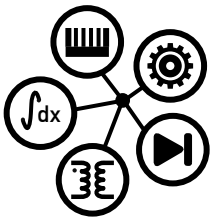

Embedded
Code Generation

*DEMO MODEL*

# Input-Series/Output-Parallel Dual Active Bridge

**Closed-loop control of an Input-Series/Output-Parallel Dual Active Bridge structure with embedded code generation for TI C2000 MCUs**

Last updated in C2000 TSP 1.11.1

**www.plexim.com**

- Request a PLECS and PLECS Coder trial license
- Get the latest TI C2000 and RT Box Target Support Package
- Check the PLECS, RT Box and TI C2000 TSP documentation

# 1 Overview

This demo models shows the simulation of a DC/DC converter system based on an Input-Series/Output-Parallel (ISOP) Dual Active Bridge (DAB) structure, as described in [1]. The converter is dedicated to energy storage applications and interfaces a DC-voltage network together with a battery-based energy storage system. The converter is operated in closed-loop control. The demo model provides an explanation of the typical workflow of the PLECS Coder, using Texas Instruments (TI) C2000 MCUs. Combined with a PLECS RT Box, the performance of the control algorithm can be verified in a Hardware-in-the-loop (HIL) simulation.

The model is split into two distinct subsystems called “Plant” and “Controller”. The plant contains the two DAB stages where the input side is connected in series and the output is in parallel. Each DAB stage has his own nested control loops. A global control strategy aims to balance the voltage on the input side equally among the two capacitors. Each subsystem is deployed to a separate real-time target. Using the PLECS Coder, the control logic in the controller subsystem is built and then flashed to a TI C2000 MCU. The plant subsystem is then deployed on the PLECS RT Box for HIL testing of the generated embedded code. The following sections provide a brief description of the model and instructions on how to simulate it.

---

**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 demo model is composed of two subsystems: the “Plant” subsystem includes the power circuit and the “Controller” subsystem includes the control loop. Both subsystems are enabled for code generation from the **Edit + Subsystem + Execution settings...** menu. This step is necessary to generate the model code for a subsystem via the PLECS Coder.

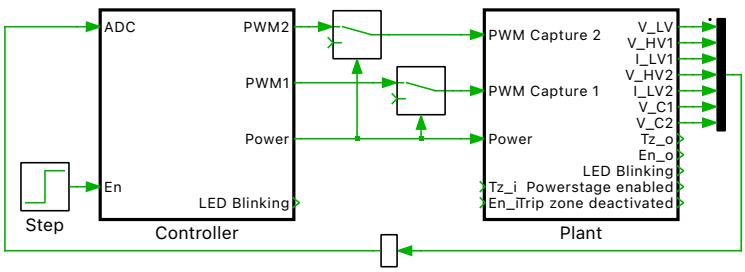


**Figure 1: Top level schematic of the plant and controller subsystems**

## 2.1 Plant

In this demo the power circuit, shown in Fig. 2, includes two DABs, where the input side is in series and the output side is connected in parallel. The DABs are implemented with the Dual Active Bridge library component from the Nanostep section of the PLECS library. The RT Box’s Nanostep solver simulates with time steps in the single-digit nanosecond range. The small step size is critical to accurately model high-frequency DC/DC converters with an inductive AC link, such as the DAB, where the power transfer is very sensitive to the phase shift between the current and PWM signals. In addition, the output side

includes a filter circuit to reduce the current ripple provided to the electrochemical battery storage system.

Each DAB has an input side capacitor and these two capacitors need a balanced voltage. Without an appropriated balancing scheme the voltages on the input capacitors will start to drift apart and one of the two capacitors will eventually take over the total input voltage of $700\,\mathrm{V}$. To reflect an imbalanced loading scenario a pseudo-random current is directly drawn (or fed) to the input capacitor of the upper DAB.

The eight PWM switching signals are brought into the Plant subsystem using two PWM Capture blocks from the RT Box component library. The measurements of the filtered output side current, output side voltage, input side voltage and battery terminal voltage are exported out of the subsystem via Analog Out ports. The discretization step size of the plant is set to $3.0\,\mu\mathrm{s}$.

