

RT Box

*DEMO MODEL*

## Boost Converter

Last updated in RT Box Target Support Package 1.8.3

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# 1 Overview

This RT Box demo model features a boost converter with a resistive load and closed-loop current control. The nominal operating condition is given at

- 52 kW power,
- 480 V input voltage and
- 108 A inductor current reference.

This document describes the implementation of the power stage and controls in PLECS and the real-time deployment of the system on two RT Boxes. For such a “virtual prototyping” configuration the two RT Boxes are connected front-to-front with two 37 pin Sub-D cables to exchange digital PWM signals and analog current measurements.

The chosen discretization step sizes and average execution times for each subsystem in the Boost converter model are shown in Tab. 1. The discretization step size parameter specifies the base sample time of the generated code and is used to discretize the state-space equations of the plant and control model. The execution time represents the actual time it takes the processor on the RT Box to calculate the plant or control model.

**Table 1: Discretization step size and average execution time of real-time models with two RT Box 1**

| Subsystem  | Discretization Step Size                              | Average Execution Time |
|------------|---|------------------------|
| Plant      | $2 \mu\text{s}$                                       | $0.9 \mu\text{s}$      |
| Controller | $50 \mu\text{s}$ ( $f_{\text{sw}} = 20 \text{ kHz}$ ) | $0.5 \mu\text{s}$      |

## 1.1 Requirements

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

- Two PLECS RT Boxes and one PLECS and PLECS Coder license
- The RT Box Target Support Library
- 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, multi-tasking is disabled since there is only one CPU core available for calculating the model, which includes both Plant and the Controller.

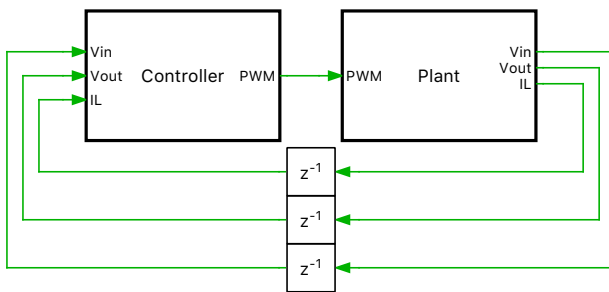
**Note** This model contains model initialization commands that are accessible from:

*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. 1. 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. Additional delays in the feedback path are also modeled.



**Figure 1: Top level schematic of the controller and boost converter model**

### 2.1 Boost Converter

A boost converter is also known as a “step-up” converter since it converts an input DC voltage to a higher DC voltage at its output. It requires at least two semiconductor switches; in this demo model a diode and an IGBT are used. The inductor represents an energy storage element with a parasitic series resistance  $R_L$ . At the output a capacitor is used as a filtering component to stabilize the load voltage. An overview of the boost converter is given in Fig. 2.

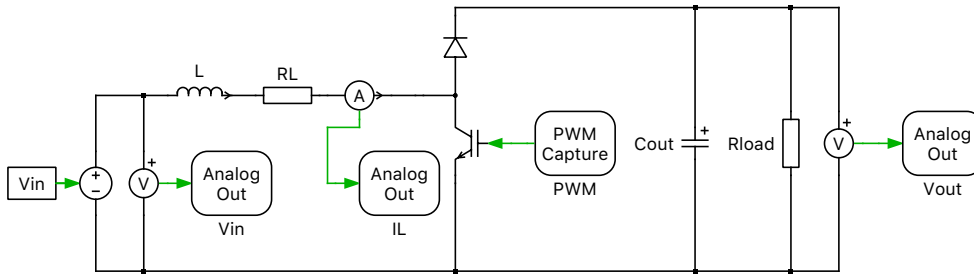
The plant model uses different blocks from the RT Box 1 Target Support Library to access the physical input and output ports of the RT Box 1:

- The PWM Capture block samples incoming switching signals every 7.5 ns. The sampled switching signals are time-averaged over each model step for high-fidelity resolution of the PWM inputs. To utilize the time-averaged PWM input in the simulation a Low-Side Switch IGBT Chopper power module is used with the “sub-cycle average” configuration selected [1].
- Analog Out blocks provide the analog signals required by the controller subsystem such as inductor current, input voltage, and output voltage. The Analog Out component contains scale and offset parameters that can be set to avoid saturating the analog outputs of the RT Box and to match IO requirements of the connected hardware or controller. Appropriate scaling factors can be determined with an offline simulation in PLECS. In the case of the inductor current, a closed-loop offline simulation reveals a maximum current value of 110 A. Along with an analog output voltage range configuration of  $\pm 5$  V, as specified by the user in the **Target** tab of the **Coder Options** window, the Analog Out scaling factor,  $I_{L, \text{scale}}$ , has been set to:

$$I_{L, \text{scale}} = 4 \text{ V} / I_{L, \text{max}} \approx 0.0364$$

The scaling factors for the other analog in- and output channels are calculated accordingly.

