

Article

Hardware-in-the-Loop Simulation Platform for Hands-On Training in Grid-Connected Photovoltaic Systems

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Abstract

The rapid expansion of photovoltaic (PV) generation has increased the need for educational and experimental platforms that allow students and researchers to study the dynamics, control strategies, and power conversion stages of grid-connected PV systems under realistic operating conditions. Although Hardware-in-the-Loop (HIL) simulation is widely used to validate power electronic converters and control algorithms, many existing platforms rely on specialized real-time simulators that limit their accessibility in academic environments. This paper presents the design and implementation of a cost-effective HIL simulation platform for grid-connected PV systems intended for research and training applications. The proposed system integrates real hardware under test within a real-time environment that emulates PV array behavior and grid conditions, combining Controller Hardware-in-the-Loop (CHIL) and Power Hardware-in-the-Loop (PHIL) techniques. A Texas Instruments C2000 microcontroller is used as the real-time digital simulator, providing an accessible alternative to conventional real-time simulation platforms. The platform architecture, the real-time PV emulator, and the experimental implementation are described and validated through simulation and experimental results. Finally, guided laboratory practices are presented to support hands-on training in PV systems and power electronics.

Keywords: hardware-in-the-loop; photovoltaic systems; real-time simulation; renewable energies



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1. Introduction

The large-scale integration of renewable energy sources (RESs) into the power grid represents one of the most significant challenges for the stability, reliability, and power quality of modern power systems. This challenge has intensified due to the rapid growth of photovoltaic (PV) systems, which in 2024 accounted for 81% of the total increase in global renewable power capacity [1]. Due to their inherent intermittency, negligible rotational inertia, and dynamic response to grid disturbances, the integration of PV systems requires advanced methods to validate both the control strategies and the power electronics used in PV-grid interfacing [2].

To study the phenomena associated with energy generation, control, and power conversion in PV plants, Real-Time Simulation (RTS) techniques have been increasingly adopted in power system research [3]. These specialized computational frameworks are

designed to simulate complete or partial real-world processes by executing computer-based models whose computational timing matches the dynamics of the physical system, thereby guaranteeing immediate feedback and interaction [4–6]. Consequently, numerous researchers have adopted RTS to accurately model and analyze the operation of energy systems and their associated power conditioning stages [7,8].

A specific case of RTS is the Hardware-In-the-Loop (HIL) technique, which integrates physical hardware components into the simulation environment, allowing real-time testing of their behavior and performance [6]. This technique combines, within a closed-loop simulation, real physical devices and software models running in a real-time digital simulator. The physical hardware components, known as Hardware Under Test (HUT), introduce non-ideal responses into the system, enabling more realistic performance evaluations [9]. In this way, HIL facilitates the evaluation of specific devices and the analysis of system behavior without requiring the full implementation of the physical system under study.

Among HIL-based simulation techniques, two main approaches stand out: Controller Hardware-in-the-Loop (CHIL) and Power Hardware-in-the-Loop (PHIL) [10–12]. In the CHIL approach, the HUT corresponds to the control hardware, enabling the evaluation of control strategies and algorithms for various applications, such as photovoltaics [13], wind turbines [14], electrical microgrids [15], and cybersecurity studies [16]. In this case, the HUT is typically referred to as the Controller Under Test (CUT). In contrast, the PHIL technique enables the testing of power hardware devices under nominal operating conditions, including, when applicable, their embedded control systems. In many experimental platforms, CHIL and PHIL techniques are combined to enable the simultaneous testing and validation of both control and power devices [17,18]. An example of such an integrated platform is illustrated in Figure 1, where the interaction between CHIL and PHIL components within a real-time simulation environment is depicted.

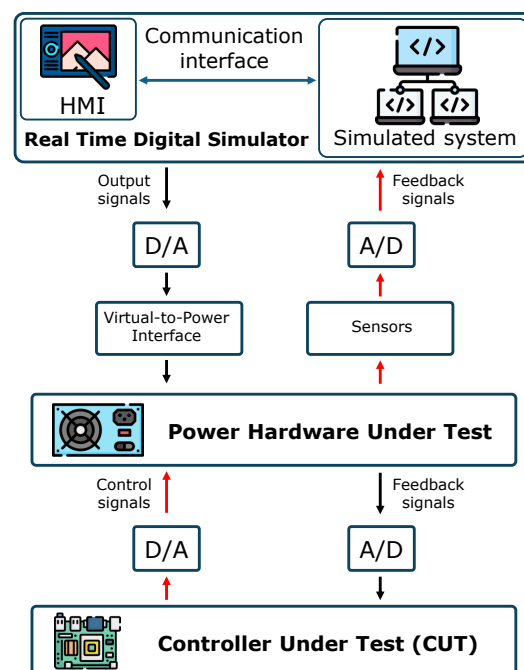


Figure 1. Integration of CHIL and PHIL techniques in a real-time test platform.

The HIL technique has been widely used to simulate grid-connected PV systems, facilitating the validation of power electronic components under different grid scenarios [19–24]. Additionally, the control strategies implemented in these devices can be evaluated in real time, providing insight into the dynamics of primary, secondary, and tertiary control systems [25–27]. In the specialized literature, numerous studies focus on modeling PV

panels and testing control systems of power conditioning units using HIL-based simulation platforms [28–34]. However, a closer examination of these works reveals that the majority rely on high-cost commercial real-time simulators such as OPAL-RT, dSPACE, or Typhoon HIL, which significantly limits their reproducibility in resource-constrained academic environments. Only a limited number of studies, such as [24,35–38], have proposed low-cost alternatives based on embedded hardware, and even these remain restricted to controller-level testing without integrating physical power hardware. This observation reinforces the need for accessible HIL platforms that combine both CHIL and PHIL capabilities within a unified and low-cost framework suitable for educational use.

In addition, HIL has been recognized as an effective technique for developing pedagogical tools aimed at training skills related to PV systems [18,39]. HIL provides practical and interactive environments where students can experiment with real hardware components while simulating the overall system, effectively bridging the gap between theory and practice [36]. This type of interactive learning allows users to gain hands-on experience with scenarios they are likely to encounter in the field when using components such as inverters, DC–DC converters, drivers, microcontrollers, sensors, and grid interfaces [40–42]. Another notable aspect of HIL as a pedagogical tool is its safety. Although handling HIL equipment requires prior knowledge of nominal operating values to ensure safe operation, the controlled HIL environment significantly reduces the risk of accidents and device damage. This aspect is particularly relevant when dealing with high-voltage PV systems or multiple configurations of PV plants, providing a safe learning environment for students and trainees.

