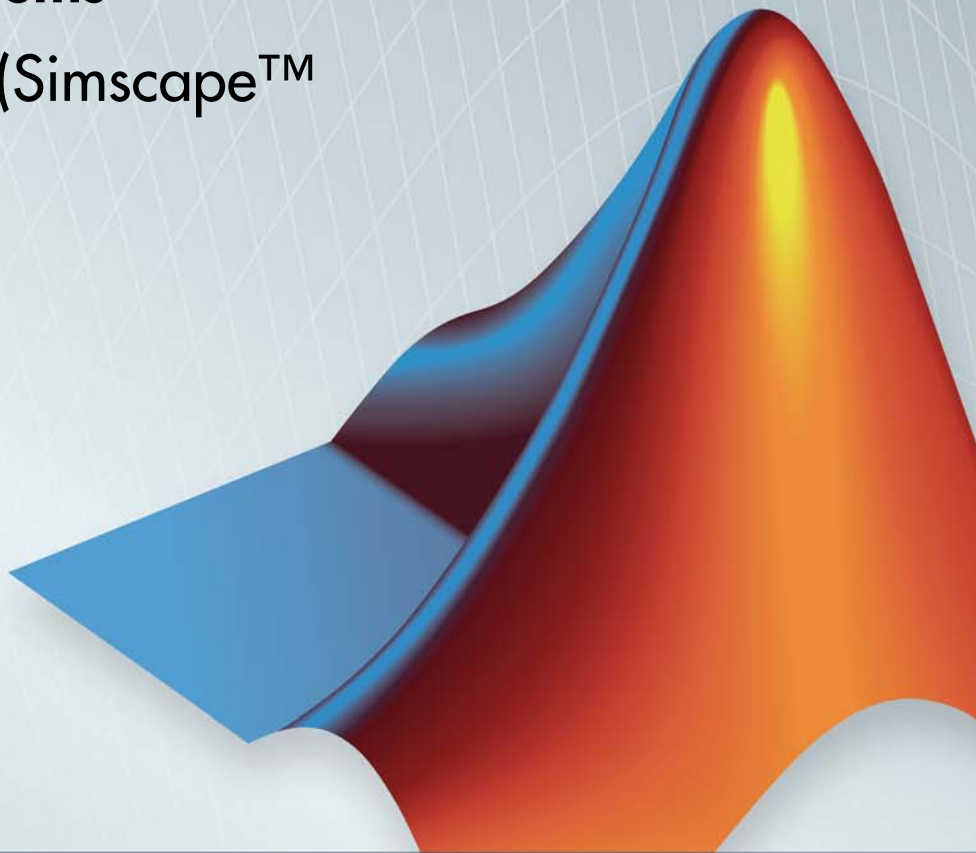


**SimPowerSystems™**

User's Guide (Simscape™  
Components)

**R2014a**



**MATLAB® & SIMULINK®**



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*SimPowerSystems™ User's Guide (Simscape™ Components)*

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# Getting Started

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# SimPowerSystems Product Description

## **Model and simulate electrical power systems**

SimPowerSystems™ provides component libraries and analysis tools for modeling and simulating electrical power systems. The libraries offer models of electrical power components, including three-phase machines, electric drives, and components for applications such as flexible AC transmission systems (FACTS) and renewable energy systems. Harmonic analysis, calculation of total harmonic distortion (THD), load flow, and other key electrical power system analyses are automated.

SimPowerSystems models can be used to develop control systems and test system-level performance. You can parameterize your models using MATLAB® variables and expressions, and design control systems for your electrical power system in Simulink®. You can add mechanical, hydraulic, pneumatic, and other components to your model using Simscape™ and test them together in a single simulation environment. To deploy models to other simulation environments, including hardware-in-the-loop (HIL) systems, SimPowerSystems supports C-code generation.

SimPowerSystems was developed in collaboration with Hydro-Québec of Montreal.

## **Key Features**

- Libraries of application-specific models, including models of common AC and DC electric drives, flexible AC transmission systems (FACTS), and renewable energy systems
- Discretization and phasor simulation modes for faster model execution
- Ideal switching algorithm for accelerated simulation of power electronic devices
- Analysis methods for obtaining state-space representations of circuits and computing load flow for machines
- Basic models for developing key electrical technologies
- Ability to extend component libraries using the Simscape language
- Support for C-code generation



# SimPowerSystems Block Libraries

## Overview of SimPowerSystems Libraries

SimPowerSystems libraries contain two top-level block libraries, representing two different technologies.

### Simscape Components Library

The SimPowerSystems Simscape Component library contains Simscape blocks specifically developed for working with multiphase electrical domains. In addition to the Simscape Foundation domains, the product contains a three-phase electrical domain, and you can use this domain to develop your own custom three-phase blocks with Simscape language. You can also view and customize source for several machine and transformer example blocks provided with the product.

The main Simscape Components library is called **pe\_lib**. It contains Simscape blocks with three-phase and single-phase electrical ports, as well as mechanical rotational and translational ports. These blocks are organized into sublibraries according to their function. You can connect these blocks directly to other Simscape blocks, from the Foundation library or from the other add-on products.

Three-phase electrical ports on Simscape Components blocks are collapsed by default, to support single-line diagrams. You can optionally expand them to separate the phases, for example, if you need to inject a single-line-to-ground fault into your circuit.

### Specialized Technology Library

The SimPowerSystems Specialized Technology library contains models of typical power equipment such as transformers, lines, machines, and power electronics. These models are proven ones coming from textbooks, and their validity is based on the experience of the Power Systems Testing and Simulation Laboratory of Hydro-Québec, a large North American utility located in Canada, and also on the experience of École de Technologie Supérieure and Université Laval. The capabilities of SimPowerSystems software for modeling a typical electrical system are illustrated in example

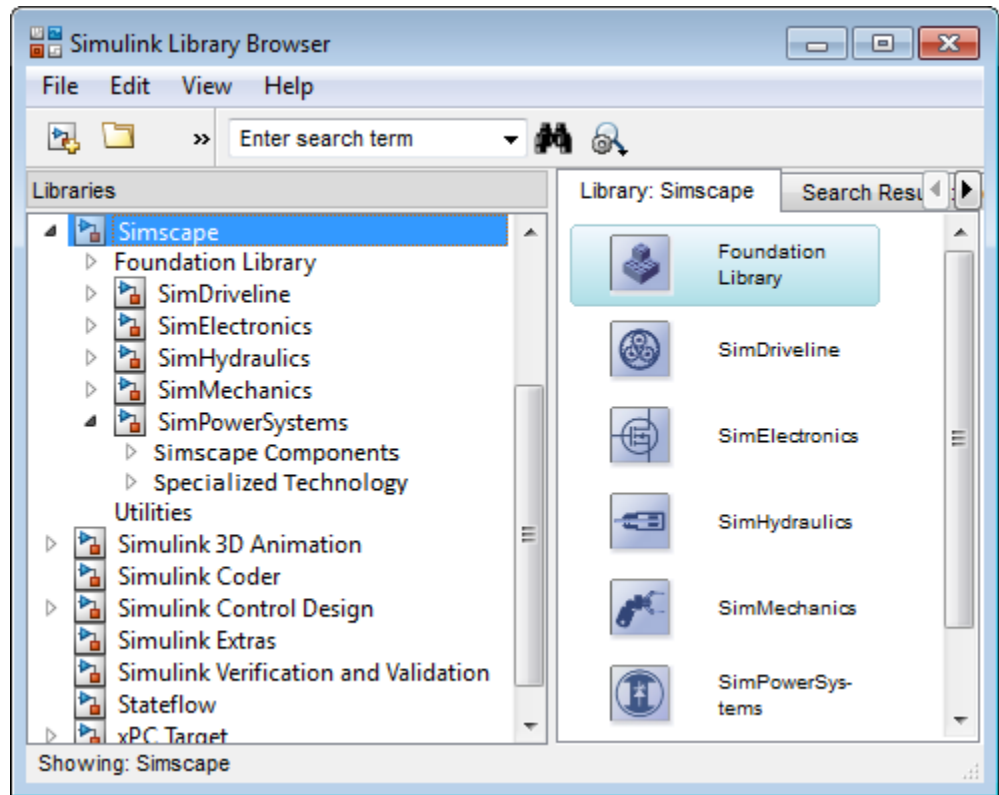
files. For users who want to refresh their knowledge of power system theory, there are also self-learning case studies.

