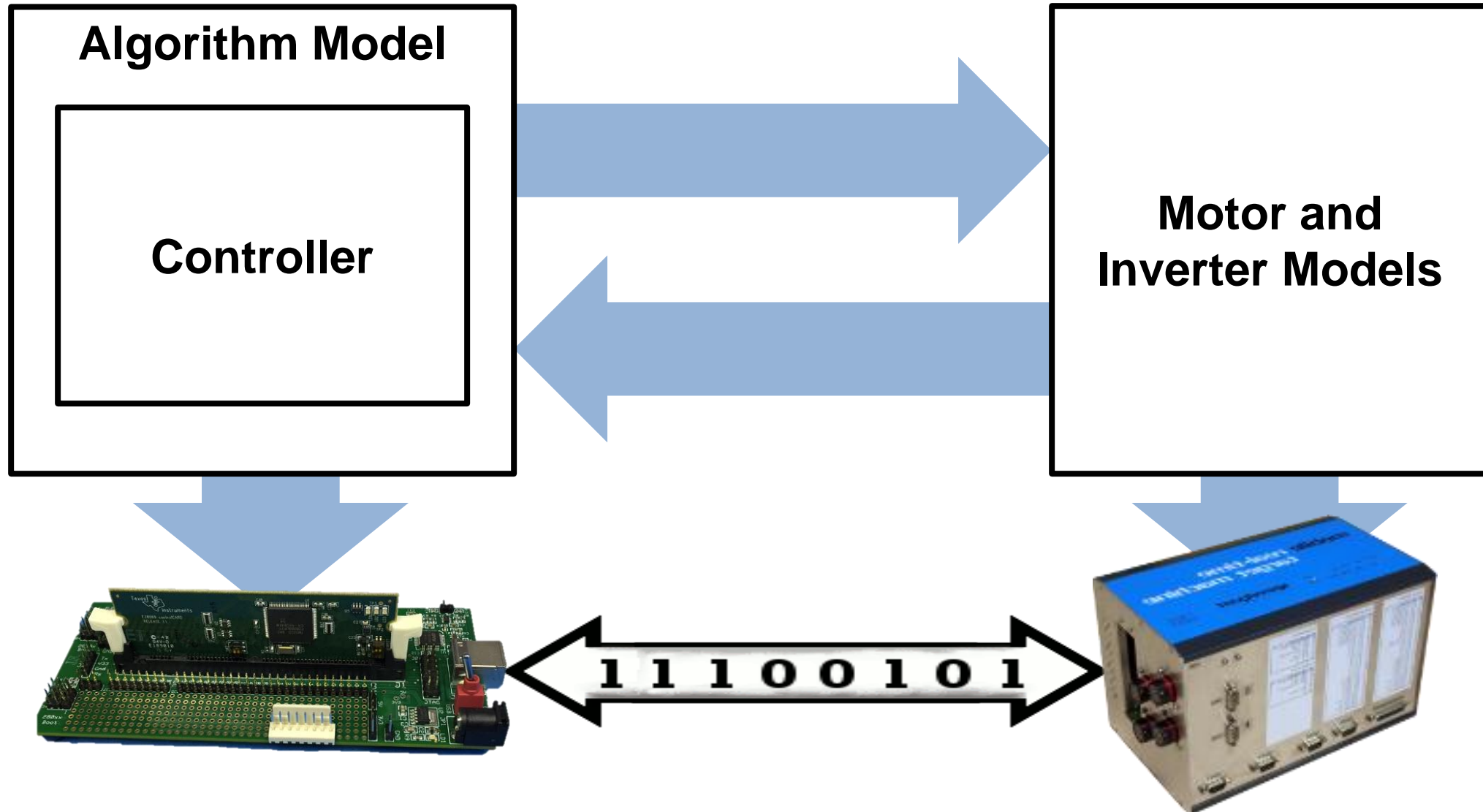


Developing a Real-Time Motor Model for HIL Testing

Joel Van Sickle **Application Engineer, Novi, MI**
Dakai Hu **Application Engineer, Novi, MI**

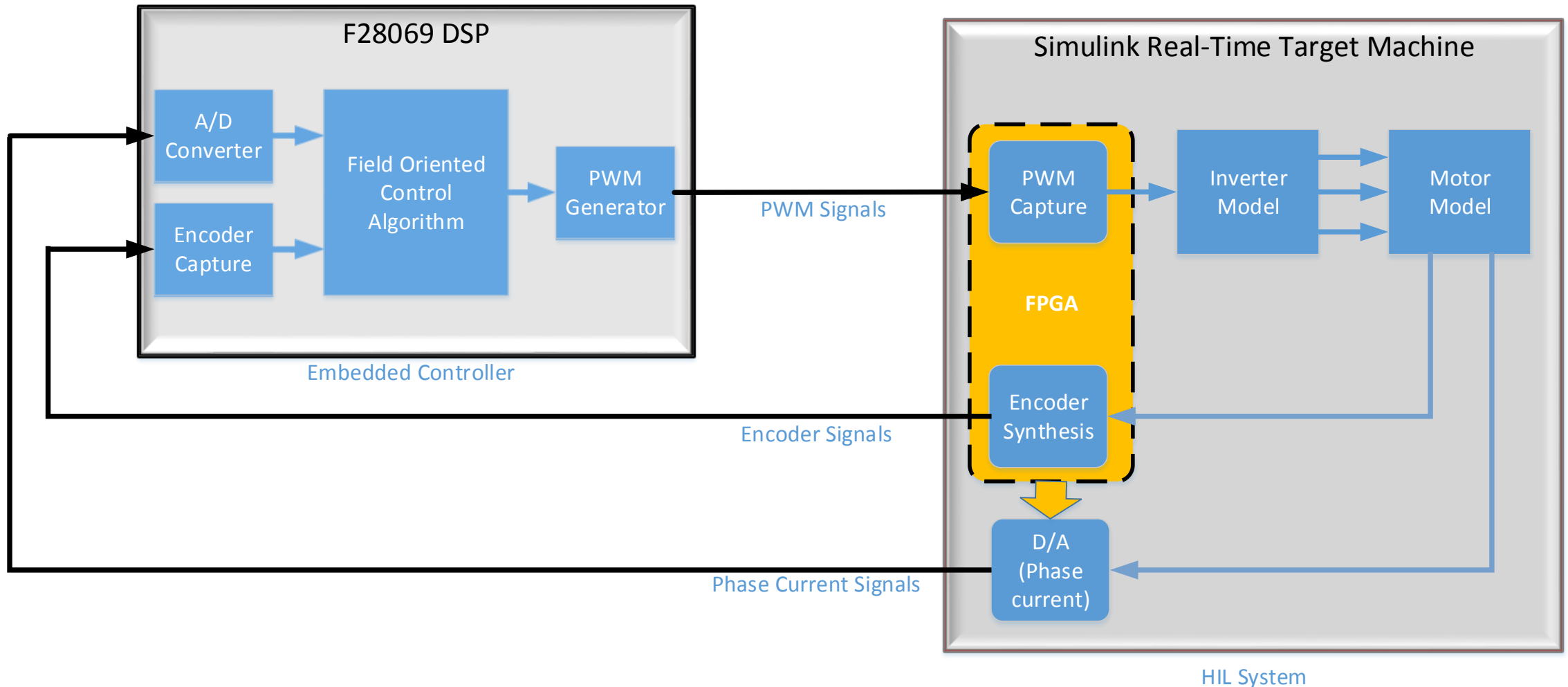


Developing a Real-Time Motor Model for HIL Testing



Connecting the embedded controller to the HIL system

PMSM HIL Connections Diagram



Developing a real-time motor model for HIL testing

- Modeling motor dynamics for a HIL system
- Deploying the motor model to a HIL system
- Testing an embedded motor controller with the HIL system

Developing a real-time motor model for HIL testing

- **Modeling motor dynamics for HIL testing**
 - Identifying model parameters
 - Use testing framework to validate model
- Deploying the motor model to a HIL system
- Testing an embedded motor controller with the HIL system

What do These Particular Models Look Like?

Permanent Magnet Synchronous Machine

The diagram shows a cross-section of a Permanent Magnet Synchronous Machine. On the left, there are four terminals labeled 1, 2, 3, and 4, corresponding to phases R, A, B, and C. The stator windings are connected to these terminals. The rotor is shown with a North (N) pole and a South (S) pole. A mechanical shaft is labeled 'm'.

Permanent Magnet Synchronous Machine

Angle = Aligned with phase A axis (original Park)

Block Parameters: Permanent Magnet Synchronous Machine

Permanent Magnet Synchronous Machine (mask) (link)

Implements a three-phase or a five-phase permanent magnet synchronous machine. The stator windings are connected in wye to an internal neutral point.

The three-phase machine can have sinusoidal or trapezoidal back EMF waveform. The rotor can be round or salient-pole for the sinusoidal machine, it is round when the machine is trapezoidal. Preset models are available for the Sinusoidal back EMF machine.

The five-phase machine has a sinusoidal back EMF waveform and round rotor. Preset models are not available for this type of machine.

Configuration Parameters Advanced

Stator phase resistance R_s (ohm):
pmsm.StatorPhaseResistance

Inductances [L_d (H) L_q (H)]:
[pmsm.InductanceLd pmsm.InductanceLq]

Specify: Torque Constant (N.m / A_peak)

Flux linkage established by magnets (V.s):
0.0050167

Voltage Constant (V_peak L-L / krpm):
3.6397

Torque Constant (N.m / A_peak):
pmsm.TorqueConstant

OK Cancel Help Apply

Surface Mount PMSM Equations

Electrical Model

$$v_d = Ri_d - L_q p \omega_r i_q + L_d \frac{d}{dt} i_d$$

$$v_q = Ri_q + p \omega_r (L_d i_d + \lambda) + L_q \frac{d}{dt} i_q$$

$$\omega_e = p \omega_r$$

$$T_e = 1.5p[\lambda i_q + (L_d - L_q)i_d i_q]$$

$$T_e = K_t i_q \text{ (assumes round rotor, } L_d = L_q \text{)}$$

Mechanical Model

$$\frac{d}{dt} \omega_r = \frac{1}{H} (T_e - \text{sgn}(\omega_r) J_0 - b \omega_r - T_{load})$$

Required Parameters

Electrical Model

$$v_d = R i_d - L_q p \omega_r i_q + L_d \frac{d}{dt} i_d$$

$$v_q = R i_q + p \omega_r (L_d i_d + \lambda) + L_q \frac{d}{dt} i_q$$

$$\omega_e = p \omega_r$$

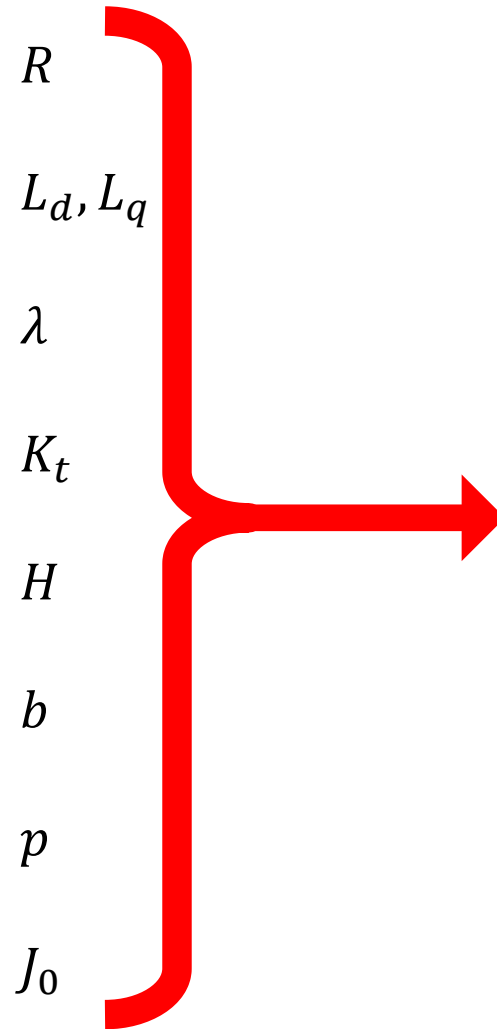
$$T_e = 1.5p [\lambda i_q + (L_d - L_q) i_d i_q]$$

$$T_e = K_t i_q \quad (\text{assumes round rotor, } L_d = L_q)$$

Mechanical Model

$$\frac{d}{dt} \omega_r = \frac{1}{H} (T_e - \text{sgn}(\omega_r) J_0 - b \omega_r - T_{load})$$

Mapping parameters to PMSM model



Block Parameters: Permanent Magnet Synchronous Machine

Permanent Magnet Synchronous Machine (mask) (link)

Implements a three-phase or a five-phase permanent magnet synchronous machine. The stator windings are connected in wye to an internal neutral point.