Although these studies demonstrate the effectiveness of HIL platforms for validating PV control strategies and power electronic converters, several limitations can be identified in the existing literature. First, many reported implementations focus primarily on the validation of specific control algorithms or converter topologies rather than on the development of comprehensive experimental platforms that can be used for educational purposes. Second, most of these platforms rely on specialized real-time simulation systems such as OPAL-RT, dSPACE, or RTDS Technologies, which typically involve high acquisition and maintenance costs. These constraints limit their accessibility in academic laboratories, particularly in undergraduate and graduate training environments where budget, scalability, and ease of implementation are critical considerations. Finally, only a limited number of studies address the integration of both control and power hardware within a single experimental framework that allows users to interact with realistic grid-connected PV scenarios, particularly in laboratory environments intended for student training.

To better contextualize the contribution of this work, Table 1 presents a comparison of representative low-cost academic HIL platforms reported in the literature. Commercial real-time simulation platforms such as OPAL-RT [22,29,33], dSPACE [33], and Typhoon HIL [32] offer high-fidelity simulation, extensive I/O capabilities, and support for both CHIL and PHIL configurations. However, their high acquisition and maintenance costs (typically ranging from tens to hundreds of thousands of dollars) significantly limit their accessibility in undergraduate and graduate laboratory environments, particularly in institutions with constrained budgets. As shown in Table 1, existing low-cost platforms either support CHIL or PHIL but not both within a single integrated framework, or they lack an explicit educational purpose.

Consequently, there remains a need for accessible, flexible, and low-cost HIL platforms that integrate both CHIL and PHIL techniques, specifically designed to support hands-on training in grid-connected PV systems and power electronics. Such platforms must provide sufficient fidelity to emulate the dynamic behavior of real PV plants under varying operating conditions, while remaining reproducible in resource-constrained

academic environments. Bridging this gap between theoretical instruction and practical experimentation is essential to prepare the next generation of engineers for the challenges of modern renewable energy systems.

Table 1. Comparison of low-cost academic HIL platforms for grid-connected PV systems.

Platform	Simulator Hardware	CHIL	PHIL	PV Emul.	Educ. Use
Bastos et al. [35] (2019)	TI DSP LaunchPad C2000Delfino F28377S	✓	×	Lim.	×
Samano-Ortega et al. [36] (2020)	NI myRIO-1900 + LabVIEW	✓	×	✓	✓
Samano-Ortega et al. [37] (2022)	NI myRIO + LabVIEW	✓	×	✓	✓
Martínez-Nolasco et al. [38] (2024)	NI myRIO-1900 + LabVIEW	✓	×	✓	Lim.
Nguyen et al. [24] (2025)	TI DSP F28379D	✓	✓	✓	×
Proposed platform	TI C2000 LAUNCHXL-F28379D	✓	✓	✓	✓

✓: applies; ×: does not apply; Lim.: limited.

To address these challenges, this paper presents the design and implementation of a HIL simulation platform for grid-connected PV systems specifically developed for educational and training purposes. The proposed system integrates a real-time PV emulator with physical hardware units under test, enabling hands-on experimentation and practical understanding of PV system dynamics under realistic operating conditions. The main contributions of this work are summarized as follows:

- The development of a cost-effective real-time HIL simulation platform for grid-connected PV systems using a Texas Instruments C2000 microcontroller as the real-time digital simulator, providing an accessible alternative to conventional commercial real-time simulation platforms.
- The integration of both CHIL and PHIL techniques within a single experimental platform, enabling the testing and validation of real control and power hardware devices under real-time simulated grid conditions.
- The implementation of a real-time PV emulator that reproduces the electrical behavior of PV arrays, allowing the evaluation of power conversion stages and control strategies in different operating scenarios. The emulator is configured from a user-friendly graphical interface in Matlab/Simulink, enhancing student interaction and supporting easy system monitoring and operation; and its architecture includes a proposed virtual-to-power stage built around a silicon carbide (SiC)-based power converter, which enables the integration of power hardware devices under test.
- The development of guided laboratory practices that use the proposed platform as a pedagogical tool to support hands-on training in PV systems, power electronics, and grid integration concepts.

The remainder of the paper is organized as follows. Section 2 outlines the architecture and operation of the HIL simulation platform and details the software models, control strategies, and hardware components used in the experimental implementation. Section 3 presents the simulation and experimental results for the real-time PV emulator, while Section 4 validates the proposed platform design through the experimental results of the entire system. Section 5 describes how the system will be used as a teaching tool for training engineering students. Finally, Sections 6 and 7 provide a discussion and outline the main conclusions of the work.

2. Design and Implementation of the HIL Simulation Platform

The architecture of the proposed platform for real-time simulation of grid-connected PV systems is illustrated in Figure 2. It consists of two main stages: a real-time PV emulator and the HUT. The PV emulator also comprises two subsystems: a Real-Time Digital Simulator (RTDS) and a virtual-to-power interface. This emulator reproduces the behavior of the PV generator, modeled and implemented in the RTDS.

The second stage of the platform includes two HUT components. One of them is the power conversion unit that interfaces the PV generator with the electrical grid, called the Power Hardware Under Test (P-HUT). The other is the control device for the power conversion unit, implemented on a real microcontroller and referred to as the CUT.

As seen in Figure 2, the PV emulator is connected to the low-voltage power grid for its power supply. Furthermore, a programmable AC power source is used to emulate the voltage at the point of common coupling (PCC) with the distribution grid, enabling testing under abnormal or varying grid conditions. Finally, a Human–Machine Interface (HMI) is used to manage the configuration of the RTDS, the CUT, and the programmable AC source, as well as to monitor signals generated by the real-time simulation.