The main Specialized Technology library is called **powerlib**. It contains sublibraries of blocks, organized according to their behavior, as well as the Powergui block that opens a graphical user interface for the steady-state analysis of electrical circuits.

## **Using the Simulink Library Browser to Access the Block Libraries**

You can access SimPowerSystems libraries through the Simulink Library Browser. To display the Library Browser, click the **Simulink Library** button in the MATLAB toolstrip, or click the **Library Browser** button in the Simulink model window.

Alternatively, you can type `simulink` in the MATLAB Command Window. Expand the **Simscape** entry in the contents tree, then expand the **SimPowerSystems** entry.



## Using the Command Prompt to Access the Block Libraries

Another way to access the block libraries is to open them individually by using the command prompt:

- To open just the SimPowerSystems Simscape Components library, type `pe_lib` in the MATLAB Command Window.
- To open just the SimPowerSystems Specialized Technology library, type `powerlib` in the MATLAB Command Window.
- To open the Simscape library (to access the utility blocks, as well as single-phase electrical sources, sensors, and other Foundation library blocks), type `simscape` in the MATLAB Command Window.

- To open the main Simulink library (to access generic Simulink blocks), type `simulink` in the MATLAB Command Window.

## Comparison of Simscape Components and Specialized Technology

SimPowerSystems software includes two technologies and corresponding libraries to model and simulate electrical power systems. You can create and simulate systems using either library. A single SimPowerSystems model can contain components from both libraries. You use electrical ports to connect the components within each technology and, ultimately, use Simulink signals to connect Simscape Components blocks to Specialized Technology blocks.

- Simscape Components libraries uses the full range of Simscape technology, and the component models are written in the Simscape language. You can directly connect these models with the Simscape Foundation library components and with components from other add-on products. You can view and customize the Simscape language source code examples for machines and transformers. Simscape Components models are fully compatible with Simscape technology, including local solver and data logging.

Simscape Components also provides three-phase electrical connection ports, which you can individually expand into separate phases as needed. By default, these three-phase ports are collapsed, to support single-line diagrams.

- Specialized Technology libraries provide components and technology specifically developed for electrical power systems. The Specialized Technology library has been refined and tuned for more than a decade. Specialized Technology models use their own electrical domain. You connect Specialized Technology blocks to other Simscape elements ultimately through Simulink signals. The Specialized Technology software provides a variety of simulation methods (continuous, discrete, phasor) and analysis tools.

## Per-Unit System of Units

### In this section...

“What Is the Per-Unit System?” on page 1-8

“Example 1: Three-Phase Transformer” on page 1-10

“Example 2: Asynchronous Machine” on page 1-11

“Base Values for Instantaneous Voltage and Current Waveforms” on page 1-13

“Why Use the Per-Unit System Instead of the Standard SI Units?” on page 1-13

### 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 a three-phase four-pole Asynchronous Machine block in SI units. 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.

# Modeling Basics

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- “Modeling Power Engineering Systems Using SimPowerSystems Simscape Components Software” on page 2-2
- “Essential Power Engineering Modeling Techniques” on page 2-4
- “Three-Phase Ports” on page 2-7
- “Switch Between Physical Signal and Electrical Ports” on page 2-9

# Modeling Power Engineering Systems Using SimPowerSystems Simscape Components Software

| In this section...   |
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| “Machine and Transformer Source Code Examples” on page 2-3                           |
| “Plotting and Display Options for Asynchronous and Synchronous Machines” on page 2-3 |
| “Choosing the Right Simscape Technology” on page 2-3                                 |

## SimPowerSystems Simscape Components Blocks and Ports

SimPowerSystems Simscape Components blocks are written in the Simscape language. The blocks are fully compatible with Simscape technology, including the local solver, code generation, and data logging.

SimPowerSystems Simscape Components blocks have composite three-phase, electrical conserving, and mechanical rotational conserving ports. You can use composite three-phase ports to build models corresponding to single-line diagrams of three-phase electrical systems. Composite three-phase ports connect to other composite three-phase ports. Electrical and mechanical rotational conserving ports connect directly to Simscape Foundation library components and Simscape add-on products such as SimElectronics®. You can use a Phase Splitter block to split a composite three-phase port into individual electrical conserving ports.

Blocks in the **Semiconductors** library of SimPowerSystems Simscape Components software have an option to switch certain ports between physical signal and electrical conserving ports. When you select electrical ports, the semiconductor block has the same ports as the equivalent semiconductor block in SimElectronics. Therefore, you can easily switch semiconductor blocks in your model between the two products. For example, suppose you have used SimPowerSystems Simscape Components semiconductor blocks to model the electronic drive circuit for a three-phase machine but want to increase the drive circuit fidelity. You can directly

replace the semiconductor blocks with higher-fidelity versions from the SimElectronics block library.

## Machine and Transformer Source Code Examples

SimPowerSystems Simscape Components software comes with Simscape language source code examples for machines and transformers, which you can view and customize. To access the example blocks, type `ThreePhaseExamples_lib` at the MATLAB command prompt. To see the example blocks in three-phase electrical models, see [Creating Components and Libraries](#).

## Plotting and Display Options for Asynchronous and Synchronous Machines

For asynchronous and synchronous machine blocks in SimPowerSystems Simscape Components software, you can perform some useful plotting and display actions using the **Power Systems** menu on the block context menu. For example, to plot torque versus speed (both in SI units) for the Asynchronous Machine Wound Rotor (fundamental) block, right-click the block. From the context menu, select **Power Systems > Asynchronous Machine > Plot Torque Speed (SI)**. The software plots the results in a figure window.

Using other options on the **Power Systems** menu, you can plot values in per unit or display base parameter values in the MATLAB Command Window. These options enable you to quickly tune the performance of your three-phase machine.

## Choosing the Right Simscape Technology

SimPowerSystems software includes two different technologies and corresponding libraries. For a comparison of the two technologies, see “Comparison of Simscape Components and Specialized Technology” on page 1-7. Choose the SimPowerSystems technology most appropriate for your modeling needs and if possible, build your model using blocks exclusively from that technology. However, if necessary, you can build a model that uses blocks from both technologies. To do so, use blocks from the **Simscape > SimPowerSystems > Specialized Technology > Interface Elements** library to interface between them.

## Essential Power Engineering Modeling Techniques

| In this section...                       |
|--|
| “Overview of Modeling Rules” on page 2-4 |
| “Required Blocks” on page 2-5            |

### Overview of Modeling Rules

SimPowerSystems Simscape Components models are essentially Simscape block diagrams refined for modeling three-phase electrical systems.

