



RT Box

DEMO MODEL

H-Bridge Converter

Last updated in RT Box Target Support Package 2.1.7

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1 Overview

This RT Box demo model features a current-controlled H-bridge circuit powering an inductive load. The model is split into two distinct subsystems called “Plant” and “Controller”. The plant contains an H-bridge converter with inductive load, and the controller employs a proportional-integral (PI) current control scheme. These subsystems can then be independently built on the PLECS RT Box either for Hardware-in-the-loop (HIL) testing of an external controller or for rapid control prototyping (RCP). The following sections provide a brief description of the model and instructions on how to simulate it.

Real-time execution on the RT Box requires the model to execute using a fixed-step solver. The discretization step size parameter specifies the base sample time of the generated code and is used to discretize the physical model and control domain state-space equations.

The execution time represents the actual time it takes to execute one calculation step of the PLECS model on the RT Box hardware. The chosen discretization step sizes and average execution times for each subsystem in this demo model are shown in Fig. 1.

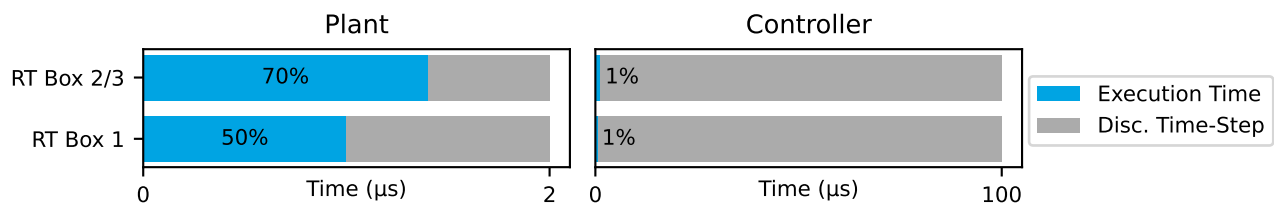


Figure 1: Performance overview for the execution on two RT Boxes

1.1 Requirements

To run this demo model, the following items are needed (available at www.plexim.com):

- Two PLECS RT Boxes and one PLECS and PLECS Coder license
- The RT Box Target Support Package
- Follow the step-by-step instructions on configuring PLECS and the RT Box in the Quick Start guide of the RT Box User Manual.
- Two 37 pin Sub-D cables to connect the boxes front-to-front.

Note that this demo model is targeted at two RT Boxes application, with one running the Plant and the other running the Controller. In this way, the execution time of each real-time target is minimized. Besides, the setup can easily transition to a HIL or RCP test later on.

However if the user has only one RT Box available, please check the corresponding models targeted for one RT Box application. In this case, two 37 pin Sub-D cables are still needed to connect in front Analog Out interface with Analog In interface, and Digital Out interface with Digital In interface.

- For RT Box 2 and 3, by default the multi-tasking feature is enabled in this demo. “Controller” part is circled with a Task frame block, and runs in one core. The rest of the circuit on the schematic belongs to the “Base task”, and runs in another core. In this way the computational effort is split onto different cores. Please check the default setting under **Scheduling** tab of the **Coder options...** window.
- For RT Box 1, single-tasking should be used which runs both the Plant and the Controller on the same one core of the RT Box 1.

Note This model contains model initialization commands that are accessible from:

PLECS Standalone: The menu **Simulation + Simulation Parameters... + Initializations**

PLECS Blockset: Right click in the **Simulink model window + Model Properties + Callbacks + InitFcn***

2 Model

The top level schematic contains two separate subsystems representing the controller and plant models, as shown in Fig. 2. Both subsystems are enabled for code generation from the **Edit + Subsystem + Execution settings...** menu. This step is necessary to generate the model code for the RT Box.