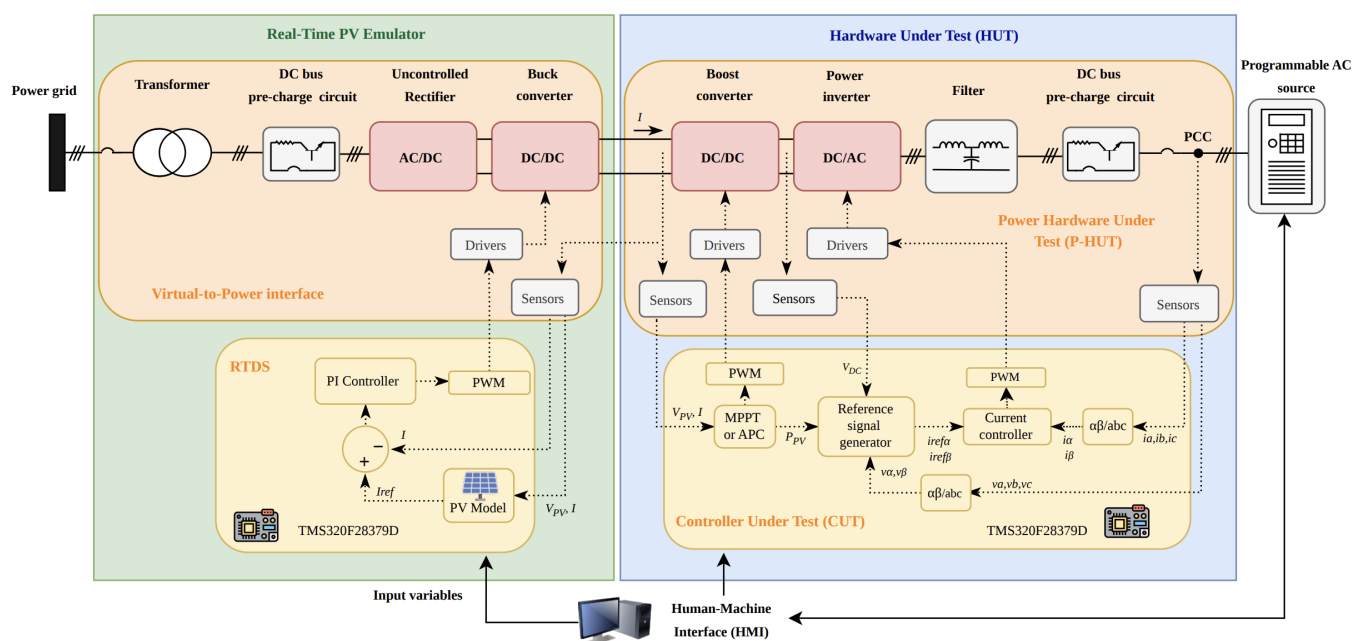


Figure 2. General scheme of the HIL simulation platform.

A description of the initial steps in the platform design was presented in [6], before its practical implementation and the final adjustments necessary to ensure proper operation. A comprehensive description of the final design, along with details of the platform's implementation, is presented below.

2.1. Real-Time PV Emulator

This stage replicates the behavior of the PV generator in real time, mirroring the performance of the real physical system. To achieve this, the PV generator model is implemented and solved in a RTDS, specifically using the LAUNCHXL-F28379D control card from Texas Instruments. The output of the executed model corresponds to the resulting PV generator output current, denoted as the reference signal I_{ref} in Figure 2.

To interface the RTDS with the HUT, a virtual-to-power stage is proposed. This interface delivers a controlled current to the P-HUT, corresponding to the output current I shown in Figure 2, which tracks the reference current I_{ref} calculated by the RTDS. Addi-

tionally, a sensing stage measures the voltage V_{PV} at the DC input terminals of the P-HUT, representing the voltage of the PV generator. This voltage signal is then fed back to the PV generator model running in the RTDS at each simulation step, allowing the system to update the generated current accordingly.

The control algorithm for the virtual-to-power interface is also implemented in the RTDS. It adjusts the duty cycle of a DC/DC buck converter to ensure that the output current generated by the interface (I) tracks the reference current computed by the RTDS (I_{ref}).

In this way, the RTDS runs both the mathematical model of the PV generator and the buck converter controller. This platform is programmed and configured from Matlab/Simulink (Version R2023b) through the user-friendly interface shown in Figure 3, enabling student interaction with the implemented models and supporting easy system monitoring and operation. The following sections provide a more detailed description of each of the subsystems introduced.

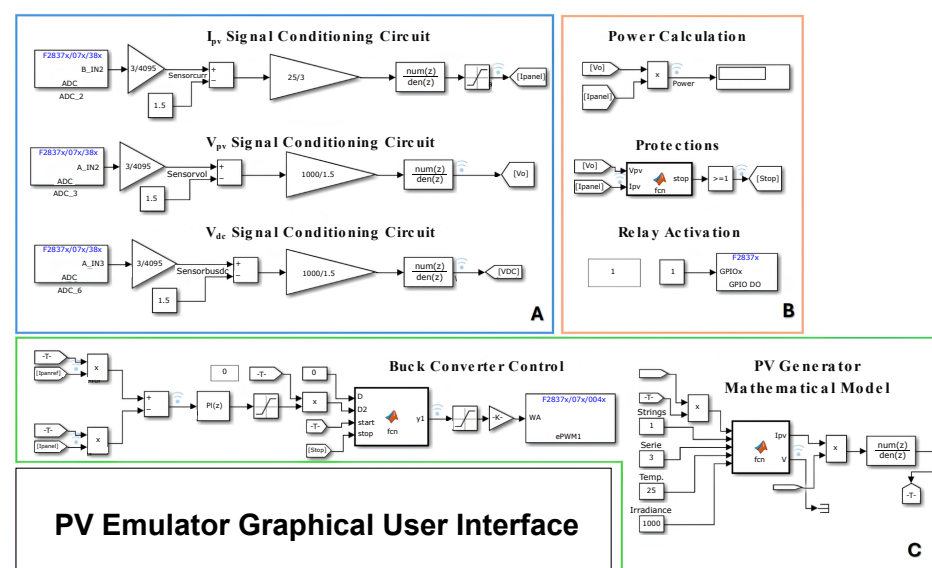


Figure 3. PV Emulator Graphical User Interface for system configuration, monitoring and operation.