SimPowerSystems Simscape Components blocks feature these port types:

- Three-phase ports, which connect the phases of a three-phase electrical system between SimPowerSystems Simscape Components blocks.

There are two three-phase port types in SimPowerSystems Simscape Components blocks, composite and expanded. You can connect a composite three-phase port only to another composite three-phase port. You can connect the individual electrical conserving ports of an expanded three-phase port only to other electrical conserving ports. For more information, see “Three-Phase Ports” on page 2-7.

- Electrical and mechanical rotational conserving ports, which connect directly to Simscape foundation blocks.

Each port type has specific Across and Through variables associated with it. To learn about the rules to follow when building an electromechanical model, see “Basic Principles of Modeling Physical Networks” in the Simscape documentation.

- Physical signal ports, which connect to Simulink blocks through the Simulink-PS Converter and PS-Simulink Converter blocks from the Simscape Utilities library. These blocks convert physical signals to and from Simulink mathematical signals.

Keep these rules in mind when using each port type in SimPowerSystems Simscape Components blocks.

- You can connect physical conserving ports only to other conserving ports of the same type. Electrical conserving ports in SimPowerSystems Simscape



Components blocks can connect directly to SimElectronics blocks and Simscape electrical components. Mechanical rotational conserving ports in SimPowerSystems Simscape Components blocks can connect directly to Simscape mechanical rotational components.

- The physical connection lines that connect conserving ports are nondirectional lines that carry physical variables (Across and Through variables) rather than signals. You cannot connect physical conserving ports to Simulink ports or to physical signal ports.
- You can branch physical connection lines. When you do so, directly connected components share the same Across variables. The value of any Through variable (e.g., current or torque) transferred along the physical connection line is divided among the multiple components connected by the branches.

For each Through variable, the sum of the values flowing into a branch point equals the sum of the values flowing out.

- You can connect physical signal ports to other physical signal ports using regular connection lines, similar to Simulink signal connections. These connection lines carry physical signals between SimPowerSystems Simscape Components blocks.
- You can connect physical signal ports to Simulink ports through converter blocks. Use the Simulink-PS Converter block to connect Simulink outputs to physical signal inports. Use the PS-Simulink Converter block to connect physical signal outputs to Simulink inports.
- Unlike Simulink signals, physical signals can have units. In SimPowerSystems Simscape Components block dialog boxes, you can specify the units along with the parameter values, where appropriate. Use the converter blocks to associate units with an input signal and to specify the desired output signal units.

For an example of these rules applied to an electromechanical model, see Three-Phase Asynchronous Machine Starting.

## Required Blocks

Each topologically distinct physical network in a diagram requires exactly one Solver Configuration block from the Simscape Utilities library. The Solver

Configuration block specifies global environment information for simulation and provides parameters for the solver that your model needs for simulation.

Each electrical network requires an Electrical Reference block. This block establishes the electrical ground for the circuit. Networks with electromechanical blocks also require a Mechanical Rotational Reference block. For more information about using reference blocks, see “Grounding Rules”.

## Three-Phase Ports

| In this section...   |
|--|
| “About Three-Phase Ports” on page 2-7                          |
| “Expand and Collapse Three-Phase Ports on a Block” on page 2-8 |

### About Three-Phase Ports

In SimPowerSystems Simscape Components software, you can connect the phases of a three-phase system between blocks using two types of port.

- Composite three-phase port
- Expanded three-phase port

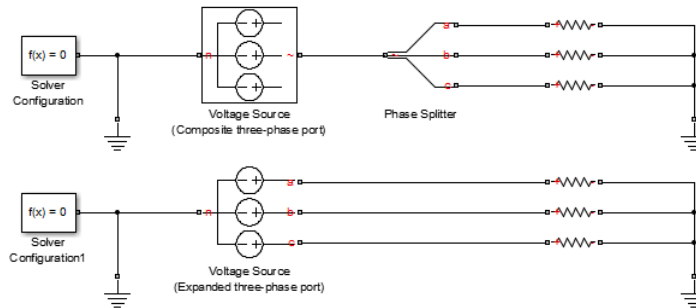
Composite three-phase ports represent three individual electrical conserving ports with a single block port. You can use composite three-phase ports to build models that correspond to single-line diagrams of three-phase electrical systems. Instead of explicitly connecting each phase of the three-phase system between blocks, you connect all three phases using a single port. You can connect composite three-phase ports only to other composite three-phase ports.

Expanded three-phase ports represent the individual phases of a three-phase system using three separate electrical conserving ports. You individually connect each phase of the three-phase system between blocks. Electrical conserving ports can connect directly to electrical components from the Simscape and SimElectronics libraries.

Composite three-phase ports produce results with the same fidelity as expanded three-phase ports. Both connection methods consider instantaneous phase voltages and currents and are suitable for modeling balanced and unbalanced three-phase electrical power systems. Each electrical conserving port in an expanded three-phase port has a Through variable of scalar current and an Across variable of scalar voltage. For a composite three-phase port, the Through variable is a three-element current, and the Across variable is a three-element voltage.

You can use the Phase Splitter block to expand a composite three-phase port into separate electrical conserving ports. The separate electrical ports can then connect to Simscape and SimElectronics electrical components.

The figure shows two simple circuits that contrast the composite and expanded connection methods. The two circuits produce the same results.



The top circuit uses a Voltage Source block with a composite three-phase port ~. The bottom circuit uses a Voltage Source block with expanded electrical conserving ports a, b, and c. In each circuit, the instantaneous phase voltages and currents are the same.

### Expand and Collapse Three-Phase Ports on a Block

SimPowerSystems Simscape Components blocks that have composite three-phase ports have an option to switch between composite and expanded ports.



- Right-click the block. On the **Simscape block choices** context menu, select **Expanded three-phase ports** or **Composite three-phase ports**.

For blocks with a single composite port ~, the expanded electrical ports are labeled a, b, and c. For blocks with more than one composite port ~1 and ~2, the expanded electrical ports are labeled a1, b1, c1 and a2, b2, c2.

## Switch Between Physical Signal and Electrical Ports

Some SimPowerSystems Simscape Components blocks have an option to switch certain ports between physical signal and electrical conserving ports. An electrical conserving port is a Simscape physical conserving port that has a Through variable of current and an Across variable of voltage. For a comparison of Simscape physical signal and physical conserving ports, see “Connector Ports and Connection Lines”.

- Right-click the block. On the **Simscape block choices** context menu, select **Electrical control port** or **PS control port**.

The block connection port switches between  (electrical conserving port) and  (physical signal port).



# Tutorials

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- “Build a Simple Three-Phase Model” on page 3-2
- “Simulate and Analyze a Three-Phase Load Model” on page 3-8
- “Create an Expanded Resistive Three-Phase Load” on page 3-10
- “Create a Reactive Three-Phase Load” on page 3-12
- “Simulate a Resistive Three-Phase Load Model” on page 3-13
- “Simulate a Reactive Three-Phase Load Model” on page 3-16

## Build a Simple Three-Phase Model

### In this section...

“Overview of Simple Three-Phase Model Tutorial” on page 3-2

“Select Blocks to Represent System Components” on page 3-2

“Build the Model” on page 3-3

“Specify Model Parameters” on page 3-5

### Overview of Simple Three-Phase Model Tutorial

This tutorial shows you how to build a SimPowerSystems Simscape Components model. The model simulates the behavior of a three-phase AC voltage source driving a simple load.