The three-phase machine can have sinusoidal or trapezoidal back EMF waveform. The rotor can be round or salient-pole for the sinusoidal machine, it is round when the machine is trapezoidal. Preset models are available for the Sinusoidal back EMF machine.

The five-phase machine has a sinusoidal back EMF waveform and round rotor. Preset models are not available for this type of machine.

Configuration Parameters **Advanced**

Stator phase resistance R_s (ohm):

Inductances [L_d (H) L_q (H)]:

Specify:

Flux linkage established by magnets (Vs):

Voltage Constant (V_{peak} L-L / krpm):

Torque Constant (N.m / A_peak):

Inertia, viscous damping, pole pairs, static friction [J (kg.m²) F (N.m.s) p () T_f (N.m)]:

Initial conditions [ω_m (rad/s) θ_{tam} (deg) i_a, i_b (A)]:

OK Cancel Help Apply

Tests to Characterize Motor and Load

Motor Tests	Parameters Identified	Identification method
Back EMF Test	Number of Pole Pairs (p) Flux Linkage Constant (λ) Torque Constant (K_t)	Calculation
Friction Test	Viscous Damping Coefficient (b) Coulomb Friction (J_0)	Curve fitting
Coast Down Test	Rotor Inertia (H)	Curve fitting
DC Voltage Step Test	Resistance (R) Inductance (L)	Parameter estimation

- For more details watch this video: [parameterizing and verifying a permanent magnet synchronous motor.](#)

Tests to Characterize Motor and Load

Motor Tests	Parameters Identified	Identification method
Back EMF Test	Number of Pole Pairs (p) Flux Linkage Constant (λ) Torque Constant (K_t)	Calculation
Friction Test	Viscous Damping Coefficient (b) Coulomb Friction (J_0)	Curve fitting
Coast Down Test	Rotor Inertia (H)	Curve fitting
DC Voltage Step Test	Resistance (R) Inductance (L)	Parameter estimation

- For more details watch this video: [parameterizing and verifying a permanent magnet synchronous motor](#).

Simulink Test Framework

The screenshot displays the Simulink Test Manager interface. The main window is titled 'Test Manager' and shows a test configuration for 'Open Loop and Coast Down'. The interface is divided into several sections:

- TESTS:** A toolbar at the top with icons for New, Open, Save, Cut, Copy, Delete, Run, Stop, Parallel, Report, Visualize, Highlight in Model, Import, Export, and Help.
- Test Browser:** A tree view on the left showing the test hierarchy: motorAndLoadTestSuite* > System Identification Tests > Open Loop and Coast Down.
- Property Table:** A table at the bottom left listing properties for the selected test.

PROPERTY	VALUE
Name	Open Loop and Coast Down
Type	Baseline Test
Model	motorCoastDownTestBench
Simulation Mode	[Model Settings]
Location	C:\zProjects\RevisionControlProjects\...
Enabled	<input checked="" type="checkbox"/>
Record Coverage	<input type="checkbox"/>
Hierarchy	motorAndLoadTestSuite » System Ide...
- Open Loop and Coast Down Configuration:** The main right-hand pane shows the configuration for the selected test. It includes sections for DESCRIPTION, REQUIREMENTS, SYSTEM UNDER TEST (with a model field set to 'motorCoastDownTestBench'), TEST HARNESS, SIMULATION SETTINGS OVERRIDES, PARAMETER OVERRIDES, CALLBACKS, INPUTS, OUTPUTS, CONFIGURATION SETTINGS OVERRIDES, and BASELINE CRITERIA. The BASELINE CRITERIA section includes a table for signal tolerances:

SIGNAL NAME	ABS TOL	REL TOL
<input checked="" type="checkbox"/> velocities.mat	15	10.00%

Suite of Tests to Run

The screenshot displays the Test Manager application window. The main pane shows the configuration for the test 'Open Loop and Coast Down' under the 'motorAndLoadTestSuite'.

Test Configuration Details:

- Name:** Open Loop and Coast Down
- Type:** Baseline Test
- Model:** motorCoastDownTestBench
- Simulation Mode:** [Model Settings]
- Location:** C:\zProjects\RevisionControlProjects\...
- Enabled:**
- Record Coverage:**
- Hierarchy:** motorAndLoadTestSuite » System Ide...

Test Configuration Parameters:

- SYSTEM UNDER TEST:** Model: motorCoastDownTestBench
- TEST HARNESS:**
- SIMULATION SETTINGS OVERRIDES:**
- PARAMETER OVERRIDES:**
- CALLBACKS:**
- INPUTS:**
- OUTPUTS:**
- CONFIGURATION SETTINGS OVERRIDES:**
- BASELINE CRITERIA:**
 - Save baseline data in test result
 - SIGNAL NAME:** velocities.mat (checked)
 - ABS TOL:** 15
 - REL TOL:** 10.00%

Test Browser (Left Panel):

- motorAndLoadTestSuite*
 - System Identification Tests
 - Open Loop and Coast Down
 - Back EMF

Model to be Tested

The screenshot shows the Test Manager application window. The 'TESTS' menu is visible at the top. The 'Test Browser' pane on the left shows a tree view with 'motorAndLoadTestSuite*' expanded to 'System Identification Tests', where 'Open Loop and Coast Down' is selected. The 'Results and Artifacts' pane on the right shows the configuration for the selected test. A blue arrow points from the 'Open Loop and Coast Down' test name in the Test Browser to the 'SYSTEM UNDER TEST' label in the configuration pane. A white box highlights the 'Model' property, which is set to 'motorCoastDownTestBench'.

PROPERTY	VALUE
Name	Open Loop and Coast Down
Type	Baseline Test
Model	motorCoastDownTestBench
Simulation Mode	[Model Settings]
Location	C:\zProjects\RevisionControlProjects\...
Enabled	<input checked="" type="checkbox"/>
Record Coverage	<input type="checkbox"/>
Hierarchy	motorAndLoadTestSuite » System Ide...

SIGNAL NAME	ABS TOL	REL TOL
<input checked="" type="checkbox"/> velocities.mat	15	10.00%

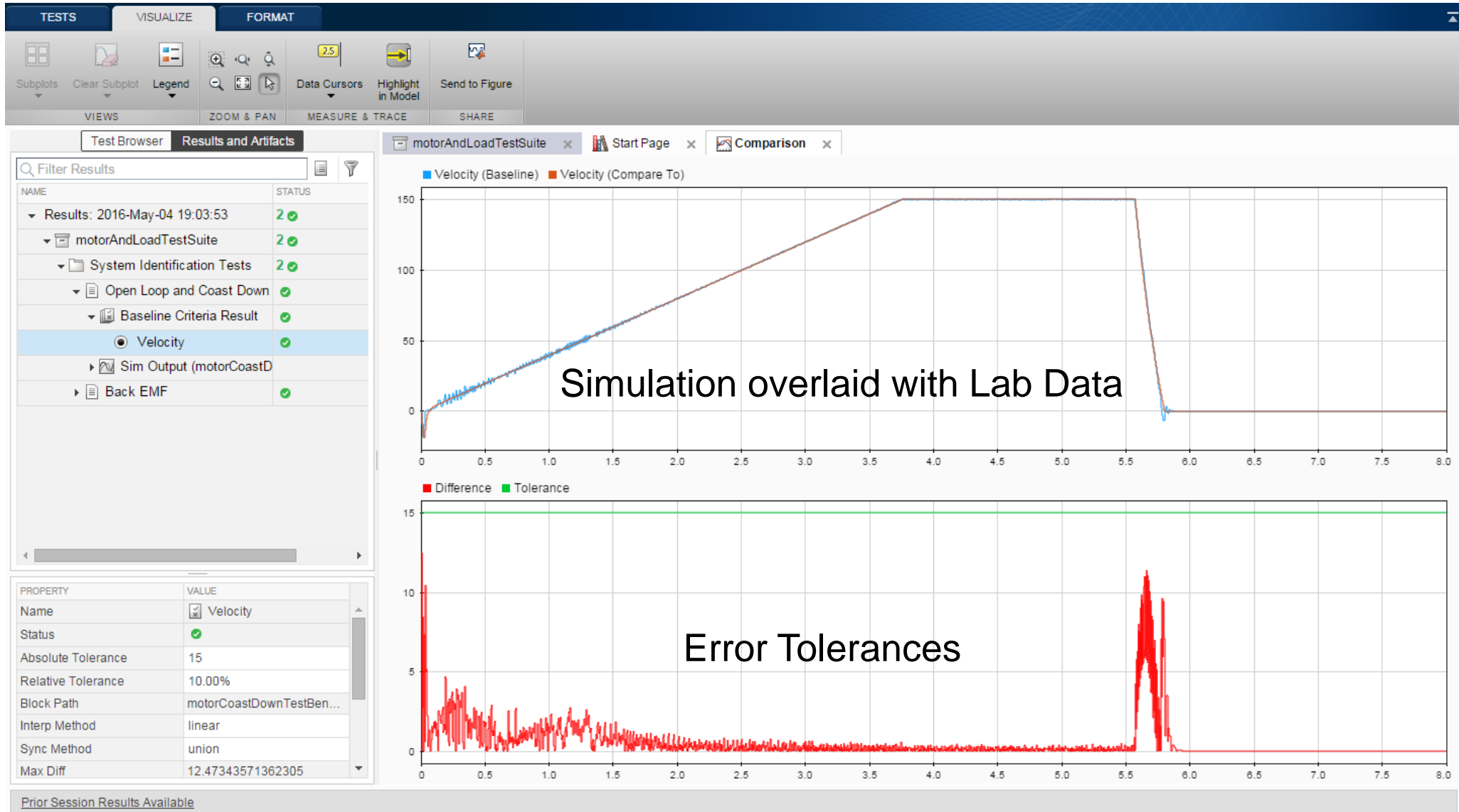
Baseline Results for Comparison

The screenshot shows the Test Manager application window. The main pane displays the configuration for the 'Open Loop and Coast Down' test. The 'SYSTEM UNDER TEST' section shows the model 'motorCoastDownTestBench'. The 'BASELINE CRITERIA' section is expanded, showing a checkbox for 'Save baseline data in test result' which is currently unchecked. Below this, a table lists signal names with checkboxes indicating their status:

SIGNAL NAME	Status
▶ <input checked="" type="checkbox"/> velocities.mat	Selected

At the bottom left of the interface, a status bar indicates 'Prior Session Results Available'.