2.1.1. PV Generator Model

The PV generator was modeled using the well-known single-diode equivalent circuit with series and parallel resistances, which was selected for its simplicity and proven accuracy [43]. The relationship between the output current (I) and the terminal voltage (V_{PV}) of the PV generator is expressed in Equation (1), where I_0 is the diode's reverse saturation current, V_T is the thermal voltage, and m is the ideality factor of the diode [4]. In this model, I_{PV} corresponds to the photogenerated current, which varies linearly according to solar irradiance [43]. The series resistance (R_S) and the parallel resistance (R_{SH}) represent contact/junction losses and leakage currents, respectively.

$$I = I_{PV} - I_0 \left[e^{\left(\frac{V_{PV} + I \cdot R_S}{m \cdot V_T} \right)} - 1 \right] - \left(\frac{V_{PV} + I \cdot R_S}{R_{SH}} \right) \quad (1)$$

The resulting PV generator model forms a non-linear equation, which is solved using the Newton–Raphson numerical method. Figure 4 shows the flow chart of the Newton–Raphson method implemented.

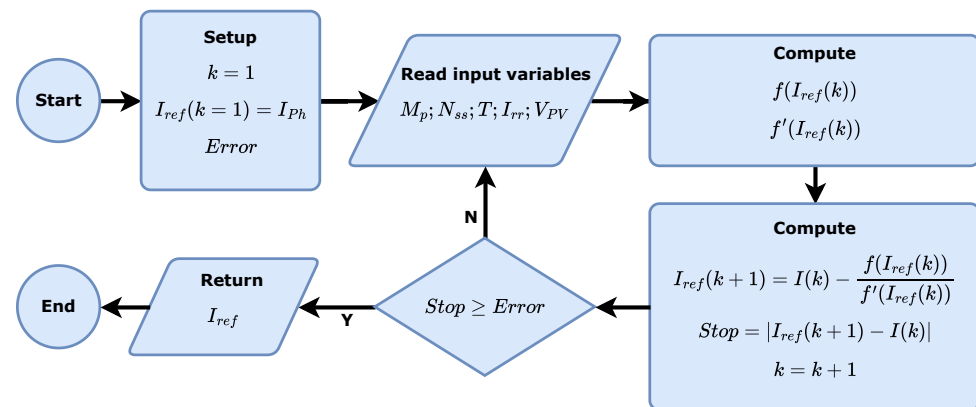


Figure 4. Newton–Raphson-based iterative process for solving the PV generator model.

In this algorithm, the input variables include the number of parallel strings in the PV array (M_p), the number of panels in series per string (N_{ss}), the cell temperature (T), the solar irradiance (I_{rr}), the measured output voltage (V_{PV}), and the measured output current (I). Based on these inputs, the function $f(I_{ref})$ is evaluated using Equation (2), along with its derivative $f'(I_{ref})$.

$$f(I_{ref}) = I_{PV} - I_0 \left[e^{\left(\frac{V_{PV} + I_{ref} \cdot R_s}{m \cdot V_T} \right)} - 1 \right] - \left(\frac{V_{PV} + I_{ref} \cdot R_s}{R_{SH}} \right) - I_{ref} \quad (2)$$

Finally, the reference signal I_{ref} is calculated as illustrated in Figure 4. A stopping criterion based on the absolute value of the current error, with a threshold of 10^{-3} A, is applied to determine convergence. Once the algorithm converges, it generates the reference current for the control algorithm of the virtual-to-power interface.

2.1.2. Virtual-to-Power Interface

This interface allows interaction between the simulated environment and the P-HUT, providing the appropriate power levels according to each subsystem. The interface includes a power circuit (shown in Figure 5), along with voltage and current sensors, as well as drivers for isolation and signal conditioning (see Figure 2).

The power circuit relies on two power electronic converters as its main elements: a three-phase uncontrolled rectifier and a SiC-based DC-DC buck converter, as detailed in Figure 5. These converters are connected to the power grid through a DC bus pre-charge circuit, a power transformer, and an autotransformer. For safety, the transformer provides galvanic isolation between the module and the electrical grid, while the autotransformer enables testing at different voltage levels. Additionally, an Acti9 iC60N 3-Pole 6 A Type C circuit breaker (CB) is installed at the input of the interface to provide overcurrent and short-circuit protection. Furthermore, the SPM-HB-SiC module employed in the DC-DC converter incorporates several built-in hardware safety features that enhance its suitability for laboratory and educational PHIL applications. These include DC-link overvoltage protection, a DC-link discharge circuit, and protective acrylic covers that reduce the risk of accidental contact with energized components.

The pre-charge circuit is responsible for gradually charging the input capacitor of the DC-DC buck converter (C_f) when the PV emulator module is initialized. Its main function is to limit the charging current and prevent excessive inrush currents that could damage the power components. The circuit consists of three 1 k Ω , 50 W wirewound resistors connected in series with a three-phase solid-state relay (SSR), model OMRON GJ-5-L. This branch is connected in parallel with a three-pole electromechanical contactor (3NO-1NC,

120 VAC, 10 A), which serves as a bypass path during normal operation. Upon system start-up, the contactor remains open and the SSR is turned on, forcing the DC-bus capacitor of the rectifier to charge through the pre-charge resistors. This arrangement limits the charging current and mitigates potentially harmful inrush currents. Once the capacitor voltage reaches a suitable level, the contactor is energized to establish a low-impedance current path, while the SSR is turned off, effectively bypassing the pre-charge resistors and minimizing conduction losses during steady-state operation.

Figure 5 details the components and key features used in the implementation of the power circuit for the virtual-to-power interface. In addition, Table 2 presents the electrical specifications and nominal operating conditions of the virtual-to-power interface, including the main parameters of the rectifier and buck converter stages used in the proposed PHIL platform.

Table 2. Electrical specifications of the virtual-to-power interface.

Parameter	Symbol	Value
Line-to-line input voltage	V_{LL}	220 Vrms
Grid frequency	f	60 Hz
Pre-charge resistance	R_c	500 Ω
Rectifier DC-bus capacitor	C_r	520 μF
Buck converter output capacitor	C_{buck}	500 μF
Buck converter inductor	L_{buck}	7.5 mH
Buck converter switching frequency	f_s	20 kHz
Buck converter nominal input voltage	V_g	310 V
Nominal output voltage	V_{PV}	310 V
Nominal output power	P_{PV}	1 kW
Nominal output current	I	11.2 Arms

