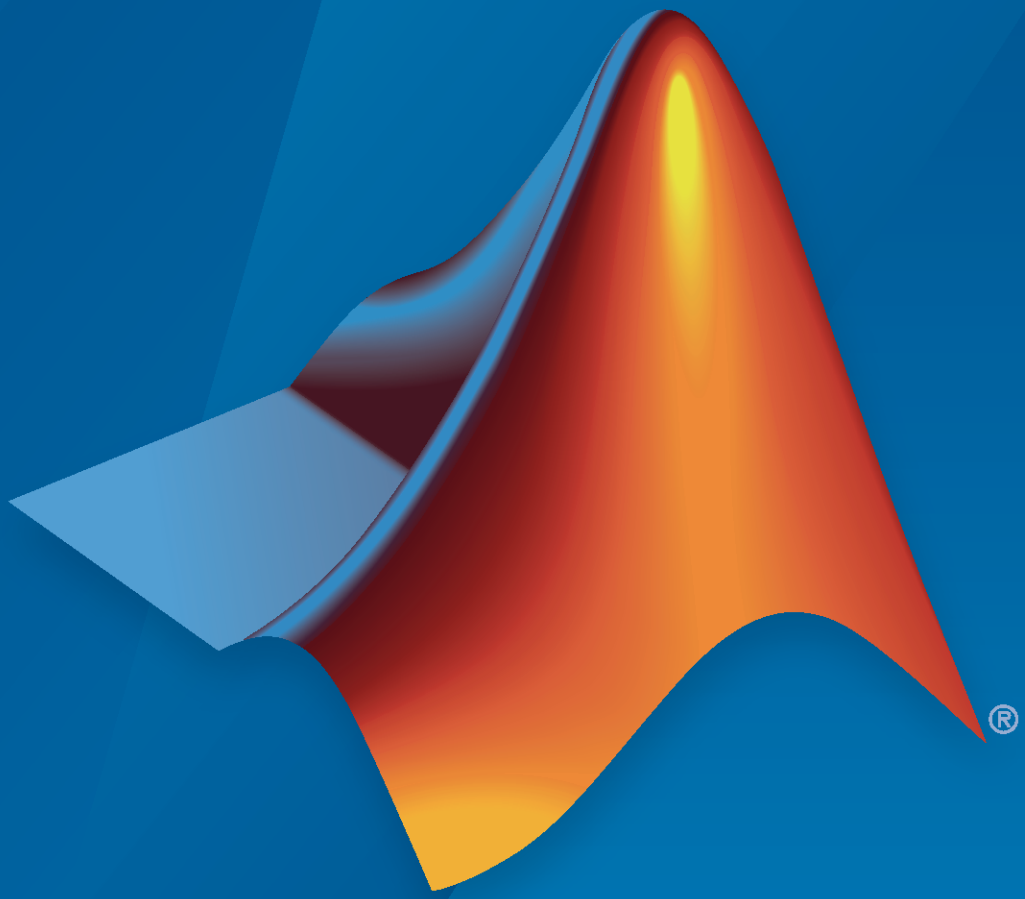
Motor Control Blockset™

User's Guide



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Motor Control Blockset™ User's Guide

Revision History

March 2020	Online only	New for Version 1.0 (Release 2020a)
September 2020	Online only	Revised for Version 1.1 (Release R2020b)
March 2021	Online only	Revised for Version 1.2 (Release R2021a)
September 2021	Online only	Revised for Version 1.3 (Release R2021b)
March 2022	Online only	Revised for Version 1.4 (Release R2022a)
September 2022	Online only	Revised for Version 1.5 (Release R2022b)

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2 Deploy and Validate System

3 Plant Modeling

4 Motor Control Blockset Examples

5 Hardware Troubleshooting

Design the Controller

Design Field-Oriented Control Algorithm

To implement the speed control algorithm for a motor, perform these tasks:

- Current scaling — Convert current from ADC counts to PU.
- Quadrature encoder position decoding — Read the quadrature encoder position counts and calculate the rotor electrical position.
- Torque control — Implement current control in the *d*-*q* axis.
- Speed control — Implement speed control.

These steps help you implement the speed control algorithm for a PMSM using Motor Control Blockset and are related to the model `mcb_pmsm_foc_qep_f28379d` used in the example “Field-Oriented Control of PMSM Using Quadrature Encoder”. They explain the procedure to tune the control parameters for *d*-axis and *q*-axis current controllers and the speed controller.

1. “Design Current and Position Scaling Subsystems” on page 1-3
2. “Design Current Controller Subsystem” on page 1-6
3. “Perform Manual Gain-Tuning of Current Controller” on page 1-10
4. “Design Speed Control Algorithm” on page 1-12
5. “Perform Manual Gain-Tuning of Speed Controller” on page 1-14

In these steps, variables are used to define datatypes and execution times of the current and speed controllers. See the initialization script linked to the example model `mcb_pmsm_foc_qep_f28379d` for details about the variables defined in these steps.

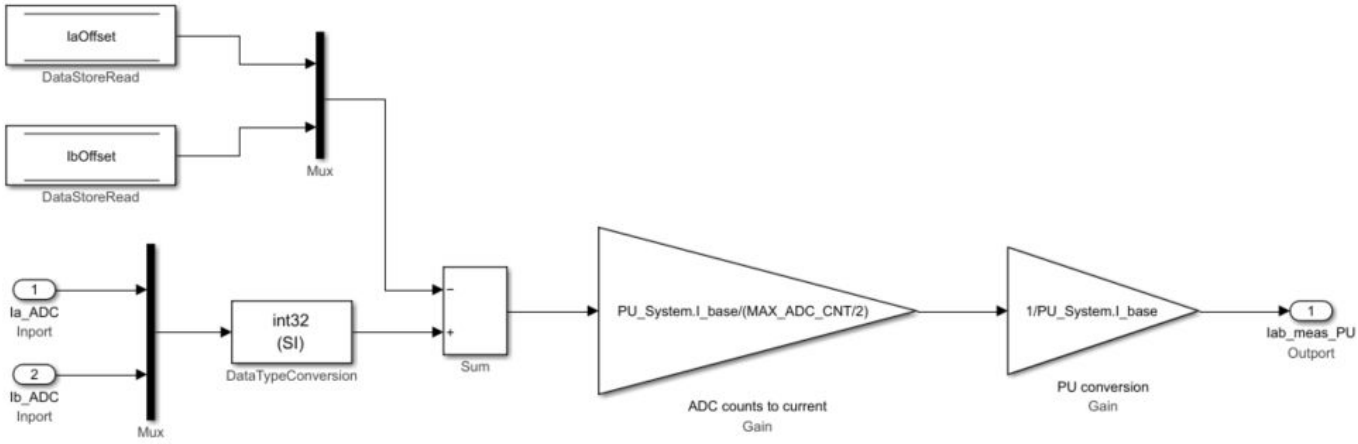
Tip A basic understanding of Simulink® is a prerequisite for following this workflow as these workflow steps do not provide details on tasks like defining a datatype in a constant block or using math operations blocks in Simulink.

See “Estimate PMSM Parameters Using Recommended Hardware” for estimating the motor parameters. Then, see “Creating Plant Model Using Motor Control Blockset” on page 3-2 to design a plant model. This helps you verify the control algorithm in simulation.

Design Current and Position Scaling Subsystems

Use these steps to design the current and position scaling subsystems:

1. Create the current scaling subsystem.



   This subsystem reads the current in ADC counts and converts it to per-unit (PU) values.

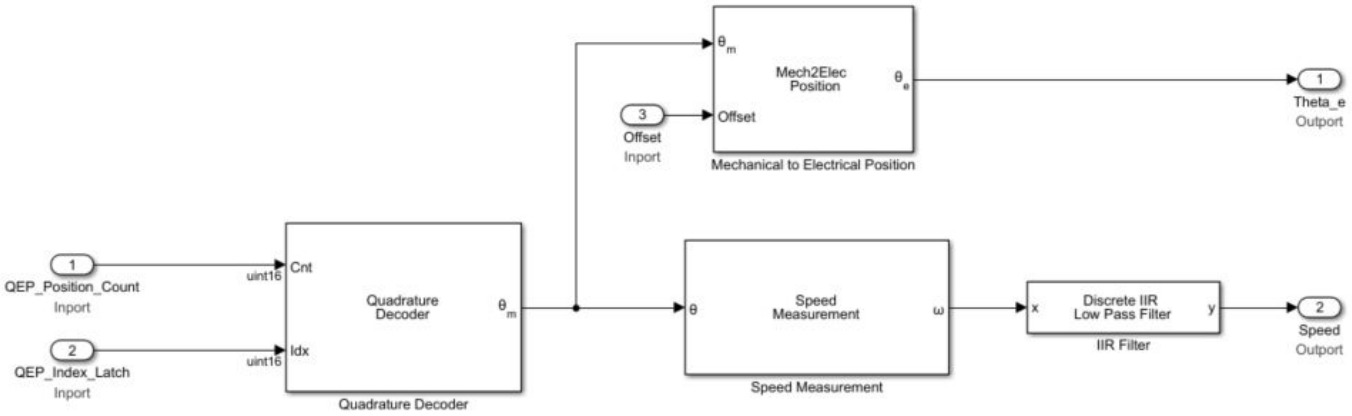
   In this subsystem, the *IaOffset* and *IbOffset* Data Store Memory blocks are the ADC offsets for current measurement and they are hardware specific. The file `mcb_SetInverterParameters.m` contains the default ADC offset (*CtSensAOffset* and *CtSensBOffset*) for few commercially available inverters. For details about ADC offset calibration in hardware, see “Run 3-Phase AC Motors in Open-Loop Control and Calibrate ADC Offset”.

   In this subsystem, the motor phase current measured in ADC counts is converted to current in PU. The `PU_System.I_base` value refers to the base current in this subsystem. For details about the PU system, see “Per-Unit System”. See the `mcb_SetPUSystem.m` file that computes the PU values for the system.

   You can use the base values for computing the real-world values from per-unit. To implement the real-world or SI unit values, see the model `mcb_pmsm_foc_qep_f28379d_SIUnit` used in the example “Field-Oriented Control of PMSM Using SI Units”.

   The *IaOffset* and *IbOffset* Data Store Memory blocks are used to share data between the current and position subsystems.

2. Create the position scaling subsystem.

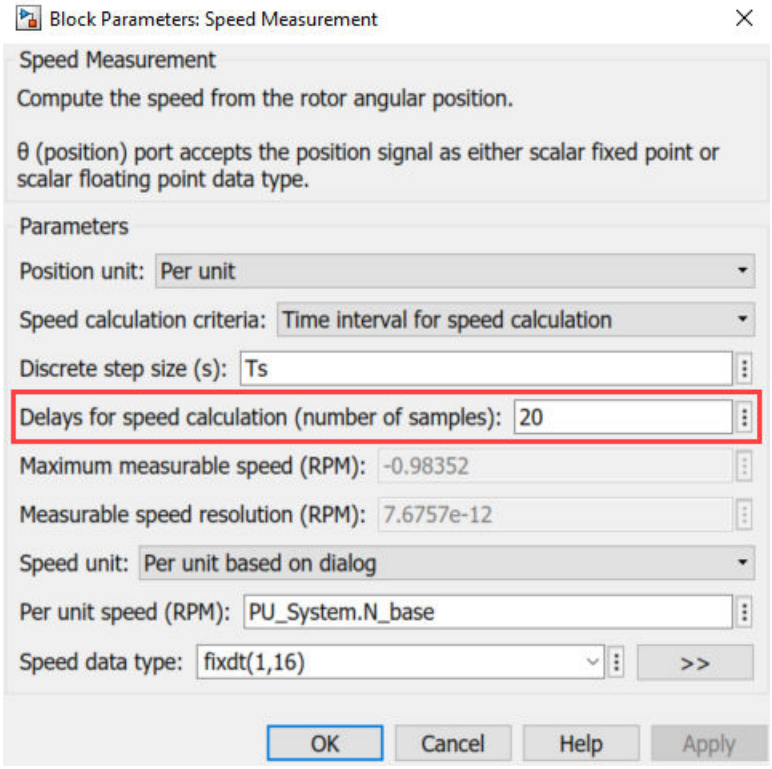


This subsystem reads the rotor position from the QEP pulse count.

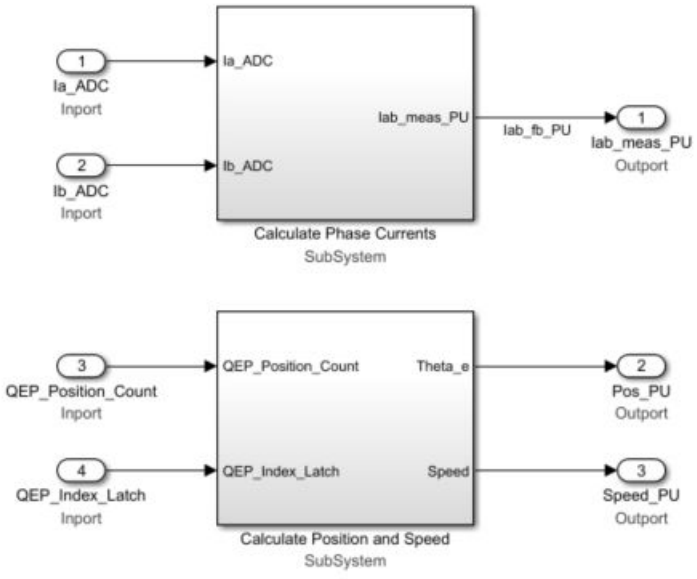
In this subsystem, the Quadrature Decoder block reads the position count from the plant model or hardware driver block. The block converts the rotor mechanical position in encoder position counts to rotor mechanical angle in PU (`0-1`).

The Mechanical to Electrical Position (Mech2Elec Position) block adjusts the rotor mechanical angle for QEP offset and converts it to electrical angle. The FOC algorithm needs the rotor electrical angle to run the motor. To calculate the QEP encoder offset, see “Quadrature Encoder Offset Calibration for PMSM Motor”.

The Speed Measurement block calculates speed from the rotor position. In the Speed Measurement block parameters dialog box, set the **Delays for speed calculation (number of samples)** parameter to `20`. We selected the value `20` in this workflow so that the block can measure the maximum speed of the motor that is under test. The Speed Measurement block outputs the speed in PU.



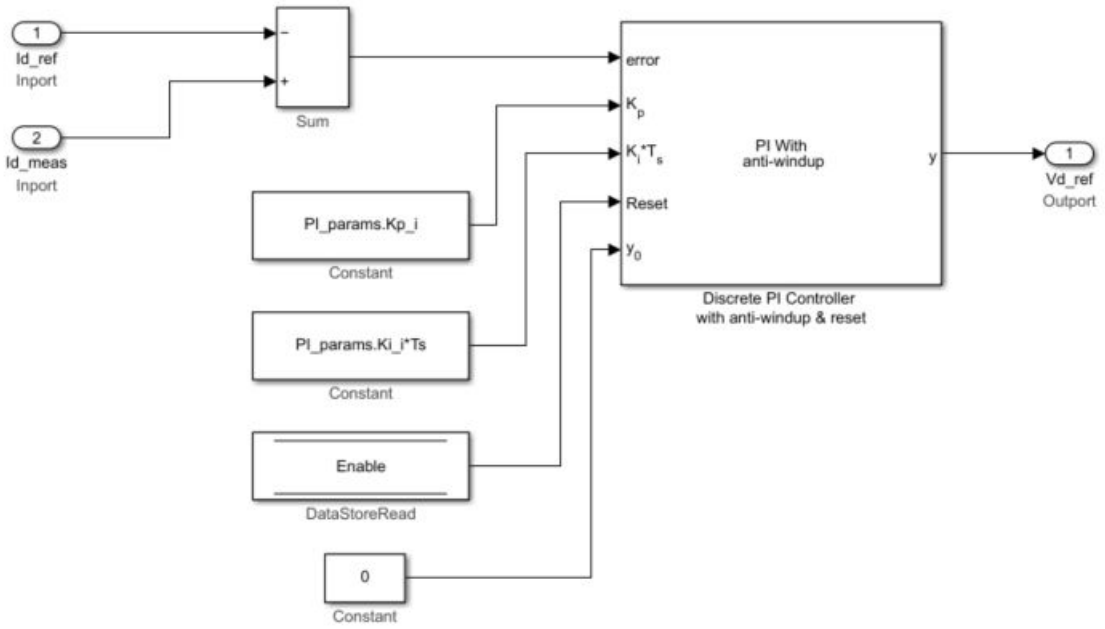
The resulting two subsystems (Calculate Phase Currents and Calculate Position and Speed) contain the current scaling and position decoding logic.



Design Current Controller Subsystem

Use these steps to design the current controller subsystem:

1. From the Motor Control Blockset library in the Simulink Library Browser, use the Discrete PI Controller with anti-windup & reset block (in the Controls/Controllers library) to design the *d*-axis and *q*-axis current control. For example, this image shows the *d*-axis current controller subsystem.



   The MATLAB® function `mcb.internal.SetControllerParameters` (in the model initialization script) calculates the PI control gains for the *d*-axis and *q*-axis current controller and the speed controller. For details about calculation of the controller gains, see "Estimate Control Gains and Use Utility Functions". For example, see the model initialization script file `mcb_pmsm_foc_qep_f28379d_data.m` (used in the example "Field-Oriented Control of PMSM Using Quadrature Encoder") that uses a sampling time (T_s) of `50` µs.

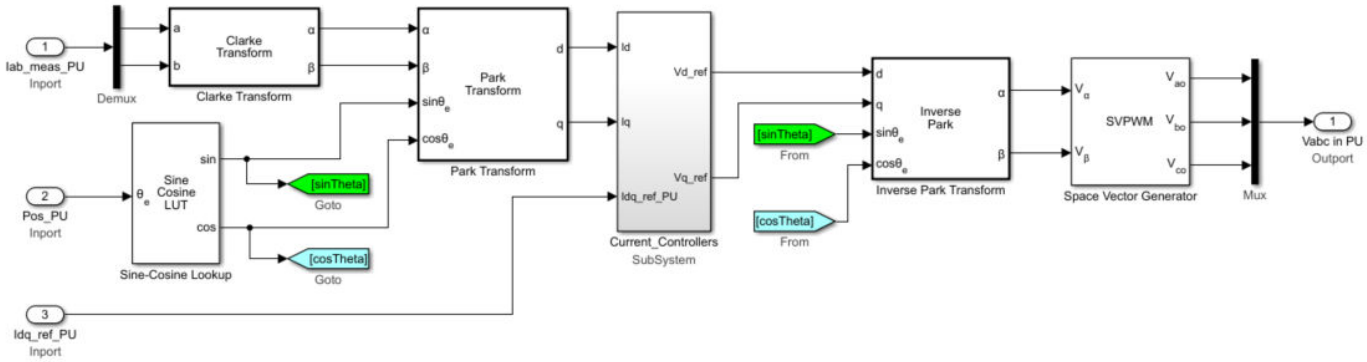
   In the subsystem diagram, the *Enable* variable is a Data Store Memory used to reset the controller. Adding *Enable* variable is optional.

   The subsystem also uses three constant blocks with these values:

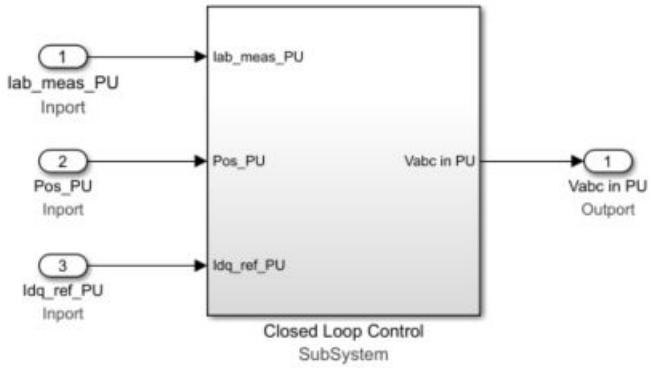
   - *PI_params.Kp_i*
   - *PI_params.Ki_i*Ts*
   - *0*

   Create a similar subsystem for the *q*-axis current PI controller. Integrate the subsystems for *d*-axis and *q*-axis PI controllers into a single subsystem (Current_Controllers) that controls the *d*-axis and *q*-axis currents.

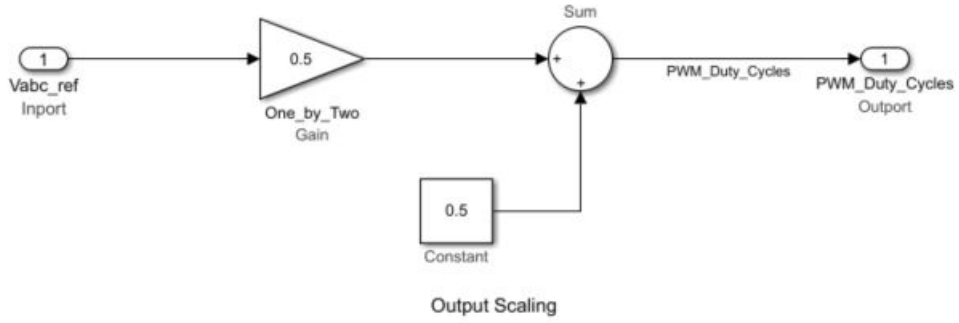
2. Add the Clarke Transform, Park Transform, Inverse Park Transform, and Space Vector Generator blocks from the `Motor Control Blockset/Controls/Math Transforms` library to the Current_Controllers subsystem (that you created in step 1) as shown in this figure.



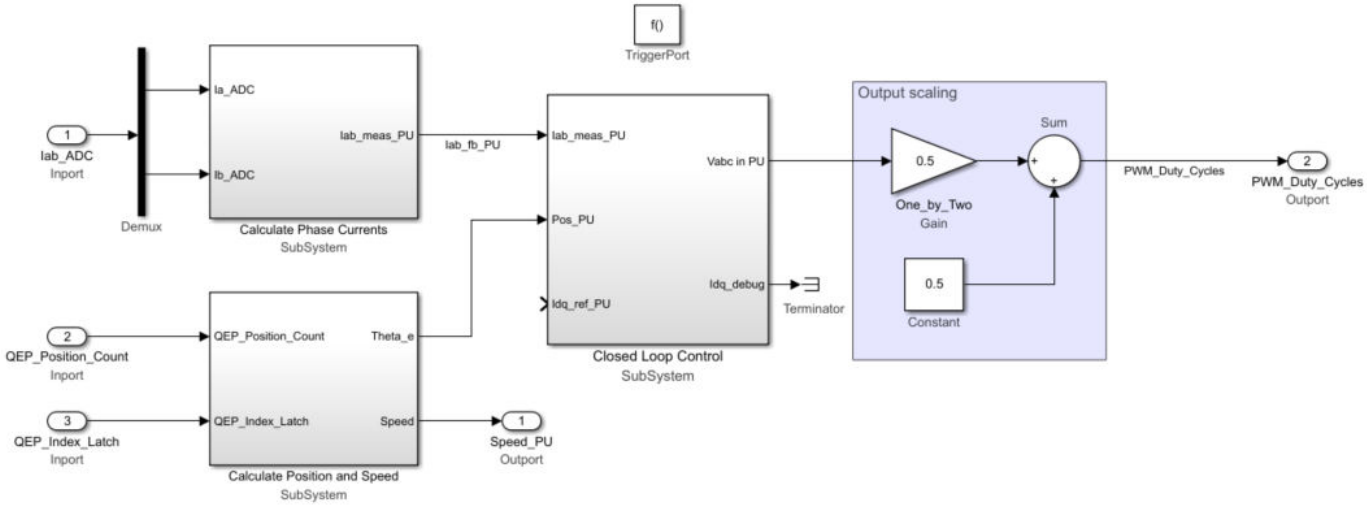
3 Integrate the components that you created in step 2 into a single subsystem (Closed Loop Control that implements closed loop field-oriented control) as shown in this figure.



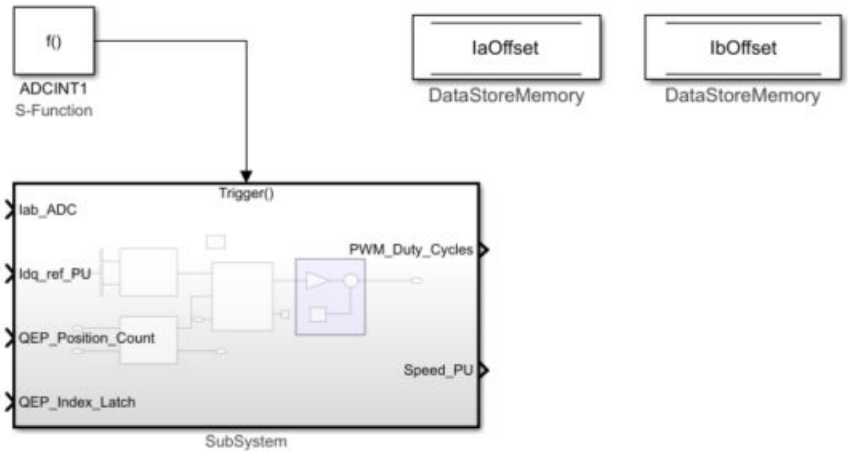
4 Create an Output Scaling subsystem to scale the Pulse Width Modulation (PWM) outputs. This subsystem outputs the normalized PWM duty cycles (`0-1`) for the plant model.



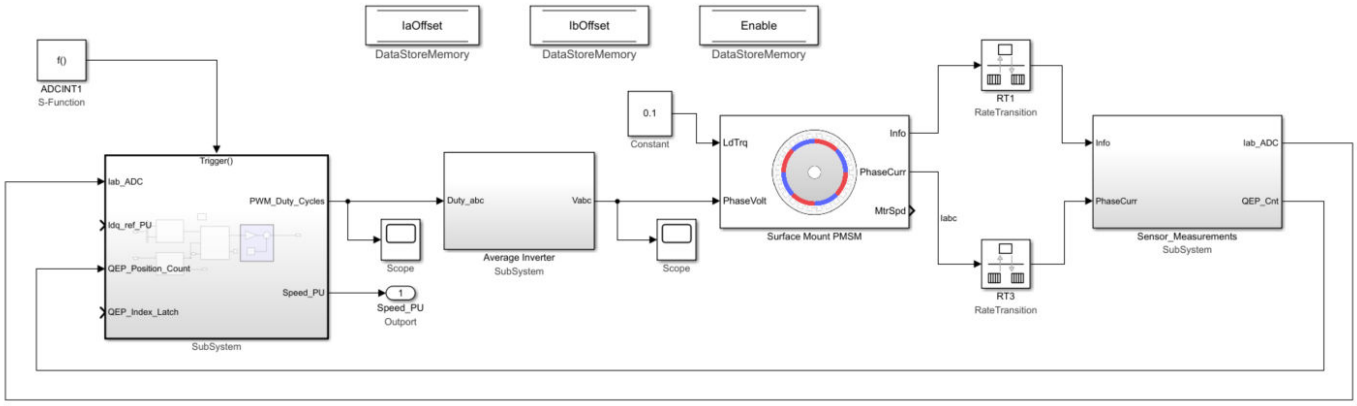
5 Create a new subsystem by integrating the current scaling (Calculate Phase Currents), QEP position decoding (Calculate Position and Speed), Closed Loop Control, and Output Scaling subsystems. Add the Trigger block from the `Simulink/Ports & Subsystems` library to this subsystem and set the **Trigger type** parameter to `function-call`.



6 Add a Function-Call Generator block from the `Simulink/Ports & Subsystems` library to the subsystem created in step 5. Set the **Sample time** parameter of the block to equal the control-loop sample time, T_s (that has a default value of `50e-6` s).



7 Integrate the plant model and the controller subsystem that you created in step 6. For detailed steps on how to create a plant model for a motor control system, see “Creating Plant Model Using Motor Control Blockset” on page 3-2.

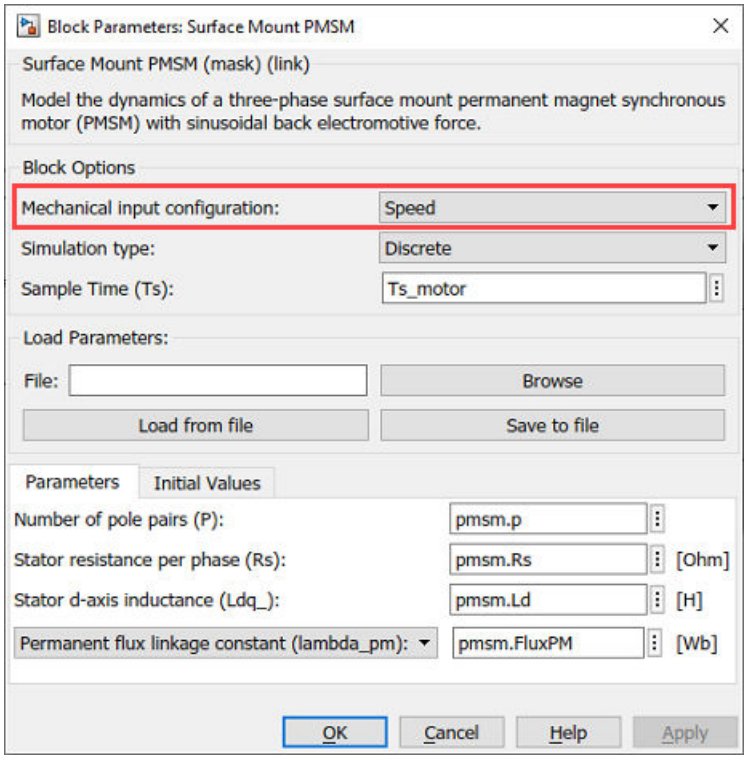

f()
ADCINT1
S-Function
IaOffset
DataStoreMemory
IbOffset
DataStoreMemory
Enable
DataStoreMemory
0.1
Constant
Trigger()
Iab_ADC
Idq_ref_PU
QEP_Position_Count
QEP_Index_Latch
PWM_Duty_Cycles
Speed_PU
SubSystem
Scope
1
Speed_PU
Outport
Duty_abc
Vabc
Average Inverter
SubSystem
Scope
LdTrq
PhaseVolt
Info
PhaseCurr
MtrSpd
Surface Mount PMSM
Iabc
RT1
RateTransition
RT3
RateTransition
Info
Iab_ADC
PhaseCurr
QEP_Cnt
Sensor_Measurements
SubSystem

Perform Manual Gain-Tuning of Current Controller

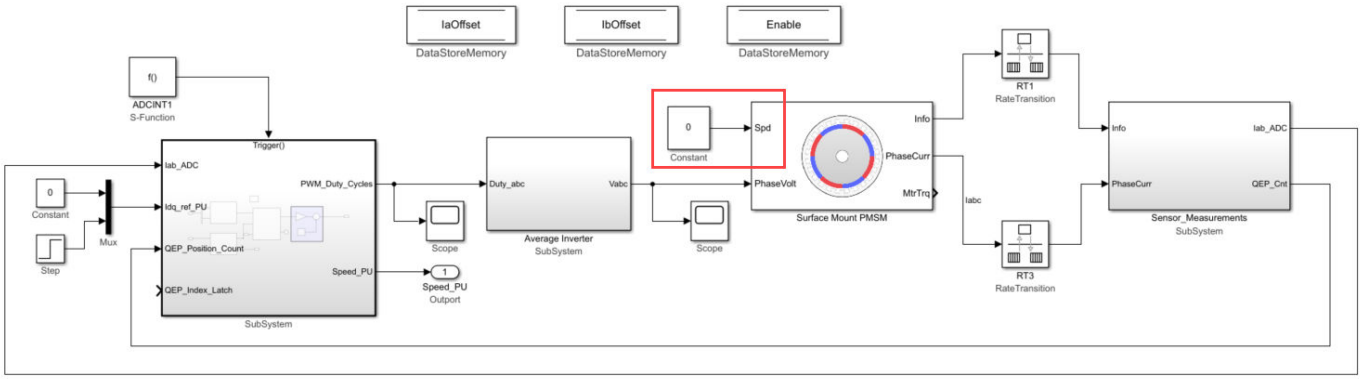
This step shows you how to manually tune the gains of the *d*-axis and *q*-axis current controllers. This step is optional, however you can use it to tune the control gain parameters.

The procedure includes adding a step change to the `Id_ref` current and analyzing the current controller performance using the step response of the `Id_meas` current to tune the *d*-axis current controller. It explains a similar process for the `Iq_ref` current to tune the *q*-axis current controller.

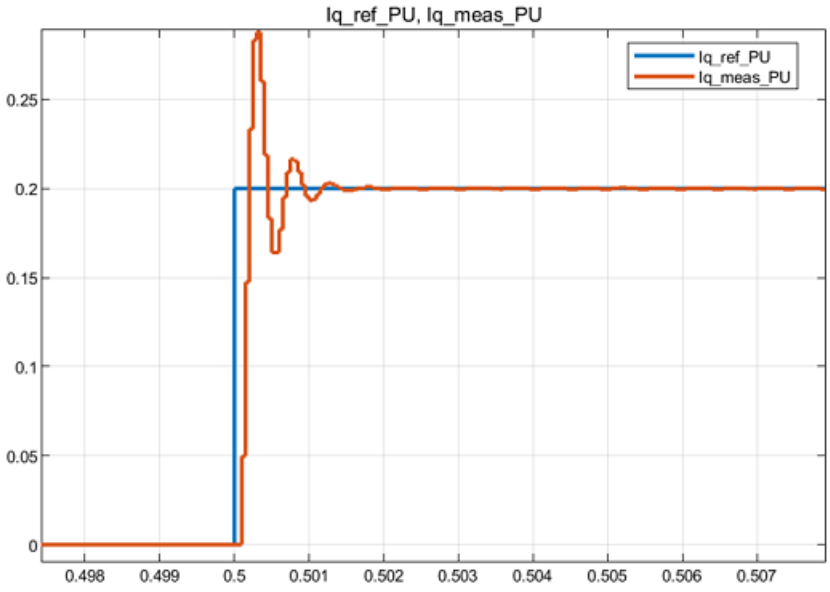
Before starting the manual tuning procedure, you should lock the rotor in the plant model to ensure that the motor does not run when you provide a step change to `Id_ref` or `Iq_ref` currents. In the Surface Mount PMSM block parameters dialog box, set the **Mechanical input configuration** parameter to `Speed`. Set the **Spd** input (of the Surface Mount PMSM block) to `0` to ensure that the rotor is locked.



The integrated plant and controller subsystem simulation model enables you to manually tune the gains of the current controllers. Provide a step input to `Iq_ref` in the range (`0` to `0.2`) PU and observe the measured `Iq_meas` current feedback. Adjust the control parameters of the *q*-axis current controller to meet your control objectives.



Simulate the model and plot the `Iq_ref_PU` and `Iq_meas_PU` current signals and analyze the step response. This helps you to tune the control parameters for the *q*-axis current controller to meet the control objectives.



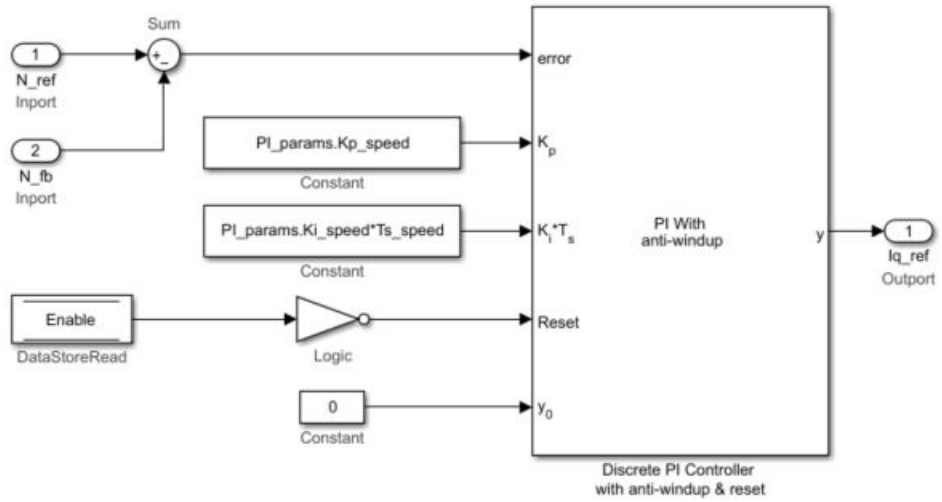
Follow the same procedure for the `Id_ref` current to tune the *d*-axis current controller. After tuning both current controllers, set the **Mechanical input configuration** parameter, in the Surface Mount PMSM block parameters dialog box, back to `Torque`.

Design Speed Control Algorithm

Use these steps to design a speed control algorithm:

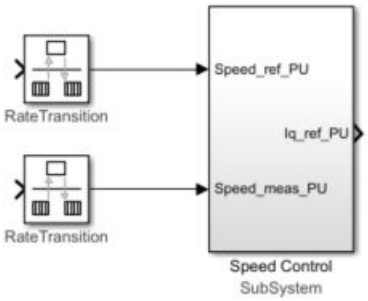
1. Create a speed controller subsystem. The current controller subsystem that you created earlier uses the `Iq_ref` current output of the speed controller subsystem as an input.

   To create a speed controller subsystem, open the Simulink Library Browser and select the Discrete PI Controller with anti-windup & reset block from the `Motor Control Blockset/Controls/Controllers` library.



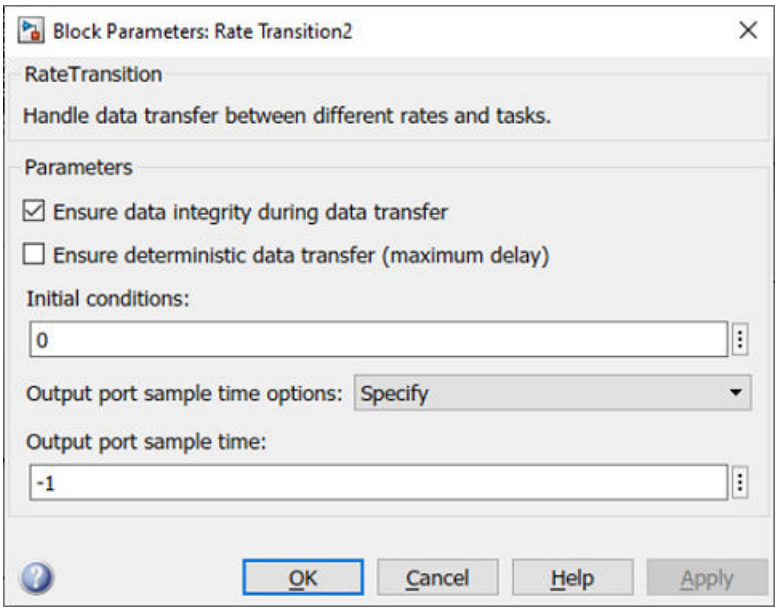
   The MATLAB function `mcb.internal.SetControllerParameters` (in the model initialization script) calculates the PI control gains for the *d*-axis and *q*-axis current controller and the speed controller. For details about calculation of the controller gains, see “Estimate Control Gains and Use Utility Functions”. For example, see the model initialization script file `mcb_pmsm_foc_qep_f28379d_data.m` (used in the example “Field-Oriented Control of PMSM Using Quadrature Encoder”) that uses a sampling time (*Ts_speed*) of `500` µs. Optionally, you can use the **Enable** Data-Store Memory block to reset the controller.

2. Create a subsystem for the speed controller and add Rate Transition blocks (from the `Simulink/Signal Attributes` library) to the subsystem inputs with a sample time of *Ts_speed* (execution time of the speed control loop).

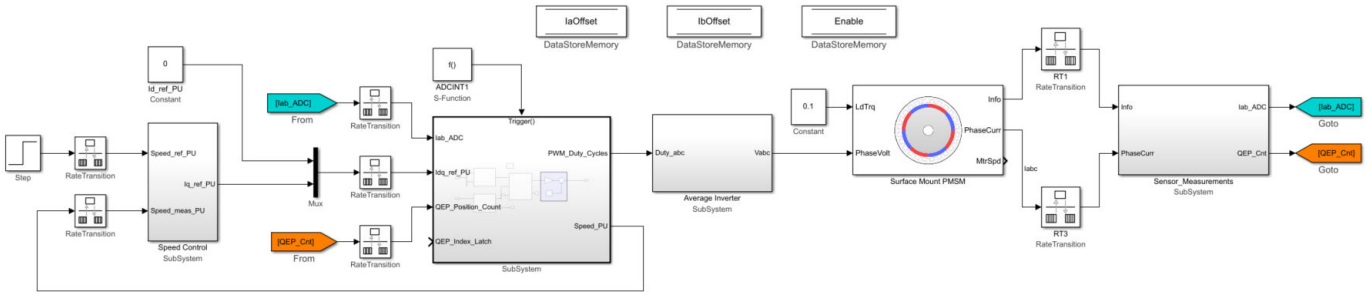


3. Integrate the speed controller subsystem (that you created in step 2) with the integrated current controller and plant model subsystems. Connect the **Iq_ref_PU** output port of the speed

controller subsystem to the current controller subsystem input port through a Rate Transition block. The Rate Transition block is needed because the two ports execute at different sample rates. This figure shows an example of the parameter settings of the Rate Transition block connected to the speed controller and the current controller subsystems.



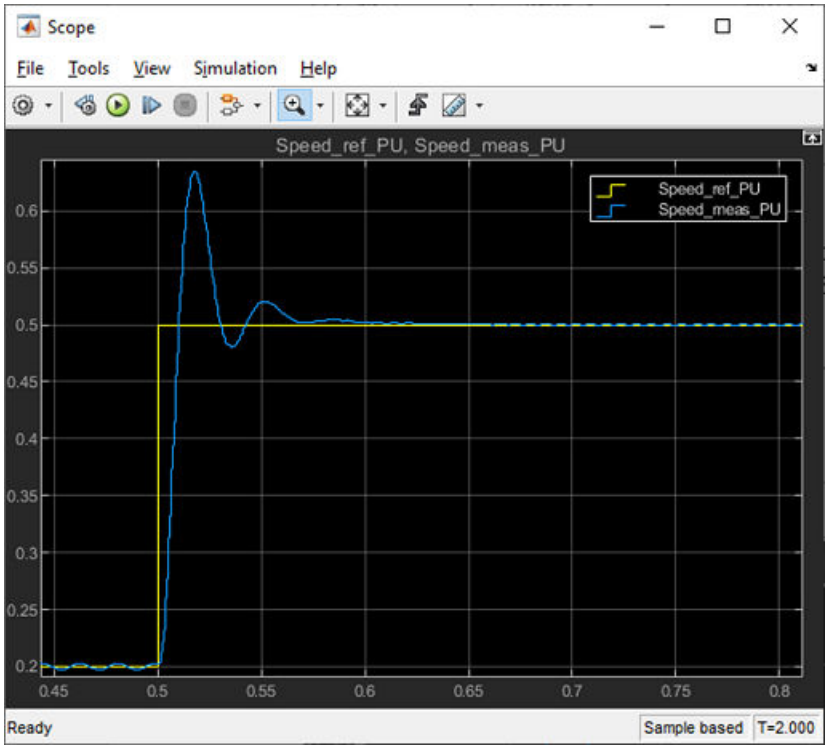
This figure shows the integrated speed controller, current controller, and plant model subsystems.



Perform Manual Gain-Tuning of Speed Controller

To manually tune the speed controller subsystem, provide a step input (in the range `0.2` to `0.5` PU) to the `Speed_ref_PU` input in the speed controller subsystem (Speed Control). Monitor the measured speed step response `Speed_meas_PU` and adjust the speed controller subsystem parameters to meet your control objectives.

This figure shows the step response of the speed controller.



This procedure shows a method to implement speed control for a PMSM in simulation. Run the simulation and analyze the controller performance.

You can generate C code from this control algorithm using Embedded Coder®. In addition, you can deploy this code and the hardware drivers to the target hardware.

Code Verification and Profiling Using PIL Testing

In processor-in-the-loop (PIL) simulation, the control algorithm executes in the target hardware, but the plant model runs on the host machine. The plant model simulates the input and output signals for the controller and communicates with the controller by using the serial communication interface. This functionality allows you to use PIL simulation to determine the execution time on the target hardware, which you can then compare with the execution time for simulating the model on the host machine.

The execution time, or the performance metric of an algorithm that you obtain from PIL simulation, helps you detect algorithm overrun on the target hardware. The PIL profiling report shows the average and maximum execution times of an algorithm on the target hardware. This example explains PIL profiling on Texas Instruments™ LAUNCHXL-F28379D hardware board.

This example uses the `mcb_pmsm_foc_sim.slx` model to show code verification in PIL simulation. This example shows PIL profiling for the Current Control subsystem in the model. This subsystem includes the Field-Oriented Control (FOC), current scaling (per-unit conversion), speed measurement, and rotor position scaling (computation of angle from the encoder position counts) algorithms. The PIL profiling report shows the average and maximum execution times of the control algorithm in the target hardware.

This example consists of these tasks:

- Verify code execution by using PIL testing by comparing the algorithm in the simulation and target hardware operating modes.
- Perform PIL profiling by measuring the algorithm execution time in the target hardware and generate the PIL profiling report.

Required MathWorks Products

- Embedded Coder
- Embedded Coder Support Package for Texas Instruments C2000™ Processors

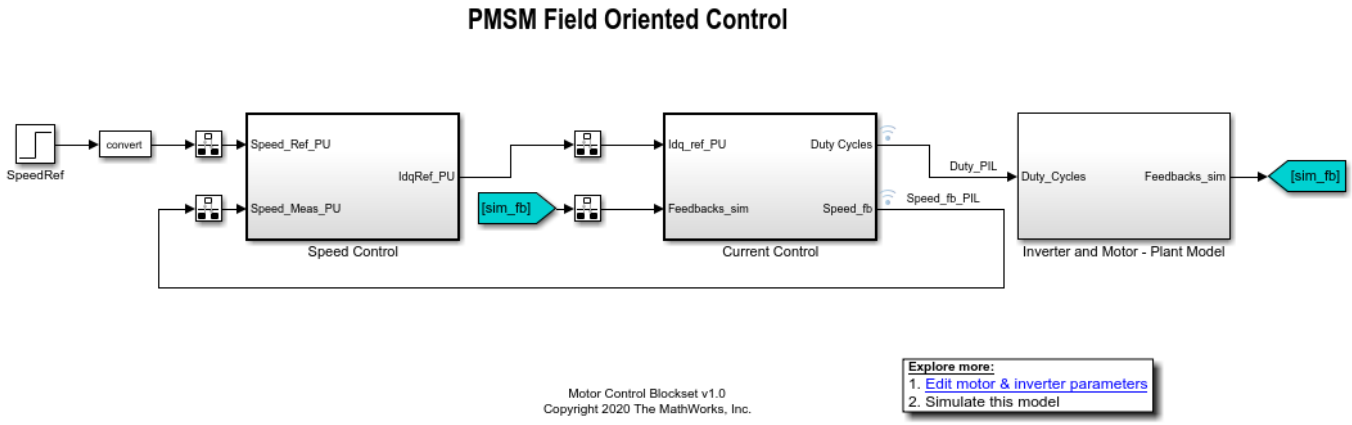
Supported Hardware

- LAUNCHXL-F28379D controller hardware board

Prepare PIL Model

1 Open the `mcb_pmsm_foc_sim.slx` model.

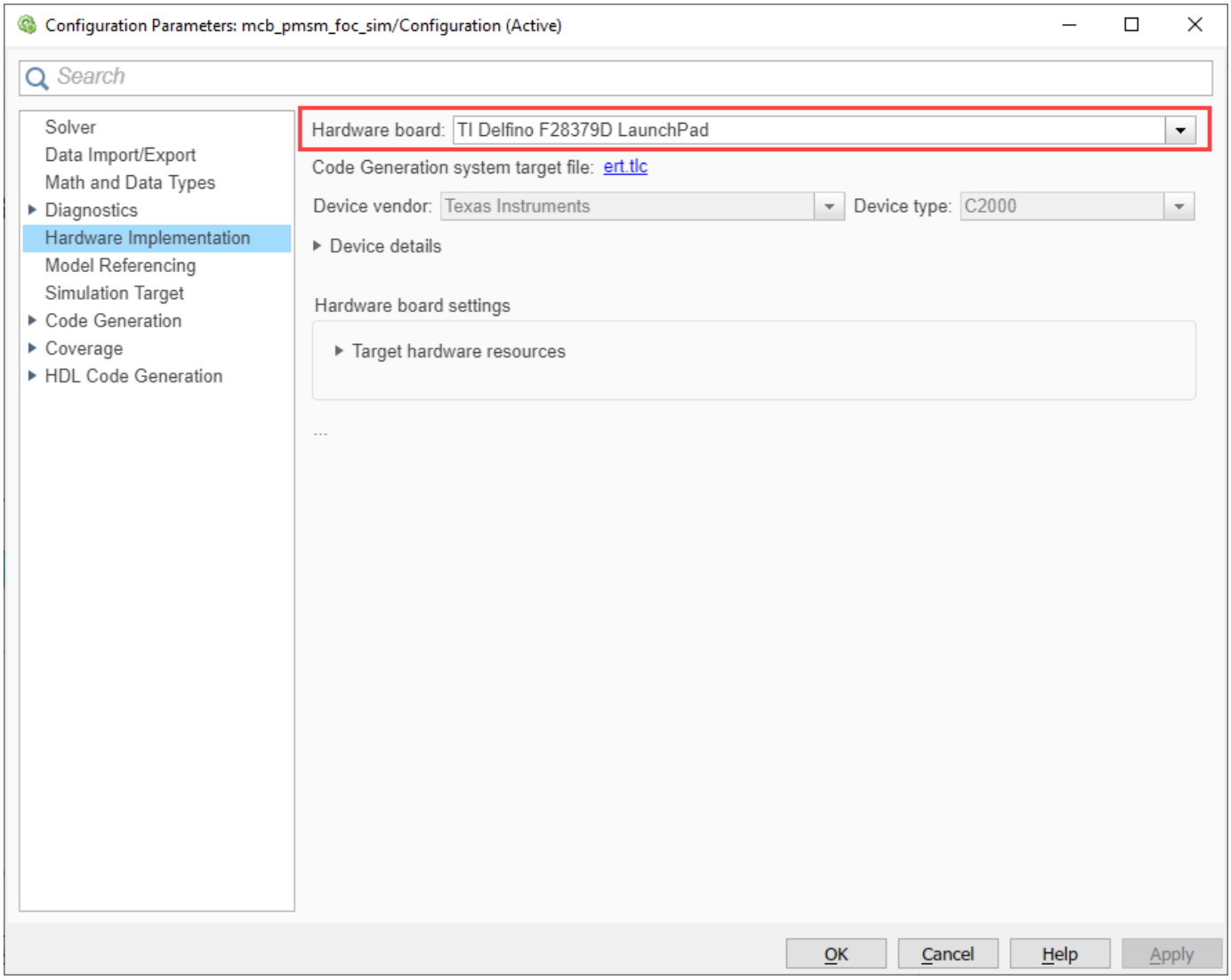
```
open_system('mcb_pmsm_foc_sim.slx');
```



This model simulates the PMSM motor and the FOC algorithm for closed-loop speed control.

2 On the **Hardware** tab of the Simulink toolstrip, click **Hardware Settings**.

3 In the **Configuration Parameters** dialog box, under **Hardware Implementation**, set the **Hardware board** field to `TI Delfino F28379D LaunchPad`.