To build the model, you add blocks from the SimPowerSystems Simscape Components block library as well as Simscape blocks.

To see the completed model, click Simple Three-Phase Model.

### Select Blocks to Represent System Components

Select blocks to model input signals and electrical characteristics of the three-phase system and display system outputs.

This table describes the role of blocks representing the system components.

| Block                       | Description   |
|-----------------------------|---|
| <b>Solver Configuration</b> | Defines solver settings that apply to all physical modeling blocks  |
| <b>Voltage Source</b>       | Ideal three-phase voltage source that maintains a sinusoidal voltage across its output terminals, regardless of the current flowing in the source |
| <b>Phase Voltage Sensor</b> | Converts the voltage across each phase of the three-phase system into a physical signal proportional to that voltage                              |



| <b>Block</b>                 | <b>Description</b>  |
|------------------------------|---|
| <b>Current Sensor</b>        | Converts the electrical current flowing in each phase of the three-phase load into a physical signal proportional to that current |
| <b>RLC</b>                   | Models the resistive, inductive, and capacitive properties of the three-phase load  |
| <b>PS-Simulink Converter</b> | Converts a physical signal to a Simulink signal   |
| <b>Scope</b>                 | Displays phase voltages and currents for the three-phase system   |
| <b>Electrical Reference</b>  | Provides the ground connection for electrical conserving ports  |
| <b>Grounded Neutral</b>      | Provides an electrical ground connection for each phase of the three-phase system   |

## Build the Model

- 1 Open the Simulink Library Browser.
- 2 Select **File > New > Model**.
- 3 Drag these blocks from the library into your model.

| <b>Block</b>                | <b>Library Path</b>  | <b>Quantity</b> |
|-----------------------------|--|-----------------|
| <b>Voltage Source</b>       | <b>Simscape &gt; SimPowerSystems &gt; Simscape Components &gt; Sources</b> | 1               |
| <b>Phase Voltage Sensor</b> | <b>Simscape &gt; SimPowerSystems &gt; Simscape Components &gt; Sensors</b> | 1               |

| <b>Block</b>          | <b>Library Path</b>  | <b>Quantity</b> |
|-----------------------|--|-----------------|
| Current Sensor        | Simscape > SimPowerSystems > Simscape Components > Sensors         | 1               |
| RLC                   | Simscape > SimPowerSystems > Simscape Components > Passive Devices | 1               |
| Electrical Reference  | Simscape > Foundation Library > Electrical > Electrical Elements   | 1               |
| Grounded Neutral      | Simscape > SimPowerSystems > Simscape Components > Connections     | 2               |
| Solver Configuration  | Simscape > Utilities   | 1               |
| PS-Simulink Converter | Simscape > Utilities   | 2               |
| Scope                 | Simulink > Sinks   | 1               |



In the Solver Configuration block:

- Select **Use local solver**.
- Set **Sample time** to 0.0001.

In Simscape-based models, the local solver is a sample-based solver that represents physical network states as discrete states. For most SimPowerSystems Simscape Components models, the local solver is an appropriate first choice. The solver updates block states once per simulation time step, as determined by **Sample time**. For simulation of a 60 Hz AC system, an appropriate sample time is a value in the order of  $1e-4$ . For more information on solver options see Solver Configuration.

If you prefer to use a continuous solver instead of a discrete solver, clear the **Use local solver** check box in the Solver Configuration block. The simulation then uses the Simulink solver specified in the model configuration parameters (**Simulation > Model Configuration Parameters**). For SimPowerSystems Simscape Components models, an appropriate solver choice is the moderately stiff solver ode23t. For a 60 Hz AC system, specify a value for **Max step size** in the order of  $1e-4$ . For more information, see “Explicit Continuous Variable-Step Solvers”.

In the Simulink Model Editor, set the simulation stop time to 0.1.

### **Load Impedance Parameters**

The RLC block models resistive, inductive, and capacitive characteristics of the three-phase load. Using the **Component structure** parameter, you can specify a series or parallel combination of resistance, inductance, and capacitance.

In the RLC block, leave the defaults:

- **Component structure** is set to R.
- **Resistance** is set to 1  $\Omega$ .

Setting **Component structure** to R models a three-phase load that is purely resistive in nature. The resistance in *each* phase is 1  $\Omega$ . “Simulate and

Analyze a Three-Phase Load Model” on page 3-8 discusses the behavior of a load with these characteristics.

### Display Parameters

Sensor blocks in the model convert the current and voltage in each phase of the three-phase system to proportional physical signals. PS-Simulink Converter blocks convert the physical signals into Simulink signals for the Scope block to display.

Of these three types of block, only the converter blocks have parameters. For this example:

- Set **Output signal unit** of the PS-Simulink Converter block to A. This setting ensures that the block outputs a signal with the same magnitude as the ampere signal that enters it.
- Set **Output signal unit** of the PS-Simulink Converter1 block to V. This setting ensures that the block outputs a signal with the same magnitude as the voltage signal that enters it.

Label the input signals to the Scope block. Double-click each line, and type the appropriate label, **Currents** or **Voltages**, as shown in the model graphic.


Save the model. You are ready to simulate the model and analyze the results.

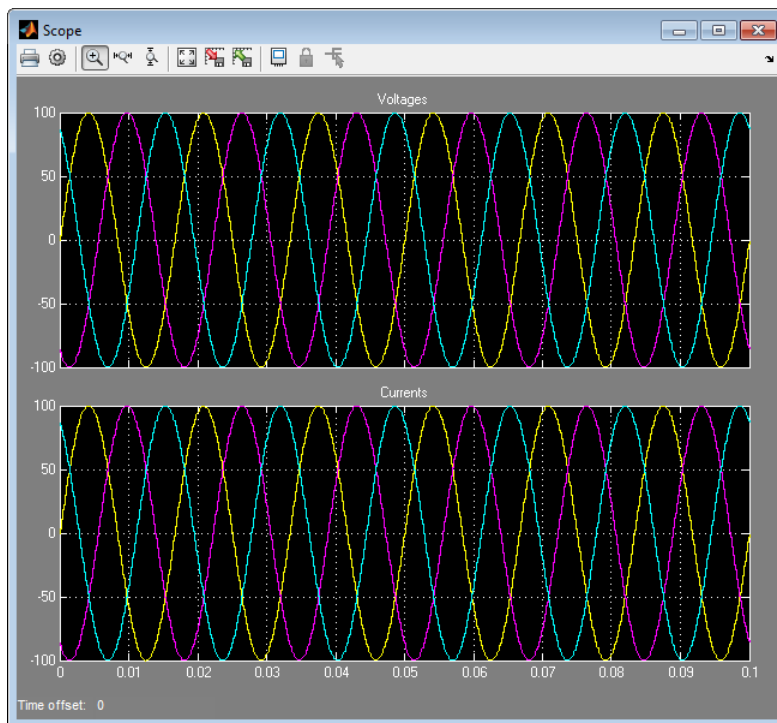
### Related Examples

- “Simulate and Analyze a Three-Phase Load Model” on page 3-8
- “Create an Expanded Resistive Three-Phase Load” on page 3-10
- “Create a Reactive Three-Phase Load” on page 3-12

## Simulate and Analyze a Three-Phase Load Model

In “Build a Simple Three-Phase Model” on page 3-2, you built a simple SimPowerSystems Simscape Components model. This procedure shows you how to run the simulation and plot the results.

