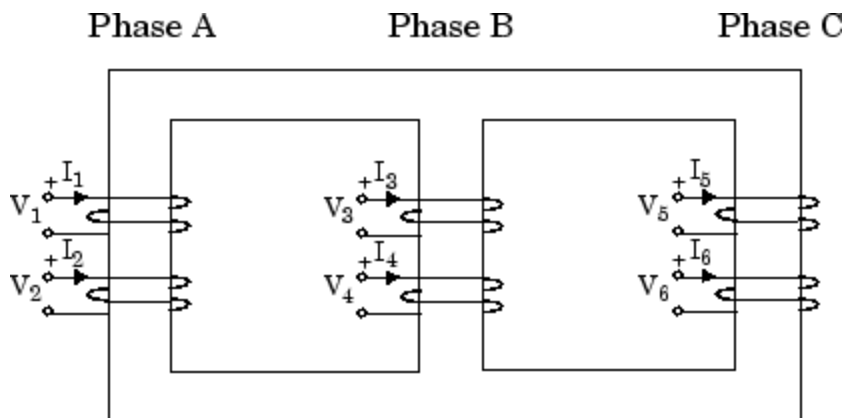
**Purpose** Implement three-phase two-winding transformer with configurable winding connections and core geometry

**Library** Elements

**Description** The standard Three-Phase Transformer (Two Windings) block uses three single-phase transformers to implement a three-phase model. When a three-phase transformer is built with a three-limb core or a five-limb core this model does not represent the couplings between windings of different phases.



A three-phase transformer using a three-limb core and two windings per phase is shown on the figure below. Windings are numbered as follows: 1, 2 for phase A, 3, 4 for phase B and 5, 6 for phase C.



This core geometry implies that winding 1 is coupled to all other windings (2 to 6), whereas in a three-phase transformer using three independent cores (as in the Three-Phase Transformer (Two Windings) block) winding 1 is coupled only with winding 2.

## Transformer Model

The Three-Phase Transformer Inductance Matrix Type (Two Windings) block implements the following matrix relationship:

# Three-Phase Transformer Inductance Matrix Type (Two Windings)

$$\begin{bmatrix} V_1 \\ V_2 \\ \dots \\ V_6 \end{bmatrix} = \begin{bmatrix} R_1 & 0 & \dots & 0 \\ 0 & R_2 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & R_6 \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \\ \dots \\ I_6 \end{bmatrix} + \begin{bmatrix} L_{11} & L_{12} & \dots & L_{16} \\ L_{21} & L_{22} & \dots & L_{26} \\ \dots & \dots & \dots & \dots \\ L_{61} & L_{62} & \dots & L_{66} \end{bmatrix} \cdot \frac{d}{dt} \begin{bmatrix} I_1 \\ I_2 \\ \dots \\ I_6 \end{bmatrix}$$

$R_1$  to  $R_6$  represent the winding resistances. The self inductance terms  $L_{ii}$  and the mutual inductance terms  $L_{ij}$  are computed from the voltage ratios, the inductive component of the no load excitation currents and the short-circuit reactances at nominal frequency. Two sets of values in positive-sequence and in zero-sequence allow calculation of the 6 diagonal terms and 15 off-diagonal terms of the symmetrical inductance matrix.

When the parameter **Core type** is set to Three single-phase cores, the model uses two independent circuits with (3x3) R and L matrices. In this condition, the positive-sequence and zero-sequence parameters are identical and you need only specifying positive-sequence values.

Calculation of the inductance matrix is performed as follows.

Assuming, the following positive-sequence parameters for the two three-phase windings 1 and 2:

$QI_1$  = Three-phase reactive power absorbed by winding 1 at no load when winding 1 is excited by a positive-sequence voltage  $Vnom_1$  with winding 2 open

$QI_2$  = Three-phase reactive power absorbed by winding 2 at no load when winding 2 is excited by a positive-sequence voltage  $Vnom_2$  with winding 1 open

$X_{112}$  = positive-sequence short-circuit reactance seen from winding 1 when winding 2 is short-circuited

$Vnom_1, Vnom_2$  = nominal line-line voltages of windings 1 and 2

The positive-sequence self and mutual reactances are given by:

## Three-Phase Transformer Inductance Matrix Type (Two Windings)

---

$$X_1(1, 1) = \frac{V_{nom_1}^2}{Q1_1}$$

$$X_1(2, 2) = \frac{V_{nom_2}^2}{Q1_2}$$

$$X_1(1, 2) = X_1(2, 1) = \sqrt{X_1(1, 1) \cdot X_1(2, 2) - X1_{12}^2}$$

The zero-sequence self reactances  $X_0(1,1)$ ,  $X_0(2,2)$  and mutual reactance  $X_0(1,2) = X_0(2,1)$  are also computed using similar equations.

Extension from the two 2x2 reactance matrices in positive-sequence and in zero-sequence

$$\begin{bmatrix} X_1(1, 1) & X_1(1, 2) \\ X_1(2, 1) & X_1(2, 2) \end{bmatrix} \quad \begin{bmatrix} X_0(1, 1) & X_0(1, 2) \\ X_0(2, 1) & X_0(2, 2) \end{bmatrix}$$

to a 6x6 matrix, is performed by replacing each of the four scalar terms by a 3x3 sub-matrix of the form:

$$\begin{bmatrix} X_s & X_m & X_m \\ X_m & X_s & X_m \\ X_m & X_m & X_s \end{bmatrix}$$

where the self and mutual terms are given by:

$$X_s = \frac{1}{3}(X_0 + 2X_1)$$

$$X_m = \frac{1}{3}(X_0 - X_1)$$



# Three-Phase Transformer Inductance Matrix Type (Two Windings)

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In order to model the core losses (active power P1 and P0 in positive- and zero-sequences), additional shunt resistances are also connected to terminals of one of the three-phase windings. If winding 1 is selected, the resistances are computed as:

$$R1_1 = \frac{Vnom_1^2}{P1_1} \quad R0_1 = \frac{Vnom_1^2}{P0_1}$$

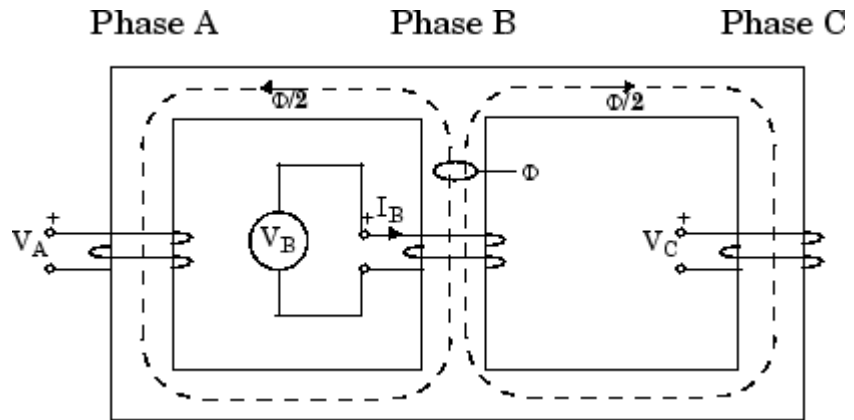
The block takes into account the connection type you select, and the icon of the block is automatically updated. An input port labeled N is added to the block if you select the Y connection with accessible neutral for winding 1. If you ask for an accessible neutral on winding 2, an extra output port labeled n2 is generated.

## Excitation Current in Zero Sequence

Often, the zero-sequence excitation current of a transformer with a 3-limb core is not provided by the manufacturer. In such a case a reasonable value can be guessed as explained below.

The figure below shows a 3-limb core with a 3-phase winding. Only phase B is excited and voltage is measured on phase A and phase C. The flux  $\Phi$  produced by phase B shares equally between phase A and phase C so that  $\Phi/2$  is flowing in limb A and in limb C. Therefore, in this particular case, if leakage inductance of winding B would be zero, voltage induced on phases A and C would be  $-k \cdot V_{B-} - V_B/2$ . In fact, because of the leakage inductance of the three windings, the average value of induced voltage ratio  $k$  when windings A, B and C are successively excited must be slightly lower than 0.5.

# Three-Phase Transformer Inductance Matrix Type (Two Windings)



Assume:

$Z_s$  = average value of the three self impedances

$Z_m$  = average value of mutual impedance between phases

$Z_1$  = positive-sequence impedance of three-phase winding

$Z_0$  = zero-sequence impedance of three-phase winding

$I_1$  = positive-sequence excitation current

$I_0$  = zero-sequence excitation current

# Three-Phase Transformer Inductance Matrix Type (Two Windings)

$$V_B = Z_s I_B$$

$$V_A = Z_m I_B = -V_B/2$$

$$V_C = Z_m I_B = -V_B/2$$

$$Z_s = \frac{(2Z_1 + Z_0)}{3}$$

$$Z_m = \frac{(Z_0 - Z_1)}{3}$$

$$V_A = V_C = \frac{Z_m}{Z_s} V_B = -\frac{\frac{Z_1}{Z_0} - 1}{2\frac{Z_1}{Z_0} + 1} V_B = -\frac{\frac{I_0}{I_1} - 1}{2\frac{I_0}{I_1} + 1} V_B = -k V_B$$

where  $k$  = ratio of induced voltage (with  $k$  slightly lower than 0.5)

Therefore, the  $I_0/I_1$  ratio can be deduced from  $k$ :

$$\frac{I_0}{I_1} = \frac{1+k}{1-2k}$$

Obviously  $k$  cannot be exactly 0.5 because this would lead to an infinite zero-sequence current. Also, when the three windings are excited with a zero-sequence voltage, the flux path should return through the air and tank surrounding the iron core. The high reluctance of the zero-sequence flux path results in a high zero-sequence current.

Let us assume  $I_1 = 0.5\%$ . A reasonable value for  $I_0$  could be 100%. Therefore  $I_0/I_1 = 200$ . According to the equation for  $I_0/I_1$  given above, one can deduce the value of  $k$ .  $k = (200-1)/(2*200+1) = 199/401 = 0.496$ .

Zero-sequence losses should be also higher than the positive-sequence losses because of the additional eddy current losses in the tank.

# Three-Phase Transformer Inductance Matrix Type (Two Windings)

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Finally, it should be mentioned that neither the value of the zero-sequence excitation current nor the value of the zero-sequence losses are critical if the transformer has a winding connected in Delta because this winding acts as a short circuit for zero-sequence.

## **Winding Connections**

The two windings of the transformer can be connected in the following manner:

- Y
- Y with accessible neutral
- Grounded Y
- Delta (D1), delta lagging Y by 30 degrees
- Delta (D11), delta leading Y by 30 degrees

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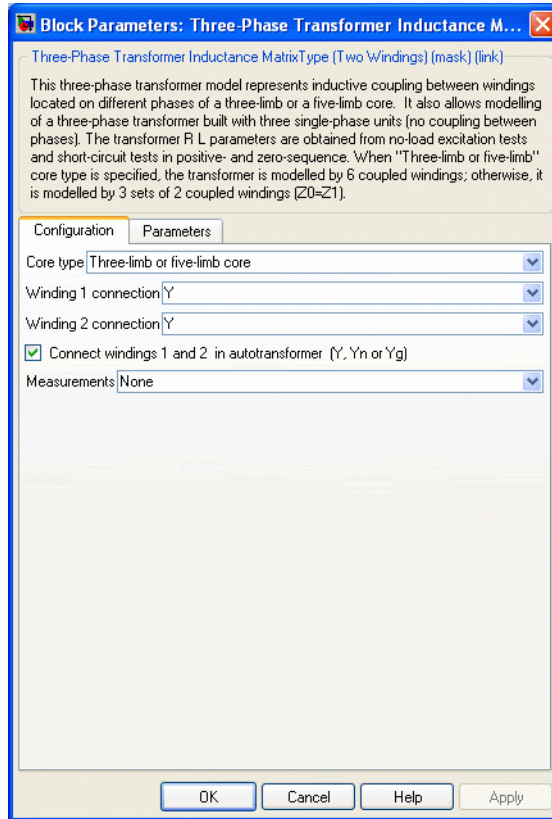
**Note** The D1 and D11 notations refer to the following clock convention. It assumes that the reference Y voltage phasor is at noon (12) on a clock display. D1 and D11 refer respectively to 1 PM (delta voltages lagging Y voltages by 30 degrees) and 11 AM (delta voltages leading Y voltages by 30 degrees).

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# Three-Phase Transformer Inductance Matrix Type (Two Windings)

## Dialog Box and Parameters

### Configuration Tab



### Core type

Select the core geometry: Three single-phase cores or Three-limb or five-limb core. If you select the first option, only the positive-sequence parameters are used to compute the inductance matrix. If you select the second option, both the positive- and zero-sequence parameters are used.

# Three-Phase Transformer Inductance Matrix Type (Two Windings)

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## Winding 1 connection

The winding connection for winding 1.

## Winding 2 connection

The winding connection for winding 2.

## Connect windings 1 and 2 in autotransformer

Check this parameter to connect windings 1 and 2 in autotransformer.

Specifying this connection connects windings 1 and 2 in series with additive voltage. If the first voltage specified in the **Nominal line-line voltages** parameter is higher than the second voltage, the low voltage tap is connected on the right side (a2,b2,c2 terminals). Otherwise, the low voltage tap is connected on the left side (A,B,C terminals). If you select this option you must specify the same winding connections for windings 1 and 2. If you select Yn for both winding 1 and winding 2, the common neutral N connector is displayed on the left side.

## Measurements

Select **Winding voltages** to measure the voltage across the winding terminals of the Three-Phase Transformer block.

Select **Winding currents** to measure the current flowing through the windings of the Three-Phase Transformer block.

Select **All measurements** to measure the winding voltages and currents.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name.

If the **Winding 1 connection** parameter is set to Y, Yn, or Yg, the labels are as follows.

# Three-Phase Transformer Inductance Matrix Type (Two Windings)

Measurement	Label
Winding 1 voltages	Uan_w1:, Ubn_w1:, Ucn_w1: or Uag_w1:, Ubg_w1:, Ucg_w1:
Winding 1 currents	Ian_w1:, Ibn_w1:, Icn_w1: or Iag_w1:, Ibg_w1:, Icg_w1:

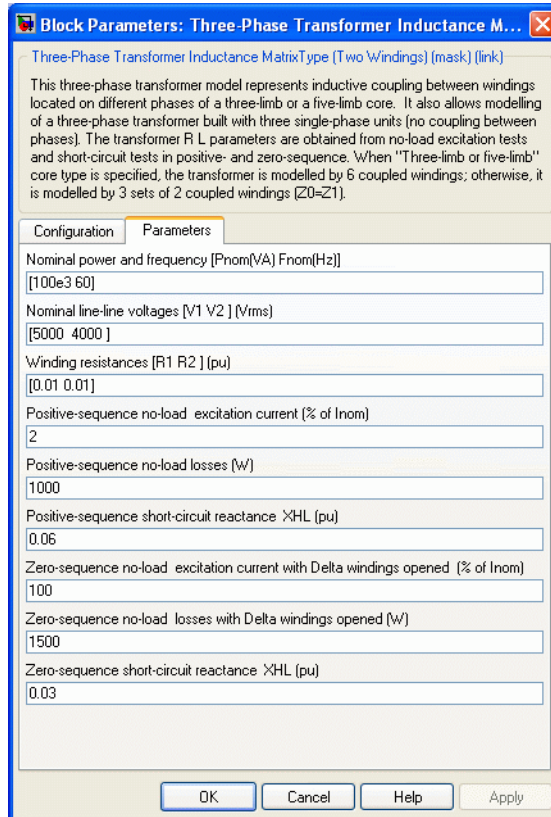
If the **Winding 1 connection** parameter is set to Delta (D11) or Delta (D1), the labels are as follows.

Measurement	Label
Winding 1 voltages	Uab_w1:, Ubc_w1:, Uca_w1:
Winding 1 currents	Iab_w1:, Ibc_w1:, Ica_w1:

The same labels apply for winding 2, except that 1 is replaced by 2 in the labels.

# Three-Phase Transformer Inductance Matrix Type (Two Windings)

## Parameters Tab



Block Parameters: Three-Phase Transformer Inductance Matrix Type (Two Windings) [mask] [link]

This three-phase transformer model represents inductive coupling between windings located on different phases of a three-limb or a five-limb core. It also allows modelling of a three-phase transformer built with three single-phase units (no coupling between phases). The transformer R L parameters are obtained from no-load excitation tests and short-circuit tests in positive- and zero-sequence. When "Three-limb or five-limb" core type is specified, the transformer is modelled by 6 coupled windings; otherwise, it is modelled by 3 sets of 2 coupled windings (Z0=Z1).

Configuration Parameters

Nominal power and frequency [Pnom(VA) Fnom(Hz)]  
[100e3 60]

Nominal line-line voltages [V1 V2] (Vrms)  
[5000 4000]

Winding resistances [R1 R2] (pu)  
[0.01 0.01]

Positive-sequence no-load excitation current (% of Inom)  
2

Positive-sequence no-load losses (W)  
1000

Positive-sequence short-circuit reactance XHL (pu)  
0.06

Zero-sequence no-load excitation current with Delta windings opened (% of Inom)  
100

Zero-sequence no-load losses with Delta windings opened (W)  
1500

Zero-sequence short-circuit reactance XHL (pu)  
0.03

OK Cancel Help Apply

### Nominal power and frequency

The nominal power rating, in volt-amperes (VA), and nominal frequency, in hertz (Hz), of the transformer.

### Nominal line-line voltages [V1 V2]

The phase-to-phase nominal voltages of windings 1 and 2 in volts RMS.



# Three-Phase Transformer Inductance Matrix Type (Two Windings)

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## **Winding resistances [R1 R2]**

The resistances in pu for windings 1 and 2.

## **Positive-sequence no-load excitation current**

The no-load excitation current in percent of the nominal current when positive-sequence nominal voltage is applied at any group of winding terminals (ABC, or abc2).

## **Positive-sequence no-load losses**

The core losses plus winding losses at no-load, in watts (W), when positive-sequence nominal voltage is applied at any group of winding terminals (ABC or abc2).

## **Positive-sequence short-circuit reactance**

The positive-sequence short-circuit reactances  $X_{12}$  in pu, where  $X_{12}$  is the reactance measured from winding 1 when winding 2 is short-circuited.

When the **Connect windings 1 and 2 in autotransformer** parameter is selected, the short-circuit reactances is labeled  $X_{HL}$ , where H and L indicate respectively the high voltage winding (either winding 1 or winding 2) and the low voltage winding (either winding 1 or winding 2).

## **Zero-sequence no-load excitation current with Delta windings opened**

The no-load excitation current in percent of the nominal current when zero-sequence nominal voltage is applied at any group of winding terminals (ABC or abc2).

If you want to measure this excitation current, you must connect the excited winding in  $Y_g$  or  $Y_n$  in order to provide a return path for the source zero-sequence currents. Also, the Delta connection of the other winding must be open; otherwise, this Delta connection would produce a short-circuit for zero sequence. You must therefore temporarily change the open winding connection from D1 or D11 to Y,  $Y_g$ ,  $Y_n$ .

# Three-Phase Transformer Inductance Matrix Type (Two Windings)

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## Zero-sequence no-load losses with Delta windings opened

The core losses plus winding losses at no-load, in watts (W), when zero-sequence nominal voltage is applied at any group of winding terminals (ABC or abc2). The Delta winding must be temporarily open in order to measure these losses.

## Zero-sequence short-circuit reactance

The zero-sequence short-circuit reactance  $X_{12}$  in pu, where  $X_{12}$  is the reactance measured from winding 1 when winding 2 is short-circuited.

When the **Connect windings 1 and 2 in autotransformer** parameter is selected, the short-circuit reactances is labeled XHL, where H and L indicate respectively the high voltage winding (either winding 1 or winding 2) and the low voltage winding (either winding 1 or winding 2).

## Limitations

This transformer model does not include saturation. If you need modeling saturation connect the primary winding of a saturable Three-Phase Transformer (Two Windings) in parallel with the primary winding of your model. Use same connection (Yg, D1 or D11) and same winding resistance for the two windings connected in parallel. Specify Y or Yg connection for the secondary winding and leave it open. Specify appropriate voltage, power ratings and desired saturation characteristics. The saturation characteristic is the characteristic obtained when then transformer is excited by a positive-sequence voltage.

If you are modeling a transformer with three single-phase cores or a five-limb core, this model will produce acceptable saturation currents because flux stays trapped inside the iron core.

For a three-limb core, it is less evident that this saturation model also gives acceptable results because zero-sequence flux circulates outside of the core and returns through the air and the transformer tank surrounding the iron core. However, as the zero-sequence flux circulates in the air, the magnetic circuit is mainly linear and its reluctance is high (high magnetizing currents). These high zero-sequence currents (100%

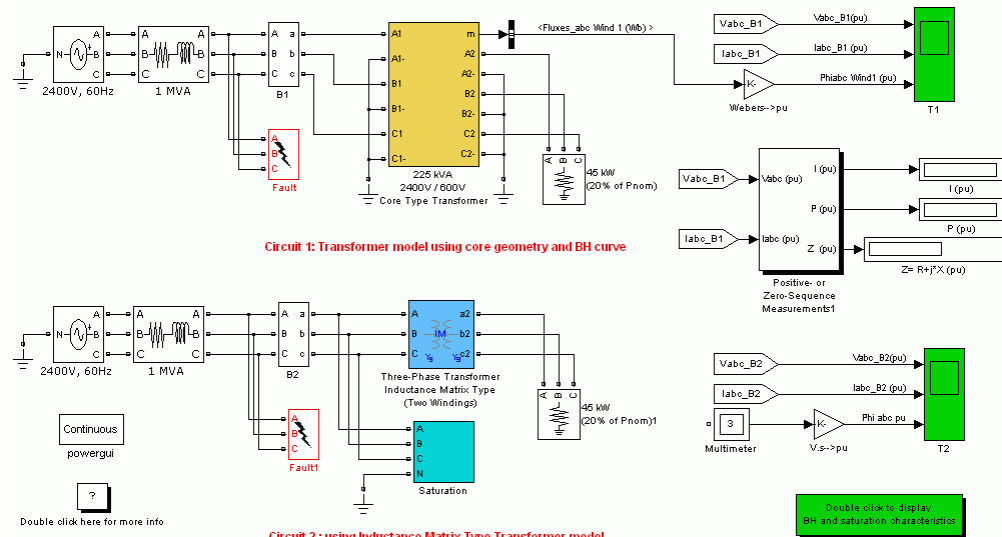
# Three-Phase Transformer Inductance Matrix Type (Two Windings)

and more of nominal current) required to magnetize the air path are already taken into account in the linear model. Connecting a saturable transformer outside the three-limb linear model with a flux-current characteristic obtained in positive sequence will produce currents required for magnetization the iron core. This model will give acceptable results whether the three-limb transformer has a delta or not.

The following example shows how to model saturation in an inductance matrix type two-winding transformer.

## Example

The power\_Transfo3phCoreType demo model uses the Three-Phase Transformer Inductance Matrix Type (Two Windings) block to model a two-winding core type transformer. It also demonstrates how to model transformer saturation.



Modeling a 225 kVA, 2400V/600V Three-Phase Core-Type Transformer

The model shows two identical circuits with a three-phase transformer rated 225 kVA, 2400 V/600V, 60Hz, connected to a 1 MVA, 2400 V power

# Three-Phase Transformer Inductance Matrix Type (Two Windings)

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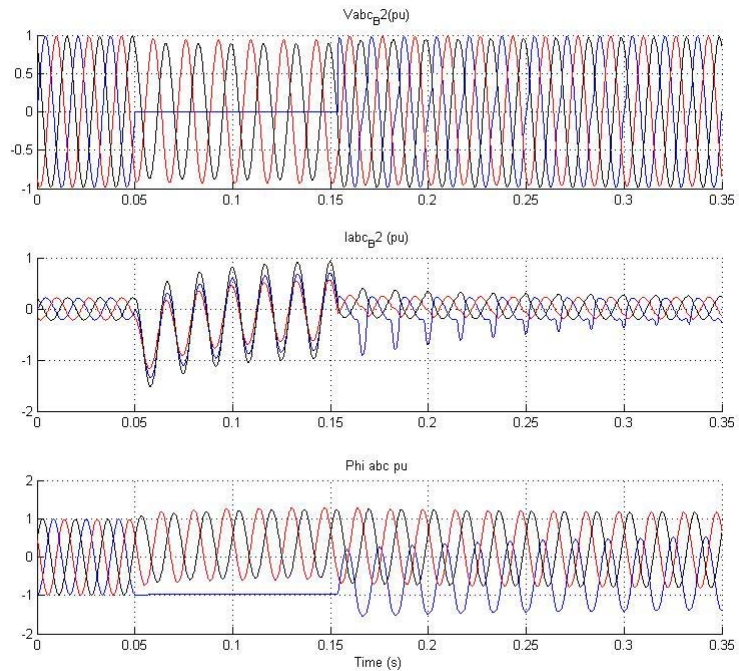
network. A 45 kW resistive load (20 % of transformer nominal power) is connected on the 600 V side. Each phase of the transformer consists of two windings, both connected in wye with a grounded neutral.

The transformers in circuit 1 and circuit 2 use two different models:

- Circuit 1 uses a physical model (yellow block) where the core geometry and the B-H characteristic of the iron used to build the core are the basic parameters used for modeling the magnetic properties of the transformer.
- Circuit 2 uses the Three-Phase Transformer Inductance Matrix Type (Two Windings) block (blue block) for modeling the linear part of the model. Saturation is modeled in the Saturation subsystem (cyan block) by three single-phase saturable transformers connected on the primary side of the linear transformer model.

The demo compares performance of both circuits when a single-phase to ground fault is applied on the high voltage terminals of the transformers. Voltages, currents, and fluxes obtained with the Inductance Matrix Type transformer are reproduced below.

# Three-Phase Transformer Inductance Matrix Type (Two Windings)



## See Also

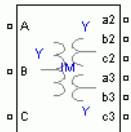
Linear Transformer, Multimeter, Three-Phase Transformer (Two Windings), Three-Phase Transformer (Three Windings), Three-Phase Transformer Inductance Matrix Type (Three Windings)

# Three-Phase Transformer Inductance Matrix Type (Three Windings)

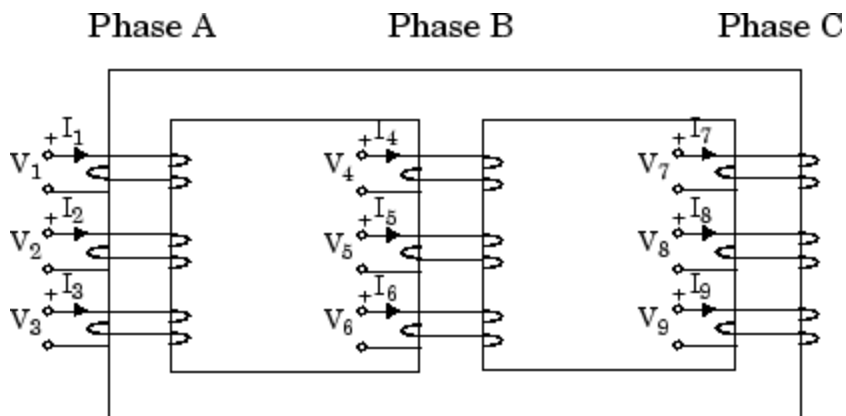
**Purpose** Implement three-phase three-winding transformer with configurable winding connections and core geometry

**Library** Elements

**Description** The standard Three-Phase Transformer (Three Windings) block uses three single-phase transformers to implement a three-phase model. When a three-phase transformer is built with a three-limb core or a five-limb core this model does not represent the couplings between windings of different phases.



A three-phase transformer using a three-limb core and three windings per phase is shown on the figure below. Windings are numbered as follows: 1, 2, 3 for phase A, 4, 5, 6 for phase B and 7, 8, 9 for phase C.



This core geometry implies that winding 1 is coupled to all other windings (2 to 9), whereas in a three-phase transformer using three independent cores (as in Three-Phase Transformer (Three Windings) block) winding 1 is coupled only with windings 2 and 3.

## Transformer Model

The Three-Phase Transformer Inductance Matrix Type (Three-Windings) block implements the following matrix relationship:

# Three-Phase Transformer Inductance Matrix Type (Three Windings)

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$$\begin{bmatrix} V_1 \\ V_2 \\ \dots \\ V_9 \end{bmatrix} = \begin{bmatrix} R_1 & 0 & \dots & 0 \\ 0 & R_2 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & R_9 \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \\ \dots \\ I_9 \end{bmatrix} + \begin{bmatrix} L_{11} & L_{12} & \dots & L_{19} \\ L_{21} & L_{22} & \dots & L_{29} \\ \dots & \dots & \dots & \dots \\ L_{91} & L_{92} & \dots & L_{99} \end{bmatrix} \cdot \frac{d}{dt} \begin{bmatrix} I_1 \\ I_2 \\ \dots \\ I_9 \end{bmatrix}$$

$R_1$  to  $R_9$  represent the winding resistances. The self inductance terms  $L_{ii}$  and the mutual inductance terms  $L_{ij}$  are computed from the voltage ratios, the inductive component of the no load excitation currents and the short-circuit reactances at nominal frequency. Two sets of values in positive-sequence and in zero-sequence allow calculation of the 9 diagonal terms and 36 off-diagonal terms of the symmetrical inductance matrix.

When the parameter **Core type** is set to `Three single-phase cores`, the model uses three independent circuits with (3x3) R and L matrices. In this condition, the positive-sequence and zero-sequence parameters are identical and you need only specifying positive-sequence values.

Calculation of the inductance matrix is performed as follows.

Assuming, the following positive-sequence parameters for two sets of three-phase windings i and j:

$Q_{1i}$  = Three-phase reactive power absorbed by winding i at no load when winding i is excited by a positive-sequence voltage  $Vnom_i$  with winding j open

$Q_{1j}$  = Three-phase reactive power absorbed by winding j at no load when winding j is excited by a positive-sequence voltage  $Vnom_j$  with winding i open

$X_{1ij}$  = positive-sequence short-circuit reactance seen from winding i when winding j is short-circuited

$Vnom_i$ ,  $Vnom_j$  = nominal line-line voltages of windings i and j

The positive-sequence self and mutual reactances are given by:

# Three-Phase Transformer Inductance Matrix Type (Three Windings)

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$$X_1(i, i) = \frac{Vnom_i^2}{Q_{1i}}$$

$$X_1(j, j) = \frac{Vnom_j^2}{Q_{1j}}$$

$$X_1(i, j) = X_1(j, i) = \sqrt{X_1(i, i) \cdot X_1(j, j) - X_{1ij}^2}$$

The zero-sequence self reactances  $X_0(i, i)$ ,  $X_0(j, j)$  and mutual reactance  $X_0(i, j) = X_0(j, i)$  are also computed using similar equations.

Extension from the two 2x2 reactance matrices in positive-sequence and in zero-sequence

$$\begin{bmatrix} X_1(i, i) & X_1(i, j) \\ X_1(j, i) & X_1(j, j) \end{bmatrix} \quad \begin{bmatrix} X_0(i, i) & X_0(i, j) \\ X_0(j, i) & X_0(j, j) \end{bmatrix}$$

to a 6x6 matrix, is performed by replacing each of the four scalar terms by a 3x3 sub-matrix of the form:

$$\begin{bmatrix} X_s & X_m & X_m \\ X_m & X_s & X_m \\ X_m & X_m & X_s \end{bmatrix}$$

where the self and mutual terms are given by:

$$X_s = \frac{1}{3}(X_0 + 2X_1)$$

$$X_m = \frac{1}{3}(X_0 - X_1)$$



# Three-Phase Transformer Inductance Matrix Type (Three Windings)

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In order to model the core losses (active power  $P_1$  and  $P_0$  in positive- and zero-sequences), additional shunt resistances are also connected to terminals of one of the three-phase winding. If winding  $i$  is selected, the resistances are computed as:

$$R_{1_i} = \frac{V_{nom_i}^2}{P_{1_i}} \quad R_{0_i} = \frac{V_{nom_i}^2}{P_{0_i}}$$

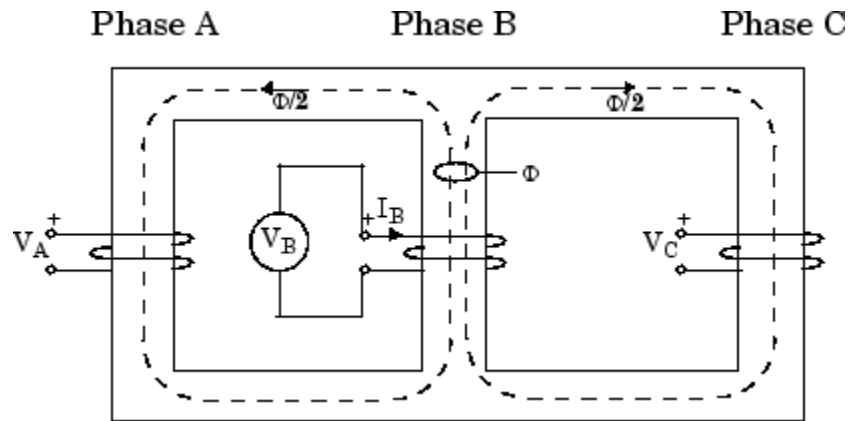
The block takes into account the connection type you select, and the icon of the block is automatically updated. An input port labeled  $N$  is added to the block if you select the  $Y$  connection with accessible neutral for winding 1. If you ask for an accessible neutral on winding 2 or 3, an extra output port labeled  $n_2$  or  $n_3$  is generated.

## Excitation Current in Zero Sequence

Often, the zero-sequence excitation current of a transformer with a 3-limb core is not provided by the manufacturer. In such a case a reasonable value can be guessed as explained below.

The figure below shows a 3-limb core with a 3-phase winding. Only phase B is excited and voltage is measured on phase A and phase C. The flux  $\Phi$  produced by phase B shares equally between phase A and phase C so that  $\Phi/2$  is flowing in limb A and in limb C. Therefore, in this particular case, if leakage inductance of winding B would be zero, voltage induced on phases A and C would be  $-k \cdot V_B - V_B/2$ . In fact, because of the leakage inductance of the three windings, the average value of induced voltage ratio  $k$  when windings A, B and C are successively excited must be slightly lower than 0.5

# Three-Phase Transformer Inductance Matrix Type (Three Windings)



Assume:

$Z_s$  = average value of the three self impedances

$Z_m$  = average value of mutual impedance between phases

$Z_1$  = positive-sequence impedance of three-phase winding

$Z_0$  = zero-sequence impedance of three-phase winding

$I_1$  = positive-sequence excitation current

$I_0$  = zero-sequence excitation current

## Three-Phase Transformer Inductance Matrix Type (Three Windings)

---

$$V_B = Z_s I_B$$

$$V_A = Z_m I_B = -V_B/2$$

$$V_C = Z_m I_B = -V_B/2$$

$$Z_s = \frac{(2Z_1 + Z_0)}{3}$$

$$Z_m = \frac{(Z_0 - Z_1)}{3}$$

$$V_A = V_C = \frac{Z_m}{Z_s} V_B = -\frac{\frac{Z_1}{Z_0} - 1}{2\frac{Z_1}{Z_0} + 1} V_B = -\frac{\frac{I_0}{I_1} - 1}{2\frac{I_0}{I_1} + 1} V_B = -k V_B$$

where  $k$  = ratio of induced voltage (with  $k$  slightly lower than 0.5)

Therefore, the  $I_0/I_1$  ratio can be deduced from  $k$ :

$$\frac{I_0}{I_1} = \frac{1+k}{1-2k}$$

Obviously  $k$  cannot be exactly 0.5 because this would lead to an infinite zero-sequence current. Also, when the three windings are excited with a zero-sequence voltage the flux path should return through the air and tank surrounding the iron core. The high reluctance of the zero-sequence flux path results in a high zero-sequence current.

Let us assume  $I_1 = 0.5\%$ . A reasonable value for  $I_0$  could be 100%. Therefore  $I_0/I_1 = 200$ . According to the equation for  $I_0/I_1$  given above, one can deduce the value of  $k$ .  $k = (200-1)/(2*200+1) = 199/401 = 0.496$ .

Zero-sequence losses should be also higher than the positive-sequence losses because of the additional eddy current losses in the tank.

# Three-Phase Transformer Inductance Matrix Type (Three Windings)

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Finally, it should be mentioned that neither the value of the zero-sequence excitation current nor the value of the zero-sequence losses are critical if the transformer has a winding connected in Delta because this winding acts as a short circuit for zero-sequence.

## **Winding Connections**

The three windings of the transformer can be connected in the following manner:

- Y
- Y with accessible neutral
- Grounded Y
- Delta (D1), delta lagging Y by 30 degrees
- Delta (D11), delta leading Y by 30 degrees

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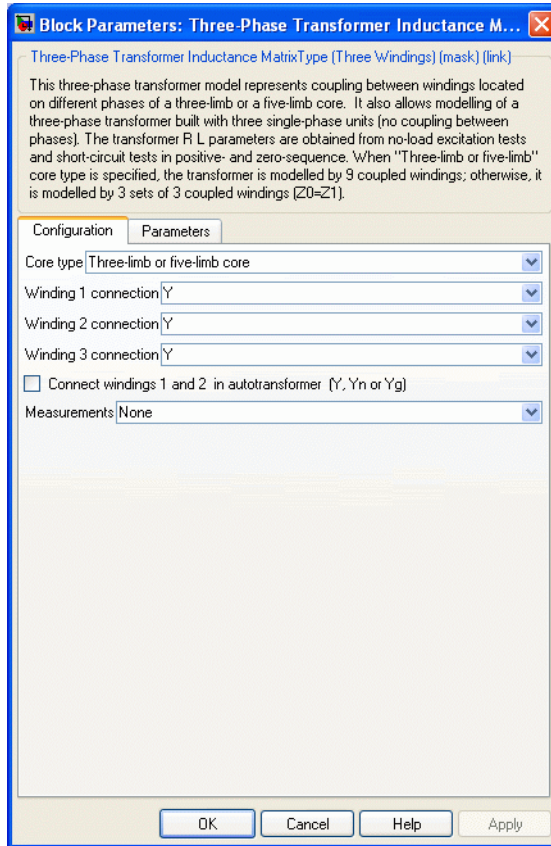
**Note** The D1 and D11 notations refer to the following clock convention. It assumes that the reference Y voltage phasor is at noon (12) on a clock display. D1 and D11 refer respectively to 1 PM (delta voltages lagging Y voltages by 30 degrees) and 11 AM (delta voltages leading Y voltages by 30 degrees).

---

# Three-Phase Transformer Inductance Matrix Type (Three Windings)

## Dialog Box and Parameters

### Configuration Tab



### Core type

Select the core geometry: Three single-phase cores or Three-limb or five-limb core. If you select the first option only the positive-sequence parameters are used to compute the inductance matrix. If you select the second option, both the positive- and zero-sequence parameters are used.

# Three-Phase Transformer Inductance Matrix Type (Three Windings)

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## Winding 1 connection

The winding connection for winding 1.

## Winding 2 connection

The winding connection for winding 2.

## Winding 3 connection

The winding connection for winding 3.

## Connect windings 1 and 2 in autotransformer

Check this parameter to connect windings 1 and 2 in autotransformer.

Specifying this connection connects windings 1 and 2 in series with additive voltage. If the first voltage specified in the **Nominal line-line voltages** parameter is higher than the second voltage, the low voltage tap is connected on the right side (a2,b2,c2 terminals). Otherwise, the low voltage tap is connected on the left side (A,B,C terminals). If you select this option you must specify the same winding connections for windings 1 and 2. If you select Yn for both winding 1 and winding 2, the common neutral N connector is displayed on the left side.

## Measurements

Select **Winding voltages** to measure the voltage across the winding terminals of the Three-Phase Transformer block.

Select **Winding currents** to measure the current flowing through the windings of the Three-Phase Transformer block.

Select **All measurements** to measure the winding voltages and currents.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name.

# Three-Phase Transformer Inductance Matrix Type (Three Windings)

---

If the **Winding 1 connection** parameter is set to Y, Yn, or Yg, the labels are as follows.

Measurement	Label
Winding 1 voltages	Uan_w1:, Ubn_w1:, Ucn_w1: or Uag_w1:, Ubg_w1:, Ucg_w1:
Winding 1 currents	Ian_w1:, Ibn_w1:, Icn_w1: or Iag_w1:, Ibg_w1:, Icg_w1:

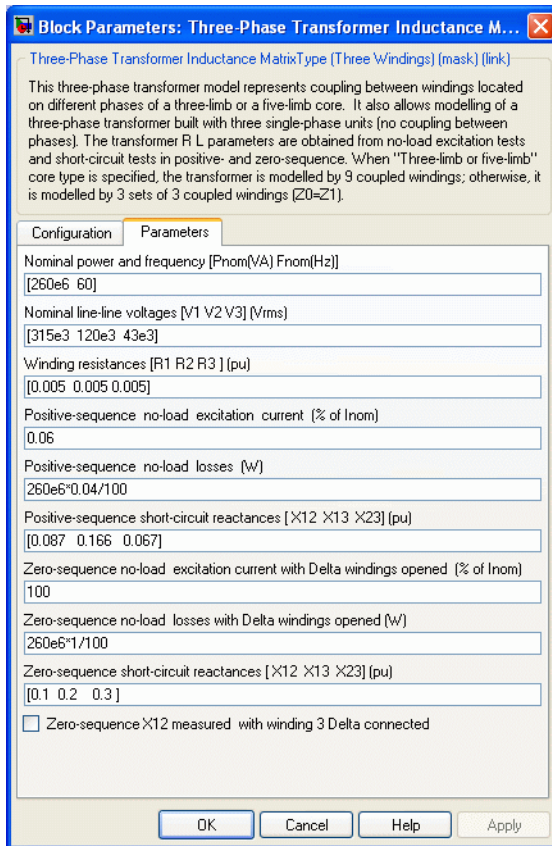
If the **Winding 1 connection** parameter is set to Delta (D11) or Delta (D1), the labels are as follows.

Measurement	Label
Winding 1 voltages	Uab_w1:, Ubc_w1:, Uca_w1:
Winding 1 currents	Iab_w1:, Ibc_w1:, Ica_w1:

The same labels apply for windings 2 and 3, except that 1 is replaced by 2 or 3 in the labels.

# Three-Phase Transformer Inductance Matrix Type (Three Windings)

## Parameters Tab



### Nominal power and frequency

The nominal power rating, in volt-amperes (VA), and nominal frequency, in hertz (Hz), of the transformer.

### Nominal line-line voltages [V1 V2 V3]

The phase-to-phase nominal voltages of windings 1, 2, 3 in volts RMS.



# Three-Phase Transformer Inductance Matrix Type (Three Windings)

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## **Winding resistances [R1 R2 R3]**

The resistances in pu for windings 1, 2 and 3.

## **Positive-sequence no-load excitation current**

The no-load excitation current in percent of the nominal current when positive-sequence nominal voltage is applied at any group of winding terminals (ABC, abc2 or abc3).

## **Positive-sequence no-load losses**

The core losses plus winding losses at no-load, in watts (W), when positive-sequence nominal voltage is applied at any group of winding terminals (ABC, abc2 or abc3).

## **Positive-sequence short-circuit reactances**

The positive-sequence short-circuit reactances  $X_{12}$ ,  $X_{23}$  and  $X_{13}$  in pu, where  $X_{ij}$  is the reactance measured from winding  $i$  when winding  $j$  is short-circuited.

When the **Connect windings 1 and 2 in autotransformer** parameter is checked, the short-circuit reactances are labeled XHL, XHT and XLT, where H, L and T indicate the following terminals: H= high voltage winding (either winding 1 or winding 2), L=low voltage winding (either winding 1 or winding 2) and T=tertiary (winding 3).

## **Zero-sequence no-load excitation current with Delta windings opened**

The no-load excitation current in percent of the nominal current when zero-sequence nominal voltage is applied at any group of winding terminals (ABC, abc2 or abc3).

If you want to measure this excitation current, you must connect the excited winding in Yg or Yn in order to provide a return path for the source zero-sequence currents. Also, the Delta connections of the other windings must be open; otherwise, these Delta connections would produce a short-circuit for zero sequence. You must therefore temporarily change the open winding connections from D1 or D11 to Y, Yg, Yn.

# Three-Phase Transformer Inductance Matrix Type (Three Windings)

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## **Zero-sequence no-load losses with Delta windings opened**

The core losses plus winding losses at no-load, in watts (W), when zero-sequence nominal voltage is applied at any group of winding terminals (ABC, abc2 or abc3). The Delta windings must be temporarily open in order to measure these losses.

## **Zero-sequence short-circuit reactances**

The zero-sequence short-circuit reactances  $X_{12}$ ,  $X_{23}$  and  $X_{13}$  in pu, where  $X_{ij}$  is the reactance measured from winding  $i$  when winding  $j$  is short-circuited. If the **Zero-sequence  $X_{12}$  measured with winding 3 Delta connected** check box is not selected,  $X_{12}$  represents the short-circuit reactance when winding 3 is not connected in Delta.

When the **Connect windings 1 and 2 in autotransformer** check box is selected, the short-circuit reactances are labeled  $X_{HL}$ ,  $X_{HT}$  and  $X_{LT}$ , where H, L and T indicate the following terminals: H= high voltage winding (either winding 1 or winding 2), L=low voltage winding (either winding 1 or winding 2) and T=tertiary (winding 3).

## **Zero-sequence $X_{12}$ measured with winding 3 Delta connected**

Select this check box if the available zero-sequence short circuit tests were obtained with tertiary winding (winding 3) connected in Delta.

## **Limitations**

This transformer model does not include saturation. If you need modeling saturation connect the primary winding of a saturable Three-Phase Transformer (Two Windings) in parallel with the primary winding of your model. Use same connection (Yg, D1 or D11) and same winding resistance for the two windings connected in parallel. Specify Y or Yg connection for the secondary winding and leave it open. Specify appropriate voltage, power ratings and desired saturation characteristics. The saturation characteristic is the characteristic obtained when the transformer is excited by a positive-sequence voltage.

# Three-Phase Transformer Inductance Matrix Type (Three Windings)

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If you are modeling a transformer with three single-phase cores or a five-limb core, this model will produce acceptable saturation currents because flux stays trapped inside the iron core.