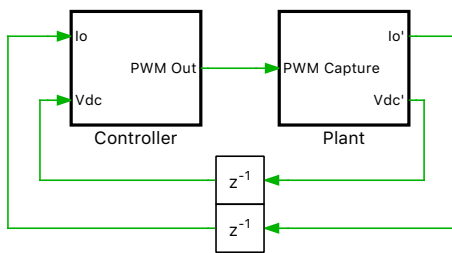


Figure 2: Top level schematic of the plant and the controller subsystems

2.1 Power Circuit

The power circuit, shown in Fig. 3, is supplied by a DC source voltage of $V_{dc} = 24\text{ V}$. The H-bridge is composed of two IGBT Half Bridge power module components, powering an inductive load. The pulse-width modulated (PWM) switching signals are obtained from the PWM Capture block of the PLECS RT Box library. The modeling of the power module components and the sub-cycle averaged handling are described in the work of [1]. The measurements of DC input voltage and output inductor current are sensed and exported out of the subsystem via Analog Out blocks from the PLECS RT Box library. The discretization step size of the plant subsystem is set to $2\text{ }\mu\text{s}$.

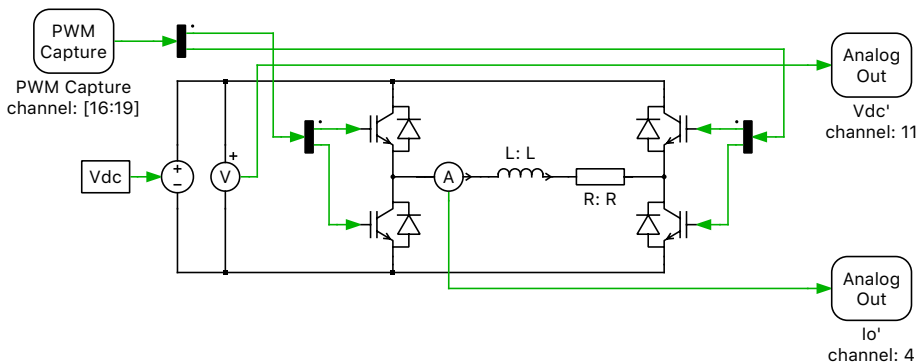


Figure 3: Power circuit of the H-Bridge with inductive load

Scaling Analog Outputs

The limits on Analog input and output voltage ranges of the of the PLECS RT Box target can be set in between -10 V to 10 V from the **Target** tab of the **Coder options...** window.

However, in a typical HIL simulation, since the Analog Out values exported out of the RT Box are fed to an embedded controller, these values are scaled and offset to be within 0 V to 3.3 V , to satisfy voltage requirements of of the MCU analog-to-digital converters (ADCs).

The plant model is based on a hardware prototype of the power circuit, comprising two phases of a BOOSTXL-DRV8305EVM BoosterPack [2] connected to an external RL load. Therefore the input voltage and the shunt currents are scaled according to the voltage and current sense circuits of the BoosterPack.

Voltage Sensing

A similar voltage sensing circuit as described in [2] is shown in Figure 4.

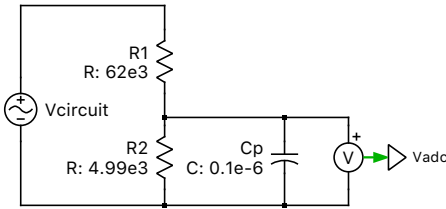


Figure 4: Schematic of a voltage sensing circuit

The equations below show the response of the voltage sensing circuit. A capacitor, C_p can be selected to create a pole in the sensing circuit to attenuate the switching frequency ripple on the sensed voltage. The pole frequency is denoted as f_p below.

$$\frac{V_{\text{adc}}}{V_{\text{circuit}}} = \frac{R_2}{(R_1 + R_2) + sR_1R_2C_p}, \quad C_p = \frac{R_1 + R_2}{2\pi f_p R_1 R_2}$$

The voltages are scaled with a gain of,

$$V_{m.K} = \frac{R_2}{R_1 + R_2} = \frac{4990}{62000 + 4990}$$

Current Sensing

As described in [2], the currents are sensed and amplified with a scaling factor of $I_m \cdot K$ and offset with offset factor of $I_m \cdot O$ using a current shunt amplifier.

$$I_{m.K} = 0.007 * 10$$

$$I_{m.O} = \frac{3.3}{2}$$

2.2 Controls

The controller subsystem, shown in Fig. 5, receives the sensed inductor current and the DC input voltage values in the Analog In blocks of the PLECS RT Box component library. These values are inversely scaled to reverse the scaling applied at the Analog Out blocks of the “Plant” subsystem.