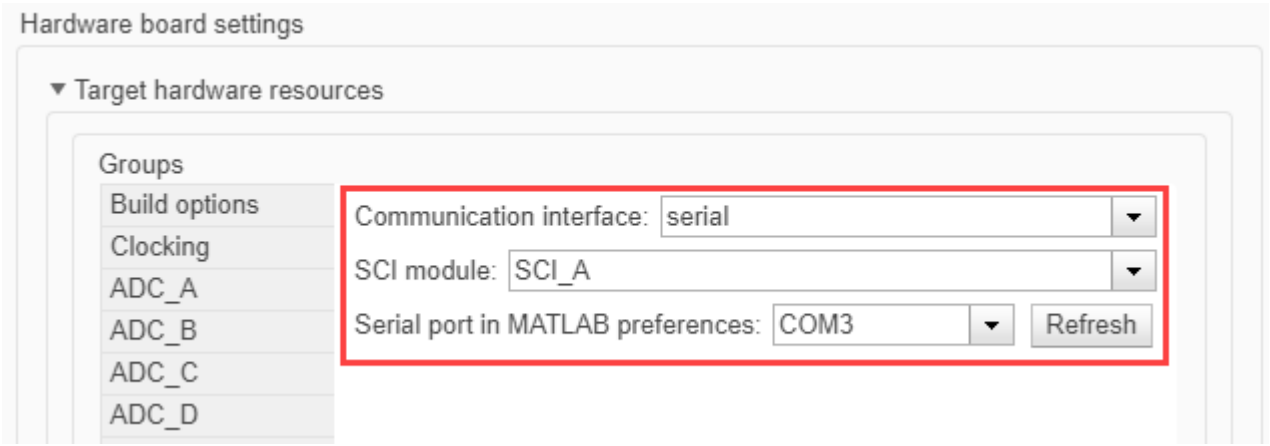
Verify Code by Using PIL

1 In the Configuration Parameters dialog box, select these configuration settings under **Hardware Implementation > Hardware board settings > Target hardware resources > PIL**:

   a **Communication Interface** — Select `serial`.

   b **SCI module** — Select `SCI_A`.

   c **Serial port in MATLAB preferences** — The model automatically detects the communication port to which you have connected the hardware. This parameter remains unchanged for the rest of the currently active MATLAB session. Click the **Refresh** button to detect the communication port again.



2 Open the `mcb_PIL_config_TI.m` script file to set the configuration parameters.

```
edit('mcb_PIL_config_TI.m');
```

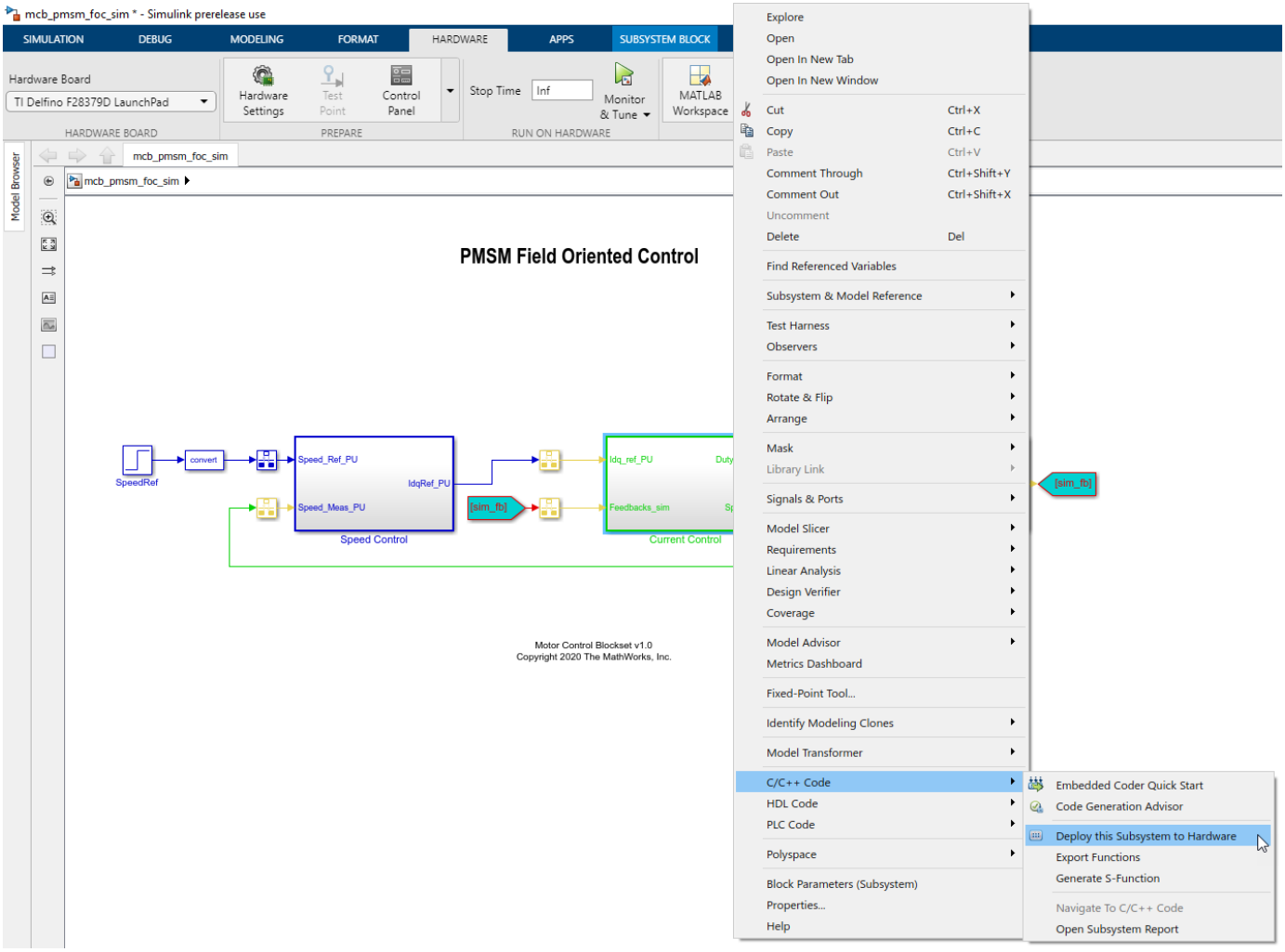
3 Update the model name and stop time in the script.

mcb_PIL_config_TI.m

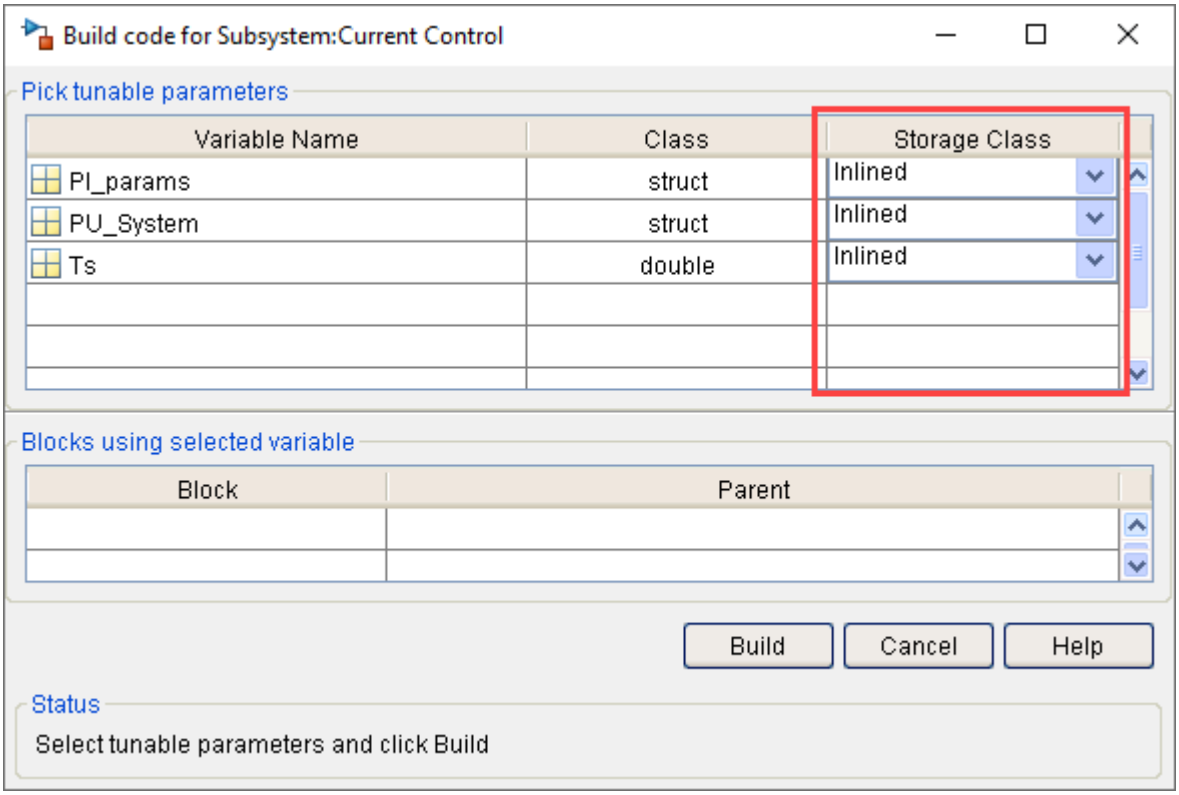
```
% mcb_PIL_config_TI initializes the congiuration parameter for PIL profiling
%
% For PIL profiling, update the below in MATLAB script
% model - name of the model identified for PIL profing
% StopTime - time required for profiling. Ensure algorithm reaches steady
% state within this specified time.
%
% This code is tested for TI LAUNCHXL-F28379D (TMS320F28379d)
%
% Note: Before running the script, ensure COM port is updated in
% config set->hardware implementation->Target hardware resources->PIL
%
% Copyright 2020 The MathWorks, Inc.

model = 'mcb_pmsm_foc_sim';
set_param(model,'StopTime','0.5');
set_param(model,'SimulationMode','normal');
set_param(model,'ReturnWorkspaceOutputs','on');
set_param(model,'CodeExecutionProfiling','on');
set_param(model,'CodeProfilingInstrumentation','coarse');
set_param(model,'CodeProfilingSaveOptions','SummaryOnly');
set_param(model,'CreateSILPILBlock','PIL');
set_param(model,'DefaultParameterBehavior','Inlined');

```

4 Run the script to update the configuration parameters of the simulation model and the PIL preferences.

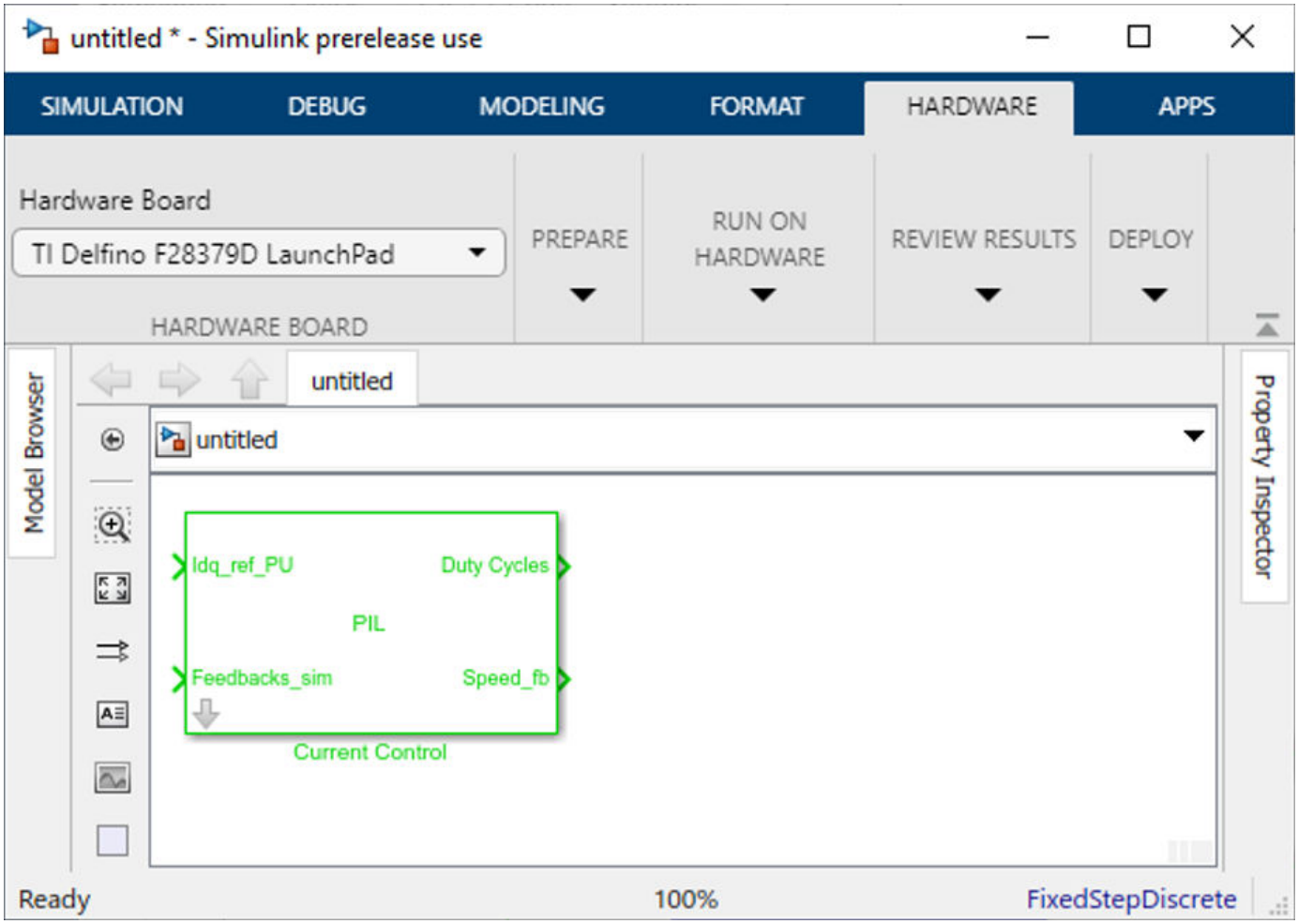
5 Right-click the Current Control subsystem in the `mcb_pmsm_foc_sim.slx` example model. Under the **C/C++ Code** menu, select **Deploy this Subsystem to Hardware**.



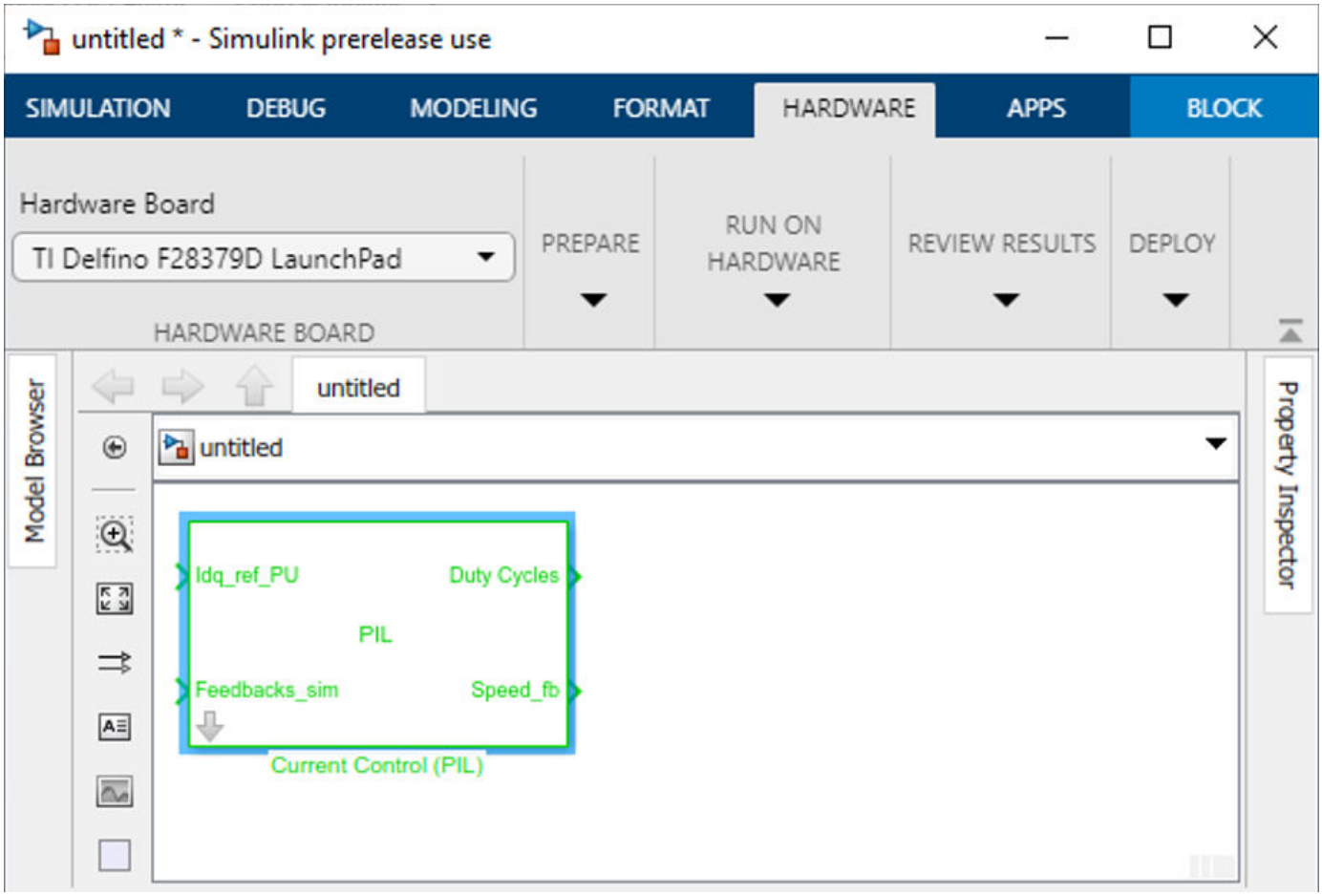
The system displays the **Build code for Subsystem** dialog box. Set the Storage Class to `Inlined` for all parameters.



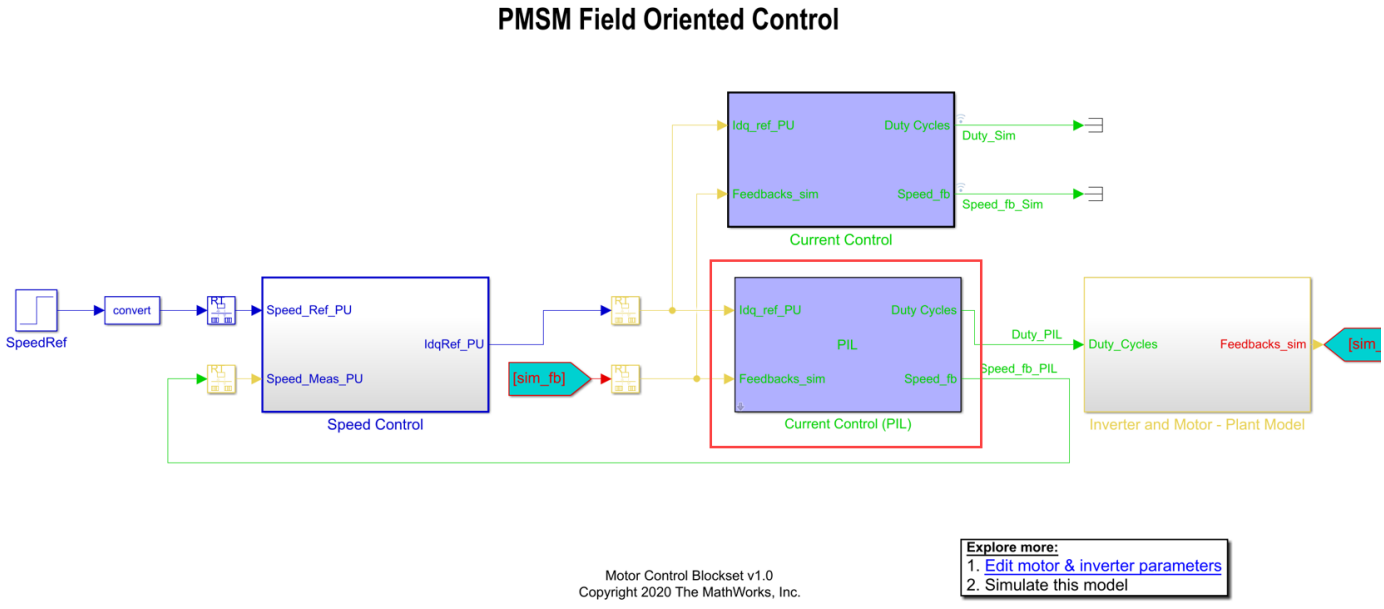
6 Click **Build** to create a model named `untitled` that includes a PIL subsystem called Current Control.



7 Rename the Current Control subsystem to Current Control (PIL).

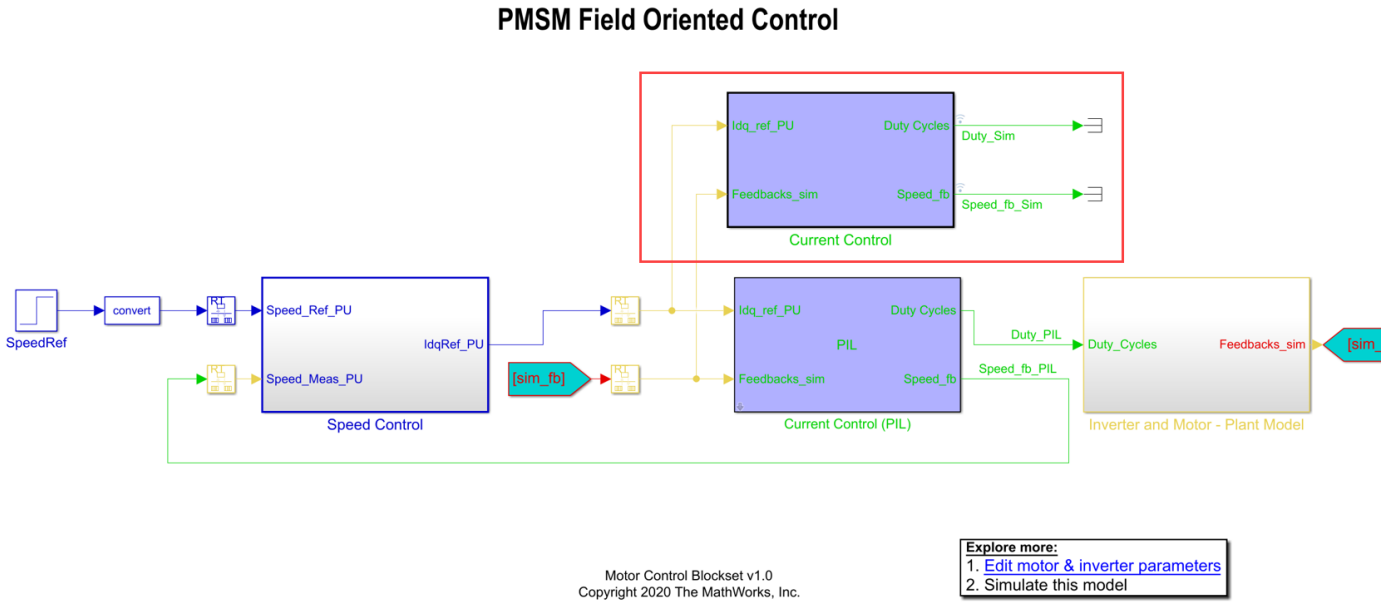


8 Copy the Current Control (PIL) subsystem and replace the Current Control subsystem in the `mcb_pmsm_foc_sim.slx` example model.

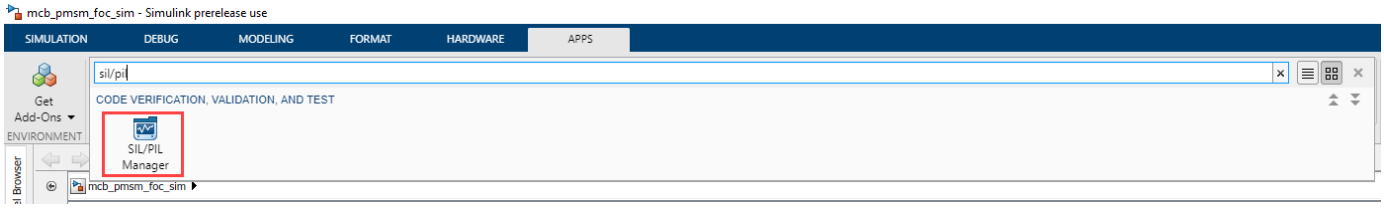


In the PIL mode, the system deploys the Current Control (PIL) subsystem to the target and executes the subsystem in the target hardware.

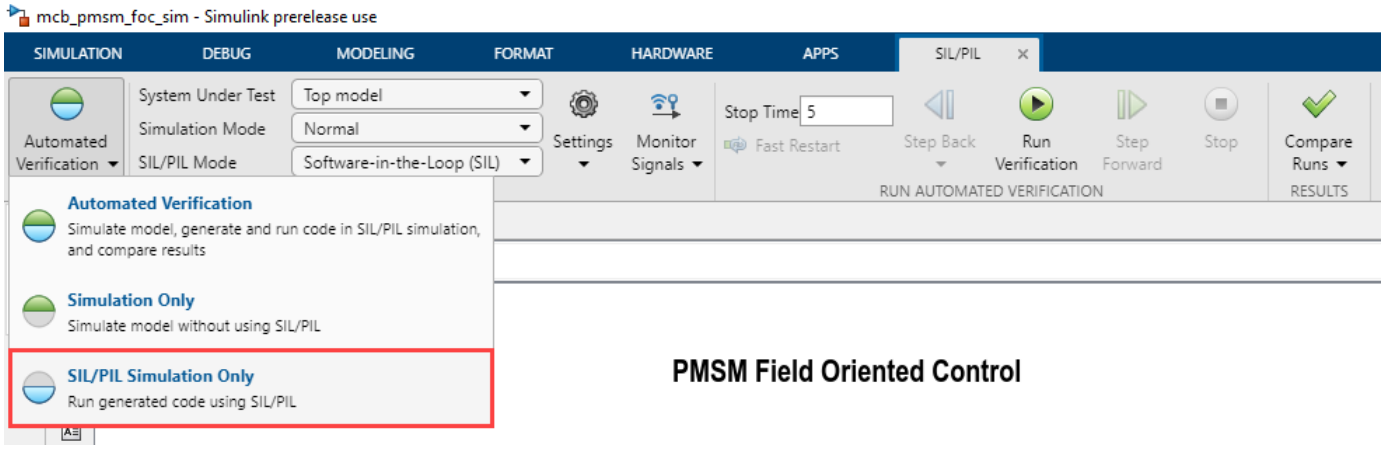
9 To compare the algorithm execution on the host machine simulation and in the PIL simulation, connect the Current Control subsystem parallely to the Current Control (PIL) subsystem. In addition, enable signal logging in the subsystem outputs.



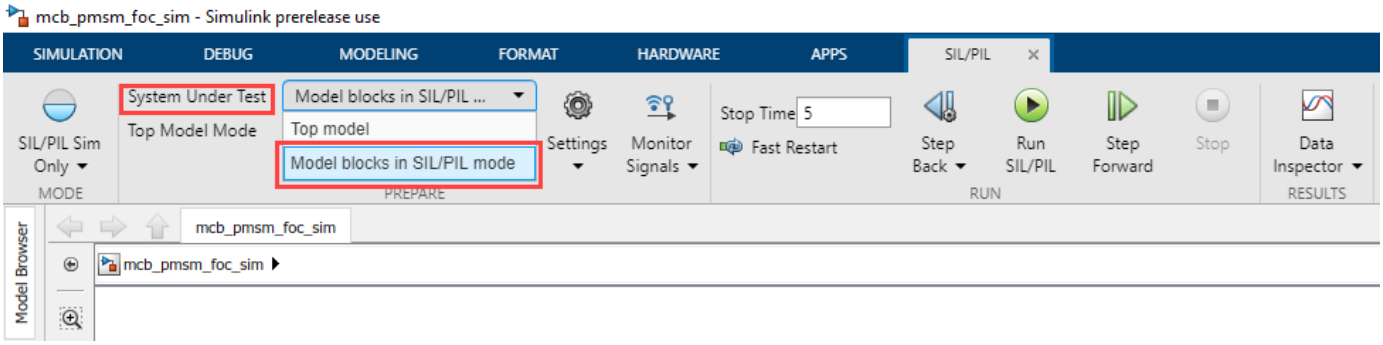
10 On the Simulink toolstrip, select the **SIL/PIL Manager** app from the **Apps** tab.



11 On the **SIL/PIL** toolstrip, select `SIL/PIL Sim Only`.



12 Select `Model blocks in SIL/PIL mode` in the **System Under Test** field.



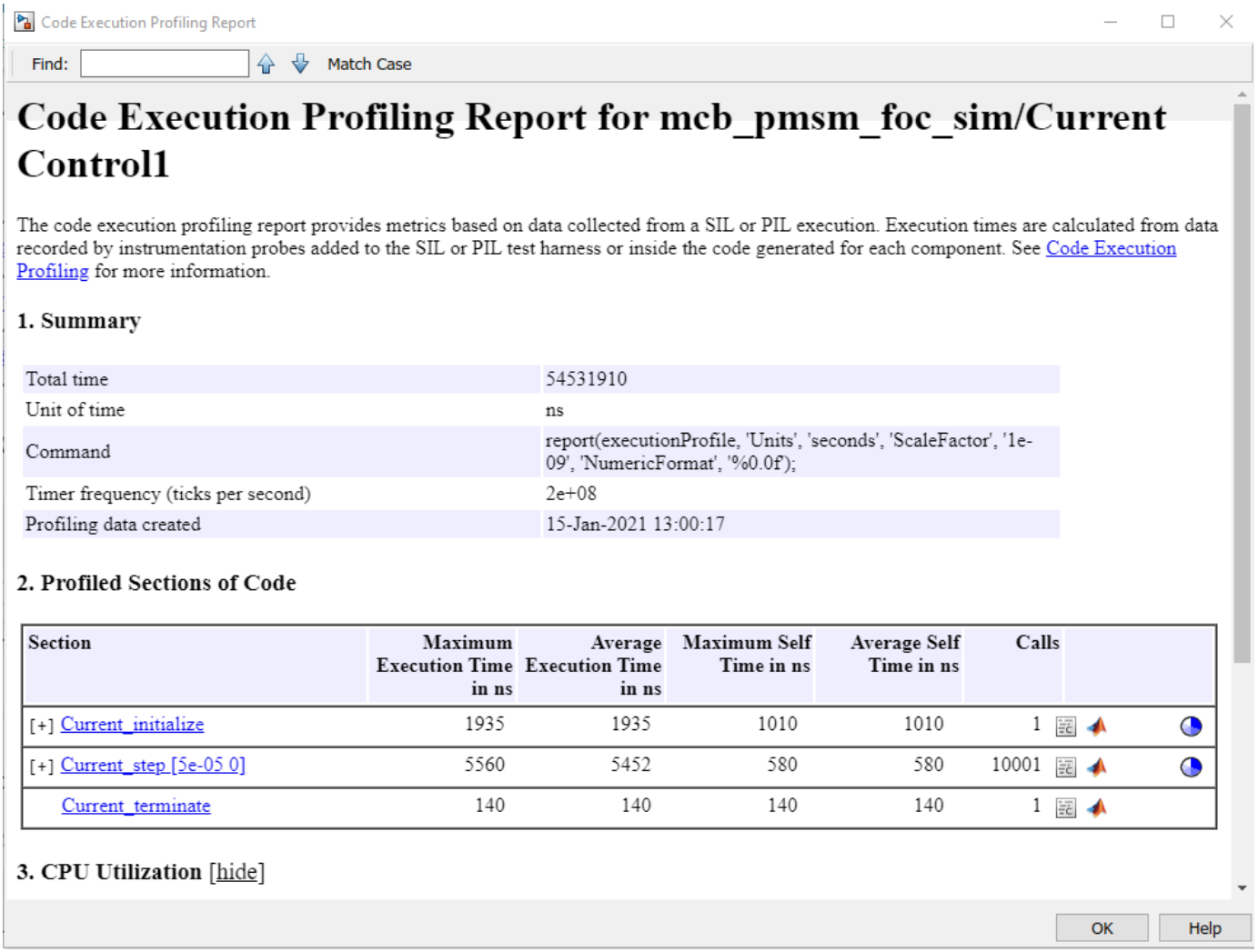
13 Click **Run SIL/PIL** on the **SIL/PIL** toolstrip to build the Current Control (PIL) subsystem and deploy it to the target.

After the system deploys the subsystem, the Current Control (PIL) subsystem executes on the target hardware processor, while the plant model runs on the host machine.

Analyze PIL Profiling Results

When PIL simulation ends, the system generates a profiling report.

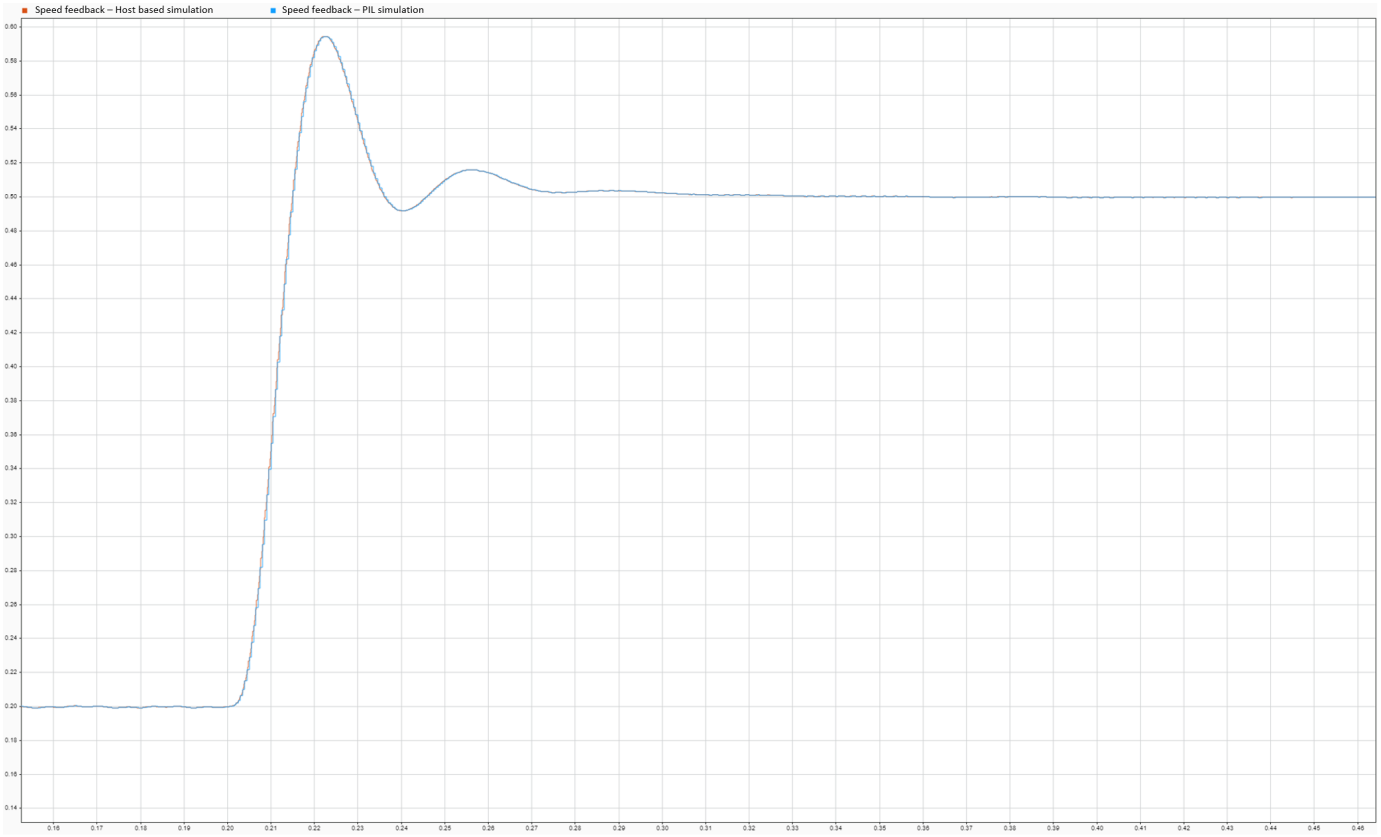
Note PIL simulation takes more time than the host-machine-based simulation. This is because of the serial communication (related to inputs and outputs of the Current Control (PIL) subsystem) between the host machine and subsystem that runs on the target hardware.



This profiling report, which is for the fixed-point datatype, shows the maximum and average execution times of the Current Control (PIL) subsystem running on the target hardware.

You can use the **Data Inspector** button on the **Simulation** tab to compare the signals logged during host-machine-based simulation and PIL simulation (executed on the target). This helps you verify the accuracy of host-machine-based simulation and PIL simulation.

This plot compares the speed feedback signals from the Current Control (PIL) and Current Control subsystems.



If the execution time exceeds 60% of the budgeted time, you can optimize the algorithm using one of these techniques:

- Execute from RAM.
- Offload some functionalities to CLA or other CPUs.
- Scale the algorithm to run at every alternate cycle.
- Move less critical functionalities like speed calculation to a slower rate.

For more details on SIL/PIL code verification, see:

- Code Verification and Validation with PIL
- Code Execution Profiling with SIL and PIL
- SIL/PIL Manager Verification Workflow

PMSM Drive Characteristics and Constraint Curves

This example shows how to use the PMSM characteristic plotting and PMSM milestone speed identification functions to obtain a control trajectory.

PMSM Drive Characteristics and Constraint Curves

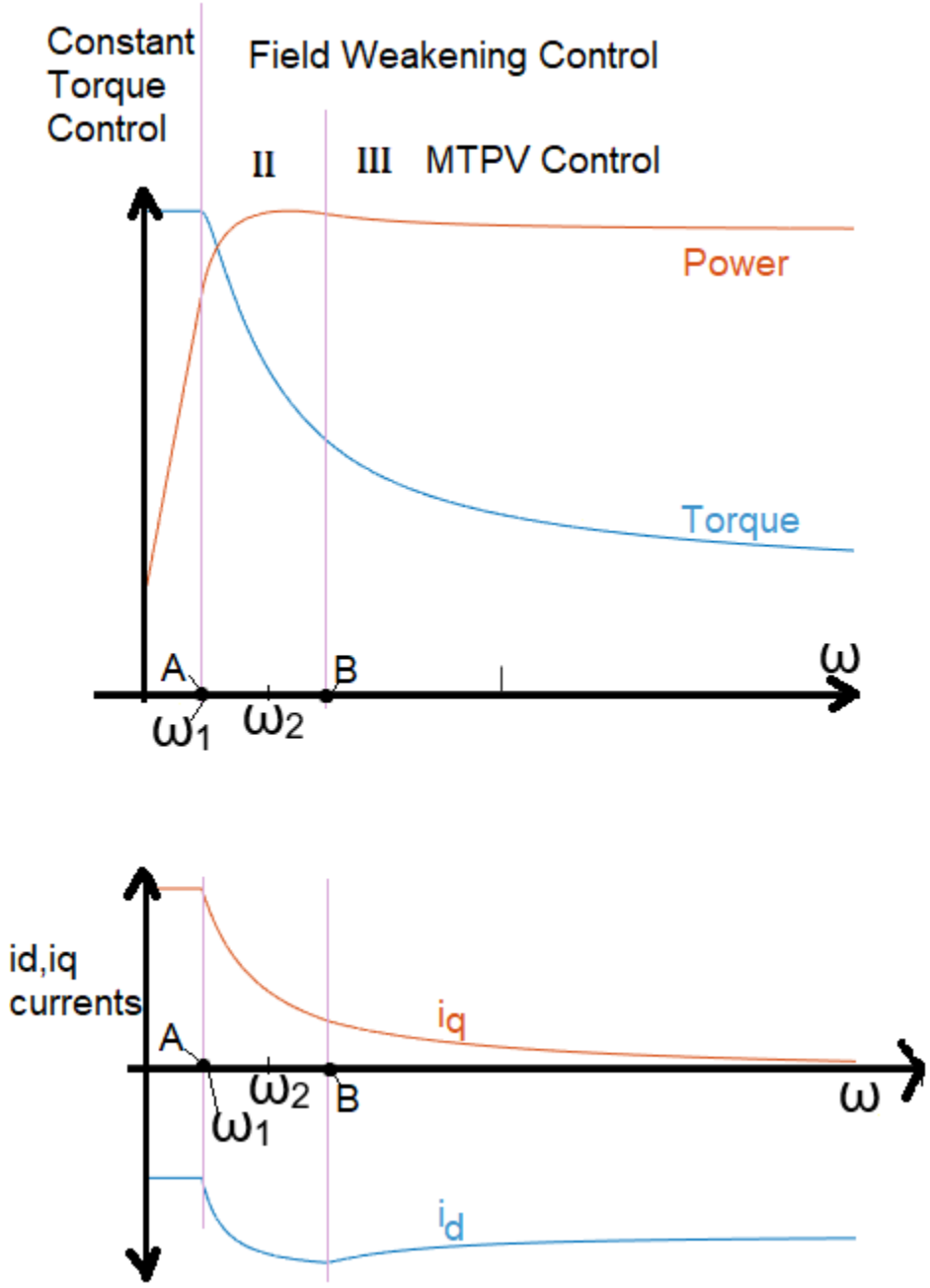
The permanent magnet synchronous motors (PMSMs) come in different configurations.

- When the permanent magnets (PMs) are mounted on the surface of the rotor, the motor is called a surface-mounted PMSM (SPMSM).
- When the PMs are embedded inside the rotor below the surface, the motor is called an interior PMSM (IPMSM).

Various parameters affect whether you select an SPMSM or IPMSM for a given application.

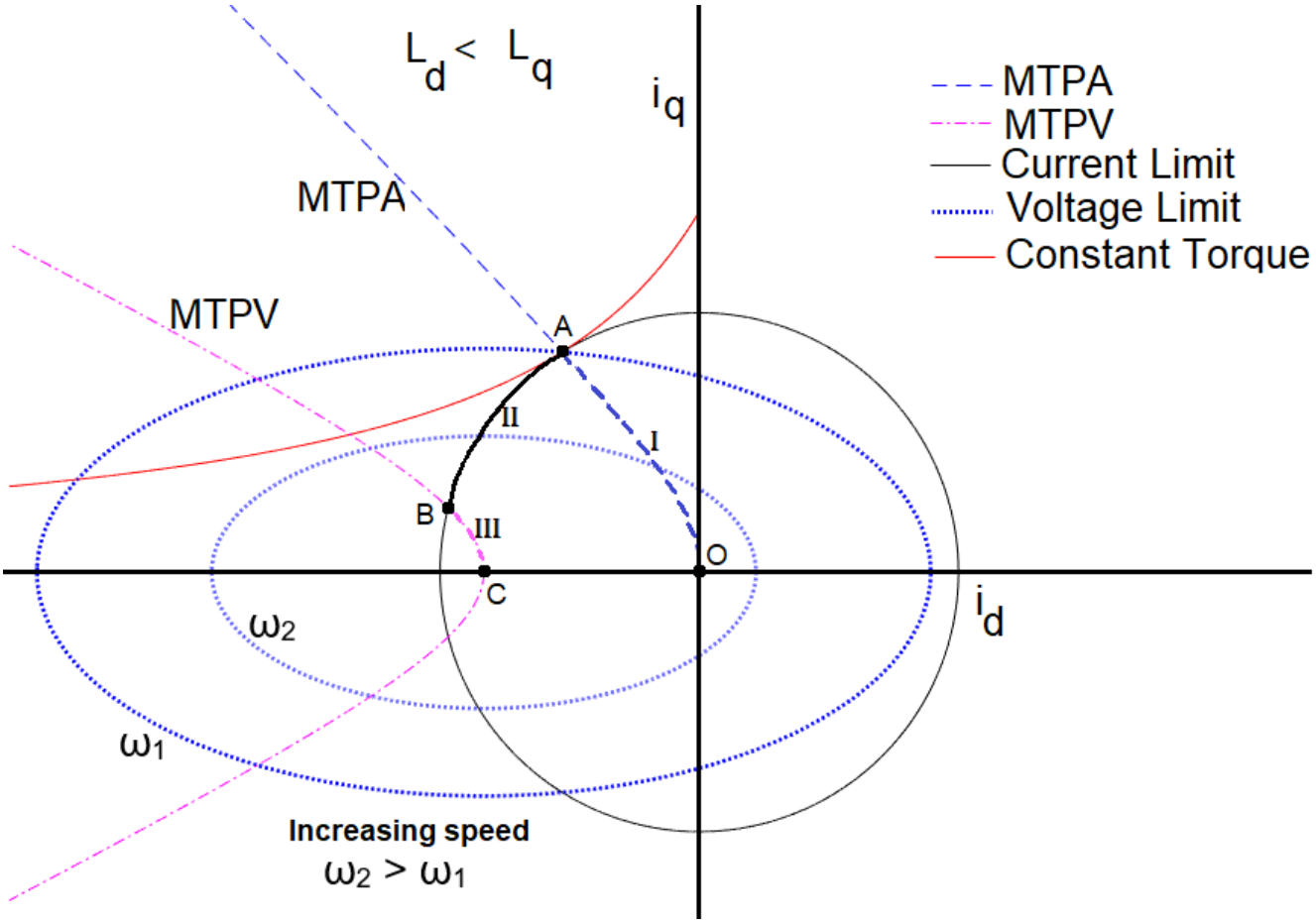
In the *d*-*q* rotor reference frame for PMSMs, the *d*-axis is the axis parallel to the rotor's magnetic orientation and the *q*-axis is the perpendicular axis, leading the *d*-axis. An SPMSM has equal *d*-axis and *q*-axis inductances. An IPMSM has a higher *q*-axis inductance than its *d*-axis inductance. This helps the IPMSM to utilize the reluctance torque in addition to the magnetic torque.

The corner speed of a PMSM is the speed at which the torque-vs-speed (drive characteristics) curve of the PMSM changes shape (has a corner) for a given current limit. When you plot the drive characteristics for rated torque (at rated current), the corner speed is also known as the rated speed or base speed.



You draw the constraint curves for a PMSM to understand the possible operational area and boundaries.

- Maximum torque per ampere (MTPA) trajectory of an IPMSM provides the highest torque for the allowed stator current.
- Maximum torque per voltage (MTPV) trajectory of an IPMSM provides the highest torque while satisfying the stator voltage constraint.
- Voltage limit curve (ellipse for an IPMSM or circle for SPMSM) is centered around a point that is called the characteristic current. This curve shrinks with increasing rotor speed.



These figures show three segments corresponding to the motor operation. The motor operates in each segment as follows.

Segment I

- To begin the operation, the motor increases the torque from zero to the rated torque.
- The operating point shifts from point O to A along the MTPA trajectory (line segment OA). This corresponds to the i_d and i_q values at the tip of MTPA.
- The motor speed ω_1, at which the voltage limit ellipse touches the MTPA curve and the current limit circle, is the rated speed. This is the first milestone speed of the characteristic curve.

Segment II

- At the operating point A, the control reaches the maximum possible current, and the field weakening strategy begins.
- The current trajectory moves along the current limit circle while maintaining the current constraint from point A to B (line segment AB).
- The operating point B is the speed at which the voltage ellipse touches the current limit circle and the MTPV curve. This is the second milestone speed of the characteristic curve.

Segment III

- Beyond the point B, the voltage ellipse shrinks further and the MTPV trajectory provides the optimal torque until the maximum speed is reached at the operating point C (line segment BC).
- The theoretical maximum speed for a friction-free motor with MTPV is infinite. Practically, the frictional components in the motor limit the maximum speed to a finite value. In Motor Control Blockset™ software, the maximum speed, including the friction, is when the frictional torque balances the motor torque produced at that speed. The practical speed limit of the motor is usually lower than this maximum speed value. Several factors regulate this limit, including mechanical stability, lower efficiency at higher speeds, and so on.
- The calculated maximum speed is the third milestone speed. In some motor configurations, MTPV is not possible. In such cases, the frictional torque limits the operating point B, and there is no operating point C. Such motors have two milestone speeds.

Additionally, note that in these figures:

- The drive characteristic curves show the operating points O, A, and B. These curves do not show the operating point C because it is far away from the remaining points.
- The operating point A is also at the rated speed ω_1. The second speed ω_2 for the curve is higher than rated speed, but lower than the speed at operating point B. The speed at the operating point B is also the speed at which the current trajectory changes direction from following the current limit circle to following the MTPV trajectory.
- The drive characteristics do not show segment **I** because the motor maintains torque at maximum value, and the i_d and i_q values remain at values corresponding to the rated torque.

This table shows the functions used in this example.

Function name	Required inputs	Optional arguments	Expected output
mcbPMSMSpeeds	pmsm, inverter	voltageEquation, constraintCurves, FWCMethod, outputAll, verbose	Milestone speeds in rpm. Matrix of d and q axis currents at milestone speeds (in electrical rad/s)
mcbPMSMCharacteristics	pmsm, inverter	voltageEquation, driveCharacteristics, constraintCurves, FWCMethod, opacity, idqExternal, speed, torque, imax	Drive characteristics plot Constraint curves plot

The `pmsm` and `inverter` arguments are structures. This table shows the fields in each structure.

Structure	Field	Description	Units
pmsm	p	Pole pairs	-
	Rs	Per phase resistance	Ohm
	Ld	D-axis inductance	Henry
	Lq	Q-axis inductance	Henry
	FluxPM	Permanent magnet flux linkage	Weber
	B	Viscous damping coefficient	Newton.Meters/(radians/second)
	I_rated	Rated current of the pmsm	Amperes
inverter	V_dc	DC bus voltage	Volts

Maximum and Milestone Speeds of PMSM

To get all the milestone speeds of the PMSM, use the `mcbPMSMSpeeds` function. The operable speeds are different for different field weakening control (FWC) strategies. The default FWC method is set to voltage current limited maximum torque (VCLMT) control, also called optimal current vector control. The function returns the speed values in rpm.

Set the fields for the `pmsm` and `inverter` structures and calculate the milestone speeds.

Run this section

```
%inverter = mcb_SetInverterParameters( 'BoostXL-DRV8305'); % Use an inverter structure from a ter
inverter.V_dc=24;
pmsm     = mcb_SetPMSMMotorParameters('BLY171D');
milestone_speeds=mcbPMSMSpeeds(pmsm,inverter);
disp(milestone_speeds);
```

```
        5393
        9373
```

```
pmsm.I_rated=8;% Assuming a higher I_rated to be able to get MTPV trajectory
[milestone_speeds]=mcbPMSMSpeeds(pmsm,inverter);
disp(milestone_speeds);
```

```
        2342
        2958
       24369
```

Speed Milestones of PMSM with Different FW Control Methods

Calculate speed milestones for different field weakening methods. When you set the `verbose` option to `1`, each command displays the milestone speeds with the description.

Set the fields for the `pmsm` and `inverter` structures and calculate the milestone speeds.