Note that in this virtual prototyping setup it does not matter which IO channels are configured, but the channel IDs must match between the “Controller” and “Plant” subsystems.



**Figure 2: Boost converter plant model**

## Design

For a boost converter in CCM and with given input and output voltages  $V_{in}$  and  $V_{out}$ , the required duty-cycle  $D$  can be calculated as follows:

$$D = 1 - \frac{V_{in}}{V_{out}} \quad (1)$$

The sizing of the input inductor  $L$  and output capacitor  $C$  are determined using the specifications of current and voltage ripple ( $\Delta I_{in,pp}$  and  $\Delta V_{out,pp}$ ) in Tab. 2.

**Table 2: Parameters set and design requirements**

| $V_{in}$    | $V_{out,nom}$ | $\Delta V_{out,pp}$ | $\Delta I_{in,pp}$ | $P_{nom}$ | $R_L$         | $f_{sw}$ |
|-------------|---------------|---------------------|--------------------|-----------|---------------|----------|
| 480 – 800 V | 950 V         | 10 V                | 5 A                | 52 kW     | 15 m $\Omega$ | 20 kHz   |

The current increases during the first part of the switching period  $t_0 \leq t \leq t_0 + DT$ , when  $V_{in}$  is applied over the inductance  $L$ . Using the state equation of the inductor and neglecting the inductor series resistance, one finds that:

$$\frac{dI_L}{dt} = \frac{\Delta I_{in,pp}}{DT_{sw}} = \frac{V_{in}}{L} \Rightarrow L = \frac{V_{in} \cdot D}{\Delta I_{in,pp} \cdot f_{sw}}$$

The required inductance  $L$  is then found at the nominal output voltage and minimum input voltage:

$$L = \frac{V_{in} \cdot \left(1 - \frac{V_{in}}{V_{out}}\right)}{\Delta I_{in,pp} \cdot f_{sw}} = 2.375 \text{ mH}$$

At nominal power, the load current and resistance values are:

$$I_{load} = \frac{P_{nom}}{V_{out}} = 54.7 \text{ A}$$

$$R_{load} = \frac{V_{out}}{I_{load}} = 17.4 \Omega$$

The value of the output capacitor  $C$  is calculated in a similar fashion to the inductor  $L$ :

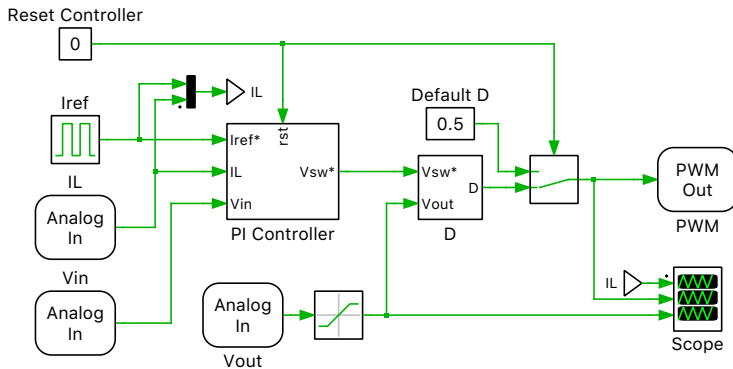
$$C = \frac{I_{load} \cdot D}{\Delta V_{out,pp} \cdot f_{sw}} = 135.4 \mu\text{F}$$

## 2.2 Current Controller

The inductor current of the boost converter is regulated by a PI controller implemented in the “Controller” subsystem, as shown in Fig 3. The current reference set point will toggle between the minimum and maximum reference values at 50 Hz. The parameters of the PI controller are calculated using the plant transfer function  $P(s)$  and the Magnitude Optimum Criterion, as described in more detail below.

The “Controller” subsystem contains the following components from the RT Box 1 Target Support Library:

- Analog In blocks provide the analog signals from the “Plant” subsystem. The input signals can be scaled and offset, similar to the Analog Out block. In this model, the Analog In scaling factors are set to the inverse of the Analog Out scaling factors. The current and voltage values in the “Control” subsystem will then correspond to unscaled voltage and current measurements in the power stage.
- The PWM Out block is configured to generate a PWM signal with a symmetrical carrier on digital output channel 0. To sample the average inductor current, the sample point of the ADC needs to be in the middle of the switching period for a symmetrical PWM scheme. To ensure consistent point-on-wave sampling, the ADC and the PWM execution need to be synchronized. With the RT Box this is achieved by synchronizing both ADC sampling and PWM update with the model step. This behavior is configured by the **Synchronization with model step** parameter of the PWM Out block. The controller runs in a single update mode with the compare value (CMP) updating always on the minimum of the triangular carrier (see **Update** setting of the PWM Out block). The PWM Out carrier waveform is updated every 7.5 ns which limits the time resolution of the PWM period. This effect is modeled in the offline simulation. In the initialization commands the closest achievable PWM carrier frequency to 20 kHz is calculated and used for the PWM Out switching frequency. The resulting PWM frequency error is less than 0.005%.



