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EXECUTIVE SUMMARY OF THE THESIS

# Real-Time Power Conversion: Development and Validation of a Hardware-in-the-Loop Platform for EV Charging System

LAUREA MAGISTRALE IN ELECTRICAL ENGINEERING - INGEGNERIA ELETTRICA

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## 1. Introduction

This thesis investigates the implementation and experimental validation of a Hardware-in-the-Loop (HIL) system for real-time digital power conversion simulation. The primary goal was to develop an HIL environment capable of simulating a high-power system (based on an existing board from ST Microelectronics) using a 5V microcontroller. The system emulates an electric vehicle on-board charger, converting three-phase AC power to DC. On the controller side, a model-based approach was followed to implement and deploy the control on hardware. A comprehensive state machine was designed for grid synchronization, startup sequences, and fault detection.

## 2. Real Time Simulator

### 2.1. Modeling of the system

The system components include a three-phase AC grid, relays, a boost inductor, a power converter, and a DC load, as shown in Fig. 1.

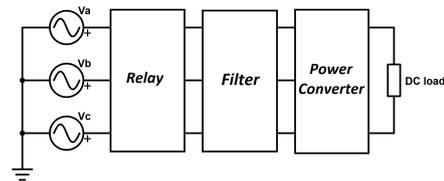


Figure 1: Full System.

The development environment for simulating the system uses Simulink and Simscape Electrical. The Simulink model, depicted in Fig. 2, includes three main parts: Input, System, and Outputs. Inputs consist of duties, relays, and switch enable signals. Duties are numbers from 0 to 1 generated by the control or an external source, which are then used to generate gate signals for the switches. Relays connect the grid to the converter and manage inrush current, while the switch enable signals allow independent control of the switches.

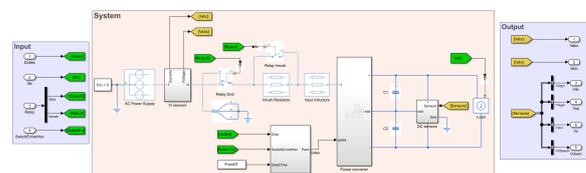


Figure 2: Simulink model.

The system, as shown in Fig. 2, includes a three-phase AC voltage source, VI sensors for measuring currents and voltages, relays for grid connection and inrush current management, an input inductor, and a power converter with gate signals for control. The DC side includes capacitors and a DC current source. Outputs consist of all measurements taken from the circuit.

To run the model in real-time on a microcontroller, an **averaged model** of the power converter is used. In this model, switching elements (MOSFETs) are replaced by their average behavior over a switching period, simplifying the analysis and making it compatible with real-time implementation. The average behavior is represented by the duty cycle ( $d$ ) of the switch, defined as:

$$d = \frac{t_{on}}{T_s} \quad (1)$$

where  $t_{on}$  is the time when the switch is on and  $T_s$  is the full period of switching. This approach allows the model to run at the order of kHz, suitable for microcontroller implementation, though it does not capture the current ripple caused by switching.

A real-time implementation requires discretization of the system. The averaged model consists of differential equations that are discretized within the MATLAB function. For example, the equation of an inductor is:

$$v_L = L \frac{di}{dt} \quad (2)$$

The state variable is the current, computed at each step of the average model. The term  $dt$  becomes  $\Delta T$ , representing the step size. At a specific instant  $t_k$ , the current is:

$$i(t_k) = i(t_{k-1}) + \frac{\Delta T}{L} v_L \quad (3)$$

An algorithm is implemented in C code to receive gate signals and compute the duty cycle required for the average model. Timer peripherals of the microcontroller are used to detect edges on the input signal. Each gate signal has a rising edge, a falling edge, and a period. Two channels of the timer are necessary for each signal: one to capture the rising edge and the other to capture the falling edge.

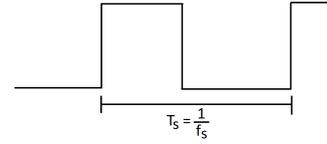


Figure 3: Gate signal.