Run this section

```
inverter = mcb_SetInverterParameters( 'BoostXL-DRV8305');
pmsm     = mcb_SetPMSMMotorParameters('BLY171D');
verbose=0; % setting the verbose=1 will also print the messages

milestone_speeds=mcbPMSMSpeeds(pmsm,inverter,'verbose',verbose,'FWCMethod','vclmt');
disp(milestone_speeds);
```

```
        5393
        9373

milestone_speeds=mcbPMSMSpeeds(pmsm,inverter,'verbose',verbose,'FWCMethod','cvcp');
disp(milestone_speeds);

        5393
        7008
        8361

milestone_speeds=mcbPMSMSpeeds(pmsm,inverter,'verbose',verbose,'FWCMethod','cccp');
disp(milestone_speeds);

        5393
        7008

milestone_speeds=mcbPMSMSpeeds(pmsm,inverter,'verbose',verbose,'FWCMethod','none'); % no id cont
disp(milestone_speeds);

        5393
        6226
```

i_d and i_q at Different Milestone Speeds for Different FW Control Methods

Calculate i_d and i_q values at the speed milestones for different field weakening methods. Each command outputs the array with columns for each milestone speed, and each row of the column provides i_d, i_q, and speed (in electrical rad/s).

Set the fields for the `pmsm` and `inverter` structures and calculate currents and milestone speeds.

Run this section

```
inverter = mcb_SetInverterParameters( 'BoostXL-DRV8305');
pmsm     = mcb_SetPMSMMotorParameters('BLY171D');

[milestone_speeds]=mcbPMSMSpeeds(pmsm,inverter,'FWCMethod','vclmt','outputAll',0);
[outputArray]=mcbPMSMSpeeds(pmsm,inverter,'FWCMethod','vclmt','outputAll',1);
disp(outputArray);

   1.0e+03 *

         0   -0.0018
    0.0018    0.0004
    2.2591    3.9262

disp(round([milestone_speeds(1) outputArray(3,1)*(60/(2*pi))/pmsm.p;    milestone_speeds(2) outpu

        5393        5393
        9373        9373

outputArray=mcbPMSMSpeeds(pmsm,inverter,'FWCMethod','cvcp','outputAll',1);
disp(outputArray);

   1.0e+03 *

         0   -0.0011   -0.0018
    0.0018    0.0014    0.0003
    2.2591    2.9355    3.5023
```

```
outputArray=mcbPMSMSpeeds(pmsm,inverter,'FWCMethod','cccp','outputAll',1);
disp(outputArray);
```

```
   1.0e+03 *

         0   -0.0011
    0.0018    0.0014
    2.2591    2.9355
```

```
outputArray=mcbPMSMSpeeds(pmsm,inverter,'FWCMethod','none','outputAll',1);
disp(outputArray);
```

```
   1.0e+03 *

         0         0
    0.0018    0.0002
    2.2591    2.6081
```

Plot Drive Characteristics

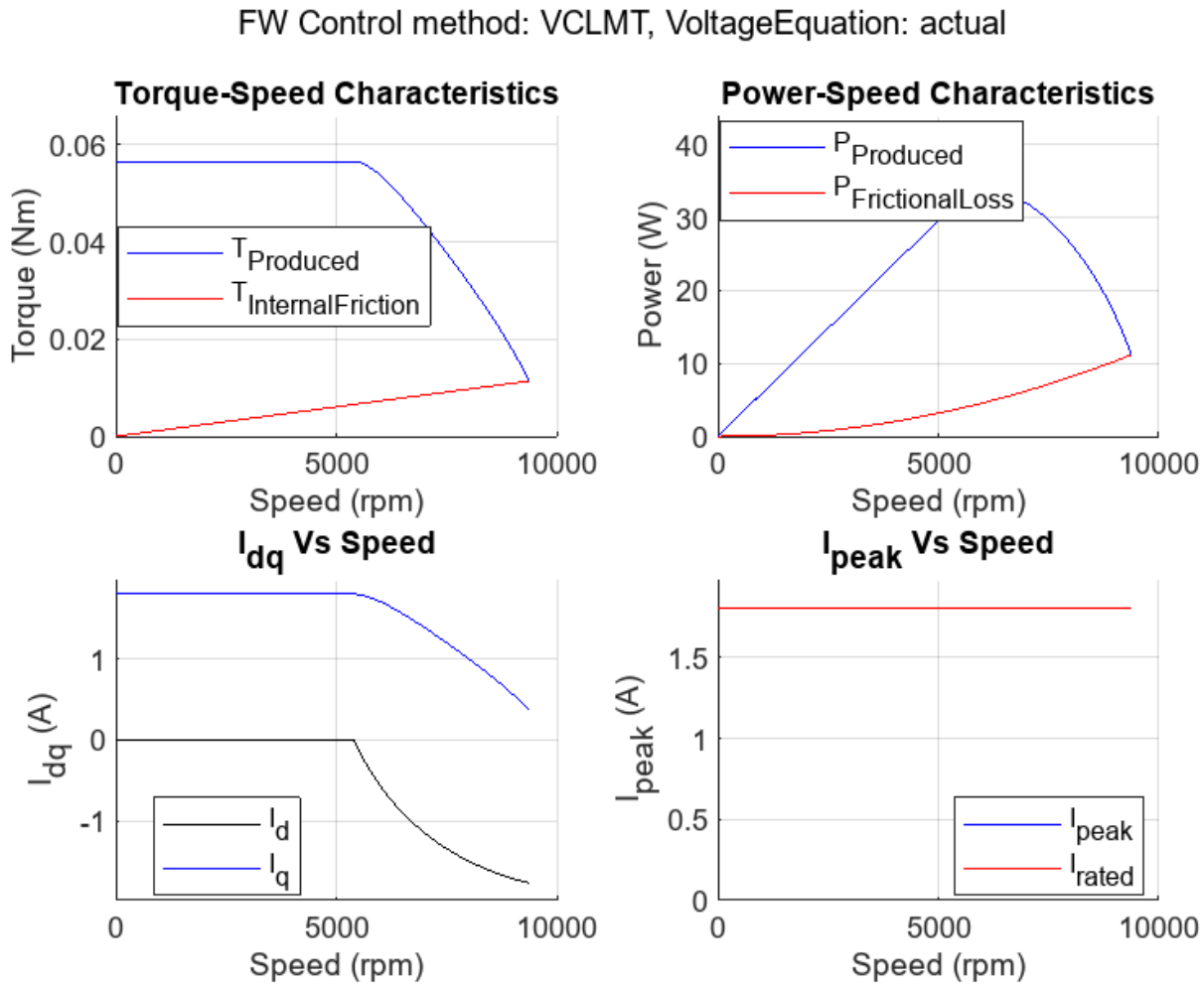
The drive characteristics display the torque-vs-speed, power-vs-speed, and current-vs-speed characteristic plots of a motor under the given operating constraints. Use the `mcbPMSMCharacteristics` function to plot the drive characteristics.

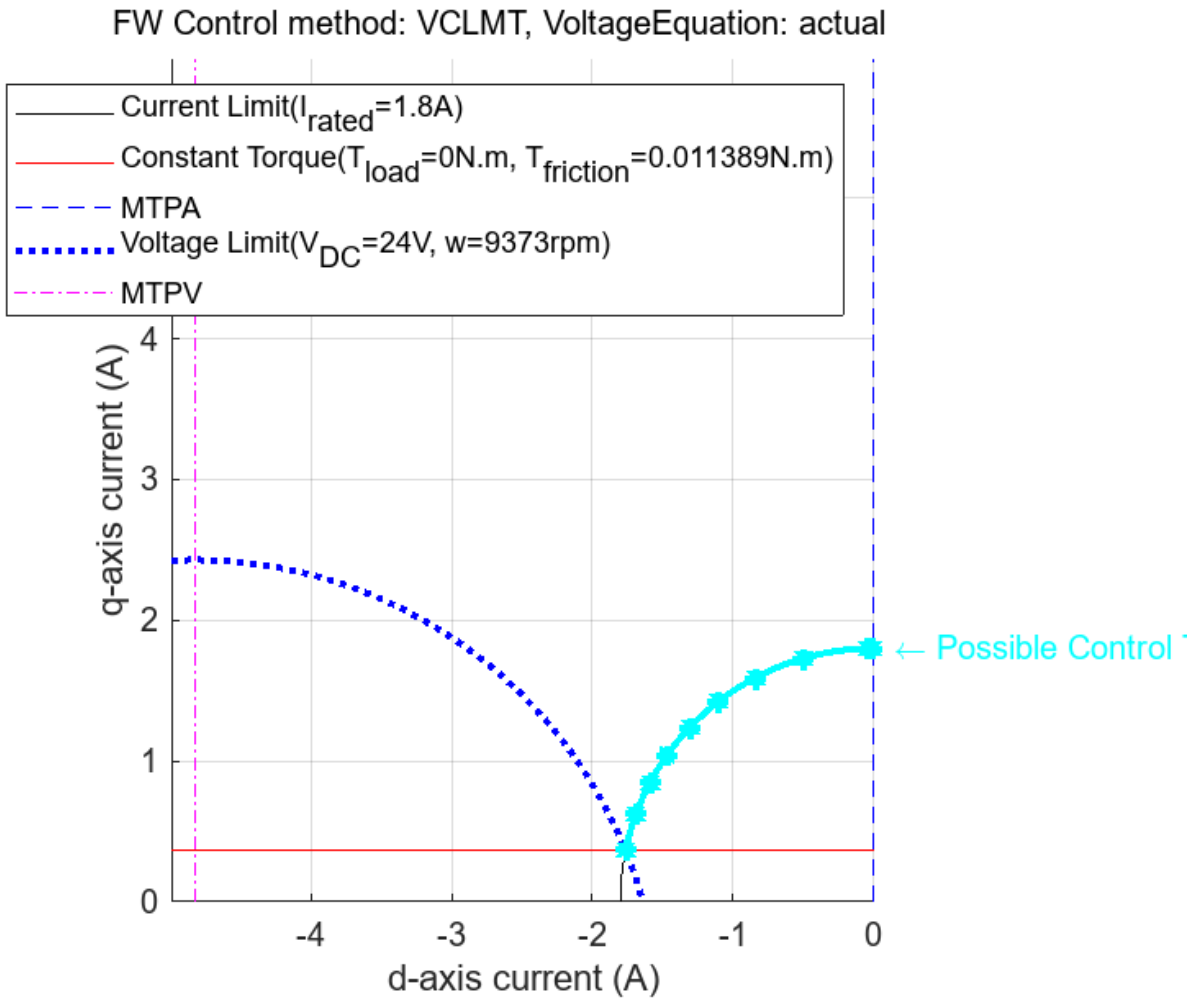
Plot the drive characteristics of the PMSM under different field weakening control methods. You can also plot the constraint curves simultaneously, in which case, you also plot the current trajectory (to get maximum torque for a given speed) for the chosen drive characteristics. When you set the `driveCharacteristics` option to 2, the function plots an additional figure in the v_d-v_q space with the voltage constraint curve and the voltage trajectory. The default field weakening control is set to VCLMT.

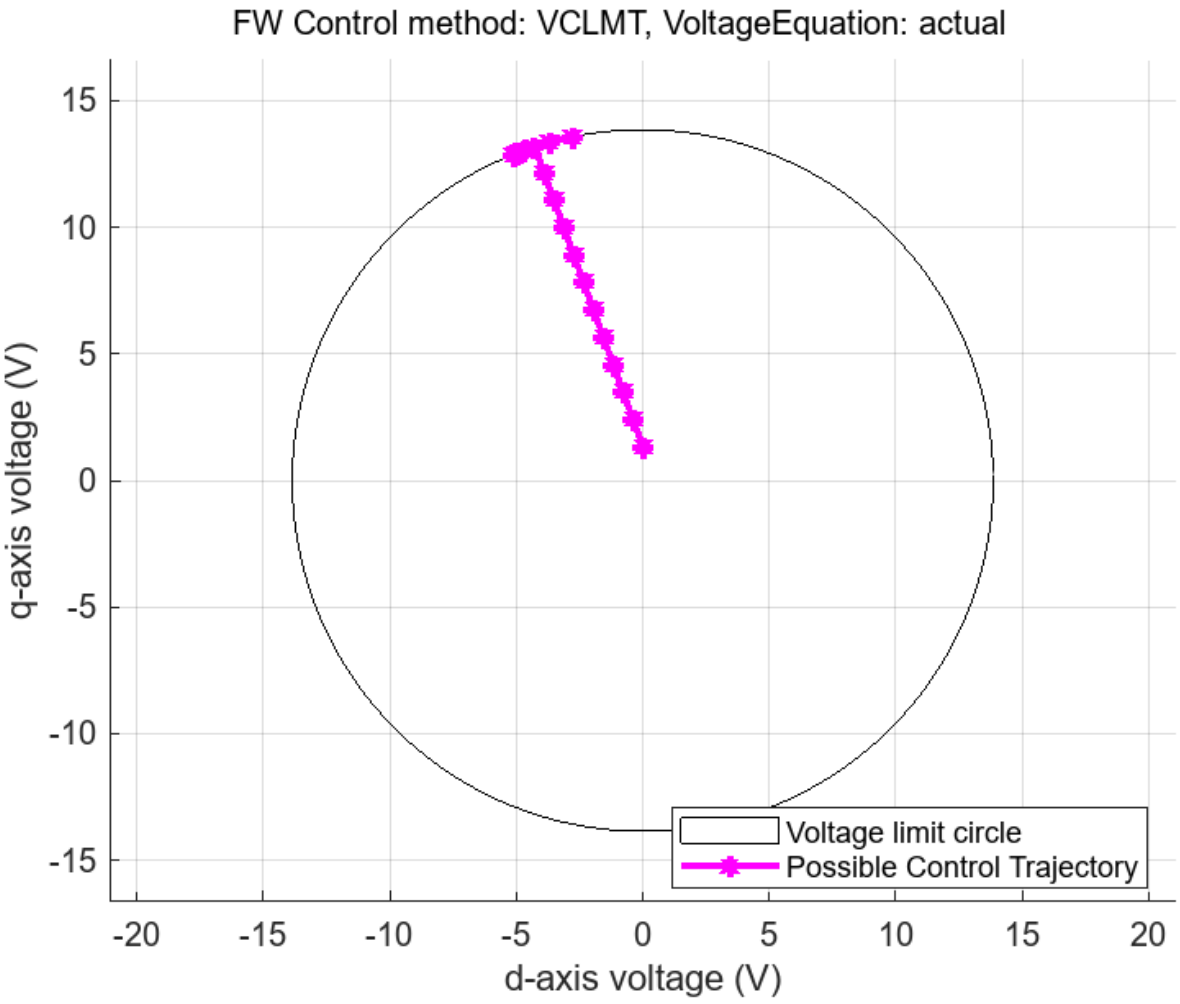
Set the fields for the `pmsm` and `inverter` structures and plot the characteristics.

Run this section

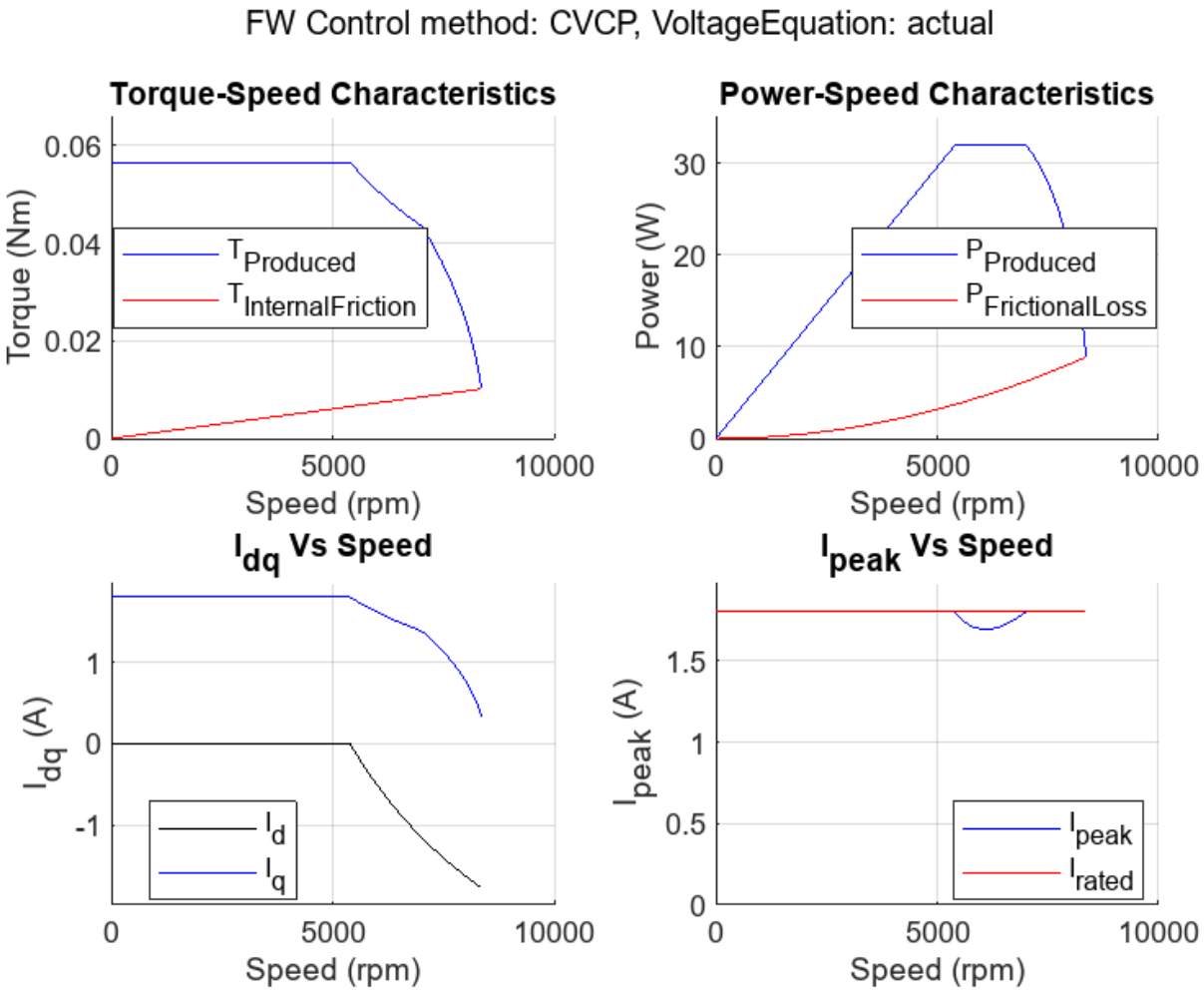
```
inverter = mcb_SetInverterParameters( 'BoostXL-DRV8305');
pmsm     = mcb_SetPMSMMotorParameters('BLY171D');
mcbPMSMCharacteristics(pmsm,inverter,'driveCharacteristics',2,'constraintCurves',1,'FWCMethod','v
```

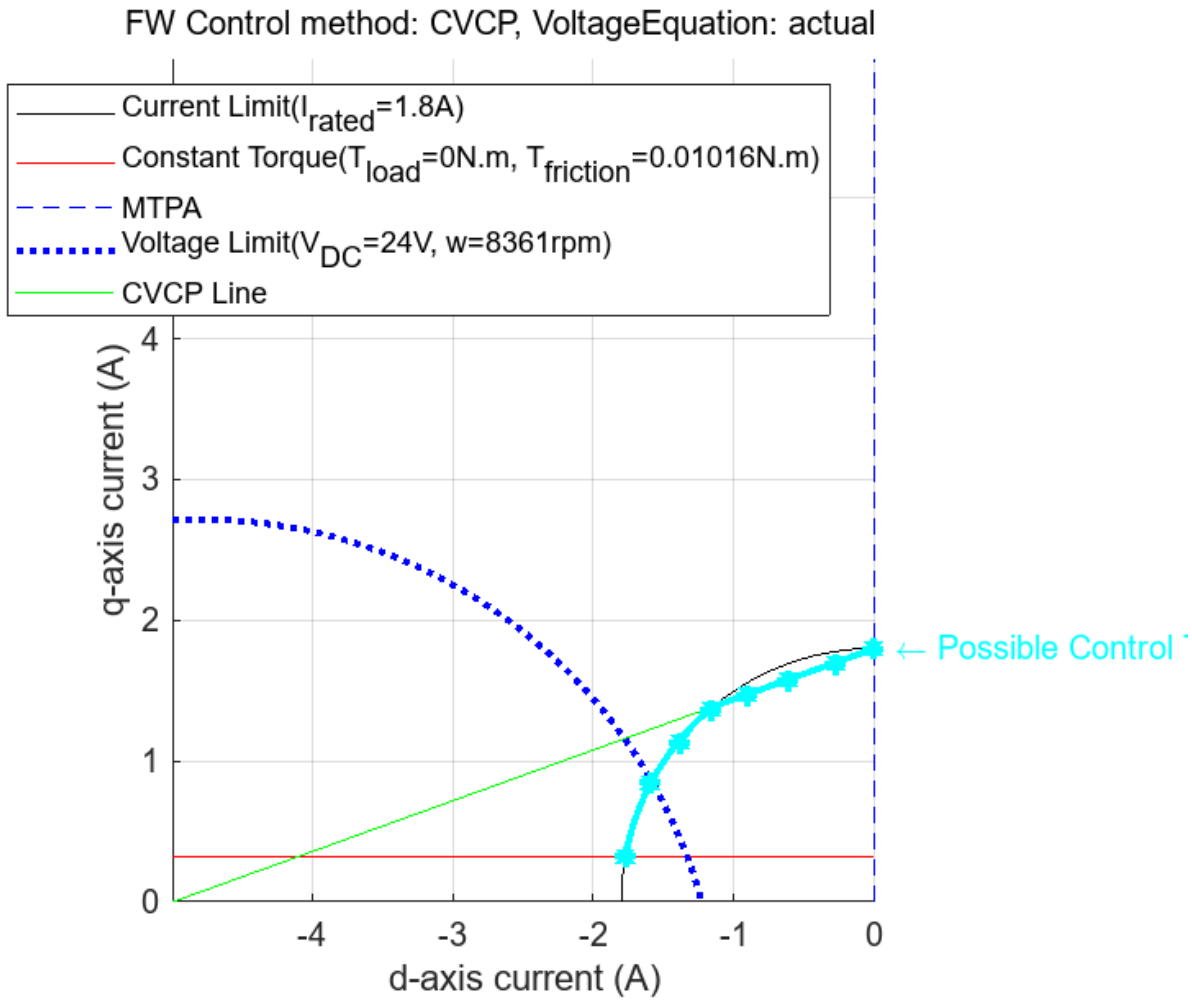

FW Control method: VCLMT, VoltageEquation: actual
Torque-Speed Characteristics
Torque (Nm)
0.06
0.04
0.02
0
0
5000
10000
Speed (rpm)
T Produced
T InternalFriction
Power-Speed Characteristics
Power (W)
40
30
20
10
0
0
5000
10000
Speed (rpm)
P Produced
P FrictionalLoss
Idq Vs Speed
Idq (A)
1
0
-1
0
5000
10000
Speed (rpm)
Id
Iq
Ipeak Vs Speed
Ipeak (A)
1.5
1
0.5
0
0
5000
10000
Speed (rpm)
Ipeak
Irated


FW Control method: VCLMT, VoltageEquation: actual
Current Limit(I_rated=1.8A)
Constant Torque(T_load=0N.m, T_friction=0.011389N.m)
MTPA
Voltage Limit(V_DC=24V, w=9373rpm)
MTPV
q-axis current (A)
d-axis current (A)
0
1
2
3
4
-4
-3
-2
-1
0
← Possible Control

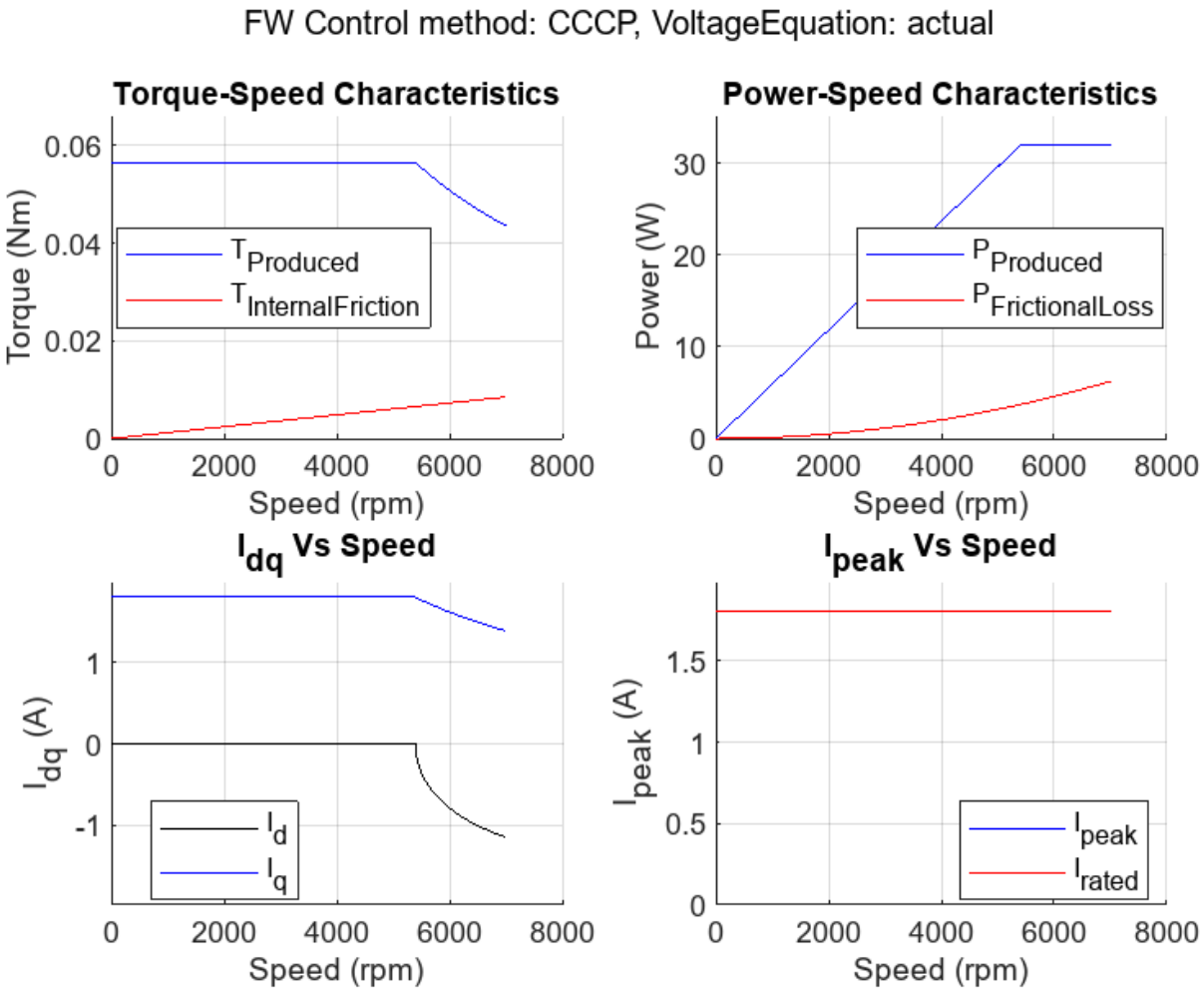


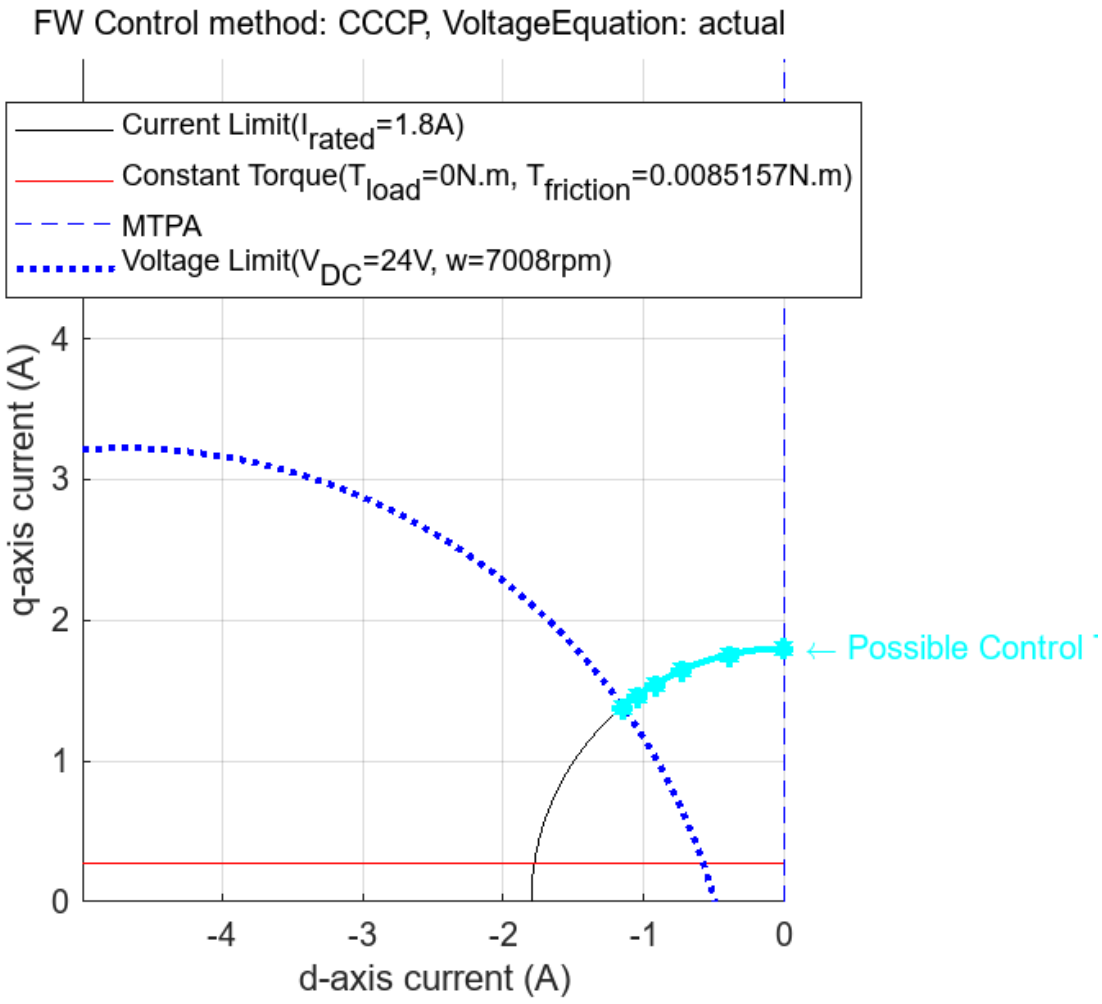

```
mcbPMSMCharacteristics(pmsm,inverter,'driveCharacteristics',1,'constraintCurves',1,'FWCMethod','
```


FW Control method: CVCP, VoltageEquation: actual
Torque-Speed Characteristics
Torque (Nm)
0.06
0.04
0.02
0
0
5000
10000
Speed (rpm)
T Produced
T InternalFriction
Power-Speed Characteristics
Power (W)
30
20
10
0
0
5000
10000
Speed (rpm)
P Produced
P FrictionalLoss
I dq Vs Speed
I dq (A)
1
0
-1
0
5000
10000
Speed (rpm)
I d
I q
I peak Vs Speed
I peak (A)
1.5
1
0.5
0
0
5000
10000
Speed (rpm)
I peak
I rated

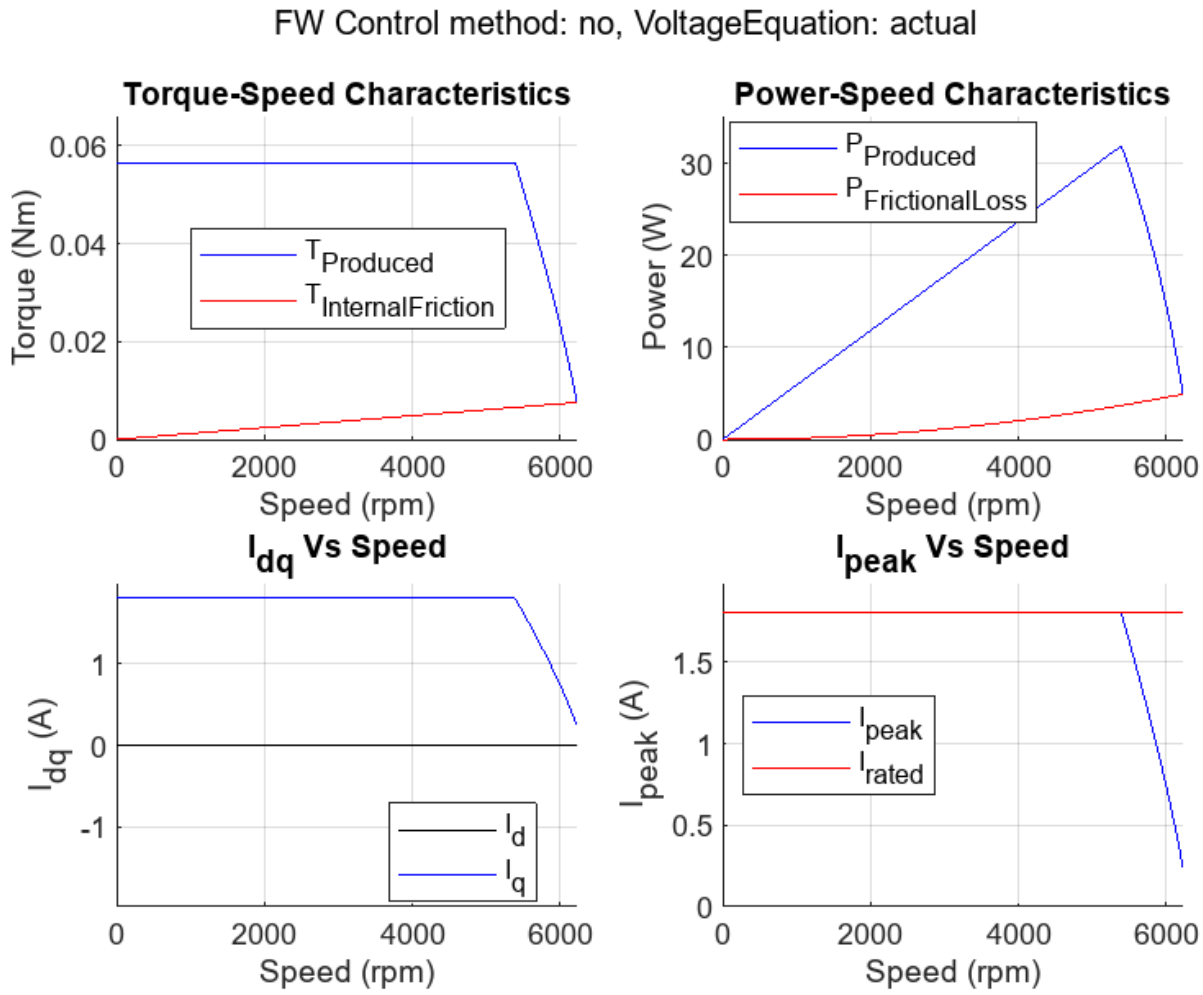


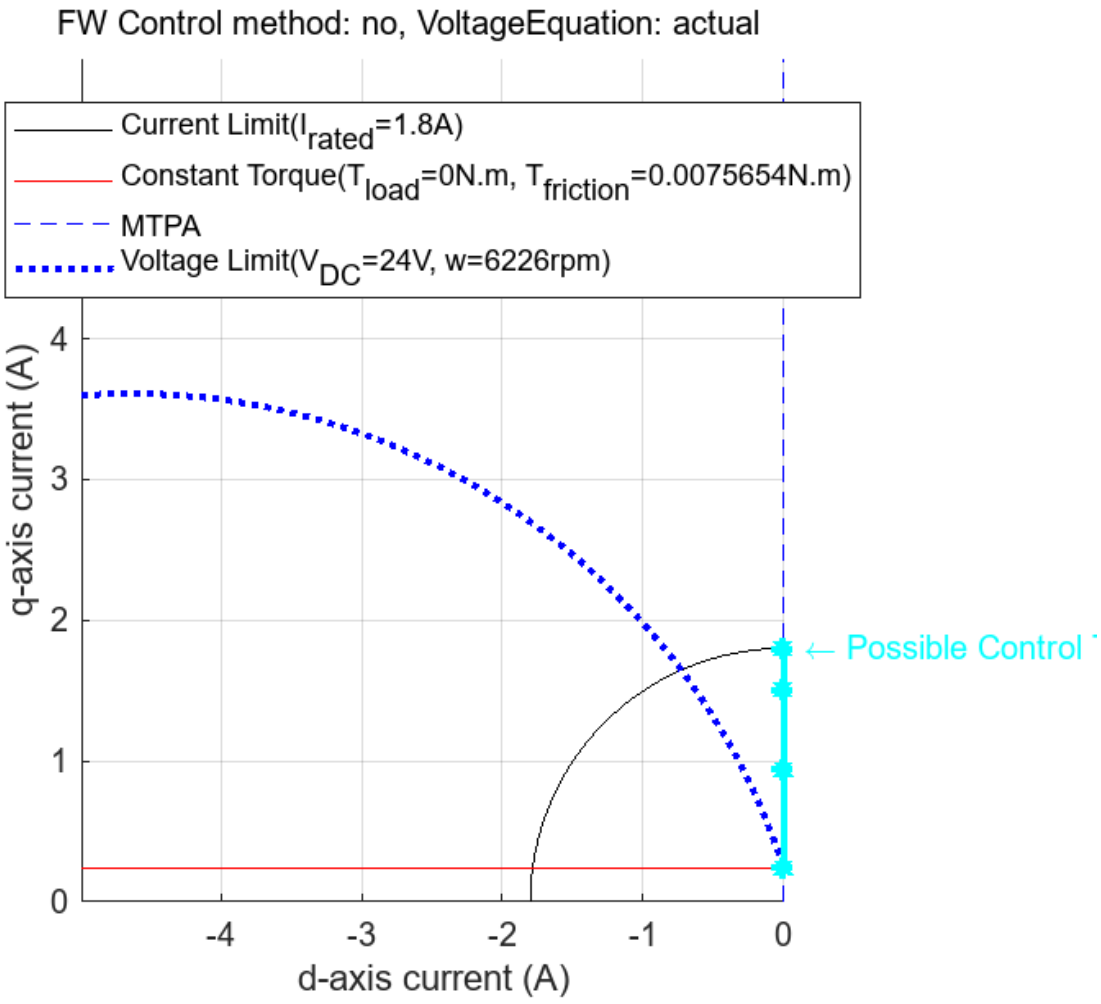

```
mcbPMSMCharacteristics(pmsm,inverter,'driveCharacteristics',1,'constraintCurves',1,'FWCMethod','
```


FW Control method: CCCP, VoltageEquation: actual
Torque-Speed Characteristics
Torque (Nm)
0.06
0.04
0.02
0
T Produced
T InternalFriction
0
2000
4000
6000
8000
Speed (rpm)
Power-Speed Characteristics
Power (W)
30
20
10
0
P Produced
P FrictionalLoss
0
2000
4000
6000
8000
Speed (rpm)
I dq Vs Speed
I dq (A)
1
0
-1
I d
I q
0
2000
4000
6000
8000
Speed (rpm)
I peak Vs Speed
I peak (A)
1.5
1
0.5
0
I peak
I rated
0
2000
4000
6000
8000
Speed (rpm)




```
mcbPMSMCharacteristics(pmsm,inverter,'driveCharacteristics',1,'constraintCurves',1,'FWCMethod','
```


FW Control method: no, VoltageEquation: actual
Torque-Speed Characteristics
Torque (Nm)
Speed (rpm)
T Produced
T InternalFriction
Power-Speed Characteristics
Power (W)
Speed (rpm)
P Produced
P FrictionalLoss
I dq Vs Speed
I dq (A)
Speed (rpm)
I d
I q
I peak Vs Speed
I peak (A)
Speed (rpm)
I peak
I rated



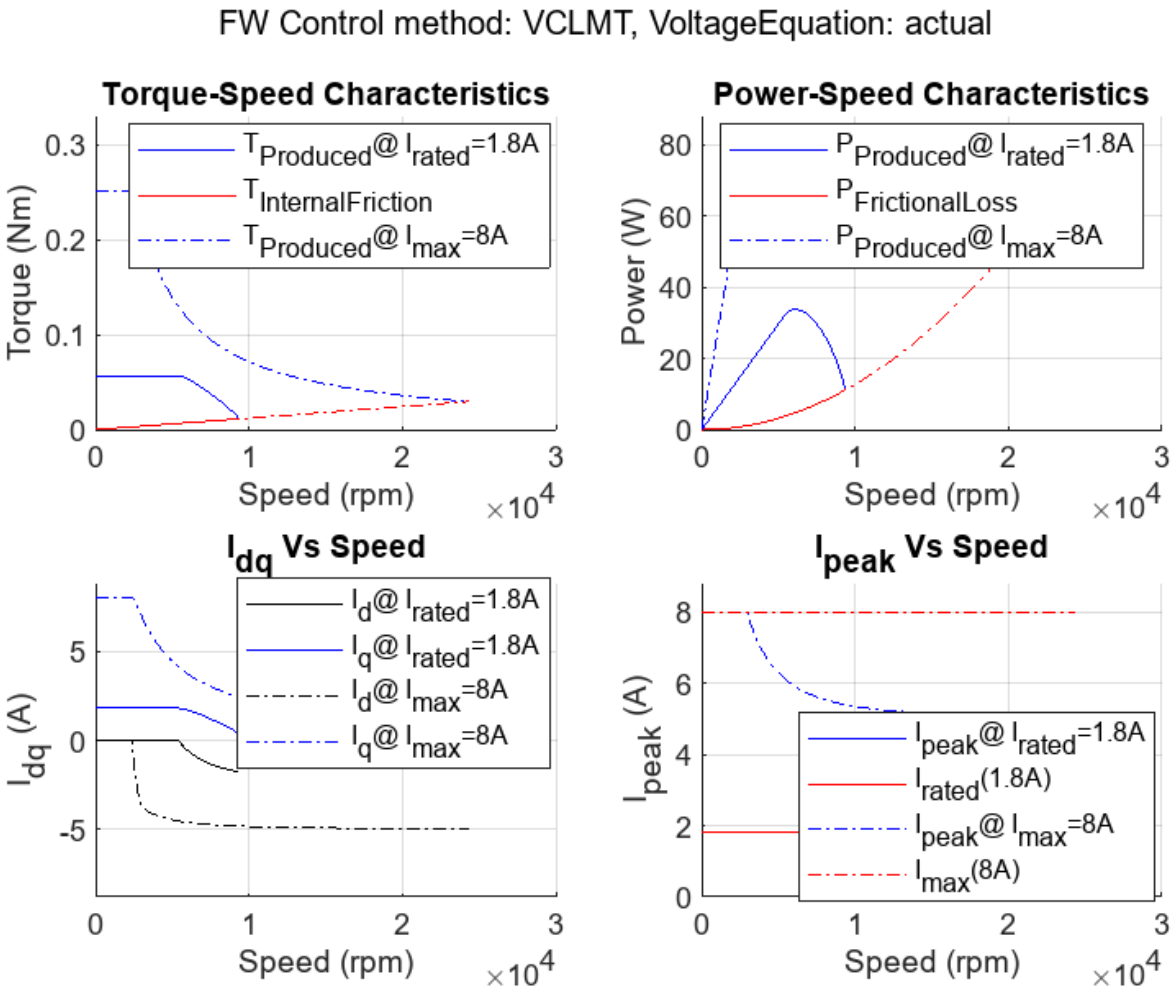
Plot Drive Characteristics for I_{max}

When the motor operates continuously supporting a constant load torque, that condition is the rated operating condition, and the operating current is the rated current. The short-term rating of the motor is higher than the continuous-current rating.

For this example, `pmsm.I_rated` is set to 1.8 A and `pmsm.I_max` is set to 8 A. You can see the comparison between the drive characteristics and use this to determine the short-term operating characteristics.

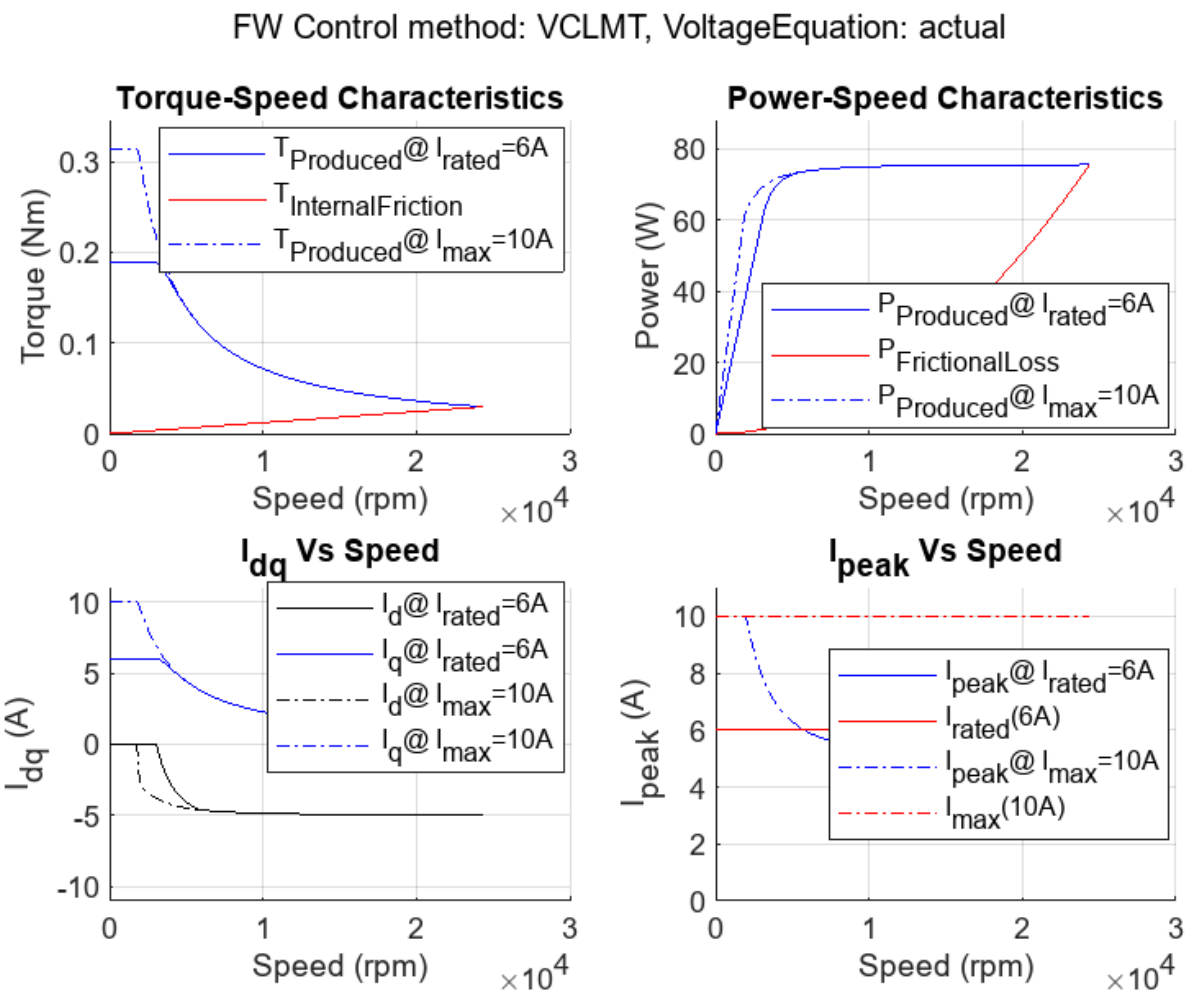
Run this section

```
inverter = mcb_SetInverterParameters( 'BoostXL-DRV8305');
pmsm     = mcb_SetPMSMMotorParameters('BLY171D');
mcbPMSMCharacteristics(pmsm,inverter,"FWCMethod","vclmt","driveCharacteristics",1,"imax",8,"cons
```



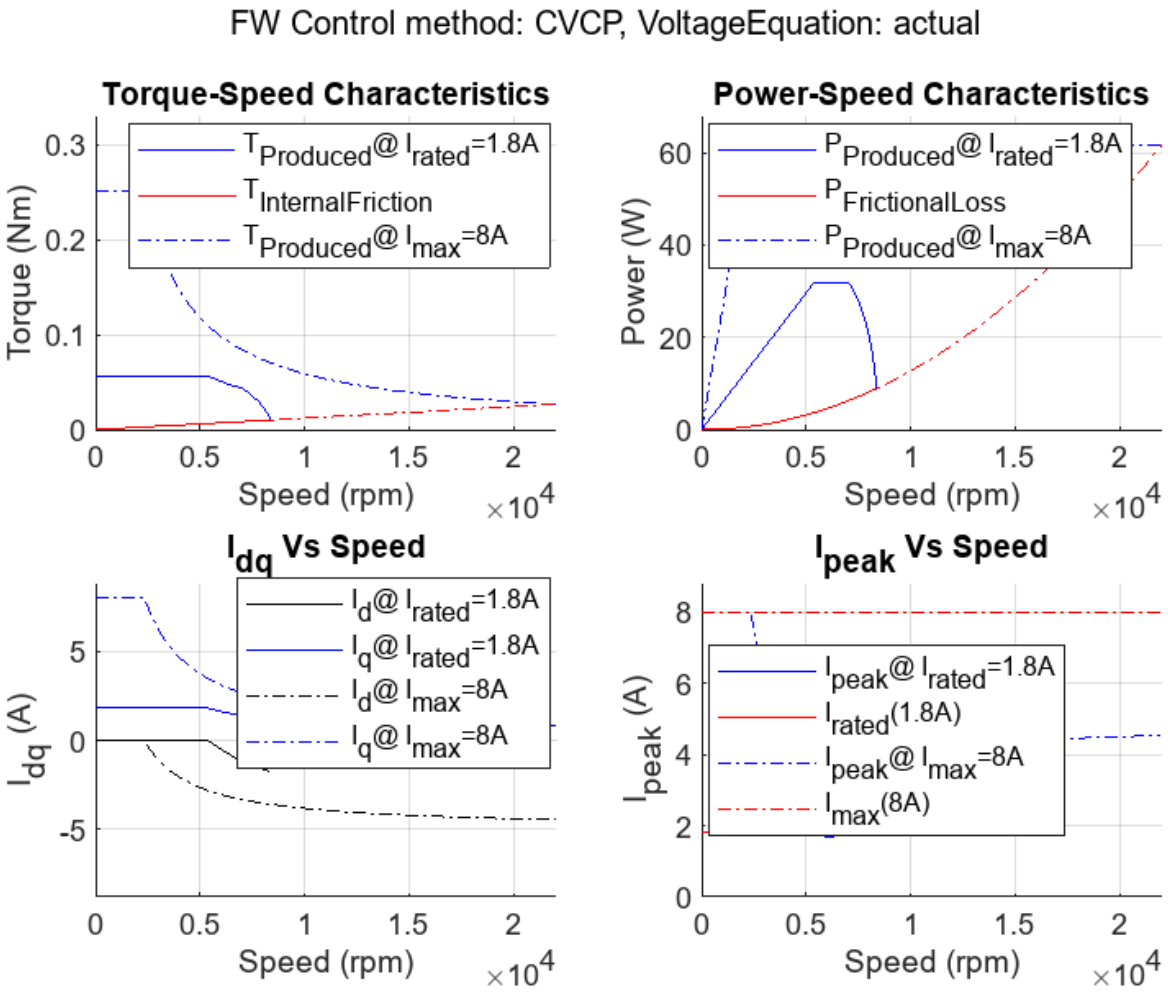
Next, assume a high continuous rating to let the motor run with MTPV under rated conditions. The maximum current I_{max} also operates the motor under the MTPV condition, resulting in no change in the maximum speed.

```
pmsm.I_rated=6;
mcbPMSMCharacteristics(pmsm,inverter,"FWCMethod","vclmt","driveCharacteristics",1,"imax",10,"cons
```

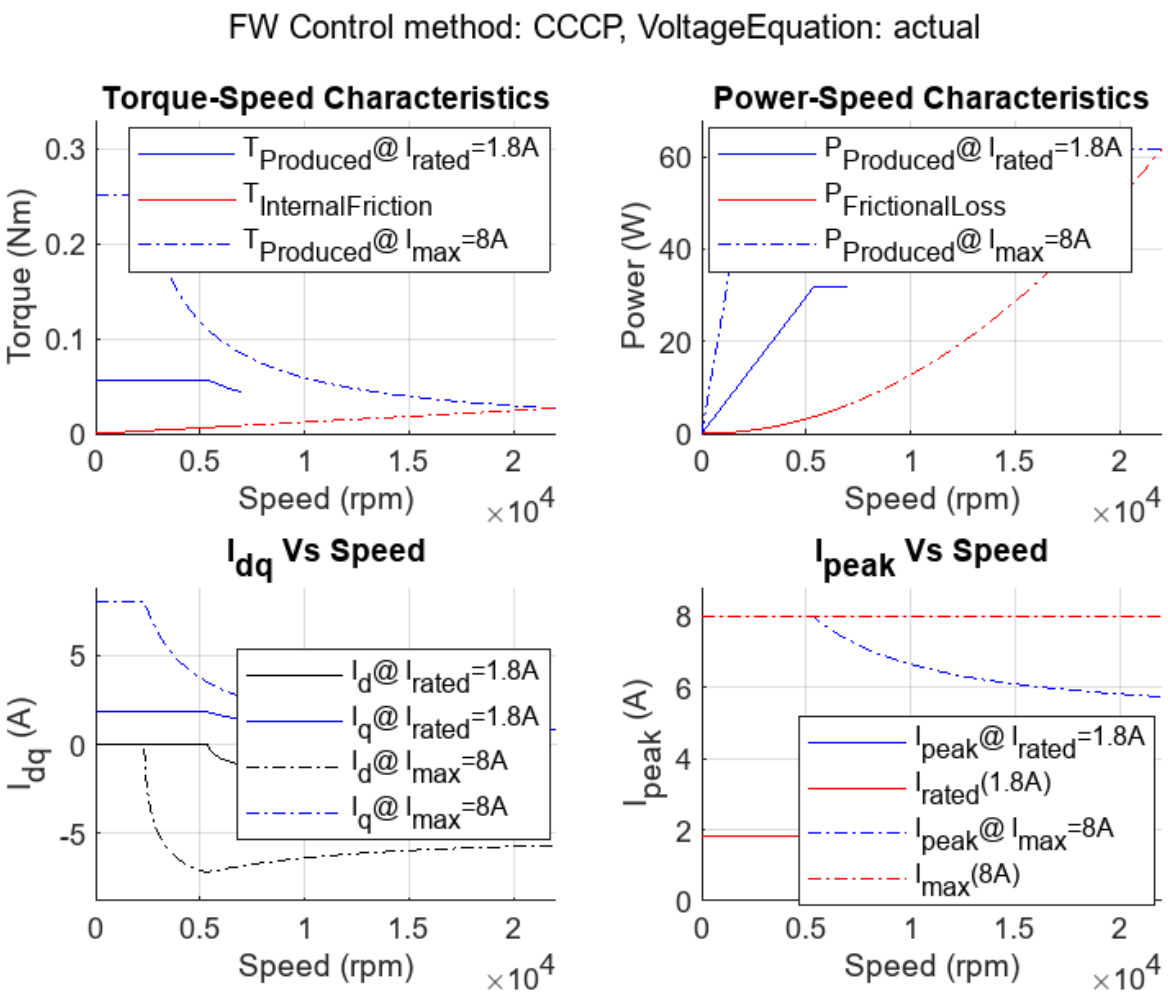


When you specify the field weakening method as `none`, you might not see a change in maximum speed for the original motor (unchanged rated current) even with higher current limit, but only the peak torque and power changes.