**Figure 3: Schematic of the current controller**

### Plant transfer function

To set the PI controller gain parameters the plant transfer function  $P(s)$  is needed.  $P(s)$  relates the change of the voltage across the  $RL$  elements  $V_{RL}$  (the input variable) to the response of the inductor currents  $I_L$  (the output variable):

$$P(s) = \frac{I_L}{V_{RL}} = \frac{1/R_L}{1 + sL/R_L} = \frac{K_1}{1 + sT_1}$$

where  $K_1 := 1/R_L$  and  $T_1 := L/R_L$

### Time delays

Several types of time delays are present in the virtual prototyping setup of this boost converter real-time model.

- Analog input sampling
- Control calculation time step
- PWM output generation
- PWM capture interface
- Plant calculation time step
- Analog output

Since the plant calculation time step is much smaller than the controller step (factor of 50), only the time delays of the controller are considered in the offline model. These are the control calculation time step itself ( $1/T_{sw}$ ) and the average PWM output delay of  $1/(2T_{sw})$  giving a total delay of  $3/(2T_{sw})$ . For the calculation of the control parameters the delay is approximated with a first-order low pass filter of the form:

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

where  $T_{\Sigma} = 3/2 \cdot T_{disc,control} = 3/2 \cdot T_{sw}$ .

### Calculation of control parameters

The control parameters of the PI controller ( $K_i$  and  $K_p$ ) 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:

$$H_{OL}(s) = \frac{1 + sT_n}{sT_i} \cdot \frac{K_1}{1 + sT_1} \cdot \frac{1}{1 + sT_{\Sigma}}$$

where  $K_p = \frac{T_n}{T_i}$  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.  $T_n = T_1$ . The remaining parameter  $T_i$  is calculated from the closed-loop transfer function and with the condition  $H_{CL}(j\omega) \approx 1$  at low frequencies  $T_i = 2K_1T_{\Sigma}$

### Anti-windup and controller reset

The controller is equipped with an anti-windup mechanism. The anti-windup feedback uses a corrective gain of:

$$K_{bc} = \frac{K_i}{K_p}.$$

The lower saturation level is 0 V (for a duty cycle of 1) and the upper saturation level is set to  $V_{out}$  (for a duty cycle of 0). Note that this assumes that the output capacitor is pre-charged to at least  $V_{in}$ . In startup situations where the output capacitor is not pre-charged the saturation level of the controller would need to be variable and adapted to the actual output voltage.

A reset option is added to the controller. Setting the value of the "Reset Controller" Constant block to 1 resets the integral part of the PI controller to its initial condition and a default duty cycle of 0.5 is applied to the PWM module.

The overall structure of the PI controller including anti-windup and reset features is given in Fig. 4.

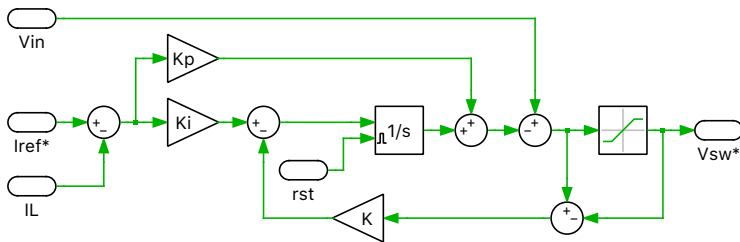


Figure 4: Schematic of the PI controller

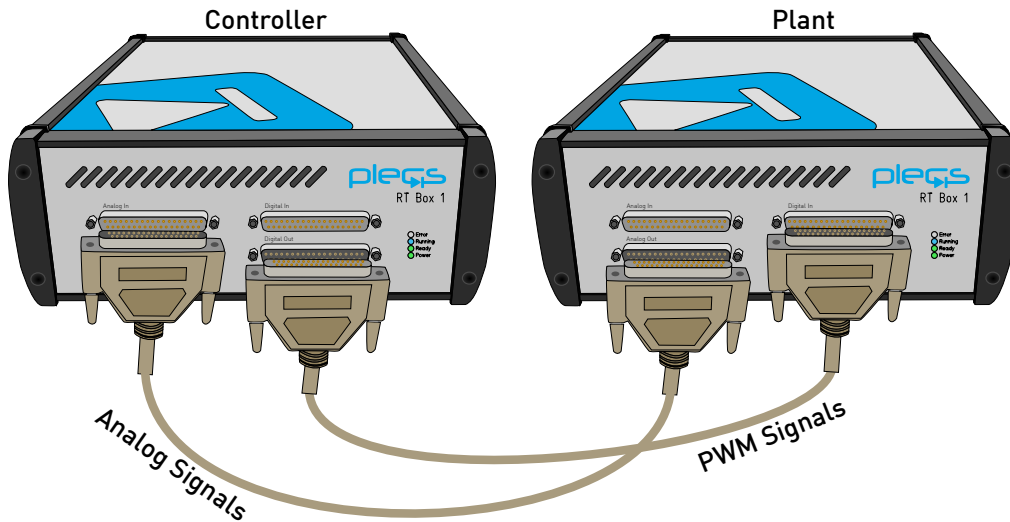


Figure 5: Interconnection of two RT Boxes running the plant and controller models