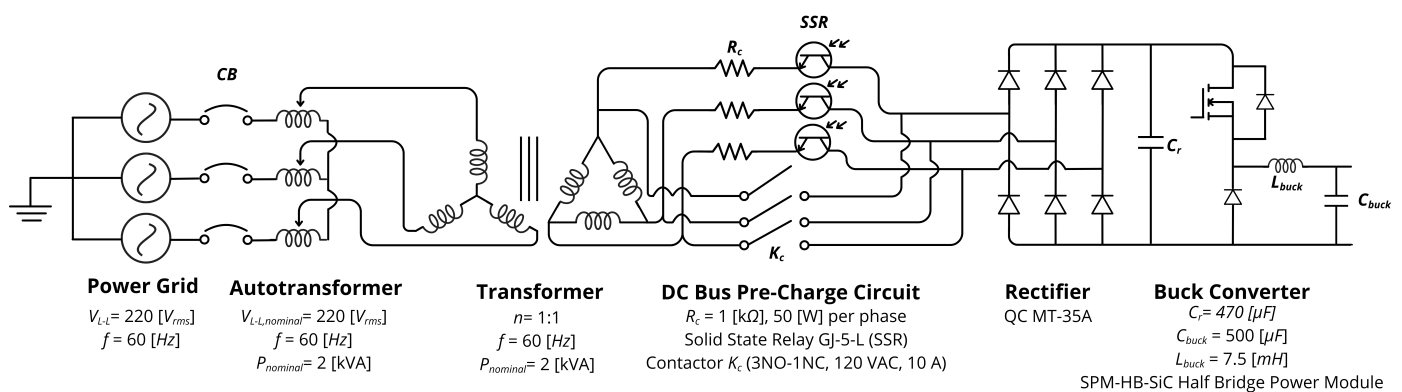


Figure 5. Schematic of the power circuit for the virtual-to-power interface.

The virtual-to-power interface enables real-time, bidirectional exchange of information between the HUT and the RTDS. The voltage V_{PV} , measured at the DC input of the P-HUT, is sent to the RTDS, while the reference current calculated by the RTDS is reproduced by the buck converter and injected into the P-HUT. This process ensures continuous and synchronized interaction between the components of the physical system and the simulated environment.

2.1.3. Control Strategy for the Virtual-to-Power Interface

As previously described, the virtual-to-power interface control system is applied to the DC-DC buck converter. Its objective is to ensure that the converter's output current accurately tracks the reference current computed by the RTDS.

Figure 6 presents the control strategy scheme. This includes a current-controlled system utilizing a proportional–integral (PI) regulator [44], which uses the error between the reference current I_{ref} (generated by the Newton–Raphson algorithm) and the measured output current (I); see Figure 2. The PI controller output determines the duty cycle of the buck converter, so the pulse width modulation (PWM) technique is used to generate the firing pulses for the converter transistor.

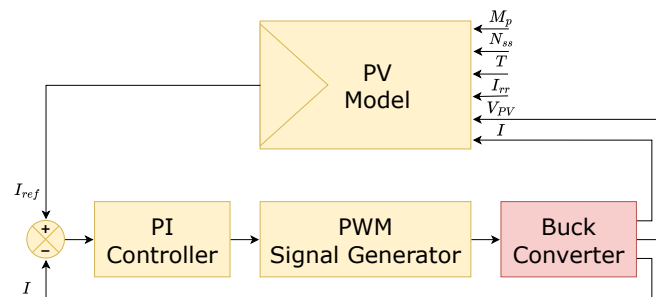


Figure 6. Control scheme of the virtual-to-power interface.

The output current controller was designed based on the small-signal model of the buck converter derived from its averaged state-space representation [45]. The nonlinear converter dynamics were linearized around the nominal operating point by introducing small perturbations in the state variables and control input while neglecting higher-order terms. The resulting small-signal model, shown in Figure 7, captures the dynamic relationship between duty-cycle variations and the output current. Based on this model, the duty-cycle-to-output-current transfer function was obtained as

$$G_p(s) = \frac{V_g}{R_e \left(L_{buck} C_{buck} s^2 + \frac{L_{buck}}{R_e} s + 1 \right)} = \frac{3.226}{3.75 \times 10^{-6} s^2 + 7.804 \times 10^{-5} s + 1}, \quad (3)$$

where V_g is the input voltage, L_{buck} is the filter inductance, C_{buck} is the output capacitance, and R_e is an equivalent load resistance which is determined from the output active power delivered by the converter. The transfer function in (3) was derived using the nominal operating conditions and electrical parameters listed in Table 2.

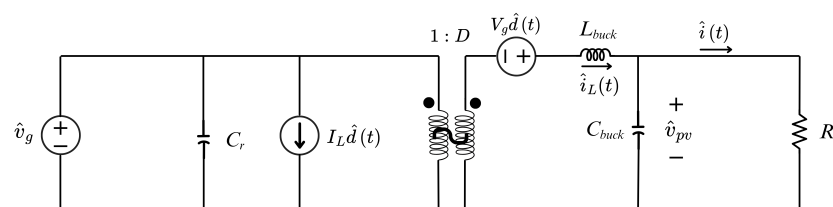


Figure 7. Small-signal model of the buck converter

To regulate the output current, a PI controller was adopted due to its simple implementation and its capability to eliminate steady-state tracking errors. The controller transfer function is defined as

$$G_c(s) = K_p + \frac{K_i}{s}, \quad (4)$$

where the proportional and integral gains were selected as $K_p = 0.013775$ and $K_i = 0.38403$, respectively. The controller design was carried out using the MATLAB (Version R2023b) SISOTOOL environment. During the tuning process, the controller parameters were adjusted to achieve a gain margin greater than 20 dB and a phase margin within the range of 45° to 70° over the entire output-power operating range, ensuring an adequate trade-off between robustness and dynamic performance.

The open-loop transfer function was obtained as

$$L(s) = G_c(s)G_p(s), \quad (5)$$

and subsequently analyzed in the frequency domain through its Bode plot, shown in Figure 8. The controller gains were adjusted to achieve a suitable compromise between dynamic response and stability. The resulting design exhibits a crossover frequency of 82.9 Hz, a phase margin of 62.9° , and a gain margin of 36.4 dB at the nominal operating point. These values indicate a well-damped response with adequate robustness against parameter variations and operating-point changes. In addition, the resulting crossover frequency of 82.9 Hz is significantly lower than the converter switching frequency (20 kHz), ensuring an adequate separation between the control-loop dynamics and the switching phenomena.