Open Loop Coast Down Test Results



Developing a real-time motor model for HIL testing

- Modeling motor dynamics for HIL testing
- **Deploying the motor model to a HIL system**
 - Profiling model execution on HIL system
 - Integrating model into HIL system
- Testing an embedded motor controller with the HIL system

Profiling model execution on the HIL system

The screenshot shows the MATLAB R2016a interface with a Simulink project open. The Command Window displays the following output:

```

>> task.t2_DeployingMotorModelToHIL.t1_profilingModelExecution
### Running min sample time test for model: motorAndLoadTestDe
*****
* Minimum achievable sample time = 26.89 (microsec) *
*
* Maximum achievable update rate = 37187.68 (Hz) *
*****
  
```

 * Minimum achievable sample time = 26.89 (microsec) *
 *
 * Maximum achievable update rate = 37187.68 (Hz) *

 * Minimum achievable sample time = 26.89 (microsec) *
 *
 * Maximum achievable update rate = 37187.68 (Hz) *

Process to Integrate Model into a HIL System

- Step 1 – Speedgoat Only
- Step 2 – Speedgoat with Loopback
- Step 3 – Speedgoat with C2000

I/O for Step 1: Speedgoat Only

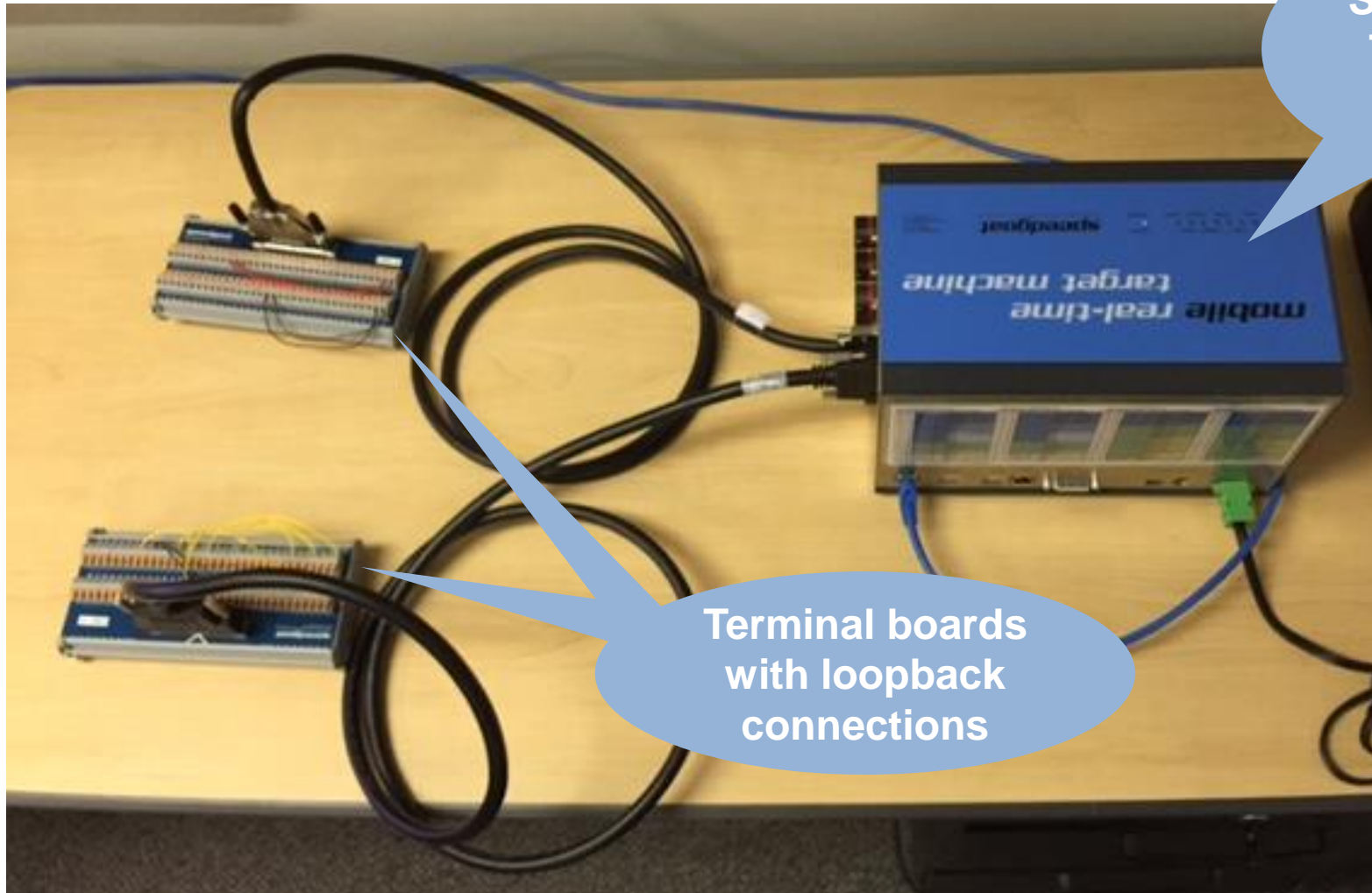
- Hardware implementation



Simulink Real
Time Target
Machine

I/O for Step 2: Speedgoat with Loopback

- Hardware implementation

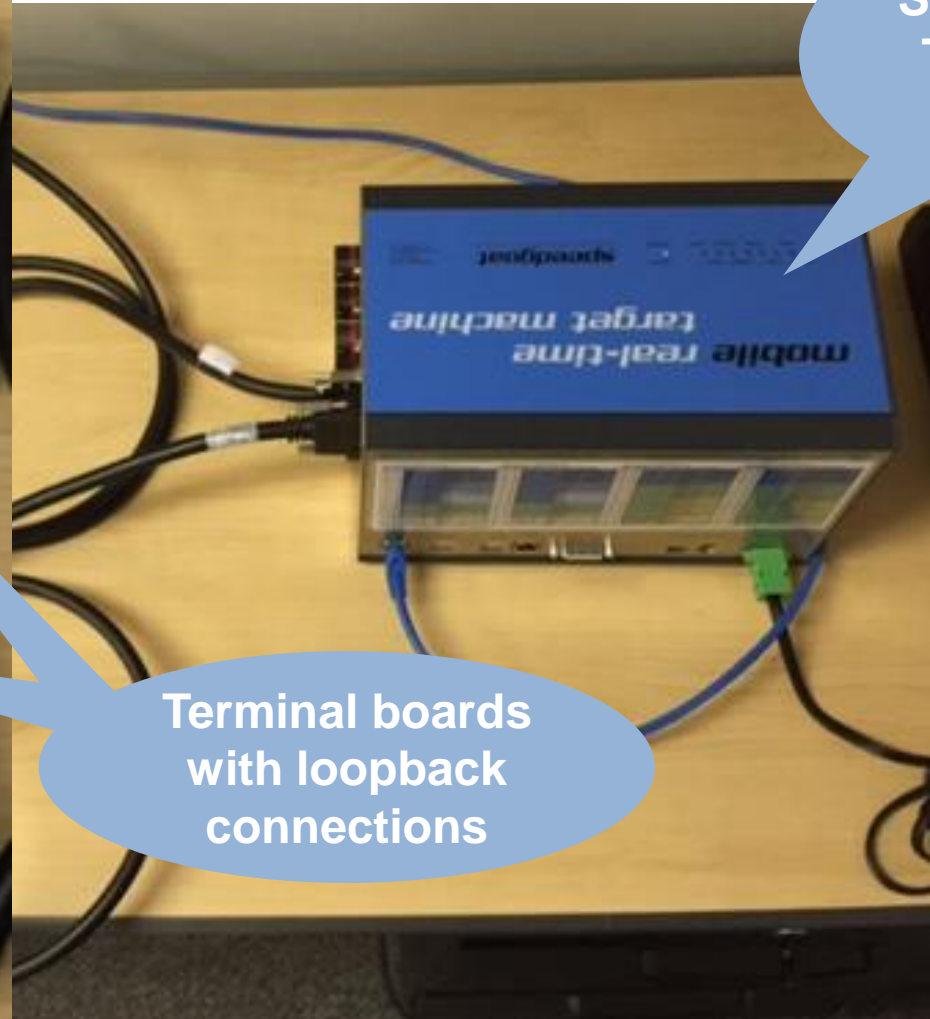
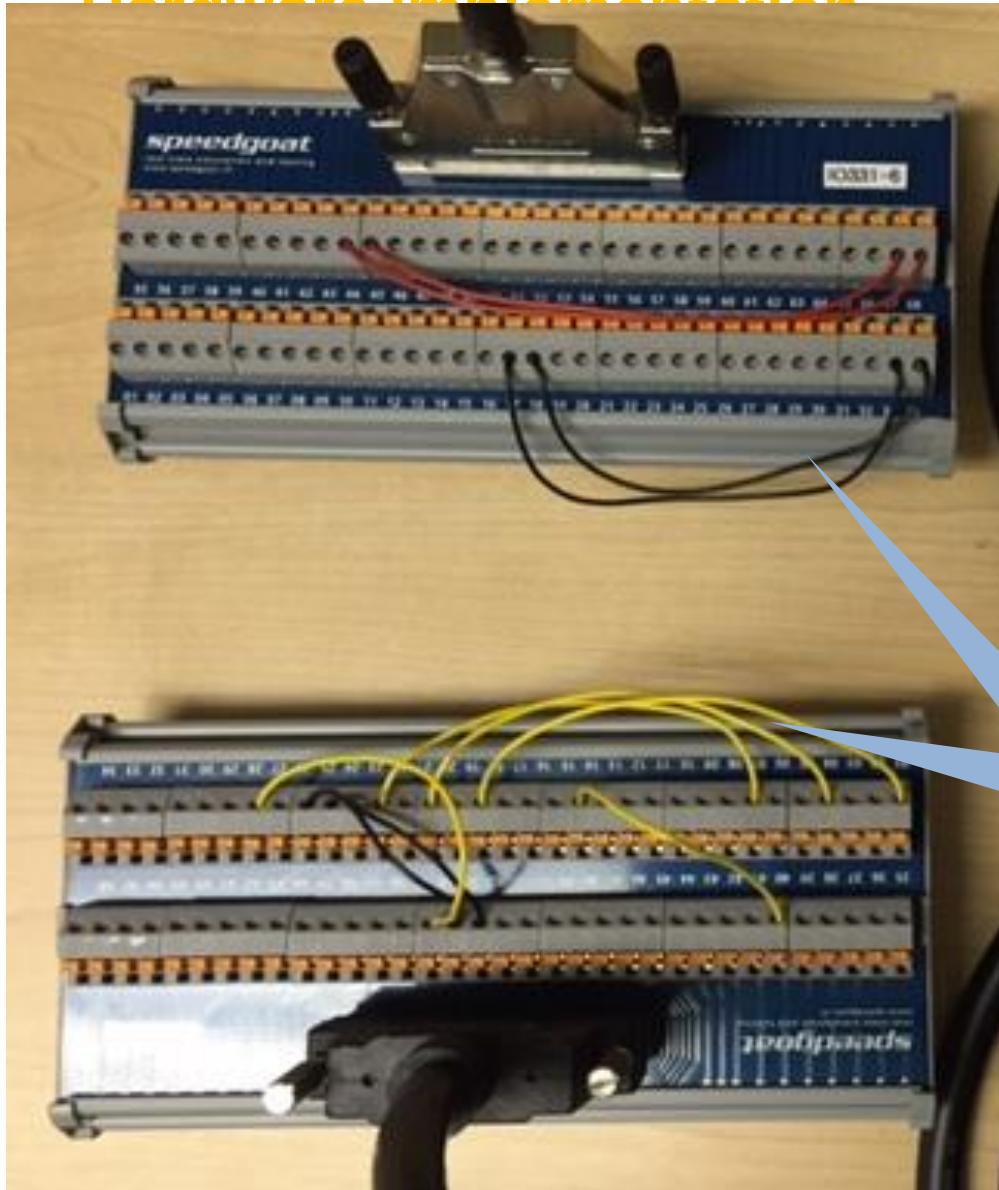