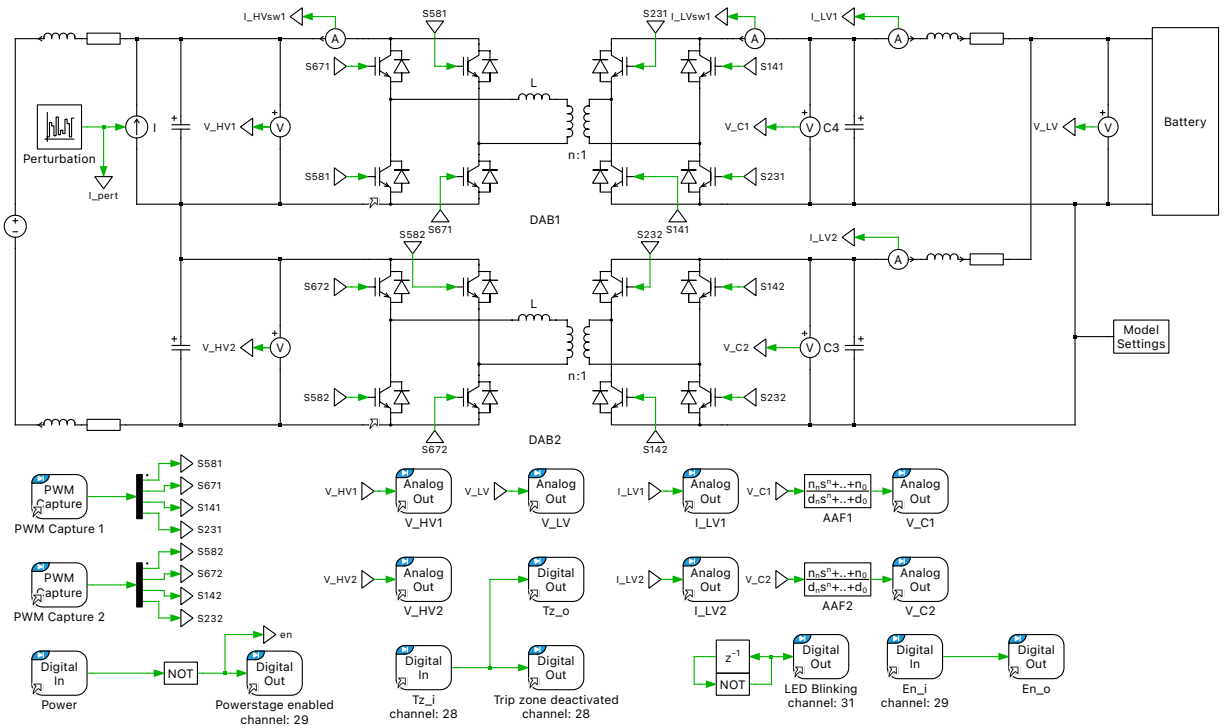


**Figure 2: Power circuit of the ISOP-DAB model running on the RT Box**

## 2.2 Controller

The controller subsystem is shown in Fig. 3. The power transfer from the input side to the output side of each DAB is controlled by a phase-shift $\varphi$ between the PWM signals of the primary and secondary full-bridges. Each stage is controlled by a cascaded control loop approach. The outer controller settles the current in the output inductor, providing a reference value for the inner voltage controller. This inner voltage controller provides a reference current which is used to calculate the required phase-shift.

The relationship between the secondary side current of a single DAB stage and phase-shift angle $\varphi$ is given by:

$$I_{LV} = \frac{nV_{\mathrm{HV}}}{2\pi^2 f_{\mathrm{sw}} L_{\mathrm{tot}}} \left(\pi - |\,\varphi\,|\right)\varphi$$

The direct inversion of the above equation is then used to calculate the required phase-shift to apply the commanded reference current $I^*_{\mathrm{LV}}$. This relationship can be written as:

$$\varphi^* = \frac{\pi}{2}\left(1 - \sqrt{1 - \frac{8 f_{\mathrm{sw}} L_{\mathrm{tot}} \mid I^*_{\mathrm{LV}} \mid}{n V_{\mathrm{HV}}}}\right) \mathrm{sign}(I^*_{\mathrm{LV}})$$