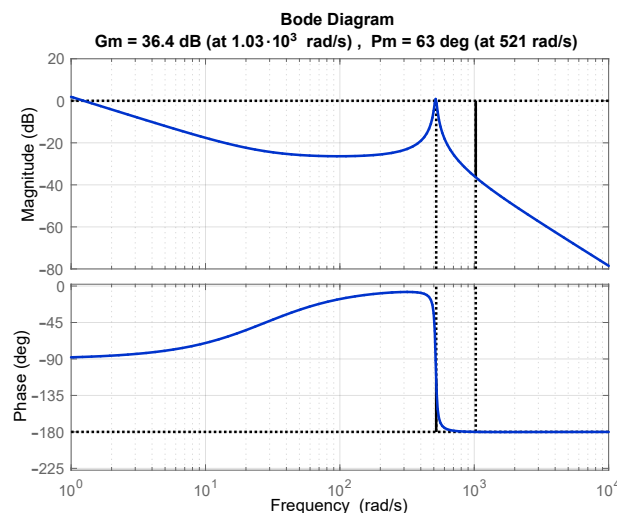


Figure 8. Open-loop Bode diagram of the buck converter current-control system.

The closed-loop transfer function is given by

$$T(s) = \frac{L(s)}{1 + L(s)}. \quad (6)$$

The closed-loop poles are located at $-9.81 \pm j527.63$ rad/s and -1.19 rad/s. Since all poles lie in the left-half complex plane, stable closed-loop operation is guaranteed. The real pole at -1.19 rad/s dominates the system dynamics due to its proximity to the imaginary axis.

To evaluate the robustness of the controller, the output power was swept from 0 to 1000 W while maintaining a constant input voltage of 310 V. For each operating point, the gain margin and phase margin were computed and are presented in Figure 9. The results demonstrate that the proposed PI controller preserves stability and satisfactory dynamic performance throughout the entire operating range. In addition, the gain-margin and phase-margin variations presented in Figure 9a,b confirm the robustness of the control system under output-power changes.

It is worth noting that an additional software-based protection mechanism was implemented in the virtual-to-power interface. This protection continuously monitors the output voltage and current (see Figure 3) and automatically disables the buck converter whenever either variable exceeds its allowable nominal limit. As a result, the interface is protected against abnormal operating conditions, thereby enhancing the safety and reliability of the PHIL platform.

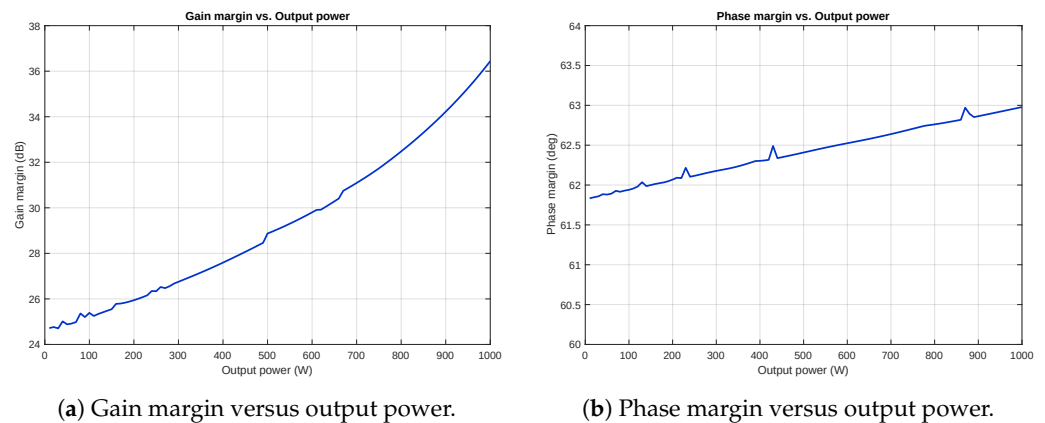


Figure 9. Variation of stability margins with output power.

2.2. Power Hardware Under Test (P-HUT)

The power hardware devices under test include power electronic converters, drivers, sensors, grid-connection filters, and other components of the power conditioning unit, as illustrated in Figure 2. This P-HUT represents the actual physical devices used to interface the PV generator with the electrical grid.

A schematic of the power devices within this conversion unit is shown in Figure 10. The unit comprises a DC-DC boost converter, DC bus capacitors, a three-phase power inverter, a passive LCL filter, and a DC bus pre-charge circuit. The boost converter is responsible for regulating the operating point of the PV generator, whereas the power inverter supplies AC current to the grid according to the active and reactive power to be delivered by the photovoltaic system. An LCL filter is employed to attenuate high-order harmonic distortion caused by inverter switching. Additionally, the pre-charge circuit ensures a gradual charging of the DC bus capacitors, thereby limiting inrush currents during system initialization. The pre-charge circuit employs the same hardware specifications and operating procedure as those described in Section 2.1.2 for the virtual-to-power interface. Finally, an Acti9 iC60N 3-Pole 6 A Type C circuit breaker (CB) is connected at the output of the P-HUT to provide overcurrent and short-circuit protection.

Figure 10 also details the components and key features of the power conversion unit. The DC bus consists of five capacitors, each one of 470 μF (reference ALA7DA471CF450). Four of these capacitors, labeled C_i , are integrated into the SPM-VFD-SiC module, which serves as the inverter. The remaining capacitor, labeled C_b , is integrated into the SPM-HB-SiC module, used to implement the boost converter. Likewise, both power converters are based on silicon carbide (SiC) transistors.

The SPM-HB-SiC and SPM-VFD-SiC power modules incorporate several built-in safety features, including DC-link overvoltage protection and a DC-link safety discharge circuit. In addition, the modules provide dedicated test points and are enclosed within protective acrylic covers, making them suitable for laboratory and educational environments.