The “Right Leg Duty-Cycle” subsystem determines the duty cycle required to maintain an average of 12 V at the right leg H-bridge output while accounting for variations in the sensed input voltage, V_{dc} .

The “Left Leg Duty-Cycle” subsystem determines the modulation index of left leg of the H-bridge based on a proportional-integral (PI) controller. The sensed inductor current is compared to a setpoint

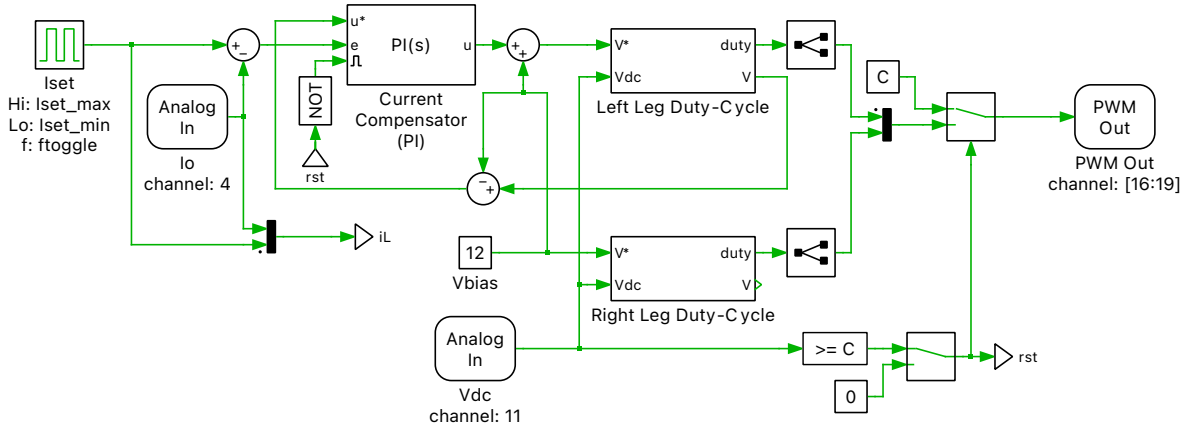


Figure 5: Controller of the H-Bridge circuit

that is toggled between -3 A and 3 A . This error is used for current compensation by the digital PI controller, which is equipped with anti-windup logic.

A few of the concepts described in this Section 2.2, related to the controller development, are based on reference [3].

Plant transfer function

To set the PI controller gain parameters a plant transfer function $P(s)$ is needed. $P(s)$ relates the change of the voltage across the inductor (L) and resistor (R), V_{RL} (the input variable), to the response of the inductor current I_L (the output variable):

$$P(s) = \frac{I_L}{V_{RL}} = \frac{1/R}{1 + sL/R} = \frac{K_1}{1 + sT_1}, \quad \text{where } K_1 := 1/R \text{ and } T_1 := L/R$$

Time constants

For reducing the order of complex systems, it is often useful to distinguish between dominant time constants and small time constants. Typically, the dominant time constants are a part of the plant transfer function, while the control system introduces several small time constants (e.g. sensors, actuators, sampling, calculation delays, fast inner control loops).

If the largest small time-constant is at least 4 times smaller than the smallest dominant time constant, i.e.,

$$\min(T_{\text{dominant}}) \geq 4 \cdot \max(T_{\text{small}})$$

then it is possible to make an important simplification for modeling of the system, which is to define one equivalent small time constant which is the sum of all small time constants in the system.