### Stage control

Each stage contains an individual secondary current reference, $I_{\mathrm{ref1}}$ and $I_{\mathrm{ref2}}$, which are obtained from a global reference current $I_{\mathrm{ref}}$, where

$$I_{\mathrm{ref}} = k \cdot I_{\mathrm{ref1}} + (1 - k) \cdot I_{\mathrm{ref2}}.$$

The distribution factor $k$ is calculated in such a way that the voltages on the two input capacitors stay equally balanced. This distribution factor $k$ can take any value between 0 and 1. The calculation of $k$ is done in the subsystem “Strategy” according to the following rule:

$$k = 0.5 + 5\left(\frac{V_{\mathrm{HV1}} - V_{\mathrm{HV2}}}{V_{\mathrm{HV1}} + V_{\mathrm{HV2}}}\right)$$

Due to this, an additional degree of freedom is introduced into the control logic which can be used to balance the voltages over the two input capacitors.

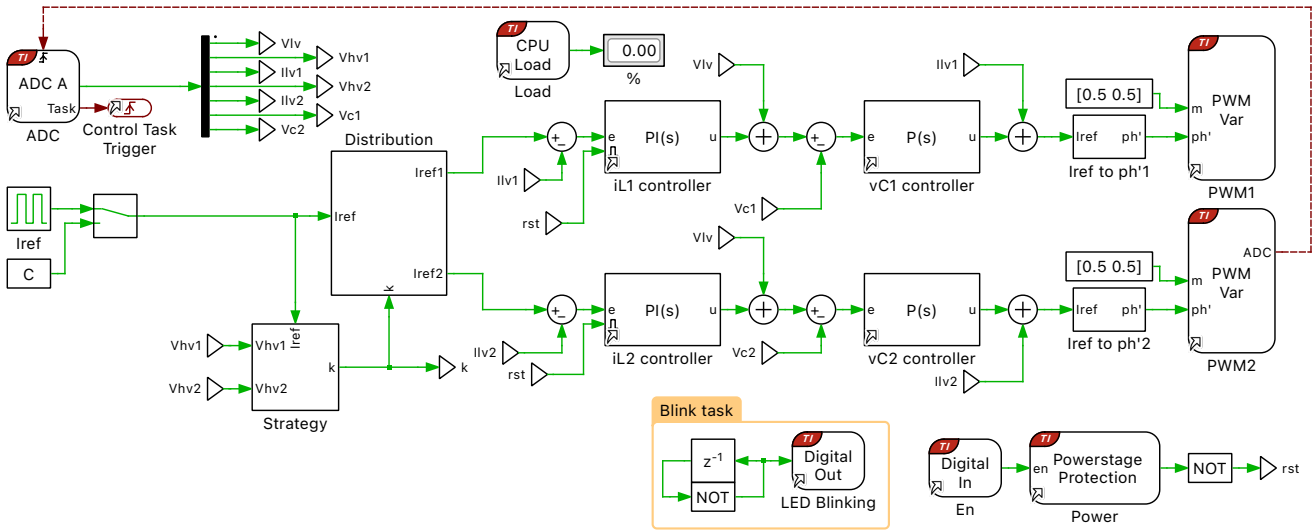


**Figure 3: Control structure of the ISOP-DAB**

### Target Blocks

The measurements of the analog signals provided by the RT Box are introduced in the Controller subsystem with an ADC block from the TI C2000 Target component library. In order to convert the detected analog voltage into a value with physical units to be used by the control algorithm, a scaling factor and an offset are provided for each channel via the parameter window of the ADC block.

Each full-bridge is operated with a constant duty cycle of 0.5. A PWM (variable) block from the TI C2000 Target component library is used to configure the physical PWM generators of the DSP. This block allows the phase shift between the PWM carriers to be dynamically adjusted.

# 3 Simulation

Like for all PLECS models an offline simulation of this demo model can be performed by clicking on **Simulation + Start**.