For a three-limb core, it is less evident that this saturation model also gives acceptable results because zero-sequence flux circulates outside of the core and returns through the air and the transformer tank surrounding the iron core. However, as the zero-sequence flux circulates in the air, the magnetic circuit is mainly linear and its reluctance is high (high magnetizing currents). These high zero-sequence currents (100% and more of nominal current) required to magnetize the air path are already taken into account in the linear model. Connecting a saturable transformer outside the three-limb linear model with a flux-current characteristic obtained in positive sequence will produce currents required for magnetization the iron core. This model will give acceptable results whether the three-limb transformer has a delta or not.

See the `power_Transfo3phCoreType` demo showing how saturation is modeled in an inductance matrix type two-winding transformer.

## See Also

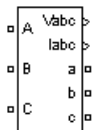
Linear Transformer, Multimeter, Three-Phase Transformer (Two Windings), Three-Phase Transformer (Three Windings), Three-Phase Transformer Inductance Matrix Type (Two Windings)

# Three-Phase V-I Measurement

**Purpose** Measure three-phase currents and voltages in circuit

**Library** Measurements

## Description



The Three-Phase V-I Measurement block is used to measure three-phase voltages and currents in a circuit. When connected in series with three-phase elements, it returns the three phase-to-ground or phase-to-phase voltages and the three line currents.

The block can output the voltages and currents in per unit (pu) values or in volts and amperes. If you choose to measure the voltages and currents in pu, the Three-Phase V-I Measurement block does the following conversions:

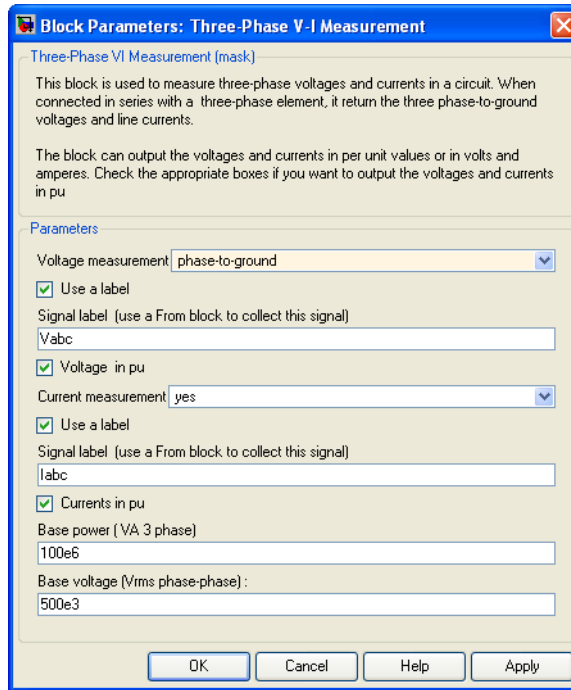
$$V_{abc}(\text{p.u.}) = \frac{V_{abc}(\text{volts})}{\left(\frac{V_{baseLL}}{\sqrt{3}} \cdot \sqrt{2}\right)}$$

$$I_{abc}(\text{p.u.}) = \frac{I_{abc}(\text{amperes})}{\left(\frac{P_{base}}{V_{baseLL} \cdot \sqrt{3}} \cdot \sqrt{2}\right)}$$

where  $V_{baseLL}$  is the base line-to-line voltage in volts RMS and  $P_{base}$  is the three-phase base power in volts-amperes. The two base values  $V_{baseLL}$  and  $P_{base}$  are specified in the Three-Phase Measurement block menu.

The steady-state voltage and current phasors measured by the Three-Phase V-I Measurement block can be obtained from the Powergui block by selecting **Steady-State Voltages and Currents**. The phasor magnitudes displayed in the Powergui stay in peak or RMS values even if the output signals are converted to pu.

## Dialog Box and Parameters



### Voltage measurement

Select no if you do not want to measure three-phase voltage. Select phase-to-ground if you want to measure the phase-to-ground voltages. Select phase-to-phase if you want to measure the phase-to-phase voltages.

### Use a label

If selected, the voltage measurements are sent to a labeled signal. Use a From block to read the voltages. The Goto tag of the From block must correspond to the label specified by the **Signal label** parameter. If not selected, the voltage measurements are available via the Vabc output of the block.

### Signal label

Specifies a label tag for the voltage measurements.

# Three-Phase V-I Measurement

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## **Voltages in pu**

If selected, the three-phase voltages are measured in pu. Otherwise they are measured in volts.

## **Base voltage (Vrms phase-phase)**

The base voltage, in volts RMS, used to convert the measured voltages in pu. The **Base voltage (Vrms phase-phase)** parameter is not visible in the dialog box if **Voltages in pu** is not selected.

## **Current measurement**

Select **yes** if you want to measure the three-phase currents that flow through the block.

## **Use a label**

If selected, the current measurements are sent to a labeled signal. Use a **From** block to read the currents. The **Goto** tag of the **From** block must correspond to the label specified by the **Signal label** parameter. If not selected, the current measurements are available via the **Iabc** output of the block.

## **Signal label**

Specifies a label tag for the current measurements.

## **Currents in pu**

If selected, the three-phase currents are measured in pu. Otherwise they are measured in amperes.

## **Base power (VA 3 phase)**

The three-phase base power, in volt-ampere (VA), used to convert the measured currents in pu. The **Base power (VA 3 phase)** parameter is not visible in the dialog box if **Currents in pu** is not selected.

## **Output signal**

Specifies the format of the measured signals when the block is used in a phasor simulation. The **Output signal** parameter is disabled when the block is not used in a phasor simulation. The phasor simulation is activated by a **Powergui** block placed in the model.

# Three-Phase V-I Measurement

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Set to **Complex** to output the measured voltages and currents as complex values. The outputs are complex signals.

Set to **Real-Imag** to output the real and imaginary parts of the measured voltages and currents.

Set to **Magnitude-Angle** to output the magnitudes and angles of the measured voltages and currents.

Set to **Magnitude** to output the magnitudes of the measured voltages and currents. The output is a scalar value.

## Inputs and Outputs

Vabc

The three measured phase-to-ground or phase-to-phase voltages. The Vabc output disappears when the **Use a label** parameter is selected or when the **Voltage measurement** menu is set to no.

Iabc

The three measured line currents. The Iabc output disappears when the **Use a label** parameter is selected or when the **Current measurement** menu is set to no.

## Example

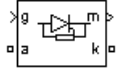
See the power\_3phseriescomp demo for a circuit using the Three-Phase V-I Measurement block.

# Thyristor

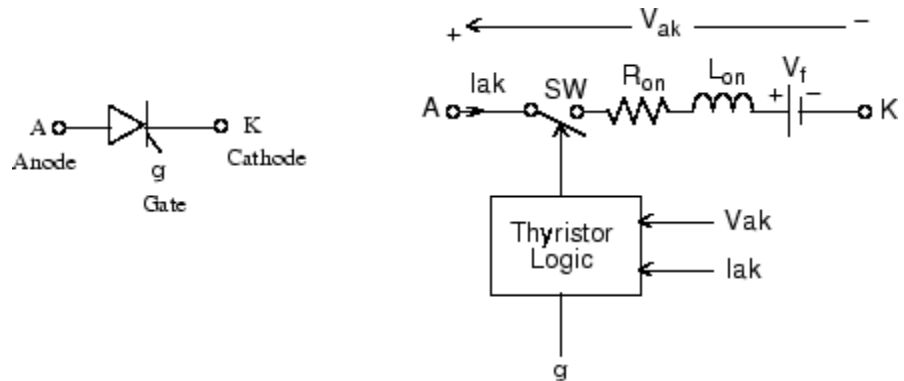
**Purpose** Implement thyristor model

**Library** Power Electronics

**Description**

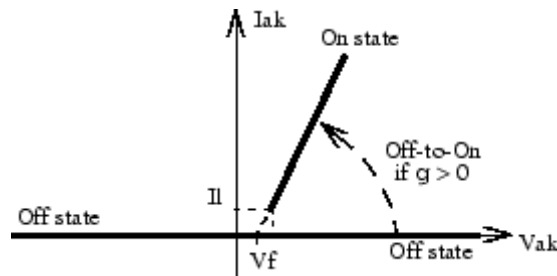


The thyristor is a semiconductor device that can be turned on via a gate signal. The thyristor model is simulated as a resistor  $R_{on}$ , an inductor  $L_{on}$ , and a DC voltage source representing the forward voltage  $V_f$ , connected in series with a switch. The switch is controlled by a logical signal depending on the voltage  $V_{ak}$ , the current  $I_{ak}$ , and the gate signal  $g$ .



The Thyristor block also contains a series  $R_s$ - $C_s$  snubber circuit that can be connected in parallel with the thyristor device.

The static VI characteristic of this model is shown below.





The thyristor device turns on when the anode-cathode  $V_{ak}$  voltage is greater than  $V_f$  and a positive pulse signal is applied at the gate input ( $g > 0$ ). The pulse height must be greater than 0 and last long enough to allow the thyristor anode current to become larger than the latching current  $I_l$ .

The thyristor device turns off when the current flowing in the device becomes 0 ( $I_{ak} = 0$ ) and a negative voltage appears across the anode and cathode for at least a period of time equal to the turnoff time  $T_q$ . If the voltage across the device becomes positive within a period of time less than  $T_q$ , the device turns on automatically even if the gate signal is low ( $g = 0$ ) and the anode current is less than the latching current. Furthermore, if during turn-on, the device current amplitude stays below the latching current level specified in the dialog box, the device turns off after the gate signal level becomes low ( $g = 0$ ).

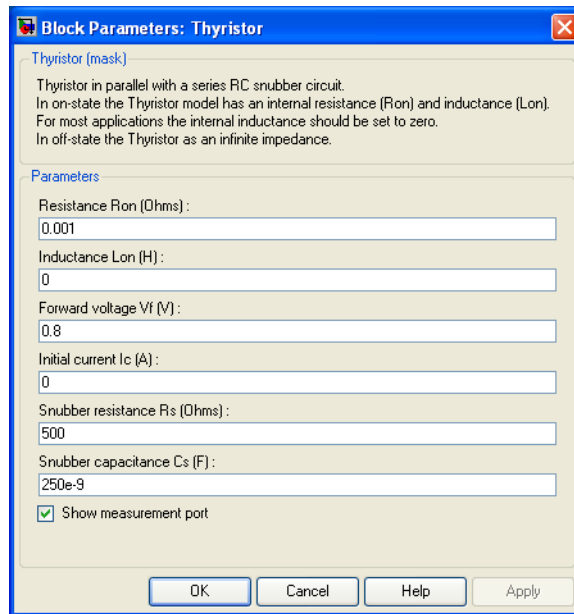
The turnoff time  $T_q$  represents the carrier recovery time: it is the time interval between the instant the anode current has decreased to 0 and the instant when the thyristor is capable of withstanding positive voltage  $V_{ak}$  without turning on again.

## Dialog Box and Parameters

### Thyristor Model and Detailed Thyristor Model

In order to optimize simulation speed, two models of thyristors are available: the thyristor model and the detailed thyristor model. For the thyristor model, the latching current  $I_l$  and recovery time  $T_q$  are assumed to be 0.

# Thyristor



## Resistance Ron

The thyristor internal resistance  $R_{on}$ , in ohms ( $\Omega$ ). The **Resistance Ron** parameter cannot be set to 0 when the **Inductance Lon** parameter is set to 0.

## Inductance Lon

The thyristor internal inductance  $L_{on}$ , in henries (H). The **Inductance Lon** parameter is normally set to 0 except when the **Resistance Ron** parameter is set to 0.

## Forward voltage Vf

The forward voltage of the thyristor, in volts (V).

## Initial current Ic

When the **Inductance Lon** parameter is greater than 0, you can specify an initial current flowing in the thyristor. It is usually set to 0 in order to start the simulation with the thyristor blocked.

You can specify an **Initial current  $I_c$**  value corresponding to a particular state of the circuit. In such a case all states of the linear circuit must be set accordingly. Initializing all states of a power electronic converter is a complex task. Therefore, this option is useful only with simple circuits.

### **Snubber resistance $R_s$**

The snubber resistance, in ohms ( $\Omega$ ). Set the **Snubber resistance  $R_s$**  parameter to `inf` to eliminate the snubber from the model.

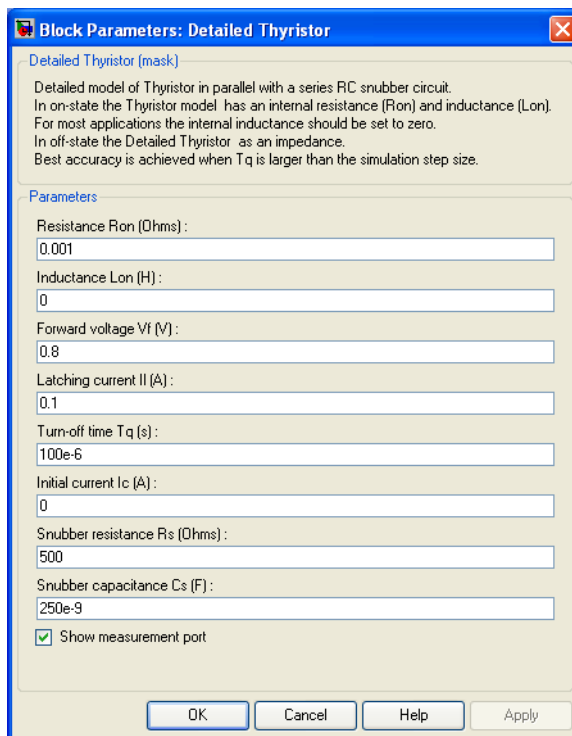
### **Snubber capacitance $C_s$**

The snubber capacitance in farads (F). Set the **Snubber capacitance  $C_s$**  parameter to `0` to eliminate the snubber, or to `inf` to get a resistive snubber.

### **Show measurement port**

If selected, add a Simulink output to the block returning the thyristor current and voltage.

# Thyristor



## Latching current $I_l$

The latching current of the detailed thyristor model, in amperes (A).

## Turn-off time $T_q$

The turnoff time  $T_q$  of the detailed thyristor model, in amperes (A).

## Inputs and Outputs

g

Simulink signal to control the gate of the Thyristor.

m

The Simulink output of the block is a vector containing two signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

Signal	Definition	Units
1	Thyristor current	A
2	Thyristor voltage	V

## Assumptions and Limitations

The Thyristor block implements a macro model of the real thyristor. It does not take into account either the geometry of the device or complex physical processes that model the behavior of the device [1, 2]. The forward breakover voltage and the critical value of the derivative of the reapplied anode-cathode voltage are not considered by the model.

Depending on the value of the inductance  $L_{on}$ , the Thyristor block is modeled either as a current source ( $L_{on} > 0$ ) or as a variable topology circuit ( $L_{on} = 0$ ). The Thyristor block cannot be connected in series with an inductor, a current source, or an open circuit, unless its snubber circuit is in use. See *Improving Simulation Performance* for more details on this topic.

Use the Powergui block to specify either continuous simulation or discretization of your electrical circuit containing Thyristor blocks. When using a continuous model, the `ode23tb` solver with a relative tolerance of  $1e-4$  is recommended for best accuracy and simulation speed.

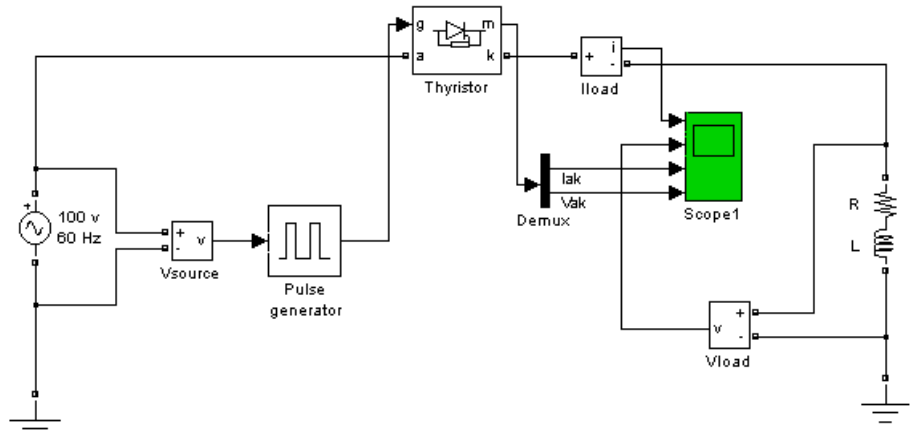
The inductance  $L_{on}$  is forced to 0 if you choose to discretize your circuit.

## Example

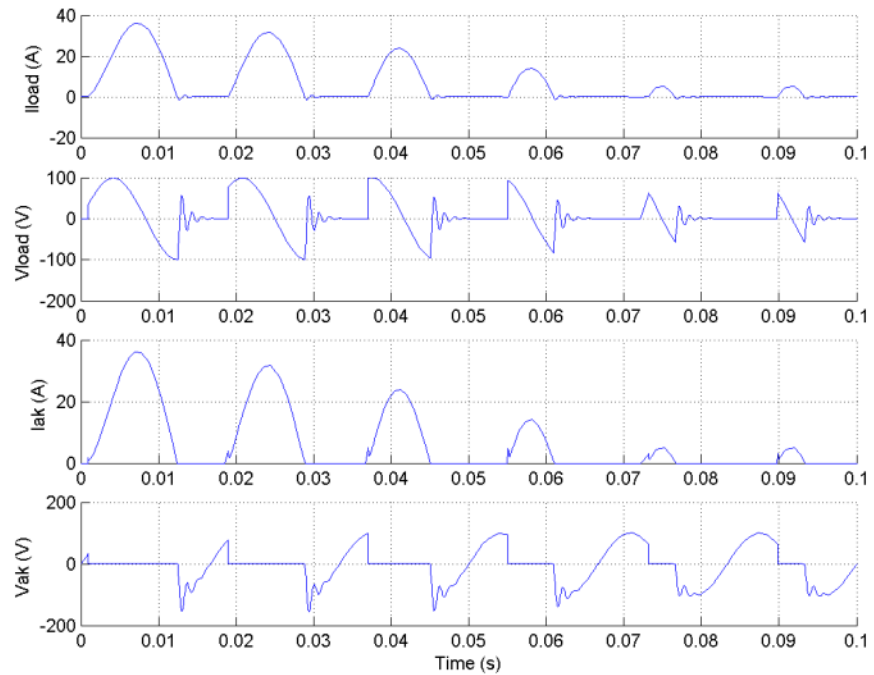
In the `power_thyristor` demo a single-pulse thyristor rectifier is used to feed an RL load. The gate pulses are obtained from a pulse generator synchronized on the source voltage. The following parameters are used:

# Thyristor

<b>R</b>		1 $\Omega$
<b>L</b>		10 mH
Thyristor block:	<b>R<sub>on</sub></b>	0.001 W
	<b>L<sub>on</sub></b>	0 H
	<b>V<sub>f</sub></b>	0.8 V
	<b>R<sub>s</sub></b>	20 $\Omega$
	<b>C<sub>s</sub></b>	4e-6 F



The firing angle is varied by a pulse generator synchronized on the voltage source. Run the simulation and observe the load current and load voltage, as well as the thyristor current and voltage.



## References

[1] Rajagopalan, V., *Computer-Aided Analysis of Power Electronic Systems*, Marcel Dekker, Inc., New York, 1987.

[2] Mohan, N., T.M. Undeland, and W.P. Robbins, *Power Electronics: Converters, Applications, and Design*, John Wiley & Sons, Inc., New York, 1995.

## See Also

Diode, Universal Bridge

# Timer

## Purpose

Generate signal changing at specified transition times

## Library

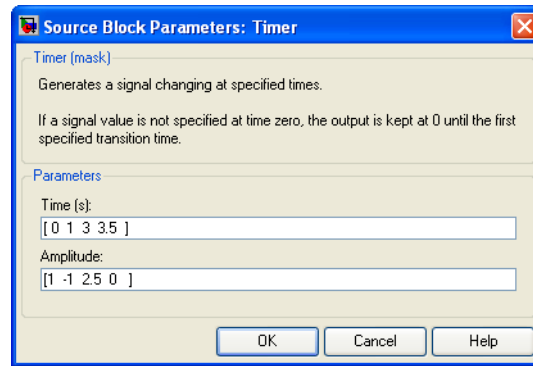
Extras/Control Blocks, Extras/Discrete Control Blocks

## Description



The Timer block generates a signal changing at specified transition times. Use this block to generate a logical signal (0 or 1 amplitudes) and control the opening and closing times of power switches like the Breaker block and the Ideal Switch block. You can also use this block to generate a signal whose amplitude changes by steps at specified transition times.

## Dialog Box and Parameters



### Time(s)

The transition times, in seconds, when the output of the block changes its value as defined by the **Amplitude** parameter. The **Time(s)** parameter must be a vector of the same length as the vector defined in the **Amplitude** parameter. The definition of the time 0 is optional. If a signal is not specified at time 0, the output is kept at zero until the first transition time specified in the **Amplitude** vector.

### Amplitude

The vector of amplitudes of signal to be generated by the Timer block. The amplitude is kept constant between transition times defined in the **Time(s)** vector.



## **Inputs and Outputs**

The output is a signal changing by steps at specified transition times.

## **Example**

See the `power_breaker` model for a circuit using the Timer block to control a circuit breaker.

# Total Harmonic Distortion

---

**Purpose** Measure total harmonic distortion (THD) of signal

**Library** Extras/Measurements

A discrete version of this block is available in the Extras/Discrete Measurements library.

## Description



The Total Harmonic Distortion block measures the total harmonic distortion (THD) of a periodic distorted signal. The signal can be a measured voltage or current.

The THD is defined as the root mean square (RMS) value of the total harmonics of the signal, divided by the RMS value of its fundamental signal. For example, for currents, the THD is defined as

$$\text{total harmonic distortion (THD)} = \frac{I_H}{I_F}$$

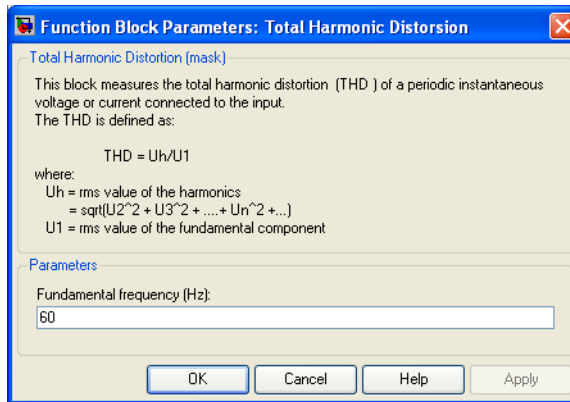
where

$$I_H = \sqrt{I_2^2 + I_3^2 + \dots + I_n^2} \quad I_n : \text{RMS value of the harmonic } n$$

$$I_F : \text{RMS value of the fundamental current}$$

It follows that the THD has a value between zero and 1. It is null for a pure sinusoidal voltage or current.

## Dialog Box and Parameters



### Fundamental frequency

The frequency, in hertz, of the fundamental signal.

## Inputs and Outputs

### signal

Connect this input to the voltage or current you want to measure the total harmonic distortion.

### THD

The output returns the THD of the input signal.

# Two-Quadrant Chopper DC Drive

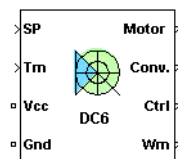
## Purpose

Implement two-quadrant chopper (buck-boost converter topology) DC drive

## Library

Electric Drives/DC drives

## Description



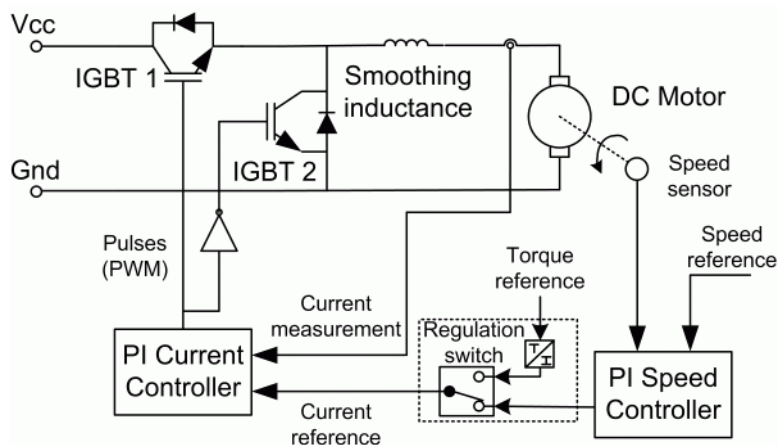
The high-level schematic shown below is built from four main blocks. The DC motor and the IGBT/Diode devices (within the Universal Bridge block) are provided with the SimPowerSystems library. More details are available in the reference pages for these blocks. The two other blocks are specific to the Electric Drives library. These blocks are the speed controller and the current controller. They allow speed or torque regulation. A “regulation switch” block allows you to toggle from one type of regulation to the other. During torque regulation the speed controller is disabled.

---

**Note** In SimPowerSystems software, the Two-Quadrant Chopper DC Drive block is commonly called the DC6 motor drive.

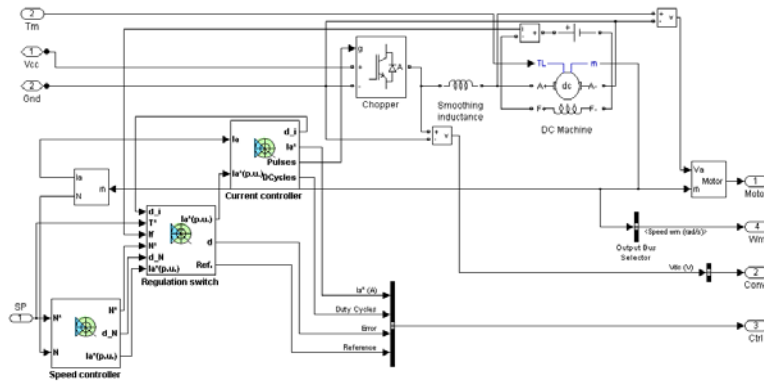
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## High-Level Schematic



# Two-Quadrant Chopper DC Drive

## Simulink Schematic



## Speed Controller

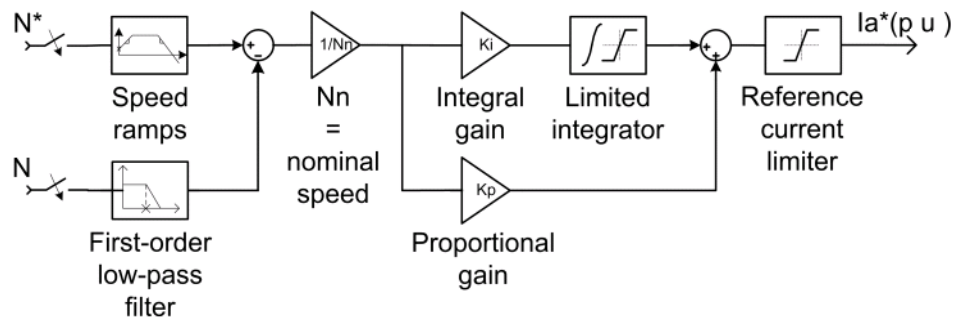
The speed regulator shown below uses a PI controller. The controller outputs the armature current reference (in pu) used by the current controller to obtain the electromagnetic torque needed to reach the desired speed. During torque regulation, the speed controller is disabled.

The controller takes the speed reference (in rpm) and the rotor speed of the DC machine as inputs. The speed reference change rate will follow user-defined acceleration and deceleration ramps in order to avoid sudden reference changes that could cause armature over-current and destabilize the system. In order to avoid negative speeds that could induce conduction of the free-wheeling diode, the speed reference has a lower limit of 0 rpm.

The speed measurement is filtered by a first-order low-pass filter.

The current reference output is limited between symmetrical lower and upper limits defined by the user. Meanwhile, at low speeds, when the back-EMF of the motor is not high enough to generate big reverse currents, the lower limit is reduced proportionally to the speed. This improves current regulation.

# Two-Quadrant Chopper DC Drive



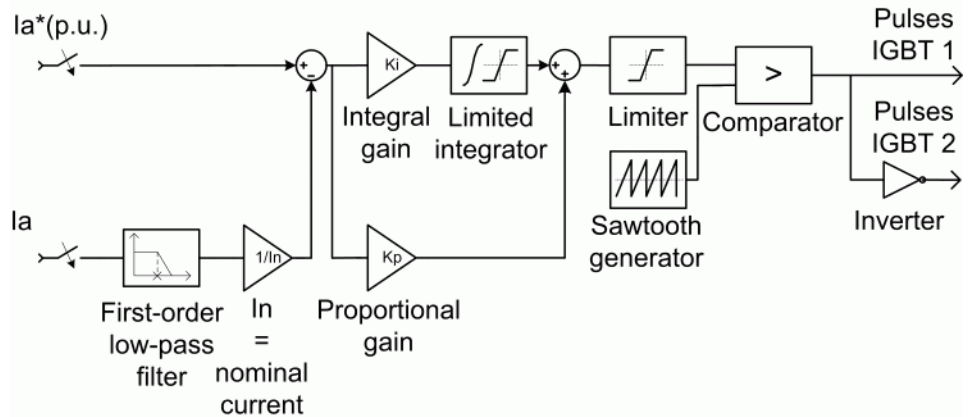
## Current Controller

The armature current regulator shown below is based on a second PI controller. The regulator controls the armature current by computing the appropriate duty ratios of the fixed frequency pulses of the two IGBT devices (Pulse Width Modulation). This generates the average armature voltage needed to obtain the desired armature current and thus the desired electromagnetic torque. For proper system behavior, the two IGBT devices have opposite instantaneous pulse values.

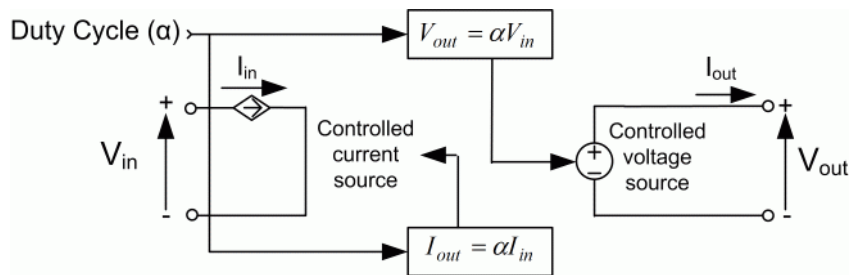
The controller takes the current reference (in pu) and the armature current flowing through the motor as inputs. The current reference is either provided by the speed controller during speed regulation or computed from the torque reference provided by the user during torque regulation. This is managed by the “regulation switch” block. The armature current input is filtered by a first-order low-pass filter.

The pulse width modulation is obtained by comparison of the PI output and a fixed frequency sawtooth carrier signal (see the figure called Pulse Width Modulation (PWM) on page 2-805).

# Two-Quadrant Chopper DC Drive



**Average-Value Two-Quadrant Chopper** The average-value converter is shown in the following figure.



It is composed of one controlled current source on the DC source side and one controlled voltage source on the motor side. The current source allows the representation of the average input current value following the next equation:

$$I_{in} = \alpha I_{out}$$

with  $\alpha$  being the firing angle value and  $I_{out}$  the armature current value. The voltage source on the motor side represents the average voltage value following the next equation:

$$V_{out} = \alpha V_{in}$$

# Two-Quadrant Chopper DC Drive

---

with  $V_{in}$  being the input voltage.

## Remarks

The machine is separately excited with a constant DC field voltage source. There is thus no field voltage control. By default, the field current is set to its steady-state value when a simulation is started.

The armature voltage is provided by an IGBT buck-boost converter controlled by two PI regulators. The converter is fed by a constant DC voltage source. Armature current oscillations are reduced by a smoothing inductance connected in series with the armature circuit.

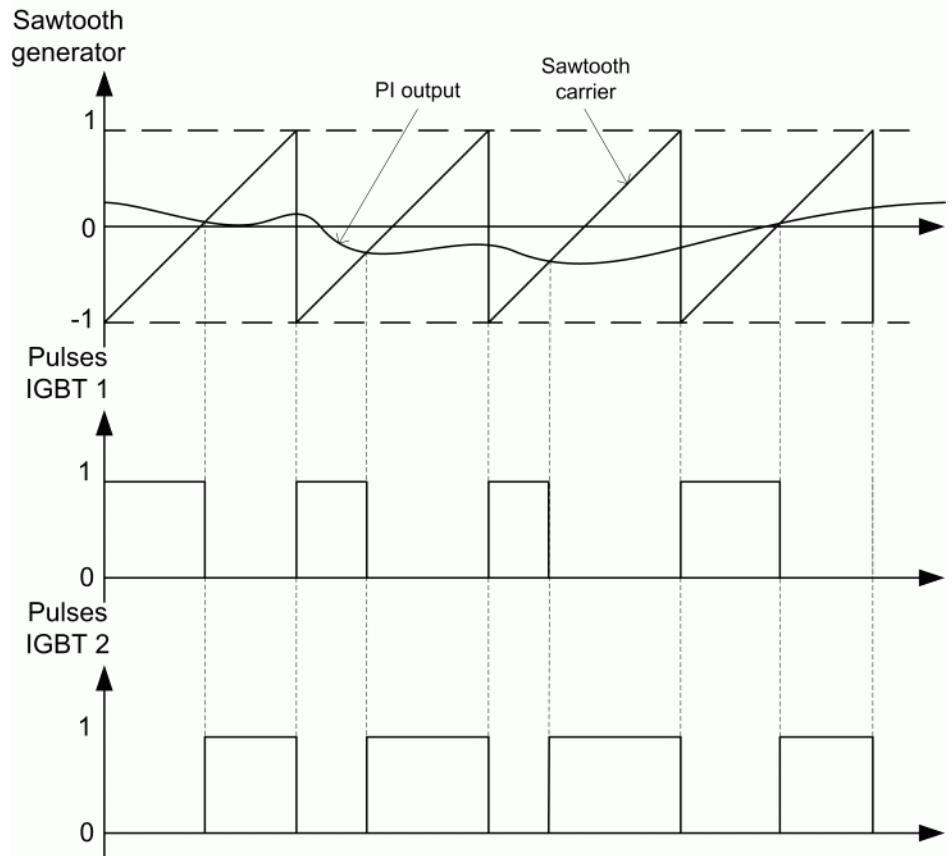
The model is discrete. Good simulation results have been obtained with a  $1 \mu\text{s}$  time step. In order to simulate a digital controller device, the control system has two different sampling times:

- The speed controller sampling time
- The current controller sampling time

The speed controller sampling time has to be a multiple of the current sampling time. The latter sampling time has to be a multiple of the simulation time step.



# Two-Quadrant Chopper DC Drive



**Pulse Width Modulation (PWM)**

# Two-Quadrant Chopper DC Drive

## Dialog Box

## DC Machine Tab

The screenshot shows a dialog box titled "2-Quadrant Chopper DC Motor Drive". It has three tabs: "DC Machine", "Converter", and "Controller". The "DC Machine" tab is selected. The dialog contains the following fields and controls:

- Electrical parameters:**
  - Mutual inductance (H): 1.234
  - Armature:**
    - Resistance (ohm): 0.78
    - Inductance (H): 0.016
  - Field:**
    - Resistance (ohm): 150
    - Inductance (H): 112.5
- Mechanical parameters:**
  - Inertia (kg\*m<sup>2</sup>): 0.05
  - Viscous friction coefficient (N-m-s): 0.01
  - Coulomb friction torque (N-m): 0
  - Initial speed (rad/s): 0
- Model detail level: Detailed (dropdown)
- Mechanical input: Torque Tm (dropdown)
- Parameters file options: Load, Save (buttons)
- OK, Cancel, Help, Apply (buttons)

The DC Machine tab displays the parameters of the DC machine block of the powerlib library. Refer to the DC Machine for more information on the DC machine block parameters.

### Model detail level

Select between the detailed and the average-value inverter.

### Mechanical input

Allows you to select either the load torque or the motor speed as mechanical input. Note that if you select and apply a load torque, you will obtain as output the motor speed according to the following differential equation that describes the mechanical system dynamics:

$$T_e = J \frac{d}{dt} \omega_r + F \omega_r + T_m$$

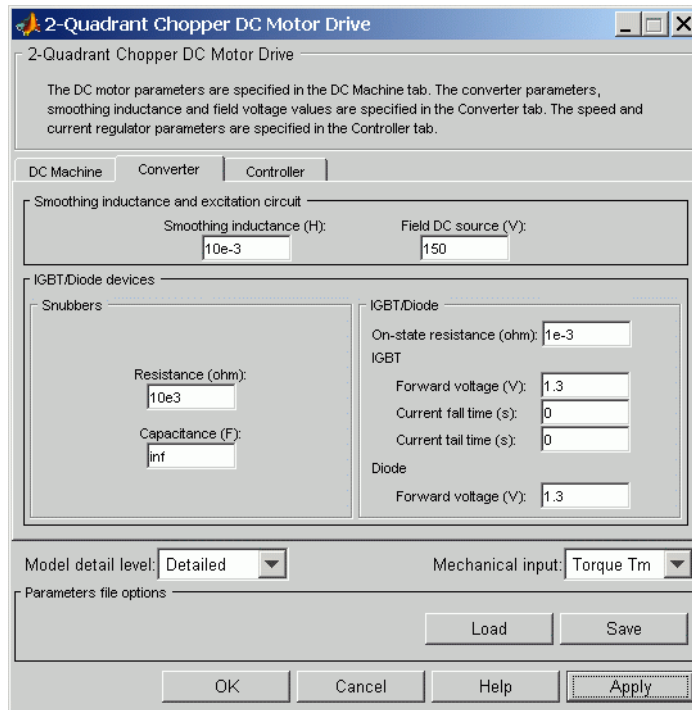
This mechanical system is included in the motor model.

However, if you select the motor speed as mechanical input then you will get the electromagnetic torque as output, allowing you to represent externally the mechanical system dynamics. Note that the internal mechanical system is not used with this mechanical input selection and the inertia and viscous friction parameters are not displayed.

See for example “Mechanical Coupling of Two Motor Drives”.

# Two-Quadrant Chopper DC Drive

## Converter Tab



## IGBT/Diode Devices Section

The IGBT/Diode section of the Converter tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the Universal Bridge for more information on the Universal Bridge block parameters.

### Smoothing Inductance

The smoothing inductance value (H).

### Field DC Source

The DC motor field voltage value (V).

# Two-Quadrant Chopper DC Drive

## Controller Tab

The screenshot shows a software window titled "2-Quadrant Chopper DC Motor Drive" with a "Controller" tab selected. The window contains several control panels and input fields:

- Regulation type:** A dropdown menu set to "Speed regulation". A "Schematic" button is located to its right.
- Speed Controller / Current Controller:** Two sub-tabs are present, with "Speed Controller" currently active.
- Nominal speed (rpm):** Input field containing "1750".
- Initial speed reference (rpm):** Input field containing "0".
- Low-pass filter cutoff frequency (Hz):** Input field containing "40".
- Sampling time (s):** Input field containing "100e-6".
- PI regulator:** A sub-panel with "Proportional gain: 50" and "Integral gain: 400".
- Speed ramps (rpm/s):** A sub-panel with "Acceleration: 1000" and "Deceleration: -1000".
- Model detail level:** A dropdown menu set to "Detailed".
- Mechanical input:** A dropdown menu set to "Torque Tm".
- Parameters file options:** A section containing "Load" and "Save" buttons.
- Bottom buttons:** "OK", "Cancel", "Help", and "Apply" buttons.

### Schematic Button

When you press this button, a diagram illustrating the speed and current controllers schematics appears.

### Regulation Type

This pop-up menu allows you to choose between speed and torque regulation.

## Controller – Speed Controller Subtab

### Nominal Speed

The nominal speed value of the DC motor (rpm). This value is used to convert motor speed from rpm to pu (per unit).

# Two-Quadrant Chopper DC Drive

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## **Initial Speed Reference**

The initial speed reference value (rpm). This value allows the user to start a simulation with a speed reference other than 0 rpm.

## **Low-Pass Filter Cutoff Frequency**

Cutoff frequency of the low-pass filter used to filter the motor speed measurement (Hz).

## **Sampling Time**

The speed controller sampling time (s). This sampling time has to be a multiple of the current controller sampling time and of the simulation time step.

## **Proportional Gain**

The proportional gain of the PI speed controller.

## **Integral Gain**

The integral gain of the PI speed controller.

## **Acceleration**

The maximum change of speed allowed during motor acceleration (rpm/s). Too great a value can cause armature over-current.

## **Deceleration**

The maximum change of speed allowed during motor deceleration (rpm/s). Too great a value can cause armature over-current.

# Two-Quadrant Chopper DC Drive

## Controller – Current Controller Subtab

The screenshot shows a software window titled "2-Quadrant Chopper DC Motor Drive". The window has three tabs: "DC Machine", "Converter", and "Controller". The "Controller" tab is active, and within it, the "Current Controller" subtab is selected. The "Regulation type" is set to "Speed regulation". A "Schematic" button is visible. The "Current Controller" section contains several input fields: "Low-pass filter cutoff frequency (Hz)" is 500, "Reference limit (p.u.)" is 1.5, "PWM switching frequency (Hz)" is 5e3, and "Sampling time (s)" is 20e-6. Below these are "Nominal values" for "Power (VA)" at 5746 and "Voltage (V)" at 240. The "PI regulator" section has "Proportional gain" at 2 and "Integral gain" at 200. At the bottom, there are "Model detail level" (set to "Detailed") and "Mechanical input" (set to "Torque Tm"). "Parameters file options" include "Load" and "Save" buttons. The bottom-most row contains "OK", "Cancel", "Help", and "Apply" buttons.

### Low-Pass Filter Cutoff Frequency

Cutoff frequency of the low-pass filter used to filter the armature current measurement (Hz).

### Reference Limit

Symmetrical current reference (pu) limit around 0 pu. 1.5 pu is a common value. Keep in mind that the lower limit is automatically reduced for low speeds (see speed controller description).

### PWM Switching Frequency

The switching frequency of the two IGBT devices (Hz).

# Two-Quadrant Chopper DC Drive

---

## Block Inputs and Outputs

### Sampling Time

The current controller sampling time (s). This sampling time has to be a submultiple of the speed controller sampling time and a multiple of the simulation time step.

### Power and Voltage nominal values

The DC motor nominal power (W) and voltage (V) values. These values are used to convert armature current from amperes to pu (per unit).

### Proportional Gain

The proportional gain of the PI current controller.

### Integral Gain

The integral gain of the PI current controller.

### SP

The speed or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration / deceleration ramps. If the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

### Tm or Wm

The mechanical input: load torque (Tm) or motor speed (Wm).

### Vcc, Gnd

The DC voltage source electric connections. The voltage must be adequate for the motor size.

### Wm or Te

The mechanical output: motor speed (Wm) or electromagnetic torque (Te).

### Motor

The motor measurement vector. This vector is composed of two elements:

- The armature voltage



# Two-Quadrant Chopper DC Drive

- The DC motor measurement vector (containing the speed, armature current, field current, and electromagnetic torque values). Note that the speed signal is converted from rad/s to rpm before output.

## Conv

The IGBT/Diode device measurement vector. This vector includes the converter output voltage. The output current is not included since it is equal to the DC motor armature current. Note that all current and voltage values of the converter can be visualized with the mulimeter block.

## Ctrl

The controller measurement vector. This vector contains:

- The armature current reference
- The duty cycle of the PWM pulses
- The speed or torque error (difference between the speed reference ramp and actual speed or between the torque reference and actual torque)
- The speed reference ramp or torque reference

## Model Specifications

The library contains a 5 hp and a 200 hp drive parameter set. The specifications of these two drives are shown in the following table.

### 5 HP and 200 HP Drive Specifications

	5 HP Drive	200 HP Drive
<b>Drive Input Voltage</b>		
Amplitude	280 V	550 V
<b>Motor Nominal Values</b>		
Power	5 hp	200 hp

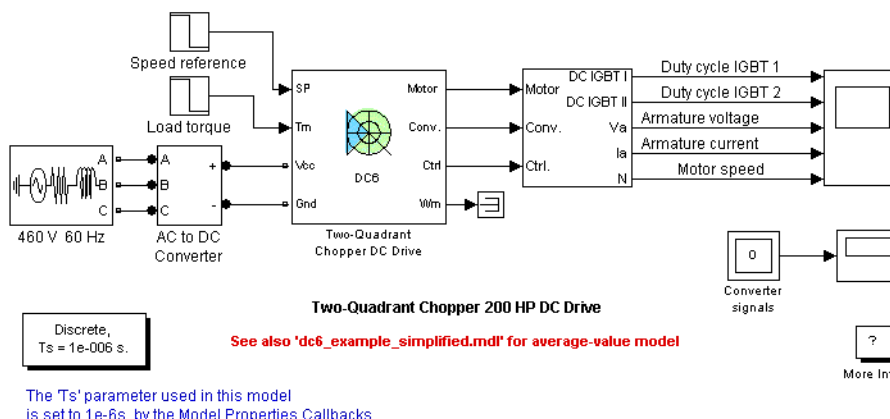
# Two-Quadrant Chopper DC Drive

## 5 HP and 200 HP Drive Specifications (Continued)

	5 HP Drive	200 HP Drive
<b>Drive Input Voltage</b>		
Speed	1750 rpm	1750 rpm
Voltage	240 V	500 V

### Example

The dc6\_example demo illustrates the two-quadrant chopper drive used with the 200 hp drive parameter set during speed regulation. A 5 hp parameter set is also available in the library.



The buck-boost converter is fed by a 630 V DC bus obtained by rectification of a 460 V AC 60 Hz voltage source. In order to limit the DC bus voltage during dynamic braking mode, a braking chopper has been added between the diode rectifier and the DC6 block. The IGBT switching frequency is 5 kHz.

The speed reference is set at 400 rpm at  $t = 0$  s. Initial load torque is 814 N.m.

## Two-Quadrant Chopper DC Drive

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Observe that the motor speed follows the reference ramp accurately (+250 rpm/s) and reaches steady state around  $t = 2$  s. The armature current follows the current reference very well, with fast response time and small ripples. Notice that the current ripple frequency is 5 kHz.