Simulink Real
Time Target
Machine

Terminal boards
with loopback
connections

I/O for Step 2: Speedgoat with Loopback

Hardware Implementation

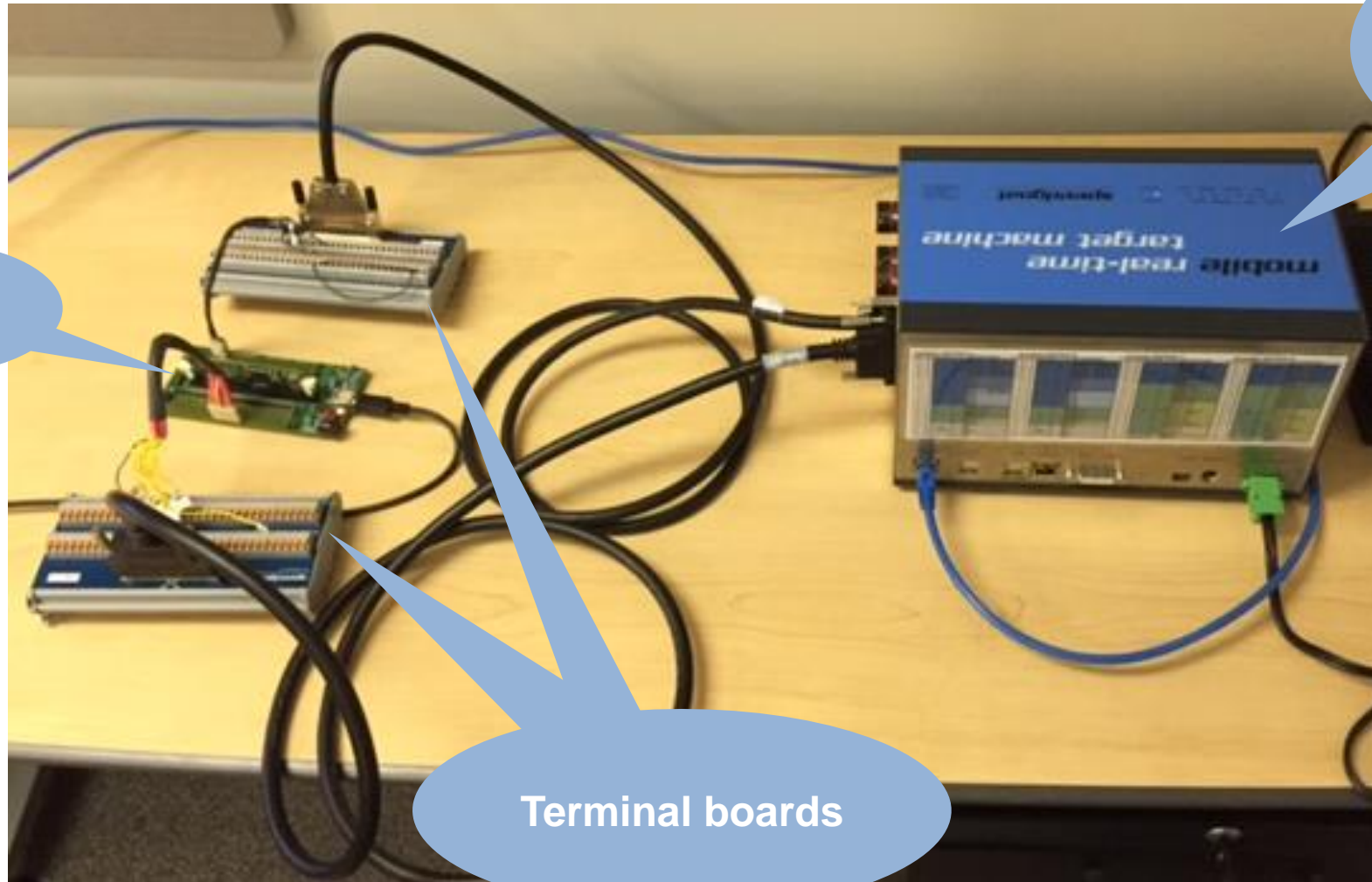


Simulink Real Time Target Machine

Terminal boards with loopback connections

I/O for Step 3: Speedgoat with C2000

- Hardware implementation



C2000

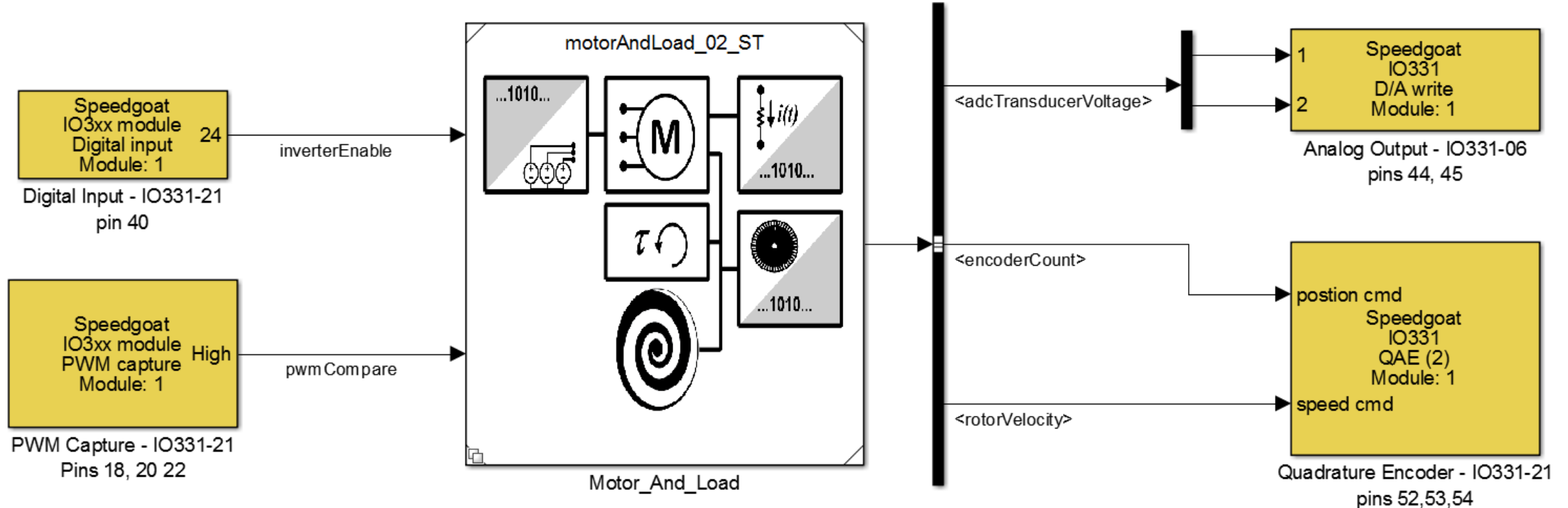
Simulink Real
Time Target
Machine

Terminal boards

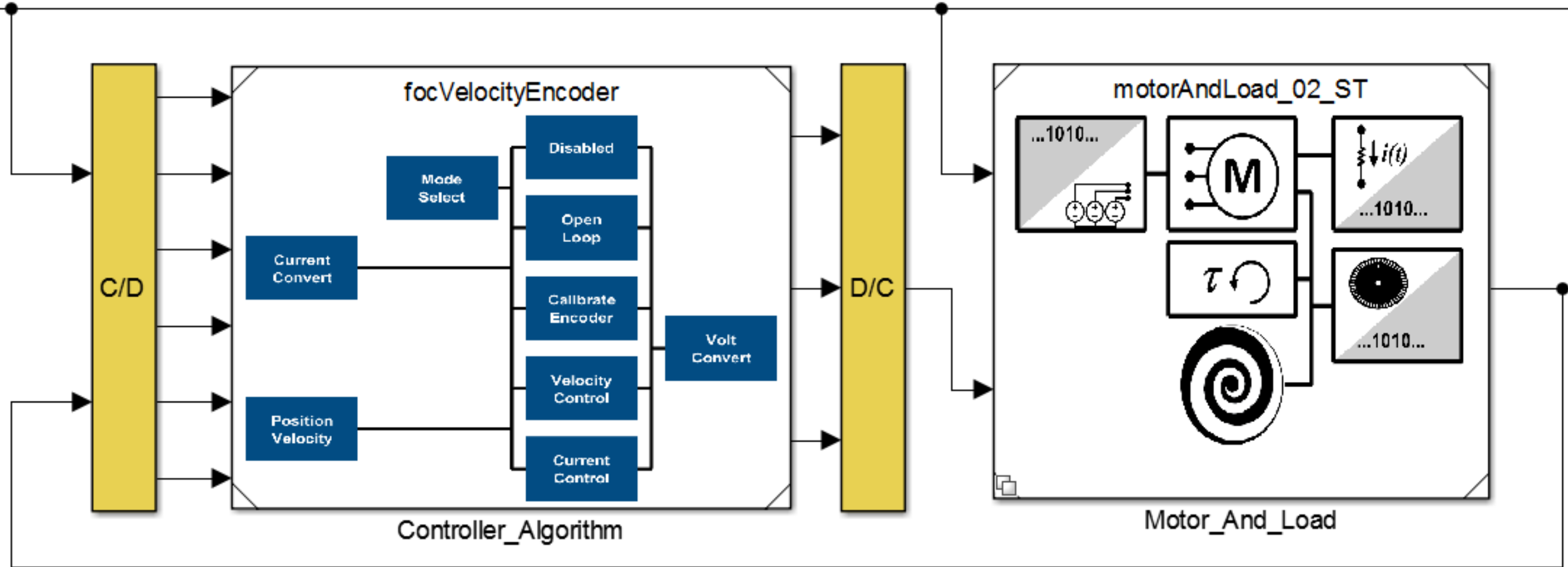
Model For Final HIL Integration

Motor and Load Test Bench

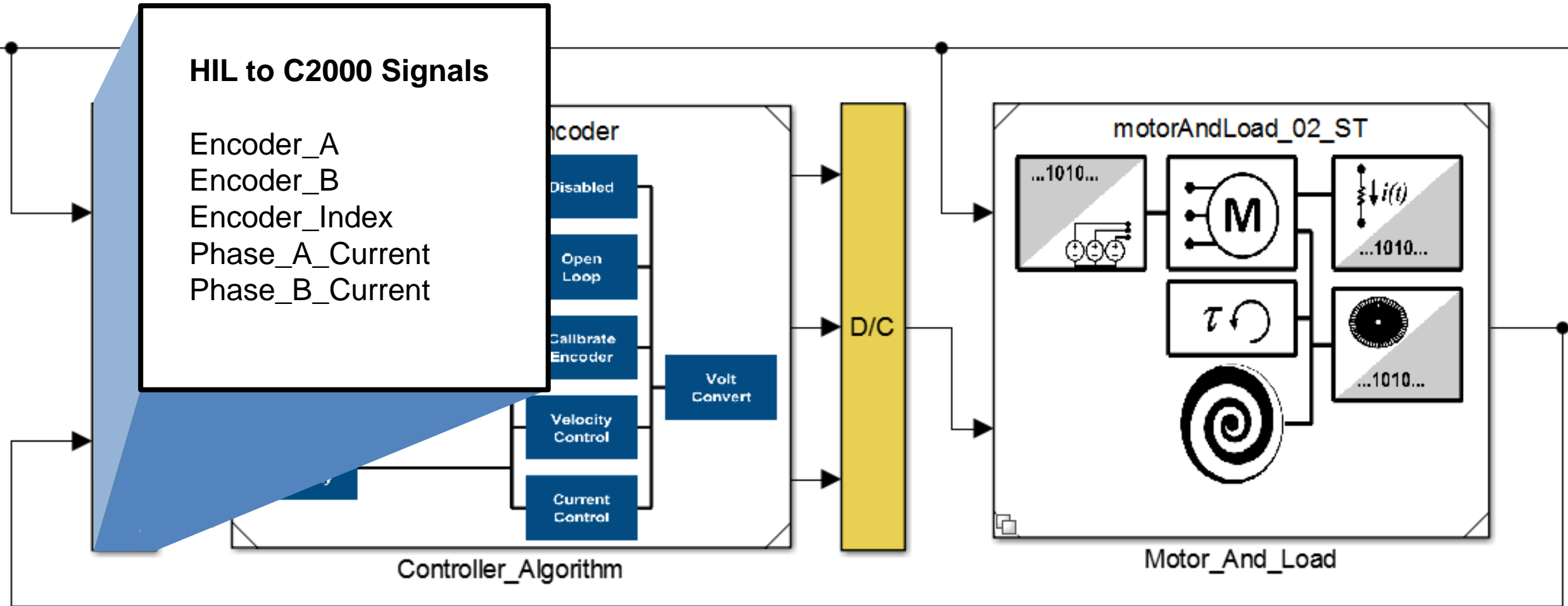
Copyright 2016 The MathWorks, Inc.