### 3 Simulation

This demo model runs both in offline mode on a PC or in real-time on the PLECS RT Box. For the real-time operation, two RT Boxes are needed that exchange digital PWM and analog sensor signals using two 37 pin Sub-D cables. The connection of the two boxes is depicted in Fig. 5.

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. 5).
- 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.

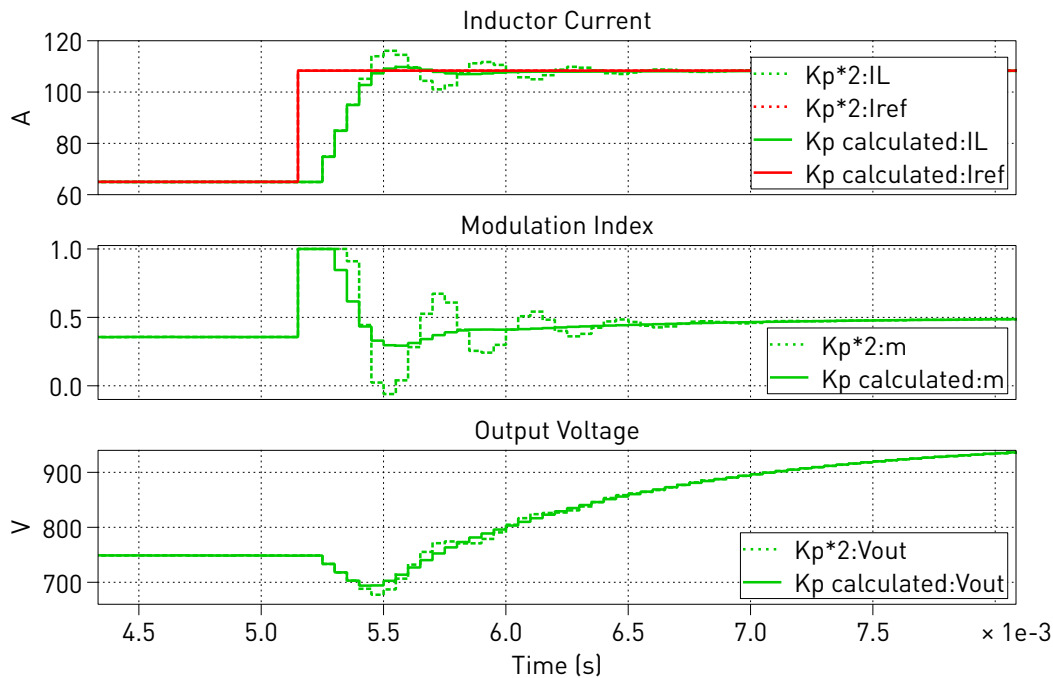
#### 3.1 External Mode

Open the **External Mode** tab of the “Controller” subsystem and click **Connect** and then **Activate autotriggering**. The PLECS Scopes in that subsystem will now update with real-time data from the RT Box. The controller subsystem has different tunable parameters:

- “Reset Controller” Constant block
- “Kp” Gain block inside the “PI Controller” subsystem
- “Ki” Gain block inside the “PI Controller” subsystem
- “Iref” Pulse Generator block

To start the system, double-click on the “Reset Controller” Constant block and change the value to 1 and then back to 0.

Notice the inductor current reference is toggling between a maximum (108 A) and minimum (65 A) value in the “Controller” subsystem. The step response of the current control-loop is shown in Fig. 6. The maximum and minimum values for the reference current can be tuned online as well as the control parameters  $K_i$  and  $K_p$ .



**Figure 6: Current control step response from 64 A to 108 A**

## 4 Conclusion

This RT Box demo model demonstrates a boost converter under closed-loop control with a continuous PI current controller and resistive load. The demo model can run in both offline simulation and in real-time on two RT Boxes. The controller subsystem runs on one RT Box with a discretization step size of  $50 \mu\text{s}$ , which is the size of the switching period, and the plant subsystem runs with a discretization step size of  $1 \mu\text{s}$  on a second RT Box.

## 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.



## Revision History:

RT Box Target Support Package 1.8.3

First release

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### *RT Box Demo Model*

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