- 1 Simulate the model.
- 2 View the phase currents and voltages. Double-click the Scope block.
- 3 Click the Autoscale button  to scale the scope axes to the data.



In this example, the **Component structure** parameter of the RLC block specifies that the electrical characteristics of the three-phase load are purely resistive. Therefore, for each phase of the three-phase system, the voltage and current remain in phase with each other. Because the resistance in each

phase is  $1 \Omega$ , the magnitude of the phase voltage is equal to the magnitude of the phase current.

## Create an Expanded Resistive Three-Phase Load

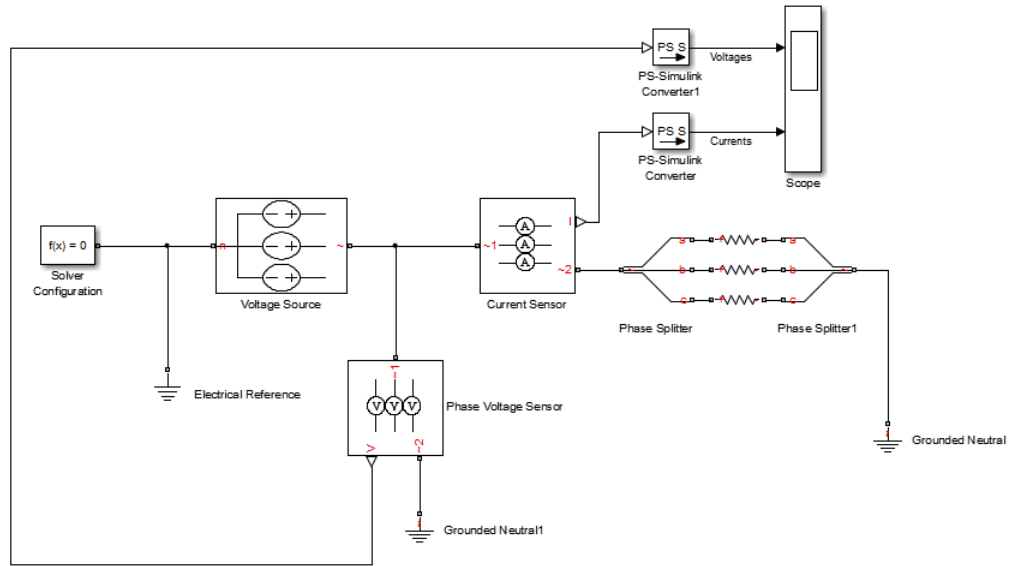
This procedure shows you how to modify the model you built in “Build a Simple Three-Phase Model” on page 3-2 to create:

- A three-phase load expanded into individual phases
- An expanded three-phase load that does not have equal resistance in each phase

In this procedure, you make changes to the original model and save the changes as new models. You then simulate each new model and analyze the results.

- 1** Open Simple Three-Phase Model.
- 2** Delete the RLC block.
- 3** Drag two copies of the Phase Splitter block into the model from the **Simscape > SimPowerSystems > Simscape Componentets > Connections** library.
- 4** Flip one of the Phase Splitter blocks horizontally. Right click the block and select **Rotate & Flip > Flip Block > Left-Right**.
- 5** Drag a Resistor element into the model from the **Simscape > Foundation Library > Electrical > Electrical Elements** library.
- 6** Hide the Resistor element label to create space for more components. Right-click the resistor and select **Format > Show Block Name** to clear this option.
- 7** Make two more copies of the Resistor element.
- 8** Connect the components as shown.





- 9 Save this version of the modified model using the name `simplethrephasemodel_expanded_balanced`.

This model name reflects that the load previously modeled by the RLC block is now expanded into individual phases. The load is still balanced, i.e., there is equal resistance in each phase.

- 10 Unbalance the load by changing the resistance in one phase. Double-click one of the resistor elements. Change **Resistance** to 2.

- 11 Save this version of the modified model using the name `simplethrephasemodel_expanded_unbalanced`.

This model name reflects that the three-phase load previously modeled by the RLC block is expanded into individual phases. The load is unbalanced, i.e., the resistance in one of the phases is higher than in the other two.

## Related Examples

- “Simulate a Resistive Three-Phase Load Model” on page 3-13

## Create a Reactive Three-Phase Load

This procedure shows you how to modify the model you built in “Build a Simple Three-Phase Model” on page 3-2 to create a reactive load. A reactive load has inductive or capacitive characteristics.


In this procedure, you make changes to the original model and save the changes as a new model. You then simulate the new model and analyze the results.

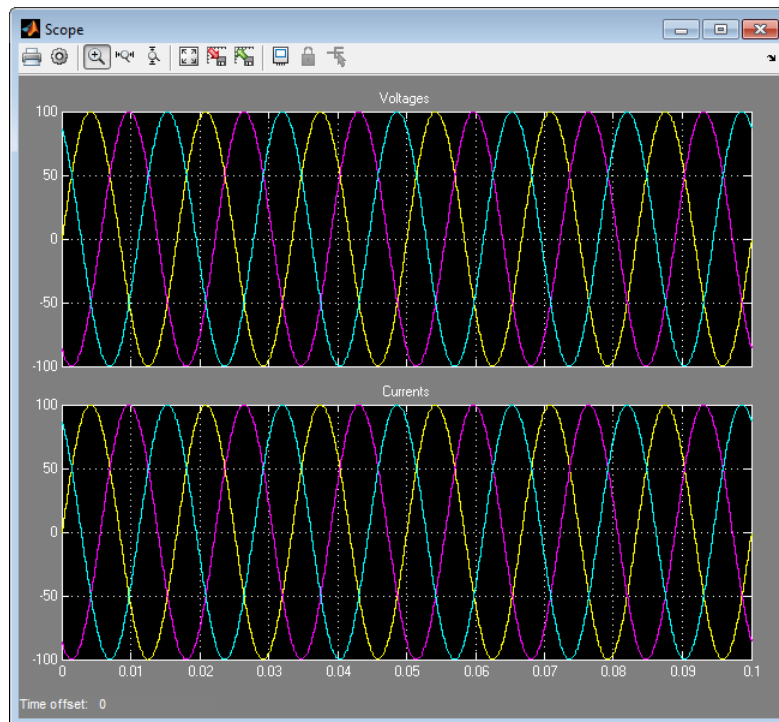
- 1** Open Simple Three-Phase Model.
- 2** In the RLC block, set:
  - **Component structure** to Series RL
  - **Inductance** to 0.002
- 3** Save this version of the model using the name `simplethreephase_model_reactive`.
  - “Simulate a Reactive Three-Phase Load Model” on page 3-16

### Related Examples

## Simulate a Resistive Three-Phase Load Model

In “Create an Expanded Resistive Three-Phase Load” on page 3-10, you built models to extend the basic model completed in “Build a Simple Three-Phase Model” on page 3-2. In this procedure, you simulate the extended models and analyze the results.