At  $t = 2.1$  s, the load torque passes from 814 N.m to 100 N.m. The motor speed recovers fast and is back at 400 rpm at  $t = 2.75$  s. The current reference lowers to about 40 A to generate a smaller electromagnetic torque, the load torque being reduced. As observed before, the armature current follows its reference perfectly.

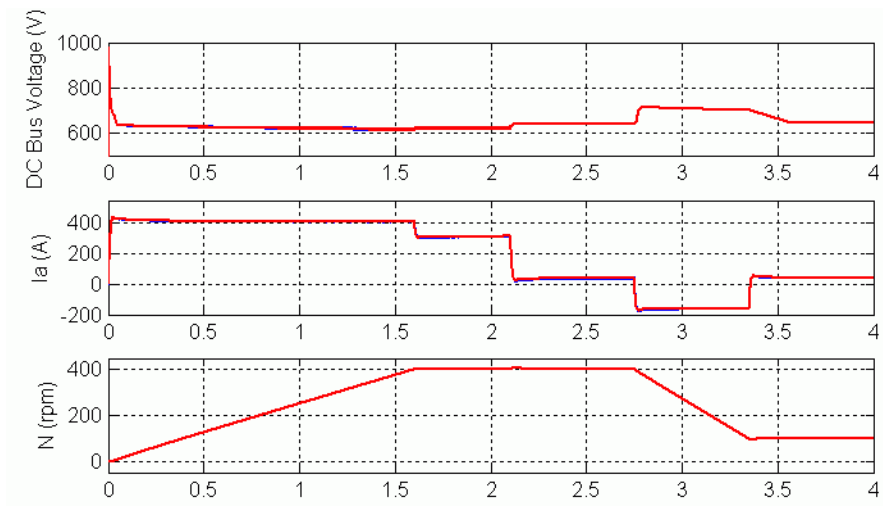
At  $t = 2.75$  s, the speed reference jumps down to 100 rpm. In order for the motor to decelerate following the negative speed ramp, the armature current reverses down to -160 A to generate a braking electromagnetic torque (dynamic braking mode). This causes the DC bus voltage to increase. The braking chopper limits the voltage value.

At  $t = 3.4$  s, the motor speed reaches 100 rpm and the current reverses back to 40 A.

At  $t = 4$  s, the speed stabilizes around its reference.

The following figure shows the DC bus voltage, armature current, and speed waveforms.

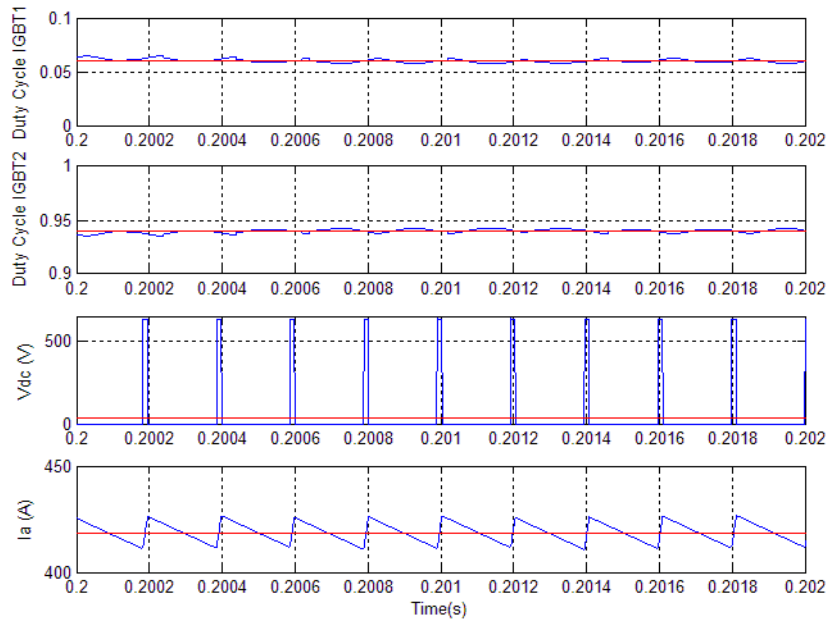
# Two-Quadrant Chopper DC Drive



**DC6 Example – DC Bus Voltage, Current, and Speed Waveforms (Blue: Detailed Converter, Red: Average-Value Converter)**

The next figure shows the duty cycles of the chopper pulses and the corresponding armature voltage and current waveforms during a time interval of 2 ms.

# Two-Quadrant Chopper DC Drive



**DC6 Example – Duty Cycles, Armature Voltage, and Current Waveforms (Blue: Detailed Converter, Red: Average-Value Converter)**

## References

- [1] Boldea, Ion, and S.A. Nasar, *Electric Drives*, CRC Press LLC, 1999.
- [2] Séguier, Guy, *Electronique de puissance*, Dunod, 1999.

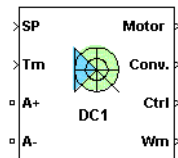
# Two-Quadrant Single-Phase Rectifier DC Drive

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**Purpose** Implement two-quadrant single-phase rectifier DC drive

**Library** Electric Drives/DC drives

## Description



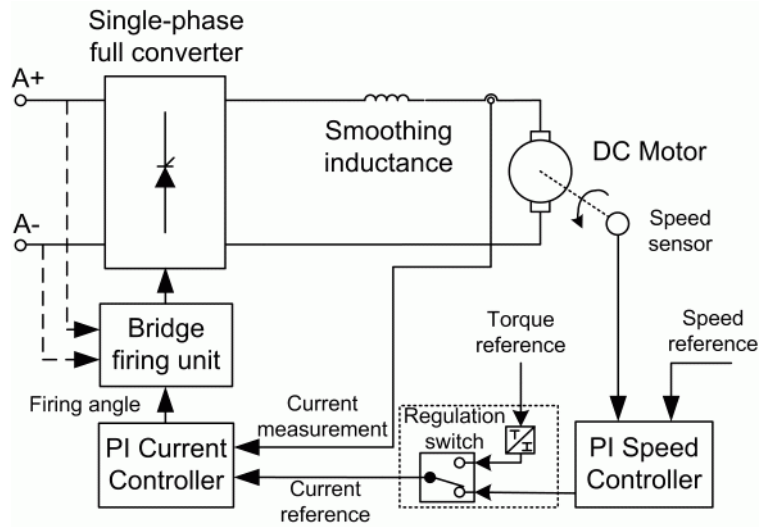
The high-level schematic shown below is built from five main blocks. The DC motor, the single-phase full converter, and the bridge firing unit are provided with the SimPowerSystems library. More details are available in the reference pages for these blocks. The two other blocks are specific to the Electric Drives library. These blocks are the speed controller and the current controller. They allow speed or torque regulation. A “regulation switch” block allows you to toggle from one type of regulation to the other. During torque regulation the speed controller is disabled. It is possible to use a simplified version of the drive containing an average-value model of the single-phase converter and allowing faster simulation.

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**Note** In SimPowerSystems software, the Two-Quadrant Single-Phase Rectifier DC Drive block is commonly called the DC1 motor drive.

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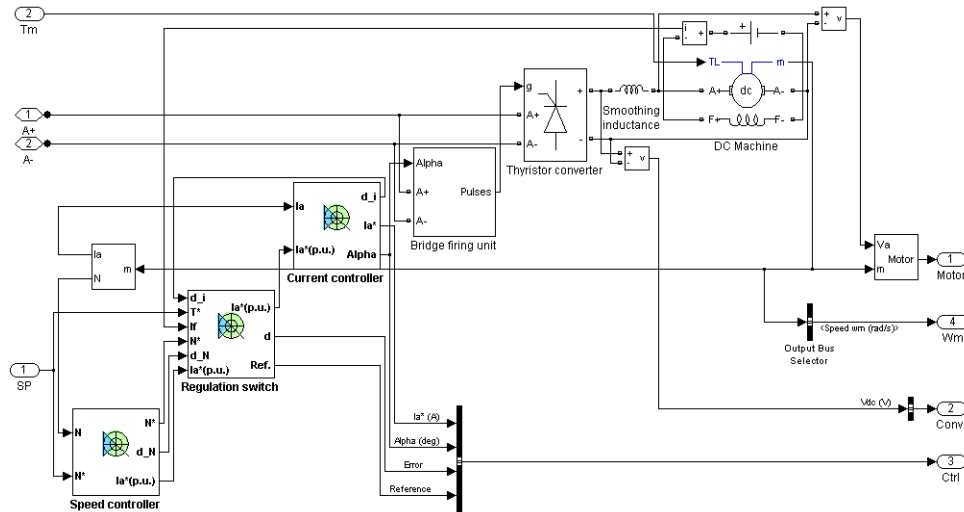
# Two-Quadrant Single-Phase Rectifier DC Drive



**High-Level Schematic**

# Two-Quadrant Single-Phase Rectifier DC Drive

## Simulink Schematic



## Speed Controller

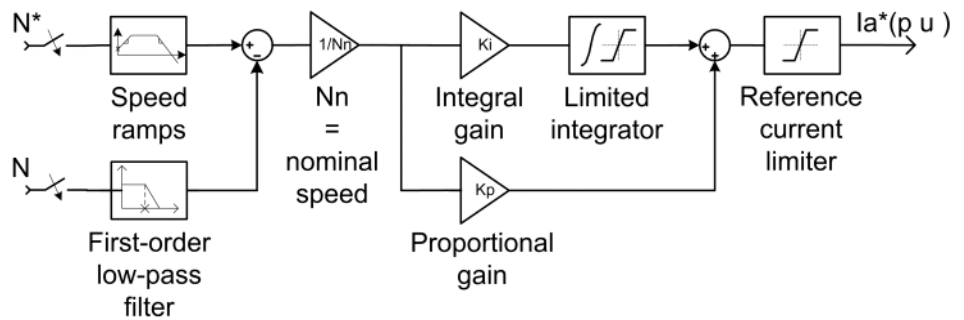
The speed regulator in the following figure uses a PI controller. The controller outputs the armature current reference (in pu) used by the current controller in order to obtain the electromagnetic torque needed to reach the desired speed. During torque regulation, the speed controller is disabled.

The controller takes the speed reference (in rpm) and the rotor speed of the DC machine as inputs. The speed reference change rate will follow user-defined acceleration and deceleration ramps in order to avoid sudden reference changes that could cause armature over-current and destabilize the system. The speed measurement is filtered by a first-order low-pass filter.

The current reference output is limited between 0 pu and an upper limit defined by the user.



# Two-Quadrant Single-Phase Rectifier DC Drive



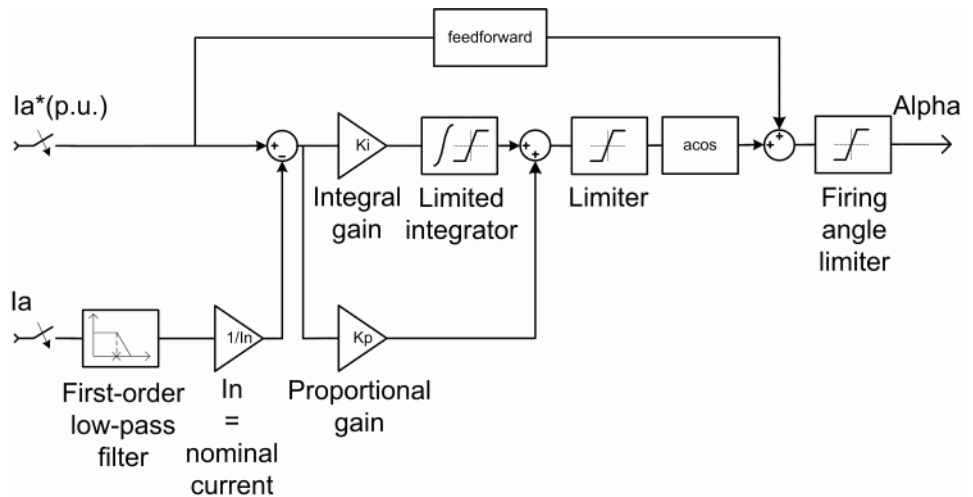
## Current Controller

The armature current regulator in the following figure is based on a second PI controller. The regulator controls the armature current by computing the appropriate thyristor firing angle. This generates the rectifier output voltage needed to obtain the desired armature current and thus the desired electromagnetic torque.

The controller takes the current reference (in pu) and the armature current flowing through the motor as inputs. The current reference is either provided by the speed controller during speed regulation or computed from the torque reference provided by the user during torque regulation. This is managed by the “regulation switch” block.

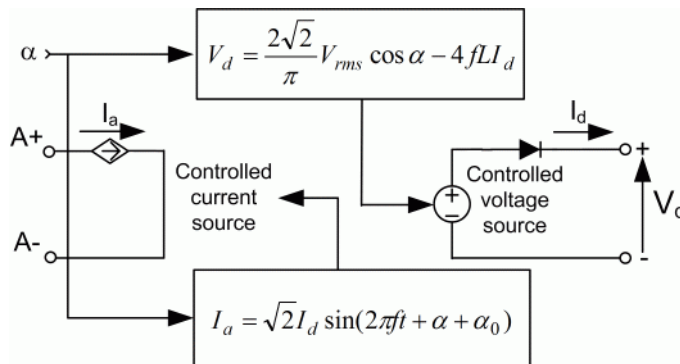
The armature current input is filtered by a first-order low-pass filter. An arccosine function is used to linearize the control system during continuous conduction. To compensate nonlinearities appearing during discontinuous conduction, a feedforward term is added to the firing angle. This improves the system’s response time. The firing angle can vary between 0 and 180 degrees. You can limit the lower and upper limits to intermediate values.

# Two-Quadrant Single-Phase Rectifier DC Drive



## Average-Value Single-Phase Rectifier

The average-value converter is shown in the following figure.



It is composed of one controlled current source on the AC side and one controlled voltage source on the DC side. The AC current source allows the representation of the fundamental single-phase current behavior following the next equation:

$$I_a = \sqrt{2} I_d \sin(2\pi f t + \alpha + \alpha_0)$$

# Two-Quadrant Single-Phase Rectifier DC Drive

with  $\alpha$  being the firing angle value,  $\alpha_0$  the phase angle of the AC side,  $f$  the AC frequency and  $I_d$  the rectified output current value. The DC voltage source represents the average voltage value of the rectified voltage waveform following the next equation:

$$V_d = \frac{2\sqrt{2}}{\pi} V_{rms} \cos\alpha - 4fLI_d$$

with  $V_{rms}$  being the input RMS voltage value and L being the source inductance value.

## Bridge Firing Unit

The bridge firing unit converts the firing angle, provided by the current controller, to four pulses applied to the thyristor gates. The bridge firing unit block contains a band-pass filter on voltage measurement to remove voltage harmonics. The discrete synchronized pulse generator block generates the pulses. Its architecture is based on the Discrete Synchronized 6-Pulse Generator block. Refer to the Synchronized 6-Pulse Generator for more information on this block. When using the average-value converter the bridge firing unit simply outputs the firing angle value needed by the converter.

## Remarks

The machine is separately excited with a constant DC field voltage source. There is thus no field voltage control. By default, the field current is set to its steady-state value when a simulation is started.

The armature voltage is provided by a single-phase rectifier controlled by two PI regulators. Armature current oscillations are reduced by a smoothing inductance connected in series with the armature circuit.

The average-value converter represents the average behavior of a single-phase rectifier for continuous armature current. This model is thus not suitable for simulating DC drives under discontinuous armature current conditions. The converter outputs a continuous voltage value equal to the average-value of the real-life rectified voltage. The armature voltage, armature current and electromagnetic torque ripples are thus not represented. The input currents have the frequency and amplitude of the fundamental current component of the real-life input currents.

# Two-Quadrant Single-Phase Rectifier DC Drive

The model is discrete. Good simulation results have been obtained with a 25  $\mu\text{s}$  time step. The control system (speed and current controllers) samples data following a user-defined sample time in order to simulate a digital controller device. Keep in mind that this sampling time has to be a multiple of the simulation time step.

The average-value converter allows the use of bigger simulation time steps since it does not generate small time constants (due to the RC snubbers) inherent to the detailed converter. For a controller sampling time of 100  $\mu\text{s}$  good simulation results have been obtained for a simulation time step of 100  $\mu\text{s}$ . This time step can of course not be higher than the controller time step.

## Dialog Box

### DC Machine Tab

The dialog box is titled "2-Quadrant Single-Phase Rectifier DC Motor Drive". It contains a text area at the top stating: "The DC motor parameters are specified in the DC Machine tab. The converter parameters, smoothing inductance and field voltage values are specified in the Converter tab. The bridge firing unit, speed and current regulator parameters are specified in the Controller tab." Below this are three tabs: "DC Machine", "Converter", and "Controller". The "DC Machine" tab is active and shows two columns of parameters: "Electrical parameters" and "Mechanical parameters".

Electrical parameters	Mechanical parameters
Mutual inductance (H): 1.234	Inertia ( $\text{kg}\cdot\text{m}^2$ ): 0.05
Armature: Resistance (ohm): 0.78 Inductance (H): 0.016	Viscous friction coefficient (N-m-s): 0.01
Field: Resistance (ohm): 150 Inductance (H): 112.5	Coulomb friction torque (N-m): 0
	Initial speed (rad/s): 0

Model detail level: Detailed Mechanical input: Torque Tm

Parameters file options: Load Save

OK Cancel Help Apply

# Two-Quadrant Single-Phase Rectifier DC Drive

---

The DC Machine tab displays the parameters of the DC machine block of the powerlib library. Refer to the DC Machine for more information on the DC machine block parameters.

## Model detail level

Select between the detailed and the average-value inverter.

## Mechanical input

Allows you to select either the load torque or the motor speed as mechanical input. Note that if you select and apply a load torque, you will obtain as output the motor speed according to the following differential equation that describes the mechanical system dynamics:

$$T_e = J \frac{d}{dt} \omega_r + F \omega_r + T_m$$

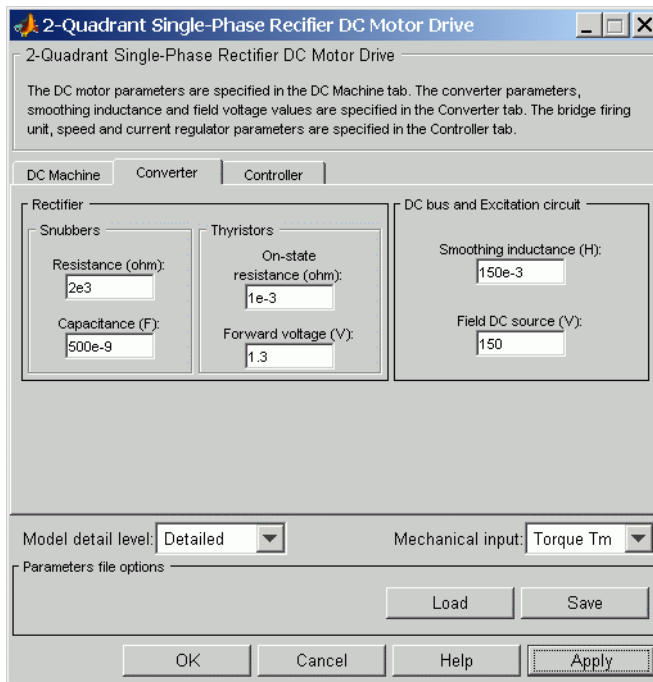
This mechanical system is included in the motor model.

However, if you select the motor speed as mechanical input then you will get the electromagnetic torque as output, allowing you to represent externally the mechanical system dynamics. Note that the internal mechanical system is not used with this mechanical input selection and the inertia and viscous friction parameters are not displayed.

See for example “Mechanical Coupling of Two Motor Drives”.

# Two-Quadrant Single-Phase Rectifier DC Drive

## Converter Tab



### Rectifier section

The Rectifier section of the Converter tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the Universal Bridge for more information on the Universal Bridge block parameters.

### Smoothing Inductance

The smoothing inductance value (H).

### Field DC Source

The DC motor field voltage value (V).

# Two-Quadrant Single-Phase Rectifier DC Drive

---

## **RMS Voltage**

RMS voltage of the single-phase voltage source connected to the A+,A- terminals of the drive (V). This parameter is not used when using the detailed rectifier.

## **Frequency**

Frequency of the single-phase voltage source connected to the A+,A- terminals of the drive (Hz). This parameter is not used when using the detailed rectifier.

## **Source Inductance**

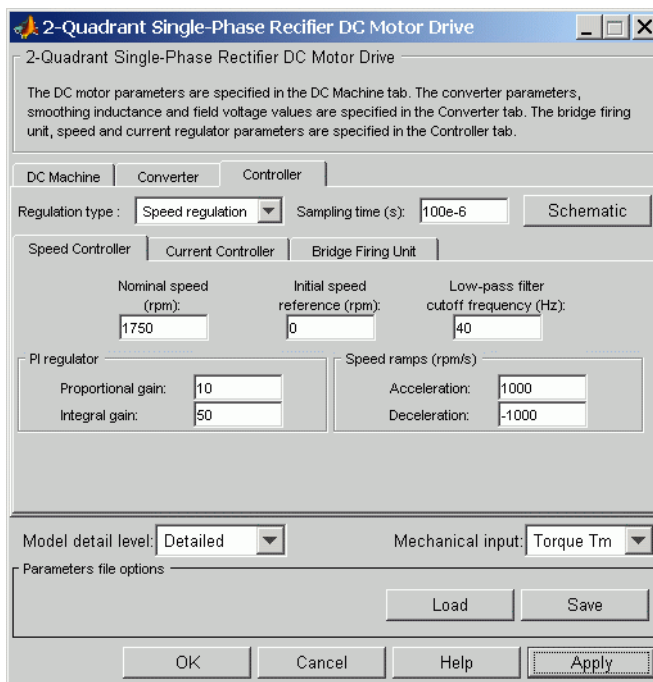
Source inductance of the single-phase voltage source connected to the A+,A- terminals of the drive (H). This parameter is not used when using the detailed rectifier.

## **Phase Angle**

Phase angle of the single-phase voltage source connected to the A+,A- terminals of the drive (deg.). This parameter is not used when using the detailed rectifier.

# Two-Quadrant Single-Phase Rectifier DC Drive

## Controller Tab



## Schematic Button

When you press this button, a diagram illustrating the speed and current controllers schematics appears.

## Regulation Type

This pop-up menu allows you to choose between speed and torque regulation.

## Sampling Time

The controller (speed and current) sampling time (s). The sampling time has to be a multiple of the simulation time step.



# Two-Quadrant Single-Phase Rectifier DC Drive

---

## **Controller – Speed Controller Subtab**

### **Nominal Speed**

The nominal speed value of the DC motor (rpm). This value is used to convert motor speed from rpm to pu (per unit).

### **Initial Speed Reference**

The initial speed reference value (rpm). This value allows the user to start a simulation with a speed reference other than 0 rpm.

### **Low-Pass Filter Cutoff Frequency**

Cutoff frequency of the low-pass filter used to filter the motor speed measurement (Hz).

### **Proportional Gain**

The proportional gain of the PI speed controller.

### **Integral Gain**

The integral gain of the PI speed controller.

### **Acceleration**

The maximum change of speed allowed during motor acceleration (rpm/s). Too great a value can cause armature over-current.

### **Deceleration**

The maximum change of speed allowed during motor deceleration (rpm/s). Too great a value can cause armature over-current.

# Two-Quadrant Single-Phase Rectifier DC Drive

## Controller – Current Controller Subtab

The DC motor parameters are specified in the DC Machine tab. The converter parameters, smoothing inductance and field voltage values are specified in the Converter tab. The bridge firing unit, speed and current regulator parameters are specified in the Controller tab.

DC Machine | Converter | **Controller**

Regulation type: Speed regulation | Sampling time (s): 100e-6 | Schematic

Speed Controller | **Current Controller** | Bridge Firing Unit

Low-pass filter cutoff frequency (Hz): 50 | Reference limit (p.u.): 1.5

Nominal values: Power (VA): 5746 | Voltage (V): 240 | PI regulator: Proportional gain: 1 | Integral gain: 80

Model detail level: Detailed | Mechanical input: Torque Tm

Parameters file options: Load | Save

OK | Cancel | Help | Apply

### Power and Voltage nominal values

The DC motor nominal power (W) and voltage (V) values. These values are used to convert armature current values from amperes to pu (per unit).

### Proportional Gain

The proportional gain of the PI current controller.

### Integral Gain

The integral gain of the PI current controller.

### Low-Pass Filter Cutoff Frequency

Cutoff frequency of the low-pass filter used to filter the armature current measurement (Hz).

# Two-Quadrant Single-Phase Rectifier DC Drive

## Reference Limit

Maximum current reference value (pu). 1.5 pu is a common value.

## Controller – Bridge Firing Unit Subtab

The screenshot shows the '2-Quadrant Single-Phase Rectifier DC Motor Drive' software window. The 'Controller' tab is selected, and the 'Bridge Firing Unit' subtab is active. The interface includes the following fields and controls:

- Regulation type:** Speed regulation (dropdown)
- Sampling time (s):** 100e-6 (text input)
- Schematic:** (button)
- Firing angle limits (degrees):**
  - Alpha min: 20 (text input)
  - Alpha max: 160 (text input)
- Synchronized pulse generator:**
  - Frequency of synchronization voltages (Hz): 50 (text input)
  - Pulse width (degrees): 10 (text input)
- Model detail level:** Detailed (dropdown)
- Mechanical input:** Torque Tm (dropdown)
- Parameters file options:** Load (button), Save (button)
- Buttons:** OK, Cancel, Help, Apply

## Alpha Min

Minimum firing angle value (deg.). 20 degrees is a common value.

## Alpha Max

Maximum firing angle value (deg.). 160 degrees is a common value.

## Frequency of Synchronization Voltages

Frequency of the synchronization voltages used by the discrete synchronized pulse generator block (Hz). This frequency is

# Two-Quadrant Single-Phase Rectifier DC Drive

---

## Block Inputs and Outputs

equal to the line frequency of the single-phase power line. This parameter is not used when using the average-value converter.

### Pulse Width

The width of the pulses applied to the four thyristor gates (deg.). This parameter is not used when using the average-value converter.

### SP

The speed or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration / deceleration ramps. If the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

### Tm or Wm

The mechanical input: load torque ( $T_m$ ) or motor speed ( $W_m$ ).

### A+, A-

The single-phase electric connections. The applied voltage must be adequate for the motor size.

### Wm or Te

The mechanical output: motor speed ( $W_m$ ) or electromagnetic torque ( $T_e$ ).

### Motor

The motor measurement vector. This vector is composed of two elements:

- The armature voltage
- The DC motor measurement vector (containing the speed, armature current, field current, and electromagnetic torque values). Note that the speed signal is converted from rad/s to rpm before output.

# Two-Quadrant Single-Phase Rectifier DC Drive

## Conv

The single-phase converter measurement vector. It includes the converter output voltage. The output current is not included since it is equal to the DC motor armature current.

Note that all current and voltage values of the bridges can be visualized with the Multimeter block.

## Ctrl

The controller measurement vector. This vector contains:

- The armature current reference
- The firing angle computed by the current controller
- The speed or torque error (difference between the speed reference ramp and actual speed or between the torque reference and actual torque)
- The speed reference ramp or torque reference

## Model Specifications

The library contains a 5 hp drive parameter set. The specifications of the 5 hp drive are shown in the following table.

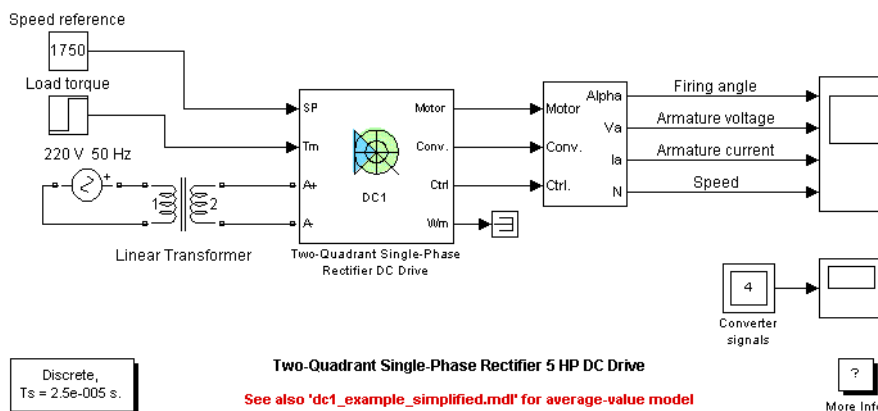
### 5 HP Drive Specifications

Drive Input Voltage		
	Amplitude	320 V
	Frequency	50 Hz
Motor Nominal Values		
	Power	5 hp
	Speed	1750 rpm
	Voltage	240 V

# Two-Quadrant Single-Phase Rectifier DC Drive

## Example

The `dc1_example` demo illustrates the single-phase rectifier drive used with the 5 hp drive parameter set during speed regulation.



The '`Ts`' parameter used in this model is set to 25e-6s by the Model Properties Callbacks

The rectifier is fed by a 220 V AC 50 Hz voltage source followed by a linear transformer to boost the voltage to a sufficient value.

The speed reference is set at 1750 rpm at  $t = 0$  s. Initial load torque is 15 N.m.

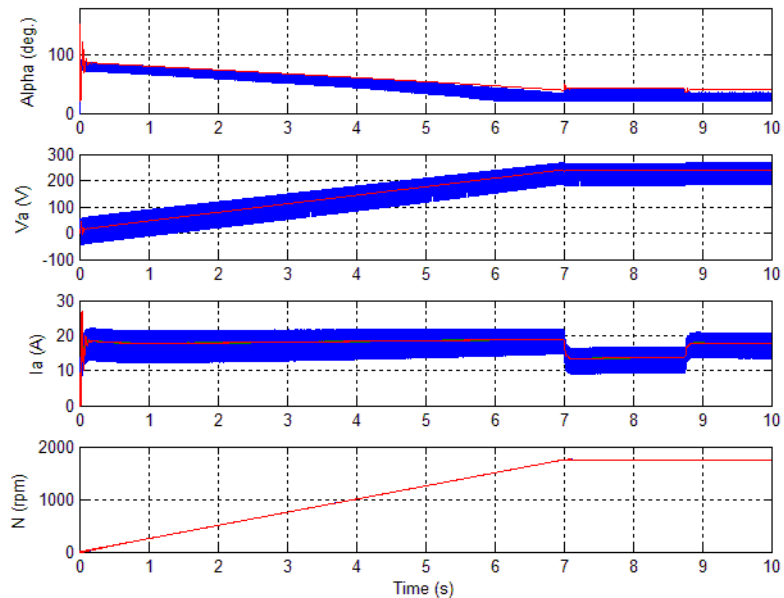
Observe that the motor speed follows the reference ramp accurately (+250 rpm/s) and reaches steady state around  $t = 8.5$  s.

The armature current follows the current reference very well, and the firing angle stays below 90 degrees, the converter being in rectifier mode (first quadrant operating mode). The lower limit of the firing angle has been set to 20 degrees.

At  $t = 8.75$  s, the load torque passes from 15 N.m to 20 N.m. The motor speed recovers fast and is back at 1750 rpm at  $t = 10$  s. The current reference rises to about 17.5 A to generate a higher electromagnetic torque to maintain the needed speed. As observed before, the armature current follows its reference perfectly.

# Two-Quadrant Single-Phase Rectifier DC Drive

The following figure illustrates the results obtained respectively with the detailed and the average-value converters. Average voltage, current, torque and speed values are identical for both models. The average firing angle values however are slightly different. Notice that the higher frequency signal components are not represented with the average-value converter.



**DC1 Example Waveforms (Blue: Detailed Converter, Red: Average-Value Converter)**

## References

- [1] Sen, P.C., *Thyristor DC Drives*, J.Wiley and Sons, 1981.
- [2] Nondahl, Thomas A., *Microprocessor Control of Motor Drives and Power Converters, tutorial course*, IEEE Industry Application Society, October 1993, pp. 7.1-7.26.

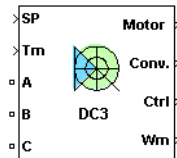
# Two-Quadrant Three-Phase Rectifier DC Drive

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**Purpose** Implement two-quadrant three-phase rectifier DC drive

**Library** Electric Drives/DC drives

## Description



The high-level schematic shown below is built from five main blocks. The DC motor, the three-phase full converter, and the bridge firing unit are provided with the SimPowerSystems library. More details are available in the reference pages for these blocks. The two other blocks are specific to the Electric Drives library. These blocks are the speed controller and the current controller. They allow speed or torque regulation. A “regulation switch” block allows you to toggle from one type of regulation to the other. During torque regulation the speed controller is disabled. It is possible to use a simplified version of the drive containing an average-value model of the three-phase converter and allowing faster simulation.

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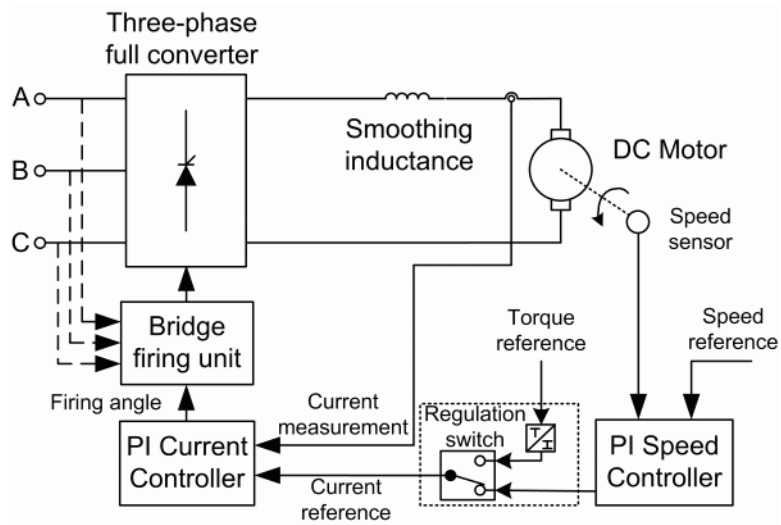
**Note** In SimPowerSystems software, the Two-Quadrant Three-Phase Rectifier DC Drive block is commonly called the DC3 motor drive.

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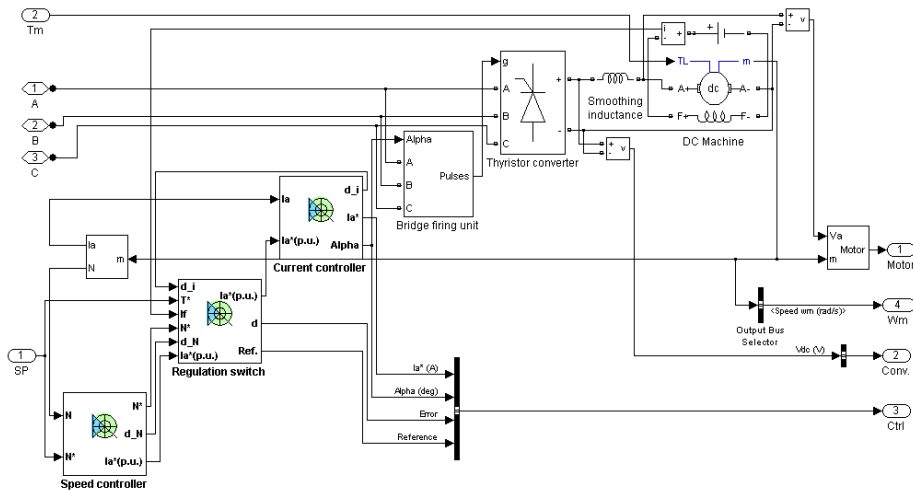


# Two-Quadrant Three-Phase Rectifier DC Drive

## High-Level Schematic



## Simulink Schematic



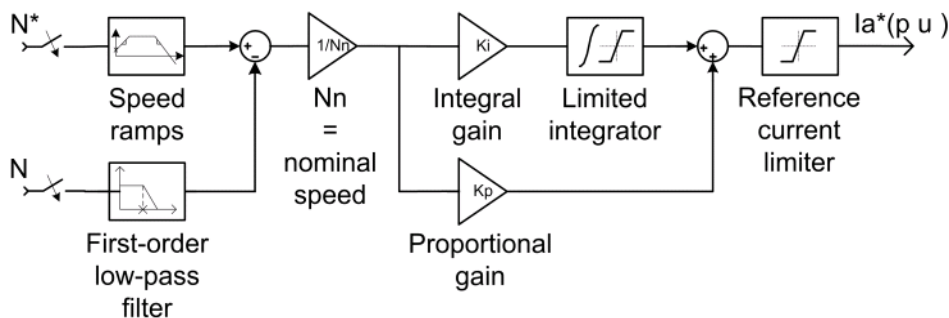
# Two-Quadrant Three-Phase Rectifier DC Drive

## Speed Controller

The speed regulator shown below uses a PI controller. The controller outputs the armature current reference (in pu) used by the current controller in order to obtain the electromagnetic torque needed to reach the desired speed. During torque regulation, the speed controller is disabled.

The controller takes the speed reference (in rpm) and the rotor speed of the DC machine as inputs. The speed reference change rate will follow user-defined acceleration and deceleration ramps in order to avoid sudden reference changes that could cause armature over-current and destabilize the system. The speed measurement is filtered by a first-order low-pass filter.

The current reference output is limited between 0 pu and an upper limit defined by the user.



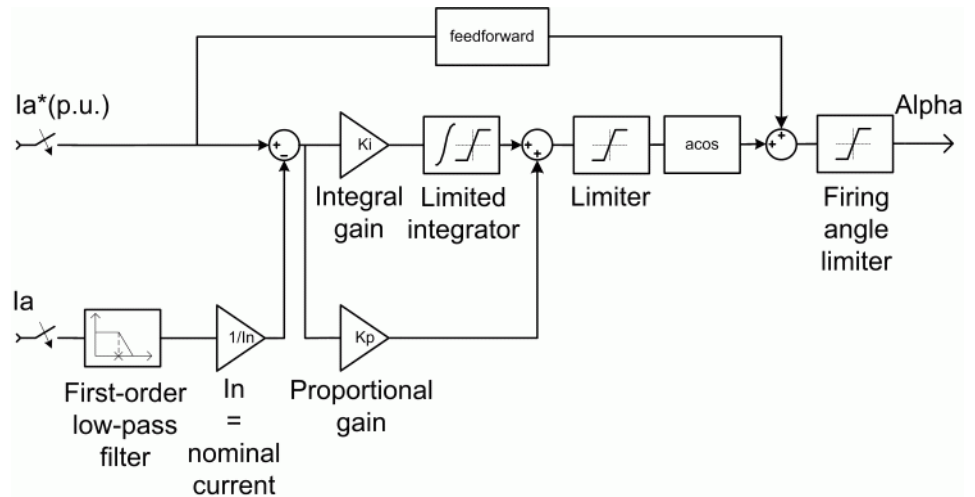
## Current Controller

The armature current regulator shown below is based on a second PI controller. The regulator controls the armature current by computing the appropriate thyristor firing angle. This generates the rectifier output voltage needed to obtain the desired armature current and thus the desired electromagnetic torque.

The controller takes the current reference (in pu) and the armature current flowing through the motor as inputs. The current reference is either provided by the speed controller during speed regulation or computed from the torque reference provided by the user during torque regulation. This is managed by the “regulation switch” block.

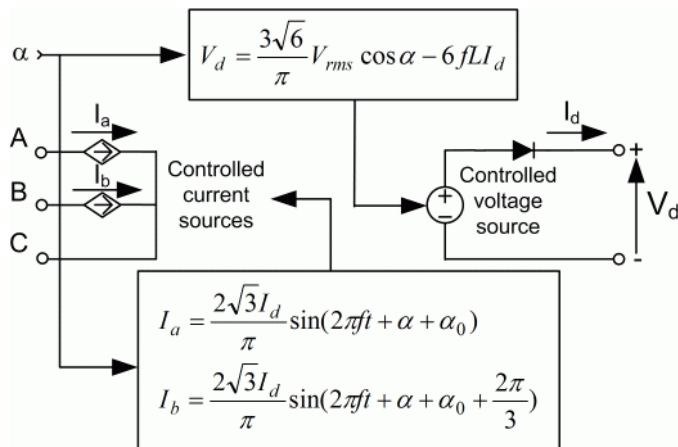
# Two-Quadrant Three-Phase Rectifier DC Drive

The armature current input is filtered by a first-order low-pass filter. An arccosine function is used to linearize the control system during continuous conduction. To compensate nonlinearities appearing during discontinuous conduction, a feedforward term is added to the firing angle. This improves the system's response time. The firing angle can vary between 0 and 180 degrees. You can limit the lower and upper limits to intermediate values.



# Two-Quadrant Three-Phase Rectifier DC Drive

**Average-Value Three-phase Rectifier** The simplified converter is shown in the following figure.



It is composed of two controlled current sources on the AC side and one controlled voltage source on the DC side. The AC current sources allow the representation of the fundamental three-phase current behaviors following the next equations:

$$I_a = \frac{2\sqrt{3}}{\pi} I_d \sin(2\pi ft + \alpha + \alpha_0)$$

$$I_b = \frac{2\sqrt{3}}{\pi} I_d \sin\left(2\pi ft + \alpha + \alpha_0 + \frac{2\pi}{3}\right)$$

with  $\alpha$  being the firing angle value,  $\alpha_0$  the phase angle of phase A,  $f$  the AC frequency and  $I_d$  the rectified output current value. The DC voltage source represents the average voltage value of the rectified voltage waveform following the next equation:

$$V_d = \frac{3\sqrt{6}}{\pi} V_{rms} \cos\alpha - 6fLI_d$$

with  $V_{rms}$  being the input phase-to-phase RMS voltage value and  $L$  being the source inductance value.

# Two-Quadrant Three-Phase Rectifier DC Drive

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## Bridge Firing Unit

The bridge firing unit converts the firing angle, provided by the current controller, to six pulses applied to the thyristor gates. The bridge firing unit block contains a band-pass filter on voltage measurement to remove voltage harmonics. The Discrete Synchronized 6-Pulse Generator block generates the pulses. Refer to the Synchronized 6-Pulse Generator for more information on this block. When using the average-value converter the bridge firing unit simply outputs the firing angle value needed by the converter.

## Remarks

The machine is separately excited with a constant DC field voltage source. There is thus no field voltage control. By default, the field current is set to its steady-state value when a simulation is started.

The armature voltage is provided by a three-phase rectifier controlled by two PI regulators. Armature current oscillations are reduced by a smoothing inductance connected in series with the armature circuit.

The average-value converter represents the average behavior of a three-phase rectifier for continuous armature current. This model is thus not suitable for simulating DC drives under discontinuous armature current conditions. The converter outputs a continuous voltage value equal to the average-value of the real-life rectified voltage. The armature voltage, armature current and electromagnetic torque ripples are thus not represented. The input currents have the frequency and amplitude of the fundamental current component of the real-life input currents.

The model is discrete. Good simulation results have been obtained with a 20  $\mu\text{s}$  time step. The control system (speed and current controllers) samples data following a user-defined sample time in order to simulate a digital controller device. Keep in mind that this sampling time has to be a multiple of the simulation time step.

The average-value converter allows the use of bigger simulation time steps since it does not generate small time constants (due to the RC snubbers) inherent to the detailed converter. For a controller sampling time of 100  $\mu\text{s}$  good simulation results have been obtained for a simulation time step of 100  $\mu\text{s}$ . This time step can of course not be higher than the controller time step.

# Two-Quadrant Three-Phase Rectifier DC Drive

## Dialog Box

### DC Machine Tab

The dialog box is titled "2-Quadrant Three-Phase Rectifier DC Motor Drive". It contains a text box with the following text: "The DC motor parameters are specified in the DC Machine tab. The converter parameters, smoothing inductance and field voltage values are specified in the Converter tab. The bridge firing unit, speed and current regulator parameters are specified in the Controller tab."

Below the text box are three tabs: "DC Machine", "Converter", and "Controller". The "DC Machine" tab is selected.

The "DC Machine" tab is divided into two main sections: "Electrical parameters" and "Mechanical parameters".

**Electrical parameters:**

- Mutual inductance (H): 1.234
- Armature:**
  - Resistance (ohm): 0.78
  - Inductance (H): 0.016
- Field:**
  - Resistance (ohm): 150
  - Inductance (H): 112.5

**Mechanical parameters:**

- Inertia (kg\*m<sup>2</sup>): 0.05
- Viscous friction coefficient (N-m-s): 0.01
- Coulomb friction torque (N-m): 0
- Initial speed (rad/s): 0

At the bottom of the dialog box, there are two dropdown menus: "Model detail level" set to "Detailed" and "Mechanical input" set to "Torque Tm". Below these are "Parameters file options" with "Load" and "Save" buttons. At the very bottom are "OK", "Cancel", "Help", and "Apply" buttons.

The DC Machine tab displays the parameters of the DC machine block of the powerlib library. Refer to the DC Machine for more information on the DC machine block parameters.

### Model detail level

Select between the detailed and the average-value inverter.

### Mechanical input

Allows you to select either the load torque or the motor speed as mechanical input. Note that if you select and apply a load torque, you will obtain as output the motor speed according to the following differential equation that describes the mechanical system dynamics:

# Two-Quadrant Three-Phase Rectifier DC Drive

$$T_e = J \frac{d}{dt} \omega_r + F \omega_r + T_m$$

This mechanical system is included in the motor model.

However, if you select the motor speed as mechanical input then you will get the electromagnetic torque as output, allowing you to represent externally the mechanical system dynamics. Note that the internal mechanical system is not used with this mechanical input selection and the inertia and viscous friction parameters are not displayed.

See for example “Mechanical Coupling of Two Motor Drives”.

## Converter Tab

2-Quadrant Three-Phase Rectifier DC Motor Drive

2-Quadrant Three-Phase Rectifier DC Motor Drive

The DC motor parameters are specified in the DC Machine tab. The converter parameters, smoothing inductance and field voltage values are specified in the Converter tab. The bridge firing unit, speed and current regulator parameters are specified in the Controller tab.