To maintain a good model frequency, a dual-core implementation is realized. The simulator emulates analog signals using PWM signals filtered to obtain the desired analog output, as if the signal comes from a DAC.

### 3. Real time Controller

#### 3.1. Modeling of the system

The purposes of the controller are [1]:

- Control the DC bus voltage
- Ensure sinusoidal current absorption
- Achieve unity power factor operation

The bidirectional converter can operate in rectifier or inverter mode. Control block requirements include measuring AC and DC voltages, synchronizing phases, setting reference values, generating gate signals (PWM), and adjusting errors [1]. A state machine manages control operations and fault detection.

#### 3.2. Development Environment and Real time implementation

The development environment used is Simulink. The control is developed and tested using the simulator. The control algorithm is implemented using Simulink *variant sink* and *variant source* blocks in order to be compatible either with desktop simulation or with code generation. The controller communicates with inputs from the simulator through sensors and actuators.

#### 3.3. Control algorithm

The controller operates in a d-q reference frame using Park and Clarke transforms. The PLL block provides the angle for the Park transform. The system's equivalent single-phase circuit is shown in Figure 4.

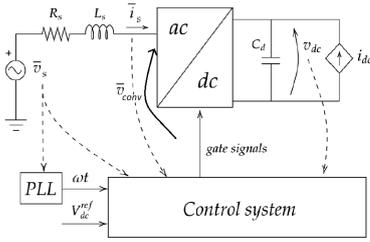


Figure 4: Equivalent single-phase circuit [1].

Two control loops are implemented: one for DC voltage regulation and the other for unity power factor operation.

### 3.4. State machine

A State Machine is deployed using Stateflow in Simulink to manage control operations and fault detection. The main state machine manages states like *Wait*, *Idle*, *Init*, *Burst (start)*, *PFC*, and *Fault*.

### 3.5. Validation of the control

The control algorithm is tested in Simulink with the Simscape model to ensure all requirements are met. The average model is used to verify that the results are comparable with the Simscape model.

## 4. Hardware implementation

The hardware is composed of a *Control board* and a *Simulator board*. Both are based on the STMicroelectronics Stellar E MCU (SR5E1E7). The SR5E1 family consists of MCUs with two 32-bit ARM Cortex-M7 cores, running at 300 MHz. The two cores can be used either in parallel or with one core in a lockstep configuration. It has 12 timers and 2 High-Resolution Timers (HRTIM) that allow the creation of complex waveforms with a resolution of 102 ps [4]. The hardware setup is shown in Fig. 5.



Figure 5: Hardware setup.

The control board is shown in *blue*, and the simulator board is shown in *green*.

### 4.1. Three-phase full bridge

The three-phase full bridge is a bidirectional two-level converter consisting of 6 MOSFETs. The detailed model of the converter is implemented in Simulink (with Simscape Electrical) and shown in Fig. 6.

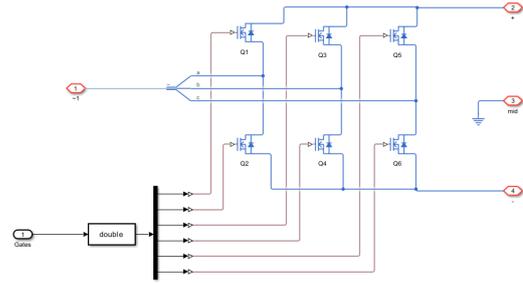


Figure 6: Three-phase full bridge Simulink model.

Input 1 of this subsystem is the AC side, while outputs 2 and 3 are the positive and negative sides of the DC side, respectively. The midpoint is not used in this configuration. Considering one leg of the converter (Q1 and Q2), it is important to note that these two switches cannot be closed simultaneously; otherwise, the leg would be short-circuited. Specifically, when the upper switch is on, the lower one must be off, and vice versa.