## 3.1 Controller Deployment

In addition to running a simulation of this demo model in offline mode on a computer, the “Controller” subsystem can be directly converted into target specific code for the TI C2000 MCUs. The default I/O configuration of all the peripheral blocks (ADC, PWM etc.) supports the TI 280039C [2], TI 28379D [3], TI 28P550SJ9 [4], TI 28P650DK9 [5] LaunchPads, and the TI 28388D [8] controlCARD.

---

**Note** For the TI 28P550SJ9 LaunchPad, switch S6 must be set to "BP".

---

Additionally, the demo model allows for code generation for the TI 280039C [6] and TI 28379D [7] controlCARDs. To configure this, go to the **Model initialization commands** window from the **Simulation + Simulation parameters... + Initialization** menu, and change the value of `board_type`, to select the desired board. You must also configure the corresponding **Target** and **Board** type in the **Coder Options** window accordingly. Furthermore, the model of the plant can be deployed on the PLECS RT Box for a hardware-in-the-loop (HIL) test of the generated code.

- Connect the MCU to the host computer through a USB cable.
- From the **System** tab of the **Coder + Coder options...** window, select “Controller”.
- Next, from the **Target** tab, select the appropriate target from the dropdown menu. Then under the **General** subtab, select the desired **Build type**.
- Then, to `Build and program` the MCU directly from PLECS, choose either `Run from Flash` or `Run from RAM` as the **Build configuration** to program the MCU either to flash memory or to RAM, respectively. Then select `LaunchPad` as the **Board** type, and click **Build**.

If programmed correctly, LED “D9” (or the LED corresponding to GPIO “DO_DSP_LED” listed in the model initialization commands) should blink.

---

**Note** If using the RT Box LaunchPad Interface board, make sure that the **RST** jumper is open throughout the simulation.

---

## 3.2 Plant Deployment for a HIL Simulation

Besides the controller this demo model also implements the power stage in the “Plant” subsystem which can be deployed on a PLECS RT Box to perform a hardware-in-the-loop (HIL) test. A typical hardware configuration is shown in Fig. 4, where the evaluation kit, a TI C2000 LaunchPad (the red board), is connected to the RT Box via an RT Box LaunchPad Interface (the green board). Follow the instructions below to run a real-time model on the RT Box. Before building on the RT Box, ensure that you have already built the "Controller" subsystem on the appropriate TI MCU, as shown in Section 3.1.

- From the **System** tab of the **Coder + Coder options...** window, select “Plant” and **Build** it onto the RT Box.
- Once the model is uploaded, from the **External Mode** tab of the **Coder options...** window, **Connect** to the RT Box and **Activate autotriggering** to observe the test results in real-time.

If programmed correctly, the LED corresponding to “DO-30” of the RT Box LaunchPad Interface board should blink.

Within the “Plant” subsystem or the power circuit running on the RT Box, the simulated voltages and currents are proportionally converted into analog signals, and delivered through Analog Out connectors on the front panel of the RT Box. These analog signals are captured by the RT Box LaunchPad Interface board and routed to the ADC input pins of the TI LaunchPad. The MCU then processes these analog signals to generate PWM switching signals, which are delivered to the RT Box via the Digital In pins.


**Figure 4: Hardware setup of the HIL verification with the RT Box**

The DAB power stage has been implemented using the Dual Active Bridge component available in the Nanostep section of the PLECS library. The RT Box's Nanostep solver simulates the converter with time steps in the single-digit nanosecond range.

- Toggle the switch "DI-29" on the RT Box LaunchPad Interface board from "High" to "Low" and then back to "High" to reset the MCU and observe the real-time waveforms in the Scope of the "Plant" subsystem. When the power stage is enabled, the LED corresponding to "DO-29" of the LaunchPad Interface board should turn on.
- If switch "DI-28" on the RT Box LaunchPad Interface board is toggled to "Low", a trip-zone event is activated that disables the output of all the PWMs. When the trip-zone event is activated, the LED corresponding to "DO-28" of the LaunchPad Interface board is turned off.
- In order to resume the system, toggle "DI-28" back to "High", turning the LED corresponding to "DO-28" on, then toggle switch "DI-29" from "High" to "Low", and then back to "High" to reset the MCU. The LED corresponding to "DO-29" should now turn on.