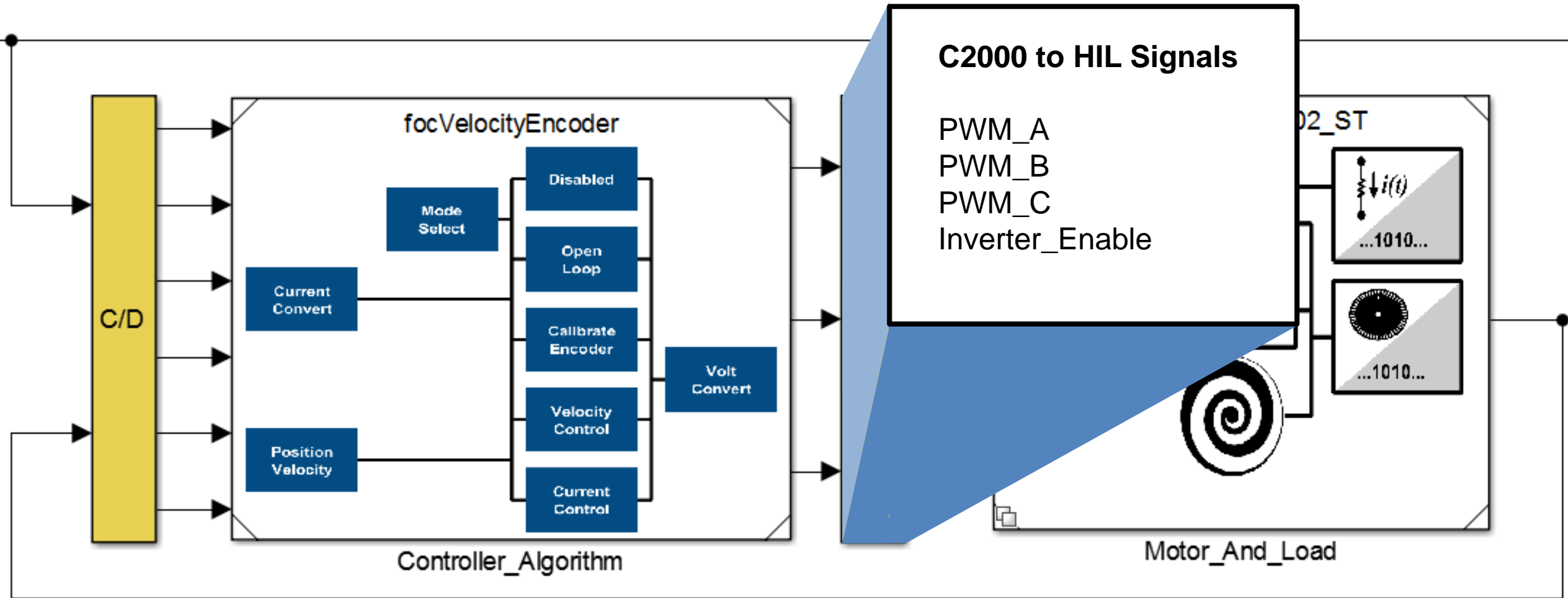
Baseline – Model and Controller on Speedgoat