DC Machine Converter Controller

Rectifier

Snubbers

Resistance (ohm): 10e3

Capacitance (F): 900e-9

Thyristors

On-state resistance (ohm): 1e-3

Forward voltage (V): 1.3

DC bus and excitation circuit

Smoothing inductance (H): 50e-3

Field DC source (V): 150

Model detail level: Detailed Mechanical input: Torque Tm

Parameters file options

Load Save

OK Cancel Help Apply

# Two-Quadrant Three-Phase Rectifier DC Drive

---

## **Rectifier section**

The Rectifier section of the Converter tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the Universal Bridge for more information on the thyristor converter parameters.

## **Smoothing Inductance**

The smoothing inductance value (H).

## **Field DC Source**

The DC motor field voltage value (V).

## **Phase-to-Phase RMS Voltage**

Phase-to-phase rms voltage of the three-phase voltage source connected to the A,B,C terminals of the drive (V). This parameter is not used when using the detailed rectifier.

## **Frequency**

Frequency of the three-phase voltage source connected to the A,B,C terminals of the drive (Hz). This parameter is not used when using the detailed rectifier.

## **Source Inductance**

Source inductance of the three-phase voltage source connected to the A,B,C terminals of the drive (H). This parameter is not used when using the detailed rectifier.

## **Phase Angle of Phase A**

Phase angle of phase A of the three-phase voltage source connected to the A,B,C terminals of the drive (deg). This parameter is not used when using the detailed rectifier.



# Two-Quadrant Three-Phase Rectifier DC Drive

## Controller Tab

2-Quadrant Three-Phase Rectifier DC Motor Drive

The DC motor parameters are specified in the DC Machine tab. The converter parameters, smoothing inductance and field voltage values are specified in the Converter tab. The bridge firing unit, speed and current regulator parameters are specified in the Controller tab.

DC Machine | Converter | **Controller**

Regulation type:  Sampling time (s):

Speed Controller | **Current Controller** | Bridge Firing Unit

Nominal speed (rpm):  Initial speed reference (rpm):  Low-pass filter cutoff frequency (Hz):

PI regulator

Proportional gain:  Integral gain:

Speed ramps (rpm/s)

Acceleration:  Deceleration:

Model detail level:  Mechanical input:

Parameters file options

### Schematic Button

When you press this button, a diagram illustrating the speed and current controllers schematics appears.

### Regulation Type

This pop-up menu allows you to choose between speed and torque regulation.

### Sampling Time

The controller (speed and current) sampling time (s). The sampling time has to be a multiple of the simulation time step.

# Two-Quadrant Three-Phase Rectifier DC Drive

---

## **Controller – Speed Controller Subtab**

### **Nominal Speed**

The nominal speed value of the DC motor (rpm). This value is used to convert motor speed from rpm to pu (per unit).

### **Initial Speed Reference**

The initial speed reference value (rpm). This value allows the user to start a simulation with a speed reference other than 0 rpm.

### **Low-Pass Filter Cutoff Frequency**

Cutoff frequency of the low-pass filter used to filter the motor speed measurement (Hz).

### **Proportional Gain**

The proportional gain of the PI speed controller.

### **Integral Gain**

The integral gain of the PI speed controller.

### **Acceleration**

The maximum change of speed allowed during motor acceleration (rpm/s). Too great a value can cause armature over-current.

### **Deceleration**

The maximum change of speed allowed during motor deceleration (rpm/s). Too great a value can cause armature over-current.

# Two-Quadrant Three-Phase Rectifier DC Drive

## Controller – Current Controller Subtab

2-Quadrant Three-Phase Rectifier DC Motor Drive

2-Quadrant Three-Phase Rectifier DC Motor Drive

The DC motor parameters are specified in the DC Machine tab. The converter parameters, smoothing inductance and field voltage values are specified in the Converter tab. The bridge firing unit, speed and current regulator parameters are specified in the Controller tab.

DC Machine | Converter | **Controller**

Regulation type: Speed regulation | Sampling time (s): 100e-6 | Schematic

Speed Controller | **Current Controller** | Bridge Firing Unit

Low-pass filter cutoff frequency (Hz): 120 | Reference limit (p.u.): 1.5

Nominal values: Power (VA): 5746 | Voltage (V): 240 | PI regulator: Proportional gain: 1.1 | Integral gain: 90

Model detail level: Detailed | Mechanical input: Torque Tm

Parameters file options: Load | Save

OK | Cancel | Help | Apply

### Power and Voltage nominal values

The DC motor nominal power (W) and voltage (V) values. These values are used to convert armature current from amperes to pu (per unit).

### Proportional Gain

The proportional gain of the PI current controller.

### Integral Gain

The integral gain of the PI current controller.

### Low-Pass Filter Cutoff Frequency

Cutoff frequency of the low-pass filter used to filter the armature current measurement (Hz).

# Two-Quadrant Three-Phase Rectifier DC Drive

## Reference Limit

Maximum current reference value (pu). 1.5 pu is a common value.

## Controller – Bridge Firing Unit Subtab

The screenshot shows a software window titled "2-Quadrant Three-Phase Rectifier DC Motor Drive". The window contains several tabs: "DC Machine", "Converter", and "Controller". The "Controller" tab is active, and within it, the "Bridge Firing Unit" subtab is selected. The interface includes a "Regulation type" dropdown set to "Speed regulation" and a "Sampling time (s)" input field set to "100e-6". Below these are three sub-tabs: "Speed Controller", "Current Controller", and "Bridge Firing Unit". The "Bridge Firing Unit" subtab contains two main sections: "Firing angle limits (degrees)" with "Alpha min:" set to 20 and "Alpha max:" set to 160; and "Synchronized pulse generator" with "Frequency of synchronization voltages (Hz)" set to 50 and "Pulse width (degrees)" set to 10. At the bottom of the window, there are buttons for "Load", "Save", "OK", "Cancel", "Help", and "Apply".

## Alpha Min

Minimum firing angle value (deg.). 20 degrees is a common value.

## Alpha Max

Maximum firing angle value (deg.). 160 degrees is a common value.

## Frequency of synchronization voltages

Frequency of the synchronization voltages used by the discrete synchronized 6-pulse generator block (Hz). This frequency is

# Two-Quadrant Three-Phase Rectifier DC Drive

## Block Inputs and Outputs

equal to the line frequency of the three-phase power line. This parameter is not used when using the average-value converter.

### Pulse Width

The width of the pulses applied to the six thyristor gates (deg.). This parameter is not used when using the average-value converter.

### SP

The speed or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration / deceleration ramps. If the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

### T<sub>m</sub> or W<sub>m</sub>

The mechanical input: load torque (T<sub>m</sub>) or motor speed (W<sub>m</sub>).

### A, B, C

The three-phase electric connections. The voltage must be adequate for the motor size.

### W<sub>m</sub> or T<sub>e</sub>

The mechanical output: motor speed (W<sub>m</sub>) or electromagnetic torque (T<sub>e</sub>).

### Motor

The motor measurement vector. This vector is composed of two elements:

- The armature voltage
- The DC motor measurement vector (containing the speed, armature current, field current, and electromagnetic torque values). Note that the speed signal is converted from rad/s to rpm before output.

### Conv

The three-phase converter measurement vector. It includes the converter output voltage. The output current is not included

# Two-Quadrant Three-Phase Rectifier DC Drive

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since it is equal to the DC motor armature current. Note that all current and voltage values of the detailed rectifier bridge can be visualized with the mulimeter block

## Ctrl

The controller measurement vector. This vector contains:

- The armature current reference
- The firing angle computed by the current controller
- The speed or torque error (difference between the speed reference ramp and actual speed or between the torque reference and actual torque)
- The speed reference ramp or torque reference

## Model Specifications

The library contains a 5 hp and a 200 hp drive parameter set. The specifications of these two drives are shown in the following table.

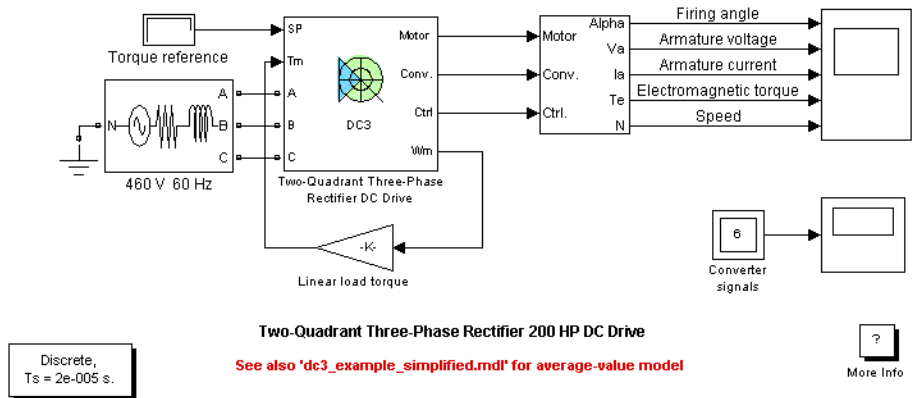
### 5 HP and 200 HP Drive Specifications

		<b>5 HP Drive</b>	<b>200 HP Drive</b>
<b>Drive Input Voltage</b>			
	Amplitude	220 V	460 V
	Frequency	50 Hz	60 Hz
<b>Motor Nominal Values</b>			
	Power	5 hp	200 hp
	Speed	1750 rpm	1750 rpm
	Voltage	240 V	500 V

# Two-Quadrant Three-Phase Rectifier DC Drive

## Example

The `dc3_example` demo illustrates the three-phase rectifier drive used with the 200 hp drive parameter set during torque regulation. A 5 hp parameter set is also available in the library.



The 'Ts' parameter used in this model is set to 20e-6s by the Model Properties Callbacks

The rectifier is fed by a 460 V AC 60 Hz voltage source.

The motor is coupled to a linear load, which means that the mechanical torque of the load is proportional to the speed.

The initial torque reference is set to 0 N.m and the armature current is null. No electromagnetic torque is produced, and the motor stays still.

At  $t = 0.05$  s, the torque reference jumps to 800 N.m. This causes the armature current to rise to about 305 A. Notice that the armature current follows the reference quite accurately, with fast response time and small overshooting. The 15 mH smoothing inductance keeps the current oscillations quite small. Observe also that the average firing angle value stays below 90 degrees, the converter being in rectifier mode.

The electromagnetic torque produced by the armature current flow causes the motor to accelerate. The speed rises and starts to stabilize

# Two-Quadrant Three-Phase Rectifier DC Drive

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around  $t = 5$  s at about 1450 rpm, the sum of the load and viscous friction torques beginning to equalize the electromagnetic torque.

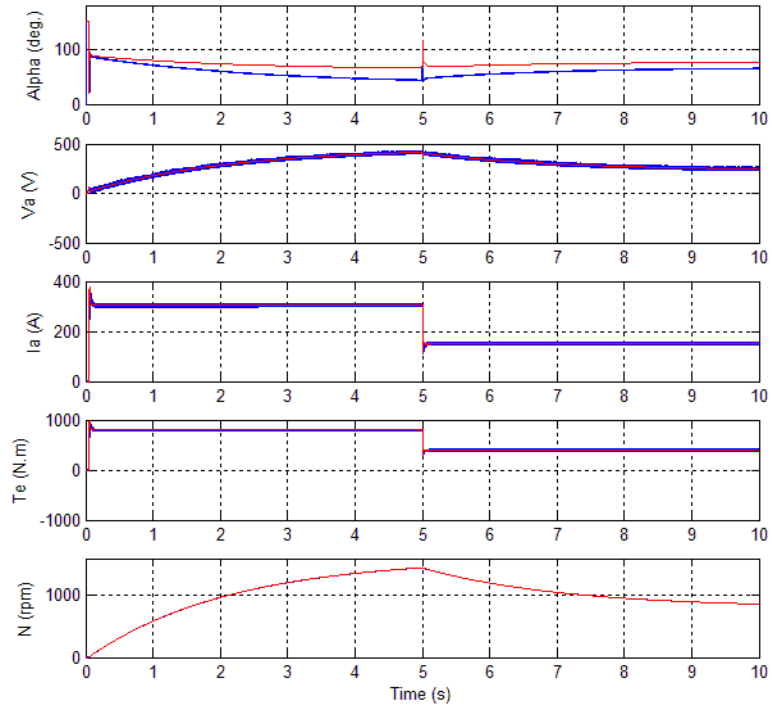
At  $t = 5$  s, the torque reference is set to 400 N.m and the armature current jumps down to about 155 A. This causes the load torque to decelerate the motor.

At  $t = 10$  s speed starts to stabilize around 850 rpm.

The following figure illustrates the results obtained respectively with the detailed and average-value converters. Average voltage, current, torque and speed values are identical for both models. The average firing angle values however are slightly different. Notice that the higher frequency signal components are not represented with the simplified converter.



# Two-Quadrant Three-Phase Rectifier DC Drive



**DC3 Example Waveforms (Blue : Detailed Converter, Red : Average-Value Converter)**

## References

- [1] Sen, P.C., *Thyristor DC Drives*, J.Wiley and Sons, 1981.
- [2] Nondahl, Thomas A., *Microprocessor Control of Motor Drives and Power Converters, tutorial course*, IEEE Industry Application Society, October 1993, pp. 7.1-7.26.

# Universal Bridge

## Purpose

Implement universal power converter with selectable topologies and power electronic devices

## Library

Power Electronics

## Description

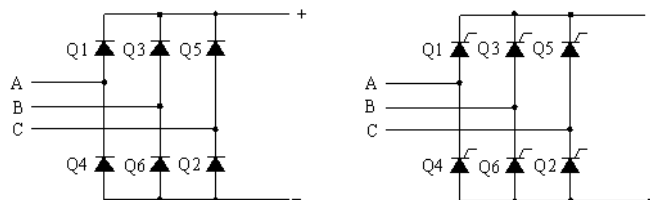


The Universal Bridge block implements a universal three-phase power converter that consists of up to six power switches connected in a bridge configuration. The type of power switch and converter configuration are selectable from the dialog box.

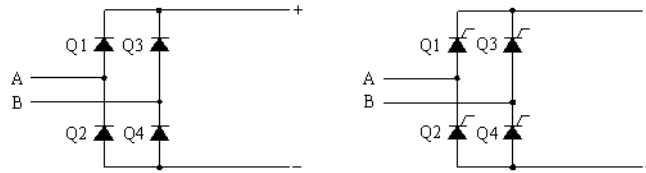
The Universal Bridge block allows simulation of converters using both naturally commutated (or line-commutated) power electronic devices (diodes or thyristors) and forced-commutated devices (GTO, IGBT, MOSFET).

The Universal Bridge block is the basic block for building two-level voltage-sourced converters (VSC).

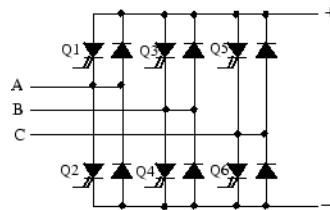
The device numbering is different if the power electronic devices are naturally commutated or forced-commutated. For a naturally commutated three-phase converter (diode and thyristor), numbering follows the natural order of commutation:



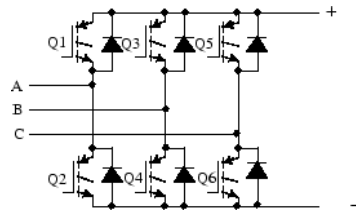
For the case of a two-phase diode or thyristor bridge, and for any other bridge configuration, the order of commutation is the following:



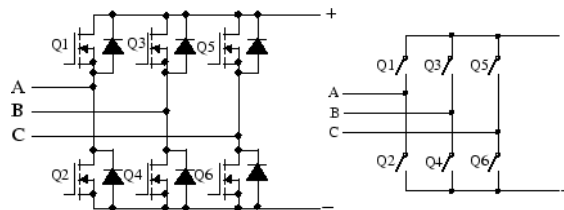
GTO-Diode bridge:



IGBT-Diode bridge:

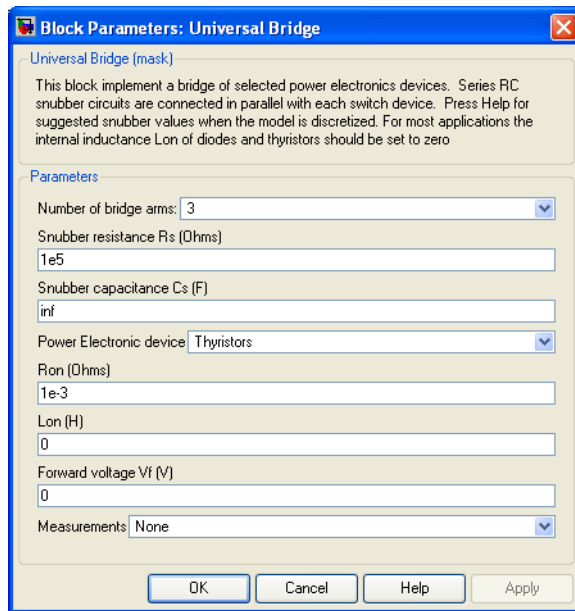


MOSFET-Diode and Ideal Switch bridges:



# Universal Bridge

## Dialog Box and Parameters



### Number of bridge arms

Set to 1 or 2 to get a single-phase converter (two or four switching devices). Set to 3 to get a three-phase converter connected in Graetz bridge configuration (six switching devices).

### Snubber resistance $R_s$

The snubber resistance, in ohms ( $\Omega$ ). Set the **Snubber resistance  $R_s$**  parameter to `inf` to eliminate the snubbers from the model.

### Snubber capacitance $C_s$

The snubber capacitance, in farads (F). Set the **Snubber capacitance  $C_s$**  parameter to 0 to eliminate the snubbers, or to `inf` to get a resistive snubber.

In order to avoid numerical oscillations when your system is discretized, you need to specify  $R_s$  and  $C_s$  snubber values for diode and thyristor bridges. For forced-commutated devices (GTO, IGBT, or MOSFET), the bridge operates satisfactorily with purely

resistive snubbers as long as firing pulses are sent to switching devices.

If firing pulses to forced-commutated devices are blocked, only antiparallel diodes operate, and the bridge operates as a diode rectifier. In this condition appropriate values of  $R_s$  and  $C_s$  must also be used.

When the system is discretized, use the following formulas to compute approximate values of  $R_s$  and  $C_s$ :

$$R_s > 2 \frac{T_s}{C_s}$$

$$C_s < \frac{P_n}{1000(2\pi f)V_n^2}$$

where

$P_n$  = Nominal power of single or three phase converter (VA)

$V_n$  = Nominal line-to-line AC voltage (V<sub>rms</sub>)

$f$  = Fundamental frequency (Hz)

$T_s$  = Sample Time (s)

These  $R_s$  and  $C_s$  values are derived from the following two criteria:

- The snubber leakage current at fundamental frequency is less than 0.1% of nominal current when power electronic devices are not conducting.
- The RC time constant of snubbers is higher than two times the sample time  $T_s$ .

# Universal Bridge

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These  $R_s$  and  $C_s$  values that guarantee numerical stability of the discretized bridge can be different from actual values used in a physical circuit.

## **Power electronic device**

Select the type of power electronic device to use in the bridge.

When you select **Switching-function based VSC**, a switching-function voltage source converter type equivalent model is used, where switches are replaced by two voltage sources on the AC side and a current source on the DC side. This model uses the same firing pulses as for other power electronic devices and it correctly represents harmonics normally generated by the bridge.

When you select **Average-model based VSC**, an average-model type of voltage source converter is used to represent the power-electronic switches. Unlike the other power electronic devices, this model uses the reference signals ( $uref$ ) representing the average voltages generated at the ABC terminals of the bridge. This model does not represent harmonics. It can be used with larger sample times while preserving the average voltage dynamics.

See the `power_sfavg` demo for an example comparing these two models to an Universal Bridge block using IGBT/Diode device.

## **Ron**

Internal resistance of the selected device, in ohms ( $\Omega$ ).

## **Lon**

Internal inductance, in henries (H), for the diode or the thyristor device. When the bridge is discretized, the `Lon` parameter must be set to zero.

## **Forward voltage Vf**

This parameter is available only when the selected **Power electronic device** is Diodes or Thyristors.

Forward voltage, in volts (V), across the device when it is conducting.

### **Forward voltages [Device Vf, Diode Vfd]**

This parameter is available when the selected **Power electronic device** is GTO/Diodes or IGBT/Diodes.

Forward voltages, in volts (V), of the forced-commutated devices (GTO, MOSFET, or IGBT) and of the antiparallel diodes.

### **[Tf (s) Tt (s)]**

Fall time Tf and tail time Tt, in seconds (s), for the GTO or the IGBT devices.

### **Measurements**

Select **Device voltages** to measure the voltages across the six power electronic device terminals.

Select **Device currents** to measure the currents flowing through the six power electronic devices. If antiparallel diodes are used, the measured current is the total current in the forced-commutated device (GTO, MOSFET, or IGBT) and in the antiparallel diode. A positive current therefore indicates a current flowing in the forced-commutated device and a negative current indicates a current flowing in the diode. If snubber devices are defined, the measured currents are the ones flowing through the power electronic devices only.

Select **UAB UBC UCA UDC voltages** to measure the terminal voltages (AC and DC) of the Universal Bridge block.

Select **All voltages and currents** to measure all voltages and currents defined for the Universal Bridge block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** menu of the Multimeter block, the measurement is identified by a label followed by the block name.

# Universal Bridge

Measurement	Label
Device voltages	Usw1 : , Usw2 : ,Usw3 : ,Usw4 : ,Usw5 : ,Usw6 :
Branch current	Isw1 : , Isw2 : , Isw3 : , Isw4 : , Isw5 : , Isw6 :
Terminal voltages	Uab : , Ubc : , Uca : , Udc :

## Inputs and Outputs

g

The gate input for the controlled switch devices. The pulse ordering in the vector of the gate signals corresponds to the switch number indicated in the six circuits shown in the Description section. For the diode and thyristor bridges, the pulse ordering corresponds to the natural order of commutation. For all other forced-commutated switches, pulses are sent to upper and lower switches of phases A, B, and C.

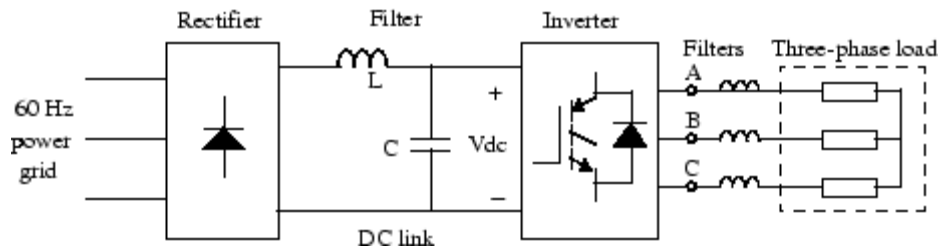
Topology	Pulse Vector of Input g
one arm	[ Q1 ,Q2 ]
two arms	[ Q1 ,Q2 ,Q3 ,Q4 ]
three arms	[ Q1 ,Q2 ,Q3 ,Q4 ,Q5 ,Q6 ]

## Example

The power\_bridges demo illustrates the use of two Universal Bridge blocks in an ac/dc/ac converter consisting of a rectifier feeding an IGBT inverter through a DC link. The inverter is pulse-width modulated (PWM) to produce a three-phase 50 Hz sinusoidal voltage to the load. In this example the inverter chopping frequency is 2000 Hz.

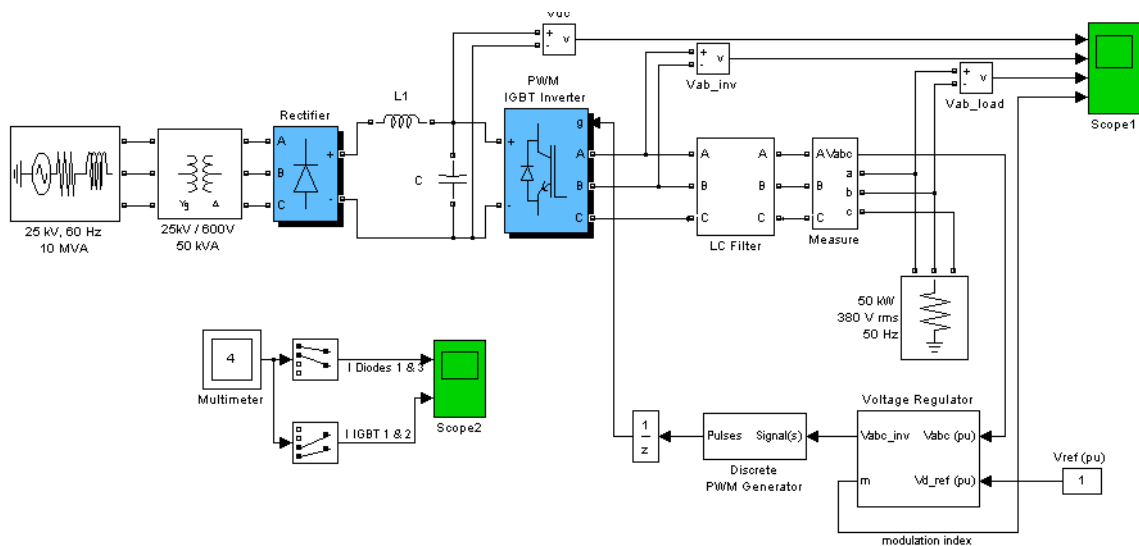


# Universal Bridge



The IGBT inverter is controlled with a PI regulator in order to maintain a 1 pu voltage (380 Vrms, 50 Hz) at the load terminals.

A Multimeter block is used to observe commutation of currents between diodes 1 and 3 in the diode bridge and between IGBT/Diodes switches 1 and 2 in the IGBT bridge.



Start simulation. After a transient period of approximately 40 ms, the system reaches a steady state. Observe voltage waveforms at DC bus, inverter output, and load on Scope1. The harmonics generated by the

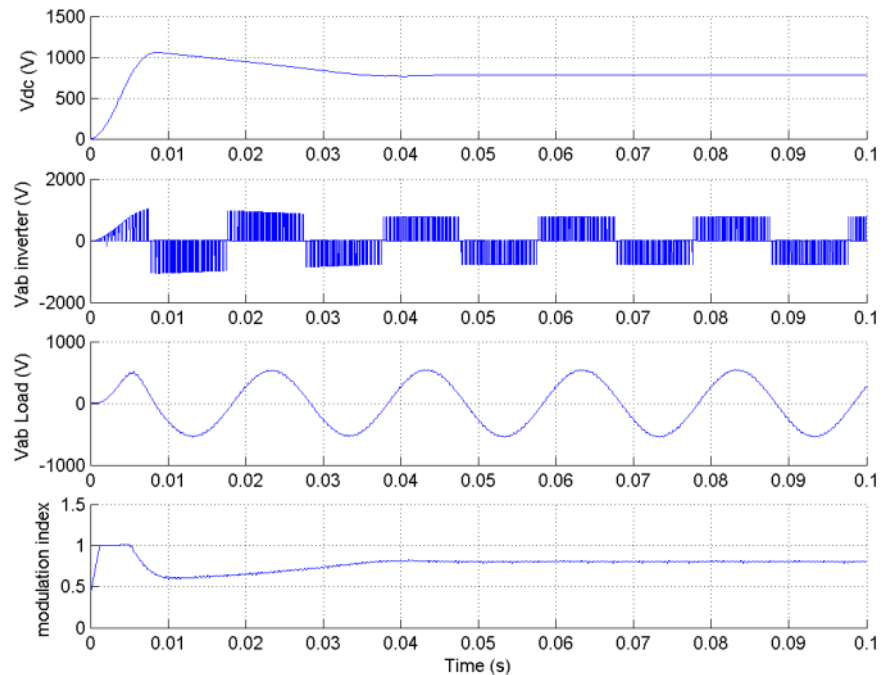
# Universal Bridge

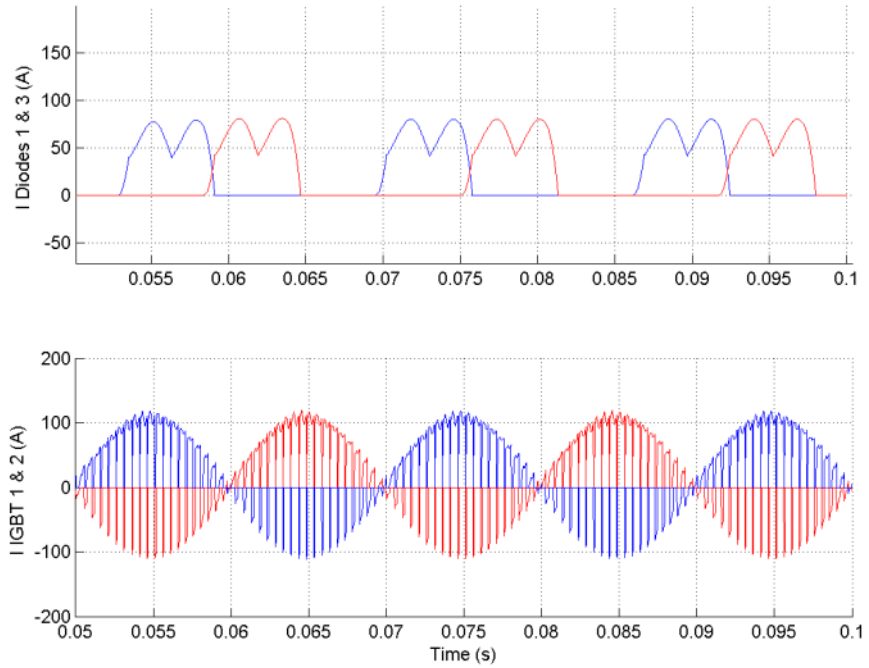
inverter around multiples of 2 kHz are filtered by the LC filter. As expected the peak value of the load voltage is 537 V (380 V RMS).

In steady state the mean value of the modulation index is  $m = 0.8$ , and the mean value of the DC voltage is 778 V. The fundamental component of 50 Hz voltage buried in the chopped inverter voltage is therefore

$$V_{ab} = 778 \text{ V} * 0.612 * 0.80 = 381 \text{ V RMS}$$

Observe diode currents on trace 1 of Scope2, showing commutation from diode 1 to diode 3. Also observe on trace 2 currents in switches 1 and 2 of the IGBT/Diode bridge (upper and lower switches connected to phase A). These two currents are complementary. A positive current indicates a current flowing in the IGBT, whereas a negative current indicates a current flowing in the antiparallel diode.





## See Also

Diode, GTO, Ideal Switch, IGBT, MOSFET, Multimeter, Three-Level Bridge, Thyristor

# Unified Power Flow Controller (Phasor Type)

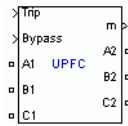
## Purpose

Implement phasor model of three-phase unified power flow controller

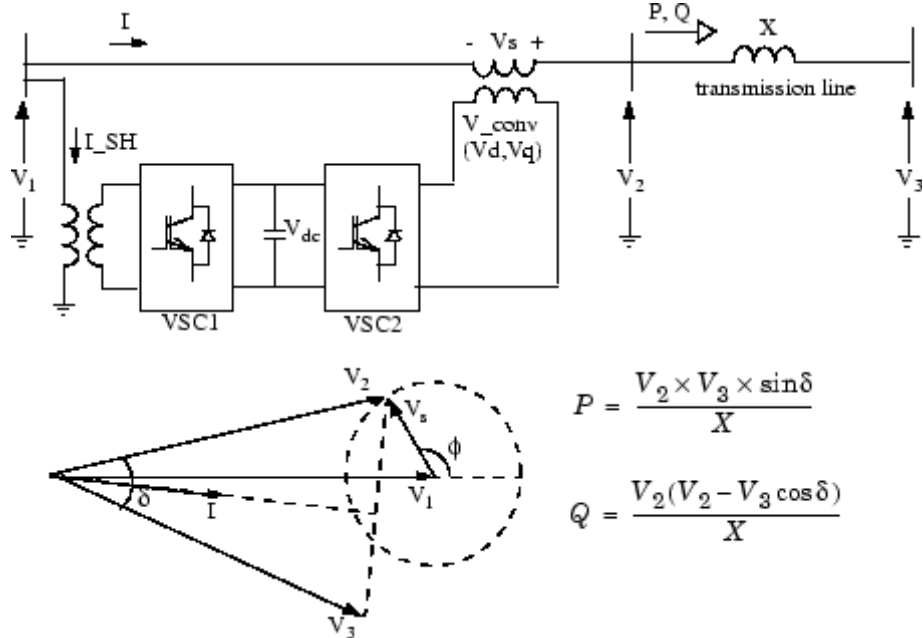
## Library

Flexible AC Transmission Systems (FACTS)/Power-Electronics Based FACTS

## Description



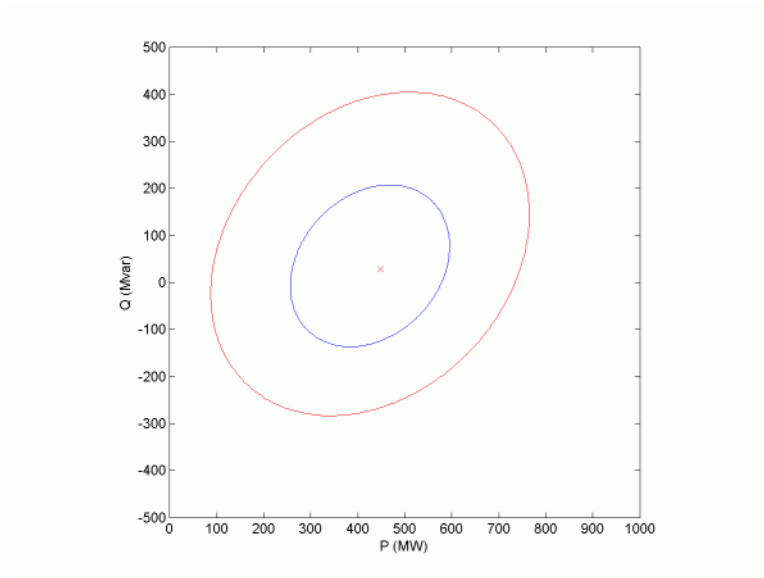
The Unified Power Flow Controller (UPFC) is the most versatile member of the Flexible AC Transmission Systems (FACTS) family using power electronics to control power flow on power grids [1]. The UPFC uses a combination of a shunt controller (STATCOM) and a series controller (SSSC) interconnected through a common DC bus as shown on the figure below.



**Single-line Diagram of a UPFC and Phasor Diagram of Voltages and Currents**

# Unified Power Flow Controller (Phasor Type)

This FACTS topology provides much more flexibility than the SSSC for controlling the line active and reactive power because active power can now be transferred from the shunt converter to the series converter, through the DC bus. Contrary to the SSSC where the injected voltage  $V_s$  is constrained to stay in quadrature with line current  $I$ , the injected voltage  $V_s$  can now have any angle with respect to line current. If the magnitude of injected voltage  $V_s$  is kept constant and if its phase angle  $[\text{PHI}]$  with respect to  $V_1$  is varied from 0 to 360 degrees, the locus described by the end of vector  $V_2$  ( $V_2=V_1+V_s$ ) is a circle as shown on the phasor diagram. As  $[\text{PHI}]$  is varying, the phase shift  $\delta$  between voltages  $V_2$  and  $V_3$  at the two line ends also varies. It follows that both the active power  $P$  and the reactive power  $Q$  transmitted at one line end can be controlled. The UPFC controllable region in the  $P$ - $Q$  plane is the area enclosed by an ellipse as shown on the figure below.



**Controllable Region for a 100 MVA UPFC connected on 500 kV, 200 km line**

# Unified Power Flow Controller (Phasor Type)

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This figure was obtained with a 100 MVA UPFC controlling active and reactive power at one end of a 500 kV, 200 km transmission line. The following parameters have been used:

- Line: length = 200km; reactance =  $0.35 \Omega / \text{km}$
- System voltage: 500 kV infinite sources V1 and V3; V1=1.0 pu, 0 degree; V3= 1.0 pu,-7.22 degrees
- Series and shunt converter rating: 100 MVA
- Series converter: nominal injected voltage = 10% of nominal line-to-ground voltage (28.9 kV); impedance (transformer leakage reactance and filters) = 0.15 pu

With V3 lagging V1 by 7.22 degrees, the natural power flow without compensation is 450 MW or 50% of the line surge impedance loading (SIL=900 MW). With an injected voltage  $V_s = 0.1$  pu any operating point inside the larger ellipse can be obtained and active power can be varied by approximately +/- 300 MW.

In addition to allow control of the line active and reactive power, the UPFC provides an additional degree of freedom. Its shunt converter operating as a STATCOM controls voltage V1 by absorbing or generating reactive power.

Both the series and shunt converters use a Voltage-Sourced Converter (VSC) connected on the secondary side of a coupling transformer. The VSCs use forced-commutated power electronic devices (GTOs, IGBTs or IGCTs) to synthesize a voltage from a DC voltage source. The common capacitor connected on the DC side of the VSCs acts as a DC voltage source. Two VSC technologies can be used for the VSCs:

- VSC using GTO-based square-wave inverters and special interconnection transformers. Typically four three-level inverters are used to build a 48-step voltage waveform. Special interconnection transformers are used to neutralize harmonics contained in the square waves generated by individual inverters. In this type of VSC,

# Unified Power Flow Controller (Phasor Type)

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the fundamental component of voltage is proportional to the voltage  $V_{dc}$ . Therefore  $V_{dc}$  has to varied for controlling the injected voltage.

- VSC using IGBT-based PWM inverters. This type of inverter uses Pulse-Width Modulation (PWM) technique to synthesize a sinusoidal waveform from a DC voltage with a typical chopping frequency of a few kilohertz. Harmonics are cancelled by connecting filters at the AC side of the VSC. This type of VSC uses a fixed DC voltage  $V_{dc}$ . Voltage is varied by changing the modulation index of the PWM modulator.

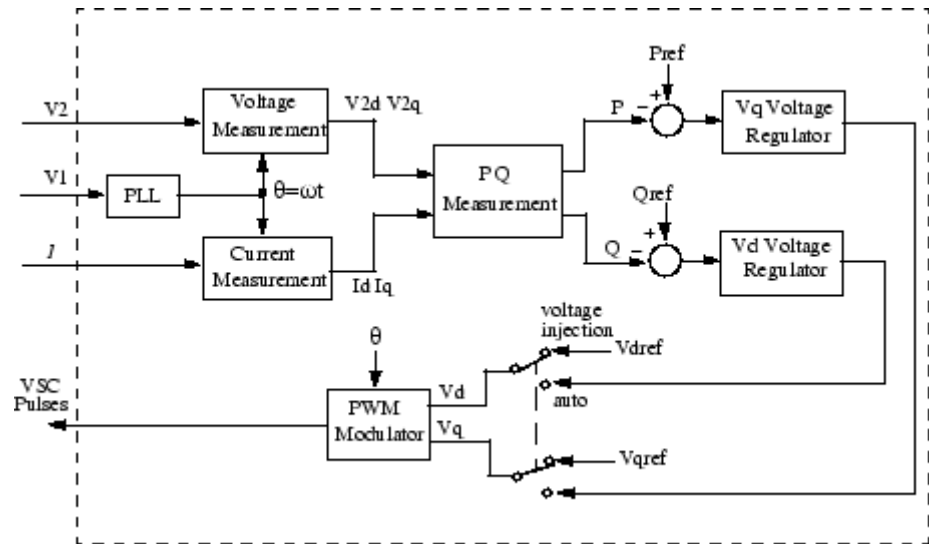
The UPFC (Phasor Type) block models an IGBT-based UPFC. However, as details of the inverter and harmonics are not represented, it can be also used to model a GTO-based UPFC in transient stability studies.

## Control System

The shunt converter operates as a STATCOM. For a description of its control system, refer to the Static Synchronous Compensator (Phasor Type). In summary, the shunt converter controls the AC voltage at its terminals and the voltage of the DC bus. It uses a dual voltage regulation loop: an inner current control loop and an outer loop regulating AC and DC voltages.

Control of the series branch is different from the SSSC. In a SSSC the two degrees of freedom of the series converter are used to control the DC voltage and the reactive power. In case of a UPFC the two degrees of freedom are used to control the active power and the reactive power. A simplified block diagram of the series converter is shown below.

# Unified Power Flow Controller (Phasor Type)



**Simplified Block Diagram of the Series Converter Control System**

The series converter can operate either in power flow control (automatic mode) or in manual voltage injection mode. In power control mode, the measured active power and reactive power are compared with reference values to produce P and Q errors. The P error and the Q error are used by two PI regulators to compute respectively the Vq and Vd components of voltage to be synthesized by the VSC. (Vq in quadrature with V1 controls active power and Vd in phase with V1 controls reactive power). In manual voltage injection mode, regulators are not used. The reference values of injected voltage Vdref and Vqref are used to synthesize the converter voltage.

The UPFC block is a phasor model which does not include detailed representation of the power electronics. You must use it with the phasor simulation method, activated with the Powergui block. It can be used in three-phase power systems together with synchronous generators, motors, dynamic loads and other FACTS and DR systems to perform transient stability studies and observe impact of the UPFC on electromechanical oscillations and transmission capacity at fundamental frequency.



# Unified Power Flow Controller (Phasor Type)

## Dialog Box and Parameters

The UPFC parameters are grouped in three categories: Power data, Control parameters (shunt converter), and Control parameters (series converter). Use the **Display** listbox to select which group of parameters you want to visualize.

### Power Data Parameters

Block Parameters: Unified Power Flow Controller (Phasor Type) (mask)

This block implements a phasor model of an Unified Power Flow Controller (UPFC).  
The output (m) is a bus signal. Use the Bus Selector block to extract individual signals.

Parameters

Display: Power data

System nominal voltage and frequency [ Vrms L-L, f[Hz] ]:  
[ 500e3, 60 ]

Shunt converter rating [VA]:  
100e6

Shunt converter impedance [ R[pu] L[pu] ]:  
[ 0.22/30, 0.22 ]

Shunt converter initial current [ Mag[pu] Pha(deg.) ]:  
[ 0, 0 ]

Series converter rating [ Snom[VA] Max. Injected voltage[pu] ]:  
[ 100e6, 0.1 ]

Series converter impedance [ R[pu] L[pu] ]:  
[ 0.16/30, 0.16 ]

Series converter initial current [ Mag[pu] Pha(deg.) ]:  
[ 0, 0 ]

DC link nominal voltage [V]:  
40000

DC link total equivalent capacitance [F]:  
750e-6

OK Cancel Help Apply

### System nominal voltage and frequency [Vrms f]

The nominal line-to-line voltage in Vrms and the nominal system frequency in hertz.

### Shunt converter ratings

The nominal rating of the shunt converter in VA.

# Unified Power Flow Controller (Phasor Type)

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## **Shunt converter impedance [R L]**

The positive-sequence resistance R and inductance L of the shunt converter, in pu based on the nominal converter rating and nominal voltage. R and L represent the resistance and leakage inductance of the shunt transformer plus the resistance and inductance of the series filtering inductors connected at the VSC output.

## **Shunt converter initial current [Mag Phase]**

The initial value of the positive-sequence current phasor (Magnitude in pu and Phase in degrees). If you know the initial value of the shunt current corresponding to the UPFC operating point you may specify it in order to start simulation in steady state. If you don't know this value, you can leave [0 0]. The system will reach steady-state after a short transient.

## **Series converter ratings [Snom, Max. Injected voltage]**

The ratings of the series converter in VA and the maximum value of the injected voltage  $V_{conv}$  on the VSC side of the transformer (see single line diagram), in pu of nominal phase-to-ground voltage.

## **Series converter impedance [R L]**

The positive-sequence resistance and inductance of the converter, in pu, based on the converter rated power and voltage. R and L represent the resistance and leakage inductance of the series transformer plus the resistance and inductance of the series filtering inductors connected at the VSC output.

## **Series converter initial current [Mag Phase]**

The initial value of the positive-sequence current phasor (Magnitude in pu and Phase in degrees). If you know the initial value of the series current corresponding to the UPFC operating point you may specify it in order to start simulation in steady state. If you don't know this value, you can leave [0 0]. The system will reach steady-state after a short transient.

## **DC link nominal voltage**

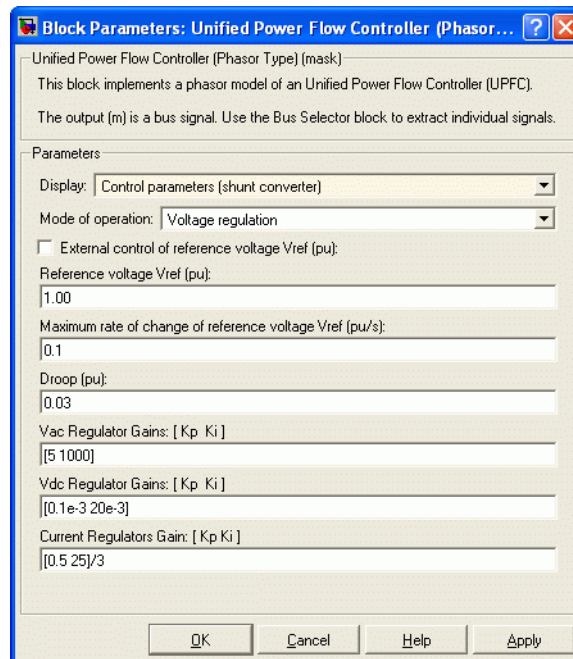
The nominal voltage of the DC link in volts.

# Unified Power Flow Controller (Phasor Type)

## DC link total equivalent capacitance

The total capacitance of the DC link in farads. This capacitance value is related to the UPFC converter ratings and to the DC link nominal voltage. The energy stored in the capacitance (in joules) divided by the converter rated power (in VA) is a time duration which is usually a fraction of a cycle at nominal frequency. For example, for the default parameters, ( $C=750 \mu\text{F}$ ,  $V_{dc}=40\,000 \text{ V}$ ,  $S_{nom}=100 \text{ MVA}$ ) this ratio  $(1/2 \times C \times V_{dc}^2) / (S_{nom})$  is 6.0 ms, which represents 0.36 cycle for a 60 Hz frequency. If you change the default values of the nominal power rating and DC voltage, you should change the capacitance value accordingly.

## Control Parameters (shunt converter)



Block Parameters: Unified Power Flow Controller (Phasor...)

Unified Power Flow Controller (Phasor Type) (mask)  
This block implements a phasor model of an Unified Power Flow Controller (UPFC).  
The output (m) is a bus signal. Use the Bus Selector block to extract individual signals.