At this stage, verify that the LEDs corresponding to "DO-28" and "DO-29" on the RT Box LaunchPad Interface board are turned on.

In order to tune the parameters of the control program in the MCU and observe any intermediate values, follow the instructions below to connect to the external mode of the TI MCU.

- From the **System** tab of the **Coder + Coder options...** window, select "Controller".
- Next, from the **External Mode** tab, select the appropriate **Target device** and click **Connect**.
- Then, **Activate autotriggering** to observe the test results in the "Controller" subsystem Scope.

In this demo model, the reference current value is toggled between $-1.5 \cdot I_{\mathrm{nom}}$ and $1.5 \cdot I_{\mathrm{nom}}$ using the Pulse Generator component in the "Controller" subsystem. The source of the reference current can also be changed to the Constant block by double-clicking on the Manual Switch component. These reference values can be changed on the fly, in real-time, since the Pulse Generator block has been added to the "Exceptions" list found in the **Parameter Inlining** tab of the **Coder options...** window, prior to building the model.

## 3.3 Results

The waveforms of the main measurements of the demo model running in real-time are shown in Fig. 5. The HV-side capacitors are imbalanced. Due to this, the controller counteracts with a distribution factor

$k$ other than $0.5$ to balance the voltage on the two capacitors. Nevertheless, the current reference command is closely followed.