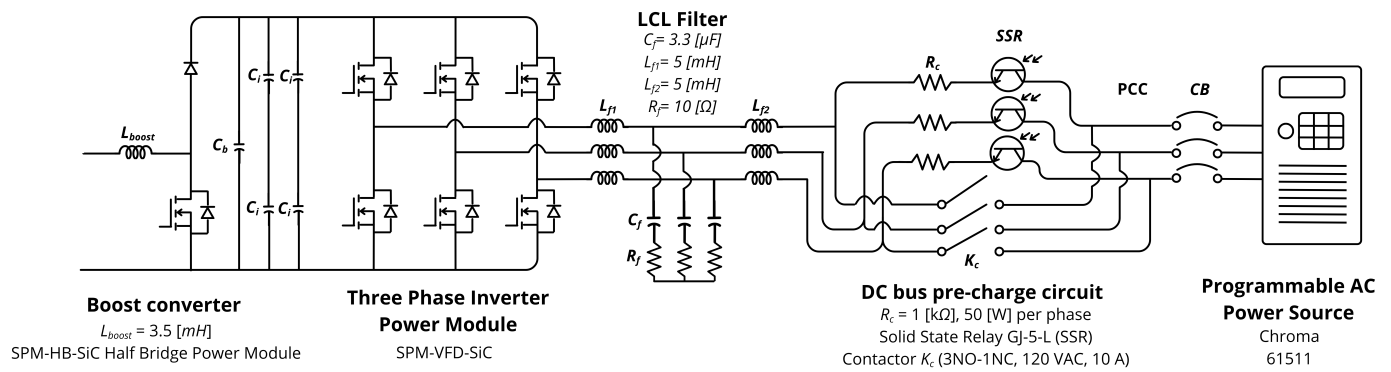


Figure 10. Schematic of the power conversion unit in the P-HUT.

2.3. Controller Under Test (CUT)

The second HUT is the embedded controller that is used to test the control algorithms of the two power electronic converters in the power conditioning unit. The control algorithms are implemented on a Texas Instruments LAUNCHXL-F28379D control card, distinct from the one employed as the RTDS to execute the PV emulator model. The control card is programmed using a MATLAB/Simulink model, enabling users to modify and implement control strategies according to the specific needs of the study, thereby facilitating the flexible design and deployment of control systems. Users can access the model through the human-machine interface, as depicted in Figure 2. The control system consists mainly of the following three loops:

2.3.1. Maximum Power Point Tracker (MPPT) and Active Power Curtailment (APC)

The MPPT is employed when the PV generator can supply its entire energy production without being constrained by the operational conditions of the distribution network or the nominal capacity of the power inverter. In this case, the MPPT algorithm continuously adjusts the output voltage of the PV generator to track and reach its maximum power point (MPP) under every operating condition. In scenarios where active power injection is restricted due to operating conditions, such as voltage sags or reactive power support requirements that risk exceeding the inverter's current limits, the APC algorithm should be triggered to limit the PV generator's power production accordingly. As these algorithms operate by adjusting the duty cycle of the DC-DC boost converter, a pulse width modulation (PWM) technique is required to generate the appropriate gate signals for the converter's switching transistor.

2.3.2. Reference Signal Generator

This algorithm determines the reference currents to be injected into the power grid, ensuring synchronization with the voltage at the PCC (v_g) [46]. This control loop typically performs three main tasks: regulating the active and reactive power injected, synchronizing the injected currents with the sequence components of the voltages in the PCC, and maintaining the DC bus voltage at its reference value. These control strategies determine the operating functions of the PV inverter in accordance with the grid operator requirements, as well as any additional grid support features that may be implemented.

2.3.3. Current Controller

This control strategy determines the reference voltage at the inverter output to ensure that the currents injected by the PV system into the grid accurately follow their reference values. Once the reference voltage is calculated, the inverter's transistor gate signals are generated using a PWM technique. This algorithm aims to provide

precise reference current tracking with minimal steady-state error, while ensuring that the current injected into the grid complies with harmonic distortion limits defined by standards such as IEEE 1547 or equivalent.

2.3.4. Algorithms Employed Under Normal Operating Conditions

While numerous algorithms have been proposed in the scientific literature for each control loop, the following were implemented in the prototype to validate system functionality under normal operating conditions:

- MPPT: The traditional Perturb and Observe (P&O) method [47] was implemented as the MPPT algorithm. Based on current (I) and voltage (V_{PV}) measurements at the output terminals of the PV generator, it determines whether to increase or decrease the duty cycle of the boost converter. The objective is to continuously adjust the operating point of the PV generator emulator to reach and maintain the MPP. This approach ensures efficient system operation, maximizing energy extraction from the PV generator under varying irradiance and temperature conditions. As normal operation is considered, no action from an APC algorithm is required.
- Reference signal generator: Reference currents are computed in the α - β reference frame using the instantaneous power theory [48]. Equation (7) expresses the resulting reference currents ($i_{ref\alpha}$ and $i_{ref\beta}$) as functions of the PCC voltages in the α - β frame (v_α and v_β), and the reference active and reactive powers (P^* and Q^* , respectively) [6].

$$\begin{bmatrix} i_{ref\alpha} \\ i_{ref\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} P^* \\ Q^* \end{bmatrix} \quad (7)$$

The reference active power is determined as the sum of the active power supplied by the PV generator (P_{PV}) and an additional component required to maintain the inverter DC bus voltage (V_{DC}) at its specified reference (V_{DCref}), with the latter obtained through a PI controller, as expressed in Equation (8). In this equation, K_P and K_I represent the proportional and integral gains of the PI controller, respectively [6].

$$P^* = P_{PV} + K_P(V_{DCref} - V_{DC}) + K_I \int (V_{DCref} - V_{DC})dt \quad (8)$$

For the experimental tests conducted in this article, the reactive power reference (Q^*) was set to zero. Nonetheless, it can be adjusted to comply with grid operator requirements or to enable specific grid support functions incorporated in the inverter.

- Current controller: A proportional-resonant (PR) controller [49] in the α - β reference frame is considered to track the reference currents. Additionally, the three-phase sinusoidal PWM technique is used to generate the inverter's firing pulses [6].

2.4. Assembled Setup

Figure 11 presents a photo of the implemented setup, showing both a top and a front perspective. The components of the real-time PV emulator are located on the left side of the image, whereas the elements of the HUT stage are on the right.

To validate the operation of the experimental setup, offline simulations were conducted prior to hardware testing for the PV emulator. These simulations served to validate the parameters of the system in a range of operating scenarios, providing a baseline for comparison with experimental data. The following section presents the results of these offline simulations and discusses their correlation with the experimental measurements. Subsequently, Section 4 presents the experimental results that validate the operation of the complete HIL platform.