Parameters

Display: Control parameters (shunt converter)

Mode of operation: Voltage regulation

External control of reference voltage Vref (pu):

Reference voltage Vref (pu): 1.00

Maximum rate of change of reference voltage Vref (pu/s): 0.1

Droop (pu): 0.03

Vac Regulator Gains: [ Kp Ki ]  
[5 1000]

Vdc Regulator Gains: [ Kp Ki ]  
[0.1e-3 20e-3]

Current Regulators Gain: [ Kp Ki ]  
[0.5 25]/3

OK Cancel Help Apply

# Unified Power Flow Controller (Phasor Type)

---

## **Mode of operation**

Specifies the shunt converter mode of operation. Select either Voltage regulation or Var Control.

## **External control of reference voltage Vref**

If this parameter is checked, a Simulink input named Vref appears on the block, allowing to control the reference voltage from an external signal (in pu). Otherwise a fixed reference voltage is used, as specified by the parameter below.

## **Reference voltage Vref**

This parameter is not visible when the **Mode of operation** parameter is set to Var Control or when the **External control of reference voltage Vref** parameter is checked.

Reference voltage, in pu, used by the voltage regulator.

## **Maximum rate of change of reference voltage Vref**

This parameter is not visible when the **Mode of operation** parameter is set to Var Control.

Maximum rate of change of the reference voltage, in pu/s, when an external reference voltage is used.

## **Droop**

This parameter is not visible when the **Mode of operation** parameter is set to Var Control.

Droop reactance, in pu/shunt converter rating  $S_{nom}$ , defining the slope of the V-I characteristic.

## **Vac Regulator Gains: [Kp Ki]**

This parameter is not visible when the **Mode of operation** parameter is set to Var Control.

Gains of the AC voltage PI regulator. Specify proportional gain  $K_p$  in (pu of I)/(pu of V), and integral gain  $K_i$ , in (pu of I)/(pu of V)/s, where V is the AC voltage error and I is the output of the voltage regulator.

# Unified Power Flow Controller (Phasor Type)

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## **Reactive power setpoint Qref**

This parameter is not visible when the **Mode of operation** parameter is set to Voltage Control.

Reference reactive power, in pu, when the shunt converter is in Var Control.

## **Maximum rate of change of reactive power setpoint Qref**

This parameter is not visible when the **Mode of operation** parameter is set to Voltage Control.

Maximum rate of change of the reference reactive power, in pu/s.

## **Vdc Regulator Gains: [Kp Ki]**

Gains of the DC voltage PI regulator which controls the voltage across the DC bus capacitor. Specify proportional gain  $K_p$  in (pu of I)/Vdc, and integral gain  $K_i$ , in (pu of I)/Vdc/s, where Vdc is the DC voltage error and I is the output of the voltage regulator.

## **Current Regulators Gains: [Kp Ki]**

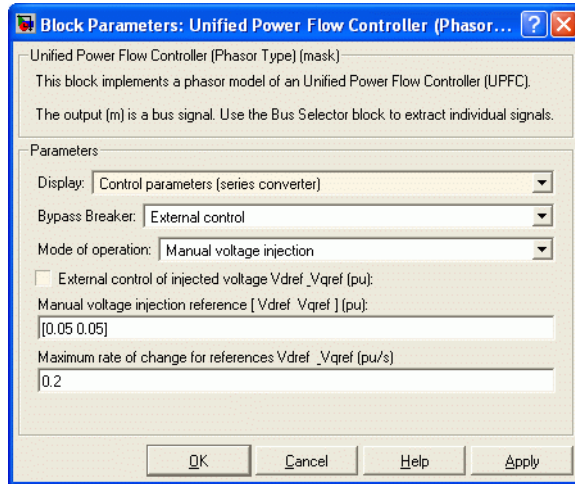
Gains of the inner current regulation loop.

Specify proportional gain  $K_p$  in (pu of V)/(pu of I), integral gain  $K_i$ , in (pu of V)/(pu of I)/s, where V is the output of the d or q current regulator and I is the Id or Iq current error.

The current regulator is assisted by a feed forward regulator. The feed forward gain in (pu of V)/(pu of I) is the shunt converter reactance (in pu) given by parameter L in the **Shunt converter impedance [R L]** parameters.

# Unified Power Flow Controller (Phasor Type)

## Control Parameters (series converter)



### Bypass Breaker

Specifies the status of the bypass breaker connected inside the block across terminals A1, B1, C1 and A2, B2, C2. Select either **External Control**, **Open** or **Closed**. If the bypass breaker is in external control, a Simulink input named **Bypass** appears on the block, allowing to control the status of the bypass breaker from an external signal (0 or 1).

### Mode of operation

Specifies the series converter mode of operation. Select either **Power flow control** or **Manual voltage injection**.

### External control of power references

This parameter is not visible when the **Mode of operation** parameter is set to **Manual voltage injection**.

If this parameter is checked, a Simulink input named **PQref** appears on the block, allowing to control the active and reactive powers from an external signal (in pu). Otherwise, fixed reference power are used, as specified by the parameter below.

# Unified Power Flow Controller (Phasor Type)

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## Reference active and reactive powers [Pref Qref]

This parameter is not visible when the **Mode of operation** parameter is set to Manual voltage injection.

Specify references values, in pu.

## Maximum rate of change for references Pref\_Qref

This parameter is not visible when the **Mode of operation** parameter is set to Manual voltage injection.

Specify maximum rate of change of Pref and Qref, in pu/s.

## Power regulator gains: [Kp Ki]

This parameter is not visible when the **Mode of operation** parameter is set to Manual voltage injection.

Gains of the PI regulators which control the line active power and reactive power. Specify proportional gain Kp in (pu of Vdq)/(pu of PQ), and integral gain Ki, in (pu of Vdq)/(pu of PQ)/s, where Vdq is the Vd or Vq injected voltage and PQ is the P or Q voltage error.

## External control of injected voltage [Vdref Vqref]

This parameter is not visible when the **Mode of operation** parameter is set to Power flow control.

If this parameter is checked, a Simulink input named Vdqref appears on the block, allowing to control the injected voltage from an external signal (in pu). Otherwise a fixed reference voltage is used, as specified by the parameter below.

## Manual voltage injection reference [Vdref Vqref]

This parameter is not visible when the **External control of injected voltage [Vdref Vqref]** parameter is checked or when the **Mode of operation** parameter is set to Power flow control.

Specify the direct-axis and quadrature-axis components of the voltage injected on the VSC side of the series transformer, in pu.

# Unified Power Flow Controller (Phasor Type)

---

## Maximum rate of change for references $V_{dref\_Vqref}$

This parameter is not visible when the **Mode of operation** parameter is set to Power flow control.

Specify maximum rate of change of the  $V_{dref}$  and  $V_{qref}$  voltages, in pu/s.

## Inputs and Outputs

A1 B1 C1

The three input terminals of the UPFC.

A2 B2 C2

The three output terminals of the UPFC.

Trip

Apply a simulink logical signal (0 or 1) to this input. When this input is high the shunt converter is disconnected and the series converter is bypassed. In addition, when the trip signal is high the shunt and series control systems are disabled. Use this input to implement a simplified version of the protection system.

Bypass

This input is visible only when the **Bypass Breaker** parameter is set to External Control.

Apply a simulink logical signal (0 or 1) to this input. When this input is high the bypass breaker is closed.

$V_{dqref}$

This input is visible only when the **External control of injected voltage  $V_{dref\_Vqref}$**  parameter is checked.

Apply a simulink vectorized signal specifying the reference voltages  $V_{dref}$  and  $V_{qref}$ , in pu.

$P_{Qref}$

This input is visible only when the **External control of power references  $P_{ref\_Qref}$**  parameter is checked.



# Unified Power Flow Controller (Phasor Type)

Apply a simulink vectorized signal specifying the reference powers  $P_{ref}$  and  $Q_{ref}$ , in pu.

m

Simulink output vector containing 34 UPFC internal signals. These signals are either voltage and current phasors (complex signals) or control signals. They can be individually accessed by using the Bus Selector block. They are, in order:

Signal	Signal Group	Signal Names	Definition
1-3	Power Vabc1 (cmplx)	Va1 (pu) Vb1 (pu) Vc1 (pu)	Phasor voltages (phase to ground) Va, Vb, Vc at the UPFC input terminals A1, B1, C1 (pu)
4-6	Power Iabc_SH (cmplx)	Ia_SH (pu) Ib_SH (pu) Ic_SH (pu)	Phasor currents Ia, Ib, Ic flowing into the shunt converter (pu)
7	Power	Vdc (V)	DC voltage (V)
8-10	Power Vabc2 (cmplx)	Va2 (pu) Vb2 (pu) Vc2 (pu)	Phasor voltages (phase to ground) Va, Vb, Vc at the UPFC output terminals A2, B2, C2 (pu)
11-13	Power Vabc_Inj (cmplx)	Va_Inj (pu) Vb_Inj (pu) Vc_Inj (pu)	Phasors of injected voltages $V_s = V_2 - V_1$ (pu)

# Unified Power Flow Controller (Phasor Type)

Signal	Signal Group	Signal Names	Definition
14_16	Power Iabc_SE (cmplx)	Ia_SE (pu) Ib_SE (pu) Ic_SE (pu)	Phasor currents Ia, Ib, Ic flowing in the series transformer from ABC1 to ABC2 (pu)
17	Control (Shunt)	Vm (pu)	Positive-sequence value of the measured voltage (pu)
18	Control (Shunt)	Vref (pu)	Reference voltage (pu)
19	Control (Shunt)	Qm (pu)	Shunt converter reactive power. A positive value indicates inductive operation.
20	Control (Shunt)	Qref (pu)	Reference reactive power (pu)
21	Control (Shunt)	Id (pu)	Direct-axis component of current (active current) flowing into the shunt converter (pu). A positive value indicates active power flowing into shunt converter.

# Unified Power Flow Controller (Phasor Type)

Signal	Signal Group	Signal Names	Definition
22	Control (Shunt)	Iq (pu)	Quadrature-axis component of current (reactive current) flowing into the shunt converter (pu). A positive value indicates capacitive operation.
23	Control (Shunt)	Idref (pu)	Reference value of direct-axis component of current flowing into shunt converter (pu)
24	Control (Shunt)	Iqref (pu)	Reference value of quadrature-axis component of current flowing into shunt converter (pu)
25	Control (Shunt)	modindex	The modulation index $m$ of the shunt converter PWM modulator. A positive number $0 < m < 1$ . $m=1$ corresponds to the maximum voltage which can be generated by the VSC without overmodulation.

# Unified Power Flow Controller (Phasor Type)

Signal	Signal Group	Signal Names	Definition
26	Control (Series)	P (pu)	Measured active power flowing out of terminals A2, B2, C2 (pu)
27	Control (Series)	Q (pu)	Measured reactive power flowing out of terminals A2, B2, C2 (pu)
28	Control (Series)	Pref (pu)	Reference active power (pu)
29	Control (Series)	Qref (pu)	Reference reactive power (pu)
30	Control (Series)	Vd_conv (pu)	Direct-axis injected voltage on VSC side of series transformer (pu)
31	Control (Series)	Vq_conv (pu)	Quadrature-axis injected voltage on VSC side of series transformer (pu)
32	Control (Series)	Vdref (pu)	Reference value of direct-axis injected voltage (pu)

# Unified Power Flow Controller (Phasor Type)

Signal	Signal Group	Signal Names	Definition
33	Control (Series)	Vqref (pu)	Reference value of quadrature-axis injected voltage (pu)
34	Control (Series)	modindex	The modulation index $m$ of the series converter PWM modulator. A positive number $0 < m < 1$ . $m=1$ corresponds to the maximum voltage $V_{conv}$ which can be generated by the series converter without overmodulation.

## Example

See the `power_upfc` demo which illustrates the use of a UPFC controlling power on a 500 kV, 60 Hz, system.

## References

[1] N. G. Hingorani, L. Gyugyi, "Understanding FACTS; Concepts and Technology of Flexible AC Transmission Systems," IEEE Press book, 2000

## See Also

Static Synchronous Compensator (Phasor Type), Static Synchronous Series Compensator (Phasor Type)

# Voltage Measurement

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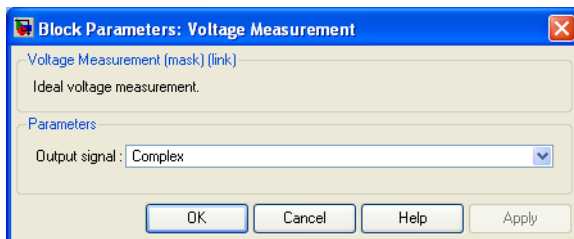
**Purpose** Measure voltage in circuit

**Library** Measurements

**Description** The Voltage Measurement block measures the instantaneous voltage between two electric nodes. The output provides a Simulink signal that can be used by other Simulink blocks.



## Dialog Box and Parameters



### Output signal

Specifies the format of the output signal when the block is used in a phasor simulation. The **Output signal** parameter is disabled when the block is not used in a phasor simulation. The phasor simulation is activated by a Powergui block placed in the model.

Set to **Complex** to output the measured current as a complex value. The output is a complex signal.

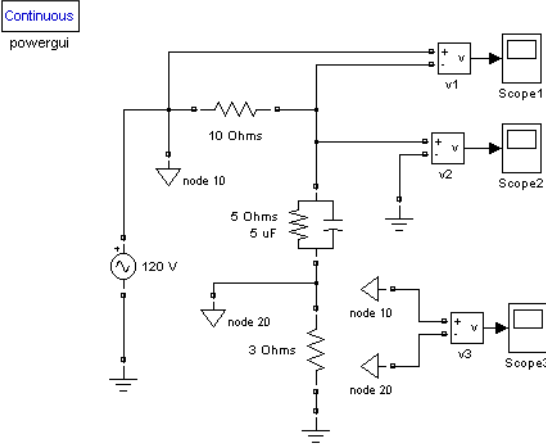
Set to **Real - Imag** to output the real and imaginary parts of the measured current. The output is a vector of two elements.

Set to **Magnitude - Angle** to output the magnitude and angle of the measured current. The output is a vector of two elements.

Set to **Magnitude** to output the magnitude of the measured current. The output is a scalar value.

## Example

The power\_voltmeasure demo uses three Voltage Measurement blocks to read voltages.



## See Also

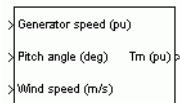
Current Measurement, Powergui, Three-Phase V-I Measurement

# Wind Turbine

**Purpose** Implement model of variable pitch wind turbine

**Library** Distributed Resources/Wind Generation

## Description



The model is based on the steady-state power characteristics of the turbine. The stiffness of the drive train is infinite and the friction factor and the inertia of the turbine must be combined with those of the generator coupled to the turbine. The output power of the turbine is given by the following equation.

$$P_m = c_p(\lambda, \beta) \frac{\rho A}{2} v_{wind}^3 \quad (2-1)$$

where

$P_m$	Mechanical output power of the turbine (W)
$c_p$	Performance coefficient of the turbine
$\rho$	Air density ( $\text{kg/m}^3$ )
$A$	Turbine swept area ( $\text{m}^2$ )
$v_{wind}$	Wind speed (m/s)
$\lambda$	Tip speed ratio of the rotor blade tip speed to wind speed
$\beta$	Blade pitch angle (deg)

Equation 2-1 can be normalized. In the per unit (pu) system we have:

$$P_{m\_pu} = k_p c_{p\_pu} v_{wind\_pu}^3 \quad (2-2)$$

where

$P_{m\_pu}$	Power in pu of nominal power for particular values of $\rho$ and $A$
$c_{p\_pu}$	Performance coefficient in pu of the maximum value of $c_p$



- $v_{\text{wind\_pu}}$  Wind speed in pu of the base wind speed. The base wind speed is the mean value of the expected wind speed in m/s.
- $k_p$  Power gain for  $c_{p\_pu}=1$  pu and  $v_{\text{wind\_pu}}=1$  pu,  $k_p$  is less than or equal to 1

A generic equation is used to model  $c_p(\lambda, \beta)$ . This equation, based on the modeling turbine characteristics of [1], is:

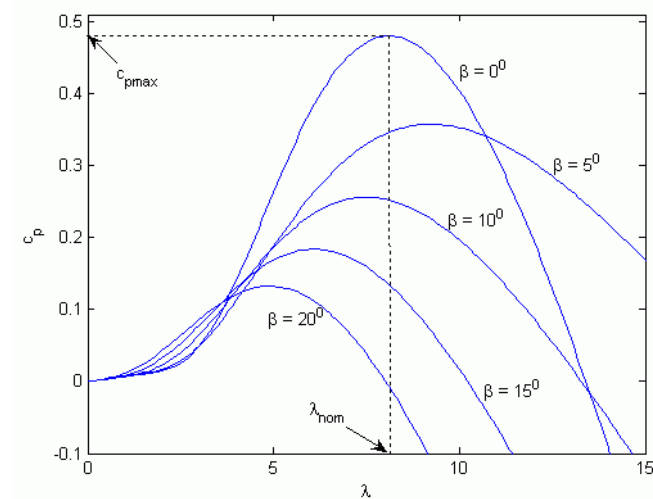
$$c_p(\lambda, \beta) = c_1 \left( \frac{c_2}{\lambda_i} - c_3 \beta - c_4 \right) e^{\frac{-c_5}{\lambda_i}} + c_6 \lambda \quad (2-3)$$

with

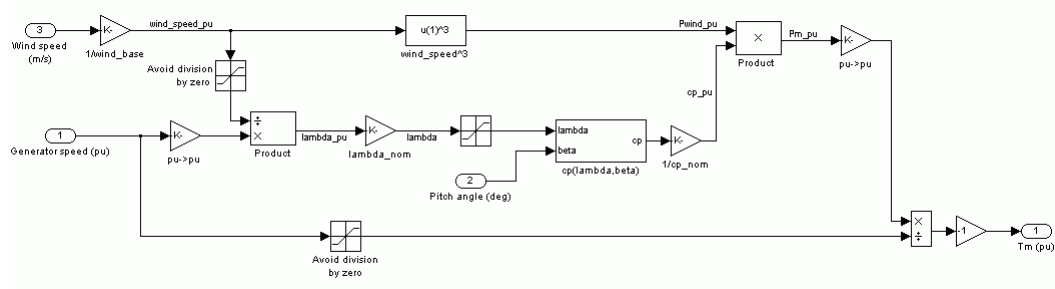
$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (2-4)$$

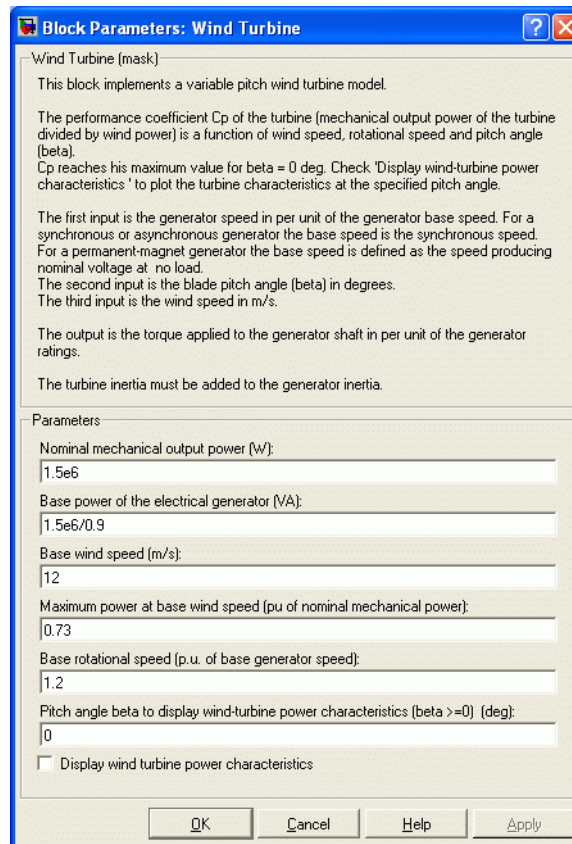
The coefficients  $c_1$  to  $c_6$  are:  $c_1 = 0.5176$ ,  $c_2 = 116$ ,  $c_3 = 0.4$ ,  $c_4 = 5$ ,  $c_5 = 21$  and  $c_6 = 0.0068$ . The  $c_p$ - $\lambda$  characteristics, for different values of the pitch angle  $\beta$ , are illustrated below. The maximum value of  $c_p$  ( $c_{p\text{max}} = 0.48$ ) is achieved for  $\beta = 0$  degree and for  $\lambda = 8.1$ . This particular value of  $\lambda$  is defined as the nominal value ( $\lambda_{\text{nom}}$ ).

# Wind Turbine



The Simulink model of the turbine is illustrated in the following figure. The three inputs are the generator speed ( $\omega_r$ \_pu) in pu of the nominal speed of the generator, the pitch angle in degrees and the wind speed in m/s. The tip speed ratio  $\lambda$  in pu of  $\lambda_{nom}$  is obtained by the division of the rational speed in pu of the base rotational speed (defined below) and the wind speed in pu of the base wind speed. The output is the torque applied to the generator shaft.





## Dialog Box and Parameters

### Nominal mechanical output power

The nominal output power in watts (W).

### Base power of the electrical generator

The nominal power of the electrical generator coupled to the wind turbine, in VA. This parameter is used to compute the output torque in pu of the nominal torque of the generator.

# Wind Turbine

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## **Base wind speed**

The base value of the wind speed, in m/s, used in the per unit system. The base wind speed is the mean value of the expected wind speed. This base wind speed produces a mechanical power which is usually lower than the turbine nominal power.

## **Maximum power at base wind speed**

The maximum power at base wind speed in pu of the nominal mechanical power. This parameter is the power gain  $k_p$  already defined.

## **Base rotational speed**

The rotational speed at maximum power for the base wind speed. The base rotational speed is in pu of the base generator speed.

## **Pitch angle beta to display wind turbine power characteristics**

The pitch angle beta, in degrees, used to display the power characteristics. Beta must be greater than or equal to zero.

## **Display wind turbine power characteristics**

If this parameter is checked, the turbine power characteristics are displayed for different wind speeds and for the specified pitch angle beta.

## **Inputs and Outputs**

### **Generator speed (pu)**

Simulink input of the generator speed in pu based on the nominal speed of the generator.

### **Pitch angle (deg)**

Simulink input of the pitch angle.

### **Wind speed (m/s)**

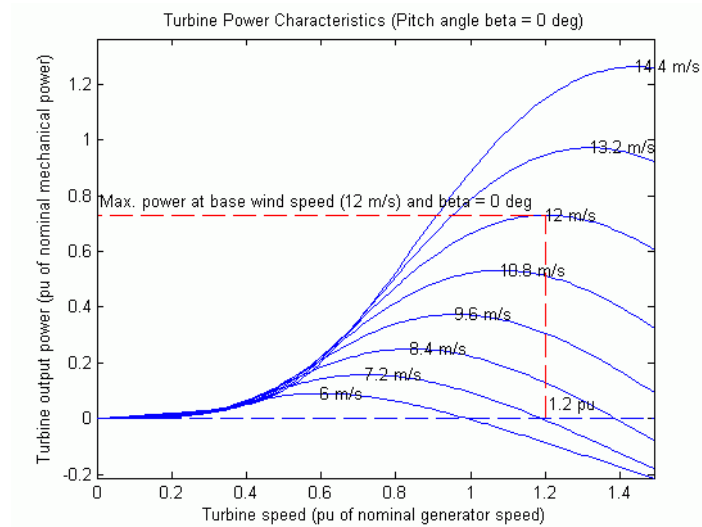
Simulink input of the wind speed in m/s.

### **Tm (pu)**

Simulink output of the mechanical torque of the wind turbine, in pu of the nominal generator torque. The nominal torque of the generator is based on the nominal generator power and speed.

## Example

The mechanical power  $P_m$  as a function of generator speed, for different wind speeds and for blade pitch angle  $\beta = 0$  degree, is illustrated below. This figure is obtained with the default parameters (base wind speed = 12 m/s, maximum power at base wind speed = 0.73 pu ( $k_p = 0.73$ ) and base rotational speed = 1.2 pu).



## References

[1] Siegfried Heier, "Grid Integration of Wind Energy Conversion Systems," John Wiley & Sons Ltd, 1998, ISBN 0-471-97143-X

## See Also

Wind Turbine Induction Generator (Phasor Type) Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

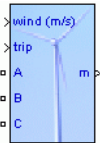
# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

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**Purpose** Implement phasor model of variable speed doubly-fed induction generator driven by wind turbine

**Library** Distributed Resources/Wind Generation

## Description



The wind turbine and the doubly-fed induction generator (WTDFIG) are shown in the figure called The Wind Turbine and the Doubly-Fed Induction Generator System on page 2-891. The AC/DC/AC converter is divided into two components: the rotor-side converter ( $C_{rotor}$ ) and the grid-side converter ( $C_{grid}$ ).  $C_{rotor}$  and  $C_{grid}$  are Voltage-Sourced Converters that use forced-commutated power electronic devices (IGBTs) to synthesize an AC voltage from a DC voltage source. A capacitor connected on the DC side acts as the DC voltage source. A coupling inductor  $L$  is used to connect  $C_{grid}$  to the grid. The three-phase rotor winding is connected to  $C_{rotor}$  by slip rings and brushes and the three-phase stator winding is directly connected to the grid. The power captured by the wind turbine is converted into electrical power by the induction generator and it is transmitted to the grid by the stator and the rotor windings. The control system generates the pitch angle command and the voltage command signals  $V_r$  and  $V_{gc}$  for  $C_{rotor}$  and  $C_{grid}$  respectively in order to control the power of the wind turbine, the DC bus voltage and the reactive power or the voltage at the grid terminals.



# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

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$T_m$	Mechanical torque applied to rotor
$T_{em}$	Electromagnetic torque applied to the rotor by the generator
$\omega_r$	Rotational speed of rotor
$\omega_s$	Rotational speed of the magnetic flux in the air-gap of the generator, this speed is named synchronous speed. It is proportional to the frequency of the grid voltage and to the number of generator poles.
$J$	Combined rotor and wind turbine inertia coefficient

The mechanical power and the stator electric power output are computed as follows:

$$P_m = T_m \omega_r$$

$$P_s = T_{em} \omega_s$$

For a loss less generator the mechanical equation is:

$$J \frac{d\omega_r}{dt} = T_m - T_{em}$$

In steady-state at fixed speed for a loss less generator  $T_m = T_{em}$  and  $P_m = P_s + P_r$

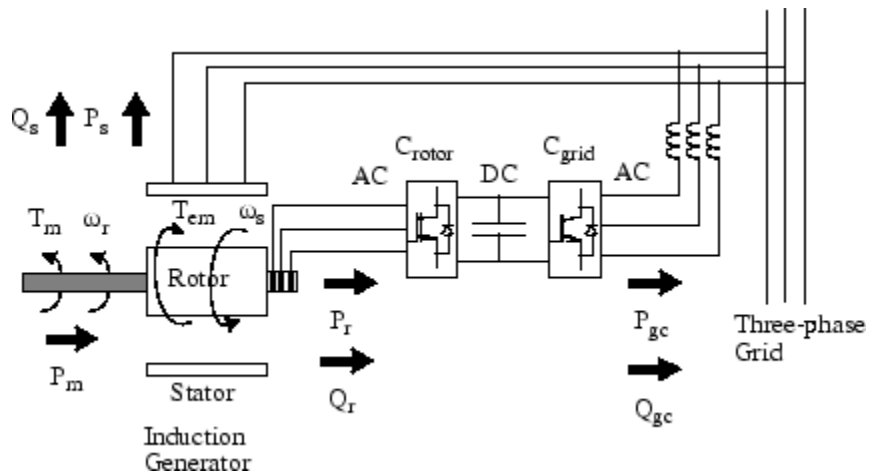
It follows that:

$$P_r = P_m - P_s = T_m \omega_r - T_{em} \omega_s = -T_m \left( \frac{\omega_s - \omega_r}{\omega_s} \right) \omega_s = -s T_m \omega_s = -s P_s$$

where  $s$  is defined as the slip of the generator:  $s = \frac{\omega_s - \omega_r}{\omega_s}$



# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)



## The Power Flow

Generally the absolute value of slip is much lower than 1 and, consequently,  $P_r$  is only a fraction of  $P_s$ . Since  $T_m$  is positive for power generation and since  $\omega_s$  is positive and constant for a constant frequency grid voltage, the sign of  $P_r$  is a function of the slip sign.  $P_r$  is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed). For super-synchronous speed operation,  $P_r$  is transmitted to DC bus capacitor and tends to rise the DC voltage. For sub-synchronous speed operation,  $P_r$  is taken out of DC bus capacitor and tends to decrease the DC voltage.  $C_{grid}$  is used to generate or absorb the power  $P_{gc}$  in order to keep the DC voltage constant. In steady-state for a loss less AC/DC/AC converter  $P_{gc}$  is equal to  $P_r$  and the speed of the wind turbine is determined by the power  $P_r$  absorbed or generated by  $C_{rotor}$ . The power control will be explained below.

The phase-sequence of the AC voltage generated by  $C_{rotor}$  is positive for sub-synchronous speed and negative for super-synchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip.

# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

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$C_{\text{rotor}}$  and  $C_{\text{grid}}$  have the capability of generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals.

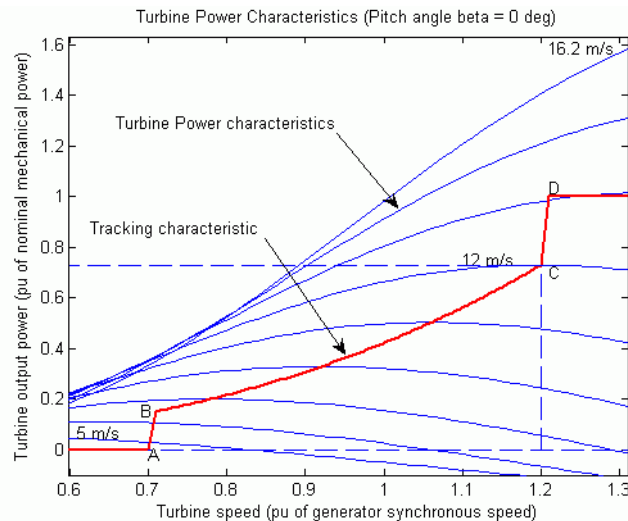
## **C\_rotor Control System**

The rotor-side converter is used to control the wind turbine output power and the voltage (or reactive power) measured at the grid terminals.

### Power Control

The power is controlled in order to follow a pre-defined power-speed characteristic, named tracking characteristic. An example of such a characteristic is illustrated in the figure called Turbine Characteristics and Tracking Characteristic on page 2-895, by the ABCD curve superimposed to the mechanical power characteristics of the turbine obtained at different wind speeds. The actual speed of the turbine  $\omega_r$  is measured and the corresponding mechanical power of the tracking characteristic is used as the reference power for the power control loop. The tracking characteristic is defined by four points: A, B, C and D. From zero speed to speed of point A the reference power is zero. Between point A and point B the tracking characteristic is a straight line, the speed of point B must be greater than the speed of point A. Between point B and point C the tracking characteristic is the locus of the maximum power of the turbine (maxima of the turbine power vs turbine speed curves). The tracking characteristic is a straight line from point C and point D. The power at point D is one per unit (1 pu) and the speed of the point D must be greater than the speed of point C. Beyond point D the reference power is a constant equal to one per unit (1 pu).

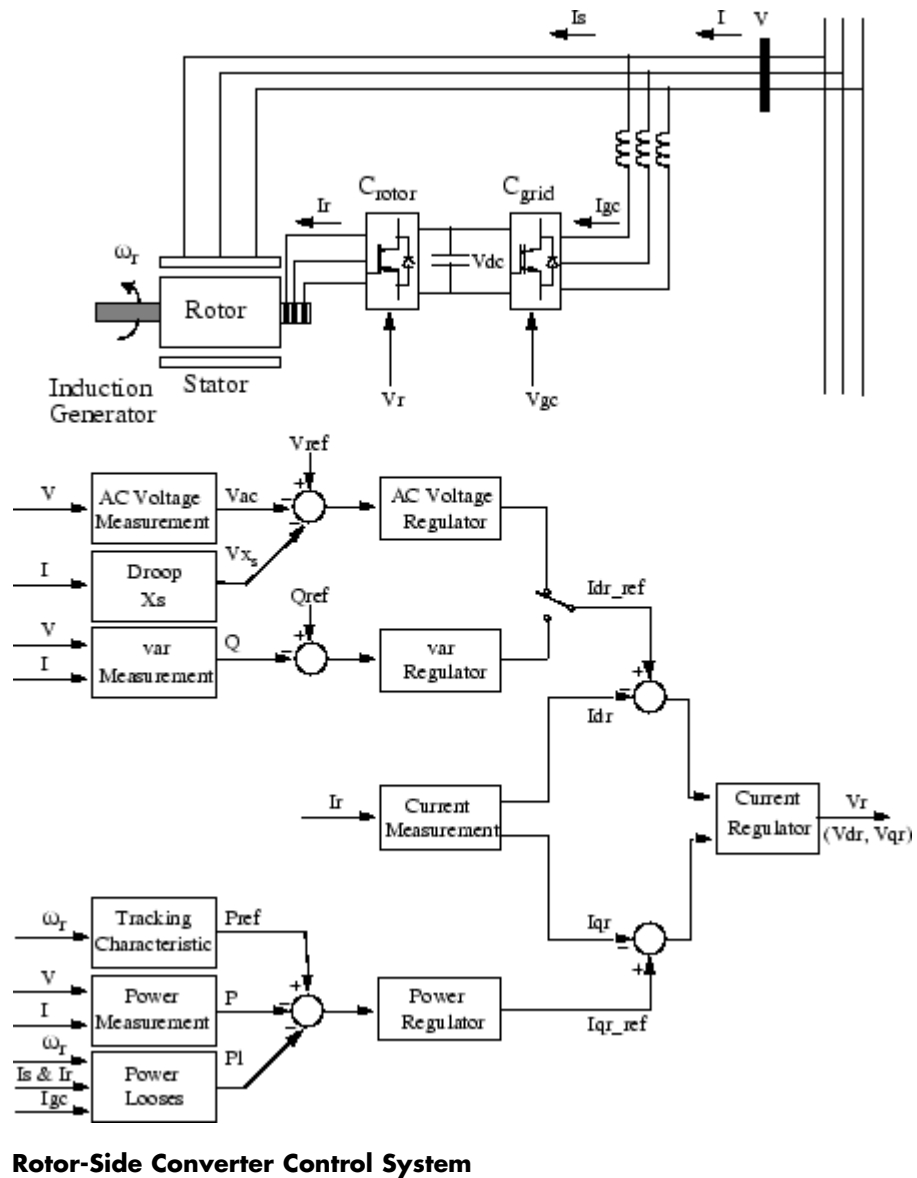
# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)



## Turbine Characteristics and Tracking Characteristic

The generic power control loop is illustrated in the figure called Rotor-Side Converter Control System on page 2-896. The actual electrical output power, measured at the grid terminals of the wind turbine, is added to the total power losses (mechanical and electrical) and is compared with the reference power obtained from the tracking characteristic. A Proportional-Integral (PI) regulator is used to reduce the power error to zero. The output of this regulator is the reference rotor current  $I_{qr\_ref}$  that must be injected in the rotor by converter  $C_{rotor}$ . This is the current component that produce the electromagnetic torque  $T_{em}$ . The actual  $I_{qr}$  component of positive-sequence current is compared to  $I_{qr\_ref}$  and the error is reduced to zero by a current regulator (PI). The output of this current controller is the voltage  $V_{qr}$  generated by  $C_{rotor}$ . The current regulator is assisted by feed forward terms which predict  $V_{qr}$ .

# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

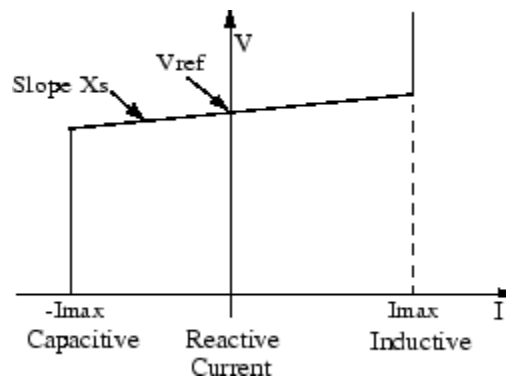


# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

## Voltage Control and Reactive Power Control

The voltage or the reactive power at grid terminals is controlled by the reactive current flowing in the converter  $C_{rotor}$ . The generic control loop is illustrated in the figure called Rotor-Side Converter Control System on page 2-896.

When the wind turbine is operated in voltage regulation mode, it implements the following V-I characteristic.



### Wind Turbine V-I Characteristic

As long as the reactive current stays within the maximum current values ( $-I_{max}$ ,  $I_{max}$ ) imposed by the converter rating, the voltage is regulated at the reference voltage  $V_{ref}$ . However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output), and the V-I characteristic has the slope indicated in the figure called Wind Turbine V-I Characteristic on page 2-897. In the voltage regulation mode, the V-I characteristic is described by the following equation:

$$V = V_{ref} + X_s \cdot I$$

where

# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

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V	Positive sequence voltage (pu)
I	Reactive current (pu/Pnom) (I > 0 indicates an inductive current)
Xs	Slope or droop reactance (pu/Pnom)
Pnom	Three-phase nominal power of the converter specified in the block dialog box

When the wind turbine is operated in var regulation mode the reactive power at grid terminals is kept constant by a var regulator.

The output of the voltage regulator or the var regulator is the reference d-axis current  $I_{dr\_ref}$  that must be injected in the rotor by converter  $C_{rotor}$ . The same current regulator as for the power control is used to regulate the actual  $I_{dr}$  component of positive-sequence current to its reference value. The output of this regulator is the d-axis voltage  $V_{dr}$  generated by  $C_{rotor}$ . The current regulator is assisted by feed forward terms which predict  $V_{dr}$ .

$V_{dr}$  and  $V_{qr}$  are respectively the d-axis and q-axis of the voltage  $V_r$ .

Note:

- for  $C_{rotor}$  control system and measurements the d-axis of the d-q rotating reference frame is locked on the generator mutual flux by a PLL which is assumed to be ideal in this phasor model.
- the magnitude of the reference rotor current  $I_{r\_ref}$  is equal to  $\sqrt{I_{dr\_ref}^2 + I_{qr\_ref}^2}$ . The maximum value of this current is limited to 1 pu. When  $I_{dr\_ref}$  and  $I_{qr\_ref}$  are such that the magnitude is higher than 1 pu the  $I_{qr\_ref}$  component is reduced in order to bring back the magnitude to 1 pu.

# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

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## C<sub>grid</sub> Control System

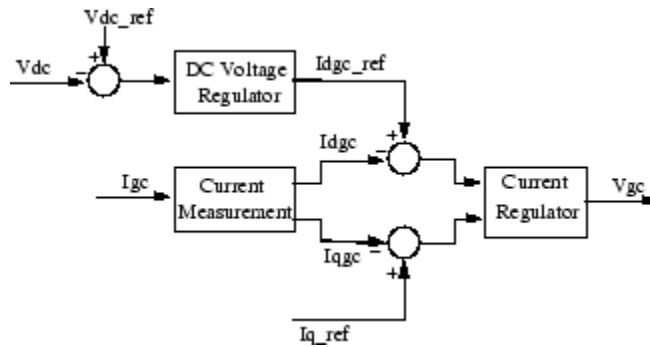
The converter C<sub>grid</sub> is used to regulate the voltage of the DC bus capacitor. In addition, this model allows using C<sub>grid</sub> converter to generate or absorb reactive power.

The control system, illustrated in the figure called Grid-Side Converter Control System on page 2-900, consists of:

- Measurement systems measuring the d and q components of AC positive-sequence currents to be controlled as well as the DC voltage V<sub>dc</sub>.
- An outer regulation loop consisting of a DC voltage regulator. The output of the DC voltage regulator is the reference current Idgc\_ref for the current regulator (Idgc = current in phase with grid voltage which controls active power flow).
- An inner current regulation loop consisting of a current regulator. The current regulator controls the magnitude and phase of the voltage generated by converter C<sub>grid</sub> (V<sub>gc</sub>) from the Idgc\_ref produced by the DC voltage regulator and specified Iq\_ref reference. The current regulator is assisted by feed forward terms which predict the C<sub>grid</sub> output voltage.

The magnitude of the reference grid converter current Igc\_ref is equal to  $\sqrt{Idgc\_ref^2 + Iq\_ref^2}$ . The maximum value of this current is limited to a value defined by the converter maximum power at nominal voltage. When Idgc\_ref and Iq\_ref are such that the magnitude is higher than this maximum value the Iq\_ref component is reduced in order to bring back the magnitude to its maximum value.

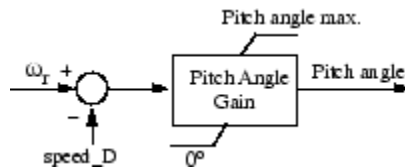
# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)



## Grid-Side Converter Control System

### Pitch Angle Control System

The pitch angle is kept constant at zero degree until the speed reaches point D speed of the tracking characteristic. Beyond point D the pitch angle is proportional to the speed deviation from point D speed. The control system is illustrated in the following figure.



### Pitch Control System

#### Turbine Model

The turbine model uses the Wind Turbine bloc of the Distributed Resources/Wind Generation library. See documentation of this model for more details.

#### Induction Generator

The doubly-fed induction generator phasor model is the same as the wound rotor asynchronous machine (see the Machines library) with the following two points of difference:



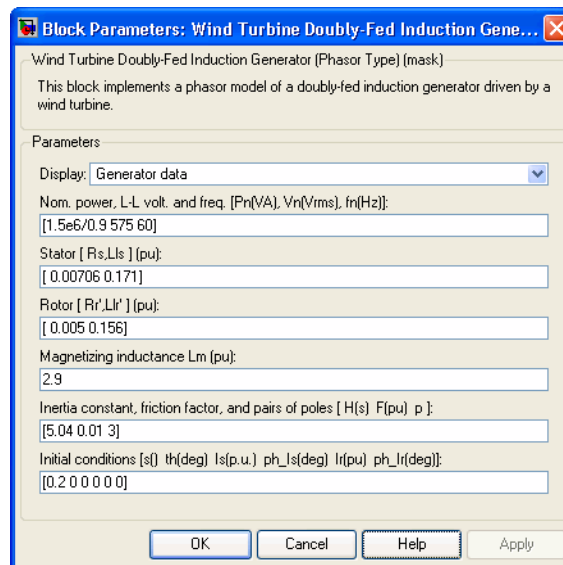
# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

- 1 Only the positive-sequence is taken into account, the negative-sequence has been eliminated.
- 2 A trip input has been added. When this input is high the induction generator is disconnected from the grid and from  $C_{rotor}$ .

## Dialog Box and Parameters

The WTDFIG parameters are grouped in four categories: Generator data, Converters data, Turbine data, and Control parameters. Use the Display listbox to select which group of parameters you want to visualize.

### Generator Data Parameters



### WTDFIG modeled using positive-sequence only

The WTDFIG is modeled by a three-wire system using two current sources. The WTDFIG does not generate any zero-sequence current, but it can generate negative-sequence currents during unbalanced system operation.

# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

---

## **Nominal power, line-to-line voltage and frequency**

The nominal power in VA, the nominal line-to-line voltage in  $V_{rms}$  and the nominal system frequency in hertz.

## **Stator [Rs, Lls]**

The stator resistance  $R_s$  and leakage inductance  $L_{ls}$  in pu based on the generator rating.

## **Rotor [Rr', Llr']**

The rotor resistance  $R_r'$  and leakage inductance  $L_{lr}'$ , both referred to the stator, in pu based on the generator rating.

## **Magnetizing inductance Lm**

The magnetizing inductance  $L_m$  in pu based on the generator rating.

## **Inertia constant, friction factor and pairs of poles**

Combined generator and turbine inertia constant  $H$  in seconds, combined viscous friction factor  $F$  in pu based on the generator rating and number of pole pairs  $p$ .

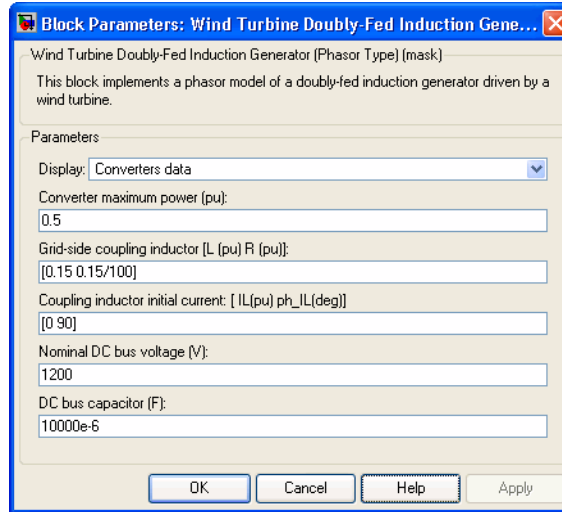
You may need to use your own turbine model, in order for example, to implement different power characteristics or to implement the shaft stiffness. Your model must then output the mechanical torque applied to the generator shaft. If the inertia and the friction factor of the turbine are implemented inside the turbine model you specify only the generator inertia constant  $H$  and the generator friction factor  $F$ .

## **Initial conditions**

The initial slip  $s$ , electrical angle  $\Theta$  in degrees, stator phasor current magnitude in pu, stator phasor current phase angle in degrees, rotor phasor current magnitude in pu and rotor phasor current phase angle in degrees.

# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

## Converters Data Parameters



### Converter maximum power

The maximum power of both  $C_{\text{grid}}$  and  $C_{\text{rotor}}$  in pu of the nominal power. This parameter is used to compute the maximum current at 1 pu of voltage for  $C_{\text{grid}}$ . The maximum current for  $C_{\text{rotor}}$  is 1 pu.

### Grid-side coupling inductor [L R]

The coupling inductance L and its resistance R in pu based on the generator rating.

### Coupling inductor initial currents

The coupling inductor initial phasor current in positive-sequence. Enter magnitude IL in pu and phase ph\_IL in degrees. If you know the initial value of the current corresponding to the WTDFIG operating point you may specify it in order to start simulation in steady state. If you don't know this value, you can leave [0 0]. The system will reach steady-state after a short transient.