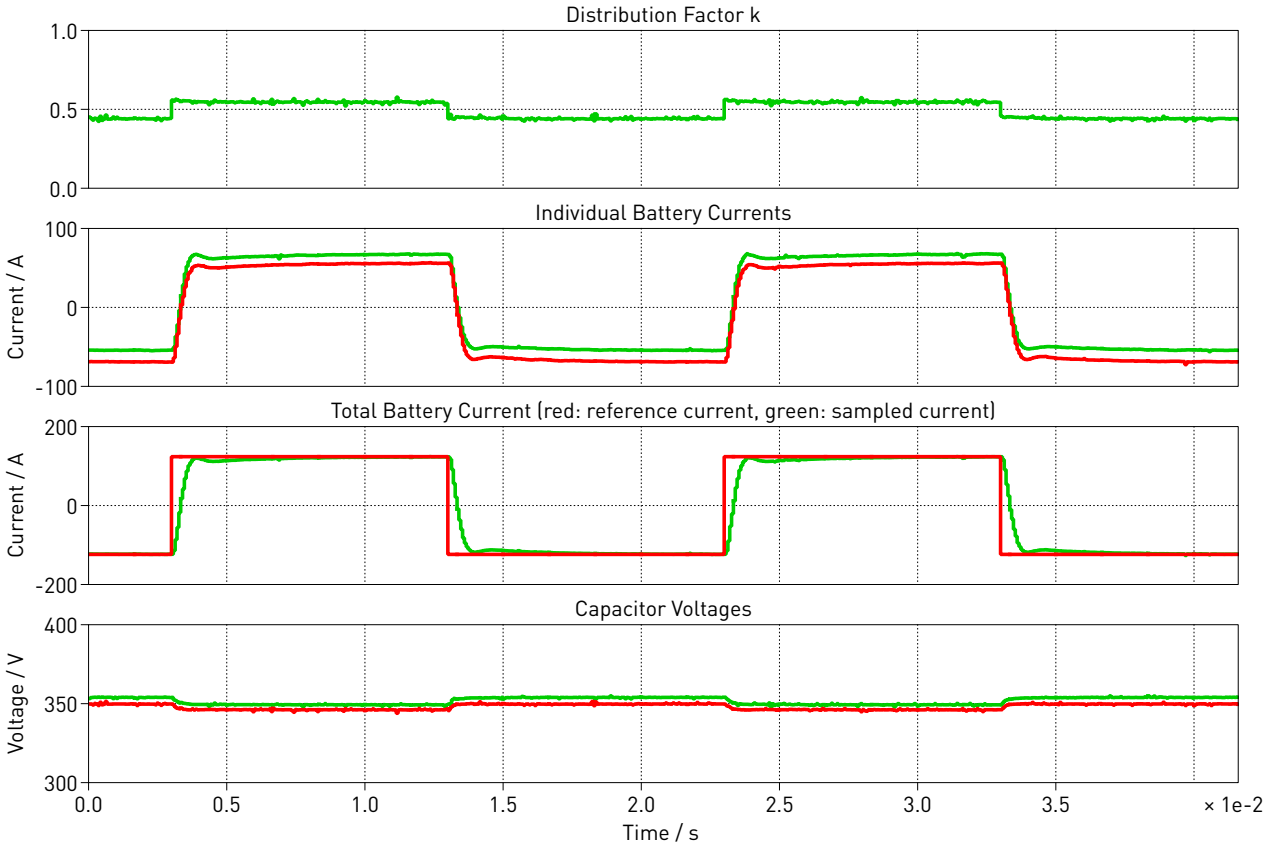


**Figure 5: Real-time measurements of distribution factor, battery side inductor currents and capacitor voltages using the PLECS RT Box 1 and a TI C2000 MCU**

# 4 Conclusion

This demo model demonstrates an ISOP DAB converter with closed-loop control based on phase-shift modulation. The model can run as an offline simulation or in real-time for hardware-in-the-loop testing. The control code running on the TI C2000 MCU can be automatically generated out of PLECS. The RT Box's Nanostep solver simulates the DABs in the "Plant" subsystem with a time step in the single-digit nanosecond range. The small step size is critical to accurately model high-frequency DC/DC converters, such as the DAB.

# References

[1] P. Barrade, E. Coulinge, A. Rufer, “Control of a Modular DC-DC Converter Dedicated to Energy Storage”, *2015 17th European Conference on Power Electronics and Applications (EPE’15 ECCE-Europe)*, Geneva, 2015, pp. 1-9.

[2] TI C2000 F280039C LaunchPad development kit,
URL: http://www.ti.com/tool/LAUNCHXL-F280039C.

[3] TI C2000 Delfino MCU F28379D LaunchPad development kit,
URL: http://www.ti.com/tool/LAUNCHXL-F28379D.

[4] TI C2000 F28P550SJ9 LaunchPad development kit,
URL: https://www.ti.com/tool/LAUNCHXL-F28P55X.

[5] TI C2000 F28P650DK9 LaunchPad development kit,
URL: https://www.ti.com/tool/LAUNCHXL-F28P65X.

[6] TI C2000 F280039C controlCARD evaluation module,
URL: https://www.ti.com/tool/TMDSCNCD280039C.

[7] TI C2000 F28379D controlCARD development kit,
URL: https://www.ti.com/tool/TMDSCNCD28379D.

[8] TI C2000 F28388D controlCARD evaluation module,
URL: https://www.ti.com/tool/TMDSCNCD28388D.

[9] PLECS TI C2000 Target Support User Manual,
URL: https://www.plexim.com/download/documentation.

### Revision History:

| | |
|---|---|
| C2000 TSP 1.2.1 | First release |
| C2000 TSP 1.4.5 | Updated the powerstage protection parameters |
| C2000 TSP 1.5.1 | Added support for 28379D LaunchPad, and 28388D and 28379D controlCARD targets, minimized the usage of double-precision math in the controller, and set the Sync to "Self" on PWM2 |
| C2000 TSP 1.6.1 | Added support for 280039C LaunchPad and controlCARD targets, and auto-pin selection |
| C2000 TSP 1.9.1 | Added support for 28P550SJ9 LaunchPad target |
| C2000 TSP 1.11.1 | Upgrade Plant to Nanostep solver, increase switching frequency |

### How to Contact Plexim:


| | | |
|---|---|---|
| ☎ | +41 44 533 51 00 | Phone |
| | +41 44 533 51 01 | Fax |
| ✉ | Plexim GmbH<br>Technoparkstrasse 1<br>8005 Zurich<br>Switzerland | Mail |
| @ | `info@plexim.com` | Email |
| | `http://www.plexim.com` | Web |


*Embedded Code Generation Demo Model*