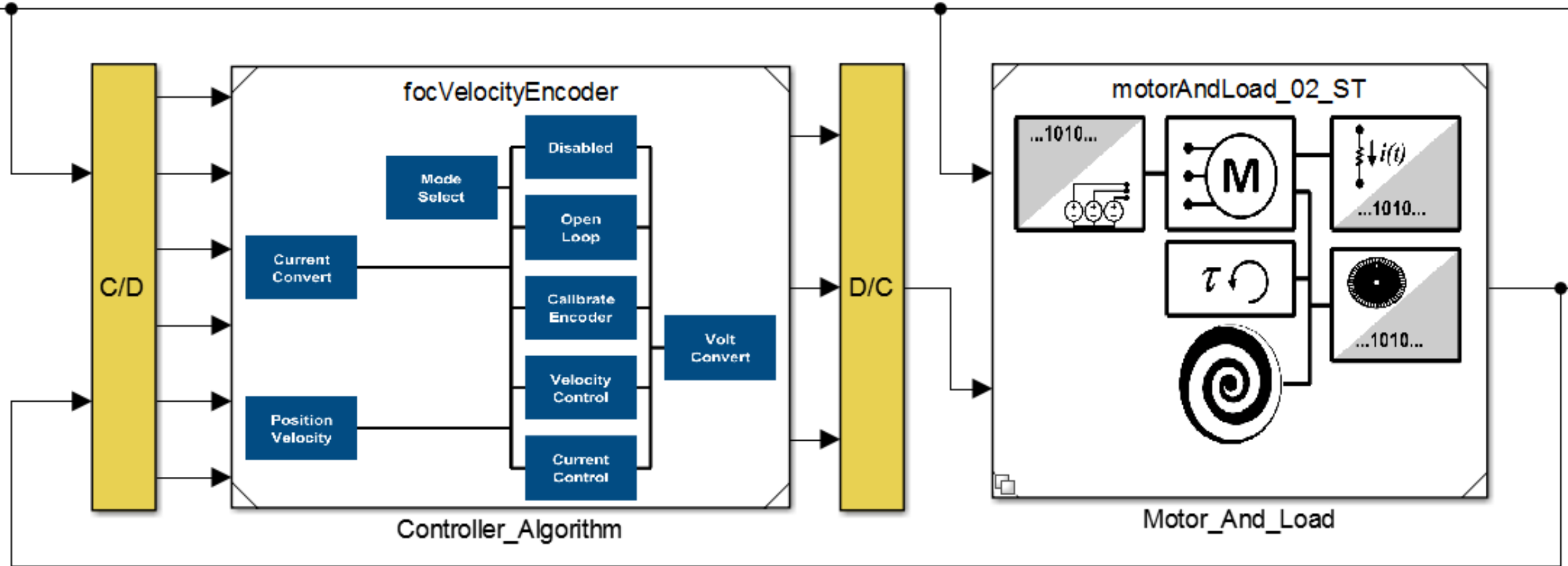
Adding I/O to Interfaces



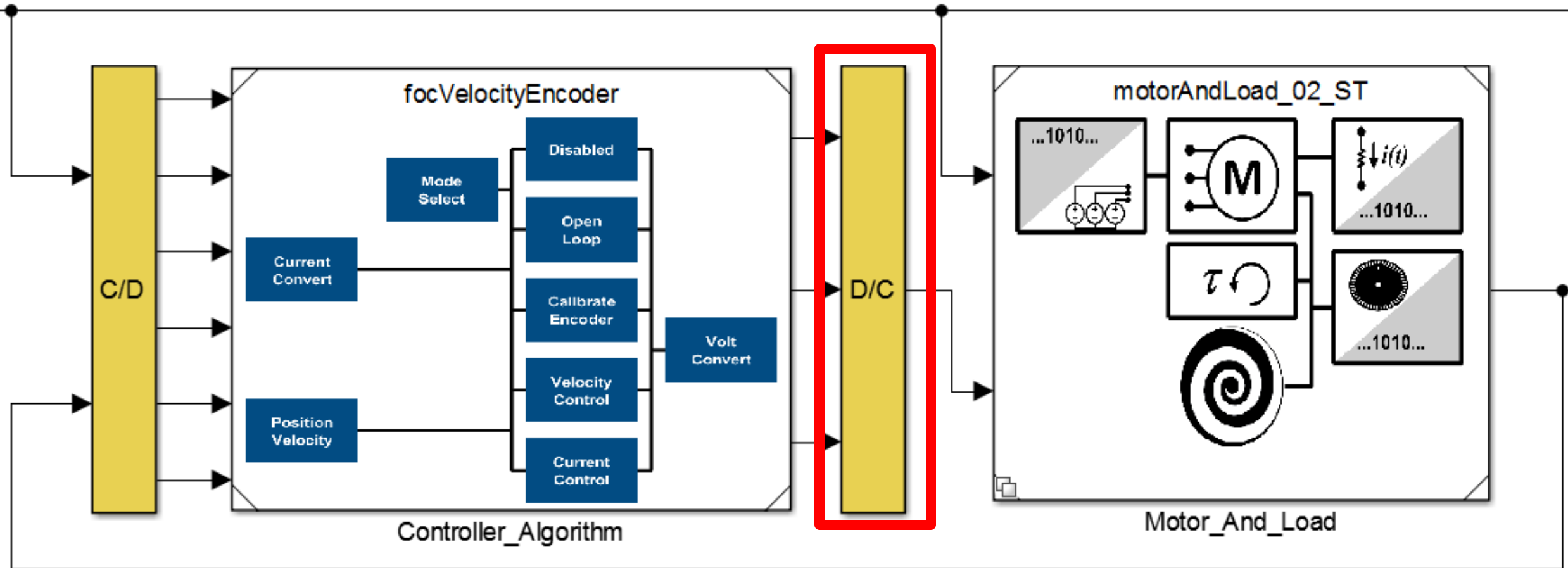
Adding I/O to Interfaces



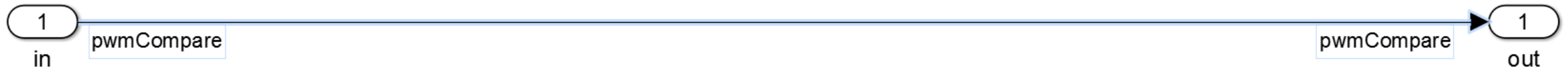
Adding I/O to Interfaces



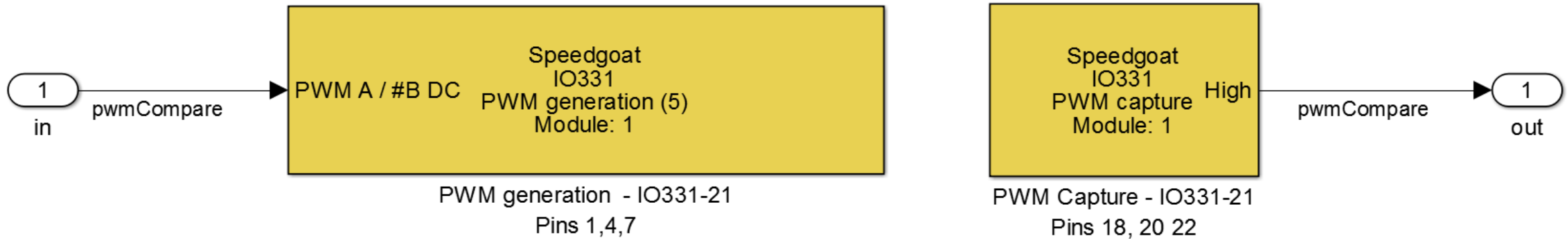
Adding I/O to Interfaces



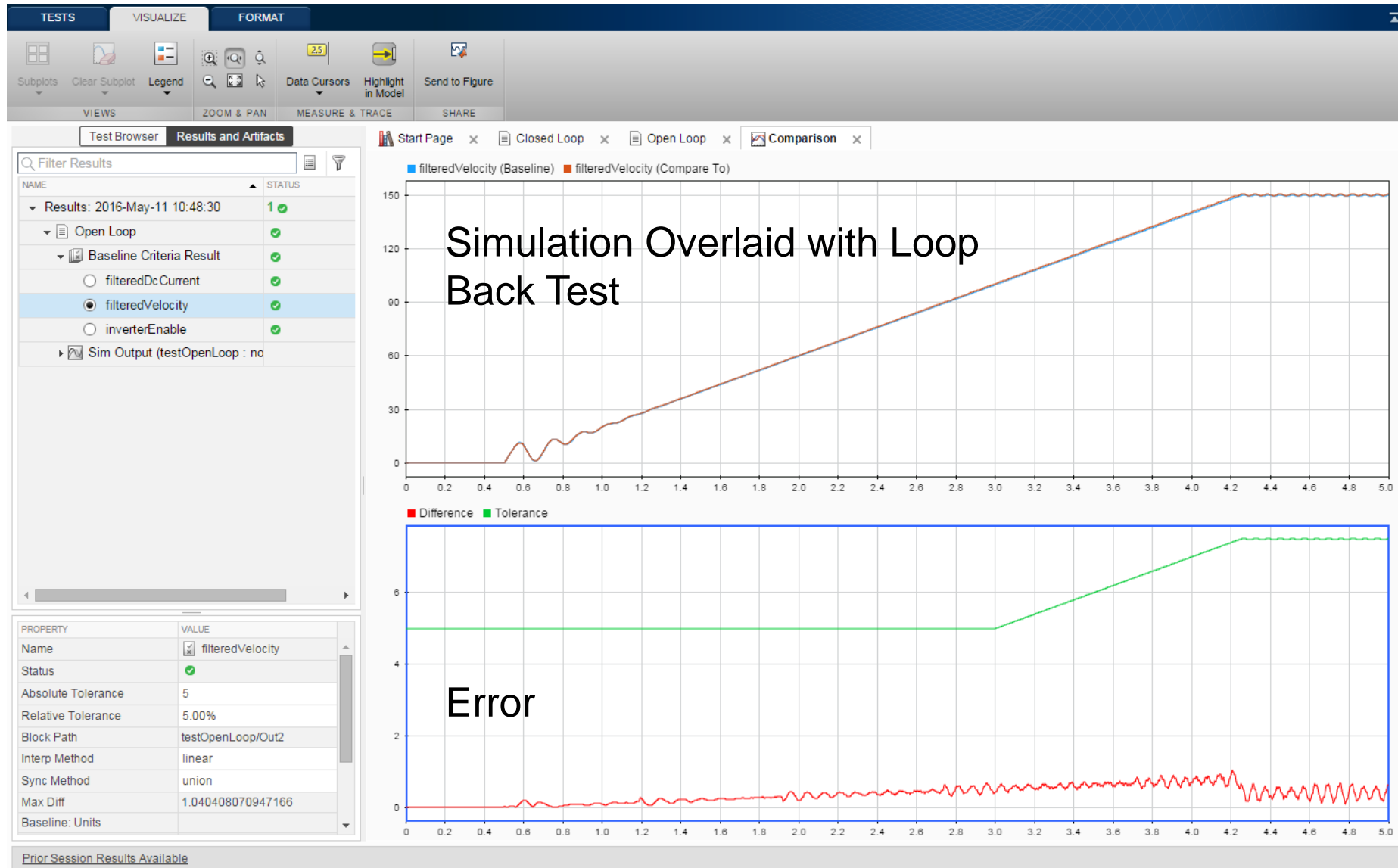
I/O for Step 1: Speedgoat Only



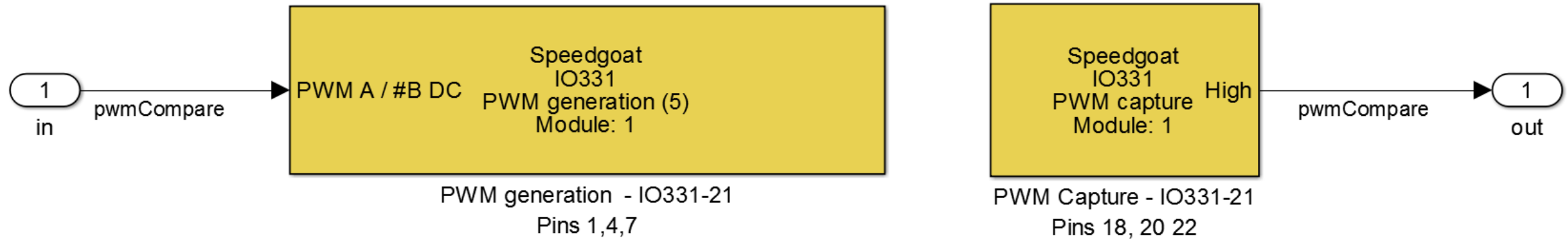
I/O for Step 2: Speedgoat with Loopback



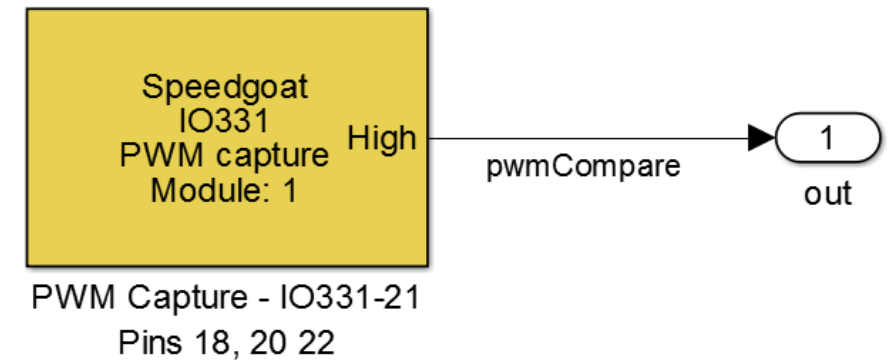
Validating Loop Back Performance with Simulink Test



I/O for Step 2: Speedgoat with Loopback



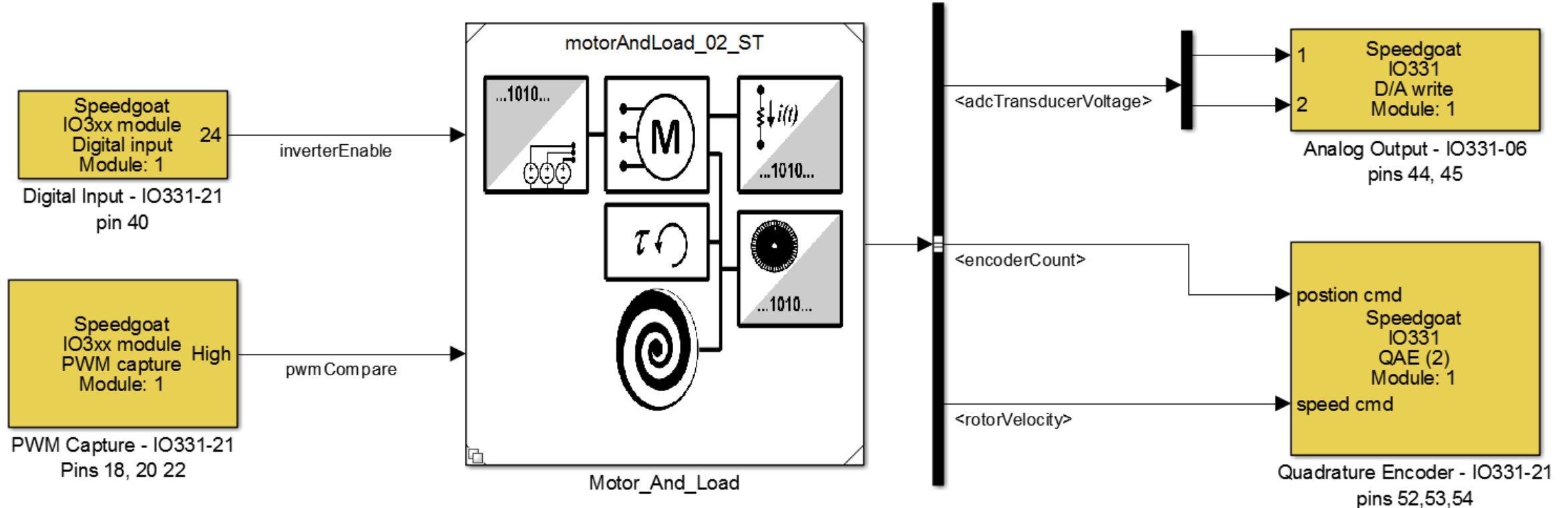
I/O for Step 3: Speedgoat with C2000



Model Ready for HIL

Motor and Load Test Bench

Copyright 2016 The MathWorks, Inc.

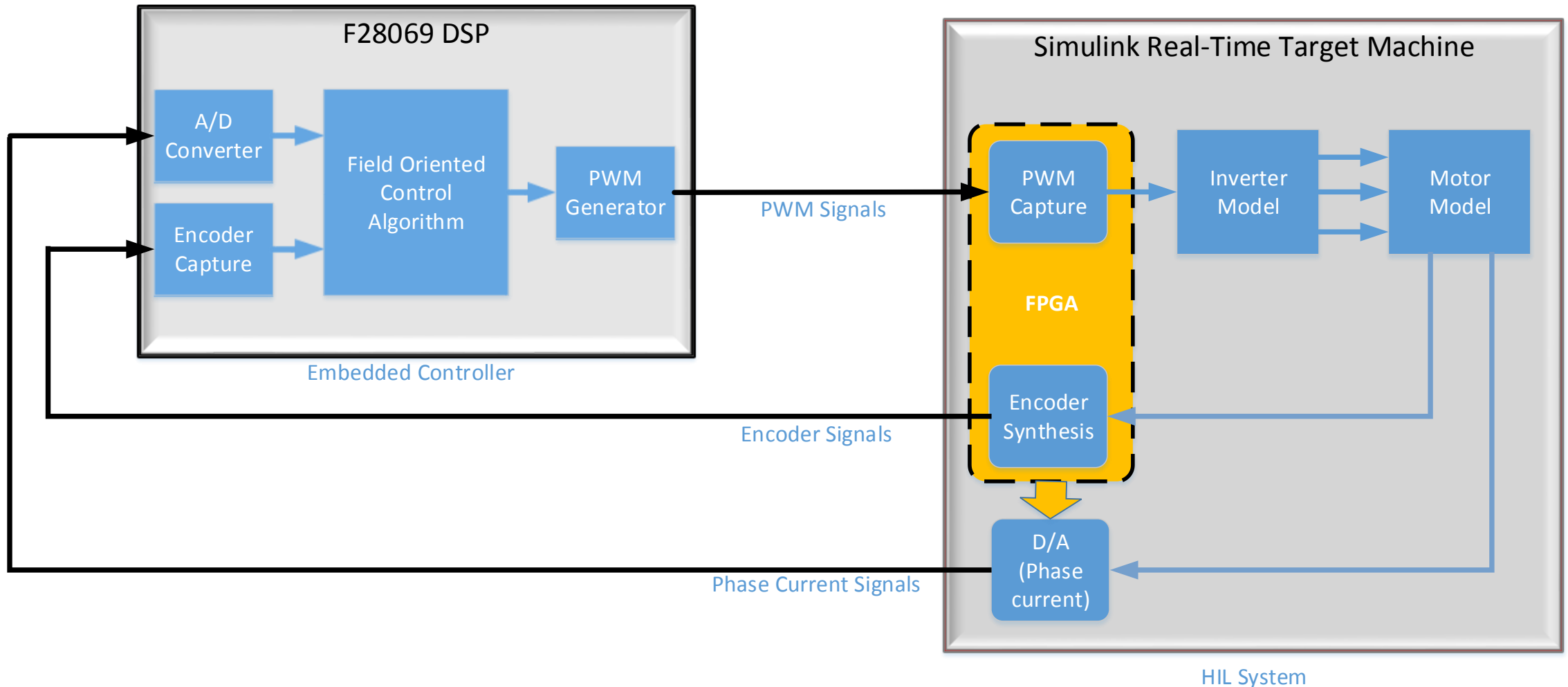


Developing a real-time motor model for HIL testing

- Modeling motor dynamics for HIL testing
- Deploying the motor model to a HIL system
- **Testing an embedded motor controller with the HIL system**
 - Connecting the embedded controller to the HIL system
 - Comparing HIL and Simulation test results