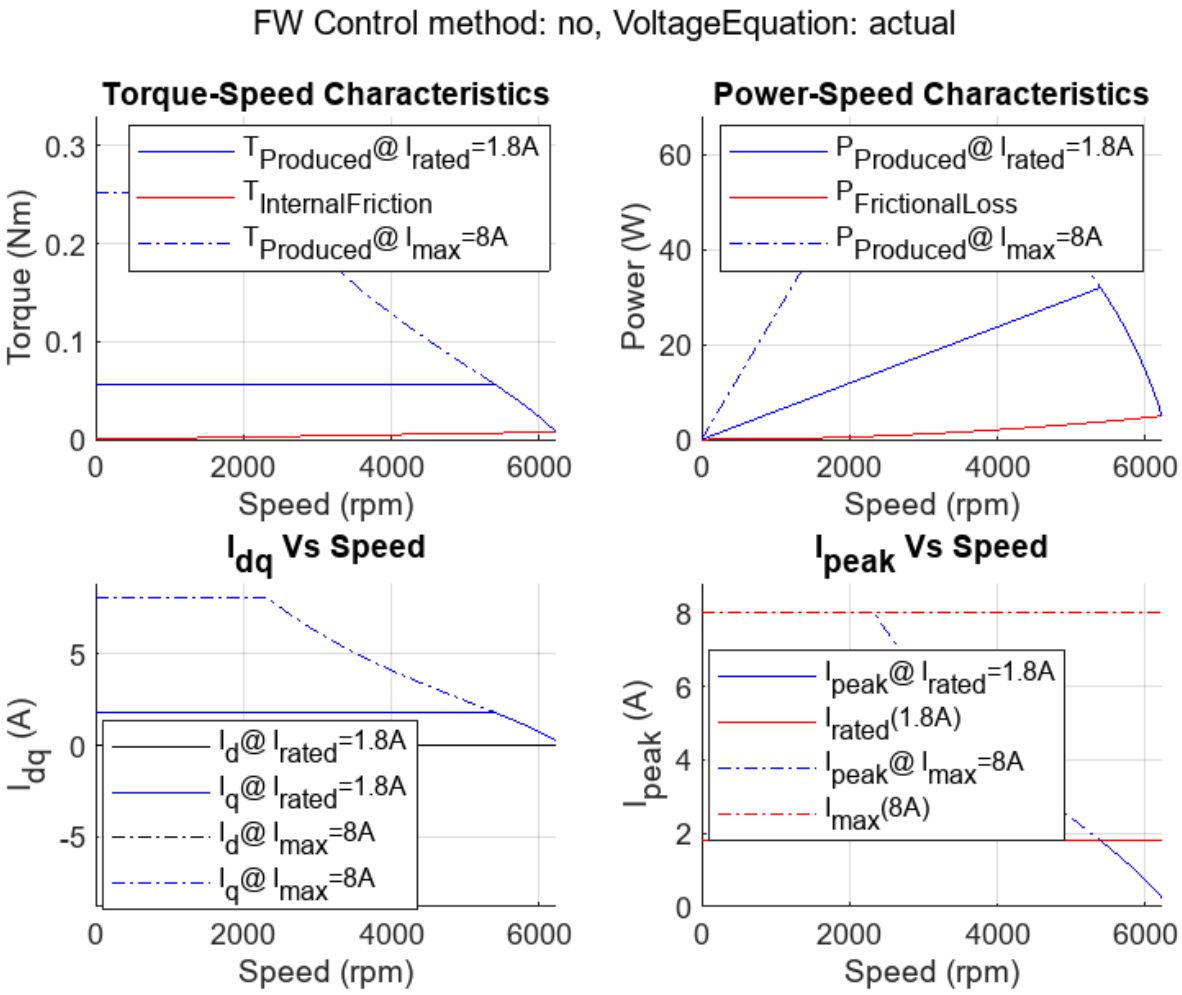
```
pmsm.I_rated=1.8; % setting the rated current to the normal (low) value)
mcbPMSMCharacteristics(pmsm,inverter,"FWCMethod","cvcp","driveCharacteristics",1,"imax",8,"const
```




```
mcbPMSMCharacteristics(pmsm,inverter,"FWCMethod","cccp","driveCharacteristics",1,"imax",8,"const
```




```
mcbPMSMCharacteristics(pmsm,inverter,"FWCMethod","none","driveCharacteristics",1,"imax",8,"const
```



Customize Drive Characteristics

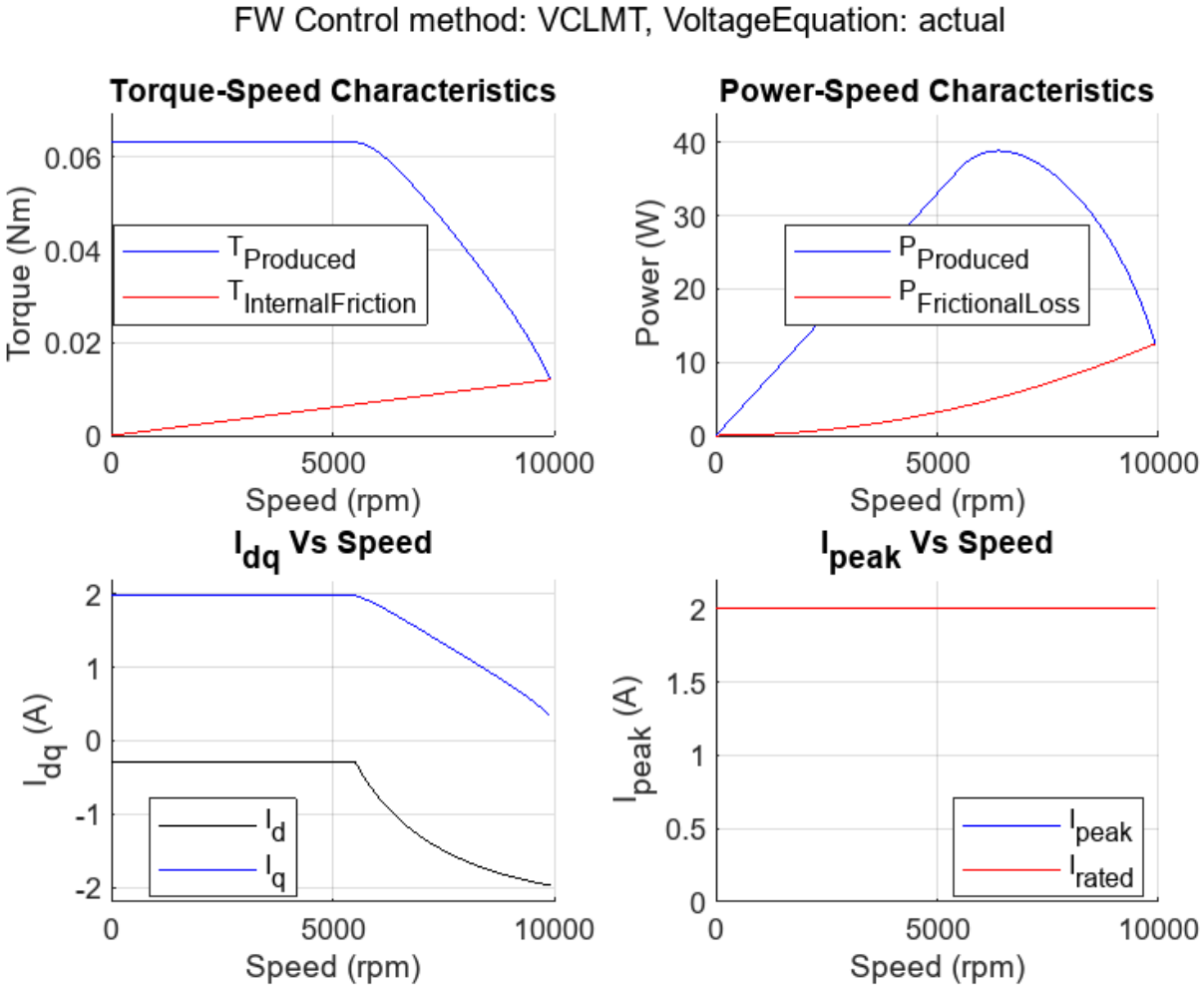
Customize the plots using the optional name-value arguments for the characteristics function.

The `pmsm` structure expects values for the `p`, `Rs`, `Ld`, `Lq`, `FluxPM`, `B` and `I_rated` fields. The `inverter` structure expects a value for the `V_dc` field. Set the field values and plot the characteristics.

Run this section

```
inverter.V_dc= 24 ;
pmsm.p=4;
pmsm.Rs= 0.45 ;
pmsm.Ld=1e-3;
pmsm.Lq=pmsm.Ld* 1.4 ;
pmsm.FluxPM=5.2e-3;
pmsm.B=1.16e-5;
```

```
pmsm.I_rated= 2 ;
w_rpm= 7000 ;
T_load= 0.01 ;
FWCMethod= vclmt ;
mcbPMSMCharacteristics(pmsm,inverter,'speed',w_rpm,'torque',T_load,'FWCMethod',FWCMethod, 'const
```



Plot Constraint Curves in i_d-i_q Space

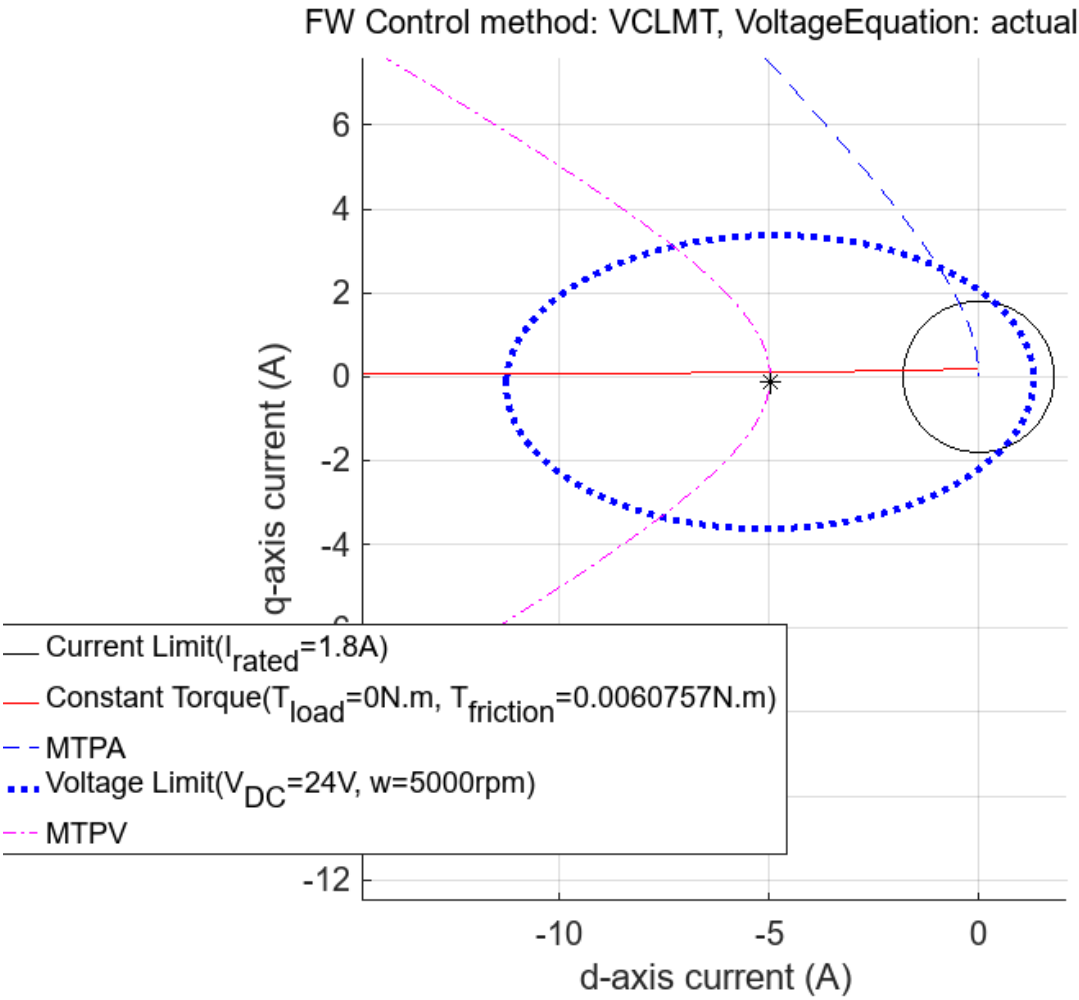
You can plot the constraint curves for PMSM in the i_d-i_q space using the `mcbPMSMCharacteristics` function.

Set the fields for the `pmsm` and `inverter` structures and plot the characteristics.

Run this section

```
inverter = mcb_SetInverterParameters( 'BoostXL-DRV8305');
pmsm     = mcb_SetPMSMMotorParameters('BLY171D');
```

```
pmsm.Rs=0.1;
pmsm.Lq=pmsm.Ld* 1.8 ;
w_rpm= 5000 ;
T_load= 0 ;
mcbPMSMCharacteristics(pmsm,inverter,'speed',w_rpm,'torque',T_load);
legend("Position", [-0.044093,0.16512,0.60536,0.2])
xlim([-14.7 2.1])
ylim([-12.5 7.6])
```



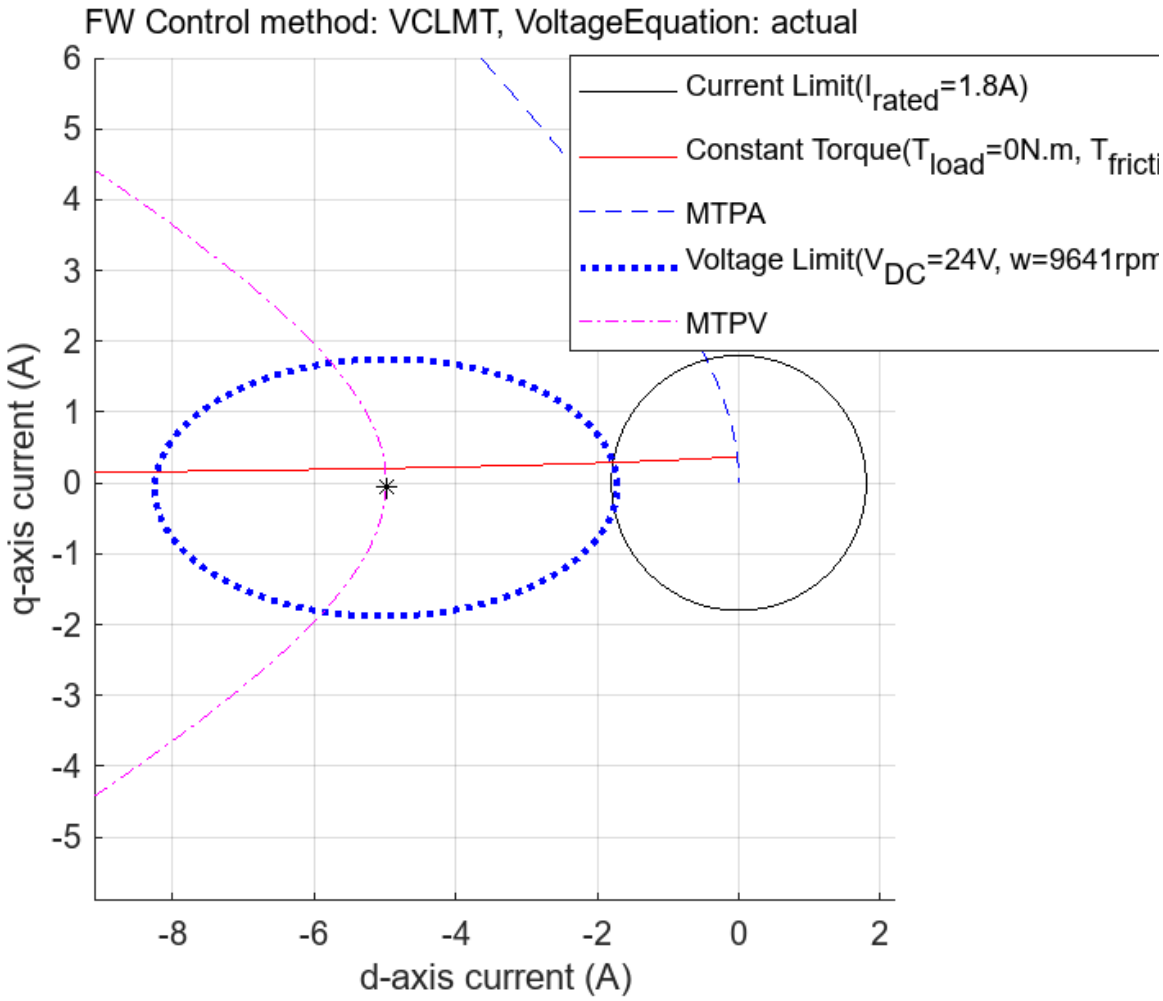
Plot Constraint Curves at Maximum Speed

The constraint curves provide a secondary check for whether the calculated speeds are correct. When you plot the constraint curves at maximum speed, the plot shows three intersecting curves: current limit circle, voltage limit curve, and constant torque curve.

Run this section

```
inverter = mcb_SetInverterParameters( 'BoostXL-DRV8305');
```

```
pmsm     = mcb_SetPMSMMotorParameters('BLY171D');
pmsm.Rs=0.1;
pmsm.Lq=pmsm.Ld* 1.8 ;
milestone_speeds=mcbPMSMSpeeds(pmsm,inverter);
mcbPMSMCharacteristics(pmsm,inverter,'speed',milestone_speeds(end),torque=0)
xlim([-9.1 2.2])
ylim([-5.9 6.0])
legend("Position",[0.57813,0.64246,0.59643,0.2869])
```



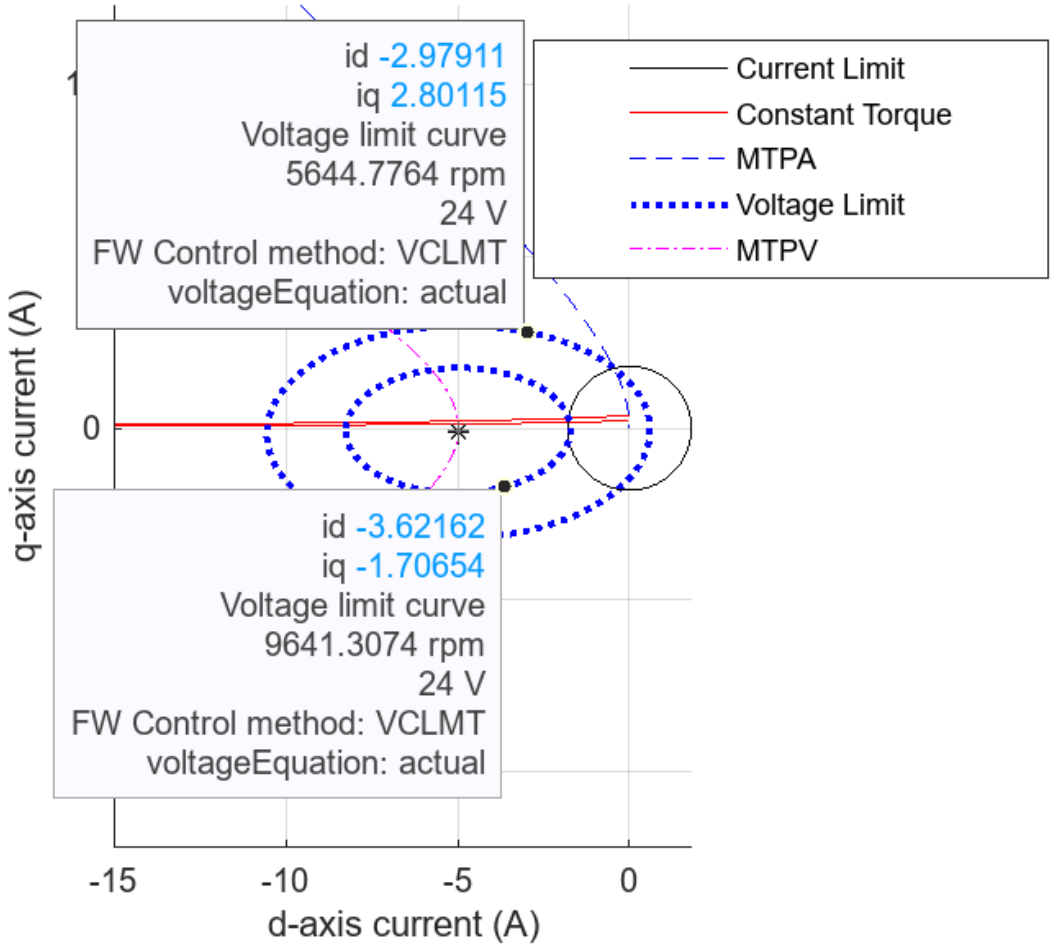
Plot Constraint Curves at Milestone Speeds

Instead of plotting the constraint curves for all the speed milestones in different figures, you can plot them together in the same characteristic plot. In addition to the intersecting curves at maximum speed, notice that at the corner speed, the MTPA curve, the current limit circle, and the voltage constraint curve intersect.

Run this section

```
inverter = mcb_SetInverterParameters( 'BoostXL-DRV8305');
pmsm     = mcb_SetPMSMMotorParameters('BLY171D');
```

```
pmsm.Lq=pmsm.Ld* 1.8 ;
pmsm.Rs=0.1;
[milestone_speeds]=mcbPMSMSpeeds(pmsm,inverter,'constraintCurves',1);
legend("Position",[0.61205,0.66151,0.375,0.22976])
ax = gca;
chart = ax.Children(3);
datatip(chart,-3.099,-3.697,"Location","southwest");
chart = ax.Children(9);
datatip(chart,-2.764,3.847,"Location","northwest");
xlim([-15.0 1.8])
ylim([-12.2 12.3])
```




```
disp(milestone_speeds);
```

```
        5645
        9641
```

Plot Constraint Curves with Different Speeds in Same Figure

Plot the constraint curves of the motor at different speeds in the same figure.

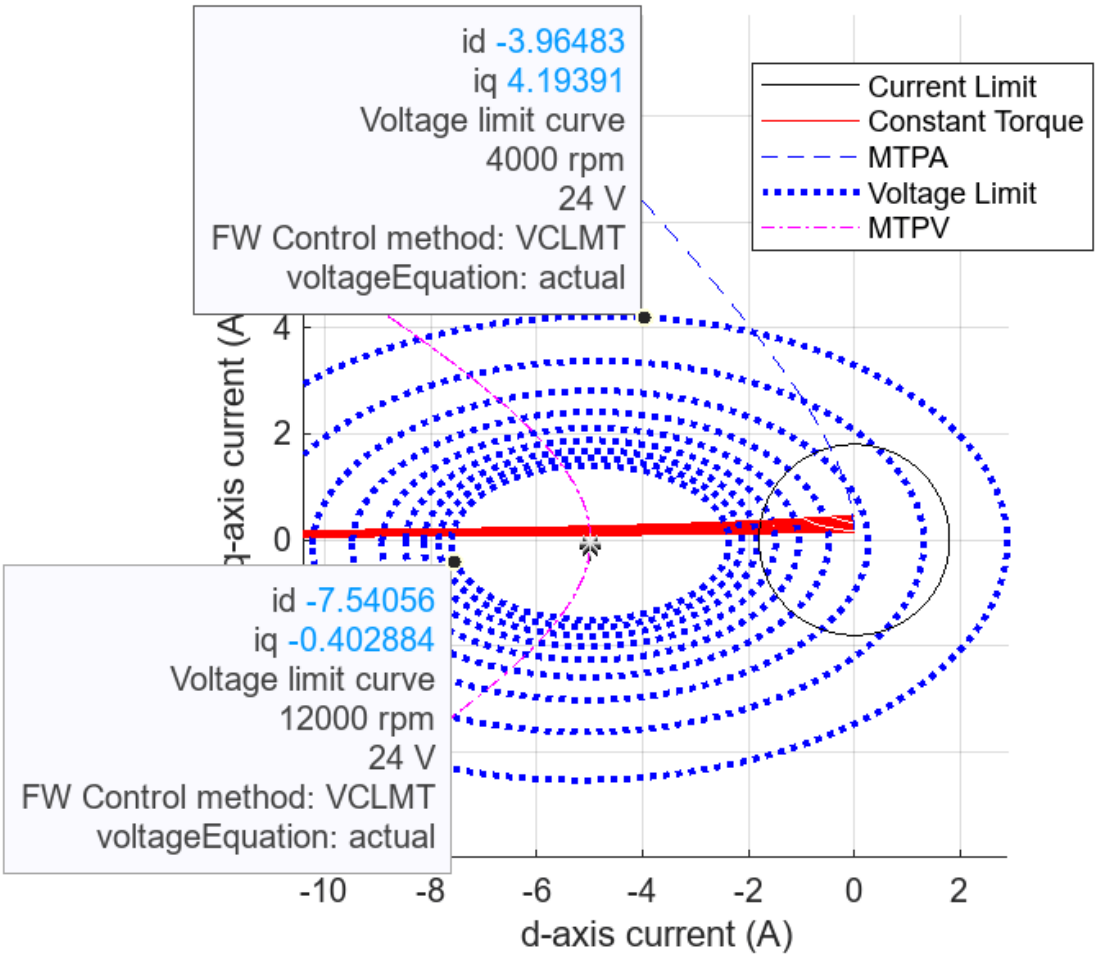
Use the `opacity` option to set the opacity of the presently plotted constraint curve.

- When you set `opacity` to `1` (default), the function creates a new figure window for plotting.
- When you set `opacity` to a value less than 1 (but more than 0), the function plots the voltage constraint, MTPA, and MTPV curves with changing opacity.

The `opacity` option is useful when you want to identify changes and track trends in these curves.

Run this section

```
inverter = mcb_SetInverterParameters( 'BoostXL-DRV8305');
pmsm     = mcb_SetPMSMMotorParameters('BLY171D');
pmsm.Rs=0.1;

pmsm.Lq=pmsm.Ld* 1.8                              ;
mcbPMSMCharacteristics(pmsm,inverter,'speed',4000,'torque',0,'opacity',1)
mcbPMSMCharacteristics(pmsm,inverter,'speed',5000,'opacity',0.8)
mcbPMSMCharacteristics(pmsm,inverter,'speed',6000,'opacity',0.7)
mcbPMSMCharacteristics(pmsm,inverter,'speed',7000,'opacity',0.6)
mcbPMSMCharacteristics(pmsm,inverter,'speed',8000,'opacity',0.5)
mcbPMSMCharacteristics(pmsm,inverter,'speed',9000,'opacity',0.4)
mcbPMSMCharacteristics(pmsm,inverter,'speed',10000,'opacity',0.3)
mcbPMSMCharacteristics(pmsm,inverter,'speed',11000,'opacity',0.2)
mcbPMSMCharacteristics(pmsm,inverter,'speed',12000,'opacity',0.1)
xlim([-7.61 1.23])
ylim([-1.55 9.05])
ax2 = gca;
chart2 = ax2.Children(3);
datatip(chart2,-7.541,-0.4029,"Location","southwest");
chart2 = ax2.Children(51);
datatip(chart2,-3.893,5.438,"Location","northwest");
xlim([-10.4 2.9])
ylim([-6.0 9.9])
```



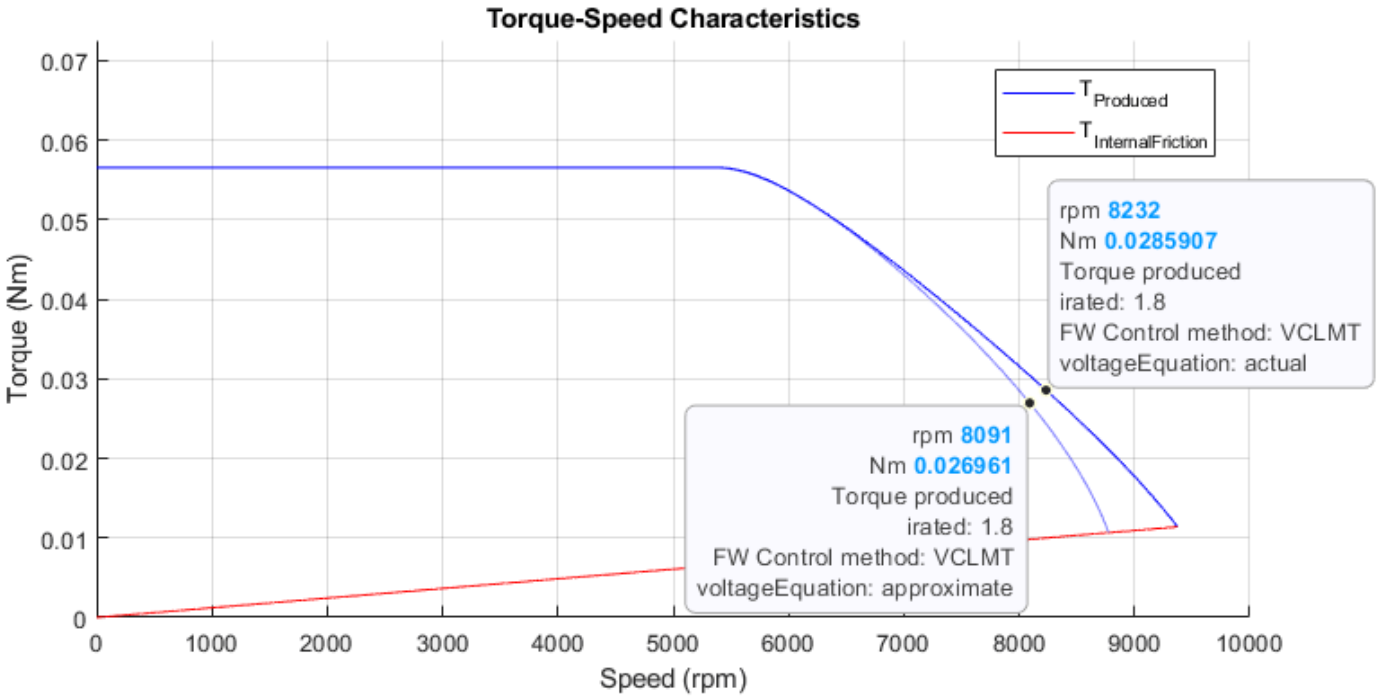
Actual vs Approximate Voltage Equations for Maximum Speed

Usually, the PMSM characteristic equations for v_d and v_q have an $i \times r$ term, which the computations ignore because this value becomes negligible at higher speeds. In this example, you can include or exclude the $i \times r$ term from the v_d and v_q equations while calculating the maximum speeds. The actual form of the equation is as follows.

$$v_d = i_d r - \omega L_q I_q$$

$$v_q = i_q r + \omega L_d i_d + \omega \psi_m$$

This figure shows the difference in the drive characteristics with actual and approximate equations.



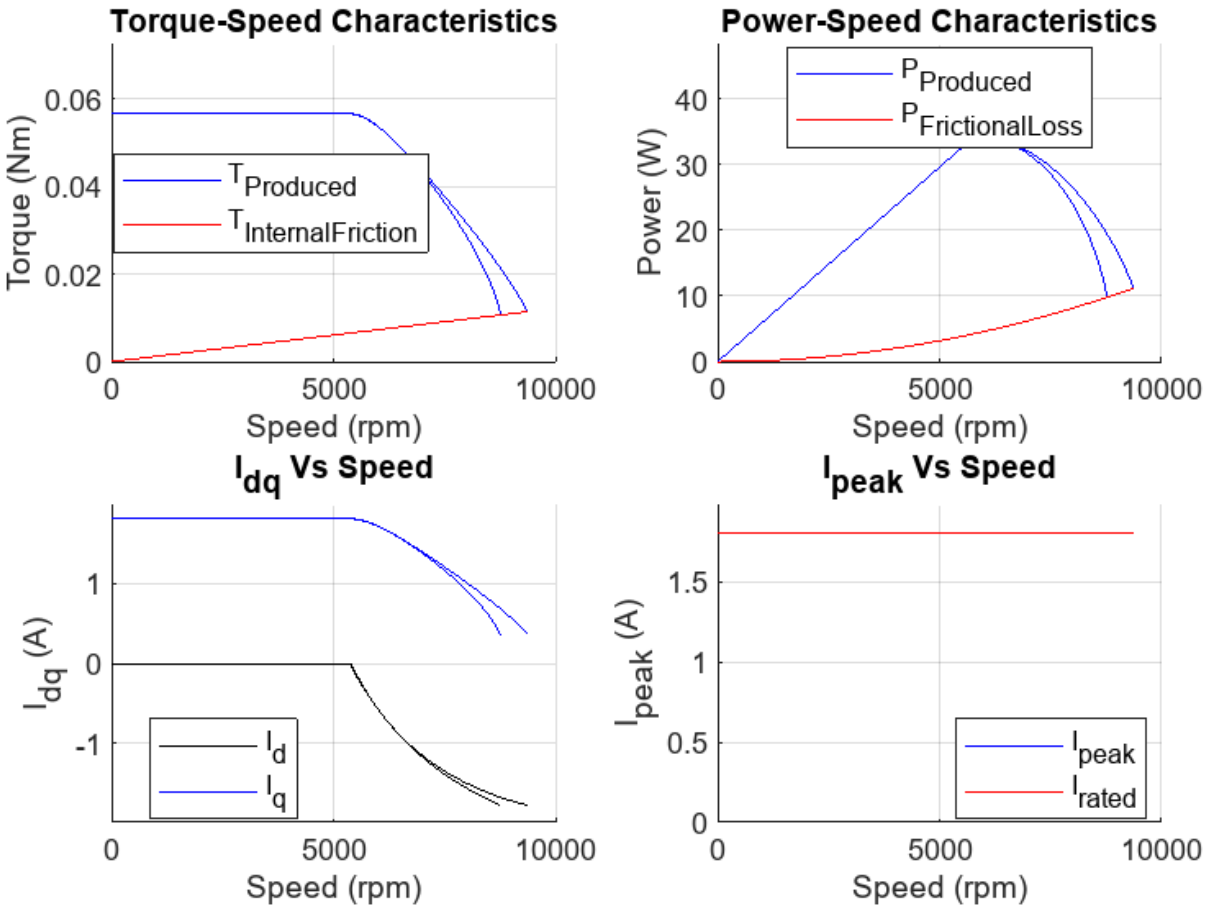
Set the fields for the `pmsm` and `inverter` structures and plot the characteristics with both the actual and approximate equations.

Run this section

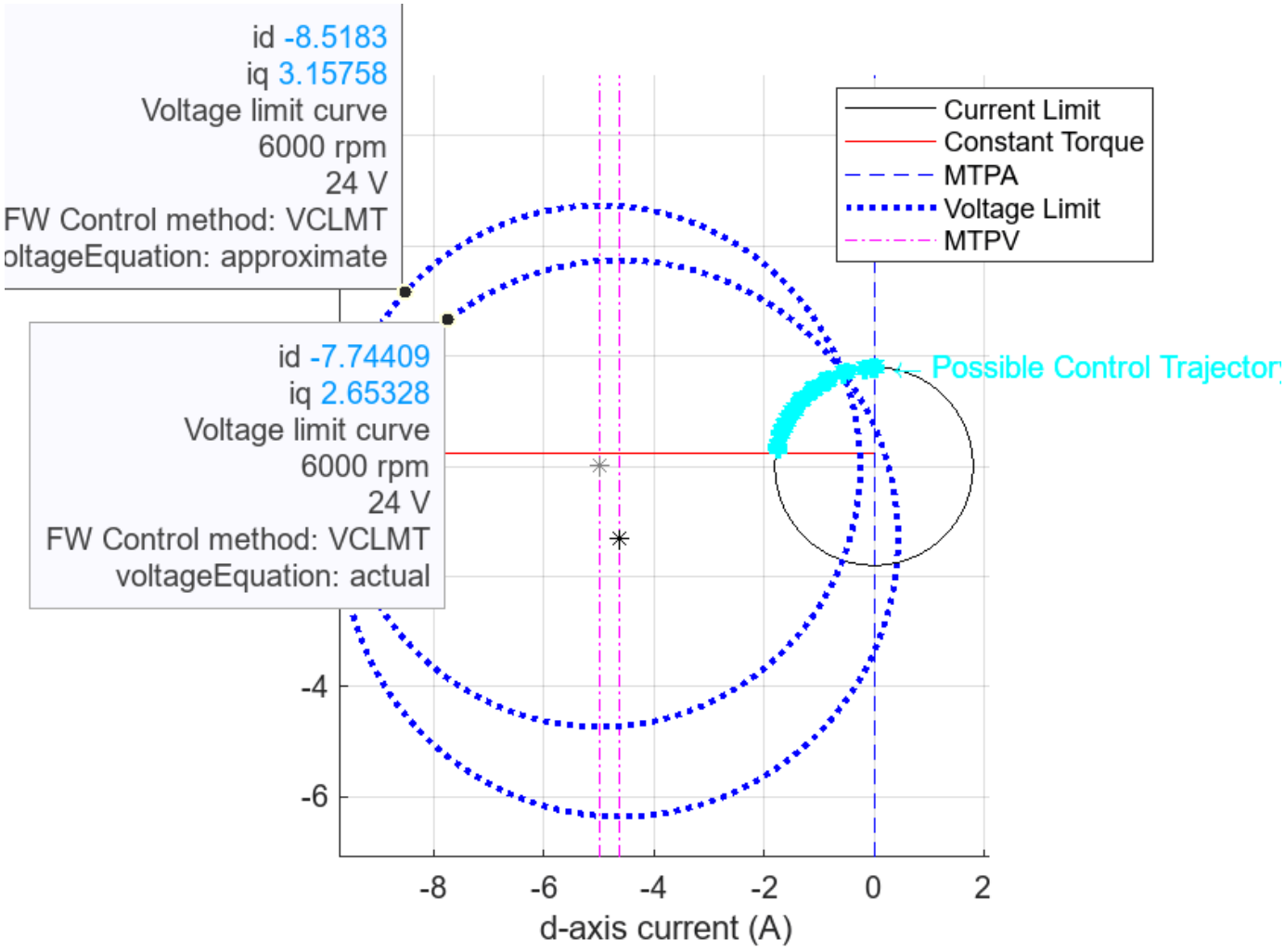
```
inverter = mcb_SetInverterParameters( 'BoostXL-DRV8305');
pmsm     = mcb_SetPMSMMotorParameters('BLY171D');
max_speed_actual_eqn=mcbPMSMSpeeds(pmsm,inverter,'verbose',verbose,'voltageEquation','actual');
max_speed_approx_eqn=mcbPMSMSpeeds(pmsm,inverter,'verbose',verbose,'voltageEquation','approximate
disp([max_speed_actual_eqn max_speed_approx_eqn])
```

```
        5393        5359
        9373        8775
```

```
temporary_speed=6000;
mcbPMSMCharacteristics(pmsm,inverter,'speed',temporary_speed,'voltageEquation','actual',driveCha
mcbPMSMCharacteristics(pmsm,inverter,'speed',temporary_speed,'voltageEquation','approximate','op
```




```
xlim([-9.7 2.1])
ylim([-7.1 7.1])
legend("Position", [0.65054,0.72607,0.25,0.19286])
ax3 = gca;
chart3 = ax3.Children(13);
datatip(chart3,-7.744,2.653,"Location","southwest");
chart3 = ax3.Children(5);
datatip(chart3,-8.518,3.158,"Location","northwest");
```



Customize Constraint Curves

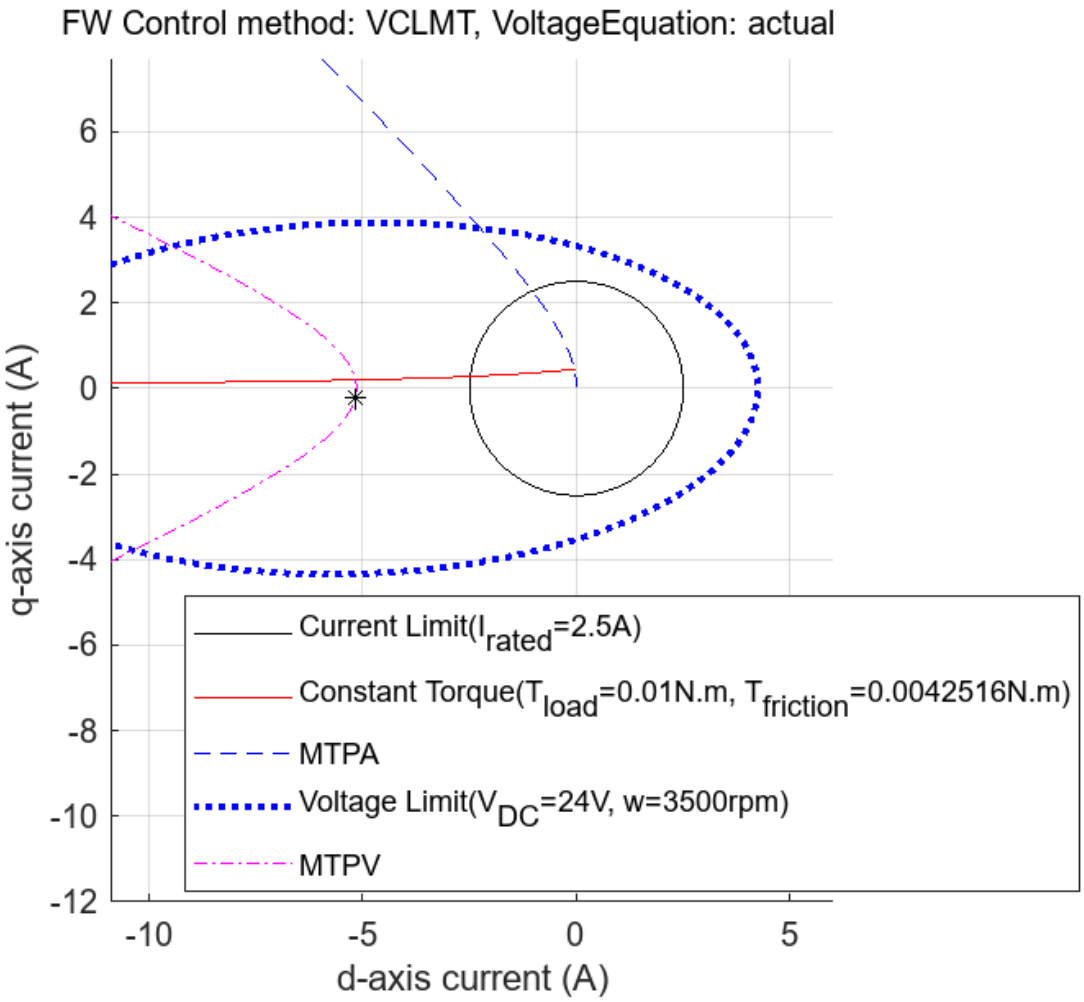
Change the parameters to plot the constraint curves.

The `pmsm` structure expects values for the `p`, `Rs`, `Ld`, `Lq`, `FluxPM`, `B` and `I_rated` fields. The `inverter` structure expects a value for the `V_dc` field. Set the field values and plot the characteristics.

Run this section

```
inverter.V_dc= 24 ;
pmsm.p=4;
pmsm.Rs= 0.15 ;
pmsm.Ld=1e-3;
pmsm.Lq=pmsm.Ld* 2.3 ;
pmsm.B=1.16e-5;
pmsm.FluxPM=5.2e-3;
```

```
w_rpm= 3500 ;
T_load= 0.01 ;
pmsm.I_rated= 2.5 ;
mcbPMSMCharacteristics(pmsm,inverter,'speed',w_rpm,'torque',T_load);
xlim([-10.9 6.0])
ylim([-12.0 7.7])

legend("Position",[0.32518,0.11984,0.61786,0.2869])
```



Case Studies

This section provides case studies that show how to find a possible control trajectory for an IPMSM and SPMSM. The case studies use the following workflow:

1. Plot the drive characteristics (including MTPV) and the constraint curves using the `mcbPMSMCharacteristics` function. For this plot, use the corner speed.

2. Use the `mcbPMSMCharacteristics` function with `driveCharacteristics` set to `0` and `opacity` set to `0.5` to plot the constraint curves over the figure generated in the previous step. For this plot, use the speed at which MTPV starts.
3. Use the `mcbPMSMCharacteristics` function with `driveCharacteristics` set to `0` and `opacity` set to `0.3` to plot the constraint curves over the figure generated in the previous step. For this plot, use the maximum speed.

Doing so plots the three voltage limiting curves overlapping the current limit circle at appropriate points in the final figures for both motors. These figures show the current trajectory for field weakening along the highlighted cyan line. This line follows the MTPV path. When the motor resistance is high enough, the MTPV curve shifts dynamically along with the speed, resulting in the current trajectory not following any single MTPV curve. The resulting cyan curve is the achievable MTPV curve because the example uses the actual equations to dynamically solve for operating points and plot the curves.

To observe the shift in the MTPV curve at different resistance values, use the drop-down menu in the following sections to pick a division factor for the resistance. With a higher resistance, the MTPV curves are farther apart, and with a lower resistance, the MTPV curves are closer to each other.

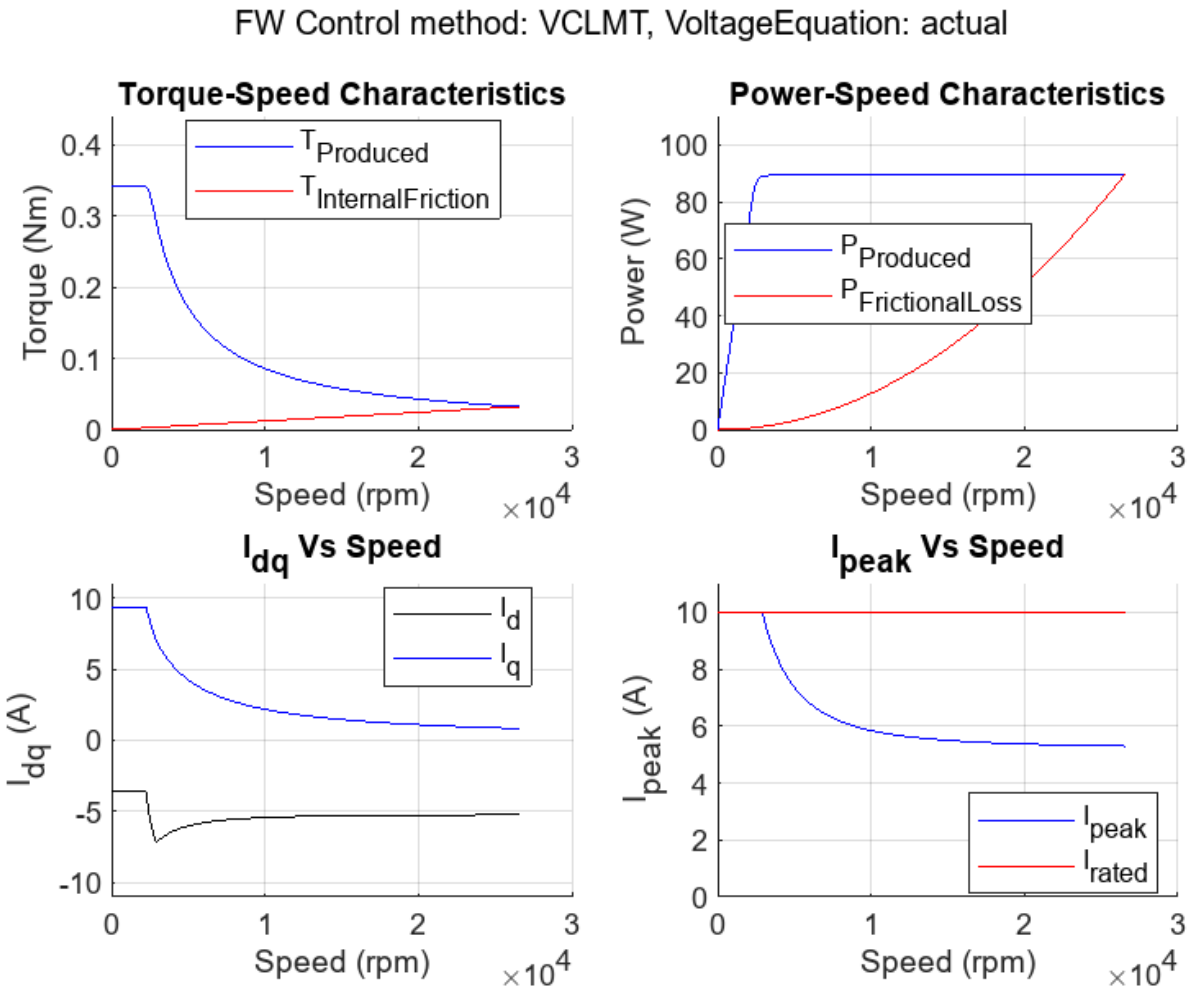
Plot these characteristics for each type of motor.