### Nominal DC bus voltage

The nominal DC bus voltage in volts.

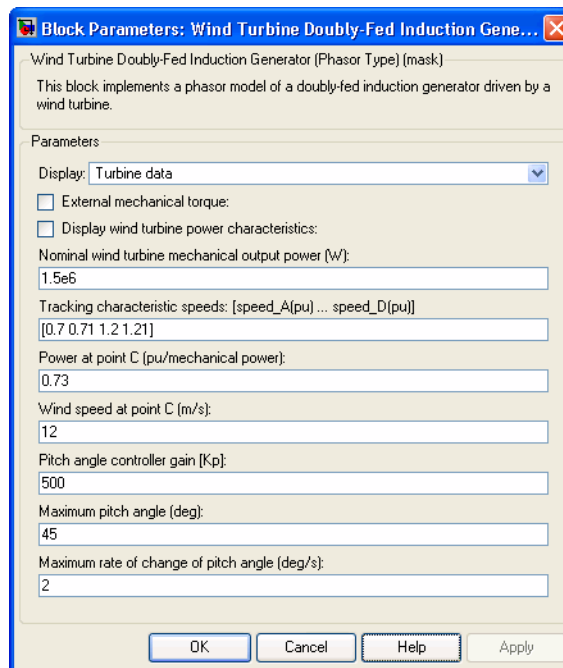
# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

## DC bus capacitor

The total capacitance of the DC link in farads. This capacitance value is related to the WTDFIG rating and to the DC link nominal voltage. The energy stored in the capacitance (in joules) divided by the WTDFIG rating (in VA) is a time duration which is usually a fraction of a cycle at nominal frequency. For example, for the default parameters, ( $C=10000 \mu\text{F}$ ,  $V_{dc}=1200 \text{ V}$ ,  $P_n=1.67 \text{ MVA}$ )

this ratio  $(1/2 \times C \times V_{dc}^2) / (P_n)$  is 4.3 ms, which represents 0.26 cycle for a 60 Hz frequency. If you change the default values of the nominal power rating and DC voltage, you should change the capacitance value accordingly.

## Turbine Data Parameters



# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

---

## **External mechanical torque**

If this parameter is checked, a Simulink input named  $T_m$  appears on the block, allowing to use an external signal for the generator input mechanical torque. This external torque must be in pu based on the nominal electric power and synchronous speed. For example, the external torque may come from a user defined turbine model. Following the convention used in the induction machine, the torque must be negative for power generation.

## **Electric Power-Speed characteristic**

This parameter is visible only when the **External mechanical torque** parameter is checked. It is used to specify a series of speed-power pairs for the tracking characteristic. The speed is in pu based on synchronous speed and the power is in pu based on nominal generator power.

## **Display wind turbine power characteristics**

If this parameter is checked, the turbine power characteristics at zero degree of pitch angle are displayed for different wind speeds. The tracking characteristic is also displayed on the same figure.

This parameter is not visible when the **External mechanical torque** parameter is checked.

## **Nominal wind turbine mechanical output power**

This parameter is not visible when the **External mechanical torque** parameter is checked.

The nominal turbine mechanical output power in watts.

## **Tracking characteristic speeds**

This parameter is not visible when the **External mechanical torque** parameter is checked.

Specify the speeds of point A to point D of the tracking characteristic in pu of the synchronous speed. `speed_B` must be greater than `speed_A` and `speed_D` must be greater than `speed_C`.

# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

---

## **Power at point C**

This parameter is not visible when the **External mechanical torque** parameter is checked.

Specify the power of point C of the tracking characteristic in pu of the **Nominal wind turbine mechanical output power**.

## **Wind speed at point C**

This parameter is not visible when the **External mechanical torque** parameter is checked.

Specify wind speed in m/s for point C. The power at point C is the maximum turbine output power for the specified wind speed.

## **Pitch angle controller gain [Kp]**

This parameter is not visible when the **External mechanical torque** parameter is checked.

Proportional gain  $K_p$  of the pitch controller. Specify  $K_p$  in degrees/(speed deviation pu). The speed deviation is the difference between actual speed and speed of point D in pu of synchronous speed.

## **Maximum pitch angle**

This parameter is not visible when the **External mechanical torque** parameter is checked.

The maximum pitch angle in degrees.

## **Maximum rate of change of pitch angle**

This parameter is not visible when the **External mechanical torque** parameter is checked.

The maximum rate of change of the pitch angle in degrees/s.

# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

## Control Parameters

Block Parameters: Wind Turbine Doubly-Fed Induction Gene... [X]

Wind Turbine Doubly-Fed Induction Generator (Phasor Type) (mask)  
This block implements a phasor model of a doubly-fed induction generator driven by a wind turbine.

Parameters

Display: Control parameters [v]

Mode of operation: Voltage regulation [v]

External grid voltage reference:  
Reference grid voltage  $V_{ref}$  (pu):  
1.0

External reactive current  $I_{q\_ref}$  for grid-side converter:  
Grid-side converter generated reactive current reference ( $I_{q\_ref}$ ) (pu):  
0

Grid voltage regulator gains: [Kp Ki]  
[1.25 300]

Droop  $X_s$  (pu):  
0.02

Power regulator gains: [Kp Ki]  
[1 100]

DC bus voltage regulator gains: [Kp Ki]  
[0.002 0.05]

Grid-side converter current regulator gains: [Kp Ki]  
[1 100]

Rotor-side converter current regulator gains: [Kp Ki]  
[0.3 8]

Maximum rate of change of reference grid voltage (pu/s):  
100

Maximum rate of change of reference power (pu/s):  
1

Maximum rate of change of converter reference currents (pu/s):  
200

OK Cancel Help Apply

### Mode of operation

Specifies the **WTDFIG** mode of operation. Select either Voltage regulation or Var regulation.

# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

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## **External grid voltage reference**

This parameter is not visible when the **Mode of operation** parameter is set to Var regulation.

If this parameter is checked, a Simulink input named Vref appears on the block, allowing to control the reference voltage from an external signal in pu. Otherwise a fixed reference voltage is used, as specified by the parameter below.

## **Reference grid voltage Vref**

This parameter is not visible when the **Mode of operation** parameter is set to Var regulation or when the **External grid voltage reference** parameter is checked.

Reference voltage, in pu, used by the voltage regulator.

## **External generated reactive power reference**

This parameter is not visible when the **Mode of operation** parameter is set to Voltage regulation.

If this parameter is checked, a Simulink input named Qref appears on the block, allowing to control the reference reactive power, at grid terminals, from an external signal in pu. Otherwise a fixed reference reactive power is used, as specified by the parameter below.

## **Generated reactive power Qref**

This parameter is not visible when the **Mode of operation** parameter is set to Voltage regulation or when the **External generated reactive power reference** parameter is checked.

Reference generated reactive power at grid terminals, in pu, used by the var regulator.

## **External reactive current Iq\_ref for grid-side converter reference**

If this parameter is checked, a Simulink input named Iq\_ref appears on the block, allowing to control the grid-side converter reactive current from an external signal in pu. Specify a positive



# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

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value for  $I_{q\_ref}$  for generated reactive power. Otherwise a fixed reactive current is used, as specified by the parameter below.

## **Grid-side converter generated reactive current reference ( $I_{q\_ref}$ )**

This parameter is not visible when the **External reactive current  $I_{q\_ref}$  for grid-side converter reference** parameter is checked.

Reference grid-side converter reactive current, in pu, used by the current regulator. Specify a positive value of  $I_{q\_ref}$  for generated reactive power.

## **Grid voltage regulator gains [Kp Ki]**

This parameter is not visible when the **Mode of operation** parameter is set to Var regulation.

Gains of the AC voltage regulator. Specify proportional gain Kp in (pu of I)/(pu of V), and integral gain Ki, in (pu of I)/(pu of V)/s, where V is the AC voltage error and I is the output of the voltage regulator.

## **Droop Xs**

This parameter is not visible when the **Mode of operation** parameter is set to Var regulation.

Droop reactance, in pu/nominal power, defining the slope of the V-I characteristic.

## **Reactive power regulator gains [Kp Ki]**

This parameter is not visible when the **Mode of operation** parameter is set to Voltage regulation.

Gains of the var regulator. Specify proportional gain Kp in (pu of I)/(pu of Q), and integral gain Ki, in (pu of I)/(pu of Q)/s, where Q is the reactive power error and I is the output of the var regulator.

# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

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## **Power regulator gains [Kp Ki]**

Gains of the power regulator. Specify proportional gain  $K_p$  in (pu of I)/(pu of P), and integral gain  $K_i$ , in (pu of I)/(pu of P)/s, where P is the power error and I is the output of the power regulator.

## **DC bus voltage regulator gains [Kp Ki]**

Gains of the DC voltage regulator which controls the voltage across the DC bus capacitor. Specify proportional gain  $K_p$  in (pu of I)/(Vdc), and integral gain  $K_i$ , in (pu of I)/(Vdc)/s, where Vdc is the DC voltage error and I is the output of the voltage regulator.

## **Grid-side converter current regulator gains [Kp Ki]**

Gains of the grid-side converter current regulator.

Specify proportional gain  $K_p$  in (pu of V)/(pu of I) and integral gain  $K_i$ , in (pu of V)/(pu of I)/s, where V is the output  $V_{gc}$  of the current regulator and I is the current error.

## **Rotor-side converter current regulator gains [Kp Ki]**

Gains of the rotor-side converter current regulator.

Specify proportional gain  $K_p$  in (pu of V)/(pu of I) and integral gain  $K_i$ , in (pu of V)/(pu of I)/s, where V is the output  $V_r$  of the current regulator and I is the current error.

## **Maximum rate of change of reference grid voltage**

This parameter is not visible when the **Mode of operation** parameter is set to Var regulation.

Maximum rate of change of the reference voltage, in pu/s, when an external reference voltage is used.

## **Maximum rate of change of reference reactive power**

This parameter is not visible when the **Mode of operation** parameter is set to Voltage regulation.

Maximum rate of change of the reference reactive power, in pu/s, when an external reference reactive power is used.

# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

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## Maximum rate of change of reference power

Maximum rate of change of the reference power in pu/s.

## Maximum rate of change of converters reference current

Maximum rate of change of the reference current in pu/s for both the rotor-side and the grid-side converters.

## Inputs and Outputs

A B C

The three terminals of the WTDFIG.

Trip

Apply a simulink logical signal (0 or 1) to this input. When this input is high the WTDFIG is disconnected and its control system is disabled. Use this input to implement a simplified version of the protection system.

Wind (m/s)

This input is not visible when the **External mechanical torque** parameter is checked.

Simulink input of the wind speed in m/s.

T<sub>m</sub>

This input is visible only when the **External mechanical torque** parameter is checked.

Simulink input of the mechanical torque. T<sub>m</sub> must be negative for power generation. Use this input when using an external turbine model.

V<sub>ref</sub>

This input is visible only when the **Mode of operation** parameter is set to **Voltage regulation** and the **External grid voltage reference** parameter is checked.

Simulink input of the external reference voltage signal.

# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

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Qref

This input is visible only when the **Mode of operation** parameter is set to **Var regulation** and the **External generated reactive power reference** parameter is checked.

Simulink input of the external reference generated reactive power signal at grid terminals.

Iq\_ref

This input is visible only when the **External reactive current Iq\_ref for grid-side converter** parameter is checked.

Simulink input of the external reference grid-side converter reactive current signal.

m

Simulink output vector containing 29 WTDFIG internal signals. These signals can be individually accessed by using the Bus Selector block. They are, in order:

	<b>Signal Signal Group</b>	<b>Signal Names</b>	<b>Definition</b>
1-3	Iabc (cmplx) (pu)	Ia (pu) Ib (pu) Ic (pu)	Phasor currents Ia, Ib, Ic flowing into the WTDFIG terminals in pu based on the generator rating.
4-6	Vabc (cmplx) (pu)	Va (pu) Vb (pu) Vc (pu)	Phasor voltages (phase to ground) Va, Vb, Vc at the WTDFIG terminals in pu based on the generator rating.

# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

Signal	Signal Group	Signal Names	Definition
7-8	Vdq_stator (pu)	Vd_stator (pu) Vq_stator (pu)	Direct-axis and quadrature-axis component of stator voltage in pu based on the generator rating. Vd_stator and Vq_stator are respectively the real and imaginary parts of the positive-sequence stator phasor voltage.
9-11	Iabc_stator (cmplx) (pu)	Ia_stator (pu) Ib_stator (pu) Ic_stator (pu)	Phasor currents Ia, Ib, Ic flowing into the stator in pu based on the generator rating.
12-13	Idq_stator (pu)	Id_stator (pu) Iq_stator (pu)	Direct-axis and quadrature-axis component of stator current in pu based on the generator rating. Id_stator and Iq_stator are respectively the real and imaginary parts of the positive-sequence stator phasor current.

# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

Signal	Signal Group	Signal Names	Definition
14-15	Vdq_rotor (pu)	Vd_rotor (pu) Vq_rotor (pu)	Direct-axis and quadrature-axis component of rotor voltage in pu based on the generator rating. Vd_rotor and Vq_rotor are respectively the real and imaginary parts of the positive-sequence rotor phasor voltage.
16-17	Idq_rotor (pu)	Id_rotor (pu) Iq_rotor (pu)	Direct-axis and quadrature-axis component of currents flowing into the rotor in pu based on the generator rating. Id_rotor and Iq_rotor are respectively the real and imaginary parts of the positive-sequence rotor phasor current.
18		wr (pu)	Generator rotor speed (pu)
19		Tm (pu)	Mechanical torque applied to the generator (pu)
20		Te (pu)	Electromagnetic torque in pu based on the generator rating.

# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

Signal	Signal Group	Signal Names	Definition
21-22	Vdq_grid_conv (pu)	Vd_grid_conv (pu) Vq_grid_conv (pu)	Direct-axis and quadrature-axis component of grid-side converter voltage in pu based on the generator rating. Vd_grid_conv and Vq_grid_conv are respectively the real and imaginary parts of the grid-side converter phasor voltage.
23-25	Iabc_grid_conv (cmplx) (pu)	Ia_grid_conv (pu) Ib_grid_conv (pu) Ic_grid_conv (pu)	Phasor currents Ia, Ib, Ic flowing into the grid-side converter in pu based on the generator rating.
26		P (pu)	WTDFIG output power. A positive value indicates power generation.
27		Q (pu)	WTDFIG output reactive power. A positive value indicates reactive power generation.
28		Vdc (V)	DC voltage (V).
29		Pitch_angle (deg)	Blade pitch angle in degrees.

# Wind Turbine Doubly-Fed Induction Generator (Phasor Type)

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## Example

See the `power_wind_dfig` demo which illustrates the steady-state and dynamic performance of the WTDFIG in a 9 MW Wind Farm connected on a 25 kV, 60 Hz, system.

## References

[1] R. Pena, J.C. Clare, G.M. Asher, "Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation," IEEE Proc.-Electr. Power Appl., Vol. 143, No. 3, May 1996

[2] Vladislav Akhmatov, "Variable-Speed Wind Turbines with Doubly-Fed Induction Generators, Part I: Modelling in Dynamic Simulation Tools," Wind Engineering Volume 26, No. 2, 2002

[3] Nicholas W. Miller, Juan J. Sanchez-Gasca, William W. Price, Robert W. Delmerico, "DYNAMIC MODELING OF GE 1.5 AND 3.6 MW WIND TURBINE-GENERATORS FOR STABILITY SIMULATIONS," GE Power Systems Energy Consulting, IEEE WTG Modeling Panel, Session July 2003

## See Also

Wind Turbine, Wind Turbine Induction Generator (Phasor Type)



# Wind Turbine Induction Generator (Phasor Type)

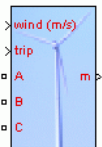
## Purpose

Implement phasor model of squirrel-cage induction generator driven by variable pitch wind turbine

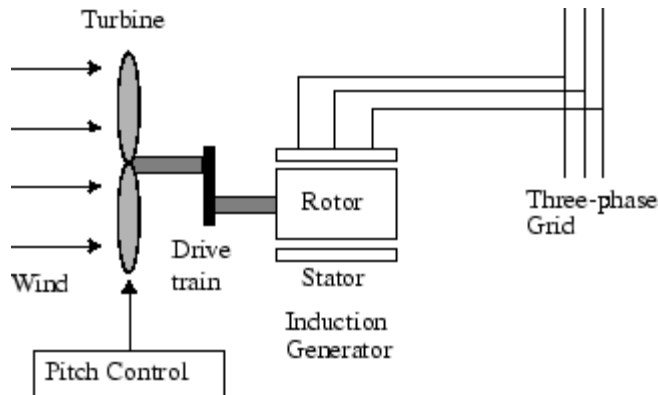
## Library

Distributed Resources/Wind Generation

## Description



The wind turbine and the induction generator (WTIG) are shown below. The stator winding is connected directly to the grid and the rotor is driven by the wind turbine. The power captured by the wind turbine is converted into electrical power by the induction generator and is transmitted to the grid by the stator winding. The pitch angle is controlled in order to limit the generator output power to its nominal value for high wind speeds. In order to generate power the induction generator speed must be slightly above the synchronous speed. But the speed variation is typically so small that the WTIG is considered to be a fixed-speed wind generator. The reactive power absorbed by the induction generator is provided by the grid or by some devices like capacitor banks, SVC, STATCOM or synchronous condenser.

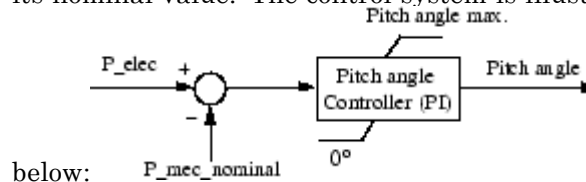


## Pitch Angle Control System

The wind turbine model uses the Wind Turbine block of the Distributed Resources/Wind Generation library. See documentation of this block for details.

# Wind Turbine Induction Generator (Phasor Type)

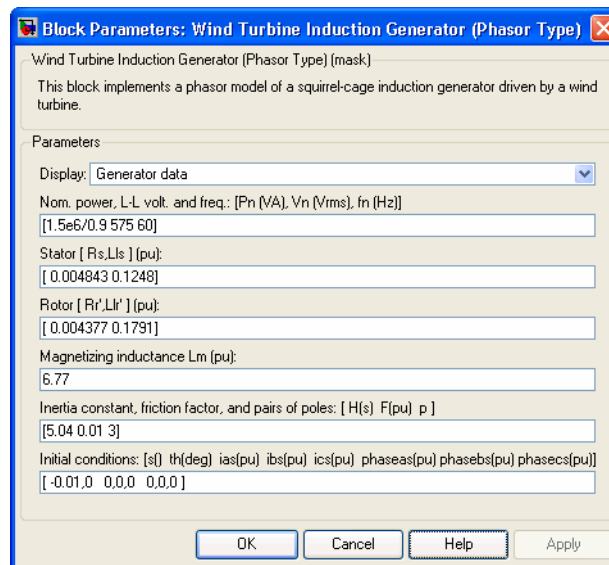
A Proportional-Integral (PI) controller is used to control the blade pitch angle in order to limit the electric output power to the nominal mechanical power. The pitch angle is kept constant at zero degree when the measured electric output power is under its nominal value. When it increases above its nominal value the PI controller increases the pitch angle to bring back the measured power to its nominal value. The control system is illustrated in the figure



## Dialog Box and Parameters

The WTIG parameters are grouped in two categories: Generator data and Turbine data». Use the Display listbox to select which group of parameters you want to visualize.

### Generator Data Parameters



# Wind Turbine Induction Generator (Phasor Type)

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## **Nominal power, line-to-line voltage and frequency**

The nominal power in VA, the nominal line-to-line voltage in  $V_{rms}$  and the nominal system frequency in hertz.

## **Stator [Rs, Lls]**

The stator resistance  $R_s$  and leakage inductance  $L_{ls}$  in pu based on the generator ratings.

## **Rotor [Rr', Llr']**

The rotor resistance  $R_r'$  and leakage inductance  $L_{lr}'$ , both referred to the stator, in pu based on the generator ratings.

## **Magnetizing inductance Lm**

The magnetizing inductance  $L_m$  in pu based on the generator ratings.

## **Inertia constant, friction factor and pairs of poles**

Combined generator and turbine inertia constant  $H$  in seconds, combined viscous friction factor  $F$  in pu based on the generator ratings and number of pole pairs  $p$ .

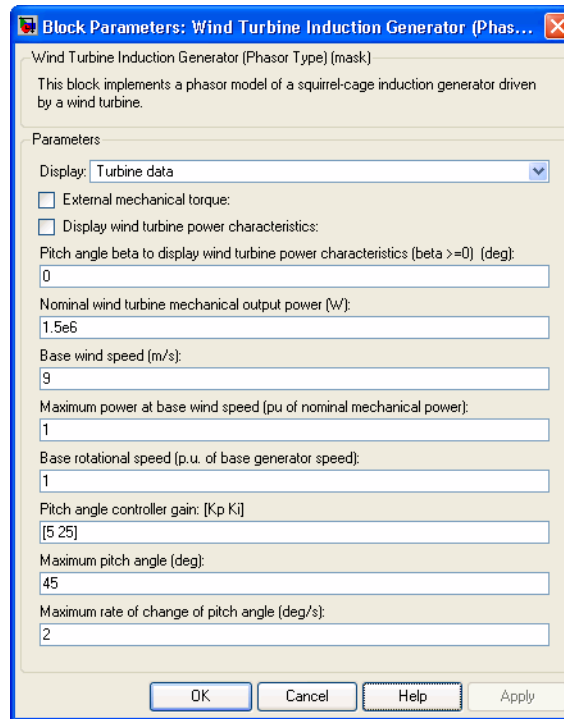
You may need to use your own turbine model, in order for example, to implement different power characteristics or to implement the shaft stiffness. Your model must then output the mechanical torque applied to the generator shaft. If the inertia and the friction factor of the turbine are implemented inside the turbine model you specify only the generator inertia constant  $H$  and the generator friction factor  $F$ .

## **Initial conditions**

The initial slip  $s$ , electrical angle  $\theta$  in degrees, stator current magnitude in pu and phase angle in degrees.

# Wind Turbine Induction Generator (Phasor Type)

## Turbine Data Parameters



Refer to the Wind Turbine for a detailed documentation.

### External mechanical torque

If this parameter is checked, a Simulink input named  $T_m$  appears on the block, allowing to use an external signal for the generator input mechanical torque. This external torque must be in pu based on the nominal electric power and synchronous speed of the generator. For example, the external torque may come from a user defined turbine model. By convention for the induction machine, the torque must be negative for power generation.

# Wind Turbine Induction Generator (Phasor Type)

---

## **Display wind turbine power characteristics**

If this parameter is checked, the turbine power characteristics at the specified pitch angle are displayed for different wind speeds.

This parameter is not visible when the **External mechanical torque** parameter is checked.

## **Nominal wind turbine mechanical output power**

This parameter is not visible when the **External mechanical torque** parameter is checked.

The nominal turbine mechanical output power in watts.

## **Base wind speed**

This parameter is not visible when the **External mechanical torque** parameter is checked.

The base value of the wind speed, in m/s, used in the per unit system. The base wind speed is the mean value of the expected wind speed. This base wind speed produces a mechanical power which is usually lower than the turbine nominal power.

## **Maximum power at base wind speed**

This parameter is not visible when the **External mechanical torque** parameter is checked.

The maximum power at base wind speed in pu of the nominal mechanical power.

## **Base rotational speed**

This parameter is not visible when the **External mechanical torque** parameter is checked.

The rotational speed at maximum power for the base wind speed. The base rotational speed is in pu of the base generator speed.

## **Pitch angle controller gain [Kp Ki]**

This parameter is not visible when the **External mechanical torque** parameter is checked.

# Wind Turbine Induction Generator (Phasor Type)

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Proportional and Integral gains  $K_p$  and  $K_i$  of the pitch controller. Specify  $K_p$  in degrees/(power deviation pu) and  $K_i$  in degrees/(power deviation pu)/s. The power deviation is the difference between actual electrical output power and the nominal mechanical power in pu of the generator nominal power.

## Maximum pitch angle (deg)

This parameter is not visible when the **External mechanical torque** parameter is checked.

The maximum pitch angle in degrees.

## Maximum rate of change of pitch angle

This parameter is not visible when the **External mechanical torque** parameter is checked.

The maximum rate of change of the pitch angle in degrees/s.

## Inputs and Outputs

A B C

The three terminals of the WTIG.

Trip

Apply a simulink logical signal (0 or 1) to this input. When this input is high the WTIG is disconnected. Use this input to implement a simplified version of the protection system.

Wind (m/s)

This input is not visible when the **External mechanical torque** parameter is checked.

Simulink input of the wind speed in m/s.

$T_m$

This input is visible only when the **External mechanical torque** parameter is checked.

Simulink input of the mechanical torque.  $T_m$  must be negative for power generation. Use this input when using an external turbine model.

# Wind Turbine Induction Generator (Phasor Type)

m

Simulink output vector containing 8 WTIG internal signals. These signals can be individually accessed by using the Bus Selector block. They are, in order:

Signal	Signal Names	Definition
1	Vabc (cmplx) (pu)	Phasor voltages (phase to ground) $V_a$ , $V_b$ , $V_c$ at the WTIG terminals in pu based on the generator ratings.
2	Iabc (cmplx) (pu)	Phasor currents $I_a$ , $I_b$ , $I_c$ flowing into the WTIG terminals in pu based on the generator ratings.
3	P (pu)	WTIG output power in pu based on the generator ratings. A positive value indicates power generation.
4	Q (pu)	WTIG output reactive power in pu based on the generator ratings. A positive value indicates reactive power generation.
5	wr (pu)	Generator rotor speed (pu)
6	Tm (pu)	Mechanical torque applied to the generator in pu based on the generator ratings.
7	Te (pu)	Electromagnetic torque in pu based on the generator ratings.
8	Pitch_angle (deg)	Blade pitch angle in degrees.

## Example

See the power\_wind\_ig demo which illustrates the steady-state and dynamic performance of the WTIG. Three WTIG blocks are used to simulate a 9 MW wind farm connected in a 25 kV, 60 Hz, system. Voltage regulation is performing by a 3 Mvar STATCOM.

# Wind Turbine Induction Generator (Phasor Type)

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## References

[1] Siegfried Heier, "Grid Integration of Wind Energy Conversion Systems," John Wiley & Sons Ltd, 1998, ISBN 0-471-97143-X

## See Also

Wind Turbine, Wind Turbine Doubly-Fed Induction Generator (Phasor Type)



# Zigzag Phase-Shifting Transformer

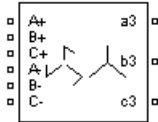
## Purpose

Implement zigzag phase-shifting transformer with configurable secondary winding connection

## Library

Elements

## Description



The Zigzag Phase-Shifting Transformer block implements a three-phase transformer with a primary winding connected in a zigzag configuration and a configurable secondary winding. The model uses three single-phase, three-winding transformers. The primary winding connects the windings 1 and 2 of the single-phase transformers in a zigzag configuration. The secondary winding uses the windings 3 of the single phase transformers, and they can be connected in one of the following ways:

- Y
- Y with accessible neutral
- Grounded Y
- Delta (D1), delta lagging Y by 30 degrees
- Delta (D11), delta leading Y by 30 degrees

---

**Note** The D1 and D11 notations refer to the following clock convention. It assumes that the reference Y voltage phasor is at noon (12) on a clock display. D1 and D11 refer respectively to 1 PM (lagging Y by 30 degrees) and 11 AM (leading Y by 30 degrees).

---

If the secondary winding is connected in Y, the secondary phase voltages are leading or lagging the primary voltages by the Phi phase angle specified in the parameters of the block. If the secondary winding is connected in delta (D11), an additional phase shift of +30 degrees is added to the phase angle. If the secondary winding is connected in delta (D1), a phase shift of -30 degrees is added to the phase angle.

# Zigzag Phase-Shifting Transformer

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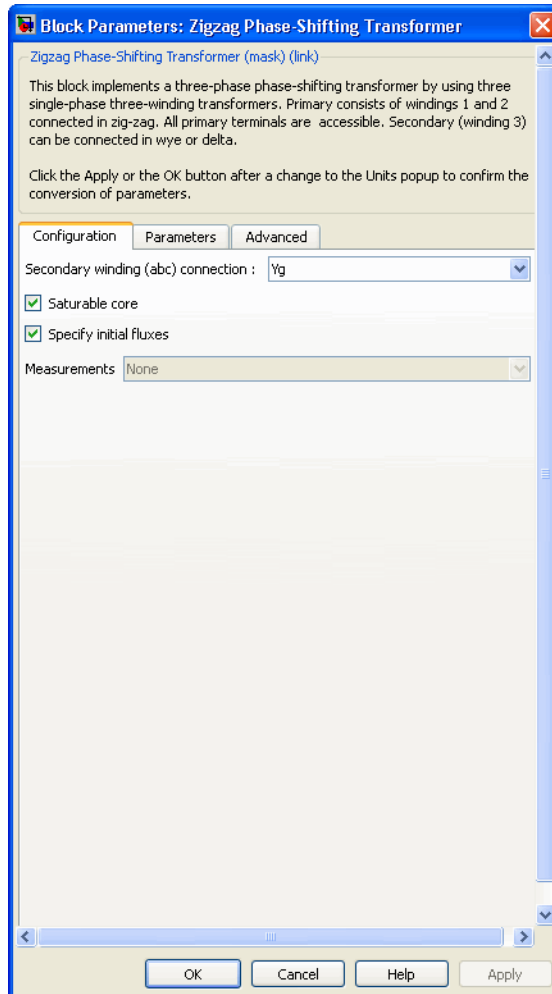
The block takes into account the connection type you have selected and the icon of the block is automatically updated. An output port labeled N is added to the block if you select the Y connection with accessible neutral for the secondary winding.

The saturation characteristic, when activated, is the same as the one described for the Saturable Transformer block.

# Zigzag Phase-Shifting Transformer

## Dialog Box and Parameters

### Configuration Tab



### Secondary winding (abc) connection

The winding connection for the secondary winding.

# Zigzag Phase-Shifting Transformer

---

## **Saturable core**

If selected, implements a saturable core.

## **Specify initial fluxes**

If selected, the initial fluxes are defined by the **Initial fluxes** parameter on the Parameters tab. The **Specify initial fluxes** parameter is available only if the **Saturable core** parameter is selected.

## **Measurements**

Select **Winding voltages** to measure the voltage across the winding terminals of the Three-Phase Transformer block.

Select **Winding currents** to measure the current flowing through the windings of the Three-Phase Transformer block.

Select **Fluxes** and **excitation currents ( $I_m + I_{Rm}$ )** to measure the flux linkage, in volt-seconds (V.s), and the total excitation current including iron losses modeled by  $R_m$  (for saturable transformers only).

Select **Fluxes** and **magnetization currents ( $I_m$ )** to measure the flux linkage, in volt-seconds (V.s), and the magnetization current, in amperes (A), not including iron losses modeled by  $R_m$  (for saturable transformers only).

Select **All measurements (V, I, Flux)** to measure the winding voltages, currents, magnetization currents, and the flux linkages. Note that the magnetization currents and the flux linkages signals are measured only if the **Saturable core** parameter is selected.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name.

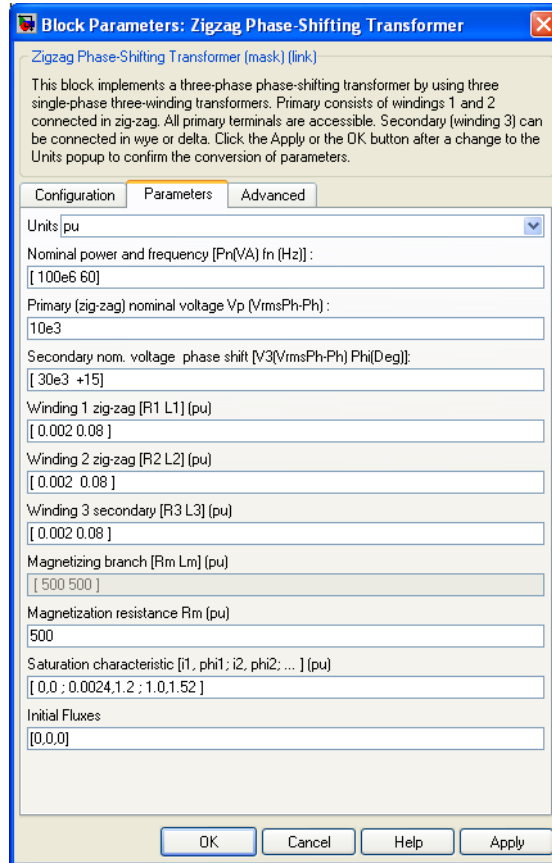
The labels used in the Multimeter are as follows.

# Zigzag Phase-Shifting Transformer

<b>Measurement</b>	<b>Label</b>
Winding voltages of primary (zigzag)	Uprim_A:, Uprim_B:, Uprim_C:
Winding currents of primary (zigzag)	Iprim_A:, Iprim_B:, Iprim_C:
Winding voltages of secondary (Y, Yn, or Yg)	Usec_A:, Usec_B:, Usec_C:
Winding voltages of secondary (delta)	Usec_AB:, Usec_BC:, Usec_CA:
Winding currents of secondary (Y, Yn, or Yg)	Isec_A:, Isec_B:, Isec_C:
Winding currents of secondary (delta)	Isec_AB:, Isec_BC:, Isec_CA:
Fluxes (windings 1 of zigzag)	Flux_A:, Flux_B:, Flux_C:
Excitation currents (windings 1 of zigzag)	Iexc_A:, Iexc_B:, Iexc_C:
Magnetization currents (windings 1 of zigzag)	Imag_A:, Imag_B:, Imag_C:

# Zigzag Phase-Shifting Transformer

## Parameters Tab



## Units

Specify the units used to enter the parameters of the Zigzag Phase-Shifting Transformer block. Select pu to use per unit. Select SI to use SI units. Changing the **Units** parameter from pu to SI, or from SI to pu, will automatically convert the parameters displayed in the mask of the block.

# Zigzag Phase-Shifting Transformer

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## **Nominal power and frequency**

The nominal power rating, in volt-amperes (VA), and nominal frequency, in hertz (Hz), of the transformer.

## **Primary (zigzag) nominal voltage $V_p$**

The phase-to-phase nominal voltage in volts RMS, for the primary winding of the transformer.

## **Secondary nom. voltage phase shift**

The phase-to-phase nominal voltage, in volts RMS, and the phase shift, in degrees, for the secondary winding of the transformer.

## **Winding 1 zig-zag [R1 L1]**

The resistance and leakage inductance of the windings 1 of the single-phase transformers used to implement the primary winding of the Zigzag Phase-Shifting Transformer.

## **Winding 2 zig-zag [R2 L2]**

The resistance and leakage inductance of the windings 2 of the single-phase transformers used to implement the primary winding of the Zigzag Phase-Shifting Transformer.

## **Winding 3 secondary [R3 L3]**

The resistance and leakage inductance of the windings 3 of the single-phase transformers used to implement the secondary winding of the Zigzag Phase-Shifting Transformer.

## **Magnetizing branch [Rm Lm]**

The **Magnetizing branch** parameter is not accessible if the **Saturable core** check box is selected.

The magnetization resistance  $R_m$  and inductance  $L_m$ , in pu, when the saturation is not simulated.

## **Magnetization resistance $R_m$**

This parameter is accessible only if the **Saturable core** parameter on the Configuration tab is selected.

The magnetization resistance  $R_m$ , in pu, when the saturation is simulated.

# Zigzag Phase-Shifting Transformer

---

## **Saturation characteristic**

This parameter is accessible only if the **Saturable core** parameter on the Configuration tab is selected.

The saturation characteristic for the saturable core. Specify a series of current/ flux pairs (in pu) starting with the pair (0,0).

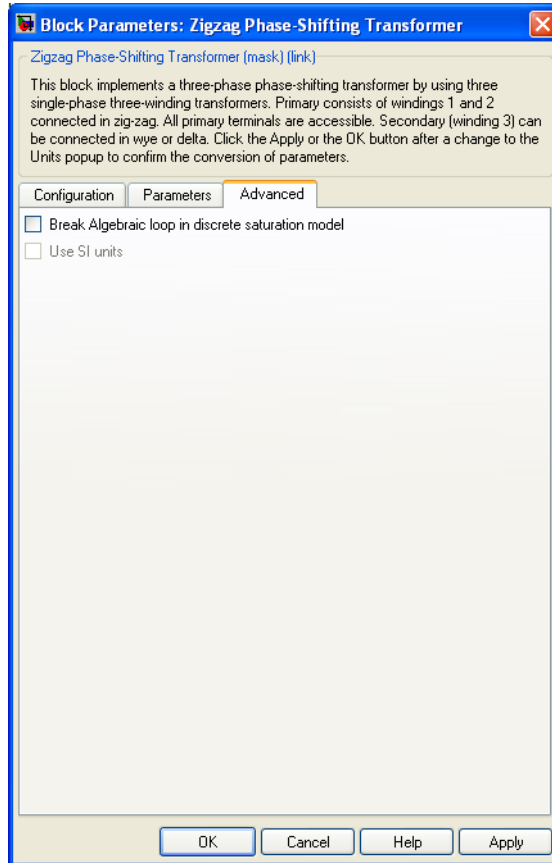
## **Initial fluxes**

Specify initial fluxes for each phase of the transformer. This parameter is accessible only if the **Specify initial fluxes** parameter on the Configuration tab is selected.



# Zigzag Phase-Shifting Transformer

## Advanced Tab



### Break Algebraic loop in discrete saturation model

When you use the block in a discrete system, you will get an algebraic loop. This algebraic loop, which is required in most cases to get an accurate solution, tends to slow down the simulation. However, to speed up the simulation, in some circumstances, you can disable the algebraic loop by selecting **Break Algebraic loop in discrete saturation model**. You should be aware that

# Zigzag Phase-Shifting Transformer

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disabling the algebraic loop introduces a one-simulation-step time delay in the model. This can cause numerical oscillations if the sample time is too large.

## **Example**

See the help text of the `power_48pulsegtoconverter` demo.

In this model, a 48-pulse GTO converter is built with four Three-Level Bridge blocks and four Zigzag Phase-Shifting Transformer blocks. Harmonic neutralization is obtained by use of appropriate phase shifts introduced by the Zigzag connections (+7.5/-7.5 degrees) and of secondary winding connections (Y or Delta).

## **See Also**

Multimeter, Three-Phase Transformer (Three Windings)

# Command Reference

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This table indicates the tasks performed by the commands described in this chapter.

<code>power_analyze</code>	Analyze electric circuit built with SimPowerSystems software
<code>power_hysteresis</code>	View and edit hysteresis characteristic for saturable core of Saturable Transformer blocks
<code>power_init</code>	Set initial state values of model built with Simulink and SimPowerSystems software
<code>power_lineparam</code>	Compute RLC parameters of overhead transmission line from its conductor characteristics and tower geometry
<code>power_statespace</code>	Compute state-space model of linear electrical circuit

# power\_analyze

---

**Purpose** Analyze electric circuit built with SimPowerSystems software

**Syntax**

```
sps = power_analyze('sys', 'structure')
sps = power_analyze('sys', 'sort')
sps = power_analyze('sys', 'ss')
[A,B,C,D,x0,states,inputs,outputs,uss,xss,yss,freqyss,Hlin]=
power_analyze(`sys`);
power_analyze('sys', 'net')
```

**Description** The `power_analyze` command computes the equivalent state-space model of the specified electrical model built with SimPowerSystems software. It evaluates the  $A$ ,  $B$ ,  $C$ ,  $D$  standard matrices of the state-space system described by the equations

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned}$$

where the state variables contained in the  $x$  vector are the inductor currents and capacitor voltages. Nonlinear elements are simulated by current sources driven by the voltages across the nonlinear elements.

The inputs of the system contained in the  $u$  vector are the voltage and current sources plus the current sources simulating the nonlinear elements. The outputs of the system contained in the  $y$  vector are the voltage and current measurements plus the voltages across the nonlinear elements.

The following conventions are used for inputs:

- Source current flowing in the arrow direction is positive.
- Positive source voltage is indicated by a + sign on the icon.

The sign conventions used for voltages and currents (state variables  $x$  and measurement outputs  $y$ ) are explained below.

## Sign Conventions for Voltages and Currents

When you measure a current using a Current Measurement block, the positive direction of current is indicated on the block icon (positive current flowing from + terminal to – terminal). Similarly, when you measure a voltage using a Voltage Measurement block, the measured voltage is the voltage of the + terminal with respect to the – terminal. However, when voltages and currents of blocks from the Elements library are measured using the Multimeter block, the voltage and current polarities are not so evident because blocks might have been rotated and there are no signs indicating polarities on the block icons.

Unlike the Simulink signal lines and input and output ports, the Physical Modeling connection lines and terminal ports  lack an intrinsic direction. The voltage and current polarities are determined instead by the block orientation. To find out the block orientation, first click the block to select it. Then enter the following command:

```
get_param(gcf, 'Orientation')
```

The following table gives the polarities of the currents and voltages measured with the Multimeter block for single-phase and three-phase RLC elements (branches or loads), surge arresters, and single-phase and three-phase breakers. The table also indicates the polarities of the corresponding state variables (inductor currents and capacitor voltages).

Block Orientation	Positive Current Direction	Measured Voltage
right	left → right	$V_{\text{left}} - V_{\text{right}}$
left	right → left	$V_{\text{right}} - V_{\text{left}}$
down	top → bottom	$V_{\text{top}} - V_{\text{bottom}}$
up	bottom → top	$V_{\text{bottom}} - V_{\text{top}}$

The natural orientation of the blocks (that is, their orientation in the Element library) is *right* for horizontal blocks and *down* for vertical blocks.

For single-phase transformers (linear or saturable), with the winding ports appearing on the left and right sides, the winding voltages are the voltages of the top terminal port with respect to the bottom terminal port, whatever the block orientation (*right* or *left*). The winding currents are the currents entering the top port.

For three-phase transformers, the voltage polarities and positive current directions are indicated by the signal labels used in the Multimeter block. For example,  $U_{an\_w2}$  = phase A-to-neutral voltage of the Y connected winding #2,  $I_{ab\_w1}$  = winding current flowing from A to B in the delta connected winding #1.

## Output Arguments: Structure

`sps = power_analyze('sys', 'structure')` creates a structure array `sps` with fields and values describing the model `sys`.

The fields of the structure array are defined in the following order.

Field	Description
<code>circuit</code>	Name of the model
<code>states</code>	char array of state variable names
<code>inputs</code>	char array of system input names
<code>outputs</code>	char array of system output names
<code>A</code>	<code>nstates-by-nstates</code> state-space <i>A</i> matrix
<code>B</code>	<code>nstates-by-ninput</code> state-space <i>B</i> matrix
<code>C</code>	<code>noutput-by-nstates</code> state-space <i>C</i> matrix
<code>D</code>	<code>noutput-by-ninput</code> state-space <i>D</i> matrix
<code>x0</code>	<code>nstates-by-1</code> vector of initial conditions
<code>Aswitch</code>	<i>A</i> matrix including closed switches
<code>Bswitch</code>	<i>B</i> matrix including closed switches

Field	Description
Cswitch	<i>C</i> matrix including closed switches
Dswitch	<i>D</i> matrix including closed switches
x0switch	Vector of initial values of switch currents
uss	ninput-by-nfreq steady-state values of inputs
xss	nstates-by-nfreq steady-state values of states
yss	noutput-by-nfreq steady-state values of outputs
Hlin	nfreq-by-noutput-by-ninput transfer function of impedances
frequencies	1-by-nfreq vector of input source frequencies
LoadFlow	Load flow information for circuits with machines
OscillatoryModes	Oscillatory modes of linear part of the system

The table uses the following conventions:

- `nstates` is the number of states.
- `ninput` is the number of inputs.
- `noutput` is the number of outputs.
- `nfreq` is the number of input source frequencies.

`states` is a string matrix containing names of the state variables. Each line of `states` begins with a prefix `Uc_` for capacitor voltages or `I1_` for inductor currents, followed by the name of the block in which the element (C or L) is found. See “Sign Conventions for Voltages and Currents” on page 3-53 for inductor current directions and capacitor voltage polarities. A string is added to this prefix for blocks containing more than two inductances or capacitors. For example, the Linear

Transformer blocks produce four lines in the `states` matrix, one for each of the three leakage inductances, with prefixes `Il_winding_x`, where `x` is the winding number of the transformer, and one line for the magnetization inductance with the prefix `Il_Lm`.

`inputs` is a string matrix containing names of the inputs of the system. Each line of `inputs` begins with a prefix `U_` for voltage sources or `I_` for current sources, followed by the name of the source block. A string can be added to the prefix for blocks containing more than one source. For example, the Synchronous Machine block produces two current inputs with prefixes `I_A:` and `I_B:` (phase A and phase B machine currents).

`outputs` is a string matrix containing names of the outputs of the state-space system (vector `y`). Each line of `outputs` begins with a prefix `U_` for voltage outputs or `I_` for current outputs, followed by the name of the block that produces the output. A string can be added to the prefix for blocks containing more than one source. For example, the Synchronous Machine block produces two voltage outputs with prefixes `U_AB:` and `U_BC:` (two machine phase-to-phase voltages). See “Sign Conventions for Voltages and Currents ” on page 3-53 for current directions and voltage polarities.

`A`, `B`, `C`, `D` are the state-space matrices of the linear part of the model.

`x0` is a vector containing the initial conditions of the state variables listed in the `states` variable.

`uss`, `xss`, and `yss` are complex matrices containing the steady-state values of inputs, states and outputs. If voltage and current sources all generate the same frequency, these are column vectors. If sources with different frequencies are used, each column of the matrices corresponds to a frequency contained in the `frequencies` vector.

`frequencies` is a row vector containing the input source frequencies ordered by increasing values.

`Hlin` is the complex transfer impedance three-dimensional array (`nfreq-by-noutput-by-ninput`) of the linear system corresponding to the frequencies contained in the `frequencies` vector. For a particular frequency, `Hlin` is defined by



```
yss(:,ifreq) = Hlin(ifreq, :, :) * uss(:,ifreq)
```

## Output Arguments: Sort

`sps = power_analyze('sys', 'sort')` returns a structure array `sps` with the following fields related to the interconnection of SimPowerSystems blocks in a model. The fields are defined in the following order.