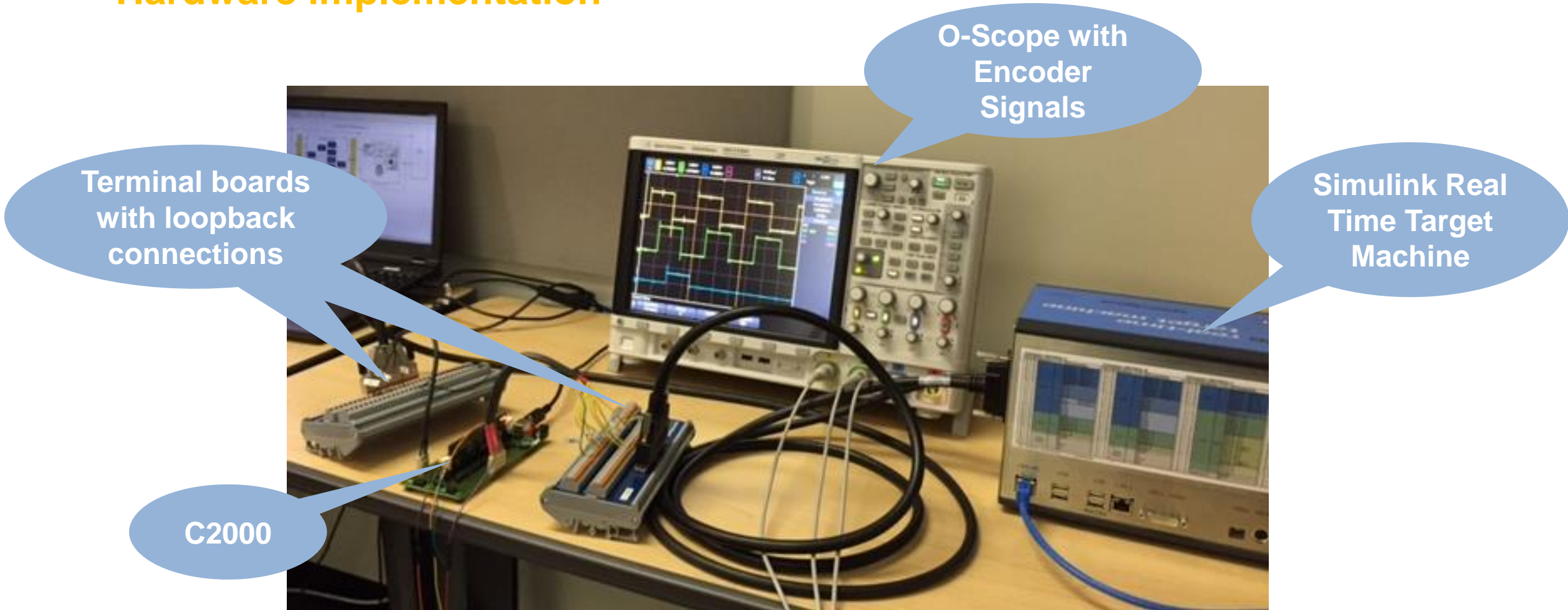
Connecting the embedded controller to the HIL system

PMSM HIL Connections Diagram

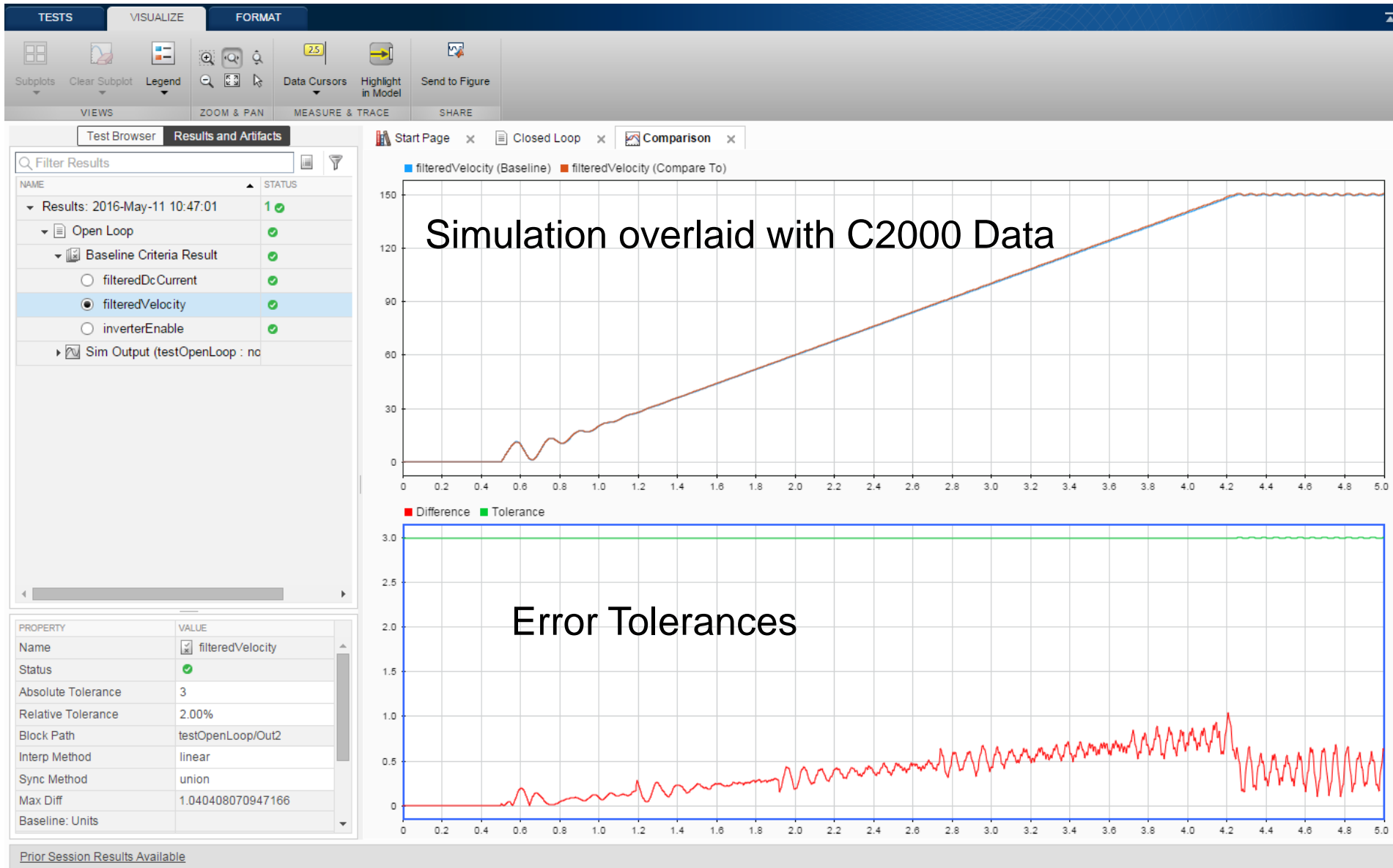


Connecting the embedded controller to the HIL system

- Hardware implementation



Testing Open Loop Performance: Velocity



Testing Closed Loop Performance: DC Current

TESTS VISUALIZE FORMAT

FILE EDIT RUN RESULTS RESOURCES

Test Browser Results and Artifacts

Filter Results

NAME	STATUS
Results: 2016-May-11 09:57:56	1 ❌
C2000	1 ❌
Closed Loop	❌
Baseline Criteria Result	❌
filteredDcCurrent	❌
filteredVelocity	✅
inverterEnable	✅
Sim Output (motorAndLoadT	

PROPERTY	VALUE
Name	filteredDcCurrent
Status	❌
Absolute Tolerance	0.1
Relative Tolerance	200.00%
Block Path	motorAndLoadTestBench...
Interp Method	linear
Sync Method	union
Max Diff	0.266841613700309
Baseline: Units	