The control board should work with the simulation board as if it were the real board: the pin mapping must be taken directly from the real board, which is available. The real board is from STMicroelectronics, model "STDES-BCBIDIR". According to the ST website: "STDES-BCBIDIR is an 11 kW bidirectional battery charger based on a three-phase two-level PFC and isolated DC-DC converter" [5]. In this specific case, the control should manage the first stage (PFC) of the system. Peripherals are directly configured in Simulink using dedicated Simulink blocks.

The simulator has as many differential equations as there are elements that accumulate energy: three inductors on the AC side and a capacitor on the DC side. The average model is divided into four main parts:

1. *Force computation*: Manages the startup

phase where all switches are off, and the circuit behaves like a diode bridge.

2. *Free-wheel*: This phase occurs if both switches are off for a certain time during the interval. This can happen only if a dead time is implemented.
3. *Voltage computation*: Computes the voltage across the capacitor on the DC side.

The equations are implemented in C code and called periodically in an interrupt. The interrupt is divided into several parts:

1. *Grid Voltages*: Continuously monitored by the controller.
2. *Relay Grid*: Closed only if all three grid relays are closed.
3. *Relay Inrush*: Manages the inrush relay.
4. *Duty Cycles*: Computed and saved in an array.
5. *DAC Output*: Manages the DAC output based on the same gain and bias used on the real board.

The simulator tests the performance of the control, including fault management. A GUI for the Stellar family microcontroller allows visualization of variables and real-time parameter changes (e.g.,  $R$ ,  $L$ ,  $C$ , source voltage).

Experimental tests are first carried out based on Simulink simulations to validate the average model. After that, a real-time simulation is conducted and compared with the desktop simulation to test the performance of the control. Below is a table with parameters of the simulator (Table 1) with some of them derived from the board "STDES-BCBIDIR".

$V_{dc_{ref}}$	800 V
Nominal power	11 kW
$V_{PhaseToGroundRMS}$	220 V
Line Frequency	50 Hz
Sample time (Simulink)	1/(60 kHz)
Sample time (real-time)	1/(65 kHz)
Input inductor	255 mH
DC capacitor	500 $\mu$ F

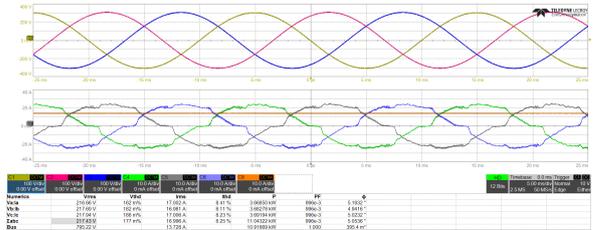
Table 1: Simulator parameters.

The sample time is different because, in Simulink, all sample times must be multiples, while in real-time, a frequency is chosen that is different from the PWM and its multiples to maintain asynchronous control and simulation. The simulations aim to test different phases to

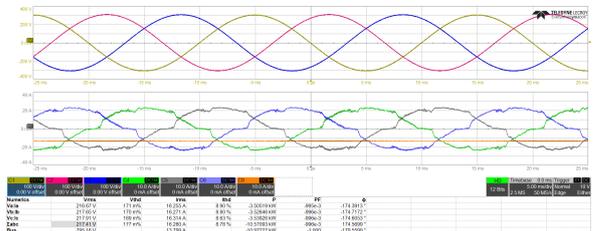
check the state machine behavior and control performance:

- **Startup phase**: Test the state machine and check that the bus is correctly charged to the reference voltage.
- **Load Step**: Check the response of AC currents and DC voltage to different load steps.
- **PFC test**: Check waveforms at nominal power.
- **Protection shut-down**: Test fault recognition and response using the GUI.

The first desktop simulation is carried out with Simscape electrical components at a frequency of 8.4 MHz. This allows for validating the average model and the control before moving to real-time simulation. The PFC at 11 kW with DC current positive and negative is shown in Fig. 7.



(a)  $I_{dc} = 13.75$  A and Deadtime = 600 ns.



(b)  $I_{dc} = -13.75$  A and Deadtime = 600 ns.