If the controller sampling frequency ($1/T_s$) is same as the switching frequency ($1/T_{sw}$), the small time constants present in the H-bridge converter model for this specific implementation are:

- small time constant for control calculation, T_{calc} , is $\frac{1}{2} T_{sw}$
- small time constant for PWM output generation, T_{pwm} , is $\frac{1}{2} T_{sw}$
- small time constant for conversion of continuous parameters to discrete, T_{sh} , is $\frac{1}{2} T_{sw}$ (explained in the section below)

The equivalent small time constant, T_{Σ} , is

$$T_{\Sigma} = T_{\text{calc}} + T_{\text{pwm}} + T_{sh}$$

$$D_{\Sigma}(s) = \frac{1}{1 + sT_{\Sigma}}$$

Calculation of control parameters

The control parameters of the PI controller (K_p and K_i) are calculated using the Magnitude Optimum Criterion. The system's open-loop transfer function $H_{OL}(s)$ is given by the product of transfer functions from the controller, plant and time delays:

$$H_{OL}(s) = \frac{1 + sT_n}{sT_i} \cdot \frac{K_1}{1 + sT_1} \cdot \frac{1}{1 + sT_\Sigma}, \quad \text{where } K_p = \frac{T_n}{T_i} \text{ and } K_i = \frac{1}{T_i}$$

The controller parameter T_n is chosen, such that the pole of the plant transfer function is canceled, i.e. $T_n = T_1$. After pole-zero cancellation, the closed-loop transfer function is a second order system. The remaining parameter T_i is calculated from setting the damping factor (ζ) of the second order system to $1/\sqrt{2} = \zeta$, resulting in $T_i = 2K_1T_\Sigma$.

The outputs from the “Right Leg Duty-Cycle” and the “Left Leg Duty-Cycle” subsystems are fed to the PWM Out block from the PLECS RT Box component library. The switching frequency is 10 kHz.

3 Simulation

This model can run both, in offline mode on a computer or in real-time mode on the PLECS RT Box. For the real-time operation, two RT Boxes (referred to as “Plant” and “Controller”) need to be set up as demonstrated in Fig. 6. Please follow the instructions below to run a real-time model on two RT Boxes:

- Connect the Analog Out interface of the “Plant” RT Box to the Analog In interface of the “Controller” RT Box, and the Digital In interface of the “Plant” RT Box to the Digital Out interface of the “Controller” RT Box (e.g. using two DB37 cables shown in Fig. 6).
- From the **System** tab of the **Coder options...** window, select the “Plant” and **Build** it onto the “Plant” RT Box. Then, select “Controller” and **Build** it onto the “Controller” RT Box.
- Once the models are uploaded, from the **External Mode** tab of the **Coder options...** window, **Connect** to both RT Boxes and **Activate autotriggering**.

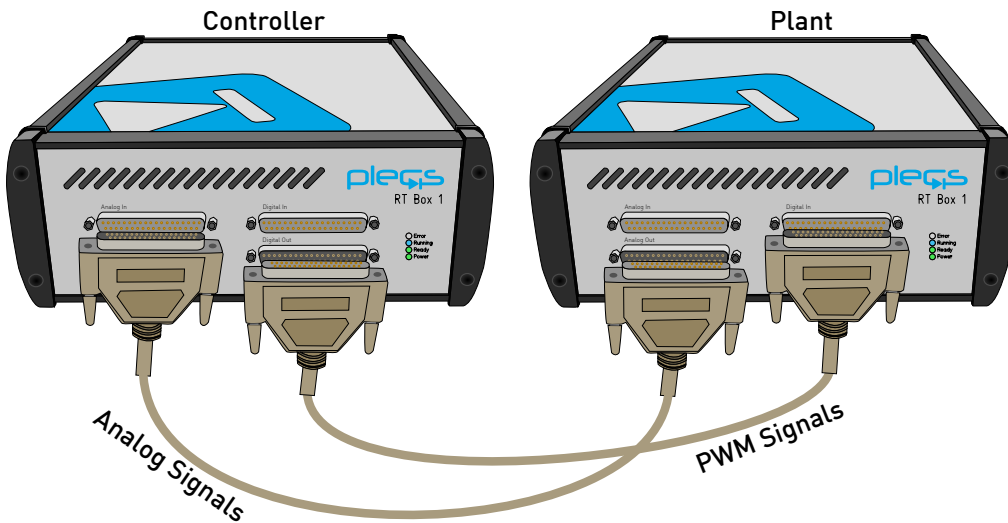
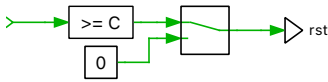