IPMSM Case Study

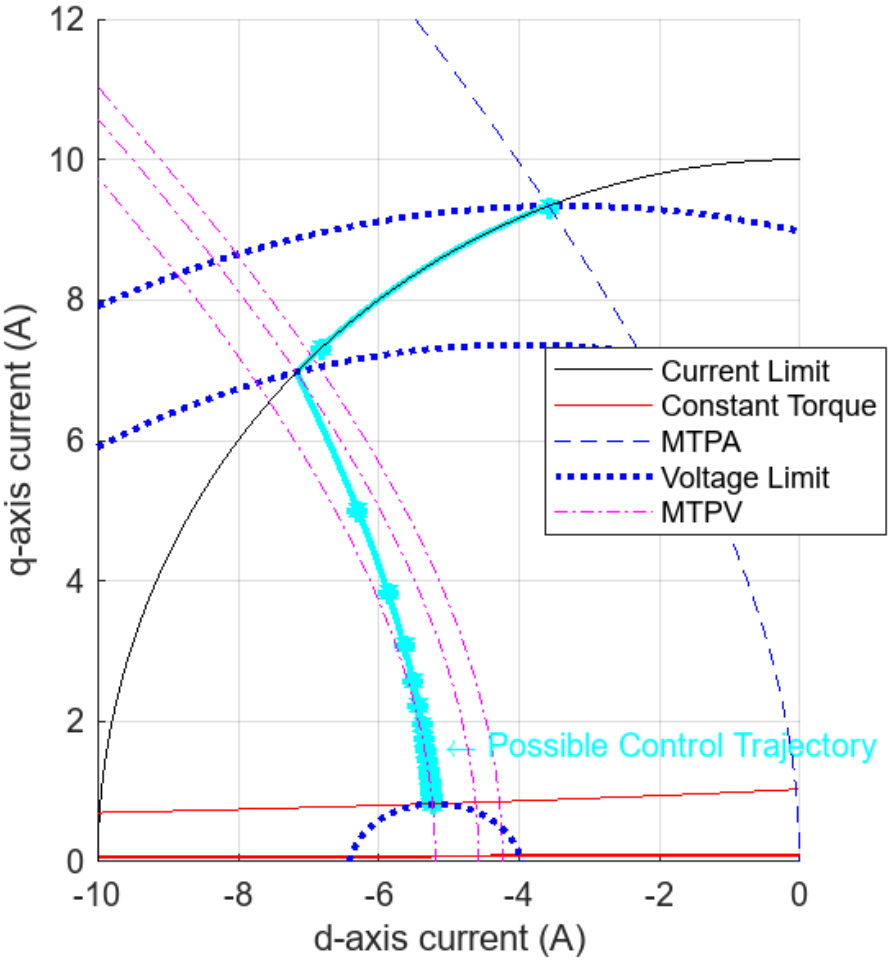
Set the field values and plot the characteristics.

Run this section

```
inverter.V_dc=24;
pmsm.p=4;
pmsm.Rs=0.45;

pmsm.Rs=pmsm.Rs/1;
pmsm.Ld=1e-3;
pmsm.Lq=1.25*pmsm.Ld;
pmsm.FluxPM=5.2e-3;
pmsm.I_rated=10;
pmsm.B=1.16e-5;
[milestone_speeds]=mcbPMSMSpeeds(pmsm,inverter);
mcbPMSMCharacteristics(pmsm,inverter,'speed',milestone_speeds(1),'driveCharacteristics',1,'const
```




```
mcbPMSMCharacteristics(pmsm,inverter,'speed',milestone_speeds(2),'driveCharacteristics',0,'const
mcbPMSMCharacteristics(pmsm,inverter,'speed',milestone_speeds(end),'driveCharacteristics',0,'con
```

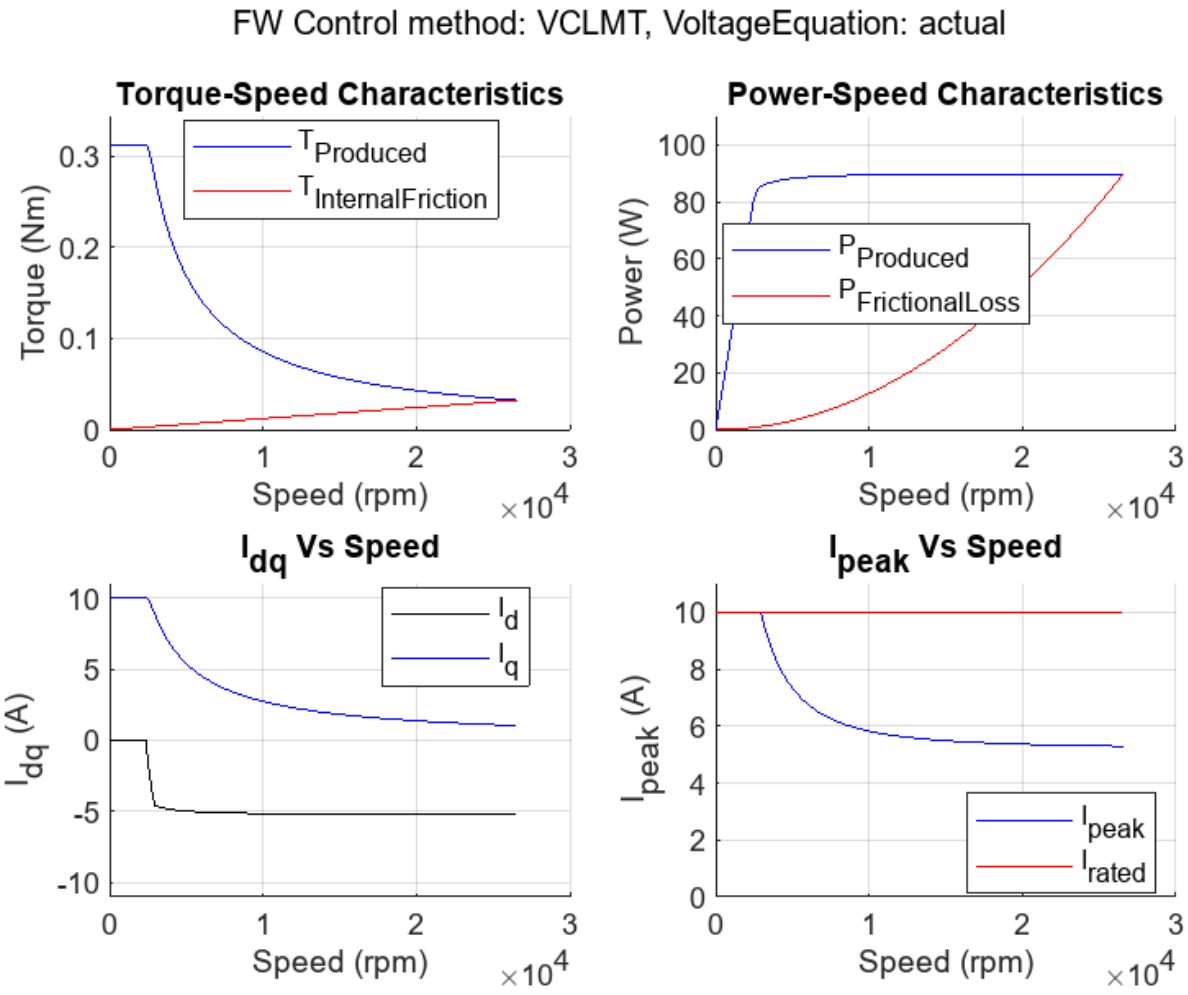


SPMSM Case Study

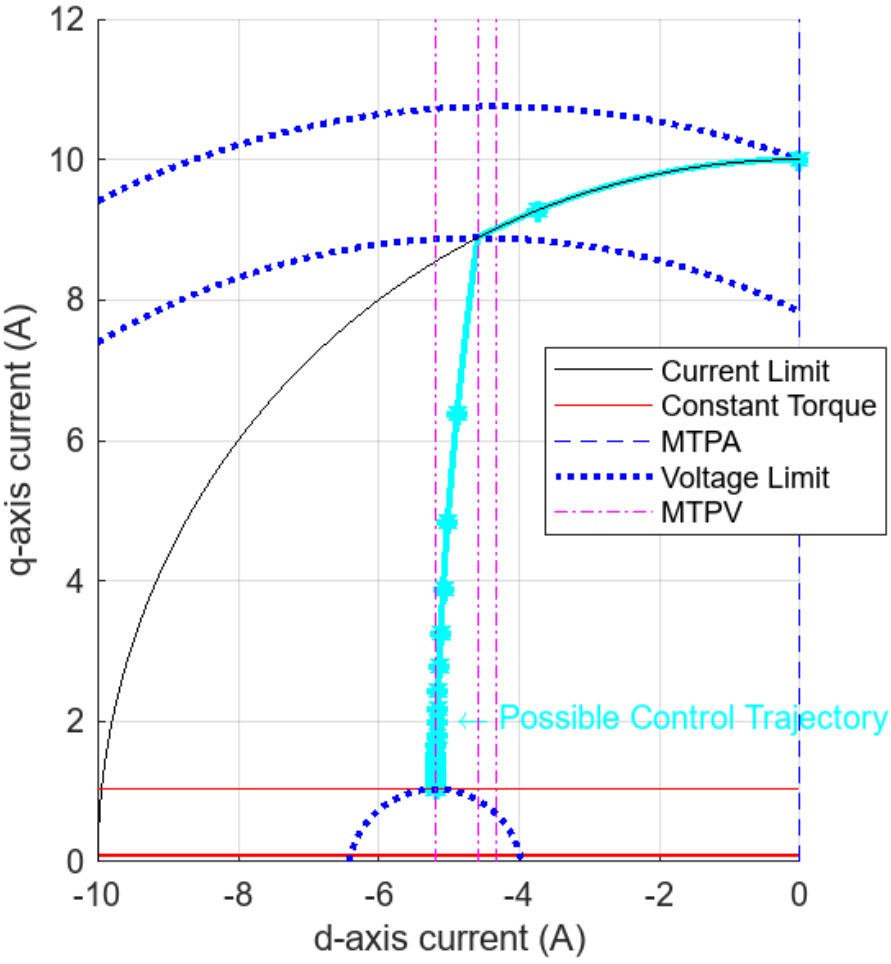
Set the field values and plot the characteristics.

Run this section

```
inverter.V_dc=24;
pmsm.p=4;
pmsm.Rs=0.45;

pmsm.Rs=pmsm.Rs/1;
pmsm.Ld=1e-3;
pmsm.Lq=pmsm.Ld;
pmsm.FluxPM=5.2e-3;
pmsm.I_rated=10;
pmsm.B=1.16e-5;
[milestone_speeds]=mcbPMSMSpeeds(pmsm,inverter);
mcbPMSMCharacteristics(pmsm,inverter,'speed',milestone_speeds(1),'driveCharacteristics',1,'const
```

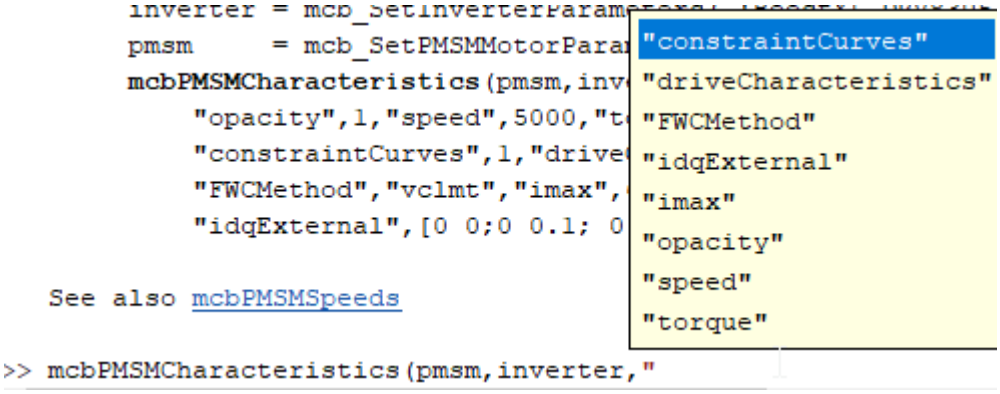



```
mcbPMSMCharacteristics(pmsm,inverter,'speed',milestone_speeds(2),'driveCharacteristics',0,'const
mcbPMSMCharacteristics(pmsm,inverter,'speed',milestone_speeds(end),'driveCharacteristics',0,'cons
```



Note: You can use the **Tab** button to get a list of supported optional arguments.

In the command line, in the live-script environment, or in the editor, the function provides suggestions for the name-value arguments.



References

[1] Mihailovic, Zoran. “Modeling and Control Design of Vsi-Fed Pmsm Drive Systems With Active Load.” Thesis, Virginia Tech, 1998. https://vtechworks.lib.vt.edu/handle/10919/31493.

[2] Li, Muyang. "Flux-Weakening Control for Permanent-Magnet Synchronous Motors Based on Z-Source Inverters." Thesis, 2014. http://epublications.marquette.edu/theses_open/284.

Deploy and Validate System

Prepare Target Hardware

Follow these steps to prepare the target hardware before you deploy the control algorithm developed using Motor Control Blockset to it.

Note You need Embedded Coder Support Package for Texas Instruments C2000 Processors to run these steps.

We recommend that you see these references before following this procedure:

- Getting Started with Embedded Coder Support Package for TI C2000 Processors
- “Getting Started with Embedded Coder Support Package for Texas Instruments C2000 Processors” (Embedded Coder Support Package for Texas Instruments C2000 Processors)

In addition, try running the motor using open-loop control first using the “Run 3-Phase AC Motors in Open-Loop Control and Calibrate ADC Offset” example.

Verify Direction of Rotation of Motor

The phase sequence of the motor connection in the target hardware determines the direction of rotation of the motor. The Motor Control Blockset example models consider the direction of rotation during the position ramp-up as a positive direction and the corresponding measured speed as positive. It is recommended that you run the motor in open-loop control with a position ramp from `0` to `1` and ensure that the position feedback is positive. The example models in Motor Control Blockset use this convention for the motor's direction of rotation.

For the supported hardware, the algorithm in the example “Quadrature Encoder Offset Calibration for PMSM Motor”, runs the motor and finds the offset between the *d*-axis of the rotor and the encoder index pulse (when the rotor is aligned to the *d*-axis of the stator). The red LED in the host model for this example turns on when the direction of rotation is opposite. When this happens, you should change the phase sequence of the motor wiring (swap any two motor wires).

See the example “Hall Offset Calibration for PMSM Motor” to identify the direction of rotation of a motor that uses Hall sensors.

Note When you use a Hall sensor, ensure that the Hall sequence updated in the Hall Speed and Position and Hall Validity blocks matches the sequence of the actual Hall signals. If you update an incorrect Hall sequence, the direction read by the target hardware is the opposite of the actual direction.

Calibrate Current Sensor

The signal conditioning circuits for the current sensor introduces a voltage offset in the analog to digital converter (ADC) input when measuring both the positive and negative current. For example, an ADC with a voltage reference of `3.3` V can have an offset of `1.65` V when using the Texas Instruments BOOSTXL-DRV8305 hardware. This offset varies due to tolerances of the passive components available in the signal conditioning circuit. It is recommended that you measure the ADC offset of the hardware during initialization.

The hardware initialization subsystem, which is used in the majority of Motor Control Blockset example models, computes the average current sensor ADC values and uses them as ADC offset values for measuring the current. The subsystem represents the ADC offset values in ADC counts.

See the example “Run 3-Phase AC Motors in Open-Loop Control and Calibrate ADC Offset” to manually calibrate the ADC offset and update the computed offset value in the model initialization script file.

See the **Hardware Init** subsystem available in the example “Field-Oriented Control of PMSM Using Quadrature Encoder” to understand the ADC offset calculations that the example model performs before starting the closed-loop motor control.

Calibrate Position Sensor

For a PMSM, the position used in the current control algorithm should align with the *d*-axis position of the rotor. By default, the quadrature encoder position sensor reads the mechanical position of the rotor with reference to its index pulse. The position offset is the position read by the quadrature encoder when *d*-axis of the rotor aligns with phase *a*. To obtain an accurate motor position, use this position offset value to correct the position read by the quadrature encoder sensor. Then provide the corrected motor position value as an input to the current control algorithm.

A mismatch between the actual rotor position and the position provided to the current controller affects the motor functionality and performance.

For more details, see the examples “Quadrature Encoder Offset Calibration for PMSM Motor” and “Hall Offset Calibration for PMSM Motor”.

Add Hardware Drivers to Simulation Model and Deploy to Target Hardware

This topic explains the steps for adding the hardware drivers to the simulation model and deploying the model to the target hardware.

This topic uses the model `mcb_pmsm_foc_sim` as a example to explain the procedure for hardware deployment. The model `mcb_pmsm_foc_sim` simulates the field-oriented control (FOC) algorithm for implementing speed control for a PMSM.

As an example, the procedure explains about deploying the speed control algorithm to the target hardware Texas Instruments LAUNCHXL-F28379D (connected to Texas Instruments BOOSTXL-DRV8305). These are the hardware interface details:

Interface	Pin on LAUNCHXL-F28379D
Phase-A input of the motor	ADCINC2
Phase-B input of the motor	ADCINB2
PWM A output from the motor	EPWM1A
PWM B output from the motor	EPWM2A
PWM C output from the motor	EPWM3A
Enable Driver BOOSTXL-DRV8305	GPIO124

These steps explain how to add the hardware driver blocks from the Embedded Coder Support Package for Texas Instruments C2000 Processors to the simulation model before deploying the control algorithm to the target hardware LAUNCHXL-F28379D (connected to BOOSTXL-DRV8305).

1. “Task Scheduling in Target Hardware” on page 2-6
2. “Adding ADC Driver Library Block” on page 2-8
3. “Adding Quadrature Encoder Driver Block” on page 2-11
4. “Add PWM Driver Block” on page 2-14
5. “Add Hardware Interrupt Trigger Block for Current Control Loop” on page 2-18
6. “Run in Open-Loop and Switch to Closed-Loop” on page 2-19
7. “Model Configuration and Hardware Deployment” on page 2-23

You can use MATLAB variables to define or customize parameters like the execution time of the current controller or the speed controller. See the model initialization script associated with the example model `mcb_pmsm_foc_sim` for details about the variables defined in these steps.

To understand the prerequisites for deploying the control algorithm to any target hardware, see “Prepare Target Hardware” on page 2-2. For details about the hardware connections, see “Hardware Connections”.

To implement a simulation model that uses FOC algorithm for a PMSM, see “Design Field-Oriented Control Algorithm” on page 1-2.

A basic understanding of Simulink is a prerequisite to follow these steps. For details about the ADC driver, the quadrature encoder driver, and the hardware interrupt block, see the example model `mcb_pmsm_foc_qep_f28379d`, which uses an architecture similar to what we describe.

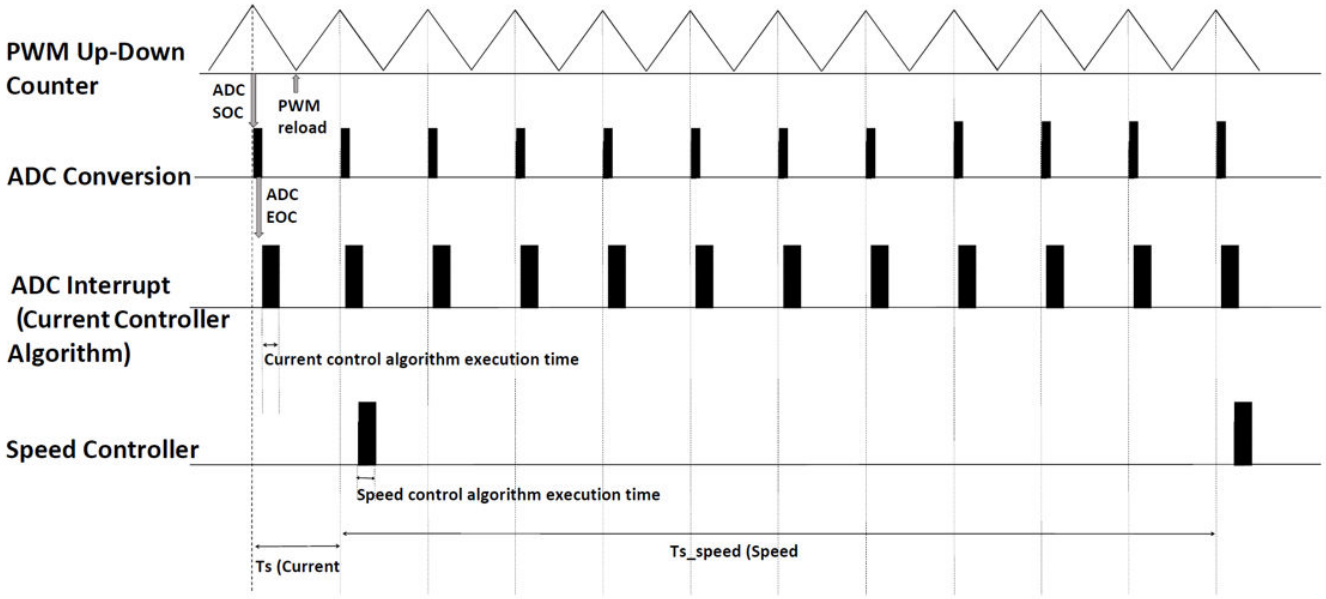
Note For target hardware other than LAUNCHXL-F28379D (connected to BOOSTXL-DRV8305), you can follow these steps, but select the driver blocks (ADC, PWM, Interrupt) from the appropriate supported hardware library.

Task Scheduling in Target Hardware

In the example model `mcb_pmsm_foc_sim`, configuring the current controller and the speed controller are the two important tasks. The current controller is scheduled to run after every T_s (`50` µsec for a `20` kHz switching frequency) and the speed controller runs after every T_{s_speed} (`10`*T_s). The current controller reads the motor phase currents and position and computes the PWM duty cycle to run the motor. The speed controller runs the control loop, calculates I_q reference for the current controller, and controls the motor speed in the closed-loop.

In the target hardware, the current controller is synchronized with the ADC interrupt (for every T_s) and the speed controller is triggered after every T_{s_speed} (`10`*T_s).

This figure shows the event sequence, interrupt trigger, and software execution time for the control algorithm running in the target hardware.



In this figure, the execution times for the current controller and speed controller are not in scale. See the processor datasheet to better understand the functionality of the processor peripherals such as the ADC (analog-to-digital converter) and the PWM (pulse-width modulation).

The model follows this event sequence:

1. The processor peripheral PWM, which is center-aligned (Up-Down Counter), triggers the start-of-conversion (SOC) event for the ADC module when the PWM counter value equals the PWM period.
2. The ADC module converts the sampled analog signal into digital counts and triggers the end-of-conversion (EOC) event.
3. The EOC triggers the ADC interrupt.
4. The current controller is scheduled to execute with the ADC interrupt.
5. The speed controller is scheduled to run after every T_{s_speed}.

You can also use SoC Blockset™ for task scheduling, profiling, and addressing challenges related to ADC-PWM synchronization, controller response, and studying different PWM settings. For details, see “Integrate MCU Scheduling and Peripherals in Motor Control Application”.

Adding ADC Driver Library Block

In the example model `mcb_pmsm_foc_sim`, the subsystem for current controller receives the motor phase current in ADC counts from the plant model that converts the motor phase current from Amperes to ADC counts. In the target hardware, the current controller reads the motor phase current from the ADC driver block. Follow this workflow to add and configure the ADC driver block.

These steps explain addition and configuration of the ADC driver blocks in detail. In the Simulink library browser, select and add the ADC block from the F2837xD library in Embedded Coder Support Package for Texas Instruments C2000 Processors. Use the following steps to configure the ADC blocks to read the phase-A and phase-B currents of the motor.

In the Texas Instruments BOOSTXL-DRV8305 inverter hardware, the phase-A current of the motor is read from ADC C2 channel and phase-B current is read from ADC B2 channel. In the ADC driver block for phase-A current (see the following figure), select **ADC module** C and conversion channel 2 to obtain the phase-A current of the motor. In the ADC driver block for phase-B current, select **ADC module** B and conversion channel 2 to obtain the phase-B current of the motor. For other target hardware, select the **ADC module** and channel where the motor phase currents are interfaced.

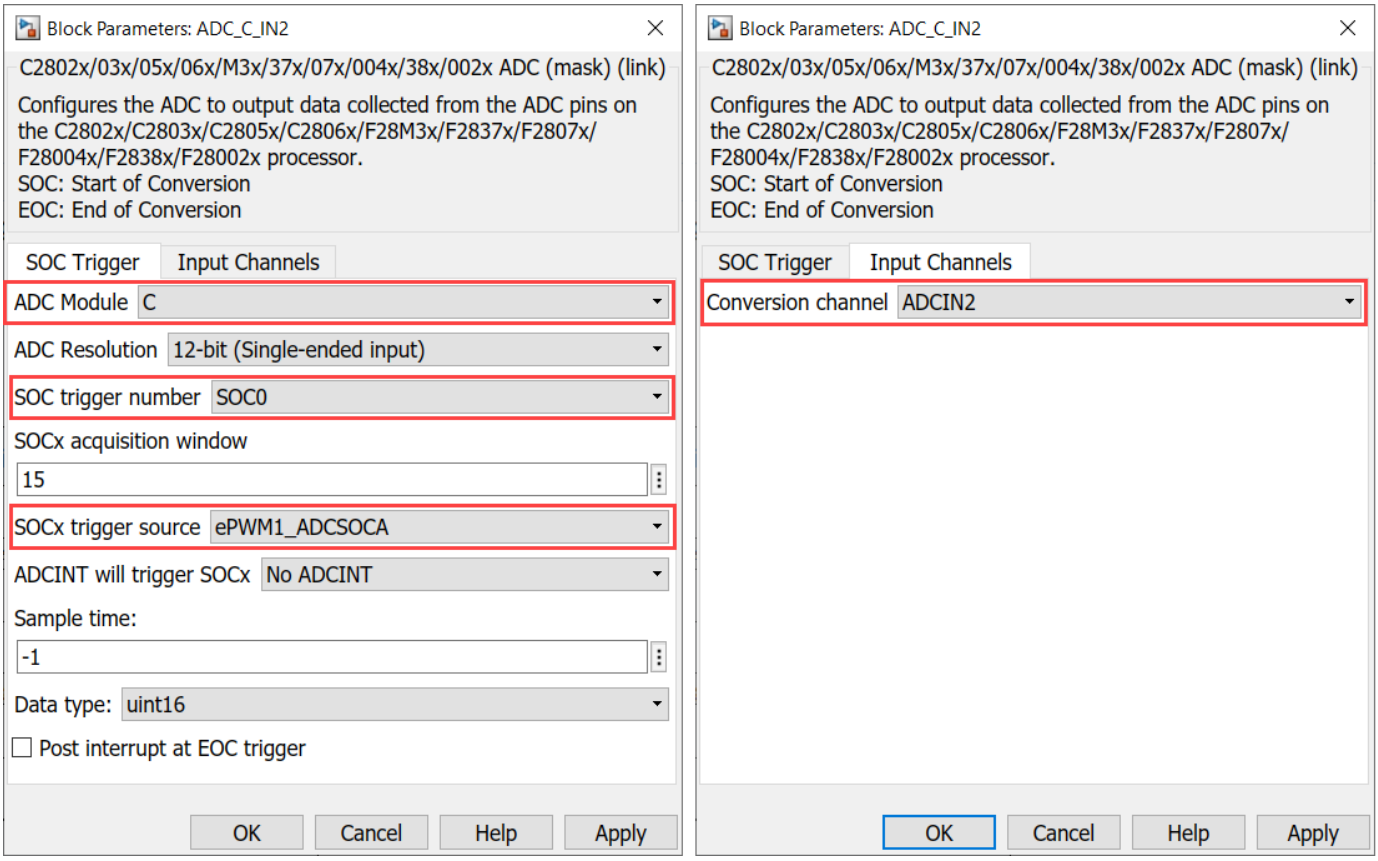
Select `ePWM1_ADCSOCA` as the SOC trigger source in the ADC driver blocks for phase-A and phase-B currents because the PWM library block triggers the start-of-conversion event SOC0 when the PWM counter equals the PWM period register.

In the ADC driver block for phase-B current (that uses **ADC module** B), select `ADCINT1`. This triggers an ADC interrupt at the end-of-conversion (EOC) event. When the ADC interrupt occurs, the FOC current control algorithm executes.

In the block parameters dialog box of ADC driver block for phase-A current, configure the ADC C module and channel 2 to read the phase-A current of the motor, as shown in this table.

Tab and Parameter in ADC Block	Settings
SOC Trigger > ADC Module	**C**
SOC Trigger > SOC trigger number	**SOC0**
SOC Trigger > SOC trigger source	**ePWM1_ADCSOCA**
Input Channels > Conversion channel	**ADCIN2**

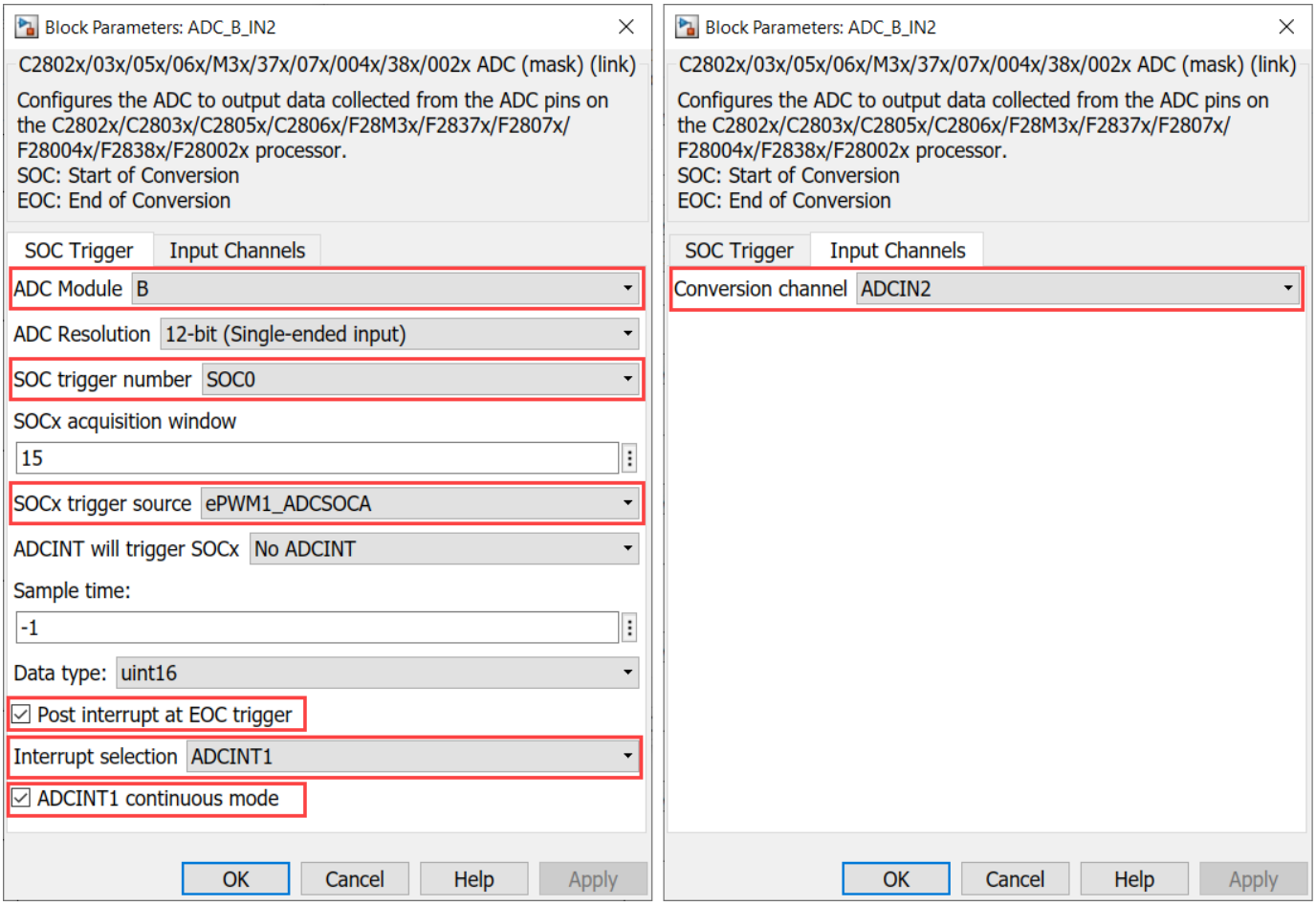
Rename the block as ADC_C_IN2.

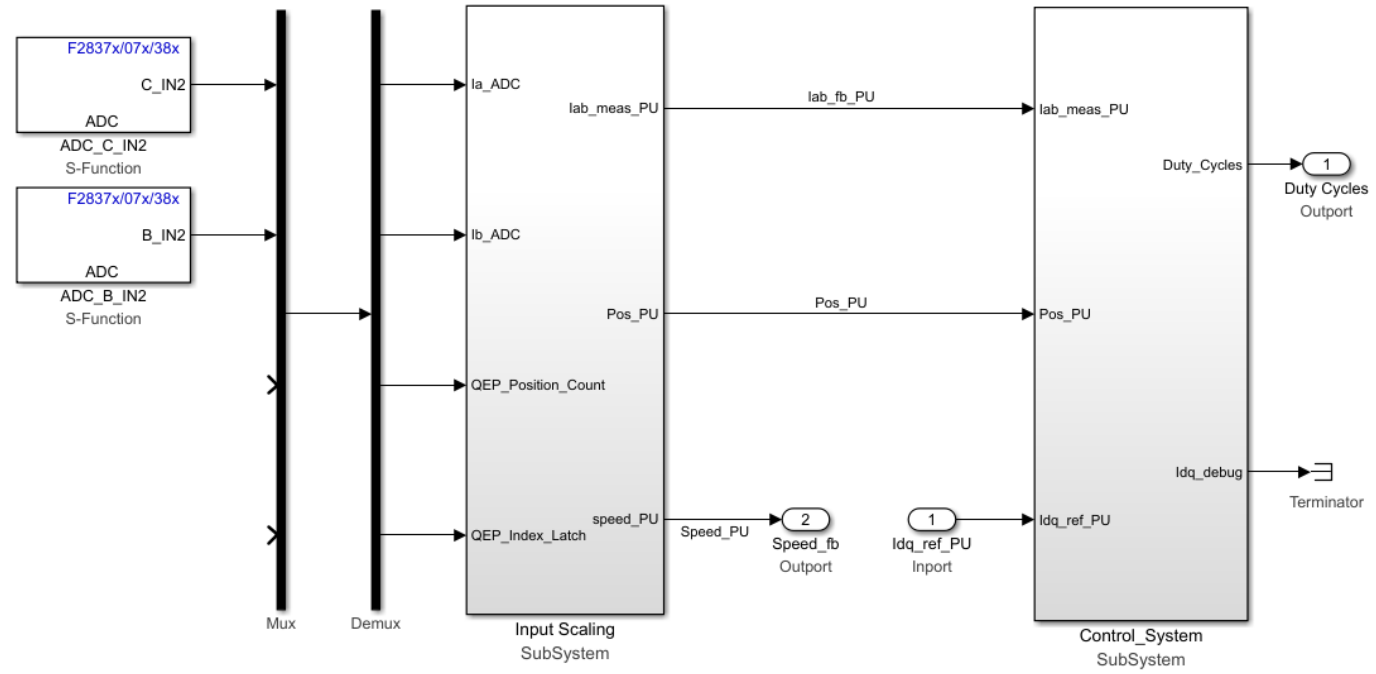


In the block parameters dialog box of ADC driver block for phase-B current, configure the ADC B module and channel 2 to read phase-B current of the motor. In addition, configure ADC interrupt as `ADCINT1`, as shown in this table.

Tab and Parameter in ADC Block	Settings
SOC Trigger > ADC Module	**B**
SOC Trigger > SOC trigger number	**SOC0**
SOC Trigger > SOC trigger source	**ePWM1_ADCSOCA**
SOC Trigger > Post interrupt at EOC trigger	on
SOC Trigger > Interrupt selection	**ADCINT1**
SOC Trigger > ADCINT1 continuous mode	on
Input Channels > Conversion channel	**ADCIN2**

Rename the block as ADC_B_IN2.


Block Parameters: ADC_B_IN2
C2802x/03x/05x/06x/M3x/37x/07x/004x/38x/002x ADC (mask) (link)
Configures the ADC to output data collected from the ADC pins on the C2802x/C2803x/C2805x/C2806x/F28M3x/F2837x/F2807x/ F28004x/F2838x/F28002x processor.
SOC: Start of Conversion
EOC: End of Conversion
SOC Trigger
Input Channels
ADC Module B
ADC Resolution 12-bit (Single-ended input)
SOC trigger number SOC0
SOCx acquisition window
15
SOCx trigger source ePWM1_ADCSOCA
ADCINT will trigger SOCx No ADCINT
Sample time:
-1
Data type: uint16
Post interrupt at EOC trigger
Interrupt selection ADCINT1
ADCINT1 continuous mode
OK
Cancel
Help
Apply
Block Parameters: ADC_B_IN2
C2802x/03x/05x/06x/M3x/37x/07x/004x/38x/002x ADC (mask) (link)
Configures the ADC to output data collected from the ADC pins on the C2802x/C2803x/C2805x/C2806x/F28M3x/F2837x/F2807x/ F28004x/F2838x/F28002x processor.
SOC: Start of Conversion
EOC: End of Conversion
SOC Trigger
Input Channels
Conversion channel ADCIN2
OK
Cancel
Help
Apply


F2837x/07x/38x
C_IN2
ADC
ADC_C_IN2
S-Function
F2837x/07x/38x
B_IN2
ADC
ADC_B_IN2
S-Function
Mux
Demux
Ia_ADC
Ib_ADC
Pos_PU
QEP_Position_Count
QEP_Index_Latch
Iab_meas_PU
speed_PU
Input Scaling
SubSystem
Speed_PU
2
Speed_fb
Outport
1
Idq_ref_PU
Inport
Iab_fb_PU
Pos_PU
Iab_meas_PU
Pos_PU
Idq_ref_PU
Duty_Cycles
1
Duty Cycles
Outport
Idq_debug
Terminator
Control_System
SubSystem

Adding Quadrature Encoder Driver Block

In the Simulink Library Browser, add the eQEP block from **Embedded Coder Support Package for Texas Instruments C2000 Processors > F2837xD**.

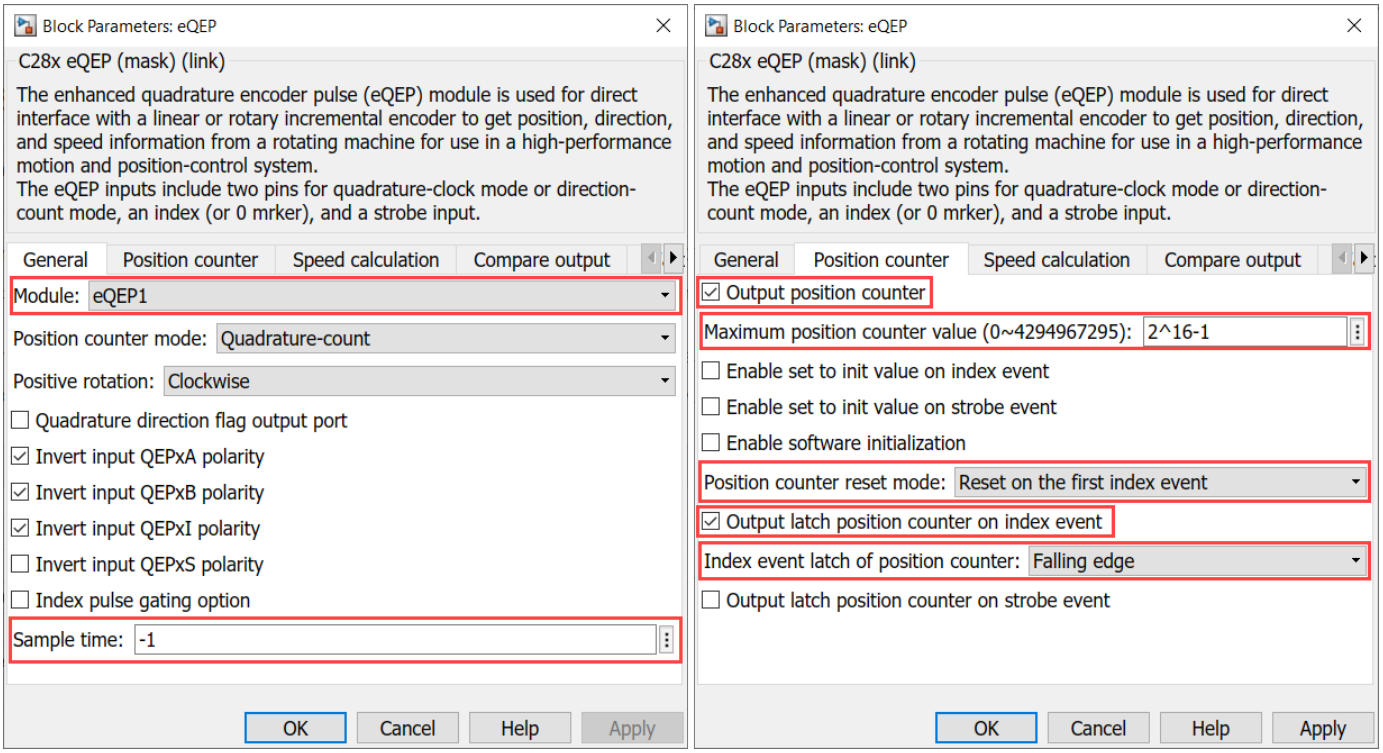
The eQEP block reads the quadrature encoder pulses and increments the position count. This block outputs the quadrature encoder pulse for the mechanical rotor position wraparound when the quadrature encoder index pulse is read.

See the section Quadrature Encoder Interface Configuration in “Model Configuration Parameters” for configurations related to the quadrature encoder.

In C28x eQEP block parameters dialog box, configure the quadrature encoder to read the quadrature encoder pulse count in the Texas Instruments processor and wrap the pulse counter output when index pulse is found as shown in this table.

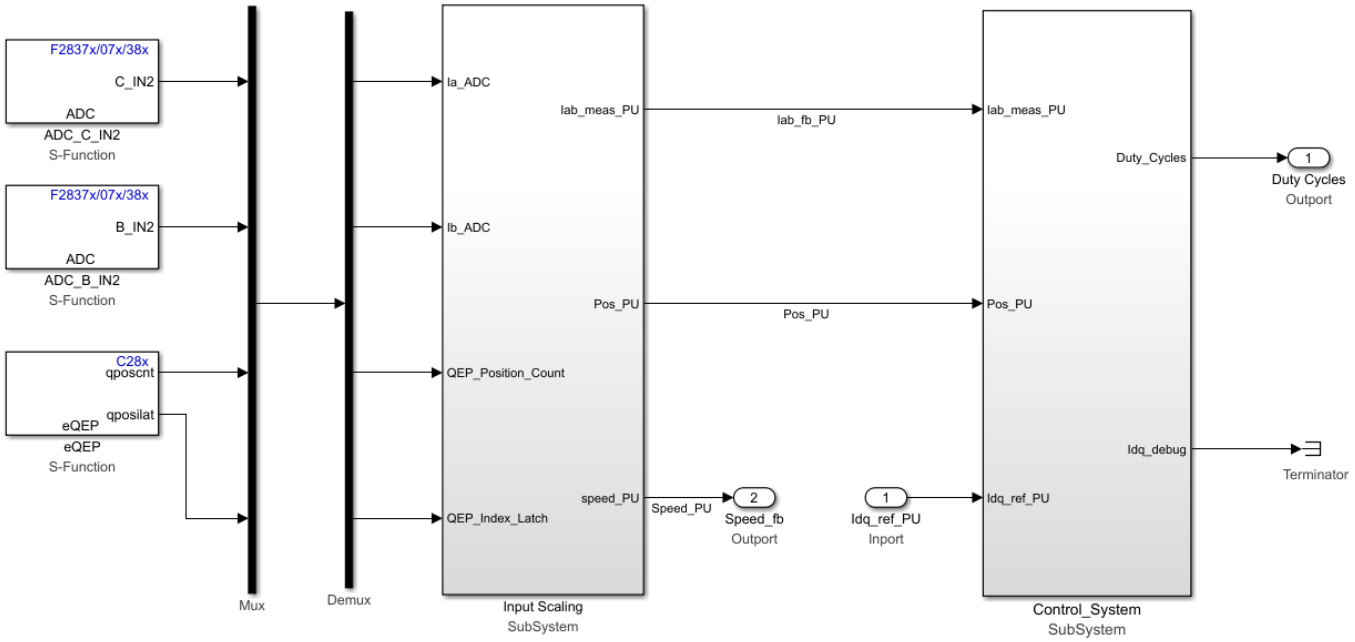
Tab and Parameter in eQEP Block	Settings
General > Module	**eQEP1**
General > Sample time	**-1**
Position counter > Output position counter	on
Position counter > Maximum position counter value (0~4294967295)	**2^16-1**
Position counter > Position counter reset mode	**Reset on the first index event**
Position counter > Output latch position counter on index event	on
Position counter > Index event latch of position counter	**Falling edge**

Rename the block as eQEP.



eQEP1 module is selected because the quadrature encoder is connected to the QEP_A interface on the LaunchPadXL28379d hardware board. The sample time is `-1` because the library block is function-call triggered by the ADC interrupt synchronously. The maximum position counter value is `2^16-1` because the position counter uses a 16-bit architecture in the library driver block. The position counter reset mode setting wraps the position count when the index pulse is read.

Add the eQEP driver block module to the `mcb_pmsm_foc_sim/Current control` subsystem as shown in this figure.


F2837x/07x/38x
C_IN2
ADC
ADC_C_IN2
S-Function
F2837x/07x/38x
B_IN2
ADC
ADC_B_IN2
S-Function
C28x
qposcnt
qposilat
eQEP
eQEP
S-Function
Mux
Demux
Ia_ADC
Ib_ADC
QEP_Position_Count
QEP_Index_Latch
lab_meas_PU
Pos_PU
speed_PU
Input Scaling
SubSystem
Speed_PU
2
Speed_fb
Outport
lab_fb_PU
Pos_PU
1
Idq_ref_PU
Inport
lab_meas_PU
Pos_PU
Idq_ref_PU
Duty_Cycles
Idq_debug
Control_System
SubSystem
1
Duty Cycles
Outport
Terminator

Add PWM Driver Block

In the Simulink Library Browser, add the ePWM block from **Embedded Coder Support Package for Texas Instruments C2000 Processors > F2837xD**.

Configure the ePWM1, ePWM2, and ePWM3 blocks for generating the PWM pulse. In the ePWM block parameters dialog box, specify the pulse width modulation (PWM) counter period register value calculated from CPU frequency and PWM frequency. For center-aligned PWM, divide the computed value by 2.

PWM counter period = CPU clock frequency / *PWM frequency* / 2

For more details, see the TMS320f28379d processor ePWM peripheral.

In the F2837x/07x/004x/38x ePWM block parameters dialog box, update these settings to configure PWM1 to generate PWM pulses in the target hardware.

Tab and Parameter in ePWM Block	Settings
General > Module	**ePWM1**
General > Timer Period	Enter the PWM period value in the CPU clock cycle • PWM counter period = CPU clock frequency / PWM frequency / 2 • For LaunchPad 28379D, clock frequency is 200 MHz. For PWM frequency of 20 kHz, PWM counter period = `200e6 / 20e3 / 2;` PWM counter period = `5000`
Counter Compare > Specify CMPA via	**Input port**
Counter Compare > CMPA initial value	Enter the PWM counter period/ 2 (`2500`)
Counter Compare > Specify CMPB via	**Input port**
Counter Compare > CMPB initial value	Enter the PWM counter period/ 2 (`2500`)
Deadband unit > Use deadband for ePWM1A	`on`
Deadband unit > Use deadband for ePWM1B	`on`
Deadband unit > Deadband polarity	**Active high complementary (AHC)**
Deadband unit > Deadband Rising edge (RED) period (0~16383)	`15`
Deadband unit > Deadband Falling edge (FED) period (0~16383)	`15`
Event Trigger > Enable ADC start of conversion for module A check box (only for PWM1)	`on`
Event Trigger > Start of conversion for module A event selection (only for PWM1)	**Counter equals to period (CTR=PRD)**

Rename the block as ePWM1.

In the F2837x/07x/004x/38x ePWM block parameters dialog box, update the settings to configure PWM2 and PWM3 to generate PWM pulses in the target hardware. PWM2 and PWM3 are synchronized with PWM1. Follow ePWM1 configurations (other than **Event Trigger**) and add these configurations.