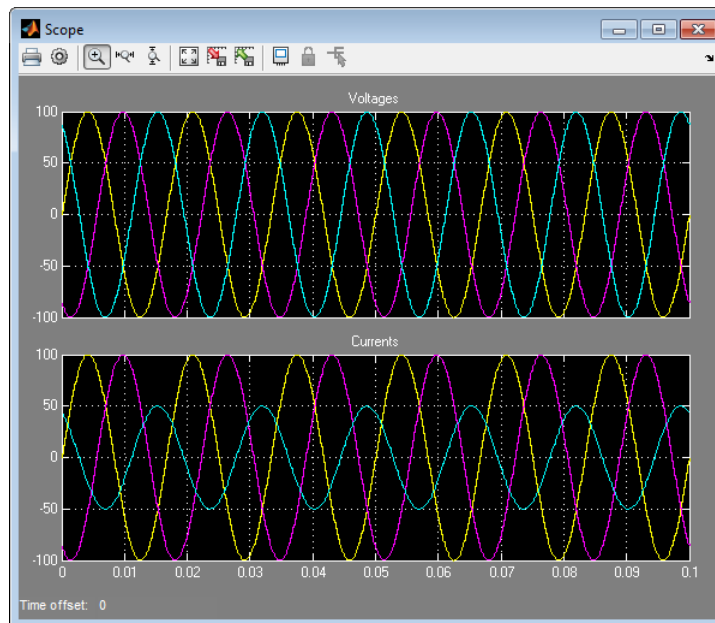
- 1 Open the `simplethreephasemodel_expanded_balanced` model.
- 2 Simulate the model.
- 3 View the simulation results. Double-click the Scope block.
- 4 Click the Autoscale button  to scale the scope axes to the data.



In “Build a Simple Three-Phase Model” on page 3-2, the **Component structure** parameter of the RLC block specifies that the three-phase load is purely resistive. In this version of the model, the load is expanded into an individual resistive element for each phase, but the resistance in each phase is unchanged. For each phase of the three-phase system, the voltage and current remain in phase with each other. Because the resistance in each phase is  $1\ \Omega$ , the magnitude of the phase voltage is equal to the magnitude of the phase current.

Comparing this result with that described in “Simulate and Analyze a Three-Phase Load Model” on page 3-8 shows that a block with composite three-phase ports (the RLC block in the original model), produces a result with the same fidelity as that of expanded phases.

- 5 Open the `simplethreephase_model_expanded_unbalanced` model.
- 6 Simulate the model. Autoscale the scope axes.




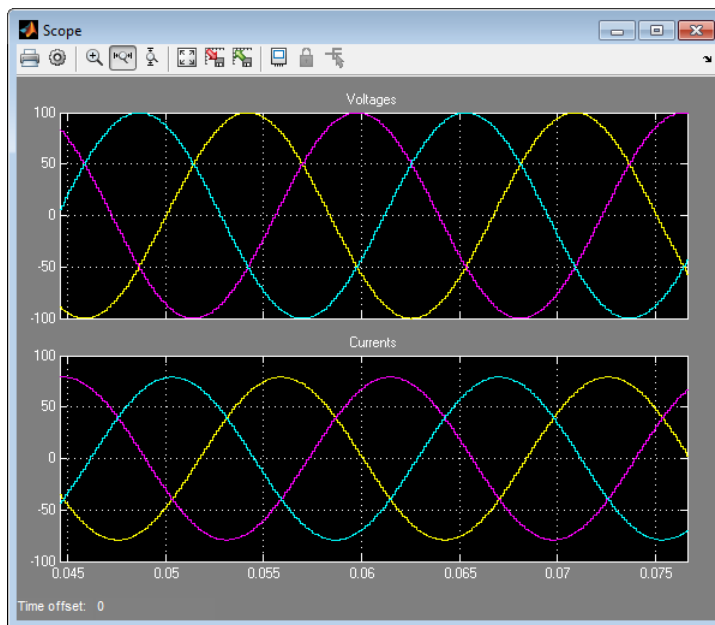
In this version of the model, one phase of the three-phase load has twice the resistance of the other two. Therefore, half as much current flows in

that phase, as the second plot shows. However, because the load remains purely resistive, the voltage and current remain in phase with each other.

## Simulate a Reactive Three-Phase Load Model

In “Create a Reactive Three-Phase Load” on page 3-12, you built a model to extend the basic model completed in “Build a Simple Three-Phase Model” on page 3-2. In this procedure, you simulate the extended model and analyze the results.

- 1 Open the `simplethreephasemodel_reactive` model.
- 2 Simulate the model.
- 3 View the simulation results. Autoscale the scope axes.
- 4 Examine the results in closer detail. For example, click the Zoom X-axis button  and drag a box over the first third of one of the plots.



In “Build a Simple Three-Phase Model” on page 3-2, the electrical characteristics of three-phase load are purely resistive. In this model, the **Component structure** parameter of the RLC block is set to `Series RL`,

meaning that the load has an inductive characteristic. The current flowing in each phase lags the voltage.





# Modeling Machines

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- “Machine Parameterization” on page 4-2
- “Machine Plotting and Display Options” on page 4-3
- “Initialize Synchronous Machines and Controllers” on page 4-5

## Machine Parameterization

In SimPowerSystems Simscape Components software, asynchronous machines are parameterized using fundamental parameters. Each synchronous machine is parameterized using standard or fundamental parameters.

Machine fundamental parameters include the values of inductances and resistances of the stator and rotor  $d$ - and  $q$ -axis equivalent circuits. These parameters fully specify the electrical characteristics of the machine, but you cannot determine them directly from machine test responses. Hence, it is more common to parameterize a synchronous machine using a standard parameter set. You can obtain the standard parameters by observing responses at the machine's terminals with suitable tests scenarios.

You can tell the parameter set a block uses because the block name includes the parameter set name, e.g. Asynchronous Machine Squirrel Cage (fundamental). The parameters you can set in the block dialog box correspond to the parameterization type.

If a machine block has a standard and a fundamental variant, base your block choice on the parameters you are most familiar with or you have available. When you use a standard block variant in your simulation, the software uses classical equations to convert the standard parameter values you enter to fundamental parameter values for use at runtime.

The field circuit and rotational ports of machine blocks use SI units. However, the pu measurement port of machine blocks outputs a vector of physical signals in per unit.

### Concepts

- “Per-Unit System of Units” on page 1-8

## Machine Plotting and Display Options

For some blocks in the Machines sublibrary in SimPowerSystems Simscape Components software, you can perform plotting and display actions using the **Power Systems** context menu.

For example, you can plot torque versus speed for the Asynchronous Machine Wound Rotor block, either in SI or per-unit units. You access these commands using the **Power Systems** menu on the block context menu.

Using other options on the **Power Systems** menu, you can display values in per unit or display base parameter values in the MATLAB Command Window. These options enable you to quickly initialize and tune your three-phase machine.

### Asynchronous Machine Options

- **Display Base Values** displays the machine per-unit base values in the MATLAB Command Window.
- **Plot Torque Speed (SI)** plots torque versus speed (both measured in SI units) in a MATLAB figure window using the present machine parameters.
- **Plot Torque Speed (pu)** plots torque versus speed (both measured in per unit) in a MATLAB figure window using the present machine parameters.

### Synchronous Machine Options

- **Display Base Values** displays the machine per-unit base values in the MATLAB Command Window.
- **Display Associated Base Values** displays associated per-unit base values in the MATLAB Command Window.
- **Associated Initial Conditions** displays associated initial conditions at the MATLAB Command Window.

### **Machine Inertia Block Options**

For the Machine Inertia block, you can display the inertia parameters and base values using the **Power Systems** menu on the block context menu. The block displays parameter values in the MATLAB Command Window.

## Initialize Synchronous Machines and Controllers

In SimPowerSystems Simscape Components software, you can specify steady-state power and voltage values for a synchronous machine. Based on the values you specify, the machine block calculates the initial field circuit and rotational input values required to achieve this steady state. Starting a machine at steady state prevents undesired transient effects in your simulation.