Field	Description
<code>circuit</code>	Name of the model
<code>SampleTime</code>	Sample time for discrete systems
<code>RlcBranch</code>	rlc matrix in the <code>power_statespace</code> format
<code>RlcBranchNames</code>	List of blocks containing the state variable
<code>SourceBranch</code>	Source matrix in the <code>power_statespace</code> format
<code>SourceBranchNames</code>	Names of the blocks defined as sources
<code>InputNames</code>	Names of the inputs of the system
<code>OutputNames</code>	Names of the outputs of the system
<code>OutputExpressions</code>	Output expression in the <code>power_statespace</code> format
<code>OutputMatrix</code>	Output expression in matrix format (internal)
<code>MeasurementBlocks</code>	Names of the voltage and current measurement blocks

`[A,B,C,D,x0,states,inputs,outputs,uss,xss,yss,frequencies,Hlin] = power_analyze('sys')` returns the state-space calculations in separate variables.

`sps = power_analyze('sys', 'ss')` creates a continuous state-space model of the model `sys` with matrices  $A$ ,  $B$ ,  $C$ ,  $D$ . You must have Control System Toolbox software installed for this option. The output is a state-space object.

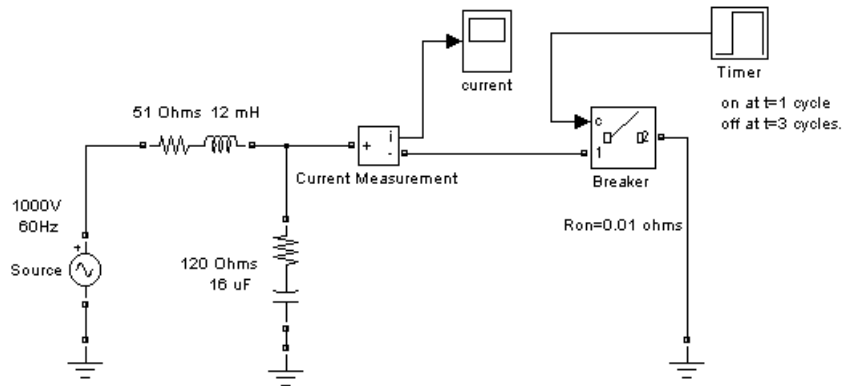
# power\_analyze

## Output Arguments: Net

`power_analyze('sys', 'net')` generates a netlist stored in a file, `sys.net`. The file contains the node numbers automatically generated by `power_analyze`, as well as parameter values of all linear elements. See the formats described in the `power_statespace` reference page.

## Example

Obtain the state-space matrices and steady-state voltages and currents for the `power_netsim2` circuit.



The command

```
sps = power_analyze('power_netsim2', 'structure')
```

returns the state-space model in the `sps` structure variable.

```
sps.A =  
    1.0e+04 *  
         0      6.2500  
    -0.0083  -1.4250
```

```
sps.uss =  
    0  
    1000
```

```
sps.xss =  
    1.0e+02 *  
    4.8392 - 5.1314i  
    0.0310 + 0.0292i  
  
sps.yss =  
    1.0e+02 *  
    8.5535 - 1.6287i  
    0  
  
sps.inputs =  
    I_Breaker  
    U_Source  
  
sps.outputs =  
    U_Breaker  
    I_Current Measurement
```

The inductor current of the 51-ohm, 12-mH block and the capacitor voltage of the 120-ohm, 16- $\mu$ F block are the two state variables in this circuit. The Breaker block is a nonlinear element that is represented by a current source (the first input) driven by the voltage across its terminals (the first output).

## See Also

`power_statespace`, `power_init`, `Powergui`

# power\_hysteresis

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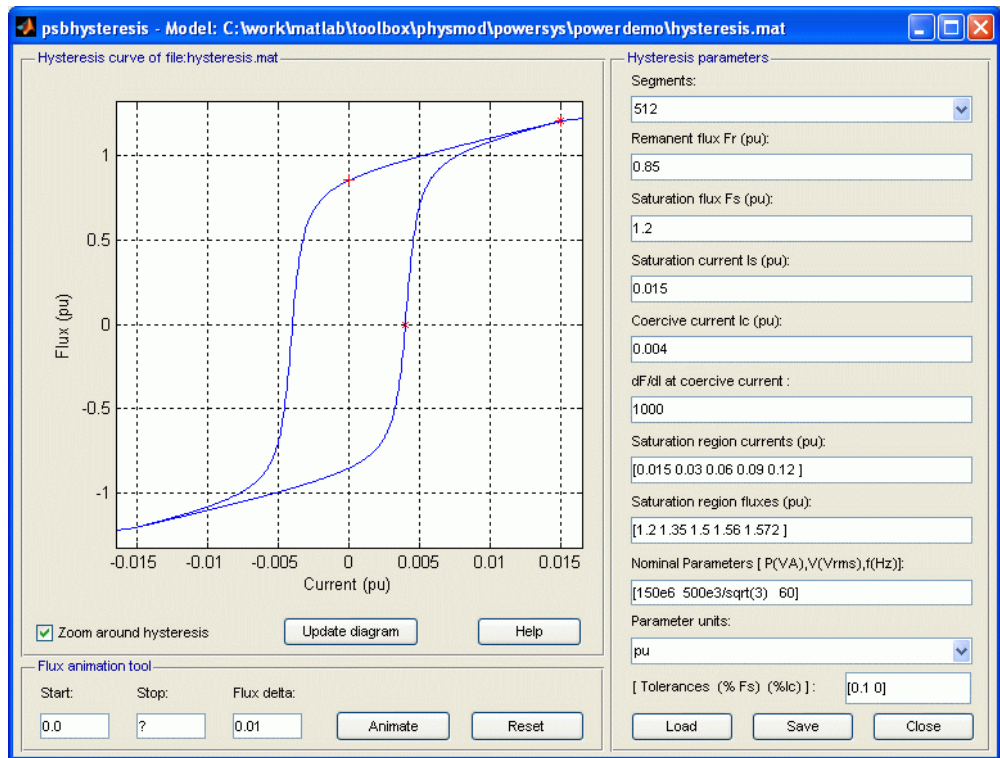
**Purpose** View and edit hysteresis characteristic for saturable core of Saturable Transformer blocks

**Syntax** `power_hysteresis`  
`power_hysteresis('MAT file name')`

**Description** The `power_hysteresis` command opens a graphical user interface (GUI) that allows you to view and edit a hysteresis characteristic for the saturable core of the Multi-Winding Transformer, the Saturable Transformer, the Three-Phase Two Windings Transformer, and the Three-Phase Three Windings Transformer blocks. Hysteresis characteristic includes the saturation region located at the limits of the hysteresis loop.

This GUI can also be activated from the Powergui block dialog box.

A default hysteresis characteristic is first displayed when you open the GUI, but you can build as many hysteresis characteristics as you want and save them in different MAT files names. You can use the same characteristic for all of your transformer blocks, or you can use different ones for each transformer block in the circuit. You need to select the **Simulate hysteresis** check box in the masks of the transformer blocks and specify a MAT file to be used by the model.



## Hysteresis Parameters

### Segments

In the pull-down menu, specify the number of linear segments used to define the right side of the hysteresis loop. The left side of the loop is the symmetric image of the right side.

### Remanent flux Fr

Specify the remanent flux point of the hysteresis characteristic (flux at zero current). It is identified by a + mark in the plot.

**Saturation flux  $F_s$** 

Specify the saturation flux point where the hysteresis loop becomes a single-valued saturation curve. It is identified by a \* mark in the plot.

**Saturation current  $I_s$** 

Specify the saturation current point where the hysteresis loop becomes a single-valued saturation curve. The saturation region is defined by the **Saturation region currents** parameter.

**Coercive current  $I_c$** 

Specify the coercive current point of the hysteresis characteristic.

 **$dF/dI$  at coercive current**

Set the slope of the flux at the coercive current point (current at zero flux).

**Saturation region currents**

Specify the vector of current values that define the saturation characteristic. The number of specified points must be the same as for the **Saturation region fluxes** parameter. You only need to specify the positive part of the characteristic.

**Saturation region fluxes**

Specify the vector of flux values that define the saturation characteristic. The number of specified points must be the same as for the **Saturation region currents** parameter. You only need to specify the positive part of the characteristic.

**Nominal Parameters**

Specify the nominal parameters (nominal power in VA, nominal voltage of winding 1 in volts RMS, and nominal frequency in Hz) used in the conversion of the hysteresis parameters.

**Parameter units**

Convert the fluxes and currents that define the hysteresis characteristic from SI to pu or from pu to SI.

**Load**

Load an existing hysteresis characteristic from a MAT file.

**Save**

Save current hysteresis characteristic into a MAT file.

**Close**

Close the hysteresis GUI window.

**Hysteresis Curve****Zoom around the hysteresis**

If selected, zoom the plot around the hysteresis curve. The default is selected.

**Update diagram**

When the parameters are entered, you can click **Display** to visualize the hysteresis characteristic.

**Flux Animation Tool**

The Flux Animation tool can be used to visualize how the simulation of the hysteresis is performed by SimPowerSystems software. This is an optional tool that is not necessary for the model parameterization. The initial trajectory will be calculated according to the defined hysteresis characteristic.

The model assumes that the last reversal point before starting flux is located on the major loop. The operating point will travel till the defined stop flux.

**Start**

Specify the starting flux.

**Stop**

Specify the flux at which the flux animation will stop.

**Flux delta**

Specify flux increment (in pu, or in SI) that is used to go from start flux to stop flux.

**Animate**

Start the Flux Animation tool.

## Reset

Reset the Flux Animation tool.

## Tolerances Tool

The Tolerances tool is an advanced tool mainly used to minimize the generation of superfluous very small internal loops or new trajectories because they have little effect and they consume computer memory space (the model can memorize at any time up to 50 embedded minor loops).

The TOL\_F parameter is the tolerance value used to detect whether, after a flux reversal, the operating point remains on the same minor loop or a new embedded loop is created. The smaller the value, the lesser is the effect on the normal trajectory behavior. The bigger the value, the lesser is the generated number of embedded minor loops.

Finally, when the distance between the I coordinate of the actual point of reversal and the penultimate one is less than TOL\_I, then evolution within these two points will follow a line segment instead of a loop.

## See Also

Powergui



<b>Purpose</b>	Set initial state values of model built with Simulink and SimPowerSystems software
<b>Syntax</b>	<pre>[x0,states] = power_init(sys) [x0,states] = power_init(sys,'look') power_init(sys,'states') power_init(sys,'ForceToZero') power_init(sys,'ResetToDefault') power_init(sys,'x0',x0) power_init(sys,'look') power_init(sys,'reset') power_init(sys,'steady')</pre>
<b>Description</b>	<p>Power_init deals with two types of state variables: the Simulink State variables and the Electrical State variables. The Simulink States consists of the entire set of state variables of a model (including the Electrical states) seen by Simulink software. The Electrical States are the particular Simulink states that defines the capacitor initial voltages and inductor initial currents of the SimPowerSystems blocks of your model.</p> <p>[x0,states] = power_init(sys) returns the initial states values and state names of your model.</p> <p>[x0,states] = power_init(sys,'look') returns the electrical initial states values and state names of sys.</p> <p>power_init(sys,'states') displays in a two-column format the initial state values and names of your model.</p> <p>power_init(sys,'ForceToZero') sets to zero the initial states your model. It uses the <b>Data import/export initial state</b> option of the Simulink <b>Configuration Parameters</b> menu to specify the initial state values. Use the <b>ResetToDefault</b> option of power_init to reset the Simulink configuration parameters to its previous settings.</p> <p>power_init(sys,'ResetToDefault') resets the initial state of Simulink configuration parameters to the settings prior to the use of the</p>

## power\_init

---

**ForceToZero** option of `power_init`. This option has no effect on system if the **ForceToZero** option is not used before.

`power_init(sys, 'x0', x0)` sets the initial state values equal to the vector specified by `x0`. The ordering of the states variables is given by the **state** option of `power_init`. This option uses the **Data import/export initial state** option of the Simulink **Configuration Parameters** menu to specify the initial state values.

`power_init(sys, 'look')` displays in a two-column format the electrical initial states names and values of your model.

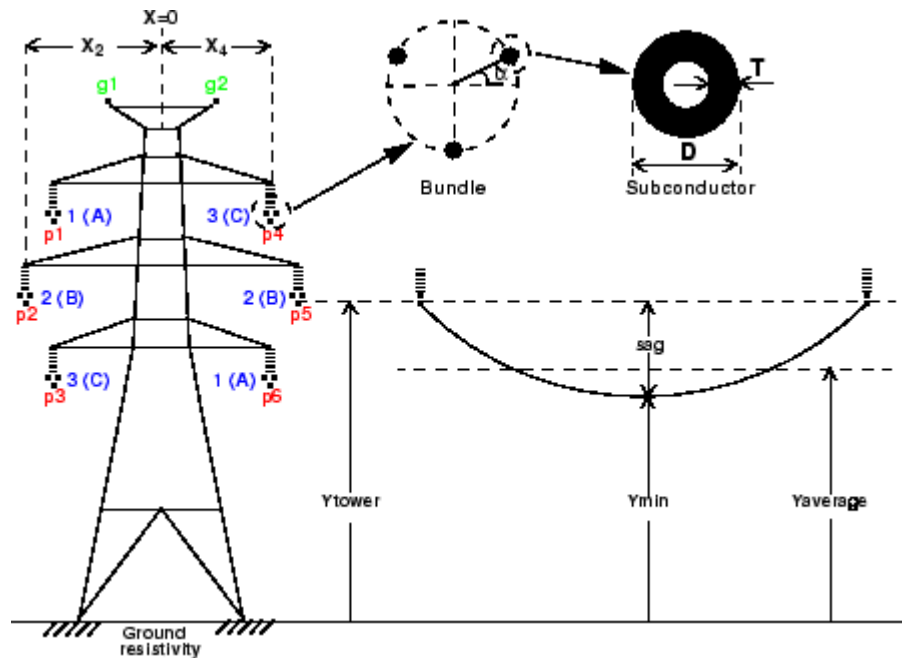
`power_init(sys, 'reset')` resets the electrical initial states of `sys` to zero.

`power_init(sys, 'steady')` sets the electrical initial states of `sys` to simulate the electrical circuit in the steady state.

### See Also

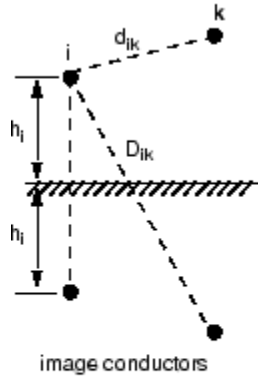
`power_analyze`, `Powergui`

- Purpose** Compute RLC parameters of overhead transmission line from its conductor characteristics and tower geometry
- Synopsis** The `power_lineparam` command opens a graphical user interface (GUI) that is used to enter the line parameters and return the electrical R, L, C line parameters. This GUI can also be activated from the Powergui block dialog box by selecting **Compute RLC Line Parameters**.
- Description** The `power_lineparam` function computes the resistance, inductance, and capacitance matrices of an arbitrary arrangement of conductors of an overhead transmission line. For a three-phase line, the symmetrical component RLC values are also computed.
- The following figure shows a typical conductor arrangement for a three-phase double-circuit line. This line configuration is used as an example to illustrate the various line parameters to be entered in the GUI.



## Configuration of a Three-Phase Double-Circuit Line

For a set of  $N$  conductors, `power_lineparam` computes three  $N$ -by- $N$  matrices: the series resistance and inductance matrices  $[R]$  and  $[L]$  and the shunt capacitance matrix  $[C]$ . These matrices are required by the Distributed Parameter Line block for modeling  $N$ -phase asymmetrical lines and by the single-phase PI Section Line block. `power_lineparam` also computes the symmetrical component RLC parameters required by the Three-Phase PI Section Line block. For two coupled conductors  $i$  and  $k$ , the self and mutual terms of the  $R$ ,  $L$ , and  $C$  matrices are computed using the concept of image conductors [1]



Self and mutual resistance terms:

$$R_{ii} = R_{int} + \Delta R_{ii} \quad \Omega/\text{km}$$

$$R_{ik} = \Delta R_{ik} \quad \Omega/\text{km}$$

Self and mutual inductance terms:

$$L_{ii} = L_{int} + \frac{\mu_0}{2\pi} \cdot \log \frac{2h_i}{r_i} + \Delta L_{ii} \quad \text{H}/\text{km}$$

$$L_{ik} = \frac{\mu_0}{2\pi} \cdot \log \frac{D_{ik}}{d_{ik}} + \Delta L_{ik} \quad \text{H}/\text{km}$$

Self and mutual potential coefficient terms:

$$P_{ii} = \frac{1}{2\pi\epsilon_0} \cdot \log \frac{2h_i}{r_i} \quad \text{km}/\text{F}$$

$$P_{ik} = \frac{1}{2\pi\epsilon_0} \cdot \log \frac{D_{ik}}{d_{ik}} \quad \text{km}/\text{F}$$

$$[C] = [P]^{-1} \quad \text{F}/\text{km}$$

where:

$\mu_0$ : permeability of free space =  $4\pi \cdot 10^{-4}$  H/km

$\epsilon_0$ : permittivity of free space =  $8.8542 \cdot 10^{-9}$  F/km

$r_i$ : radius of conductor i in meters

$d_{ik}$ : distance between conductors i and k in meters

$D_{ik}$ : distance between conductor i and image of k in meters

$h_i$ : average height of conductor i above ground, in meters

$R_{int}$ ,  $L_{int}$ : internal resistance and inductance of conductor

$\Delta R_{ii}$ ,  $\Delta R_{ik}$ : Carson R correction terms due to ground resistivity

$\Delta L_{ii}$ ,  $\Delta L_{ik}$ : Carson L correction terms due to ground resistivity

The conductor self inductance is computed from the magnetic flux circulating inside and outside the conductor, and produced by the current flowing in the conductor itself. The part of flux circulating inside the conducting material contributes to the so called internal inductance  $L_{int}$ , which is dependant on the conductor geometry. Assuming a

hollow or solid conductor, the internal inductance is computed from the T/D ratio where D is the conductor diameter and T is the thickness of the conducting material (see the figure named Configuration of a Three-Phase Double-Circuit Line on page 3-18). The conductor self inductance is computed by means of modified Bessel functions from the conductor diameter, T/D ratio, resistivity, and relative permeability of conducting material and specified frequency [1].

The conductor self inductance can be also computed from parameters that are usually found in tables provided by conductor manufacturers: the Geometric Mean Radius (GMR) or the so called "Reactance at one-foot spacing."

The GMR is the radius of the equivalent hollow conductor with zero thickness, thus producing no internal flux, giving the same self inductance. The conductor self inductance is then derived from the GMR using the following equation.

$$L_{ii} = \frac{\mu_0}{2\pi} \cdot \log \frac{2h_i}{GMR} + \Delta L_{ii} \text{ H/km}$$

For a solid conductor (T/D=0.5), the GMR is given by

$$GMR = r \cdot e^{-\mu_r/4}$$

where:  $r$  = radius of conductor

$\mu_r$  = relative permeability of conducting material

The GMR obtained from the above equation assumes a uniform current density in the conductor. This assumption is strictly valid in DC. In AC, the GMR is slightly higher. For example for a 3 cm diameter solid aluminum conductor ( $R_{dc} = 0.040 \text{ } \Omega/\text{km}$ ), the GMR increases from 1.1682 cm in DC to 1.1784 cm at 60 Hz. Manufacturers usually give the GMR at the system nominal frequency (50 Hz or 60 Hz).

The reactance  $X_a$  at 1-foot spacing (or 1-meter spacing if metric units are used) is the positive-sequence reactance of a three-phase line having one foot (or one meter) spacing between the three phases and infinite

conductor heights. The reactance at one-foot spacing (or 1-meter spacing) at frequency  $f$  is related to the GMR by the following equation

$$X_a = \omega \cdot \frac{\mu_0}{2\pi} \cdot \log \frac{1}{GMR} \quad \Omega/\text{km}$$

where: GMR = Geometric Mean Radius in feet or meters

$\omega = 2\pi \cdot f$  in rad/s

$f$  = frequency in hertz

The conductor resistance matrix at a particular frequency depends on the DC resistance of the conductor corrected for skin effect and ground resistivity. In fact, both the resistance matrix and the inductance matrix are dependent on the ground resistivity and frequency.

Correction terms for the R and L terms as developed by J.R. Carson in 1926 [2] are implemented in `power_lineparam`.

When you type the `power_lineparam` command, the GUI is displayed as shown below.

# power\_lineparam

**Power\_lineparam. Line Data of DefaultLineParameters.mat**

Units:

Frequency (Hz):

Ground resistivity (ohm.m):

Comments:  
 Example of a 735-kV three-phase line.  
 3 bundles of 4 Bersfort ACSR 1355 MCM conductors, 2 steel ground wires.  
 Ytower and Ymin are the average heights of conductors.

**Line Geometry**

Number of phase conductors (bundles):

Number of ground wires (bundles):

Conductor (bundle)	Phase number	X (feet)	Y tower (feet)	Y min (feet)	Conductor (bundle) type
p 1	1	-42	68	68	1
p 2	2	0	68	68	1
p 3	3	42	68	68	1
g 1	0	-29.5	108	108	2
g 2	0	29.5	108	108	2

**Conductor and Bundle Characteristics**

Number of conductor types or bundles types:

Conductor internal inductance evaluated from:

Include conductor skin effect

Conductor (bundle) type	Conductor Outside diameter (inches)	Conductor T/D ratio	Conductor GMR (inches)	Conductor DC resistance (Ohm/mi)	Conductor relative permeability	Number of conductors per bundle	Bundle diameter (inches)	Angle of conductor 1 (degrees)
1	1.4	0.375	0.562724	0.06903	1	4	25.456	45
2	0.4375	0.5	0.170363	5.8	1	1	0	0

Load Save Compute RLC Parameters Help Close

The default parameters are for a single-circuit three-phase line with two ground wires. You enter your own line parameters in three different sections:

- The upper-left section where you enter general parameters (units, frequency, ground resistivity, and comments)
- The table of conductor types defining the conductor characteristics for each type (bottom section)
- The table of conductors specifying the line geometry and the conductor types (upper-right section)



## General Parameters

### Units

In the pull-down menu, select `metric` if you want to specify conductor diameter, GMR and bundle diameter in centimeters and conductor positions in meters. Select `english` if you want to specify conductor diameter, GMR and bundle diameter in inches and conductor positions in feet.

### Frequency

Specify the frequency in hertz to be used to evaluate RLC parameters.

### Ground resistivity

Specify the ground resistivity in ohm.meters. A zero value (perfectly conducting ground) is allowed.

### Comments

Use this window to type comments that you want to save with the line parameters, for example, voltage level, conductor types and characteristics, etc.

## Conductor and Bundle Characteristics

### Number of conductor types or bundle types

Specify the number of conductor types (single conductor or bundle of subconductors) to be used. This parameter determines the number of rows of the table of conductors types. The phase conductors and ground wires can be either single conductors or bundles of subconductors. For voltage levels of 230 kV and above, phase conductors are usually bundled to reduce losses and electromagnetic interferences due to corona effect. Ground wires are usually not bundled.

For a simple AC three-phase line, single- or double-circuit, there are usually two types of conductors: one type for the phase conductors and one type for the ground wires. More than two types will be necessary for several lines in the same corridor, DC bipolar lines or distribution feeders where neutral and sheaths of TV and telephone cables are represented.

In the table of conductor types, two rows are visible at a time. If more than two conductor types are specified, a scroll bar appears at the right side of the table to give you access to the different rows of the table.

### **Conductor internal inductance evaluated from**

Select one of the following three parameters to specify how the conductor internal inductance is computed: T/D ratio, Geometric Mean Radius (GMR), or Reactance  $X_a$  at 1-foot spacing (or 1-meter spacing if the **Units** parameter is set to metric).

If you select T/D ratio, the internal inductance is computed from the T/D value specified in the table of conductors, assuming a hollow or solid conductor, where D is the conductor diameter and T is the thickness of the conducting material (see the figure named Configuration of a Three-Phase Double-Circuit Line on page 3-18). The conductor self inductance and resistance are computed from the conductor diameter, T/D ratio, DC resistance, and relative permeability of conducting material and specified frequency.

If you select Geometric Mean Radius (GMR), the conductor GMR is used to evaluate the internal inductance. When the conductor inductance is evaluated from the GMR, the specified frequency does not affect the conductor inductance. You have therefore to provide the manufacturer's GMR for the desired frequency (usually 50 Hz or 60 Hz). When you are using the T/D ratio option, the corresponding conductor GMR at the specified frequency is displayed.

Selecting Reactance  $X_a$  at 1-foot spacing (or 1-meter spacing) uses the positive-sequence reactance at the specified frequency of a three-phase line having 1-foot (or 1-meter) spacing between the three phases to compute the conductor internal inductance.

## **Include conductor skin effect**

Select this check box to include the impact of frequency on conductor AC resistance and inductance (skin effect). If this parameter is not checked, the resistance is kept constant at the value specified by the **Conductor DC resistance** parameter and the inductance is kept constant at the value computed in DC, using the **Conductor outside diameter** and the **conductor T/D ratio**. When skin effect is included, the conductor AC resistance and inductance are evaluated considering a hollow conductor with T/D ratio (or solid conductor if  $T/D = 0.5$ ). The T/D ratio is used to evaluate the AC resistance even if the conductor inductance is evaluated from the GMR or from the reactance at one-foot spacing or one-meter spacing. The ground skin effect is always considered and it depends on the ground resistivity.

## **Conductor (bundle) type**

Lists the conductor or bundle types by increasing number, starting from 1 and ending at the value specified in the parameter **Number of conductor types or bundle types**. You cannot change this value.

## **Conductor outside diameter**

Specify the conductor outside diameter in centimeters or inches.

## **Conductor T/D ratio**

Specify the T/D ratio of the hollow conductor, where T is the thickness of conducting material and D is the outside diameter. This parameter can vary between 0 and 0.5. A T/D value of 0.5 indicates a solid conductor. For Aluminum Cable Steel Reinforced (ACSR) conductors, you can ignore the steel core and consider a hollow aluminum conductor (typical T/D ratios comprised between 0.3 and 0.4). The T/D ratio is used to compute the conductor AC resistance when the **Include conductor skin effect** parameter is checked. It is also used to compute the conductor self inductance when the parameter **Conductor internal inductance evaluated from** is set to T/D ratio.

## **Conductor GMR**

This parameter is accessible only when the parameter **Conductor internal inductance evaluated from** is set to Geometric Mean Radius (GMR). Specify the GMR in centimeters or inches. The GMR at 60 Hz or 50 Hz is usually provided by conductor manufacturers. When the parameter **Conductor internal inductance evaluated from** is set to T/D ratio, the value of the corresponding GMR giving the same conductor inductance is displayed. When the parameter **Conductor internal inductance evaluated from** is set to Reactance  $X_a$  at 1-foot spacing or (1-meter spacing), the title of the column changes to the parameter name explained below.

## **Reactance $X_a$ at 1-meter spacing (1-foot spacing)**

This parameter is accessible only when **Conductor internal inductance specified from** is set to Reactance  $X_a$  at 1-meter spacing or (1-foot spacing). Specify the  $X_a$  value in ohms/km or ohms/mile at the specified frequency. The  $X_a$  value at 60 Hz or 50 Hz is usually provided by conductor manufacturers.

## **Conductor DC resistance**

Specify the DC resistance of conductor in ohms/km or ohms/mile.

## **Conductor relative permeability**

Specify the relative permeability  $\mu_r$  of the conducting material.  $\mu_r = 1.0$  for nonmagnetic conductors (aluminum, copper). This parameter is not accessible when the **Include conductor skin effect** parameter is not checked.

## **Number of conductors per bundle**

Specify the number of subconductors in the bundle or 1 for single conductors.

## **Bundle diameter**

Specify the bundle diameter in centimeters or inches. This parameter is not accessible when the **Number of conductors per bundle** is set to 1. When you specify bundled conductors, the subconductors are assumed to be evenly spaced on a circle. If this is not the case, you must enter individual subconductor positions

in the **Line Geometry** table and lump these subconductors together by giving them the same **Phase number** parameter.

**Angle of conductor 1**

Specify an angle in degrees that determines the position of the first conductor in the bundle with respect to a horizontal line parallel to ground. This angle determines the bundle orientation. This parameter is not accessible when the **Number of conductors per bundle** is set to 1.

**Line  
Geometry****Number of phase conductors (bundles)**

Specify the number of phase conductors (single conductors or bundles of subconductors) to be used. This parameter, together with the **Number of ground wires (bundles)** parameter, determines the number of rows of the table of conductors.

**Number of ground wires (bundles)**

Specify the number of ground wires (single conductors or bundles of subconductors) to be used. Ground wires are usually not bundled. This parameter, together with the **Number of phase conductors (bundles)** parameter, determines the number of rows of the table of conductors.

In the table of conductors, five rows are visible at a time. If more than five conductors (phase conductors plus ground wires) are specified, a scroll bar appears at the right side of the table to give you access to the different rows of the table.

**Conductor (bundle)**

Lists the conductor or bundle identifiers. Phase conductors are identified p1, p2, ..., pn. Ground wires are identified g1, g2, ..., gn.

**Phase number**

Specify the phase number to which the conductor belongs. Several conductors may have the same phase number. All conductors having the same phase number are lumped together and will be considered as a single equivalent conductor in the R L C matrices. For example, if you want to compute the line parameters of a three-phase line equivalent to a double-circuit line such as the one

represented in the figure named Configuration of a Three-Phase Double-Circuit Line on page 3-18, you specify phase numbers 1, 2, 3 for conductors p1, p2, p3 (circuit 1) and phase numbers 3, 2, 1 for conductors p4, p5, p6 (circuit 2), respectively. If you prefer to simulate this line as two individual circuits and have access to the six phase conductors, you would rather specify phase numbers 1, 2, 3, 6, 5, 4 respectively for conductors p1, p2, p3, p4, p5 and p6.

In three-phase systems, the three phases are usually labeled A, B, C. The correspondence with the phase number is

1, 2, 3, 4, 5, 6, 7, 8, 9,... = A, B, C, A, B, C A, B, C,...

You can also use the phase number to lump conductors of an asymmetrical bundle.

For ground wires, the phase number is forced to zero. All ground wires are lumped with the ground and they do not contribute to the R L C matrix dimensions. If you need to access the ground wire connections in your model, you must specify these ground wires as normal phase conductors and connect them to the ground by yourself.

### **X**

Specify the horizontal position of the conductor in meters or feet. The location of the zero reference position is arbitrary. For a symmetrical line you normally choose  $X = 0$  at the center of the line.

### **Y tower**

Specify the vertical position of the conductor (at the tower) with respect to ground, in meters or feet.

### **Y min**

Specify the vertical position of the conductor with respect to ground at mid span, in meters or feet.

The average height of the conductor (see the figure named Configuration of a Three-Phase Double-Circuit Line on page 3-18) is given by

$$Y_{average} = Y_{min} + \frac{sag}{3} = \frac{2Y_{min} + Y_{tower}}{3}$$

where:  $Y_{tower}$  = height of conductor at tower  
 $Y_{min}$  = height of conductor at mid span  
 $sag = Y_{tower} - Y_{min}$

Instead of specifying two different values for  $Y_{tower}$  and  $Y_{min}$ , you may specify the same  $Y_{average}$  value.

#### Conductor (bundle) type

Specify one of the conductor or bundle type numbers listed in the first column of the table of conductor characteristics.

#### Compute RLC parameters

Computes the RLC parameters. After completion of the parameters computation, results are displayed in a new window entitled **Display RLC Values**.

### Display RLC Values

The frequency and ground resistivity used for evaluation of the RLC matrices are first displayed. Then come the computed RLC parameters.

---

**Note** The R, L, C parameters are always displayed respectively in ohms/km, henries/km, and farads/km, even if the english units have been used to specify the input parameters.

---

If the number of phase conductors is 3 or 6, the symmetrical component parameters are also displayed:

- For a three-phase line (one circuit), R10, L10, and C10 vectors of two values are displayed for positive-sequence and zero-sequence RLC values.

- For a six-phase line (two coupled three-phase circuits), R10, L10 and C10 vectors of five values containing the following RLC sequence parameters: positive-sequence and zero-sequence of circuit 1, mutual zero-sequence between circuit 1 and circuit 2, positive-sequence and zero-sequence of circuit 2.

The **Display RLC Values** window also allows you to download parameters into your workspace and/or into your transmission line models.

### **Send RLC parameters to workspace**

Sends the three RLC matrices as well as the symmetrical component parameters in the MATLAB workspace. The following variables are created in your workspace: R\_matrix, L\_matrix, C\_matrix, and R10, L10, C10 for symmetrical components.

### **Send RLC parameters to block**

Sends the RLC parameters into one of the following three blocks that you have previously selected in your model: the Distributed Parameter Line block (either matrices or sequence RLC parameters), the single-phase PI Section Line block (one dimension matrix required) or the Three-Phase PI Section Line block (sequence components only).

### **Selected block**

Clicking this button confirms the block selection. The name of the selected block appears in the left window.

### **RLC matrices sequences**

Downloads either RLC matrices or RLC sequence parameters into the selected block.

### **Create a report**

Creates a file XXX.rep containing the line input parameters and the computed RLC parameters. The MATLAB editor opens to display the contents of the XXX.rep file.

### **Close**

Closes the **Display RLC Values** window.



## Save/Load

You can save and reload your line data. You can also load typical line data provided with SimPowerSystems software.

### Save

Saves your line data by generating a `.mat` file that contains the GUI information and the line data.

### Load

Opens a window where you have to select either **Typical line data** (examples of line configurations provided with SimPowerSystems software) or **User defined line data** (your own line data). A browser then opens for selecting the desired `.mat` file.

## Typical Line Data

In the **Load** menu, selecting **Typical line data** allows you to load one of the following line configurations:

Line_25kV_4wires.mat	25-k V, three-phase distribution feeder with accessible neutral conductor.
Line_315kV_2circ.mat	315-k V, three-phase, double-circuit line using bundles of two conductors. Phase numbering is set to obtain the RLC parameters of the two individual circuits (six-phase line).
Line_450kV.mat	Bipolar +/-450-k V DC line using bundles of four conductors.
Line_500kV_2circ.mat	500-k V, three-phase, double-circuit line using bundles of three conductors. Phase numbering is set to obtain the RLC parameters of the three-phase line circuit equivalent to the two circuits connected in parallel.
Line_735kV.mat	735-k, V three-phase, line using bundles of four conductors.

## Examples

The following two examples illustrate the inputs and outputs of the power\_lineparam GUI.

### Example 1

The first case is an academic example. It uses a simple line consisting of two conductors spaced by 1 meter at an average height of 8 meters above a perfect ground (ground resistivity  $\rho_g = 0$ ). The two conductors are solid aluminum conductors (resistivity  $\rho_c = 28.3 \cdot 10^{-9} \Omega \cdot \text{m}$  at  $20^\circ \text{C}$ ) having a 15-mm diameter.

The DC resistance per km of each conductors is

$$r = \frac{\rho_c \cdot l}{A} = \frac{28.3 \times 10^{-9} \times 1000}{\pi \cdot \left(\frac{15 \times 10^{-3}}{2}\right)^2} = 0.1601 \Omega/\text{km}$$

As ground is supposed to be perfect, the off diagonal terms of the R matrix are zero and the diagonal terms represent the conductor resistances:

$$R = \begin{bmatrix} 0.1601 & 0 \\ 0 & 0.1601 \end{bmatrix} \Omega/\text{km}$$

For the solid conductors, the GMR is

$$GMR = r \cdot e^{-1} r^{1/4} = \frac{1.5}{2} e^{-1/4} = 0.5841 \text{ cm}$$

The self and mutual inductances are computed as follows. The  $\Delta L$  correction terms are ignored because ground resistivity is zero.

$$L_{11} = L_{22} = \frac{\mu_0}{2\pi} \cdot \log \frac{2h_i}{GMR} = 2 \times 10^{-4} \log \frac{2 \times 8}{0.5841 \times 10^{-2}} = 1.583 \times 10^{-3} \text{ H/km}$$

$$L_{12} = L_{21} = \frac{\mu_0}{2\pi} \log \frac{D_{12}}{d_{12}} = 2 \times 10^{-4} \log \frac{\sqrt{16^2 + 1}}{1} = 0.5549 \times 10^{-3} \text{ H/km}$$

$$L = \begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix} = \begin{bmatrix} 1.583 \times 10^{-3} & 0.5549 \times 10^{-3} \\ 0.5549 \times 10^{-3} & 1.583 \times 10^{-3} \end{bmatrix} \text{ H/km}$$

The self and mutual capacitances are computed as follows:

$$P_{11} = P_{22} = \frac{1}{2\pi\epsilon_o} \log \frac{2h}{r_i} = 1.7975 \times 10^7 \log \frac{2 \times 8}{0.75 \times 10^{-2}} = 1.3779 \times 10^8 \text{ km/F}$$

$$P_{12} = P_{21} = \frac{1}{2\pi\epsilon_o} \log \frac{D_{12}}{d_{12}} = 1.7975 \times 10^7 \log \frac{\sqrt{16^2 + 1}}{1} = 4.9872 \times 10^7 \text{ km/F}$$

$$C = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix}^{-1} = \begin{bmatrix} 8.352 \times 10^{-9} & -3.023 \times 10^{-9} \\ -3.023 \times 10^{-9} & 8.352 \times 10^{-9} \end{bmatrix} \text{ F/km}$$

Enter the line parameters in the power\_lineparam GUI as shown below. Make sure that the specified frequency is 50 Hz and select T/D ratio for computing the line inductance. Do not check **Include conductor skin effect**.

# power\_lineparam

Power\_lineparam. Line Data of example1\_doc.mat

Units: metric  
Frequency (Hz): 50  
Ground resistivity (ohm.m): 0

Comments:  
Example 1  
Two 15mm diameter, solid copper wires spaced by 1 meter, at 8 meters above a perfectly conducting ground.

Line Geometry

Number of phase conductors (bundles): 2  
Number of ground wires (bundles): 0

Conductor (bundle)	Phase number	X (m)	Y tower (m)	Y min (m)	Conductor (bundle) type
p 1	1	0	8	8	1
p 2	2	1	8	8	1
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-

Conductor and Bundle Characteristics

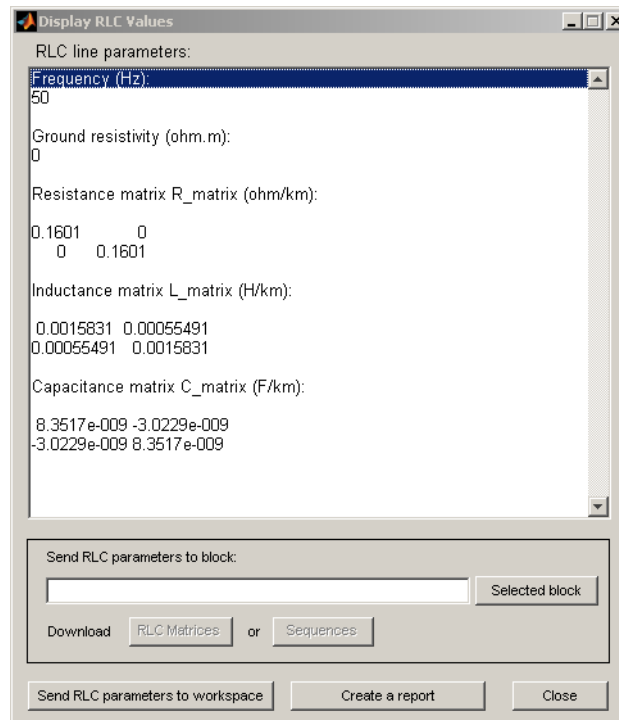
Number of conductor types or bundle types: 1  
Conductor internal inductance evaluated from: T.D ratio  
 Include conductor skin effect

Conductor (bundle) type	Conductor outside diameter (cm)	Conductor T.D ratio	Conductor GMR (cm)	Conductor DC resistance (Ohm/km)	Conductor relative permeability	Number of conductors per bundle	Bundle diameter (cm)	Angle of conductor 1 (degrees)
1	1.5	0.5	0.584335	0.1601	1	1	0	0
-	-	-	-	-	-	-	-	-

Load Save Compute RLC line parameters Help Close

Notice that the displayed GMR value (0.58433 cm) is the GMR value that should be used to include the change of conductor inductance due to frequency. This GMR value is slightly higher than the theoretical DC value (0.5841 cm). This 0.04% increase is due to skin effect at 50 Hz which produces a non uniform current distribution. In our case, the line parameters will be evaluated in DC because we are not including the skin effect.

Click **Compute RLC Parameters**. A new window **Display RLC Values** opens. Compare the RLC matrices with their theoretical values.



The PI model for a 1-km line is obtained from the RLC matrices. The PI RLC values are deduced from the self and mutual terms of the RLC matrices, as explained below. Subscript *s* and *m* designate the self and mutual terms in the RLC matrices.

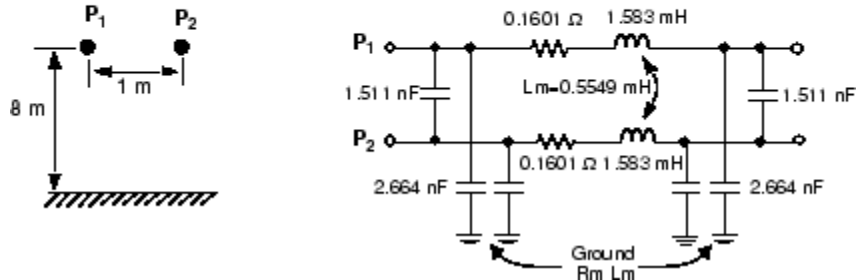
# power\_lineparam

$$R_{p1}=R_{p2} = R_s = 0.1601 \Omega/\text{km}; \quad L_{p1}=L_{p2} = L_s = 1.583 \text{ mH}/\text{km}$$

$$C_{p1}= C_{p2}= C_s + C_m = 8.352 - 3.023 = 5.329 \text{ nF}/\text{km}$$

(2.664 nF at each end of PI section)

$$C_{p1p2} = - C_m = 3.023 \text{ nF}/\text{km} \quad (1.511 \text{ nF at each end of PI section})$$



You can also vary the ground resistivity and the frequency and observe their impact on the resistance and inductance of the conductor and of the ground return.

Vary the ground resistivity from zero to 10000  $\Omega \cdot \text{m}$  while keeping the frequency constant at 50 Hz. You should get values listed in the table below. The expressions  $R_s$ - $R_m$  and  $L_s$ - $L_m$  represent respectively the resistance and the inductance of the conductor, whereas  $R_m$  and  $L_m$  are the resistance and the inductance of the ground return.

### Impact of Ground Resistivity (Frequency = 50 Hz; Skin Effect Not Included)

Ground Resistivity (W.m)	Conductor $R_s$ - $R_m$ (W/km)	Ground $R_m$ (W/km)	Conductor $L_s$ - $L_m$ (mH/km)	Ground $L_m$ (mH/km)
0	0.1601	0	1.028	0.5549
10	0.1601	0.04666	1.029	1.147
100	0.1601	0.04845	1.029	1.370
10 000	0.1601	0.04925	1.029	1.828

When the ground resistivity varies in a normal range (between 10  $\Omega\cdot\text{m}$  for a humid soil and 10 000  $\Omega\cdot\text{m}$  for a dry rocky ground), the ground resistance remains almost constant at 0.05  $\Omega/\text{km}$ , whereas its inductance increases from 1.15 mH/km to 1.83 mH/km.

Now select **Include conductor skin effect** and repeat computation with different frequencies ranging from 0.05 Hz to 50 kHz, while keeping a ground resistivity of 100  $\Omega\cdot\text{m}$ .

### Impact of Frequency (Ground Resistivity = 100 $\Omega\cdot\text{m}$ ; with Conductor Skin Effect)

Frequency (Hz)	Conductor Rs-Rm (W/km)	Ground Rm (W/km)	Conductor Ls-Lm (mH/km)	Ground Lm (mH/km)
0.05	0.1601	4.93e-5	1.029	2.058
50	0.1606	0.04844	1.029	1.370
500	0.2012	0.4666	1.022	1.147
5000	0.5442	4.198	0.9944	0.9351
50 000	1.641	32.14	0.9836	0.7559

This table shows that frequency has a very large impact on ground resistance and much lower influence on ground inductance. Because of skin effect in the ground, when frequency increases, the ground current flows closer to the surface, reducing the equivalent section of the ground conductor and thus increasing its resistance. As ground current travels at a lower depth at high frequencies, this also means that the loop inductance of conductor plus ground return (or self inductance  $L_s$ ) decreases.

Because of conductor skin effect, frequency has a noticeable impact on conductor resistance from a few hundreds of hertz but a negligible impact on conductor inductance. At nominal system frequency (50 Hz or 60 Hz), the increase of conductor resistance with respect to DC resistance (0.1601  $\Omega/\text{km}$ ) is only 0.3%.

# power\_lineparam

## Example 2

This example corresponds to a 500-kV, three-phase, double-circuit line. Using the **Load** button, load the `Line_500kV_2circ.mat` line configuration saved in the typical line data. The `power_lineparam` GUI is shown below:

The screenshot shows the `Power_lineparam` GUI window titled "Power\_lineparam. Line Data of Line\_500kV\_2circ.mat".

**Units:** metric

**Frequency (Hz):** 60

**Ground resistivity (ohm.m):** 100

**Comments:**  
Example of a 500-kV three-phase, double-circuit line. 6 bundles of 3 ACSR conductors + 2 steel ground wires.  
To obtain the (6x6) R L C matrices as well as sequence parameters for the two individual circuits, change the "Phase number" parameters of phase conductors p4, p5, p6 (circuit 2), respectively to 6, 5, 4.