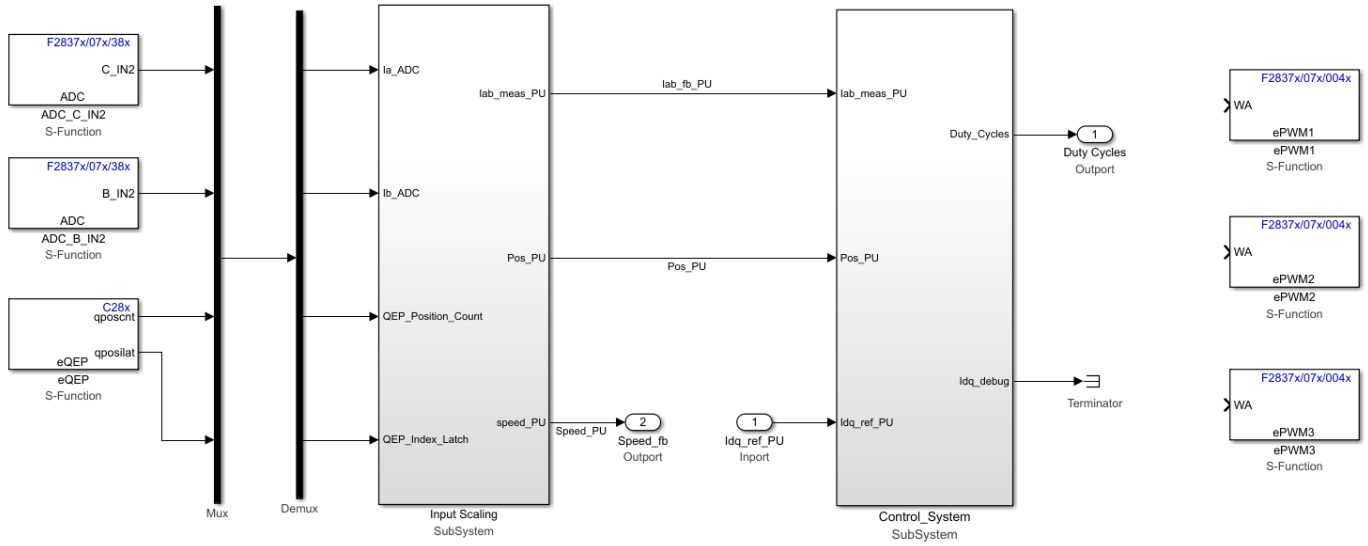
Tab and Parameter in ePWM Block	Settings
General > Module	**ePWM2**
General > Timer Period	Enter the PWM period value in the CPU clock cycle • PWM counter period = CPU clock frequency / PWM frequency / 2 • For LaunchPad 28379D, clock frequency is 200 MHz. For PWM frequency of 20 kHz, PWM counter period = `200e6 / 20e3 / 2;` PWM counter period = 5000
General > Synchronization action	**Set counter to phase value specified via dialog**
General > Counting direction after phase synchronization	**Count up after sync**
General > Phase offset value (TBPHS)	0
Counter Compare > Specify CMPA via	**Input port**
Counter Compare > CMPA initial value	Enter the PWM counter period/ 2 (2500)
Counter Compare > Specify CMPB via	**Input port**
Counter Compare > CMPB initial value	Enter the PWM counter period/ 2 (2500)
Deadband unit > Use deadband for ePWM1A	on
Deadband unit > Use deadband for ePWM1B	on
Deadband unit > Deadband polarity	**Active high complementary (AHC)**
Deadband unit > Deadband Rising edge (RED) period (0~16383)	15
Deadband unit > Deadband Falling edge (FED) period (0~16383)	15

Rename the blocks as ePWM2 and ePWM3.

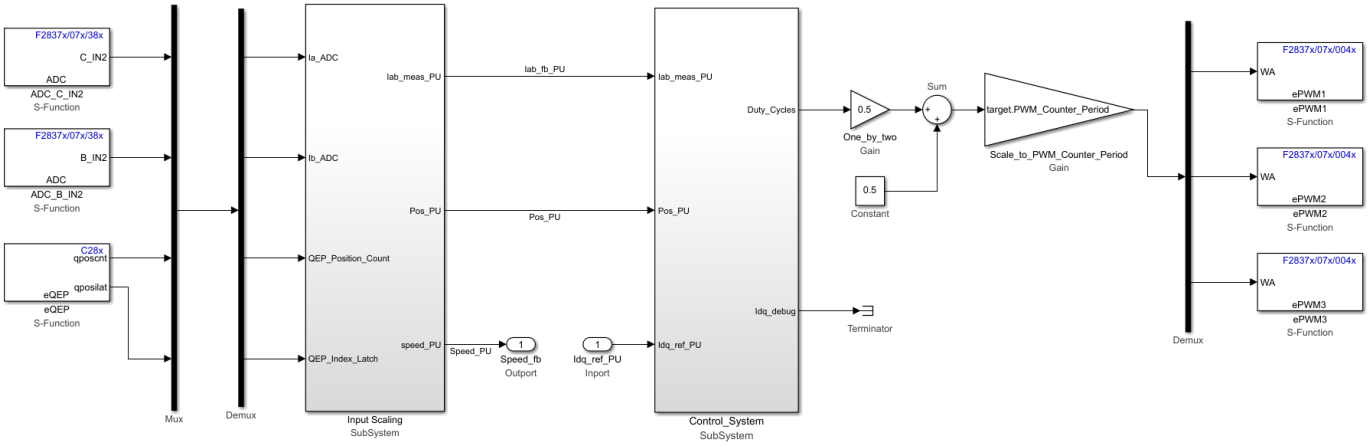
The range varies from 0 to *PWM_counter_period*. PWM outputs when PWM up-counter matches CMPA and PWM down-counter matches CMPB. By default, the system inputs a duty cycle of 50% by selecting PWM counter period / 2.

On the **Event Trigger** tab of PWM1 module, configure the ADC start of conversion event to begin when the PWM counter equals the PWM period.

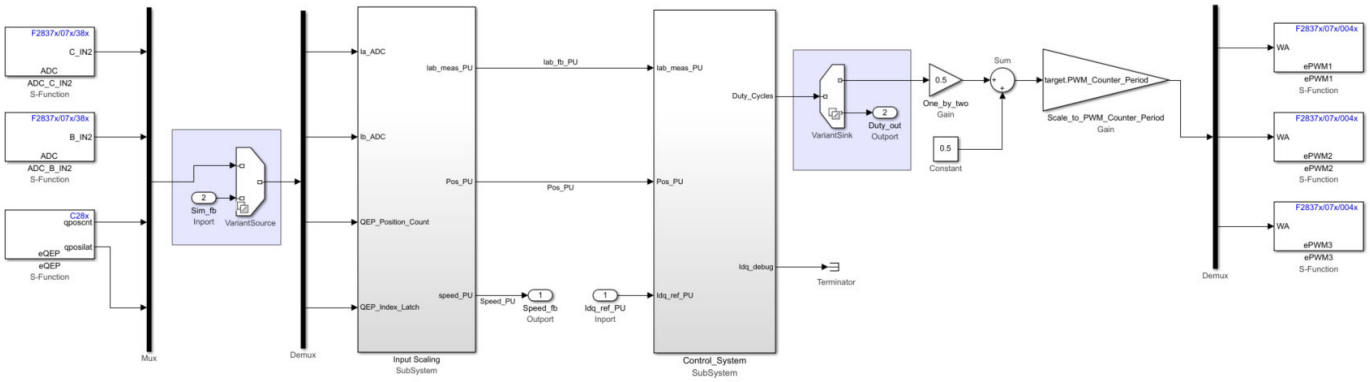
Synchronize the ePWM2 and ePWM3 blocks with the ePWM1 block by setting the synchronization timing to the moment when the PWM counter equals to zero in the ePWM2 and ePWM3 blocks.



The ePWM blocks expect the duty cycle value to range from `0` to the PWM counter period value (`5000`). The Control_System subsystem outputs the PWM in the range `-1` to `1`. The model needs to scale the output to `0` to `5000` (PWM counter period value).



For simulation, add a variant source/sink to the hardware driver block for simulation and code generation.


F2837x/07x/38x
C_IN2
ADC
ADC_C_IN2
S-Function
F2837x/07x/38x
B_IN2
ADC
ADC_B_IN2
S-Function
C28x
qposcnt
qposilat
eQEP
eQEP
S-Function
Mux
2
Sim_fb
Inport
VariantSource
Demux
Ia_ADC
Ib_ADC
QEP_Position_Count
QEP_Index_Latch
Iab_meas_PU
Pos_PU
speed_PU
Input Scaling
SubSystem
Speed_PU
1
Speed_fb
Outport
1
Idq_ref_PU
Inport
Iab_fb_PU
Iab_meas_PU
Pos_PU
Idq_ref_PU
Duty_Cycles
Idq_debug
Control_System
SubSystem
Terminator
VariantSink
2
Duty_out
Outport
0.5
One_by_two
Gain
0.5
Constant
Sum
target.PWM_Counter_Period
Scale_to_PWM_Counter_Period
Gain
Demux
F2837x/07x/004x
WA
ePWM1
ePWM1
S-Function
F2837x/07x/004x
WA
ePWM2
ePWM2
S-Function
F2837x/07x/004x
WA
ePWM3
ePWM3
S-Function

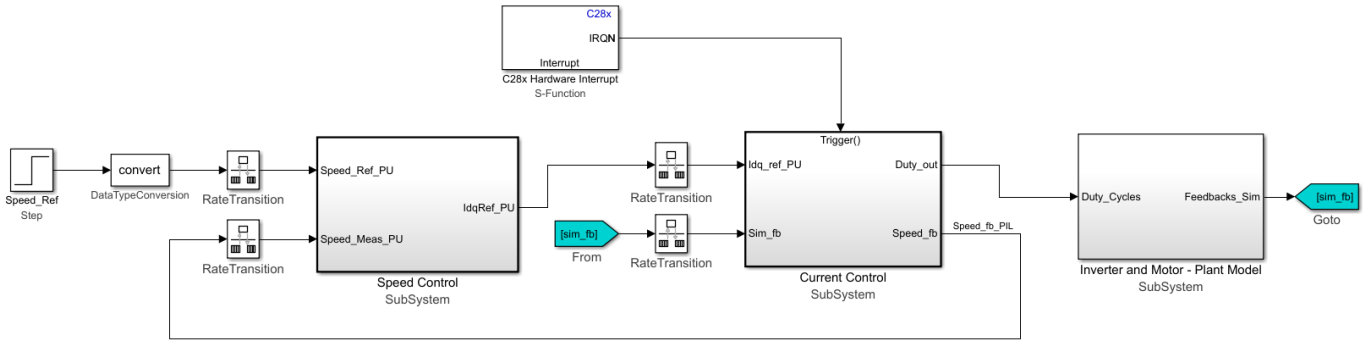
Add Hardware Interrupt Trigger Block for Current Control Loop

In the Simulink Library Browser, select and add the C28x Hardware Interrupt block from **Embedded Coder Support Package for Texas Instruments C2000 Processors > Scheduling**.

In the block parameters dialog box, update the settings to configure the hardware interrupt ADCINT1. Also, identify and update the CPU and PIE interrupts for the hardware interrupt ADCINT1.

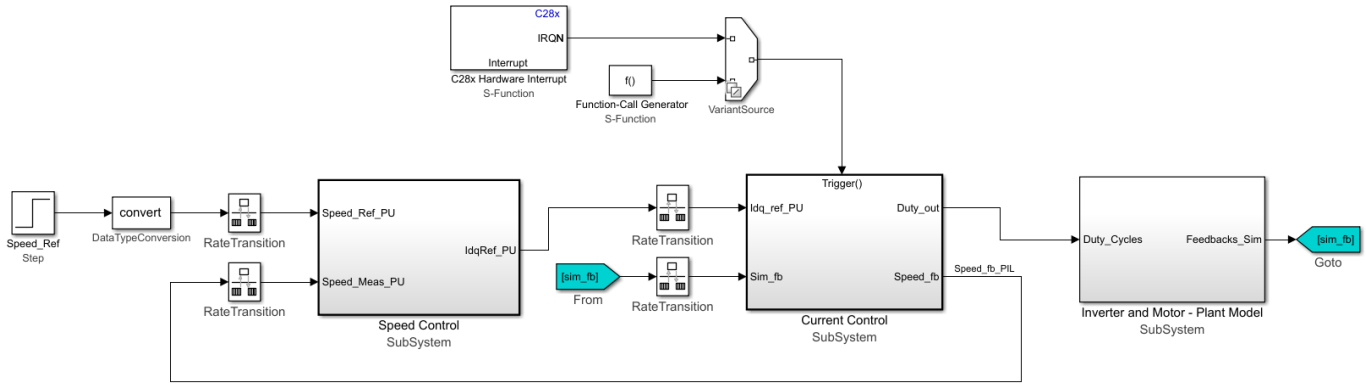
Parameter in C28x Hardware Interrupt Block	Settings
CPU interrupt numbers	**[1]**
PIE interrupt numbers	**[2]**

In the current control subsystem, add a Trigger block and set the **Trigger type** block parameter to `function-call`. Connect this subsystem trigger input to the C28x Hardware Interrupt block as shown in this figure.



In the Rate Transition block input to Current Control subsystem, change the **Output port sample time** to `-1`.

Add a Function-Call Generator block in variant source to support the model simulation. In the Function-Call Generator block, set the **Sample time** parameter as T_s (`50e-6`).



Simulate the model with the updated driver blocks and check the simulation results in the Simulation Data Inspector. Variants ensure that ADC, PWM drivers, and interrupts are not active during simulation.

Run in Open-Loop and Switch to Closed-Loop

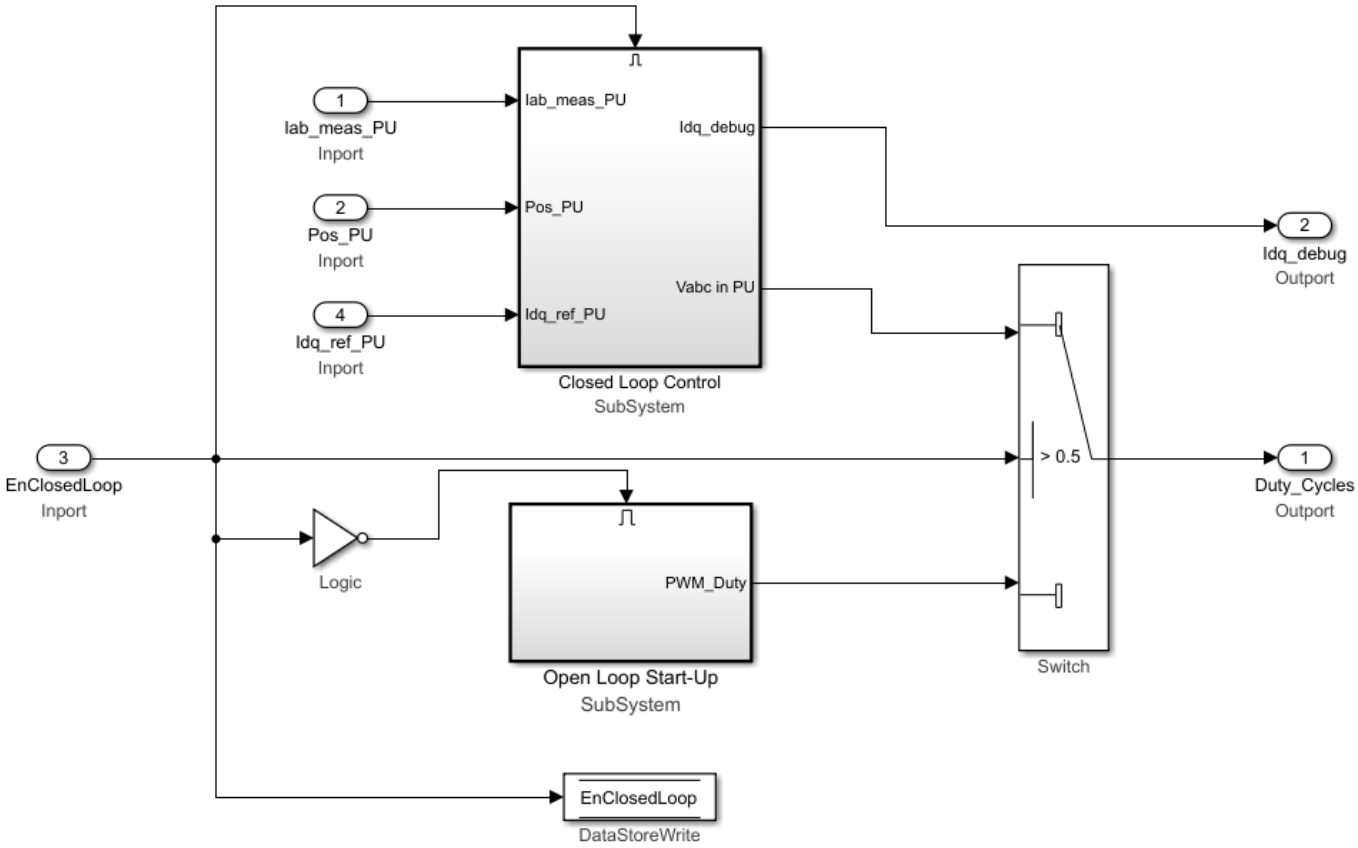
When operating a permanent magnet synchronous motor (PMSM) with a quadrature encoder sensor, we need an initial position to start running the motor. Because we do not have a method to determine the initial position at the beginning (before starting the motor), run the motor using open-loop control and ensure that the quadrature encoder index pulse is read at least once. At the quadrature encoder index pulse, the quadrature encoder sensor resets its position to align with the mechanical angle of the motor. The motor switches from an open-loop run to closed-loop speed control to maintain the reference speed. This step is only applicable for a quadrature encoder sensor (and is not needed for a Hall position sensor). A Hall sensor outputs the initial position of the rotor segment from the Hall signal port inputs.

Follow these steps to implement an open-loop motor run with a transition to closed-loop control:

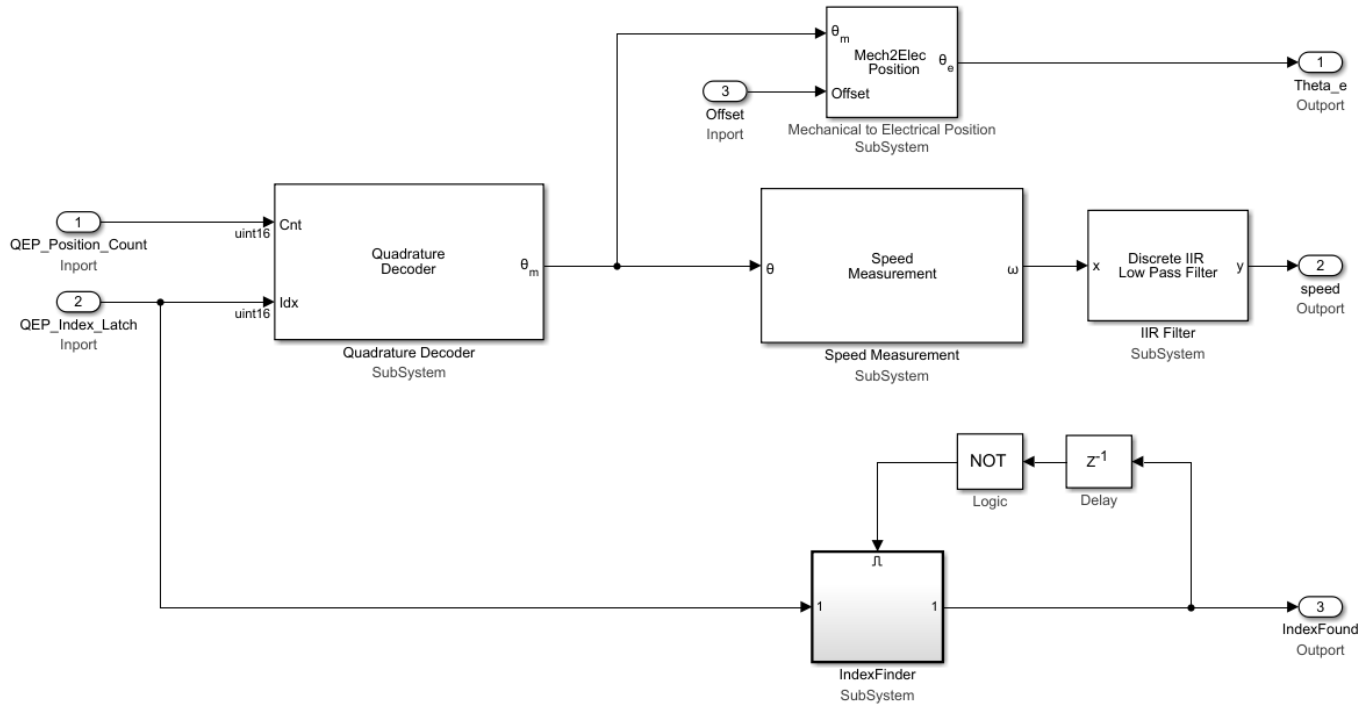
1. Copy the `mcb_pmsm_foc_qep_f28379d/Current Control/Control_system` subsystem to your model. This adds the algorithm to run the motor in open-loop. This subsystem switches the control from open-loop to closed-loop if *EnClosedLoop* input is 1. Add an input port **EnClosedLoop**.

   Addition of the **Open Loop Start-Up** subsystem adds the Data Store Read blocks for *Enable* and *SpeedRef*. In addition, add the Data Store Memory blocks for *Enable*, *EnClosedLoop*, and *SpeedRef* at the topmost level of the model.

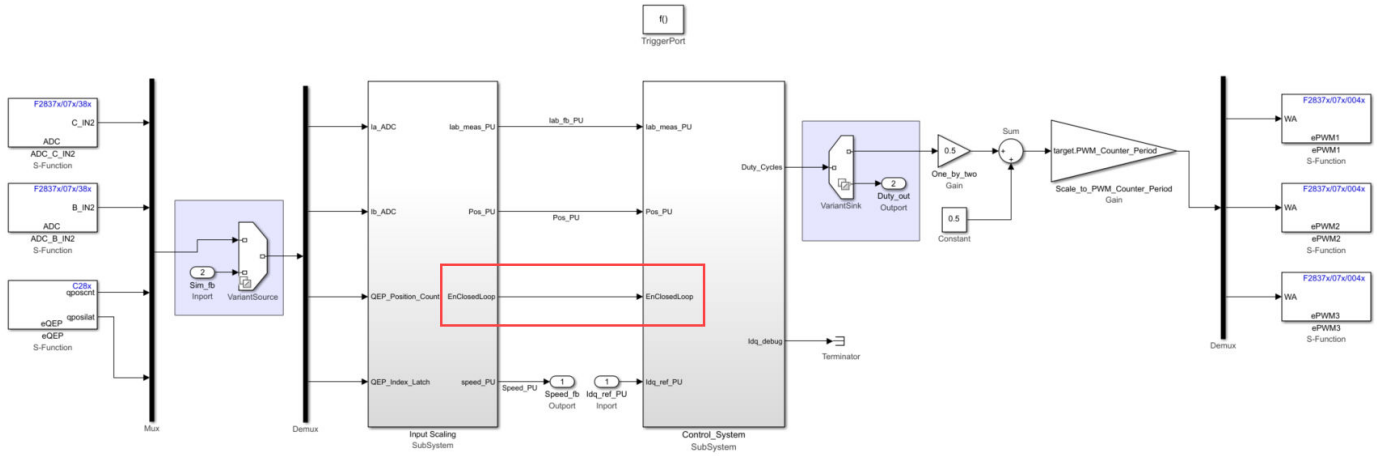
   When the open-loop run begins, the sign of *SpeedRef* (for algorithm details, see the **Open Loop Start-Up** subsystem) decides the direction of the initial motor run. If *SpeedRef* is negative, the motor spins in the opposite direction during the open-loop run.



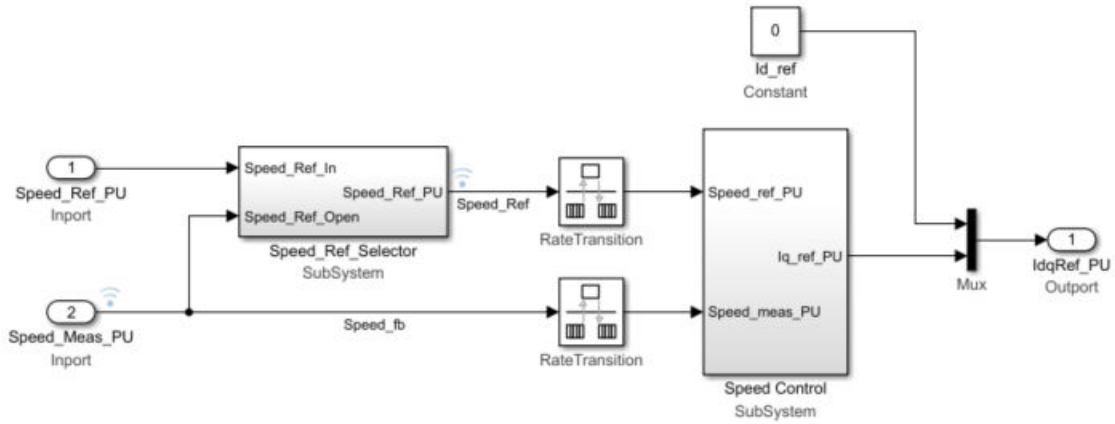
2 Copy the `mcb_pmsm_foc_qep_f28379d/Current Control/Input Scaling/Calculate Position and Speed` subsystem to your model. This adds the `IndexFinder` subsystem to your model. When quadrature encoder index pulse is detected for the first time, this subsystem sets the `IndexFound` port to `1`. Add an output port (that is connected to the `IndexFound` port) to the **Calculate Position and Speed** subsystem and rename it to `EnClosedLoop`.



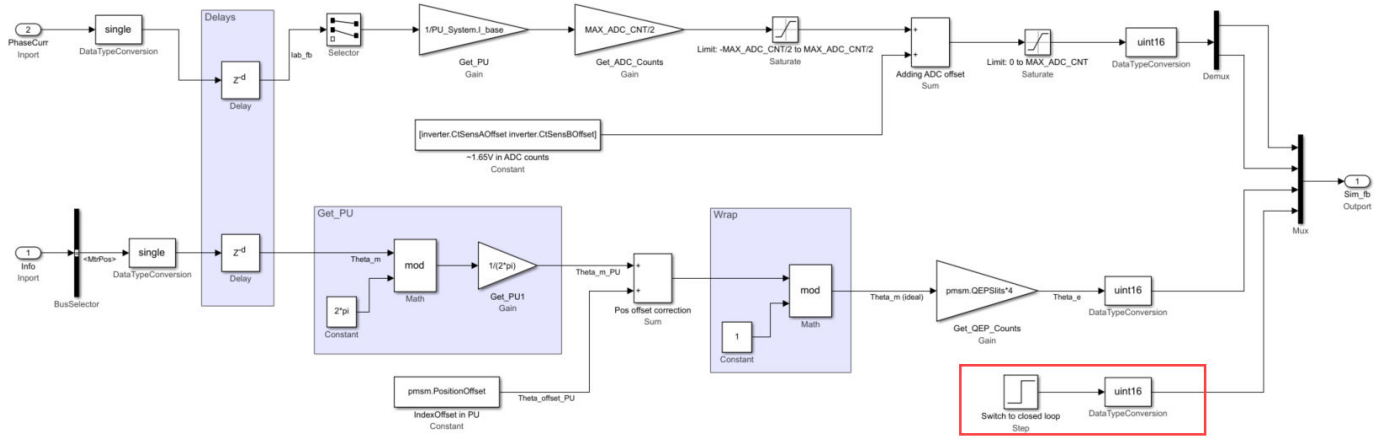
3 Connect the output port `EnClosedLoop` from the **Input Scaling** subsystem to the input port `EnClosedLoop` in the **Control_System** subsystem as shown in this figure.



4 Copy the `mcb_pmsm_foc_qep_f28379d/Speed Control/Speed_Ref_Selector` subsystem to your model and integrate it with the speed controller subsystem. When the closed-loop control begins, this subsystem provides the `Speed_Ref` ouput signal. For a smooth transition from open-loop to closed-loop, the speed measured is used as the speed reference during the open-loop run. Add a Data Store Write block *SpeedRef* to the `PI_Controller_Speed` input port.



5 In the plant model, add a step input to simulate the IndexFinder block for simulation. Rename the step input to `Switch to closed loop`. See the `mcb_pmsm_foc_qep_f28379d/Inverter and Motor - Plant Model/Sensor_Measurments` subsystem to see how the step input switches to closed-loop. Select the step time of `0.1` and sample time of T_{s_motor}.



6 Create Data Store Memory blocks for *EnClosedLoop*, *Enable*, and *SpeedRef*. *Enable* block is used to reset the PI integrator before running the motor.

Add these default values in the Data Store Memory blocks:

- *Enable* = `1`
- *EnClosedLoop* = `0`
- *SpeedRef* = `0.25`

The Data Store Memory blocks are used to share data across the subsystem.

7 Run the simulation and observe the speed reference and the speed feedback signals.

Model Configuration and Hardware Deployment

Use these steps to select the target hardware in the Configuration Parameters dialog box.

1. In the Simulink model, click **Hardware > Hardware Settings** to open the Configuration Parameters dialog box.
2. Open the **Hardware Implementation** tab and set **Hardware board** to **TI Delfino F28379D LaunchPad**.

For any other custom board, navigate to the **Hardware Implementation** tab of the Configuration Parameters dialog box and select the appropriate processor and edit the peripheral details in **Hardware board settings > Target hardware resources**.

For the solver and quadrature encoder interface configuration details, see “Model Configuration Parameters”.

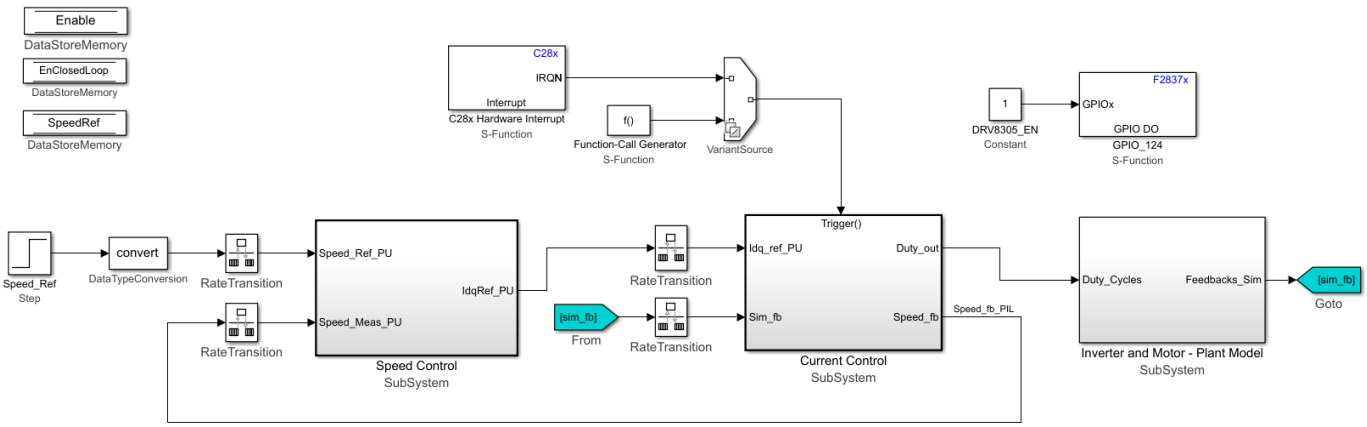
Connect the Texas Instruments BOOSTXL-DRV8305 board and QEP connector to the Texas Instruments LaunchPad XL hardware board. For hardware connection details related to Texas Instruments C2000 LaunchPadXL, see “Hardware Connections”. The BOOSTXL-DRV8305 (attached to the LaunchPadXL board) requires an enable signal. This signal is connected to the GPIO124 pin of the processor.

In the Simulink Library Browser, add **Embedded Coder Support Package for Texas Instruments C2000 Processors > F2837xD > Digital Output**. In the Digital Output block parameters dialog box, change these settings:

Parameter in Digital Output Block	Settings
GPIO Group	**GPIO120~GPIO127**
GPIO124	on

Rename the block as GPIO_124.

Add a constant block with the value 1 as an input to the GPIO124 block as shown in this figure.



On the **Hardware** tab of the Simulink model, select **Build, Deploy & Start**. This generates the C code, CCS project, and a target-specific `.out` file. The system uses serial communication to download this target specific `.out` file to the target hardware and runs the downloaded algorithm in the hardware.

When the model is deployed to the target, the motor runs in open-loop and then runs in closed-loop speed control. This example recommends that you use serial communication to monitor and debug the signals. For details about implementing serial receive and transmit communications between the host and target models, see the example model `mcb_pmsm_foc_qep_f28379d`. From the Serial Receive block, update the *Enable* Data Store Memory block to start and stop the motor using the serial commands received from the host model.

Validate System

In this section...

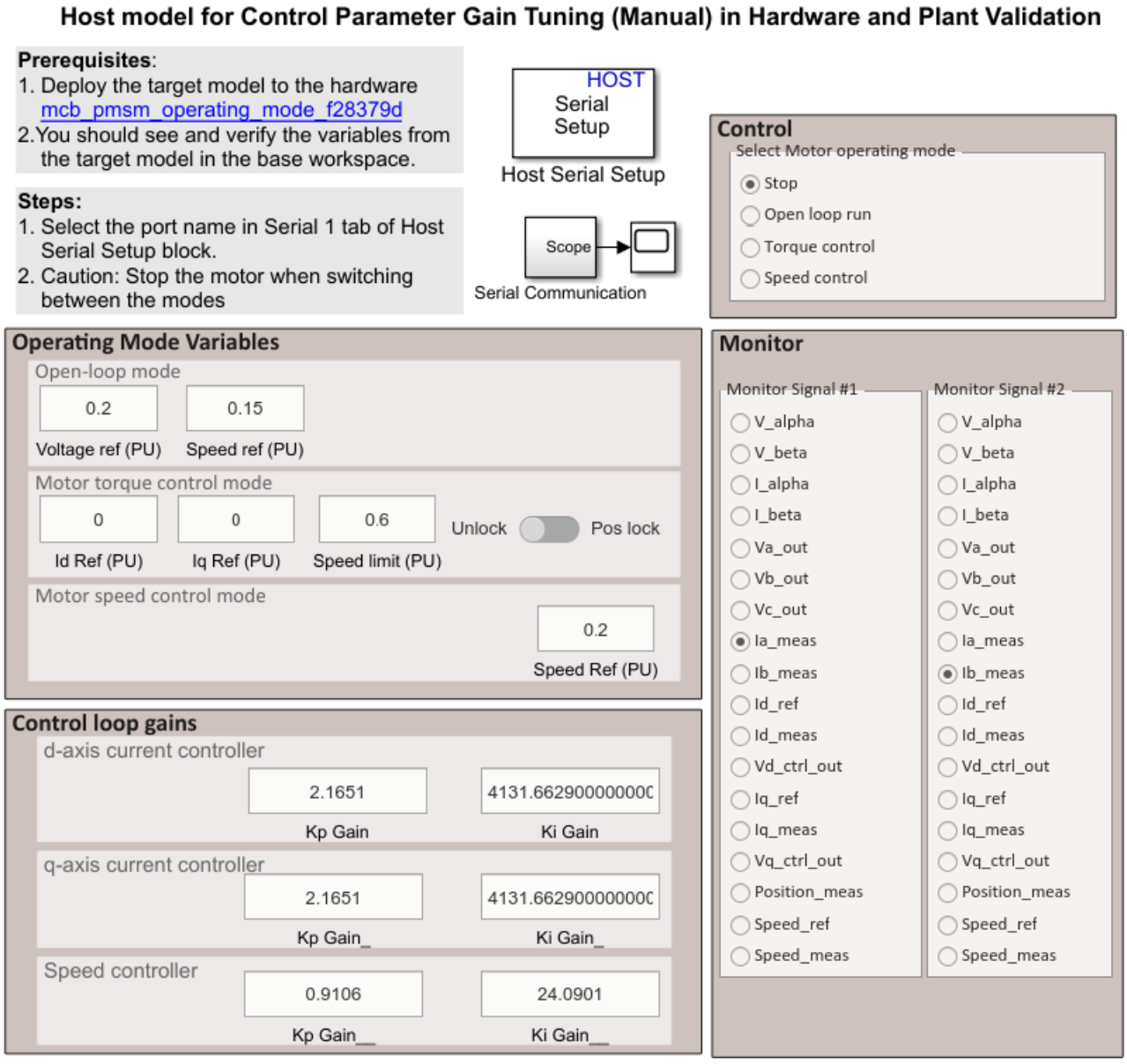
This section explains how to evaluate the accuracy of the plant (motor and inverter) model of the physical motor and load connected to the motor. Validate the plant model and verify that the results are close to the physical system measurements before using the plant model for implementing advanced algorithms. You can validate the system by comparing the step response of speed control and current control during simulation and after deployment to the target hardware connected to the motor.

Use the example “Tune Control Parameter Gains in Hardware and Validate Plant” to measure the step response of the current and speed controllers. The host model in this example communicates the current reference to the target hardware and measures the step response of the current controller.

- You can use any speed control example from Motor Control Blockset to validate the system.
- Validate speed control by comparing the step response during simulation with the hardware test values.
- Validate the *d*-axis current control by electrically or mechanically locking the rotor and comparing the step response during simulation with the hardware test results.

  You can use another method to validate the *d*-axis current control. Run the motor at a constant speed and provide a step change in the reference *d*-axis current. This requires two modifications in the speed control subsystem of the target model. Set a constant speed reference input. Command I_d reference from the host model. Compare the step response of the *d*-axis current during simulation with the response obtained during the hardware tests.
- Validate the *q*-axis current control by mechanically coupling the motor with an external dynamometer running in speed control. This requires two modifications in the speed control subsystem of the target model. Discard the I_d and I_q reference from the speed PI controller output. Command I_d reference from the host model. Compare the step response of the *q*-axis current during simulation with the response obtained during the hardware tests.

Warning When capturing the step response in *d*-axis current control, always use a positive step. Negative values of I_d can damage the permanent magnet in the PMSM.



See the example “Tune Control Parameter Gains in Hardware and Validate Plant” to deploy the model to the hardware. Perform motor parameter estimation because an accurate plant model is important to ensure that the simulation results match the hardware test results.

Calculate Physical Motor Load in Target Hardware

Before comparing the controller responses during simulation with the responses obtained after target hardware deployment, the load torque in plant simulation must match the motor load in the physical system. Follow these steps to calculate the load torque in the physical system and update the calculated load torque in the plant model.

1. Run the host model to connect it to the target hardware through serial communication.
2. Set **Select Motor operating mode** to **Speed control**.

   The motor spins in speed control.
3. Select **Id_meas** in **Monitor Signal #1** and **Iq_meas** in **Monitor signal #2**. Read the `Id_meas` and `Iq_meas` values from the scope.
4. Convert the per-unit (PU) current to Amperes by multiplying it with `PU_System.I_base`.
5. Calculate the load torque in Nm using this equation:

   $T_{\text{load}} = 1.5 \times pole\_pair \times [(flux\_pm \cdot I_{\text{q}}) + (L_{\text{d}} - L_{\text{q}})I_{\text{d}} \cdot I_{\text{q}}]$

   where,

   $flux\_pm$ = Permanment magnet flux linkage (pmsm.Flux_PM)

   $L_{\text{d}},\ L_{\text{q}}$ = Inductance in Henry (pmsm.Ld, pmsm.Lq)

   $I_{\text{d}},\ I_{\text{q}}$ = Current measured in Amperes

   $\text{I}_{\text{d\_meas}}$, the measured I_{d} current (in PU), equals `0`.
6. In the `mcb_pmsm_operating_mode_f28379d/Motor and Inverter/Plant Model (sim)` sub system, provide the calculated load torque value as an input to the **LdTrq** port of the PMSM motor block.

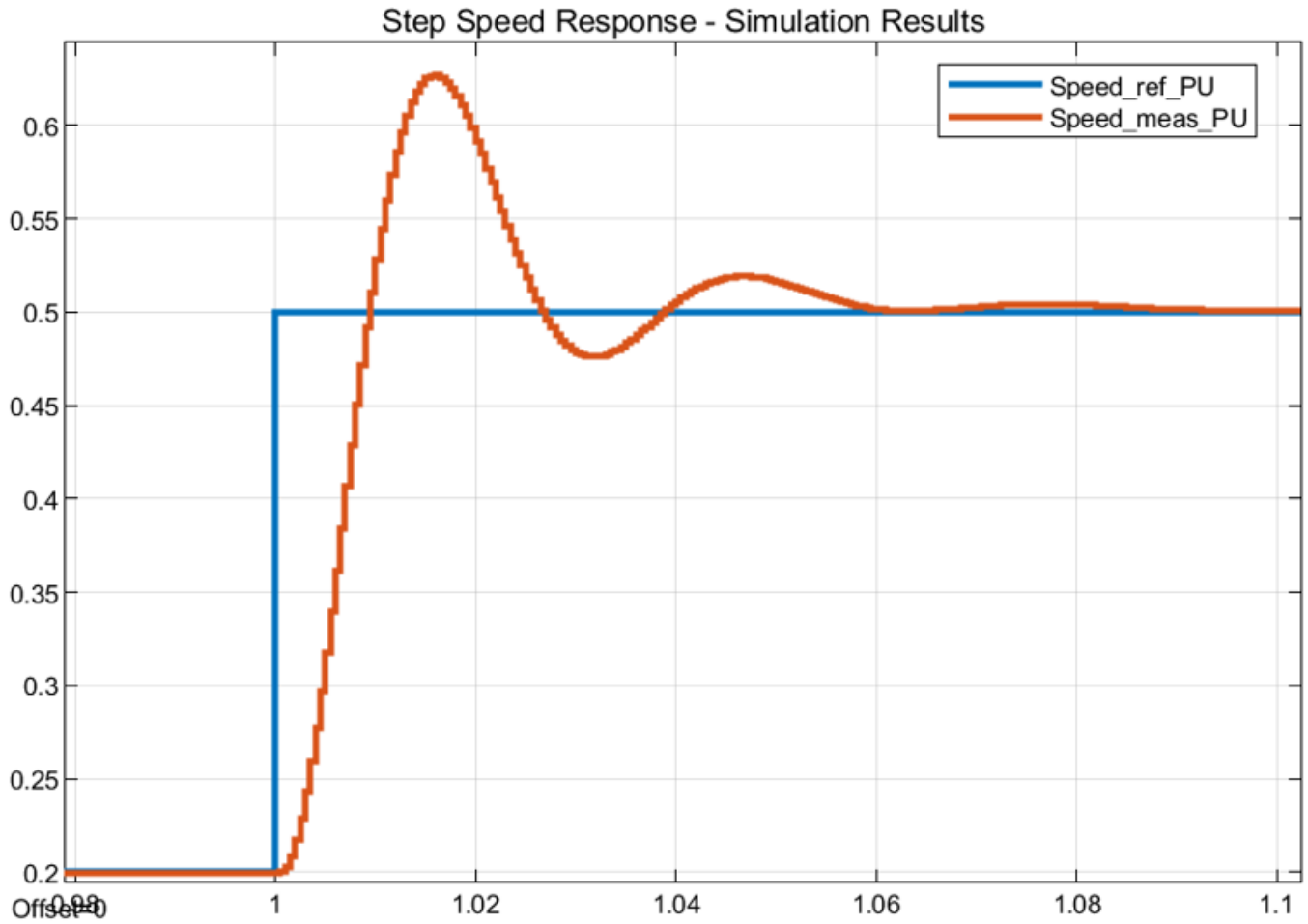
Compare Speed Controller Response During Simulation With Target Hardware Results

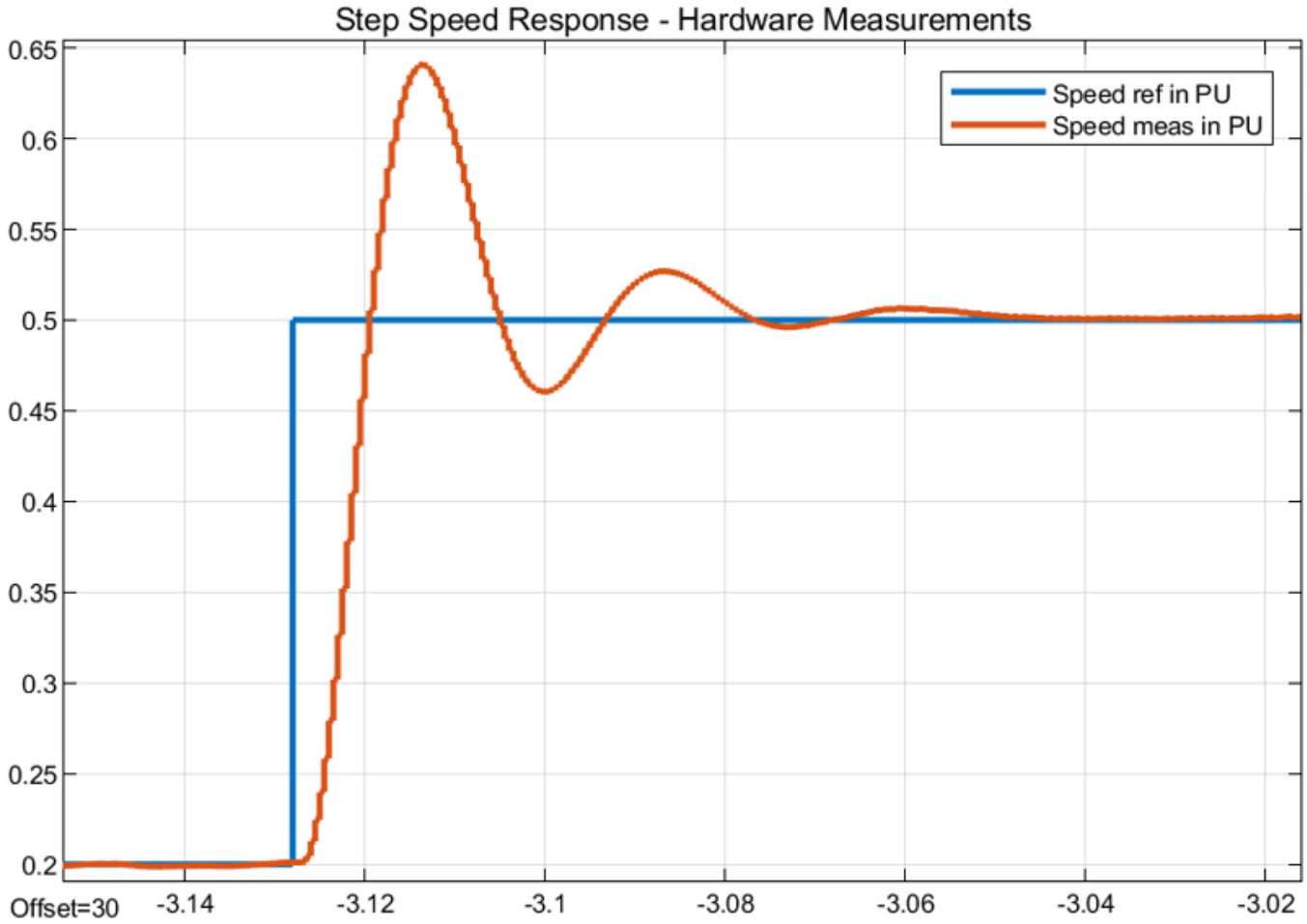
During simulation, provide a speed step input and note the speed response. On the target hardware, command the speed reference step input and observe the speed feedback. Compare the resulting step response during simulation with the response obtained from target hardware to determine the accuracy of the plant model.

1. Simulate the model `mcb_pmsm_operating_mode_f28379d`. Plot the reference speed and the measured speed signals. By default, this example provides a step input of `0.2` to `0.5` to the simulation model.
2. Run the host model to communicate with the target hardware.
3. Change **Select Motor operating mode** from **Stop** to **Speed control**.
4. In the host model, select **Speed_ref** in **Monitor Signal#1** and **Speed_meas** in **Monitor Signal#2**.
5. Open the scope in the host model.
6. In host model interface, change the `speed_ref` from `0.2` to `0.5` and observe the step change in the scope.
7. Compare the step response obtained from the hardware with the simulation results.

Step Response Analysis for Speed Controller

Compare the step response obtained from simulation with the measurements obtained from the target hardware. The results may vary depending on the tolerances in the plant model. Generally, simulation results are close to the values measured on the target hardware.


Step Speed Response - Simulation Results
Speed_ref_PU
Speed_meas_PU
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
Offset=0
1
1.02
1.04
1.06
1.08
1.1



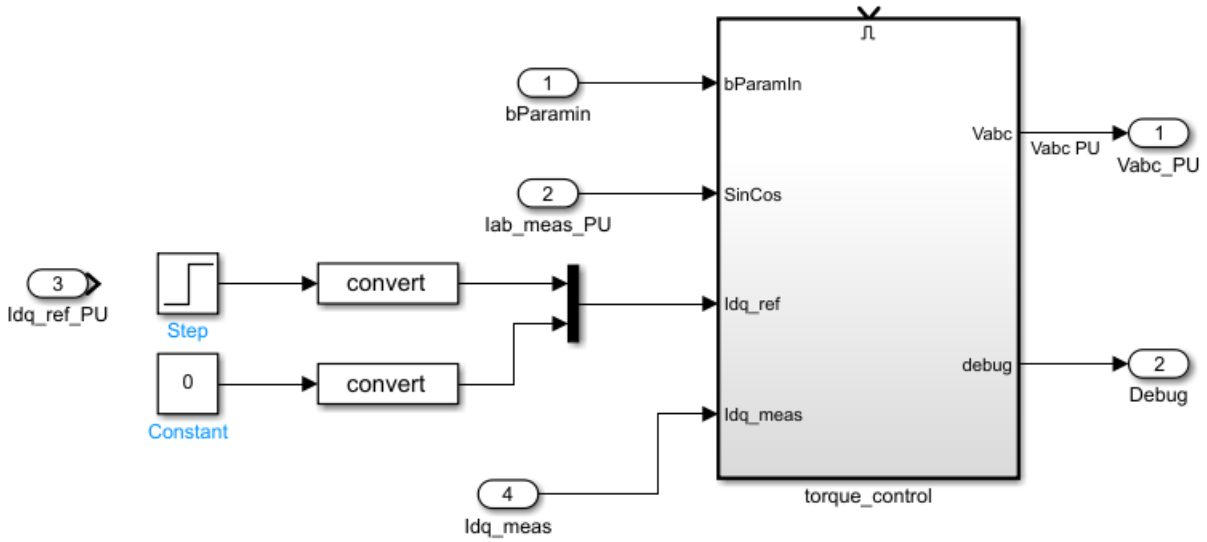
	Peak overshoot (%)	Peak time (ms)	Rise time (ms)	Settling time (ms)
Simulation results	20.13%	16.023	5.561	61.027
Hardware results	22 %	14.324	5.041	51.148

Compare Current Controller Response During Simulation With Target Hardware Results

During simulation, provide a step current reference and note the current response. This example needs some changes to simulate the current reference step input. Follow these steps to perform the model changes. When using the target hardware, command the current reference step input and observe the current feedback. Compare the resulting step response in simulation with the response obtained from the target hardware to determine the accuracy of the plant model.

1. For hardware measurements, run the host model.
2. Change **Select Motor operating mode** from **Stop** to **Torque control**.
3. Select **Id_ref** in **Monitor Signal#1** and **Id_meas** in **Monitor Signal#2** in the host model.
4. Open the scope in the host model.