Figure 7: Three phase full bridge real-time simulation at full load.

## 4.2. Three level T-Type

The Three Level T-Type (TLTT) is a three-level, three-phase bidirectional converter consisting of 12 MOSFETs. The detailed model is shown in Fig. 8.

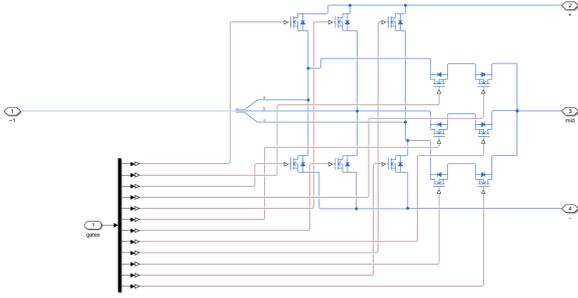


Figure 8: Three Level T-Type Simulink model.

The control implemented for TLTT is the same as that already described for the three-phase full bridge. The main difference is the duty computation block. This converter has 12 switches, where 6 of them are the negations of the others. The upper switch of each leg is modulated together with the left switch of the horizontal side, while the lower switch of the vertical leg is modulated with the right switch of the horizontal side.

The evaluation board of the bidirectional converter is the "STDES-PFCBIDIR," which is a 15 kW, three-phase, three-level Active Front End (AFE) bidirectional converter for industrial and electric vehicle DC fast charging applications [3]. The board is shown in Fig. 9.

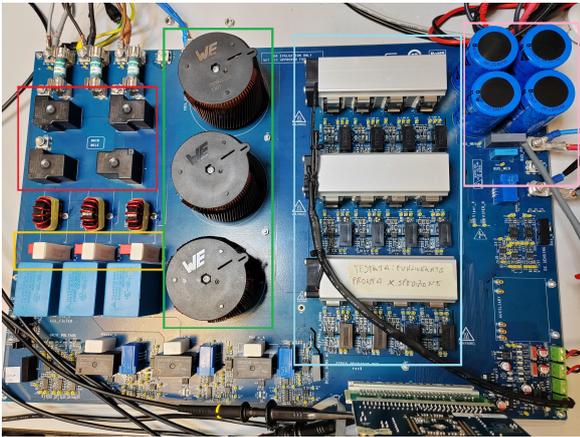


Figure 9: STDES-PFCBIDIR board.

From Fig. 9, it is possible to recognize:

- **Red area:** Relay grid. There are 4 relays because one is for the neutral.
- **Yellow area:** Inrush relay.
- **Green area:** Boost inductors.
- **Light blue area:** MOSFETs with gate drivers.
- **Pink area:** DC capacitors.

The structure of the firmware for the simulator

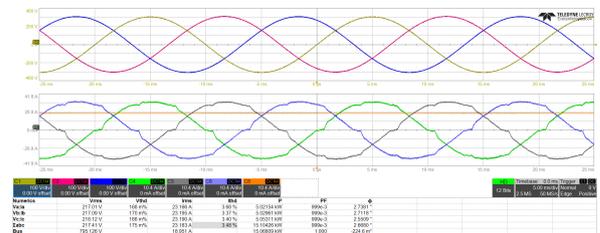
is consistent with that of the three-phase full bridge. Simulations are carried out starting from Simulink. Below is a table with parameters of the simulator (Table 2) derived from the board "STDES-PFCBIDIR" that can be taken directly from the ST website [2].

$V_{dc_{ref}}$	800 V
Nominal power	15 kW
$V_{PhaseToGroundRMS}$	220 V
Line Frequency	50 Hz
Sample time (Simulink)	1/(60 kHz)
Sample time (real-time)	1/(65 kHz)
Input inductor	381 mH
DC capacitors	1 mF

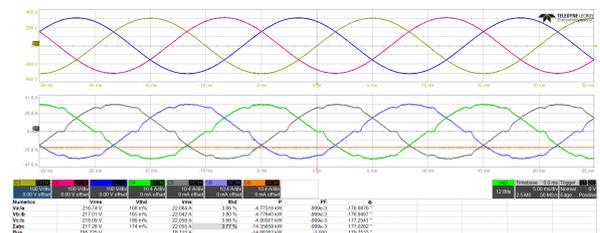
Table 2: Simulator parameters - TLTT.