- 1** Calculate the required power and voltage characteristics of your load circuit.
- 2** In the **Initial Conditions** tab of the dialog box, set **Specify initialization by** to **Electrical power and voltage output**.
- 3** Enter the required power and voltage values and click **OK**.
- 4** Right-click the machine block and select **Power Systems > Synchronous Machine > Associated Initial Conditions**.

SimPowerSystems calculates the field circuit and rotational port values required to start the machine in steady state and displays them in the MATLAB Command Window.

- 5** Use these values to input parameters to the blocks connected to the field circuit and rotational ports of the synchronous machine.

---

**Note** If you set **Specify initialization by** to **Mechanical and magnetic states**, Simulink does not calculate the machine's associated initial conditions.

---



# Customization

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- “Three-Phase Electrical Domain” on page 5-2
- “Customizing Machine Models” on page 5-4
- “Custom Synchronous Machine” on page 5-6

## Three-Phase Electrical Domain

In addition to the Simscape Foundation domains, SimPowerSystems Simscape Components software contains a three-phase electrical domain. You can use this domain to develop your own custom three-phase blocks using Simscape language.

The three-phase electrical domain declaration is shown below.

```
domain electrical
    % Three-Phase Electrical Domain

    % Copyright 2012-2013 The MathWorks, Inc.

    parameters
        Temperature = { 300.15 , 'K' }; % Circuit temperature
        GMIN        = { 1e-12 , '1/Ohm' }; % Minimum conductance, GMIN
    end

    variables
        V = { [ 0 0 0 ], 'V' };
    end

    variables(Balancing = true)
        I = { [ 0 0 0 ], 'A' };
    end

end
```

It contains the following variables and parameters:

- Across variable  $V$  (voltage), declared as a three-element row vector, in volts
- Through variable  $I$  (current), declared as a three-element row vector, in amperes
- Parameter *Temperature*, specifying the circuit temperature
- Parameter *GMIN*, specifying minimum conductance

To refer to this domain in your custom component declarations, use the following syntax:



`pe.electrical.three_phase.electrical`

## **Related Examples**

- “Custom Synchronous Machine” on page 5-6

## **Concepts**

- “Customizing Machine Models” on page 5-4
- “Custom Components”
- “Foundation Domains”

## Customizing Machine Models

The `ThreePhaseExamples` library, included in the product examples, contains the following custom three-phase components:

- Permanent Magnet Synchronous Motor
- Synchronous Machine
- Zigzag Transformer

You can use these simplified example models to write your own machine and transformer component files.

To open the custom library, at the MATLAB command prompt, type `ThreePhaseExamples_lib`. Double-click any block in the library to open its dialog box, and then click the **Source code** link in the block dialog box to open the Simscape source file for this block in the MATLAB Editor.

To customize the block for your application, edit the source file and save it in a package directory.

For example, you can create a folder called `+MyMachines` and save the source files for your customized machines in this folder. Create this folder in your working directory, or in another directory that is on the MATLAB path. Running the `ssc_build` command on this package generates the `MyMachines_lib` library model. This library contains all your custom machine blocks and is located in the same directory where you have created the `+MyMachines` folder. Open the `MyMachines_lib` library by double-clicking it or by typing its name at the MATLAB command prompt.

For more information on packaging and deploying Simscape component files, see “Generate Custom Block Libraries from Simscape Component Files”.

Things to keep in mind when writing component files:

- If you create a new custom component by modifying an existing one, do not forget to change the name of the component and the name of the resulting block.

- The component name must be the same as the name of the Simscape file. For example, if you plan to save your component in a file called `MyComponent.ssc`, change the declaration line in the file:

```
component MyComponent
```

- The comment line immediately following the component declaration (that is, the first line beginning with the `%` character) defines the name of the block, as it appears in the custom library next to the block icon and at the top of the block dialog box. If you do not specify this comment, then the component name serves as the block name. The block name must be unique within the subpackage (sublibrary) where it resides.
- Additional comments, below the line specifying the block name, are interpreted as the block description. You do not have to modify them when copying an existing file, but if you change the way the component works, it makes sense to reflect the change in the block description. The block description is for informational purposes only.
- When modifying component equations, if you introduce additional terms, make sure to add the appropriate variables or parameters to the component declaration section. For example, if you add zero-sequence dynamics to the component equations, declare an additional parameter for stator zero-sequence inductance,  $L_0$ , and an additional variable for the initial stator zero-sequence magnetic flux linkage.

The “Custom Synchronous Machine” on page 5-6 tutorial shows how you can modify the Synchronous Machine component file and customize it for use in your applications. For more information on writing customized component files, see “Custom Components”.