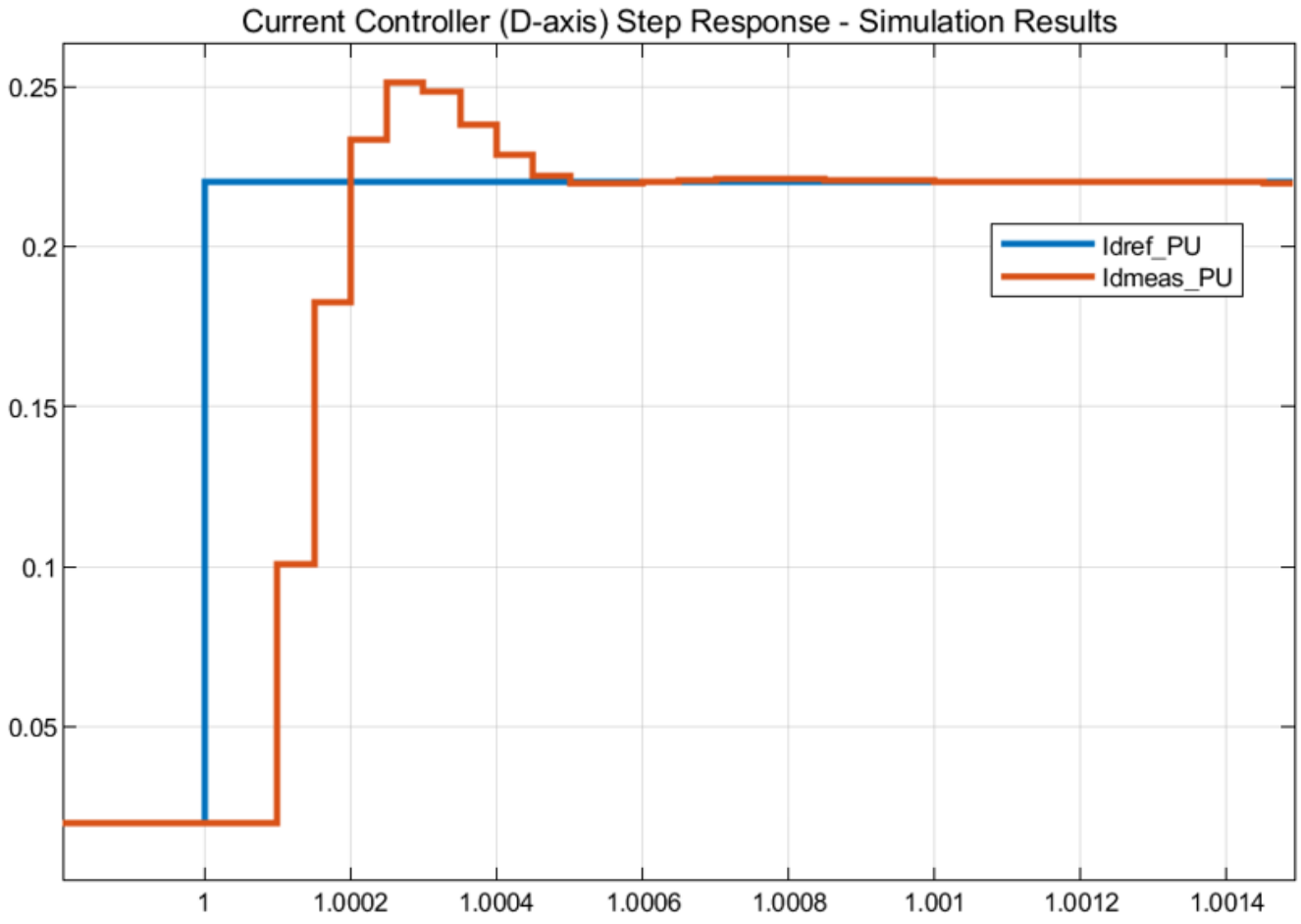
5. Change `Id_ref` from `0.02` to `0.22` and observe the step change in the scope. Ensure that the motor is not running. The scope displays the step response for the `Id_ref` input.
6. For simulation, make these two changes in the model. In the `mcb_pmsm_operating_mode_f28379d/TorqueControl/Control Modes/torque_control` subsystem add a step input for the *d*-axis current controller. Choose a step input of `0.02` to `0.22` at `1` second. Select time sample as `-1`. In the data-type conversion block, select the output datatype as `fixdt(1,32,17)`.

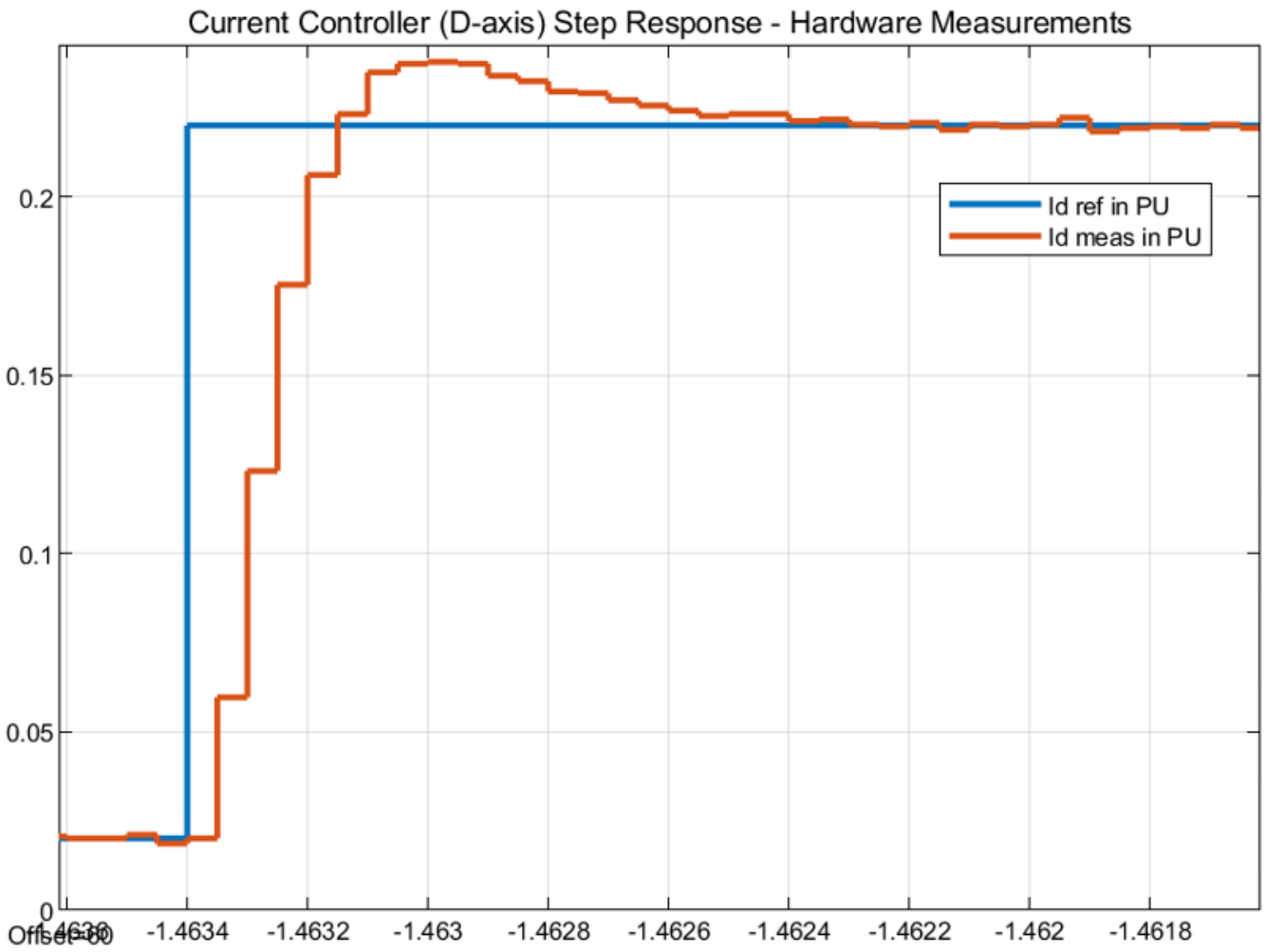


7. In the PMSM motor block available in the `mcb_pmsm_operating_mode_f28379d/Motor and Inverter/Plant Model (sim)` subsystem, change the **Mechanical input configuration** to **Speed** and input `0` to the **Spd** input port.
8. Run the simulation and measure the `Idref_PU` and `Idmeas_PU` values in the Simulation Data Inspector.
9. Compare the step response obtained from the hardware with the simulation results.

Step Response Analysis for d-axis Current Controller

Compare the scope results obtained from simulation with the measurements from the target hardware. The results may vary depending on the tolerances in the plant model. With an accurate plant model, the simulation results are closer to the measured results from the target hardware.


Current Controller (D-axis) Step Response - Simulation Results
0.25
0.2
0.15
0.1
0.05
1
1.0002
1.0004
1.0006
1.0008
1.001
1.0012
1.0014
Idref_PU
Idmeas_PU



	Peak overshoot (%)	Peak time (µs)	Rise time (µs)	Settling time (µs)
Simulation results	14 %	300	150	500
Hardware results	8.18 %	400	150	800

The accuracy of the plant model improves the accuracy of simulation, and therefore, it helps match the simulation results to the hardware test results.

Tip If the simulation results differ considerably from the hardware measurements, verify the delay and scaling factor in the plant model.

Note For the *q*-axis current controller, align the motor to the *d*-axis and mechanically lock the rotor. Follow this for the *d*-axis current controller for comparative analysis. You can achieve external mechanical locking through the mechanical braking system or by coupling with a dynamo-meter motor running in speed control.

Plant Modeling

Creating Plant Model Using Motor Control Blockset

An accurate plant model is a vital part of motor control system development. After creating an accurate plant model, you can verify the functionality of the control system, conduct closed-loop model-in-the-loop tests, tune the controller gains using simulation, and optimize the algorithm before you deploy the model in the actual plant.

When you create a plant model using Motor Control Blockset, you model these components to simulate the functional behavior in a simulation environment:

- Permanent Magnet Synchronous Motor (PMSM)
- Average-value Inverter
- Sensors and signal conditioning circuits
- Processor peripherals: Analog-to-Digital converter (ADC) and Pulse-width-modulator (PWM)

You can verify the functionality of the plant model you create by:

1. Reading the normalized PWM duty cycle from the control algorithm.
2. Simulating the motor for the connected load.
3. Obtaining the output motor phase current (in terms of ADC counts) and the output motor position (in terms of encoder pulse counts) from the simulation.

The workflow to create a plant model involves these steps.

Note See the plant model in the `mcb_pmsm_foc_qep_f28379d.slx` model that is used in the example “Field-Oriented Control of PMSM Using Quadrature Encoder”.

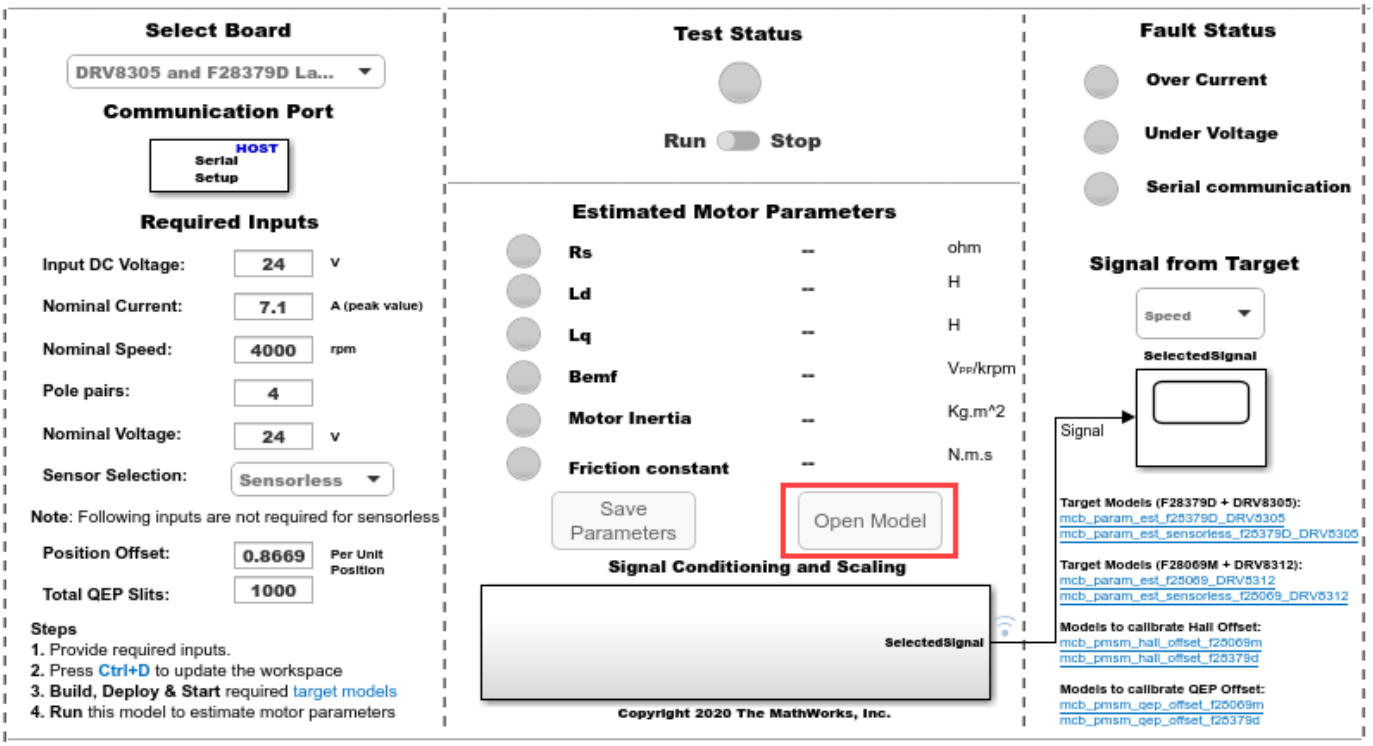
1. “Use PMSM Block and Motor Parameters to Design Plant Model” on page 3-3
2. “Add Average-Value Inverter Block” on page 3-5
3. “Create Motor Phase Current Sensing and Signal Conditioning Subsystem” on page 3-6
4. “Create Position Sensing Subsystem” on page 3-7
5. “Add Delay in Plant Model” on page 3-8
6. “Integrate Blocks and Subsystems” on page 3-9

Use PMSM Block and Motor Parameters to Design Plant Model

You can use the surface mount or interior PMSM blocks from Motor Control Blockset in two ways to create a plant model.

- Estimate motor parameters by using Motor Control Blockset and open a Simulink model with PMSM motor block (auto-populated with estimated parameters):

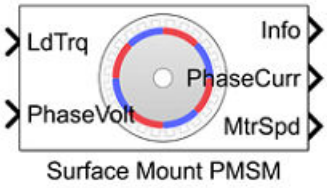
  The Motor Control Blockset parameter estimation workflow helps you to determine the motor parameters by performing a series of tests on the motor. For details, see “Estimate PMSM Parameters Using Recommended Hardware”. After successfully estimating the motor parameters, click **Open Model** in the parameter estimation host model. A new model opens with the Interior PMSM block updated with the estimated motor parameters.

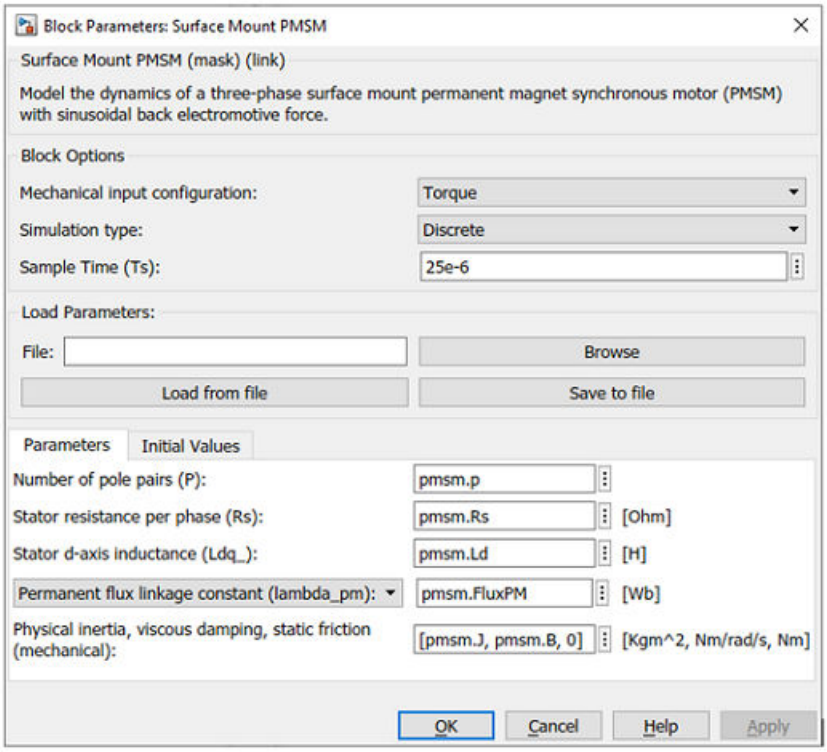


- Create a new model and manually add the PMSM motor block from the Motor Control Blockset library:

  Create a new Simulink model and add the Surface Mount PMSM block from the Motor Control Blockset library in the Simulink library browser. Open the block mask and enter the motor parameters manually. You can obtain these parameters by using:

  - The Motor Control Blockset parameter estimation workflow. For details, see “Estimate PMSM Parameters Using Recommended Hardware”.
  - The motor datasheet or from other known sources.





In Surface Mount PMSM block, set the **Simulation type** parameter to `Discrete` and the **Sample Time (Ts)** parameter to `25e-6` (half of the control frequency). Discrete simulation improves the simulation speed.

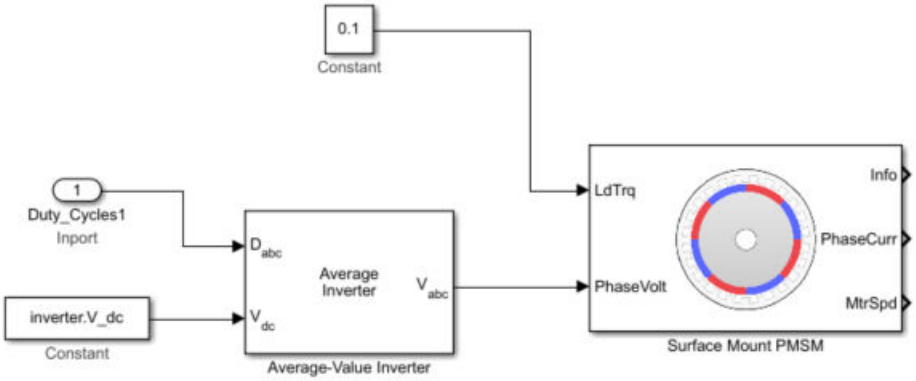
If the parameters are available in a MAT-file, click the **Browse** button on the block parameters dialog to locate the MAT-file and then click **Load from file** to load the parameters.

The files containing the default motor parameters are available in the location `<matlabroot>\toolbox\autoblks\autoblksshared\mcbtemplates` as a reference.

In the Surface Mount PMSM block parameters dialog, you can also represent the motor parameters as workspace variables and use the model initialization script (m-script) to automatically update these variables using the model initialization callback. Parameters of some commercially available motors are available in the file `mcb_SetPMSMMotorParameter.m` as a reference. For details about this m-script file, see “Estimate Control Gains and Use Utility Functions”.

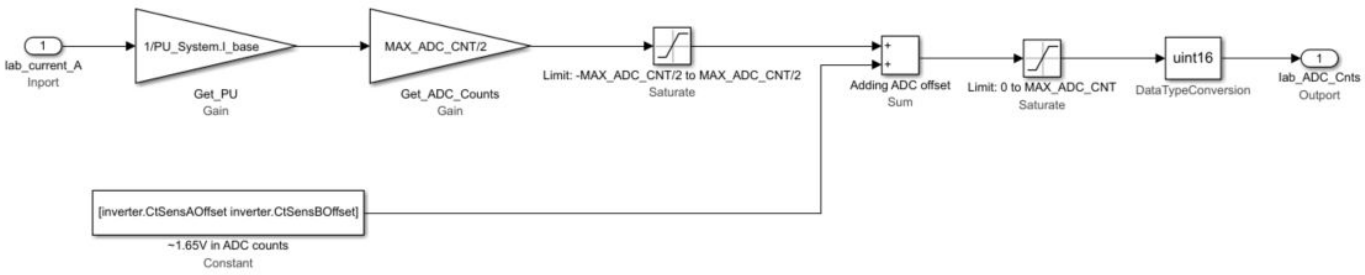
Add Average-Value Inverter Block

In the Simulink model that contains the Surface Mount PMSM block, add an Average-Value Inverter block from the Motor Control Blockset library. The Average-Value Inverter block reads the normalized PWM duty-cycle and DC voltage input (in volts) and outputs the phase voltages. Connect the $\mathbf{V_{abc}}$ output port of the Average-Value Inverter block to the **PhaseVolt** input port of the Surface Mount PMSM block.



Create Motor Phase Current Sensing and Signal Conditioning Subsystem

In the physical hardware, the motor current read by the current sensors is filtered and scaled to an ADC measurable range. The ADC peripheral in the processor reads the current signals and outputs the ADC counts for the current control algorithm. This figure shows an example of how you can model the motor phase current sensing and signal conditioning algorithms.



The maximum measurable peak current is considered as the base current. The ADC counts can be calculated from the base current and full-scale ADC values, along with the ADC offset, by using this equation:

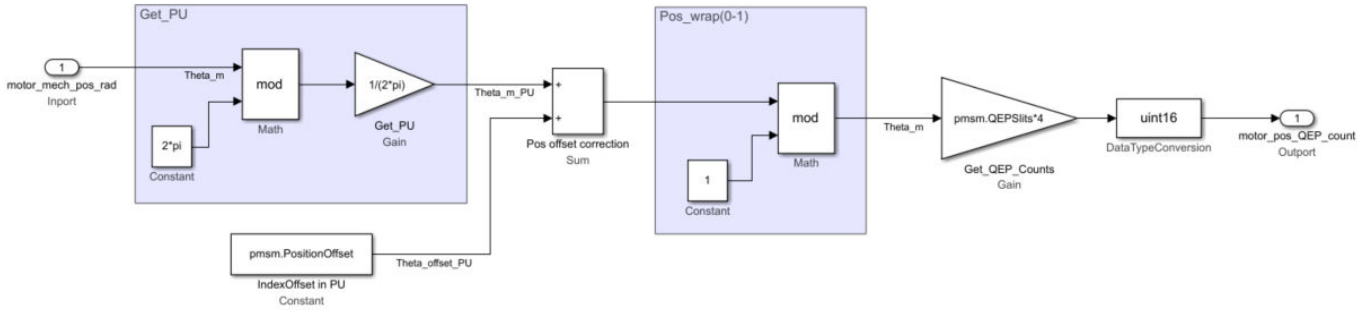
$$\text{ADC counts} = \frac{\left(\text{Full scale ADC counts}/2\right)}{\text{Base current (in amperes)}} + \text{ADC offset}$$

For the default inverter and signal conditioning circuit parameters for commercially available inverters, see the `mcb_SetInverterParameters.m` file. To add a new inverter configuration, create an inverter type in this file and use this in the model initialization script for parameter initialization. If you are using low-pass filters for measuring the current, add an average model to filter the current.

Create Position Sensing Subsystem

The position sensing subsystem reads the motor position from the Surface Mount PMSM block and simulates the QEP encoder pulse counts. The Surface Mount PMSM block outputs the mechanical position of the motor in rad/s.

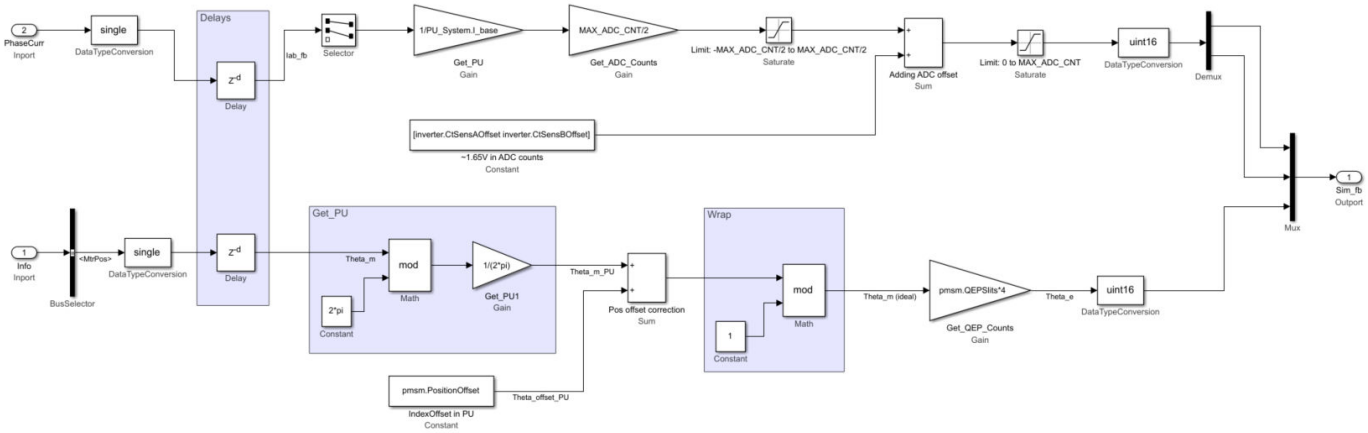
Convert the position in the range `0` to `2π` rad/s to QEP encoder counts as shown in this figure.



For details about detecting the QEP index position offset with respect to the rotor *d*-axis, see “Quadrature Encoder Offset Calibration for PMSM Motor”.

Add Delay in Plant Model

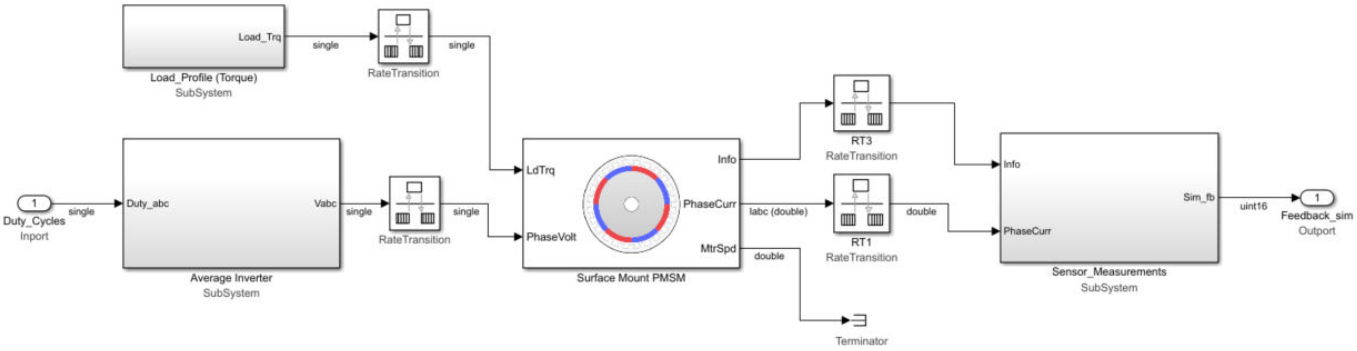
You can add delays in the plant model to simulate the control algorithm processing delays in the hardware and the PWM switching delays. The algorithm processing delay in the processor is the time taken to update the PWM. PWM switching delay is usually half the switching time period.



For adding delays in the discrete time solver with a sample rate of $T_s/2$ (half the switching time period), the processor computation delay and PWM switching delay are factored as Z^{-1} ($T_s/2$).

Integrate Blocks and Subsystems

The final step of designing the plant model using Motor Control Blockset is to integrate the blocks and subsystems that you created earlier. The completed plant model accepts the normalized PWM from the controller and outputs the motor phase currents and position.



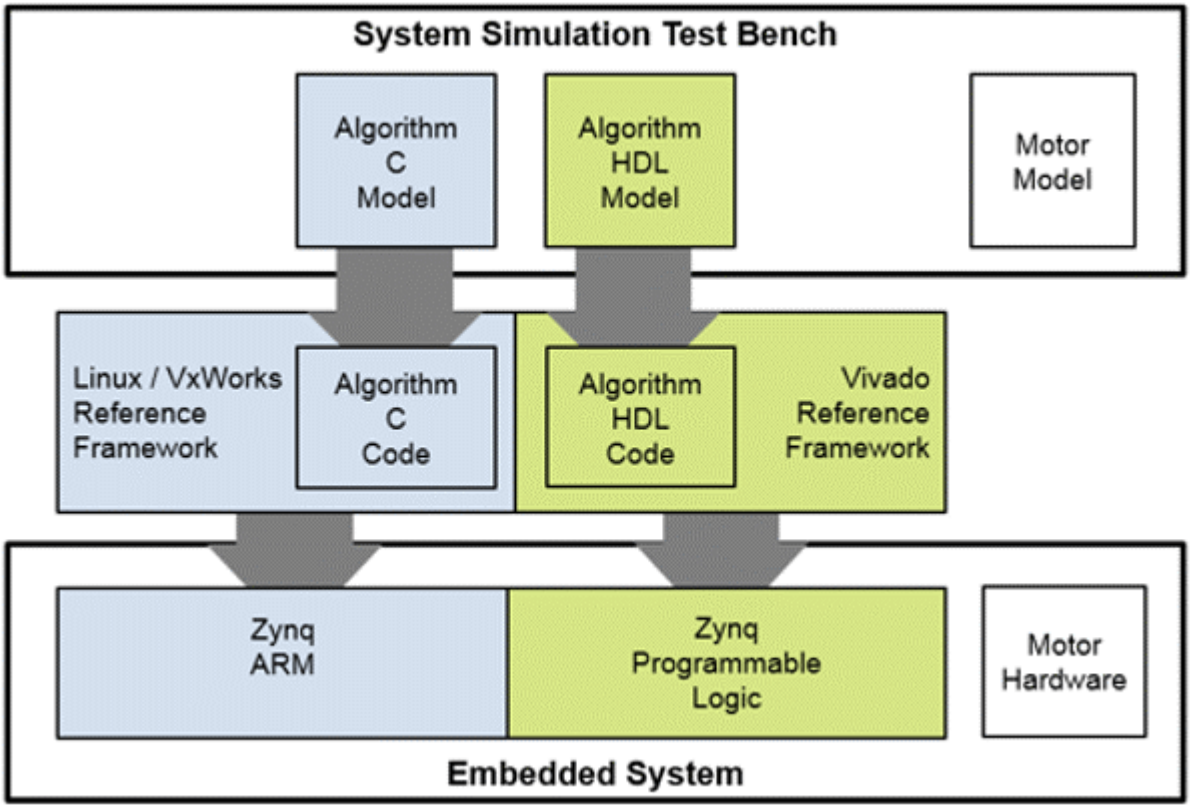
Motor Control Blockset Examples

FOC Algorithm for a PMSM Using Motor Control Blockset and Trenz Electronic™ Motor Control Development Kit

This example shows how to use a Field-Oriented Control (FOC) algorithm for a Permanent Magnet Synchronous Machine (PMSM) by using blocks from the Motor Control Blockset on an FPGA device.

The example lets you test the control algorithm by using a closed loop system simulation then lets you generate HDL code for the control algorithm. The example includes a Simulink Project that provides the models and reference design. Use the project with HDL Workflow Advisor for bit stream generation and for running an external model that interacts with the processor.

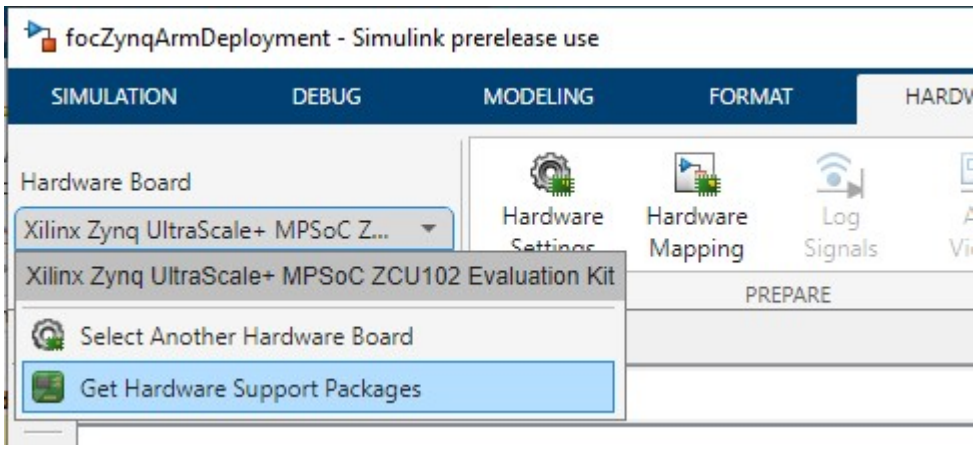
You can apply the techniques shown in this example to develop most controller algorithms. This image shows the generalized workflow from model simulation to deployment of the controller algorithm onto an embedded hardware board.



Simulate a system test bench to gain insight into the behavior of the controller algorithm design. Then explore the design to see how the algorithm is partitioned. The high rate portion of the algorithm is partitioned into a model that is configured for HDL code generation. The low rate portion of the algorithm is partitioned into a model that is configured for C code generation. Generate C and HDL code from these models and learn how you can integrate this code into your design.

After exploring the algorithmic C and HDL code, automate deployment of the algorithmic code into reference frameworks for the processor and programmable logic. Then, execute a test on the deployed application, log the results, and compare them to the simulation results.

Because this example deploys a bitstream and ARM executable to a Xilinx Zynq, you must set up the Xilinx Zynq hardware board prior to starting the example. To ensure the correct setup of your environment, complete the “Getting Started with Targeting Xilinx Zynq Platform” (HDL Coder) example with your hardware configuration prior to starting this example. The figure shows the **Hardware Board** selection.



Required Products

To run this example, these products are required:

- MATLAB
- Simulink
- Embedded Coder
- Embedded Coder Support Package for Xilinx® Zynq® Platform
- HDL Coder™
- HDL Coder Support Package for Xilinx Zynq-7000 Platform
- Motor Control Blockset
- Trenz Electronic™ Motor Control Development Kit TE0820
- Brushless DC motor: 24V, 4000 RPM, Hall Sensors and 1250 CPR Indexed Encoder

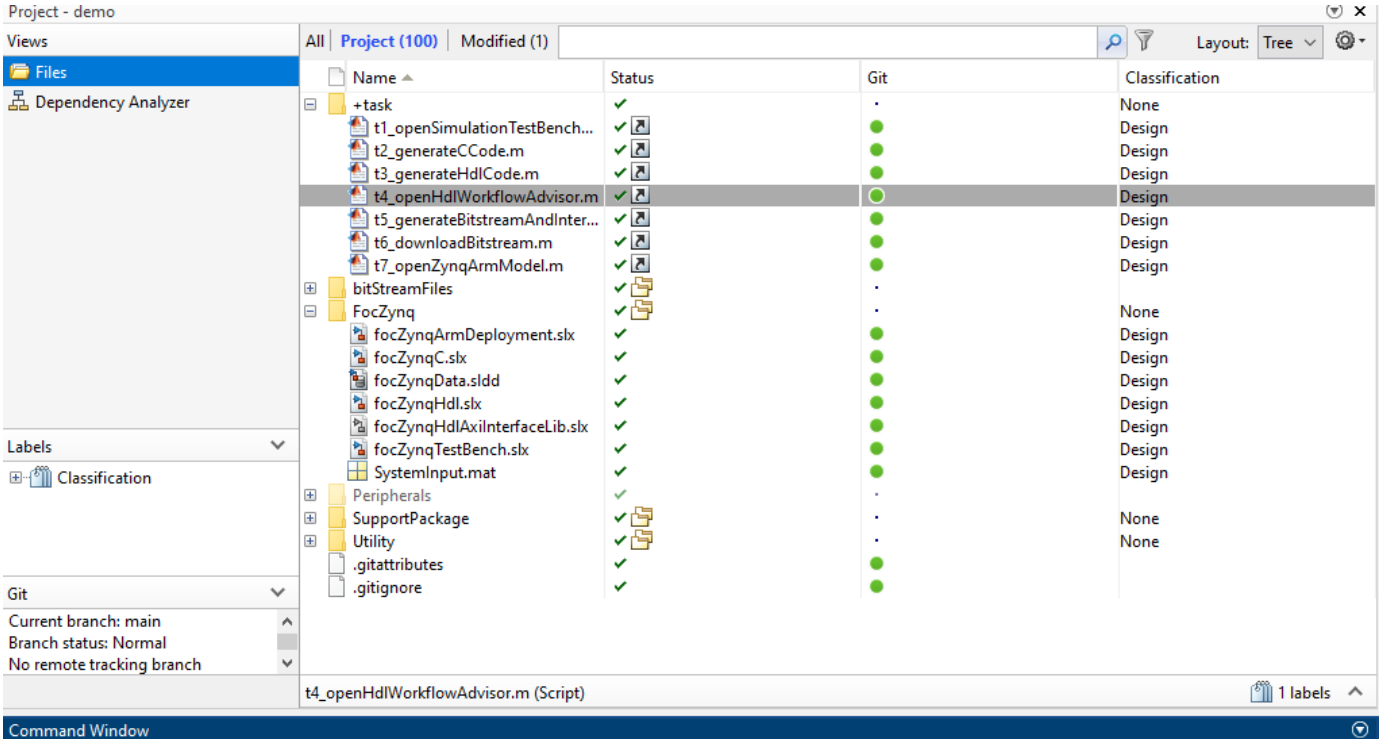
Create Working Copy of Simulink Project

To setup the example, create a working copy of the Simulink Project.

1 Run the `mcb_foc_fpga_demo_start` script to create the project. In the Command Window, type:

```
mcb_foc_fpga_demo_start
```

The `+task` folder in the project has scripts to automate the various activities. This image provides a summary of activates and dependencies. For more information about Simulink Project, see “What Are Projects?”



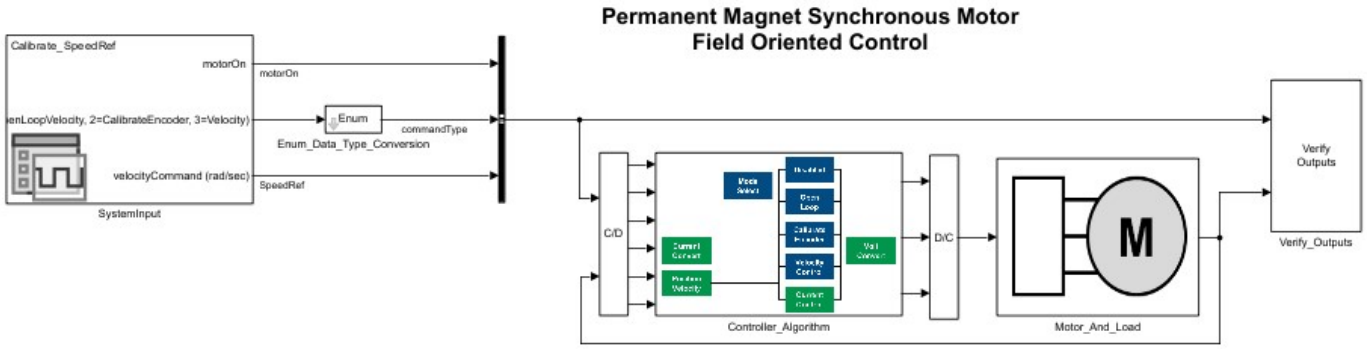
Simulate Algorithm Behavior

You can use project shortcuts to open the model and simulate algorithm behavior.

1. Select Shortcut Management to view the available project shortcuts.
2. Right-click the shortcut and identify the Open and Run context menu items.
3. Run the `task.t1_openSimulationTestBenchModel` shortcut to open the `focZynqTestBench` model. You can run the project shortcut or in the Command Window, type:

   ```
   task.t1_openSimulationTestBenchModel
   ```

   The `Motor_And_Load` subsystem consists of a mathematical model of a surface PMSM, motor load, encoder, and current sensor. The `Controller_Algorithm` subsystem includes an I/O engineering unit conversion, an electrical position calculation, a rotor velocity calculation, a mode scheduler, and four control modes (disabled, open loop velocity control, encoder calibration, and closed loop velocity control). The C/D and D/C subsystems convert the data from continuous-time, variable time step solver and floating-point data types, to discrete-time, fixed time step solver and fixed-point data types, simulation.

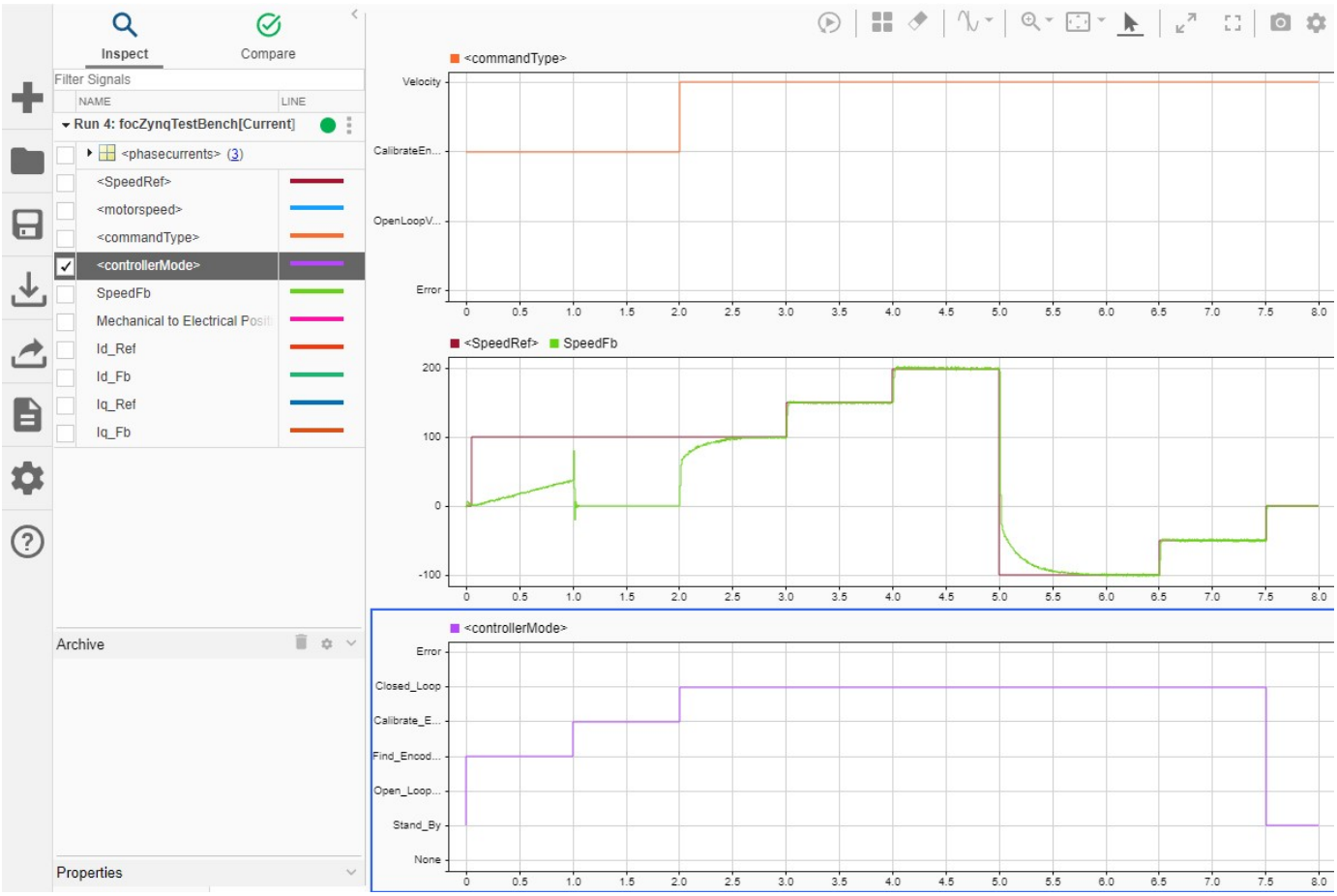


4 On the **Simulation** tab of the Simulink Toolstrip, click **Run** to simulate the model.

5 When the model finishes running, open the **Simulation Data Inspector**. On the **Simulation** tab, click **Data Inspector**. For more information on the Simulation Data Inspector, see .

6 In the **Simulation Data Inspector**, select the **<commandType>**, **<SpeedRef>**, **<SpeedFb>**, and **<controllerMode>** signals.

   For the first two seconds, the controller is commanded to calibrate the encoder position sensor. The encoder position sensor must be calibrated before the controller can achieve closed loop control. During the first portion of position calibration, the motor accelerates using open loop control in order to identify the index pulse of the encoder.



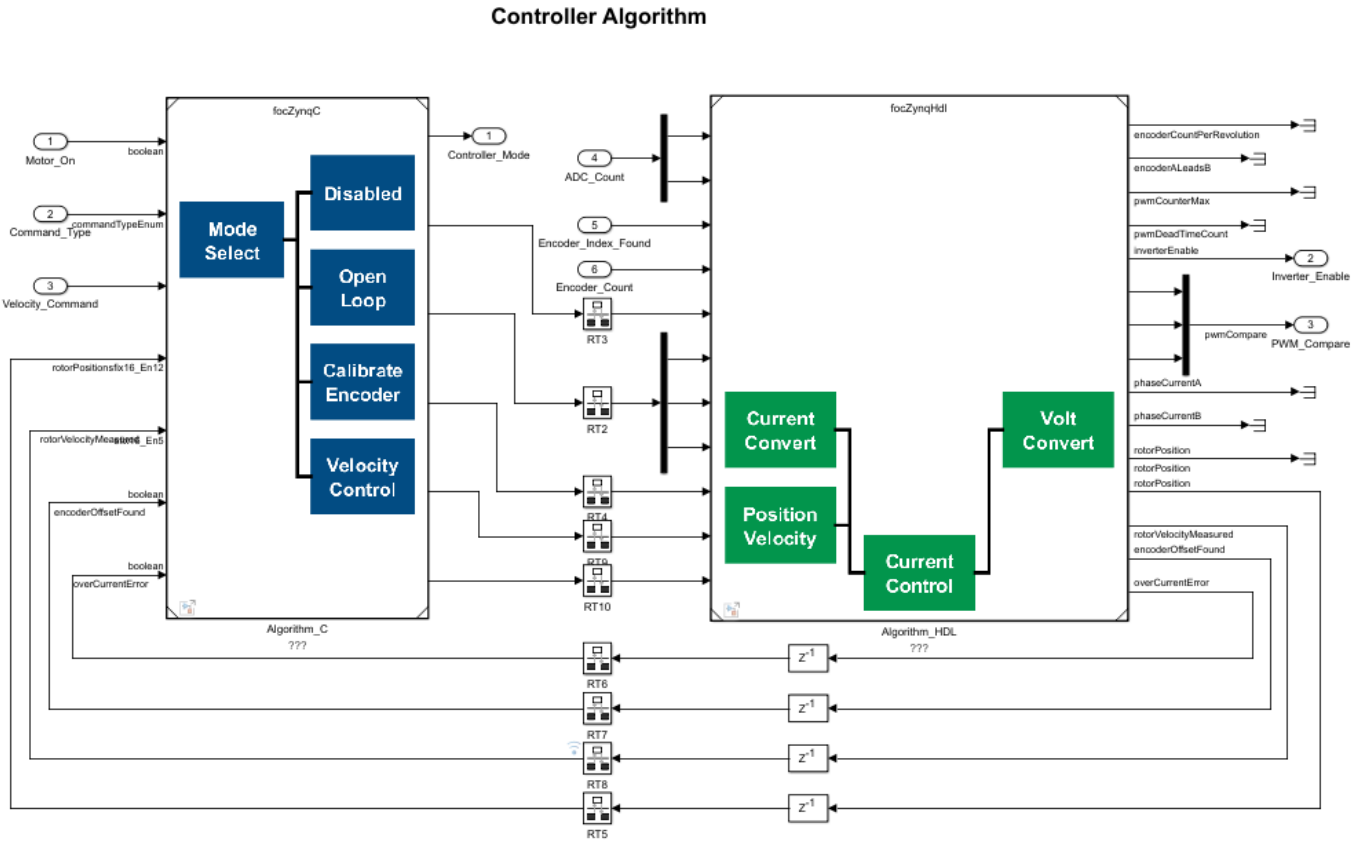
After the index is found, the controller commands and holds a zero position until the encoder offset is identified. During this period the velocity is zero. After two seconds, the controller changes into closed loop control and follows the commanded velocity profile. During closed loop velocity control, the FOC regulates phase current in the PMSM.

Partition Algorithm and Generate Code

You can partition the controller algorithm into complementary software and hardware implementations with generation of C and HDL code for the software and hardware implementations, respectively. Inspecting reports created during the code generation show how you can integrate this code into your own embedded design.

1 In the `focZynqTestBench` model, open the `Controller_Algorithm` subsystem. The controller algorithm contains the `Algorithm_C` and `Algorithm_HDL` blocks, which references the `focZynqC` and `focZynqHDL` models, respectively. The `focZynqC` model contains the portion of the algorithm to be implemented in software. Similarly, the `focZynqHDL` model contains the portion of the algorithm to be implemented on FPGA hardware.

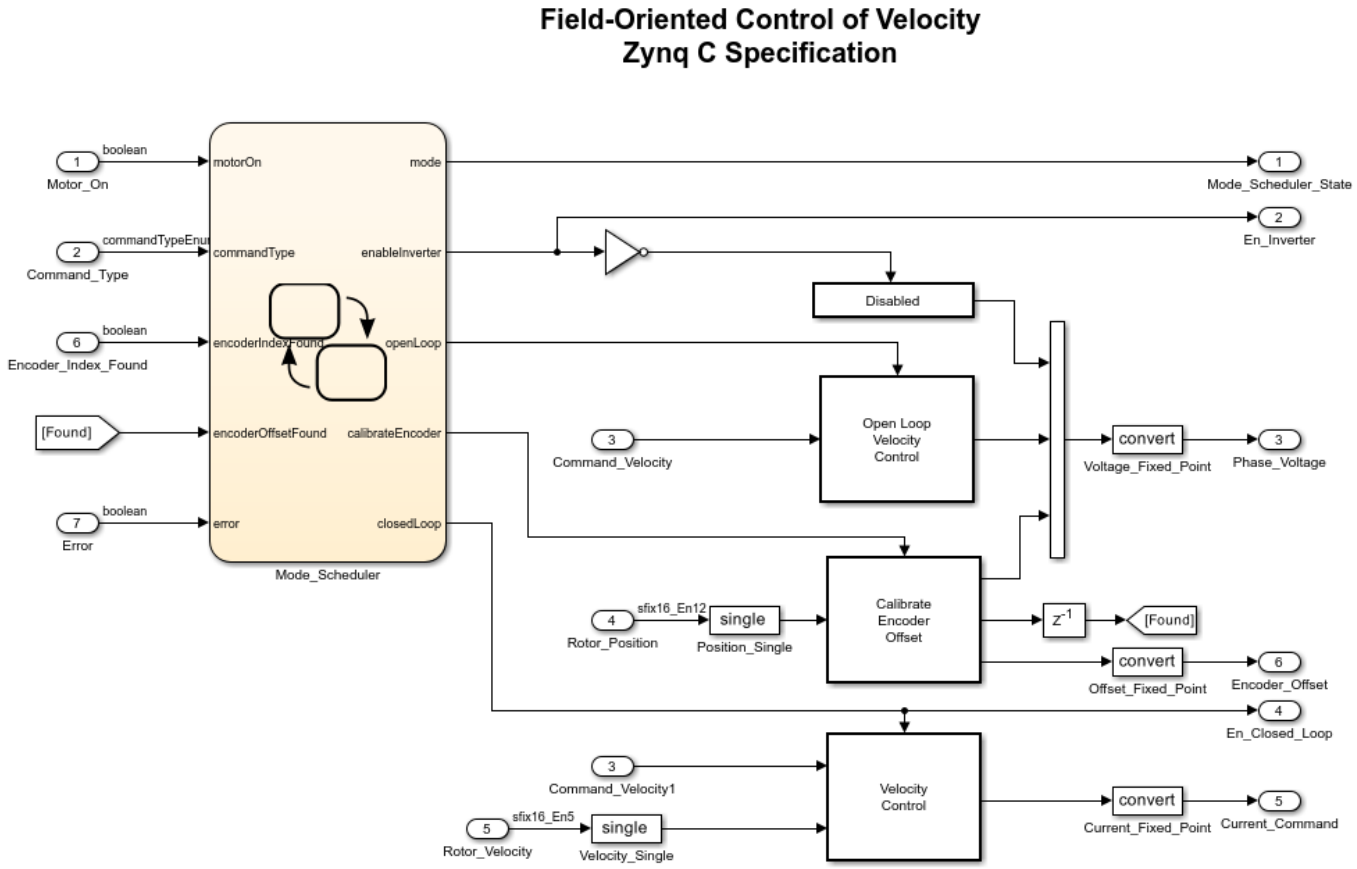
   The parameters for the model are stored in data dictionary. To access or modfy the parameters, select **Modeling > Model Explorer > focZynqTestBench > ExternalData**.