**Line Geometry**

Number of phase conductors (bundles): 6

Number of ground wires (bundles): 2

Conductor (bundle)	Phase number	X (m)	Y tower (m)	Y min (m)	Conductor (bundle) type
p 1	1	-8.5	46.4	34.6	1
p 2	2	-14.4	35.2	23.4	1
p 3	3	-8.5	24	12.2	1
p 4	3	8.5	46.4	34.6	1
p 5	2	14.4	35.2	23.4	1

**Conductor and Bundle Characteristics**

Number of conductor types or bundles types: 2

Conductor internal inductance evaluated from: T/D ratio

Include conductor skin effect

Conductor (bundle) type	Conductor outside diameter (cm)	Conductor T/D ratio	Conductor GMR (cm)	Conductor DC resistance (Ohm/km)	Conductor relative permeability	Number of conductors per bundle	Bundle diameter (cm)	Angle of conductor 1 (degrees)
1	3.1293	0.375	1.25602	0.05208	1	3	57.735	30
2	0.9525	0.5	0.370904	4.102	1	1	0	0

Buttons: Load, Save, Compute RLC Parameters, Help, Close

Power is transmitted over six phase conductors forming the two three-phase circuits. The line is protected against lightning by two ground wires. The phase conductors use bundles of three subconductors. Subconductors are located at the top of an equilateral triangle of 50 cm side, corresponding to a 57.735 cm bundle diameter. This



line configuration corresponds to the one shown in the figure named Configuration of a Three-Phase Double-Circuit Line on page 3-18.

Phase numbering has been set to obtain the line parameters of the three-phase line equivalent to the two circuits connected in parallel. Click **Compute RLC Parameters** to display the RLC matrices and sequence parameters.

The positive-sequence and zero-sequence parameters of the transposed line are displayed in the **Display Results** window in the R10 and L10 vectors:

$$R1 = 0.009009 \text{ } \Omega/\text{km} \quad R0 = 0.2556 \text{ } \Omega/\text{km}$$

$$L1 = 0.4408 \text{ mH/km} \quad L0 = 2.601 \text{ mH/km}$$

$$C1 = 25.87 \text{ nF/km} \quad C0 = 11.62 \text{ nF/km}$$

You can also get the parameters of the two individual circuits and have access to the six phase conductors. Change the phase numbers of conductors p4, p5, and p6 (circuit 2) to 6, 5, 4, respectively. The positive-sequence, zero-sequence and mutual zero-sequence parameters of the transposed line are listed below:

$$R1 = 0.01840 \text{ } \Omega/\text{km} \quad R0 = 0.2649 \text{ } \Omega/\text{km} \quad R0m = 0.2462 \text{ } \Omega/\text{km}$$

$$L1 = 0.9296 \text{ mH/km} \quad L0 = 3.202 \text{ mH/km} \quad L0m = 2.0 \text{ mH/km}$$

$$C1 = 12.57 \text{ nF/km} \quad C0 = 7.856 \text{ nF/km} \quad C0m = -2.044 \text{ nF/km}$$

As the line is symmetrical, the positive- and zero-sequence parameters for circuit 2 are identical to the parameters of circuit 1.

## References

- [1] Dommel, H., et al., *Electromagnetic Transients Program Reference Manual* (EMTP Theory Book), 1986.
- [2] Carson, J. R., "Wave Propagation in Overhead Wires with Ground Return," *Bell Systems Technical Journal*, Vol. 5, pp 539-554, 1926.

## power\_lineparam

---

### **See Also**

Powergui, Distributed Parameter Line, PI Section Line, Three-Phase  
PI Section Line

**Purpose**

Compute state-space model of linear electrical circuit

**Synopsis**

You must call `power_statespace` with a minimum of seven input arguments.

```
[A,B,C,D,states,x0,x0sw,r1sw,u,x,y,freq,Asw,Bsw,Csw,Dsw,Hlin] =
power_statespace(r1c,switches,source,line_dist,yout,y_type,unit
)
```

You can also specify optional arguments. To use these optional arguments, the number of input arguments must be 12, 13, 14 or 16.

```
[A,B,C,D,states,x0,x0sw,r1sw,u,x,y,freq,Asw,Bsw,Csw,Dsw,Hlin] =
power_statespace(r1c,switches,source,line_dist,yout,y_type,unit
,
net_arg1,net_arg2,net_arg3,...,netsim_flag,fid_outfile,
freq_sys,ref_node,vary_name,vary_val)
```

**Description**

The `power_statespace` command computes the state-space model of a linear electrical circuit expressed as

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

where  $x$  is the vector of state-space variables (inductor currents and capacitor voltages),  $u$  is the vector of voltage and current inputs, and  $y$  is the vector of voltage and current outputs.

When you build a circuit from SimPowerSystems blocks of the **powerlib** library, `power_statespace` is automatically called by the `power_analyze` command. `power_statespace` is also available as a stand-alone command for expert users. This allows you to generate state-space models without using the SimPowerSystems block modeling interface and to access options that are not available through **powerlib**. For example, using `power_statespace`, you can model transformers and mutual inductances with more than three windings.

The linear circuit can contain any combination of voltage and current sources, RLC branches, multiwinding transformers, mutually coupled inductances, and switches. The state variables are inductor currents and capacitor voltages.

The state-space representation (matrices A,B,C,D, and vector  $x_0$ ) computed by `power_statespace` can then be used in a Simulink system, via a State-Space block, to perform simulation of the electrical circuit (see “Example” on page 3-54). Nonlinear elements (mechanical or power electronic switches, transformer saturation, machines, distributed parameter lines, etc.) can be connected to the linear circuit.

These Simulink models are interfaced with the linear circuit through voltage outputs and current inputs of the state-space model. You can find the models of the nonlinear elements provided with SimPowerSystems software in the **powerlib\_models** library (see Improving Simulation Performance).

### Input Arguments

The number of input arguments must be 7, 12, 13, 14, or 16. Arguments 8 to 16 are optional. The first seven arguments that must be specified are

- **r1c**: Branch matrix specifying the network topology as well as the resistance R, inductance L, and capacitance C values. See format below.
- **switches**: Switch matrix. Specify an empty variable if no switches are used. See format below.
- **source**: Source matrix specifying the parameters of the electrical voltage and current sources. Specify an empty variable if no sources are used. See format below.
- **line\_dist**: Distributed parameter line matrix. Specify an empty variable if no distributed lines are used. See format below.
- **yout**: String matrix of output expressions. See format below.
- **y\_type**: Integer vector indicating output types (0 for voltage output, 1 for current output).

- **unit**: String specifying the units to be used for R, L, and C values in the `rlc` matrix. If `unit = 'OHM'`, R L C values are specified in ohms  $\Omega$  at the fundamental frequency specified by `freq_sys` (default value is 60 Hz). If `unit = 'OMU'`, R L C values are specified in ohms ( $\Omega$ ), millihenries (mH), and microfarads ( $\mu\text{F}$ ).

The last nine arguments are optional. The first three are used to pass arguments from the `power_analyze` command. Hereafter, only the arguments to be specified when `power_statespace` is used as a stand-alone command are described:

- **net\_arg1, net\_arg2, net\_arg3**: Used to pass arguments from `power_analyze`. Specify an empty variable `[]` for each of these arguments.
- **netsim\_flag**: Integer controlling the messages displayed during the execution of `power_statespace`. Default value is 0.  
  
If `netsim_flag = 0`, the version number, number of states, inputs, outputs, and modes are displayed. Output values are displayed in polar form for each source frequency.  
  
If `netsim_flag = 1`, only version number, number of states, inputs, and outputs are displayed.  
  
If `netsim_flag = 2`, no message is displayed during execution.
- **fid\_outfile**: File identifier of the `power_statespace` output file containing parameter values, node numbers, steady-state outputs, and special messages. Default value is 0.
- **freq\_sys**: Fundamental frequency (Hz) considered for specification of  $X_L$  and  $X_C$  reactances if `unit` is set to `'OHM'`. Default value is 60 Hz.
- **ref\_node**: Reference node number used for ground of PI transmission lines. If -1 is specified, the user is prompted to specify a node number.
- **vary\_name**: String matrix containing the symbolic variable names used in output expressions. These variables must be defined in your MATLAB workspace.

## Output Arguments

- `vary_val`: Vector containing the values of the variable names specified in `vary_name`.
- `A,B,C,D`: state-space matrices of the linear circuit with all switches open.

`A(nstates, nstates) , B(nstates, ninput),`  
`C(noutput, nstates) , D(noutput, ninput),`

where `nstates` is the number of state variables, `ninput` is the number of inputs, and `noutput` is the number of outputs.

- `states`: String matrix containing the names of the state variables. Each string has the following format:

Inductor currents: `I1_bxx_nzz1_zz2`

Capacitor voltages: `Uc_bxx_nzz1_zz2`

where

`xx` = branch number

`zz1` = first node number of the branch

`zz2` = second node number of the branch

The last lines of the `states` matrix, which are followed by an asterisk, indicate inductor currents and capacitor voltages that are not considered as state variables. This situation arises when inductor currents or capacitor voltages are not independent (inductors forming a cut set – for example, inductors connected in series – or capacitors forming a loop). The currents and voltages followed by asterisks can be expressed as a linear combination of the other state variables:

- `x0`: Column vector of initial values of state variables considering the open or closed status of switches.
- `x0sw`: Vector of initial values of switch currents.

- `r1sw`: Matrix (`nswitch,2`) containing the R and L values of series switch impedances in ohms ( $\Omega$ ) and henries (H). `nswitch` is the number of switches in the circuit.
- `u, x, y`: Matrices `u(ninput,nfreq)`, `x(nstates,nfreq)`, and `y(noutput,nfreq)` containing the steady-state complex values of inputs, states, and outputs. `nfreq` is the length of the `freq` vector. Each column corresponds to a different source frequency, as specified by the next argument, `freq`.
- `freq`: Column vector containing the source frequencies ordered by increasing frequency.
- `Asw, Bsw, Csw, Dsw`: State-space matrices of the circuit including the closed switches. Each closed switch with an internal inductance adds one extra state to the circuit.
- `Hlin`: Three-dimensional array (`nfreq, noutput, ninput`) of the `nfreq` complex transfer impedance matrices of the linear system corresponding to each frequency of the `freq` vector.

### Format of the RLC Input Matrix

Two formats are allowed:

- Six columns: Implicit branch numbering. Branch numbers correspond to the RLC line numbers.
- Seven columns: Explicit branch numbering. Branch number `Nobr` is assigned by the user.

Each line of the RLC matrix must be specified according to the following format.

[`node1, node2, type, R, L, C, Nobr`] for RLC branch or line branch

[`node1, node2, type, R, L, C, Nobr`] for transformer magnetizing branch

[`node1, node2, type, R, L, U, Nobr`] for transformer winding

[`node1, node2, type, R, L, U, Nobr`] for mutual inductances

- **node1**: First node number of the branch. The node number must be positive or zero. Decimal node numbers are allowed.
- **node2**: Second node number of the branch. The node number must be positive or zero. Decimal node numbers are allowed.
- **type**: Integer indicating the type of connection of RLC elements, or, if negative, the transmission line length:

**type** = 0: Series RLC element

**type** = 1: Parallel RLC element

**type** = 2: Transformer winding

**type** = 3: Coupled (mutual) winding

If **type** is negative, the transmission line is modeled by a PI section of length  $|\text{type}|$ . See details below.

For a mutual inductor or a transformer having  $N$  windings,  $N+1$  consecutive lines must be specified in RLC matrix:

- 1**  $N$  lines with **type** = 2 or **type** = 3; (one line per winding). Each line specifies  $R/L/U$  or  $R/Xl/Xc$  where  $[R/L, R/Xl =$  winding resistance and leakage reactance for a transformers or winding resistance and self reactance for mutually coupled windings.  $U$  is the nominal voltage of transformer winding (specify 0 if **type** = 3).
- 2** One extra line with **type** = 1 for the magnetizing branch of a transformer (parallel  $Rm/Lm$  or  $Rm/Xm$ ) or one line with **type** = 0 for a mutual impedance (series  $Rm/Lm$  or  $Rm/Xm$ ).

For a transformer magnetizing branch or a mutual impedance, the first node number is an internal node located behind the leakage reactance of the first winding. The second node number must be the same as the second node number of the first winding.

To model a saturable transformer, you must use a nonlinear inductance instead of the linear inductance simulating the reactive losses. Set



the  $L_m/X_m$  value to 0 (no linear inductance) and use the Saturable Transformer block, set with proper flux-current characteristics.

This block can be found in the **powerlib\_models/Continuous** library. It must be connected to the linear part of the system (State-Space block or S-function) between a voltage output (voltage across the magnetizing branch) and a current input (current source injected into the transformer internal node). See the “Example” on page 3-54.

If type is negative, its absolute value specifies the length (km) of a transmission line simulated by a PI section. For a transmission line, the R/L/C or R/Xl/Xc values must be specified in  $\Omega/\text{km}$ , mH/km, and  $\mu\text{F}/\text{km}$ , or in  $\Omega/\text{km}$ .

Parameter	Description
R	Branch resistance ( $\Omega$ )
Xl	Branch inductive reactance ( $\Omega$ at <code>freq_sys</code> ) or transformer winding leakage reactance ( $\Omega$ at <code>freq_sys</code> )
L	Branch inductance (mH)
Xc	Branch capacitive reactance ( $\Omega$ at <code>freq_sys</code> ). The negative sign of Xc is optional.
C	Capacitance ( $\mu\text{F}$ )
U	Nominal voltage of transformer winding. The same units (volts or kV) must be used for each winding. For a mutual inductance ( <code>type=3</code> ), this value must be set to zero.

Zero value for R, L or Xl, C or Xc in a series or parallel branch indicates that the corresponding element does not exist.

The following restrictions apply for transformer winding R-L values. Null values are not allowed for secondary impedances if some transformer secondaries form loops (as in a three-phase delta connection). Specify a very low value for R or L or both (e.g.,  $1\text{e-}6$  pu

## Format of the Source Input Matrix

based on rated voltage and power) to simulate a quasi-ideal transformer. The resistive and inductive parts of the magnetizing branch can be set to infinite (no losses; specify  $X_m = R_m = \text{inf}$ ).

Three formats are allowed:

- Five columns: All sources are generating the same frequency specified by `freq_sys`.
- Six columns: The frequency of each source is specified in column 6.
- Seven columns: The seventh column is used to specify the type of nonlinear element modeled by the current source.

Each line of the source matrix must be specified according to the following format:

```
[ node1, node2, type, amp, phase, freq, model ]
```

- `node1, node2`: Node numbers corresponding to the source terminals. These are the polarity conventions:
  - Voltage source: `node1` is the positive terminal.
  - Current source: Positive current flowing from `node1` to `node2` inside the source.
- `type`: Integer indicating the type of source: 0 for voltage source, 1 for current source.
- `amp`: Amplitude of the AC or DC voltage or current (V or A).
- `phase`: Phase of the AC voltage or current (degree).
- `freq`: Frequency (Hz) of the generated voltage or current. Default value is 60 Hz. For a DC voltage or current source, specify `phase = 0` and `freq = 0`. `amp` can be set to a negative value. The generated signals are  
$$\text{amp} * \sin(2\pi * \text{freq} * t + \text{phase})$$
 for AC, `amp` for DC.

- **model1:** Integer specifying the type of nonlinear element modeled by the current source (saturable inductance, thyristor, switch,...). Used by `power_analyze` only.

### Order in Which Sources Must Be Specified

The commands that compute the state-space representation of a system expect the sources in a certain order. You must respect this order in order to obtain correct results. You must be particularly careful if the system contains any switches. This is the proper ordering of sources:

- 1** The currents from all switches that have a null inductance ( $L_{on} = 0$ ), if any.
- 2** The currents from all nonlinear models that have a finite inductance (switches with  $L_{on} > 0$ , the magnetizing inductance in saturable transformers, etc.), if any.
- 3** All other voltage and current sources in any order, if any.

Refer to the Example section below for an example illustrating proper ordering of sources for a system containing nonlinear elements.

### Format of the Switches Input Matrix

Switches are nonlinear elements simulating mechanical or electronic devices such as circuit breakers, diodes, or thyristors. Like other nonlinear elements, they are simulated by current sources driven by the voltage appearing across their terminals. Therefore, they cannot have a null impedance. They are simulated as ideal switches in series with a series R-L circuit. Various models of switches (circuit breaker, ideal switch, and power electronic devices) are available in the **powerlib\_models** library. They must be interconnected to the linear part of the system through appropriate voltage outputs and current inputs.

The switch parameters must be specified in a line of the switches matrix in seven different columns, according to the following format.

```
[ node1, node2, status, R, L/X1, no_I , no_U ]
```

Parameter	Description
node1, node2	Node numbers corresponding to the switch terminals
status	Code indicating the initial status of the switch at $t = 0$ : 0 = open; 1 = closed
R	Resistance of the switch when closed ( $\Omega$ )
L/X1	Inductance of the switch when closed (mH) or inductive reactance ( $\Omega$ at $\text{freq\_sys}$ )

For these last two fields, you must use the same units as those specified for the RLC matrix. Either field can be set to 0, but not both.

The next two fields specify the current input number and the voltage output number to be used for interconnecting the switch model to the State-Space block. The output number corresponding to the voltage across a particular switch must be the same as the input number corresponding to the current from the same switch (see Example section below):

- **no\_I**: Current input number coming from the output of the switch model
- **no\_U**: Voltage output number driving the input of the switch model

## Format of the Line\_Dist Matrix

The distributed parameter line model contains two parts:

- 1** A linear part containing current sources and resistances that are connected at the line sending and receiving buses together with the linear circuit.
- 2** A nonlinear part available in the Distributed Parameter Line block of the Elements library. This block performs the phase-to-mode transformations of voltage and currents and simulates the transmission delays for each mode. The *distributed\_param\_line* block must be connected to appropriate voltage outputs and current

inputs of the linear part of the system. The line parameters have to be specified in the `line_dist` matrix and also in the Distributed Parameter Line block.

Each row of the `line_dist` matrix is used to specify a distributed parameter transmission line. The number of columns of `line_dist` depends on the number of phases of the transmission line.

For an `nphase` line, the first  $(4 + 3 * nphase + nphase^2)$  columns are used. For example, for a three-phase line, 22 columns are used.

[`nphase`, `no_I`, `no_U`, `length`, `L/Xl`, `Zc`, `Rm`, `speed`, `Ti`]

Parameter Description	
<code>nphase</code>	Number of phases of the transmission line
<code>no_I</code>	Input number in the source matrix corresponding to the first current source <code>Is_1</code> of the line model. Each line model uses $2*nphase$ current sources specified in the source matrix as follows: <code>Is_1</code> , <code>Is_2</code> ,..., <code>Is_nphase</code> for the sending end followed by <code>Ir_1</code> , <code>Ir_2</code> ,..., <code>Ir_nphase</code> for the receiving end.
<code>no_U</code>	Output number of the state-space corresponding to the first voltage output <code>Vs_1</code> feeding the line model. Each line model uses $2*nphase$ voltage outputs in the source matrix as follows: <code>Vs_1</code> , <code>Vs_2</code> ,..., <code>Vs_nphase</code> for the sending end followed by <code>Vr_1</code> , <code>Vr_2</code> ,..., <code>Vr_nphase</code> for the receiving end.
<code>length</code>	Length of the line (km)
<code>Zc</code>	Vector of the <code>nphase</code> modal characteristic impedances ( $\Omega$ )
<code>Rm</code>	Vector of the <code>nphase</code> modal series resistances ( $\Omega/\text{km}$ )

## Format of the Yout Matrix

Parameter	Description
speed	Vector of the nphase modal propagation speeds (km/s)
Ti	Transformation matrix from mode to phase currents such that $I_{\text{phase}} = T_i * I_{\text{mod}}$ . The nphase * nphase matrix must be given in vector format, [col_1, col_2,... col_nphase].

The desired outputs are specified by a string matrix *yout*. Each line of the *yout* matrix must be an algebraic expression containing a linear combination of states and state derivatives, specified according to the following format.

Parameter	Description
Uc_bn	Capacitor voltage of branch <i>n</i>
I1_bn	Inductor current of branch <i>n</i>
dUc_bn	Derivative of Uc_bn or I1_bn
Un, In	Source voltage or current specified by line <i>n</i> of the source matrix
U_nx1_x2	Voltage between nodes x1 and x2 = Ux1 -Ux2
I_bn	Current in branch <i>n</i> flowing from node1 to node2 (See format of RLC matrix). For a parallel RLC branch, I_bn corresponds to the total current IR + IL + IC.
I_bn_nx	Current flowing into node x of a PI transmission line specified by line <i>n</i> of the RLC matrix. This current includes the series inductive branch current and the capacitive shunt current.

Each output expression is built from voltage and current variable names defined above, their derivatives, constants, other variable names, parentheses and operators (+ - \* / ^), in order to form a valid MATLAB expression. For example

```
yout =
char(['R1*I_b1+Uc_b3-L2*dI1_b2', 'U_n10_20', 'I2+3*I_b5' ]);
```

If variable names are used (R1 and L2 in the above example), their names and values must be specified by the two input arguments `vary_name` and `vary_val`.

### Sign Conventions for Voltages and Currents

Parameter	Sign Convention
$I_{bn}$ , $I_{l_{bn}}$ , $I_n$	Branch current, inductor current of branch $n$ , or current of source $\#n$ is oriented from node1 to node2
$I_{bn_{nx}}$	Current at one end (node $x$ ) of a PI transmission line. If $x = \text{node1}$ , the current is entering the line. If $x = \text{node2}$ , the current is leaving the line.
$U_{c_{bn}}$ , $U_n$	Voltage across capacitor or source voltage ( $U_{\text{node1}} - U_{\text{node2}}$ )
$U_{nx1_{x2}}$	Voltage between nodes $x1$ and $x2 = U_{x1} - U_{x2}$ . Voltage of node $x1$ with respect to node $x2$ .

### Order in Which Outputs Must Be Specified

The commands that compute the state-space representation of a system expect the outputs to be in a certain order. You must respect this order in order to obtain correct results. You must be particularly careful if the system contains any switches. The following list gives the proper ordering of outputs:

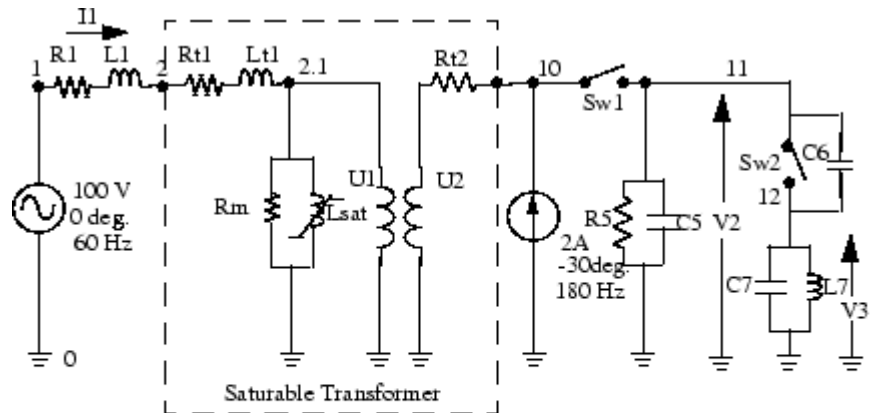
- 1 The voltages across all switches that have a null inductance ( $L_{on} = 0$ ), if any
- 2 The currents of all switches that have a null inductance ( $L_{on} = 0$ ), if any, in the same order as the voltages above

- 3 The voltages across all nonlinear models that have a finite inductance (switches with  $L_{on} > 0$ , the magnetizing inductance in saturable transformers, etc.)
- 4 All other voltage and current measurements that you request, in any order

Refer to the Example section below for an example illustrating proper ordering of outputs for a system containing nonlinear elements.

## Example

The following circuit consists of two sources (one voltage source and one current source), two series RLC branches (R1-L1 and C6), two parallel RLC branches (R5-C5 and L7-C7), one saturable transformer, and two switches (Sw1 and Sw2). Sw1 is initially closed whereas Sw2 is initially open. Three measurement outputs are specified (I1, V2, and V3). This circuit has seven nodes numbered 0, 1, 2, 2.1, 10, 11, and 12. Node 0 is used for the ground. Node 2.1 is the internal node of the transformer where the magnetization branch is connected.



$R1 = 0.1 \Omega$        $Rt1 = 0.05 \Omega$ ;  $Lt1 = 1.5 \text{ mH}$ ;  $U1 = 100 \text{ V}$        $C5 = 1 \mu\text{F}$ ;  $R5 = 200 \Omega$   
 $L1 = 1.0 \text{ mH}$        $Rt2 = 0.20 \Omega$ ;  $Lt2 = 0.0 \text{ mH}$ ;  $U2 = 200 \text{ V}$        $C6 = 1 \text{ nF}$   
 $Rm = 1000 \Omega$        $C7 = 2 \mu\text{F}$ ;  $L7 = 0.5 \text{ H}$

Sw1:  $R=0.01 \text{ W}$ ;  $L=0\text{H}$ ; initial state = closed  
 Sw2:  $R=0.1 \text{ W}$ ;  $L=0\text{H}$ ; initial state = open



## Linear State-Space

You can use the `power_statespace` command to find the state-space model of the linear part of the circuit. The nonlinear elements `Sw1`, `Sw2`, and `Lsat` must be modeled separately by means of current sources driven by the voltages appearing across their terminals. Therefore you must provide three additional current sources and three additional voltage outputs for interfacing the nonlinear elements to the linear circuit.

You can find the state-space model of the circuit by entering the following commands in a MATLAB script file. The example is available in the `power_circ2ss.m` file. Notice that an output text file named `power_circ2ss.net` containing information on the system is requested in the call to `power_statespace`.

```
unit='OMU'; % Units = ohms, mH, and uF

rlc=[
%N1 N2 type R L C(uF)/U(V)
1 2 0 0.1 1 0 %R1 L1
2 0 2 0.05 1.5 100 %transfo Wind.#1
10 0 2 0.20 0 200 %transfo Wind.#2
2.1 0 1 1000 0 0 %transfo mag. branch
11 0 1 200 0 1 %R5 C5
11 12 0 0 0 1e-3 %C6
12 0 1 0 500 2 %L7 C7
];

source=[
%N1 N2 type U/I phase freq
10 11 1 0 0 0 %Sw1
11 12 1 0 0 0 %Sw2
2.1 0 1 0 0 0 %Saturation
1 0 0 100 0 60 %Voltage source
0 10 1 2 -30 180 %Current source
];
```

# power\_statespace

---

```
switches=[
%N1 N2 status R(ohm) L(mH) I# U# #
10 11 1 0.01 0 1 1 %Sw1
11 12 0 0.1 0 2 2 %Sw2
];

%outputs
%
% Both switches have Lon=0, so their voltages must be the first
outputs,
% immediately followed by their currents (in the same order as
the voltages).
% The voltage across all nonlinear models that don't have L=0
follow
% (in this case the saturable transformer's magnetizing
inductor).
% The measurements that you request follow, in any order.
%
y_u1='U_n10_11'; %U_Sw1= Voltage across Sw1
y_u2='U_n11_12'; %U_Sw2= Voltage across Sw2
y_i3='I1'; %I1= Switch current Sw1
y_i4='I2'; %I2= Switch current Sw2
y_u5='U_n2.1_0'; %U_sat= Voltage across saturable reactor
y_i6='I_b1'; %I1 measurement
y_u7='U_n11_0'; %V2 measurement
y_u8='U_n12_0'; %V3 measurement

yout=char(y_u1,y_u2,y_i3,y_i4,y_u5,y_i6,y_u7,y_u8); % outputs
y_type=[0,0,1,1,0,1,0,0]; %output types; 0=voltage 1=current

% Open file that contains power_statespace output information
fid=fopen('power_circ2ss.net','w');

[A,B,C,D,states,x0,x0sw,r1sw,u,x,y,freq,Asw,Bsw,Csw,Dsw,Hlin]=
power_statespace(rlc,switches,source,[],yout,y_type,unit,[],[],
[],0,fid);
```

## Command Line Messages

While `power_statespace` is executing, the following messages are displayed.

```
Computing state space representation of linear electrical circuit
(V2.0)...
(4 states ; 5 inputs ; 7 outputs)
```

```
Oscillatory modes and damping factors:
F=159.115Hz zeta=4.80381e-08
```

```
Steady state outputs @ F=0 Hz :
```

```
y_u1= 0Volts
y_u2= 0Volts
y_i3= 0Amperes
y_i4= 0Amperes
y_u5= 0Volts
y_i6= 0Amperes
y_u7= 0Volts
y_u8= 0Volts
```

```
Steady state outputs @ F=60 Hz :
```

```
y_u1 = 0.009999 Volts < 3.168 deg.
y_u2 = 199.4 Volts < -1.148 deg.
y_i3 = 0.9999 Amperes < 3.168 deg.
y_i4 = 0 Amperes < 0 deg.
y_u5 = 99.81 Volts < -1.144 deg.
y_i6 = 2.099 Amperes < 2.963 deg.
y_u7 = 199.4 Volts < -1.148 deg.
y_u8 = 0.01652 Volts < 178.9 deg.
```

```
Steady state outputs @ F=180 Hz :
```

```
y_u1 = 0.00117 Volts < 65.23 deg.
y_u2 = 22.78 Volts < 52.47 deg.
y_i3 = 0.117 Amperes < 65.23 deg.
y_i4 = 0 Amperes < 0 deg.
y_u5 = 11.4 Volts < 53.48 deg.
y_i6 = 4.027 Amperes < 146.5 deg.
```

```
y_u7 = 22.83 Volts < 52.47 deg.  
y_u8 = 0.0522 Volts < 52.47 deg.
```

## State-Space Output

The names of the state variables are returned in the `states` string matrix.

```
states  
states =  
I1_b2_n2_2.1  
Uc_b5_n11_0  
Uc_b6_n11_12  
I1_b7_n12_0  
I1_b1_n1_2*  
Uc_b7_n12_0*
```

Although this circuit contains a total of six inductors and capacitors, there are only four state variables. The names of the state variables are given by the first four lines of the `states` matrix. The last two lines are followed by an asterisk indicating that these two variables are a linear combination of the state variables. The dependencies can be viewed in the output file `power_circ2ss.net`.

```
The following capacitor voltages are dependent:  
Uc_b7_n12_0 = + Uc_b5_n11_0 - Uc_b6_n11_12  
The following inductor currents are dependent:  
I1_b1_n1_2 = + I1_b2_n2_0
```

The A,B,C,D matrices contain the state-space model of the circuit without nonlinear elements (all switches open). The `x0` vector contains the initial state values considering the switch Sw1 closed. The `Asw`, `Bsw`, `Csw`, and `Dsw` matrices contain the state-space model of the circuit considering the closed switch Sw1. The `x0sw` vector contains the initial current in the closed switch.

```
A  
A =
```

```
-4.0006e+05 0 0 0
           0 -4995 0 -499.25
           0 -4992.5 0 4.9925e+05
           0 2 -2 0
```

Asw

Asw =

```
-80.999 -199.99 0 0
4.9947e+05 -5244.7 0 -499.25
4.9922e+05 -5242.1 0 4.9925e+05
           0 2 -2 0
```

The system source frequencies are returned in the `freq` vector.

```
freq
freq =
      0      60     180
```

The corresponding steady-state complex outputs are returned in the (6-by-3) `y` matrix where each column corresponds to a different source frequency.

For example, you can obtain the magnitude of the six voltage and current outputs at 60 Hz as follows.

```
abs(y(:,2))
ans =
    0.0099987
    199.42
    0.99987
     0
    99.808
     2.0993
    199.41
    0.016519
```

The initial values of the four state variables are returned in the `x0` vector. You must use this vector in the State-Space block to start the simulation in steady state.

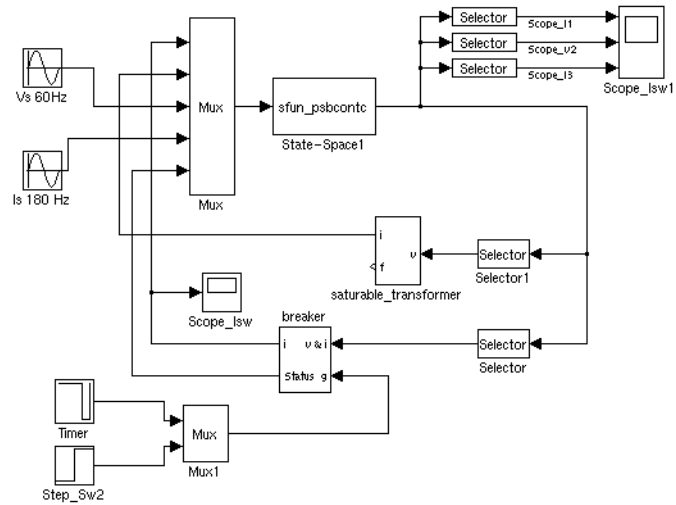
```
x0
x0 =
    2.3302
   14.111
   14.07
   3.1391e-05
```

The initial values of switch currents are returned in `x0sw`. To start the simulation in steady state, you must use these values as initial currents for the nonlinear model simulating the switches.

```
x0sw
x0sw =
    0.16155
    0
```

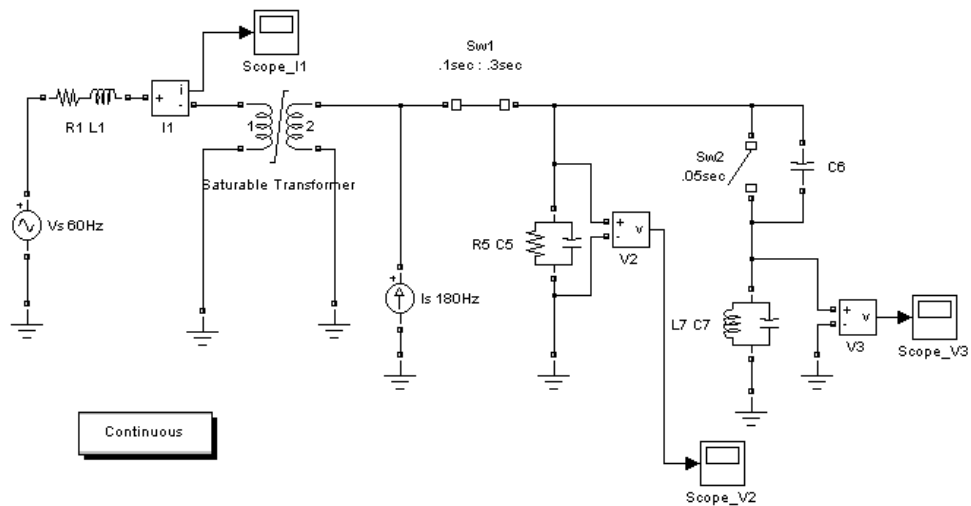
The Simulink diagram of the circuit shown in the following figure is available in the `power_circ2ss_slk` model. If no resistive switches had been used, the linear part of the circuit could have been simulated with the State-Space block of the Simulink/Continuous library. However, as resistive switches are used, the `sfun_psbcontc` S-function is used instead of the State-Space block. This S-function reevaluates the state-space matrices during simulation when the circuit topology is changing (after a switch is opened or closed). Appropriate inputs and outputs are used to connect the switch and saturable reactance models to the linear system. Notice that the status of each switch is fed back from the breaker to the S-function, after the inputs mentioned earlier. You can find the Breaker and Saturable Transformer blocks in the **powerlib\_models/Continuous** library containing all the nonlinear continuous models used by SimPowerSystems software. As the breaker model is vectorized, a single block is used to simulate the two switches Sw1 and Sw2.

If you use the **powerlib** library to build your circuit, the same Simulink system is generated automatically by the `power_analyze` command. The **powerlib** version of this system is also available in the `power_circ2ss_sps` model and is shown below.



**power\_circ2ss\_slk.mdl Example Diagram**

# power\_statespace



**power\_circ2ss\_sps.mdl Example Diagram**

## See Also

[power\\_analyze](#)



# Technical Conventions

---

This appendix describes the two units of measurement used in this manual.

- “International System of Units” on page A-2
- “Per Unit” on page A-3

## International System of Units

This guide uses the International System of Units (SI), as described in the following table.

<b>Quantity</b>	<b>Unit</b>	<b>Symbol</b>
Time	second	s
Length	meter	m
Mass	kilogram	kg
Energy	joule	J
Current	ampere	A
Voltage	volt	V
Active power	watt	W
Apparent power	volt-ampere	VA
Reactive power	var	var
Impedance	ohm	$\Omega$
Resistance	ohm	$\Omega$
Inductance	henry	H
Capacitance	farad	F
Flux linkage	volt-second	V. s
Rotation speed	radians per second revolutions per minute	rad/s rpm
Torque	newton-meter	N.m
Inertia	kilogram-meter <sup>2</sup>	kg.m <sup>2</sup>
Friction factor	newton-meter-second	N.m.s

## Per Unit

### In this section...

“What Is the Per Unit System?” on page A-3

“Example 1: Three-Phase Transformer” on page A-5

“Example 2: Asynchronous Machine” on page A-6

“Base Values for Instantaneous Voltage and Current Waveforms” on page A-8

“Why Use the Per Unit System Instead of the Standard SI Units?” on page A-8

### What Is the Per Unit System?

The per unit system is widely used in the power system industry to express values of voltages, currents, powers, and impedances of various power equipment. It is mainly used for transformers and AC machines.

For a given quantity (voltage, current, power, impedance, torque, etc.) the per unit value is the value related to a base quantity.

$$\text{base value in p.u.} = \frac{\text{quantity expressed in SI units}}{\text{base value}}$$

Generally the following two base values are chosen:

- The base power = nominal power of the equipment
- The base voltage = nominal voltage of the equipment

All other base quantities are derived from these two base quantities. Once the base power and the base voltage are chosen, the base current and the base impedance are determined by the natural laws of electrical circuits.

$$\text{base current} = \frac{\text{base power}}{\text{base voltage}}$$

$$\text{base impedance} = \frac{\text{base voltage}}{\text{base current}} = \frac{(\text{base voltage})^2}{\text{base power}}$$

For a transformer with multiple windings, each having a different nominal voltage, the same base power is used for all windings (nominal power of the transformer). However, according to the above definitions, there are as many base values as windings for voltages, currents, and impedances.

The saturation characteristic of saturable transformer is given in the form of an instantaneous current versus instantaneous flux-linkage curve: [ $i_1$   $\phi_1$ ;  $i_2$   $\phi_2$ ; ... , in  $\phi_{in}$ ].

When the Per Unit system is used to specify the transformer R L parameters, the flux linkage and current in the saturation characteristic must be also specified in pu. The corresponding base values are

$$\text{base instantaneous current} = (\text{base rms current}) \times \sqrt{2}$$

$$\text{base flux linkage} = \frac{(\text{base rms voltage}) \times \sqrt{2}}{2\pi \times (\text{base frequency})}$$

where current, voltage, and flux linkage are expressed respectively in volts, amperes, and volt-seconds.

For AC machines, the torque and speed can be also expressed in pu. The following base quantities are chosen:

- The base speed = synchronous speed
- The base torque = torque corresponding at base power and synchronous speed

$$\text{base torque} = \frac{\text{base power (3 phases) in VA}}{\text{base speed in radians/second}}$$

Instead of specifying the rotor inertia in  $\text{kg}\cdot\text{m}^2$ , you would generally give the inertia constant  $H$  defined as

$$H = \frac{\text{kinetic energy stored in the rotor at synchronous speed in joules}}{\text{machine nominal power in VA}}$$

$$H = \frac{\frac{1}{2} \times J \cdot \omega^2}{P_{nom}}$$

The inertia constant is expressed in seconds. For large machines, this constant is around 3 to 5 seconds. An inertia constant of 3 seconds means that the energy stored in the rotating part could supply the nominal load during 3 seconds. For small machines,  $H$  is lower. For example, for a 3 HP motor, it can be between 0.5 and 0.7 second.

### Example 1: Three-Phase Transformer

Consider, for example, a three-phase two-winding transformer. The following typical parameters could be provided by the manufacturer:

- Nominal power = 300 kVA total for three phases
- Nominal frequency = 60 Hz
- Winding 1: connected in wye, nominal voltage = 25 kV RMS line-to-line  
resistance 0.01 pu, leakage reactance = 0.02 pu
- Winding 2: connected in delta, nominal voltage = 600 V RMS line-to-line  
resistance 0.01 pu, leakage reactance = 0.02 pu
- Magnetizing losses at nominal voltage in % of nominal current:  
Resistive 1%, Inductive 1%

The base values for each single-phase transformer are first calculated:

- For winding 1:

Base power	$300 \text{ kVA}/3 = 100\text{e}3 \text{ VA/phase}$
Base voltage	$25 \text{ kV}/\text{sqrt}(3) = 14434 \text{ V RMS}$

Base current	$100e3/14434 = 6.928 \text{ A RMS}$
Base impedance	$14434/6.928 = 2083 \ \Omega$
Base resistance	$14434/6.928 = 2083 \ \Omega$
Base inductance	$2083/(2\pi*60) = 5.525 \text{ H}$

- For winding 2:

Base power	$300 \text{ kVA}/3 = 100e3 \text{ VA}$
Base voltage	$600 \text{ V RMS}$
Base current	$100e3/600 = 166.7 \text{ A RMS}$
Base impedance	$600/166.7 = 3.60 \ \Omega$
Base resistance	$600/166.7 = 3.60 \ \Omega$
Base inductance	$3.60/(2\pi*60) = 0.009549 \text{ H}$

The values of the winding resistances and leakage inductances expressed in SI units are therefore

- For winding 1:  $R_1 = 0.01 * 2083 = 20.83 \ \Omega$ ;  $L_1 = 0.02 * 5.525 = 0.1105 \text{ H}$
- For winding 2:  $R_2 = 0.01 * 3.60 = 0.0360 \ \Omega$ ;  $L_2 = 0.02 * 0.009549 = 0.191 \text{ mH}$

For the magnetizing branch, magnetizing losses of 1% resistive and 1% inductive mean a magnetizing resistance  $R_m$  of 100 pu and a magnetizing inductance  $L_m$  of 100 pu. Therefore, the values expressed in SI units referred to winding 1 are

- $R_m = 100 * 2083 = 208.3 \text{ k}\Omega$
- $L_m = 100 * 5.525 = 552.5 \text{ H}$

## **Example 2: Asynchronous Machine**

Now consider the three-phase four-pole Asynchronous Machine block in SI units provided in the Machines library of **powerlib**. It is rated 3 HP, 220 V RMS line-to-line, 60 Hz.

The stator and rotor resistance and inductance referred to stator are

- $R_s = 0.435 \Omega$ ;  $L_s = 2 \text{ mH}$
- $R_r = 0.816 \Omega$ ;  $L_r = 2 \text{ mH}$

The mutual inductance is  $L_m = 69.31 \text{ mH}$ . The rotor inertia is  $J = 0.089 \text{ kg}\cdot\text{m}^2$ .

The base quantities for one phase are calculated as follows:

Base power	$3 \text{ HP} \cdot 746 \text{ VA} / 3 = 746 \text{ VA/phase}$
Base voltage	$220 \text{ V} / \sqrt{3} = 127.0 \text{ V RMS}$
Base current	$746 / 127.0 = 5.874 \text{ A RMS}$
Base impedance	$127.0 / 5.874 = 21.62 \Omega$
Base resistance	$127.0 / 5.874 = 21.62 \Omega$
Base inductance	$21.62 / (2\pi \cdot 60) = 0.05735 \text{ H} = 57.35 \text{ mH}$
Base speed	$1800 \text{ rpm} = 1800 \cdot (2\pi) / 60 = 188.5 \text{ radians/second}$
Base torque (3-phase)	$746 \cdot 3 / 188.5 = 11.87 \text{ newton-meters}$

Using the above base values, you can compute the values in per units.

$$R_s = 0.435 / 21.62 = 0.0201 \text{ pu} \quad L_s = 2 / 57.35 = 0.0349 \text{ pu}$$

$$R_r = 0.816 / 21.62 = 0.0377 \text{ pu} \quad L_r = 2 / 57.35 = 0.0349 \text{ pu}$$

$$L_m = 69.31 / 57.35 = 1.208 \text{ pu}$$

The inertia is calculated from inertia  $J$ , synchronous speed, and nominal power.

$$H = \frac{\frac{1}{2} \times J \cdot \omega^2}{P_{nom}} = \frac{\frac{1}{2} \times 0.089 \times (188.5)^2}{3 \times 746} = 0.7065 \text{ seconds}$$

If you open the dialog box of the Asynchronous Machine block in pu units provided in the Machines library of **powerlib**, you find that the parameters in pu are the ones calculated above.

## **Base Values for Instantaneous Voltage and Current Waveforms**

When displaying instantaneous voltage and current waveforms on graphs or oscilloscopes, you normally consider the peak value of the nominal sinusoidal voltage as 1 pu. In other words, the base values used for voltage and currents are the RMS values given above multiplied by  $\sqrt{2}$ .

## **Why Use the Per Unit System Instead of the Standard SI Units?**

Here are the main reasons for using the per unit system:

- When values are expressed in pu, the comparison of electrical quantities with their "normal" values is straightforward.

For example, a transient voltage reaching a maximum of 1.42 pu indicates immediately that this voltage exceeds the nominal value by 42%.

- The values of impedances expressed in pu stay fairly constant whatever the power and voltage ratings.

For example, for all transformers in the 3 kVA to 300 kVA power range, the leakage reactance varies approximately between 0.01 pu and 0.03 pu, whereas the winding resistances vary between 0.01 pu and 0.005 pu, whatever the nominal voltage. For transformers in the 300 kVA to 300 MVA range, the leakage reactance varies approximately between 0.03 pu and 0.12 pu, whereas the winding resistances vary between 0.005 pu and 0.002 pu.

Similarly, for salient pole synchronous machines, the synchronous reactance  $X_d$  is generally between 0.60 and 1.50 pu, whereas the subtransient reactance  $X'_d$  is generally between 0.20 and 0.50 pu.

It means that if you do not know the parameters for a 10 kVA transformer, you are not making a major error by assuming an average value of 0.02 pu for leakage reactances and 0.0075 pu for winding resistances.



The calculations using the per unit system are simplified. When all impedances in a multivoltage power system are expressed on a common power base and on the nominal voltages of the different subnetworks, the total impedance in pu seen at one bus is obtained by simply adding all impedances in pu, without taking into consideration the transformer ratios.



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