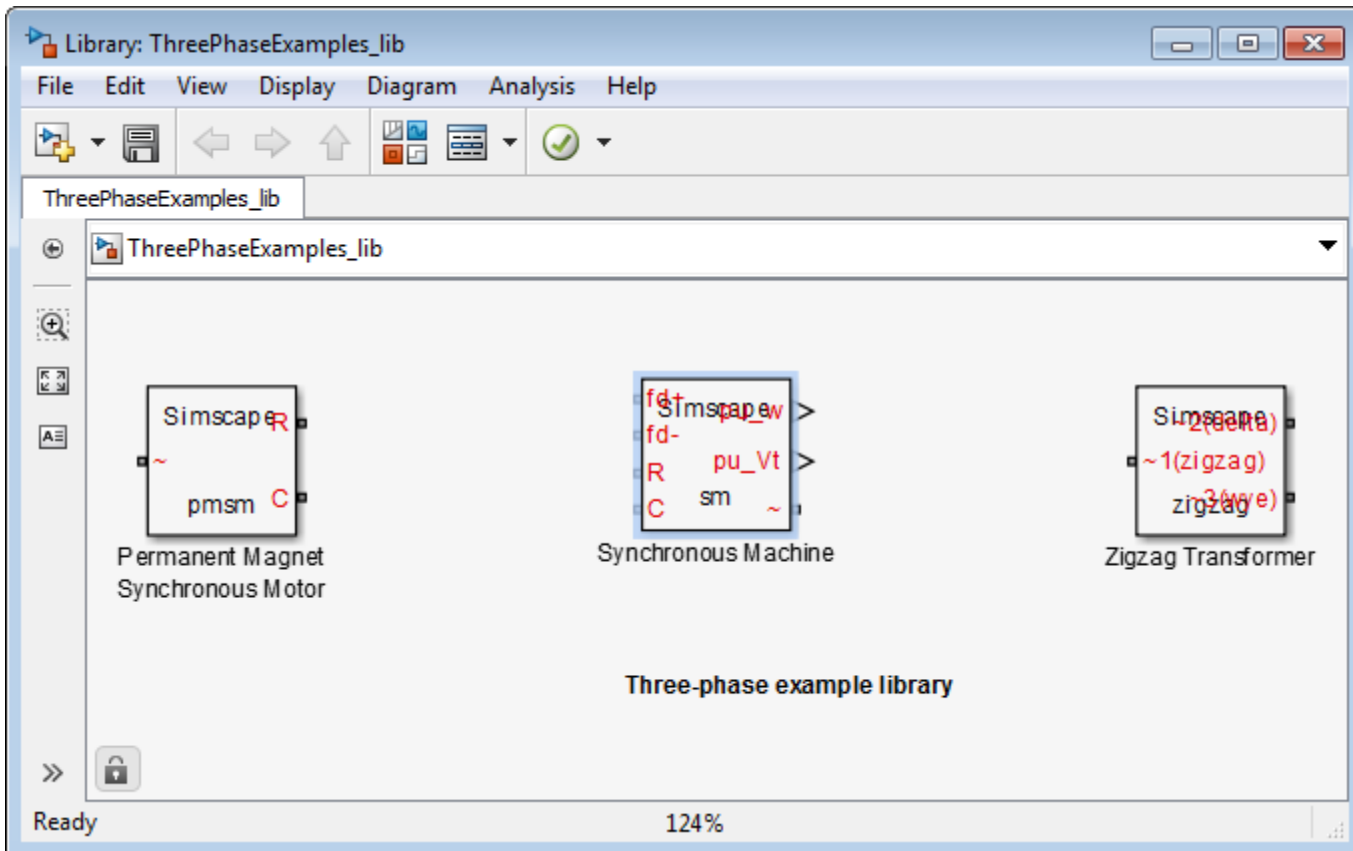
## Custom Synchronous Machine

The ThreePhaseExamples library, included in the product examples, contains simplified example models that you can use to write your own machine and transformer component files. The Synchronous Machine component in the ThreePhaseExamples library is similar to the Synchronous Machine Round Rotor (fundamental) block, but its equations have been simplified to omit zero-sequence dynamics. The Synchronous Machine block is therefore suitable for balanced operation only.

This example shows how you can further simplify the component file and make a custom machine block that does not account for the stator rate of change of flux.

- 1** In your working directory, create a new folder called `+MyMachines`. This folder will contain the source files for your customized machines.
- 2** To open the library of simplified component examples, at the MATLAB command prompt, type:

```
ThreePhaseExamples_lib
```



3 Double-click the Synchronous Machine block.

4 In the block dialog box, click the **Source code** link.

The Simscape source file for this block opens in the MATLAB Editor.

5 Change the name of the component, the name of the block, and the block description by replacing the first ten lines of the file:

```
component sm
% Synchronous Machine
% Synchronous machine (SM) with a round rotor parameterized using
% fundamental per-unit parameters. The SM model includes field and damper
```

```
% windings on the d-axis and two damper windings on the q-axis. The stator  
% d.psi/dt terms are included, as is the effect of speed variation on the  
% stator voltages. The defining equations are simplified by omitting the  
% zero-sequence dynamics: the model is suitable for balanced operation.
```

```
% Copyright 2012-2013 The MathWorks, Inc.
```

```
with:
```

```
component sm1  
% Simplified Synchronous Machine  
% This synchronous machine does not include the stator d.psi/dt terms.
```

- 6** To remove the stator rate of change of flux terms, scroll down to the equations section and modify the stator voltage equations from:

```
% Per unit stator voltage equations  
pu_ed == oneOverOmega*pu_psid.der - pu_psiq*pu_velocity - Ra*pu_id;  
pu_eq == oneOverOmega*pu_psiq.der + pu_psid*pu_velocity - Ra*pu_iq;
```

```
to:
```

```
% Per unit stator voltage equations  
pu_ed == -pu_psiq*pu_velocity - Ra*pu_id;  
pu_eq == pu_psid*pu_velocity - Ra*pu_iq;
```

- 7** Save the file in the +MyMachines folder as sm1.ssc. The name of the Simscape file must match the component name.

- 8** To generate the custom library containing the new block, at the MATLAB command prompt, type:

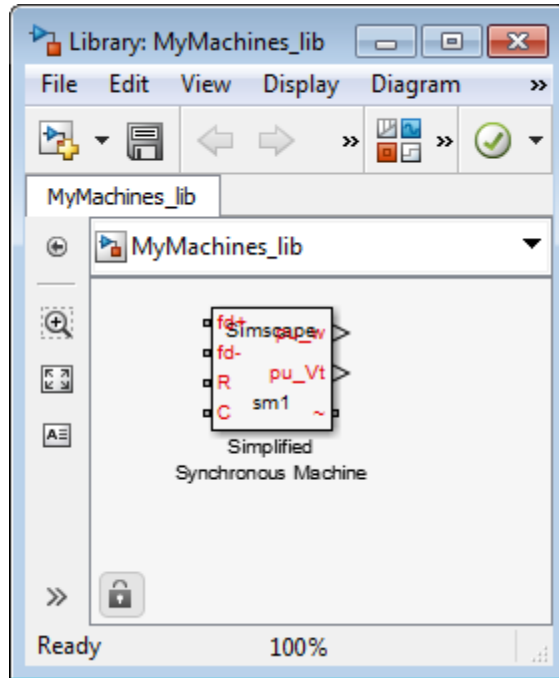
```
ssc_build MyMachines
```

This command generates the MyMachines\_lib library model in your working directory.

- 9** To open the custom library, at the MATLAB command prompt, type:

```
MyMachines_lib
```

The library contains the Simplified Synchronous Machine block, which you can now use in your models.



## See Also

`ssc_build`

## Related Examples

- “Generate Custom Block Libraries from Simscape Component Files”

## Concepts

- “Customizing Machine Models” on page 5-4
- “Three-Phase Electrical Domain” on page 5-2
- “Custom Components”
- “Customizing the Block Name and Appearance”
- “Component Equations”





# Simulation and Analysis of Power Engineering Systems

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- “Selecting a Solver for Power Engineering Systems” on page 6-2
- “Simulating Power Engineering Systems” on page 6-3

## Selecting a Solver for Power Engineering Systems

In SimPowerSystems Simscape Components models, as with Simscape, you must include a Solver Configuration block in each topologically distinct physical network.

The Solver Configuration block has a local solver option. In Simscape-based models, the local solver is a fixed-step, sample-based solver that represents physical network states as discrete states. To use the local solver, select the **Use local solver** check box in the Solver Configuration block.

For most SimPowerSystems Simscape Components models, the local solver is an appropriate choice. The local solver updates SimPowerSystems Simscape Components block states once per simulation time step, as determined by the value of the **Sample time** parameter. For simulation of a 60 Hz AC system, an appropriate sample time is a value in the order of  $1e-4$ . Any non-Simscape-based blocks in the model use the global Simulink solver specified in the model configuration parameters.

You can also use the global Simulink solver instead of the local solver to solve your physical network. To do so, clear the **Use local solver** check box in the Solver Configuration block. All blocks in the model then use the Simulink solver specified in the model configuration parameters.

For a model with only SimPowerSystems Simscape Components blocks, an appropriate Simulink solver choice is the moderately stiff solver ode23t, using the default variable-step type. For a 60 Hz AC system, specify a value for **Max step size** in the order of  $1e-4$ .

However, you can select any of the Simulink solvers available in the model configuration parameters. Choose a solver based on the block states and dynamics of your overall system. Specify a solver type (variable or fixed-step) and step size based on the simulation fidelity you want.

To learn more about making an appropriate solver choice for your simulation, see “Simulation” in the Simscape documentation.

## Simulating Power Engineering Systems

SimPowerSystems Simscape Components models are Simscape block diagrams refined for modeling and simulating three-phase electrical power systems. Therefore, SimPowerSystems Simscape Components and Simscape simulations behave in the same way. In addition, Simscape techniques for simulation setup and troubleshooting apply to SimPowerSystems Simscape Components models.

To learn about:

- The simulation behavior of Simscape models, see “How Simscape Simulation Works”.
- Techniques for finding system operating points and linearizing the response of Simscape models, see “Trimming and Linearization”.
- Troubleshooting Simscape simulations, see “Troubleshooting”.