Figure 6: Hardware configuration for the real-time operation with two RT Boxes

Note A reset option is added to the controller. As shown below, the Manual Signal Switch in the “Controller” subsystem in its default Up position enables switching. Change it to the Down position resets the integral part of the PI controller to its initial condition and disables switching on the H-Bridge.



The inductor current measurements can be viewed using the scope found in the “Plant” subsystem as well as the scope in the “Controller” subsystem. The inductor current reference is toggled between -3 A and 3 A using the “Iset” (Pulse Generator) component of the “Controller” subsystem. These reference values can be changed on the fly, in real-time, since the “Iset” component has been added to the “Exceptions” list found in the **Parameter Inlining** tab of the **Coder options...** window, prior to building the model.

The step response of the inductor current in real-time is shown in Fig. 7.

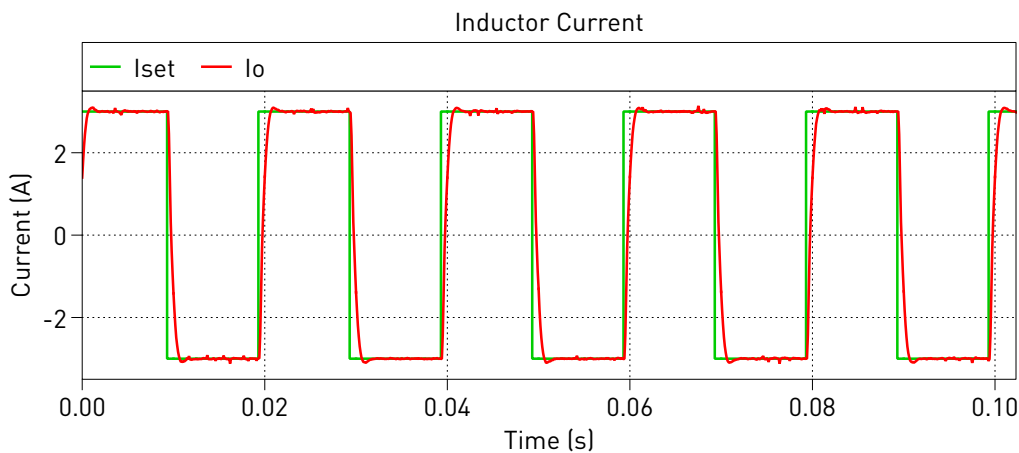


Figure 7: Step response of the inductor current in real-time

A trigger control for a desired **Trigger channel** can be set from the **External Mode** tab.

4 Conclusion

This model demonstrates an H-bridge converter with a discrete current controller that can be run in both offline mode, as well as in real-time. The model also demonstrates the **Parameter Inlining** feature using a current controller reference that can be changed in real-time.

References

- [1] J. Allmeling, and N. Felderer, “Sub cycle average models with integrated diodes for real-time simulation of power converters,” *IEEE Southern Power Electronics Conference (SPEC)*, 2017.
- [2] TI DRV8305N 3-Phase Motor Drive BoosterPack Evaluation Module
URL: <http://www.ti.com/tool/BOOSTXL-DRV8305EVM>.
- [3] Conception de systèmes automatiques, Hansruedi Bühler, Presses Polytechniques Romandes, Lausanne 1988, ISBN 2-88074-149-1

Revision History:

RT Box Target Support Package 1.8.3	First release
RT Box Target Support Package 2.1.5	Turn on Assertions in IGBT Half Bridges and add deadtime in the PWM Out block
RT Box Target Support Package 2.1.7	Modify the controller subsystem and add the enable/disable switching scheme

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