The desktop simulations are performed as for the three-phase full bridge to validate the model. After that, real-time simulations are carried out at the nominal power of 15 kW (in both AC to DC conversion and DC to AC conversion) and are shown in Fig. 10. The deadtime value is set to 600 ns.

The full load test is shown in Fig. 10.



(a)  $I_{dc} = 18.75$  A.



(b)  $I_{dc} = -18.75$  A.

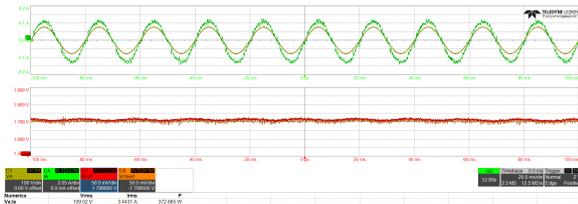
Figure 10: TLTT real-time simulation at full load.

Despite having the same deadtime value, the currents of the three-phase full bridge exhibit a better sinusoidal shape. This is demonstrated by the current THD, which is 8% for the three-phase full bridge and 3.7% for the three-level

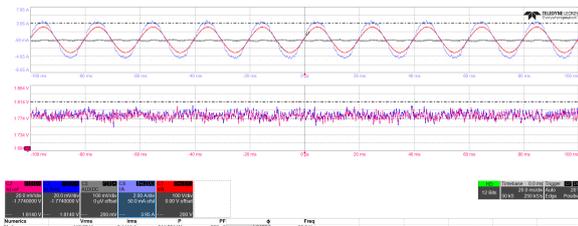
T-type. Although the THD is not entirely realistic because it is based on an average model, it provides an indication of the current distortion. In Fig. 10, the power is 15 kW (or -15 kW) and the voltage is in phase with the current (or in counterphase), indicating that the PFC is working as expected.

The HIL platform allows testing the control safely and without the need for a laboratory equipped with adequate instruments and power for a 15 kW converter. The control of the TLTT is tested and validated with HIL and is ready to be tested on the real board. Tests are carried out starting from half of nominal quantities, which means 110 V phase to ground AC voltage and 400 V as a reference voltage on the DC bus.

The board was already presented in Fig. 9. To complete the setup, a three-phase AC generator and a DC electronic load are used. A PFC test is carried out and the result is shown in Fig. 11.



(a) Results with HIL.



(b) Results with STDES-PFCBIDIR.

Figure 11: 1 kW test - TLTT.

Fig. 11a and Fig. 11b have the same setup on the oscilloscope. On the high side of the oscilloscope, there is the voltage  $V_a$  and the current  $I_a$  in physical value (with the difference that in Fig. 11b variables are taken directly from the circuit while in Fig. 11a they are taken from test points of the control board and then rescaled through the oscilloscope). On the low side,  $id\_ref$  and  $id\_feed$  coming from DAC1 and DAC2 of the control board are shown. The power of phase A is shown in the bottom part of the oscilloscope. Assuming a balanced system, the power is about 1 kW. The current is sinusoidal,  $id\_feed$  follows

$id\_ref$ , and the results are comparable.

## 5. Conclusions

This thesis demonstrated the feasibility of a (HIL) platform for real-time digital power conversion simulation, focusing on electric vehicle on-board chargers. Using a model-based design, the HIL system integrated control algorithms to address power conversion challenges, achieving stability and high performance. Experimental validation confirmed the platform's ability to emulate real-world conditions and its value for future innovations in digital power conversion. Future work could improve the MOSFET model to capture switching transients more accurately, enhancing control algorithm testing and fault management. This would extend the HIL platform's applicability for advanced research in electric vehicle charging systems and power conversion technologies

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