Prior Session Results Available

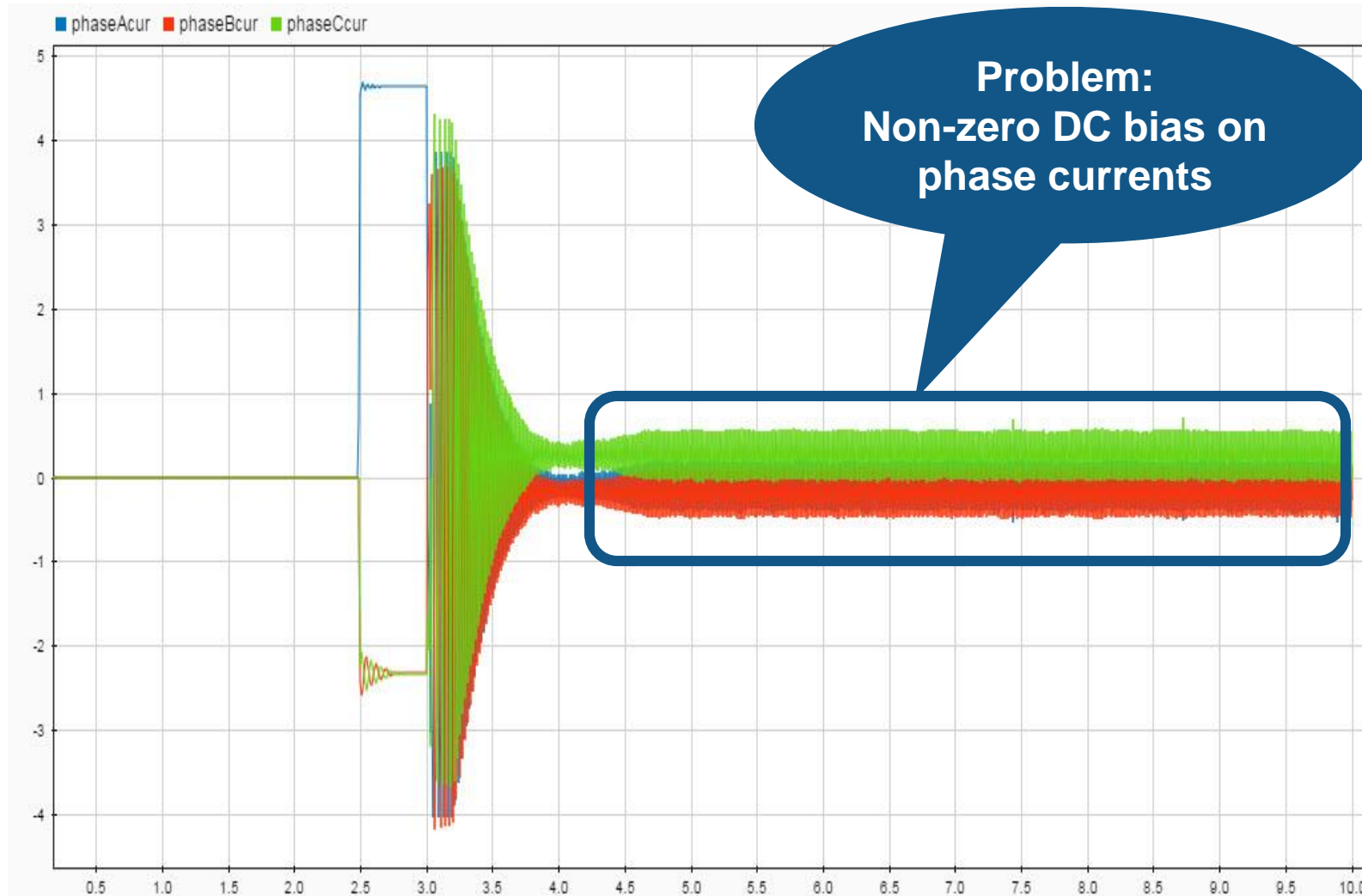
C2000 x Start Page x Comparison x

Simulation overlaid with C2000 Data

Error Tolerances

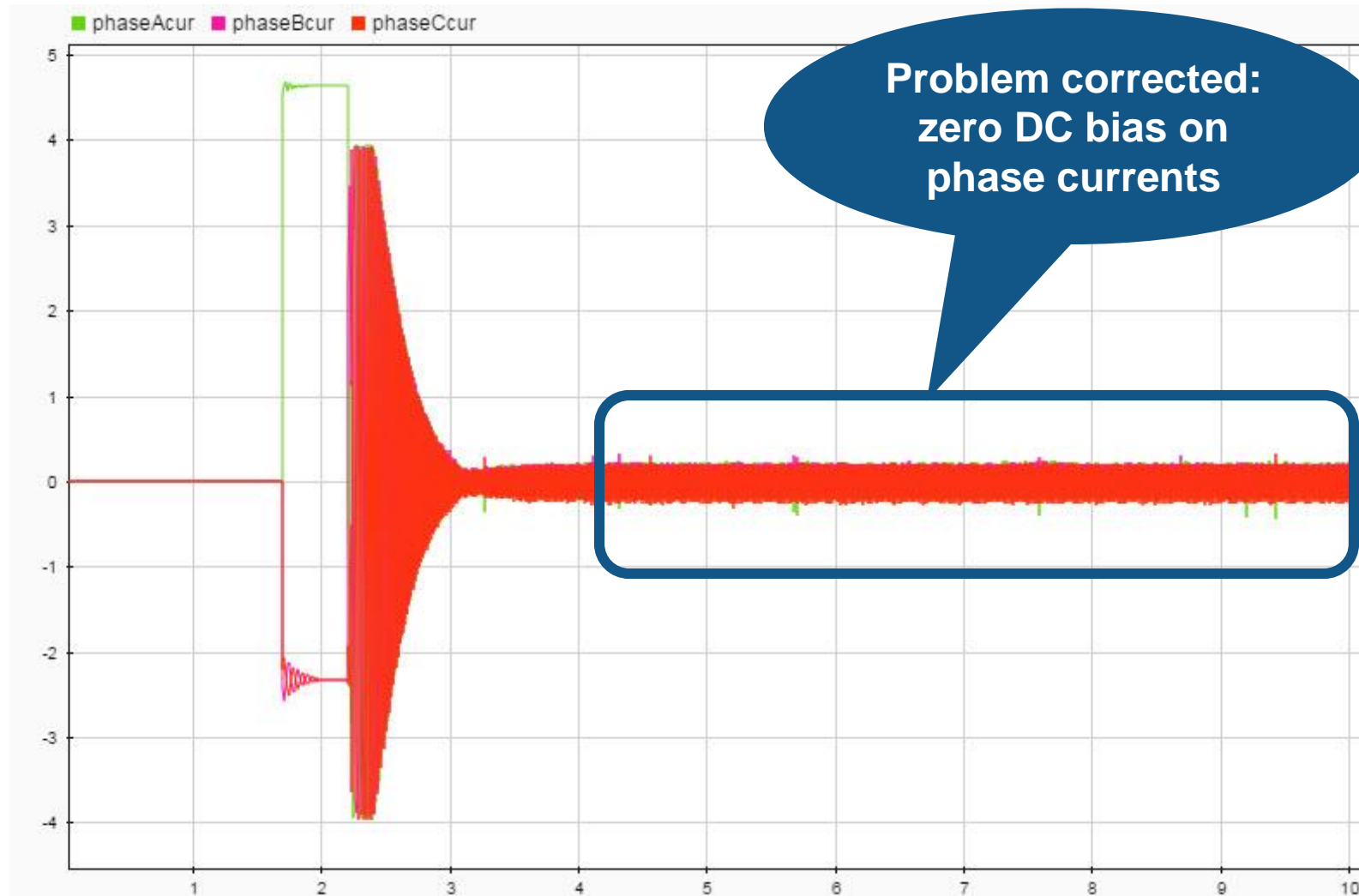
Connecting the embedded controller to the HIL system

- Troubleshooting issues

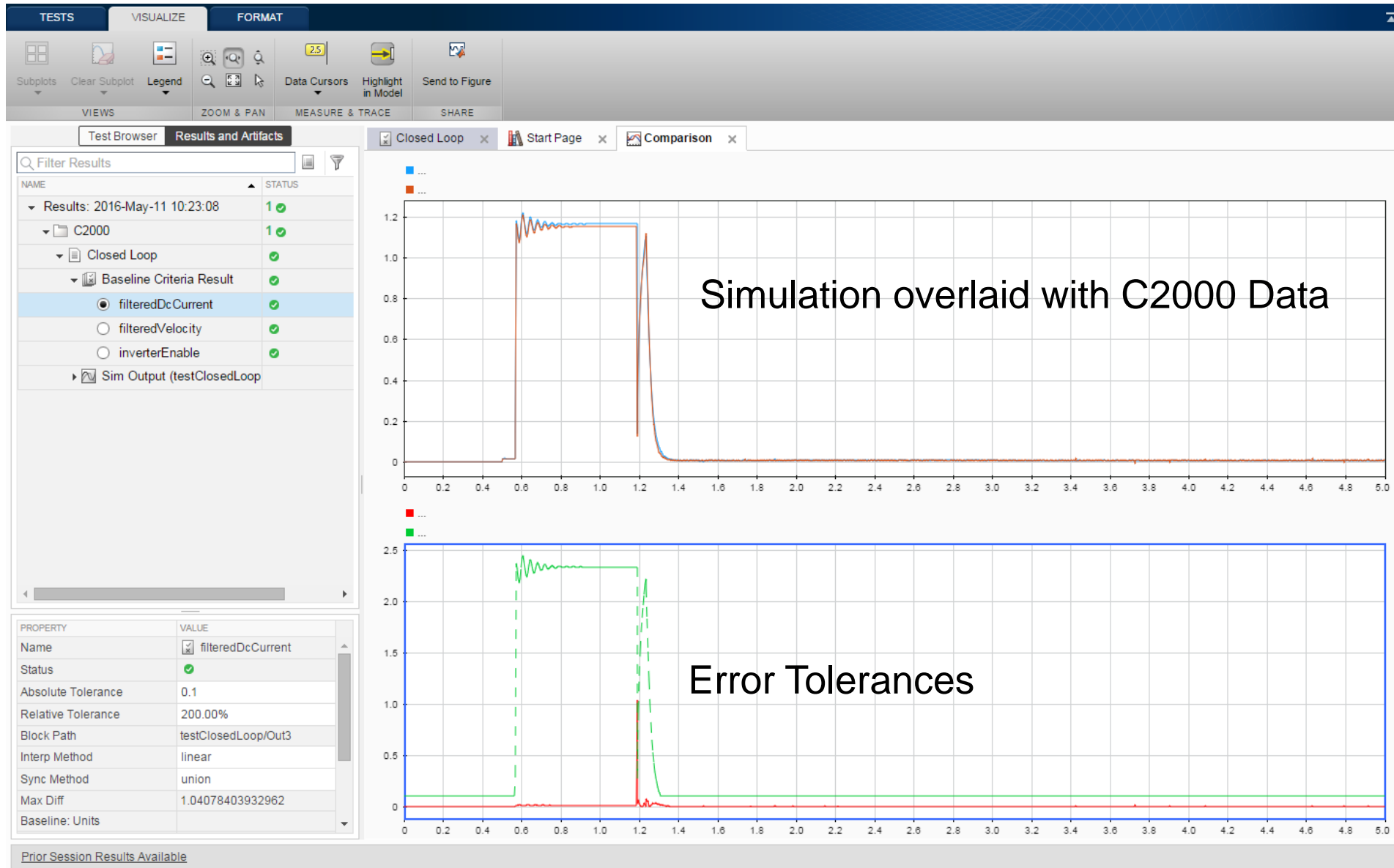


Connecting the embedded controller to the HIL system

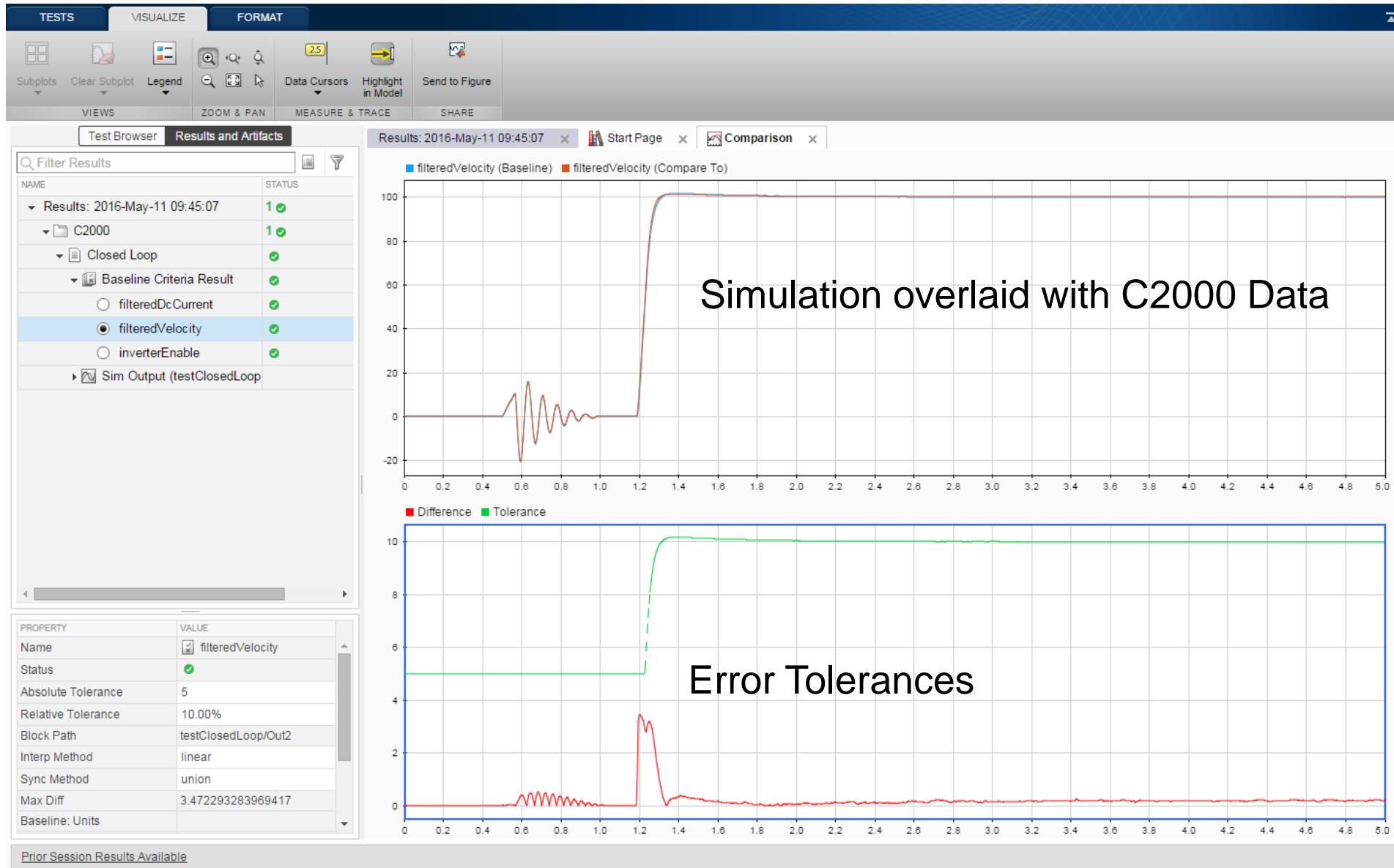
- Troubleshooting issues



Testing Closed Loop Performance: DC Current



Testing Closed Loop Performance: Velocity



Developing a real-time motor model for HIL testing

- Modeling motor dynamics for HIL testing
 - Identifying model parameters
 - Use testing framework to validate model

- Deploying the motor model to a HIL system
 - Profiling model execution on HIL system
 - Integrating model into HIL system

- Testing an embedded motor controller with the HIL system
 - Connecting the embedded controller to the HIL system
 - Comparing HIL and simulation test