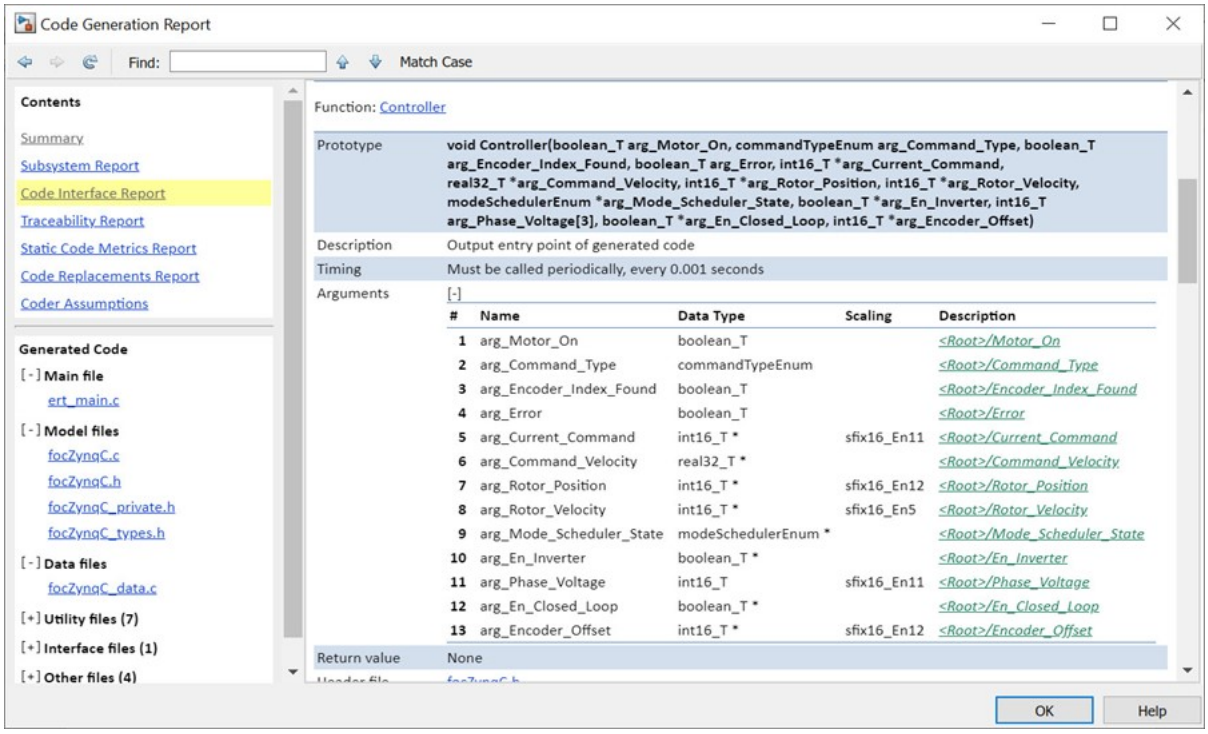
2 Run the `task.t2_generateCCode` function to open the `focZynqC` model, generate C code, and generate a report. You can run the project shortcut or in the Command Window, type:

```
task.t2_generateCCode
```

The `focZynqC` model contains the mode scheduler, velocity control loop, open-loop velocity controller, and routine to automatically calibrate the encoder offset.



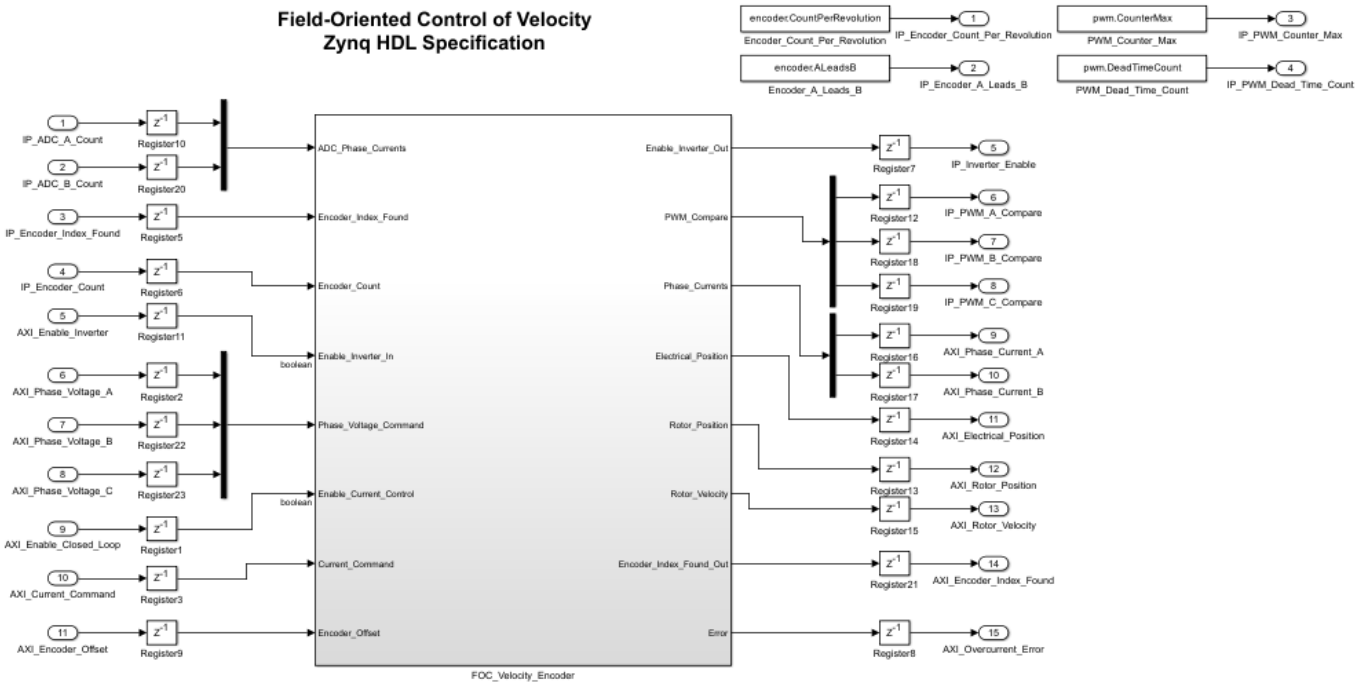
3 The Code Generation Report shows how the generated code corresponds to the model. If you are new to the Code Generation report, you can start with the **Code Interface Report** to view the function interface of the code. The C code is portable and can be integrate with any floating-point embedded processor that uses ANSI-C compiler. For more information on the Code Generation Report, see “Reports for Code Generation” (Simulink Coder).



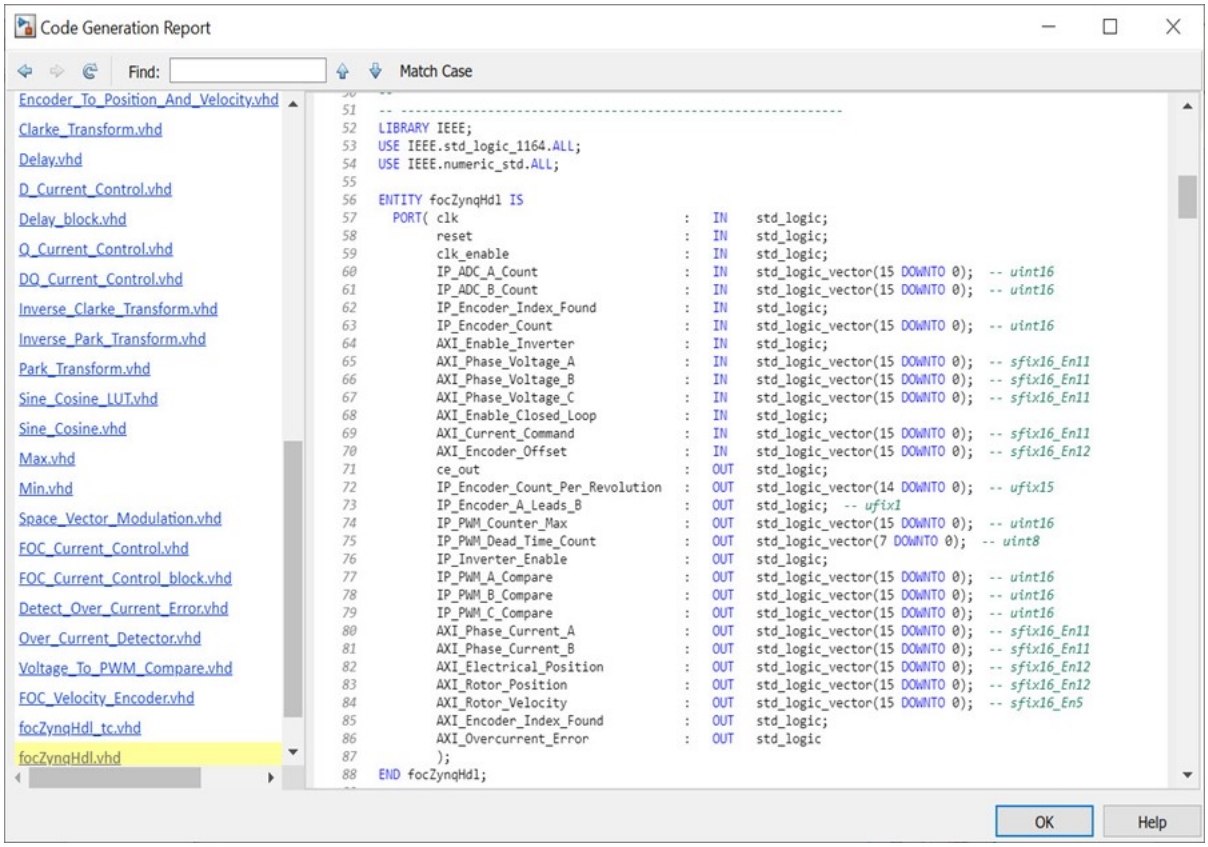
4 Run the `task.t3_generateHdlCode` function to open the `focZynqHdl` model, generate HDL code, and generate a report. You can run the project shortcut or in the Command Window, type:

```
task.t3_generateHdlCode
```

The `focZynqHdl` model contains the electrical position calculation, rotor velocity calculation, over-current checks, and the field-oriented controller.



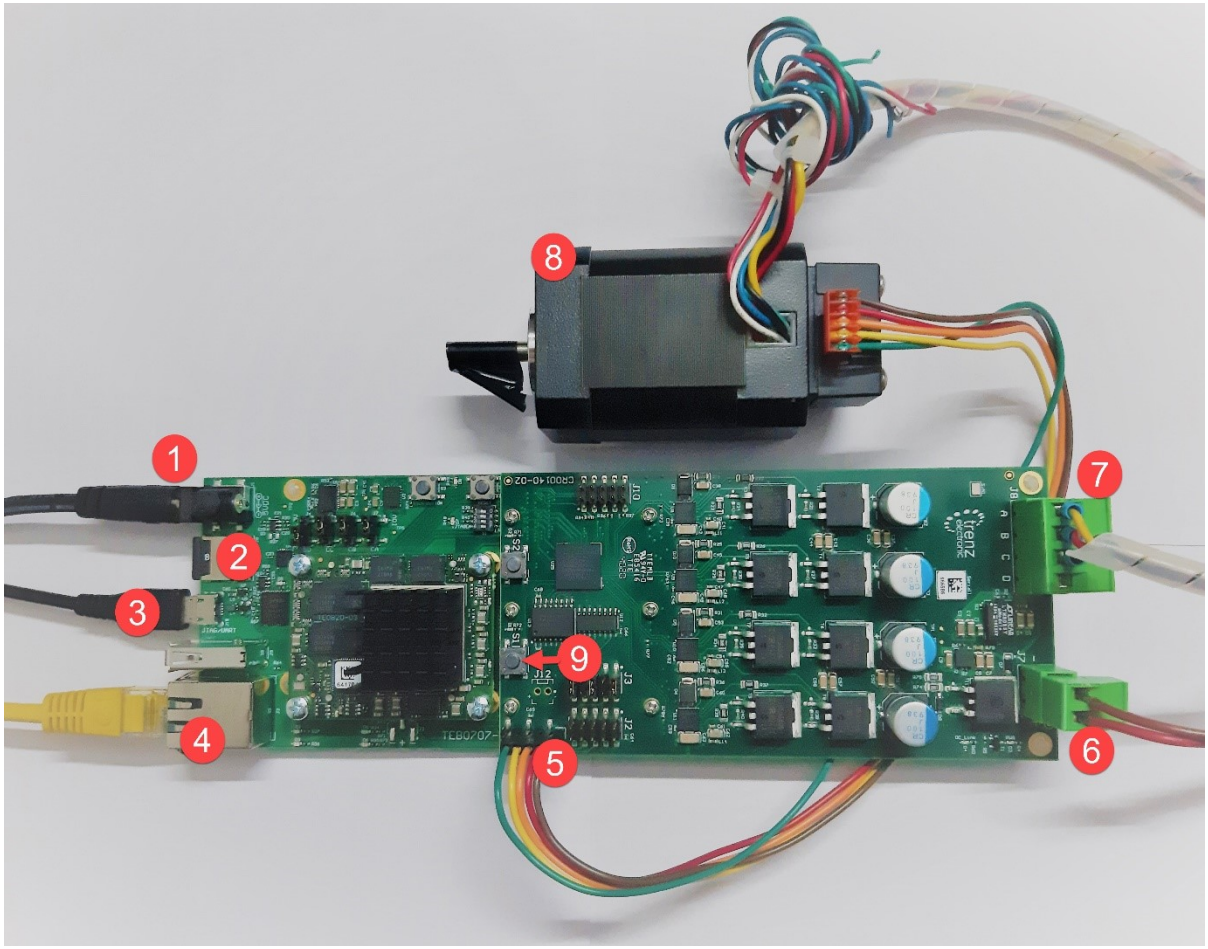
5 The Code Generation Report shows how the HDL code corresponds to the model. If you are new to the Code Generation report, you can start by exploring the **Generated Source Files** pane of the report and selecting the `focZynqHdl.vhd` file that contains the entity specification. The HDL code for the algorithm is portable and can integrate with any FPGA that supports VHDL code.



Setup Xilinx Zynq Platform and Motor Boards

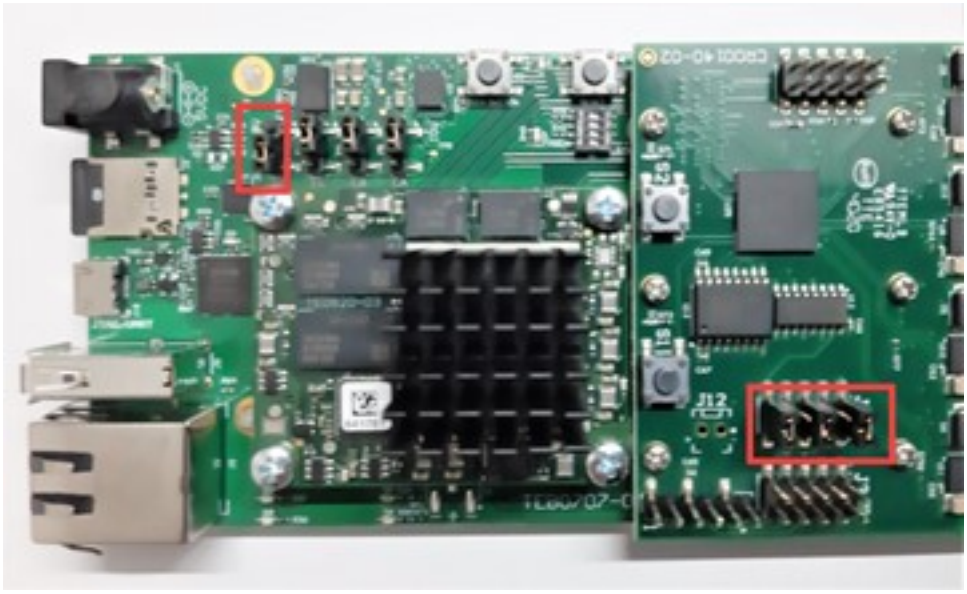
To setup and connect the hardware boards listed in “Required Products” on page 4-3:

1. Run the Hardware Setup for the Xilinx Zynq platform. For information on the hardware setup, see Install Support for Xilinx Zynq Platform. Please install both Embedded Coder Support Package for Xilinx Zynq Platform and HDL Coder™ Support Package for Xilinx Zynq Platform.
2. Connect the Trenz board as shown. The call outs in the image are:
    1. 5 V DC Power Supply
    2. SD – Card
    3. Micro USB cable for UART and JTAG
    4. Ethernet cable
    5. Encoder connector
    6. 24 V DC Power Supply
    7. Motor Power cable (A, B, C)
    8. 24 V Brushless DC Motor
    9. Switch 1 (S1) controls power to the driver board



3 Detailed view of the jumper settings and the encoder cable connection.

Ensure Jumper J4 on the carrier module is set to SD and J3 on the Motor Driver card is set accordingly.



Ensure the encoder cable is inserted according to the above picture. For more information on the jumper settings, please visit Trenz Electronic website.

4 Download the Zybo Zynq Linux image, extract the ZIP file archive and copy the contents to the microSD card. Insert the microSD card in connector J4.

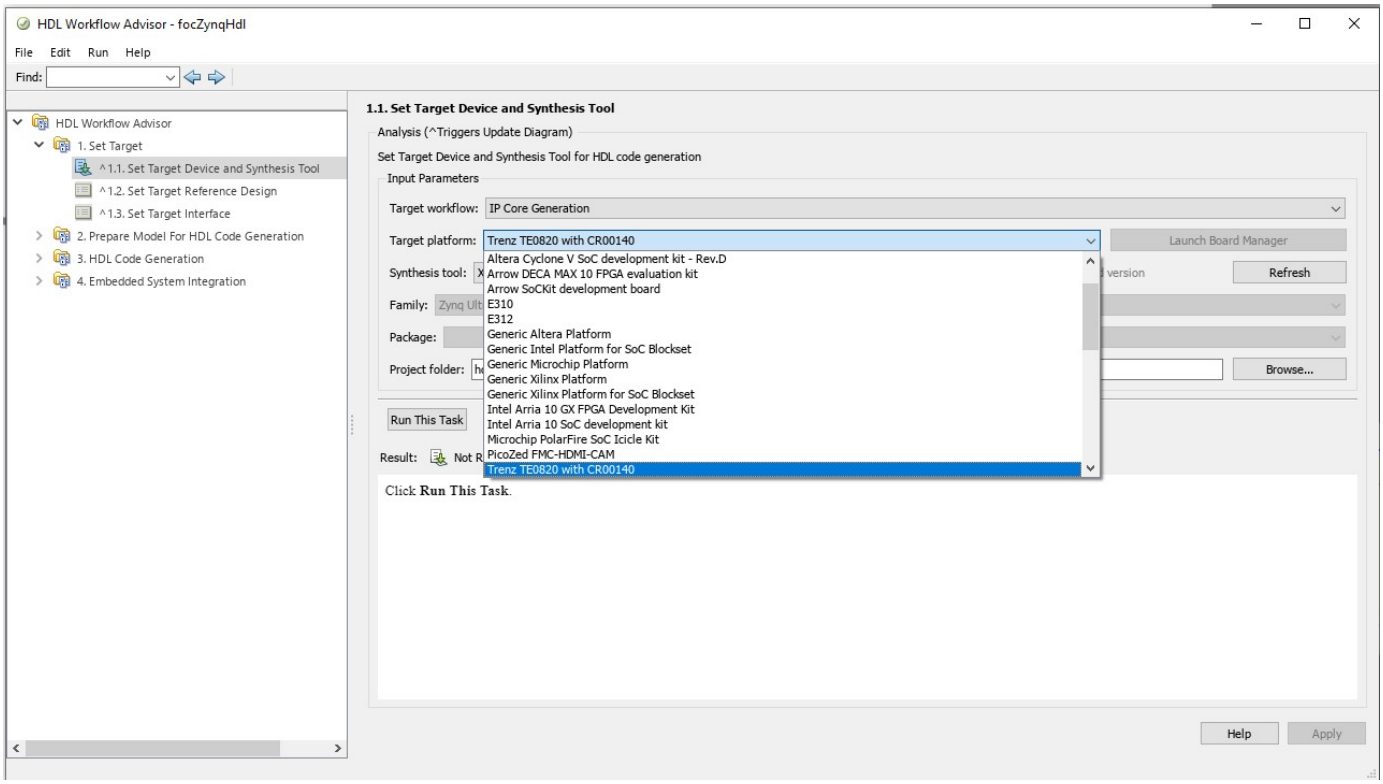
Deploy Bitstream to Programmable Logic

To use the HDL Workflow Advisor to generate HDL code for the algorithm, package HDL into an IP core, integrate the IP core into a Xilinx reference design, and create a bitstream:

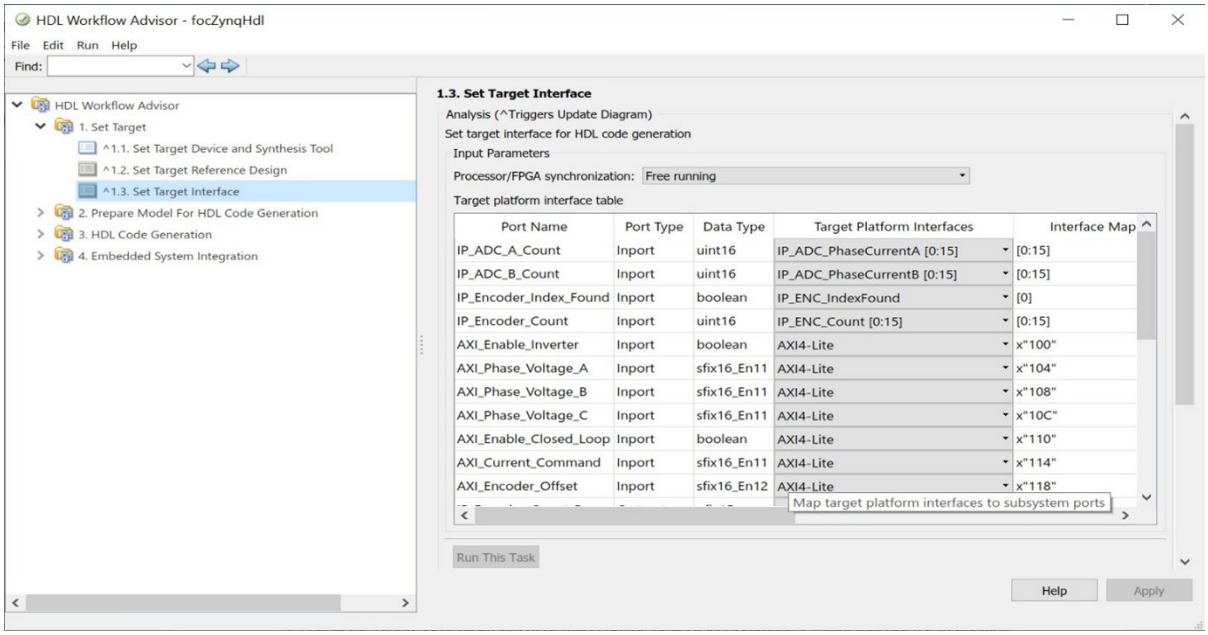
1 Run the task.t4_openHdlWorkflowAdvisor function to open HDL Workflow Advisor.
task.t4_openHdlWorkflowAdvisor

2 On the HDL Workflow Advisor > 1. Set Target > 1.1 Set Target Device and Synthesis Tool group, the Target platform is set to Trenz TE0820 with CR00140.Trenz TE0820 with CR00140 is a

Vivado reference design containing the ADC, encoder, and PWM components. For information on how the creation of this reference design, see “Define Custom Board and Reference Design for Zynq Workflow” (HDL Coder).

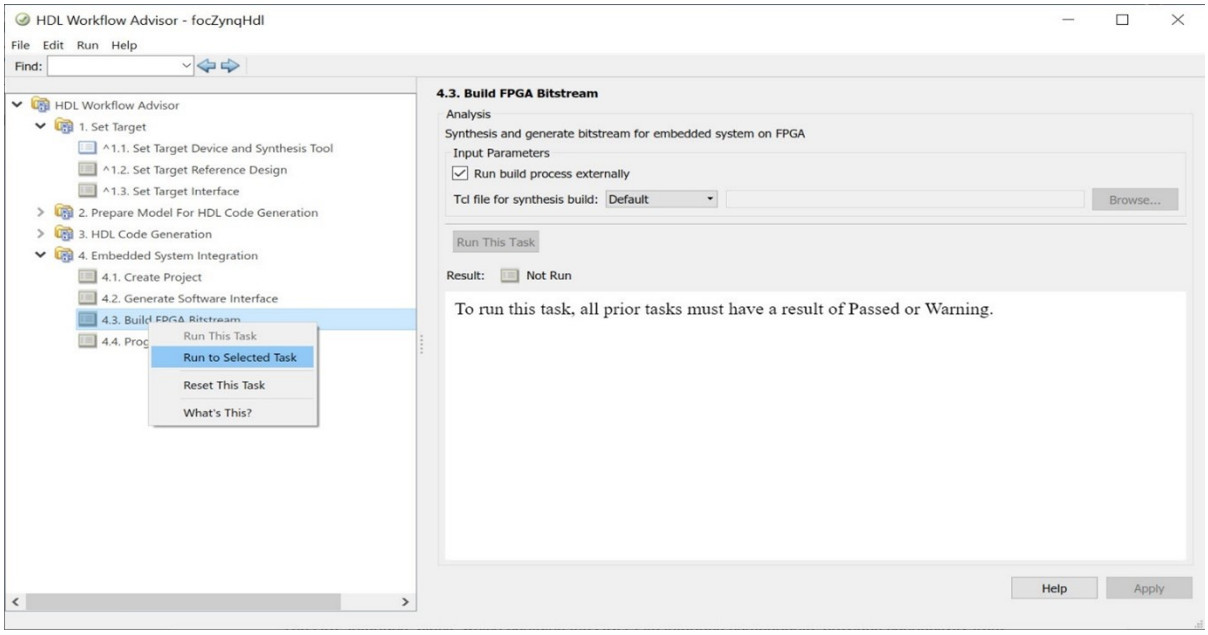


3 Select **1.2. Set Target Interface** to identify the ports. The **Target Platform Interfaces** with the prefix IP refer to connections that are registered with the Trenz motor control reference design.

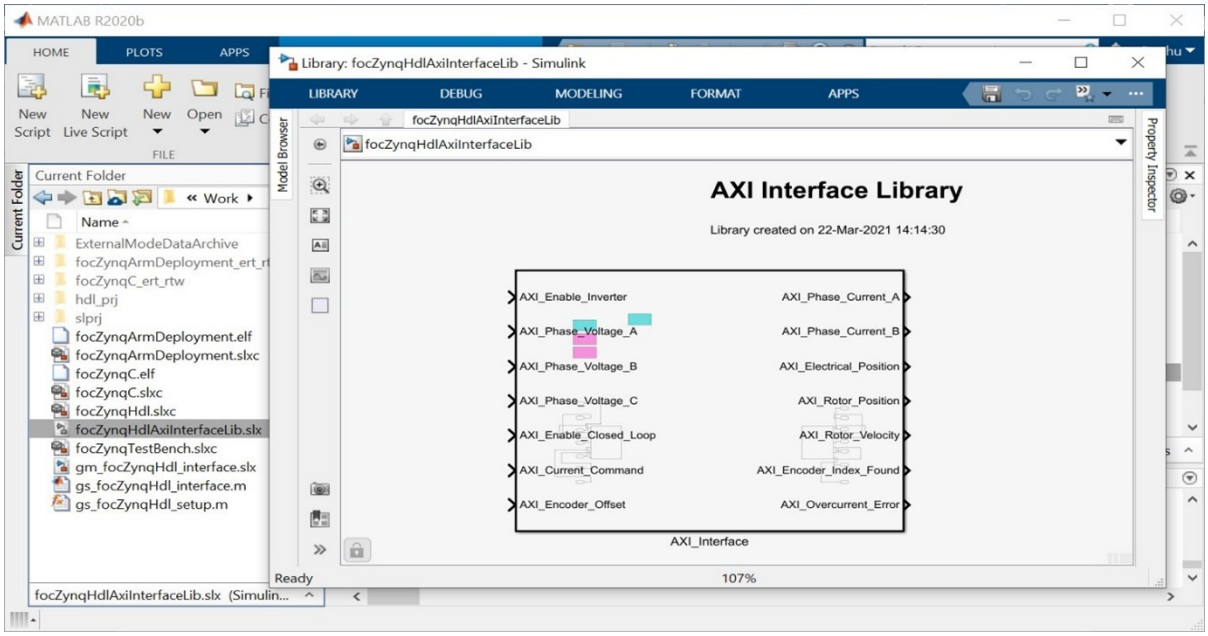


4 Select **4.3 Build FPGA Bitstream** > **Run to Selected Task** or run the `task.t5_generateBitstreamAndInterfaceBlock` function from the project to generate the HDL code for the algorithm and create the FPGA bitstream from the Xilinx reference design. You can run the project shortcut or in the Command Window, type:

```
task.t5_generateBitstreamAndInterfaceBlock
```



5 Follow the progress of bitstream generation on the new DOS Command Prompt that opens. In addition to generating a bitstream, additionally the customized target generates the `focZynqHdlAxiInterfaceLib` software interface library. The library contains an `AXI_Interface` block. The `AXI_Interface` block, which contains the AXI4-Lite interface components, provides connectivity from the model deployed on the ARM processor to the model deployed on the programmable logic.



6 Run task **4.4 Program Target Device** or run the `task.t6_downloadBitstream` function from the project to program the FPGA. You can run the project shortcut or in the Command Window, type:

```
task.t6_downloadBitstream
```

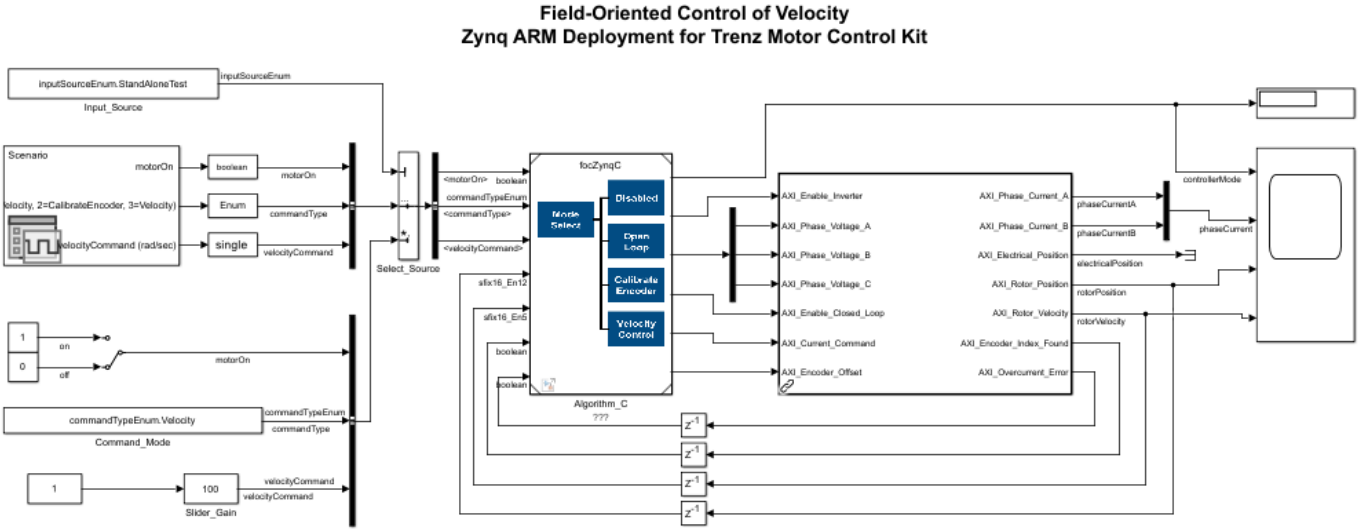
Deploy Executable to ARM processor

You can generate C code for the controller and automate integrating this code with a Linux reference framework to build, deploy, and run the model as an executable to the ARM processor. Data logged from the model running on the processor can then be compared the results of the simulation.

1 Run the `task.t7_openZynqArmModel` function to open the `focZynqArmDeployment` model. You can run the project shortcut or in the Command Window, type:

```
task.t7_openZynqArmModel
```

The `focZynqArmDeployment` model can generate C code, automate integrating with a Linux ARM reference framework, and deploy the executable to the ARM processor on the Xilinx Zynq platform. The deployment model references the original controller model and contains test stimulus, scope, and `AXI_Interface` library block created in “Deploy Bitstream to Programmable Logic” on page 4-13.

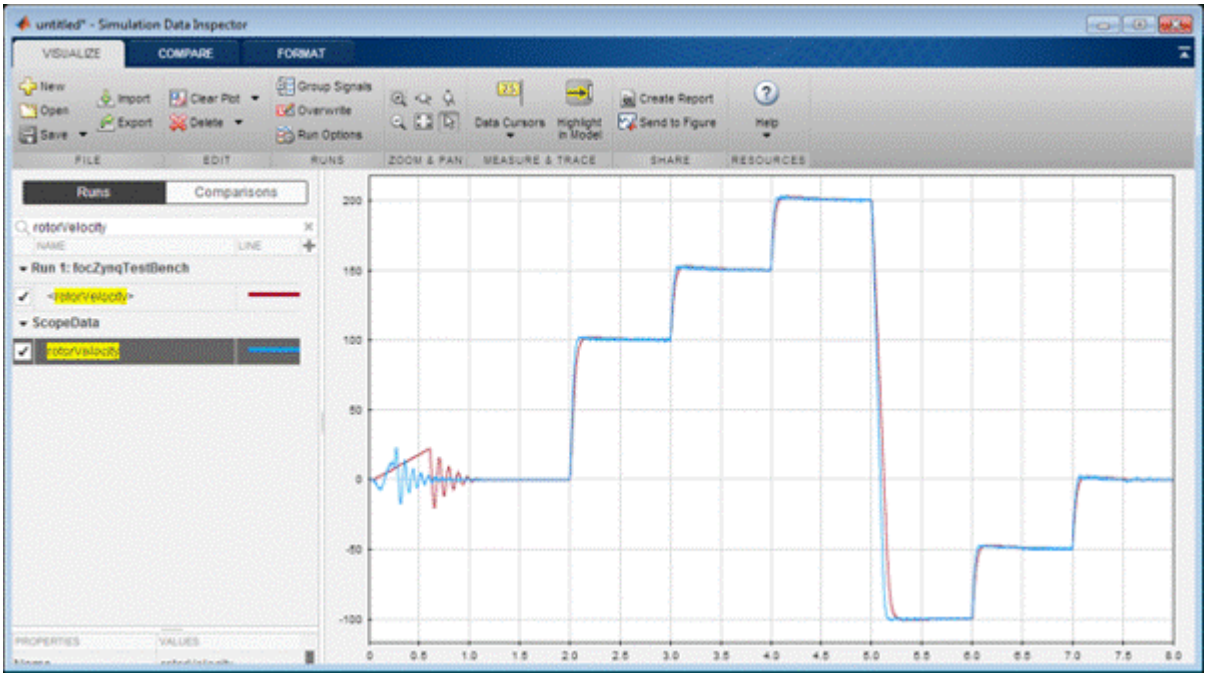


2 On the Hardware tab, click **Monitor & Tune** to build, deploy, and run the model as an executable on the ARM processor. The generated code is compiled against the reference framework to create an executable. While executing, Simulink monitors the signals, showing them in the scope.

   a Press the S1 switch located on the Motor Driver card once. This connects the 24V to the MOSFETS and the motor should run for 8 seconds. In case of any unexpected behavior from the device, use the S1 switch to disconnect the power.

3 Open the Simulation Data Inspector to view the logged signals and compare them to the signals logged previously from `focZynqTestBench` model. On the Simulation tab, click **Data** Inspector.

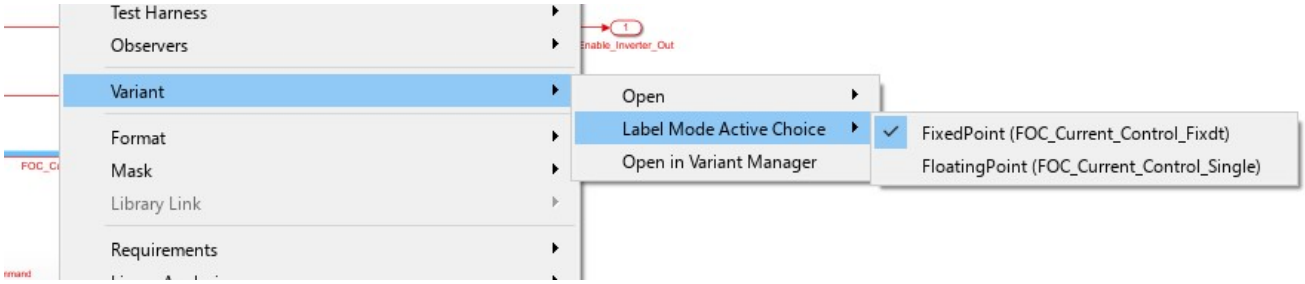
4 In the Simulation Data Inspector, select the `rotorVelocity` signal. During the encoder calibration mode, the signals initially differ then agree since the simulated and real motors started with different rotor positions. In contrast, closed loop velocity control in simulation and hardware are very similar. Differences occur because the simulation model of the motor and sensors use data sheet values and do not explicitly account for the manufacturing tolerances of the physical motor.



More to Try in This Example

More workflow options that you can explore from this example include:

- Continue to explore the files in this example to gain more insight into how simulation, code generation, and automation deployment can help you develop a controller for your hardware.
- HDL Coder supports floating-point single precision data types. In the floating-point variant of the `foczynqhdl` model, you can use the ability of HDL Coder to generate HDL code from a model containing a mix of fixed-point and floating-point data types. Follow the same tasks in the example to implement the control algorithm with single-precision current control on a Xilinx Zynq SoC platform. To open the floating-point variant ,right-click `focZynqHdl/FOC_Velocity_Encoder/FOC_Current_Control`. In the **Variant**, select **Label Mode Active Choice** > **FloatingPoint**.



See Also

External Websites

- Motor Control Development Kit with Xilinx Zynq UltraScale+ ZU2CG-1E MPSoC Module | With Xilinx FPGA | Development Boards | Trenz Electronic | Products | Trenz Electronic GmbH Online Shop

- Xilinx Zynq Support from MATLAB and Simulink - Hardware Support - MATLAB & Simulink
- Trenz Electronic Motor Control Development Kit Support from Simulink - Hardware Support - MATLAB & Simulink

Hardware Troubleshooting

Check ADC Inputs

Description

The analog to digital converter (ADC) can measure incorrect values. For example, in custom-designed analog circuits, currents measured by ADC can be incorrect due to noise, out-of-phase measurements, or sampling issues. This results in faulty feedback to the control system that leads to instability.

Action

Verify ADC Pin

See the hardware schematics and verify that you identified and configured the correct ADC pins for a given measurement (a-phase, b-phase).

Verify ADC Block Configuration

Open the ADC block and verify that the **Input Channels**, **ADC module**, **SOC trigger**, **SOCx acquisition window** parameters are configured correctly.

ADC sampling begins with the SOC event. In some cases, for example, when sensing the current through the shunt resistors, ADC sampling requires synchronization with the bottom leg switches. In this case, verify that the SOC event is configured correctly with ADC-PWM interrupt synchronization. This also results in reduced EMI/EMC noise in the sampling because ADC conversion happens outside the PWM transition. For more information, see “Task Scheduling in Target Hardware” on page 2-6.

Reduce Noise in ADC Sampling

You may notice noise in the ADC samples. This may happen either if there is EMI/EMC or if sampling is faster than what the device can support. EMI/EMC can be reduced by improving the hardware design.

To avoid problems due to faster sampling, see the device datasheet and determine the maximum supported clock frequency of the ADC. For example, if you are using a Texas Instruments TMS320F28379D series microcontroller, it can support a CPU clock frequency of 200 MHz, but the maximum clock frequency supported by the ADC module is 50 MHz. Use this value to set **ADC clock prescaler (ADCCLK)** parameter on the **Hardware Implementation** tab in the **Configuration Parameter** dialog box of your model.

Check VDD of Current Measurement Device

Many current measurement devices derive VDD from the DC power supply (V_{DC}). In addition, the device enable pin also determines the supply voltage to the internal current measurement circuit (for example, Texas Instruments BOOSTXL-DRV8305). Absence of VDD (or the device enable pin) results in 0 V at the ADC of the target hardware. Ensure that these conditions are not present in your hardware.

Check ADC Current Conventions

Check if you are using the correct conventions for ADC current sensing. Motor Control Blockset considers the current entering the motor (or leaving the inverter) as positive. This convention changes with the hardware because of the differences in the inverting or non-inverting op-amp and

the analog current sensing circuit. Check the inverter current sensing circuit op-amp and set the `inverter.invertingAmp` variable (control parameter) to:

- 1 — If the current sensing circuit detects the current entering motor as positive.
- –1 — If the current sensing circuit detects the current entering motor as negative.

For more information about setting a control parameter, see “Estimate Control Gains and Use Utility Functions”.

Test Readability of Unipolar and Bipolar Signals

Check if the measurement circuit is designed to read unipolar and bipolar signals.

Check if the `inverter.ISenseVoltPerAmp` variable (control parameter) is set correctly according to the hardware specification. For more information about this parameter, see “Estimate Control Gains and Use Utility Functions”.

DC signal measurement circuits are usually unipolar. For example, BoostXL-DRV8305 has a DC voltage measurement circuit that converts the voltage range of 0 – 44.3 V to 0 – 3.3 V at the ADC. Voltage ADCs cannot measure negative voltages.

AC signal measurement circuits are usually bipolar. For example, BoostXL-DRV8305 has an AC current measurement circuit that converts the current range of –23.57 to +23.57 A to 0 – 3.3 V at the ADC with an offset of 1.65V.

Check ADC Offset and Gain computation

Verify the ADC offset values before deploying and executing the code on the target hardware. For more information, see “Current Sensor ADC Offset and Position Sensor Calibration”.

Check the accuracy of the computed gain for conversion of the ADC counts to signal value in the real world as described in the previous section.

Check ADC Resolution

Check the ADC resolution to determine the minimum value of the signal that it can measure. For example, a 3.3 V 12-Bit ADC that can measure ±16.5 A has a resolution of 0.1 Volts/Ampere. The minimum current that the ADC can measure (excluding EMI/EMC and noise) is approximately 8 mA.

Determine the minimum measurable current by the ADC. Verify that this current is greater than the ADC signal-to-noise ratio, tolerance, and errors. Ensure that you simulate and check the model before deploying it to the target hardware.

Low ADC resolution can result in difficulties when implementing sensorless algorithms to control motors that consume very small currents (for example, 50 mA AC) on no load. In addition, EMI/EMC and noise affects ADC measurements. It is a good practice to simulate the model and verify if the ADC resolution is appropriate. Increase the gain of the sensor amplifier on the hardware to increase the ADC resolution.

Verify PWM Outputs

Description

The motor control algorithm generates the pulse width modulation (PWM) signals to control the motor through inverter. In some cases, the PWM signals can be incorrect due to improper switching frequency, wrong interrupt and PWM generation configurations, or error in the duty cycles. Incorrect PWM signals result in improper switching of the inverter.

Action

Verify PWM Frequency

Use an oscilloscope to verify that the generated PWM signals has the expected switching frequency. In embedded targets, configuration of the PWM module depends on factors such as target hardware and clock frequency. For example, you can use these equations to calculate PWM_Counter_Period for Texas Instruments C2000 targets that have the ePWM module configured to work with the Up-Down counting mode:

CPU_frequency (Hz) = 200e6

PWM_frequency (Hz) = 20e3

PWM_Counter_Period (PWM timer counts) = CPU_frequency/ PWM_frequency/ 2

Verify PWM Generation

Ensure that you feed a correct PWM duty cycle to the switching device (for example, MOSFET or IGBT). PWM generation depends on these active-high and active-low configurations:

- Active high — 25% duty results in 25% on-time for upper leg MOSFET or IGBT (recommended).
- Active low — 25% duty results in 75% on-time for upper leg MOSFET or IGBT.

In addition, check if there is any inversion of the PWM signal between the target and MOSFET due to the gate driver or isolator circuit (25% gate pulse must be 25% on-time by the driver chip).

Verify Interrupt Configuration

Majority of the controller algorithms are designed to work with the ADC-PWM synchronization for advantages like current sensing, reduced EMI/EMC interference.

ADC sampling begins with the SOC event. In some cases, for example, when sensing the current through the shunt resistors, ADC sampling requires synchronization with the bottom leg switches. In this case, verify that the SOC event is configured correctly with the ADC-PWM interrupt synchronization. This also results in reduced EMI/EMC noise in the sampling because ADC conversion happens outside the PWM transition. For more information, see “Task Scheduling in Target Hardware” on page 2-6.

Verify Updates to PWM Duty

Verify if the PWM duty is updated or refreshed in synchronization with the PWM module. To implement a robust control, it is a good practice to timely refresh the PWM duty (for example, once in T_{pwm}, preferably before T_{pwm}/ 2).

Check Behavior at PWM Generation Limits

Check the datasheet of the PWM driver circuit for support at the 0% duty and 100% duty limits. For functional safety, it is a good practice to limit the maximum duty cycle somewhere between 95 and 98% by setting the corresponding value in the DQ Limiter block.

Check for Incorrect PWM Generation Configuration

Verify that the hardware uses the correct PWM generation configuration. For example, BoostXL-DRV8305 supports 3-PWM mode, 6-PWM mode, and 1-PWM mode.

Check for Default Dead Bands

Check if there are dead bands introduced by the motor driver board. Consider this while generating dead bands from the PWM module.

Confirm Maximum Switching Frequency

Determine the maximum possible switching frequency for the inverter and driver from the device datasheets. Ensure that the model does not exceed this value.

Check Hardware Connections

Description

When you try to run the motor, you may face problems due to incorrect hardware connections. This may result in rise in temperature of the motor, inverter, hardware board or an abnormal behavior such as uncontrolled motor speed.

Action

Verify Hardware Connections

Check the wiring and connections before getting started. For details, see “Hardware Connections”. For instructions to determine the serial port connected to the hardware, see “Find Communication Port”.

Manually Check Rotation of Shaft

Verify that the shaft of your motor is rotating freely with minimal rotational friction. A mechanical failure in the bearings may result in thermal overloads, which can damage the motor windings.

Verify Rated Currents for Motor and Inverter

Determine the rated currents of the motor and inverter from the manufacturer datasheet. Ensure that you do not overload the motor for durations longer than what the original equipment manufacturer (OEM) has specified.

Check Motor and Inverter Temperature

Ensure that the temperature of the motor windings and inverter heat sink are within the expected temperature range. Overloading the hardware results in excessive heat that can damage the hardware.

Verify Measurements from Analog Circuits

Verify the range of the signals that you measure from the analog circuits (for example, the maximum current of the inverter).

Check for Additional Resistors

After you complete the process of estimating the motor parameters, you should not change the motor connections because this leads to differences in the contact and cable resistances. In addition, verify that the initialization script of the model takes into consideration any additional resistors present in the power circuit.

Verify Fault Pin and Enable Pin Connections

Check and verify that the fault pins and enable pins are connected correctly on the target hardware board.

Test Algorithm Design

Description

When simulating or running a model on the target hardware, you can face problems because of defects in the implementation of the control algorithm. This can lead to an uncontrolled motor speed, differences in the current waveforms or mismatch in PI controller gains between simulation and target hardware.

Action

Verify Parameters and Other Input Data

Verify that you identified and entered the inputs (for example, motor and inverter parameters, clock speed, and switching frequency) correctly. If the input data is incorrect, the motor control algorithm will not work. Use the Motor Control Blockset parameter estimation tool to compute the motor parameters. For more details, see “Estimate PMSM Parameters Using Recommended Hardware”.

Verify Waveforms of Measured Currents

After you load the motor shaft, verify that the waveforms for the measured signals match the shape visible in the simulations. For example, field-oriented control ensures perfect sinusoidal waveforms for currents. For exceptions, see “Check ADC Inputs” on page 5-2.

Verify Control System Design

Verify that all the controllers used in the model (for example, PI controllers and sliding mode observer) are designed correctly.

You can start by simulating the model by using the estimated motor parameters before deploying the model to the target hardware. Observe and verify the step responses for the current and speed by using both simulation and deployment on the target hardware.

Model-Based Design ensures that correct simulation of the model results in identical outcomes on the target hardware with identical gains (that match the gain values computed during simulation) for all the controllers.

Verify Signal Representation

Check if you can represent the signals correctly for a selected data type. For example, it is not possible to store the value 1024 in the 8-bit data-type. Similarly, it may not be possible to represent some gain values in the selected fixed-point resolution.

Verify Base Values for PU Representation

If you are working with the Per-Unit system, please check that the base value of a quantity (for example, base current), is selected correctly. For more details, see “Per-Unit System”.

Check Generated Code

Description

When simulating or running a model on the target hardware, you may face problems due to errors in the software architecture of a model. These errors can affect the performance of control algorithm and increase the code execution time on the hardware.

Action

Check Sample Times

Verify the base rates and other execution rates of the model by using **Debug > Information Overlays > Sample Time > Colors**. The different sample times of the model decide the execution of different tasks in the simulation and in the generated code.

Check for Overruns

Verify that there are no overruns beyond the available sample time. Algorithms with overruns affect the control system stability. If required, optimize the model for code execution. For more details, see “Code Verification and Profiling Using PIL Testing” on page 1-15.

Verify Low-Priority Interrupt Service Routines (ISR)

Verify that the low-priority interrupt service routines (ISR) (for example, speed control loop and communication service routines) are executed according to the design and are not ignored by any overruns in the high-priority ISRs.

Check Execution Order Priority

Check that the model uses a correct execution order priority. Verify that all the interrupts are configured correctly.

Verify Software Initialization

To allow the analog circuits to get ready, check that the software initialization delay (for example, ADC blanking time, PWM driver, and charge pump) is greater than the required value specified by the manufacturer (for example, 2µs).

Check Hardware Initialization

Verify that you initialized the target hardware and inverter correctly. Generally, the driver is disabled, which brings all the switches to a high impedance state and initializes the important variables to the default values.

Verify Third-Party Tool Version

Verify that you are using the recommended versions of the third-party tools. Check that bugs in the third-party software do not cause regressions.