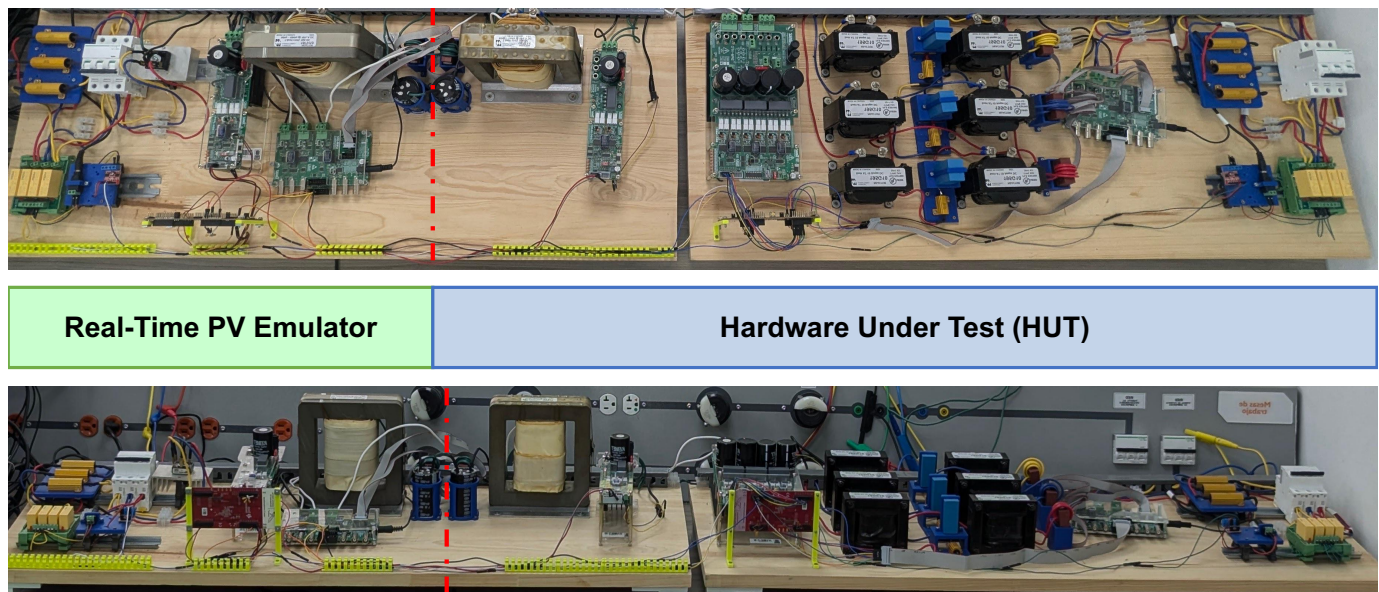


Figure 11. Top and front photo of the implemented system.

3. PV Emulator Testing

The performance of the proposed real-time PV emulator was evaluated through both offline simulations in Matlab/Simulink and experimental tests on the implemented prototype. This test was configured to replicate the Current–Voltage (I–V) characteristic of the PV generator under various irradiance levels. During this experiment, the emulator’s behavior was independently examined, without including the HUT. The objective was to verify the proper operation of the emulator itself, ensuring its capability to accurately reproduce the desired photovoltaic characteristics before being integrated with the HUT.

The PV generator was set up to emulate three series-connected A10J-S72-180 PV panels, each panel rated at 180 W, with an open-circuit voltage of 44.06 V and a short-circuit current of 5.31 A under standard test conditions (STCs). Table 3 summarizes the parameters used in both the offline simulations and the experimental tests. As seen, the real-time simulation was executed with a simulation step of 200 μ s (5 kHz).

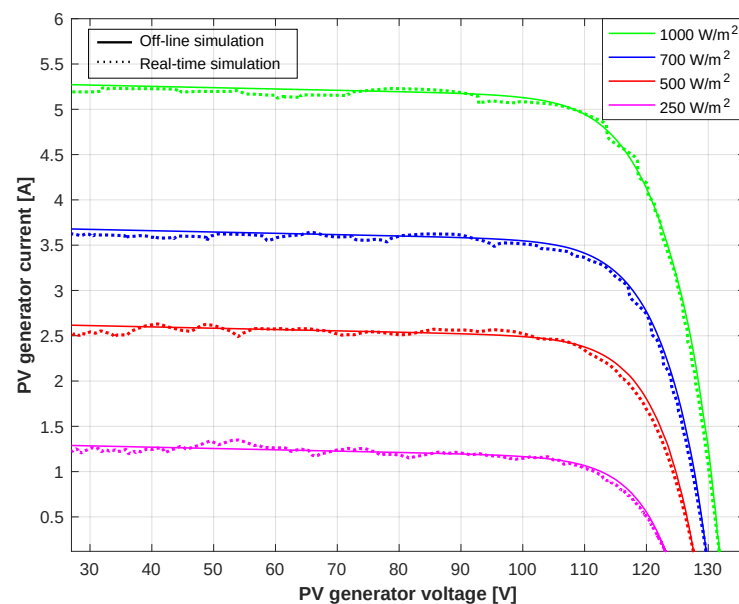
The tests were conducted under four different levels of uniform irradiance on the PV panels: 250 W/m², 500 W/m², 700 W/m², and 1000 W/m². For consistency and to isolate the effect of irradiance, the cell temperature was kept constant 25°C throughout all tests.

To reproduce the characteristic curve of the PV generator during the experimental test, a manual rheostat was connected to the output of the emulator (output of the buck converter) and its resistance was swept from 1 k Ω to 5 Ω for each irradiance level considered. Furthermore, the switching frequency for the DC–DC buck converter was set to 20 kHz, and the input voltage of this converter was kept at 140 V. This approach enables the tracing of the I–V curve by systematically varying the operating point across a wide range of current and voltage values for the PV emulator. The test aimed to observe how changes in solar irradiance influence the output current and voltage of the PV generator, as well as to validate the expected non-linear behavior of the PV modules.

Figure 12 presents the I–V curves obtained for the four irradiance levels, both from off-line simulations and from the experimental test using the real-time PV emulator. As expected, increasing irradiance results in a higher short-circuit current, while the open-circuit voltage experiences only a slight increase. This behavior is consistent with the theoretical characteristics of PV cells, confirming the accuracy of the simulated PV model.

Table 3. Parameters used for testing the PV emulator

Parameter	Value
Number of series-connected panels	3
PV generator voltage at MPP (STC)	110.2 V
PV generator current at MPP (STC)	4.9 A
PV generator power at MPP (STC)	540 W
PV cell temperature	25 °C
Irradiance levels on the PV generator	250 W/m ²
	500 W/m ²
	700 W/m ²
	1000 W/m ²
Buck converter input voltage	140 V
Buck converter switching frequency	20 kHz
Operating frequency for the PI controller	5 kHz
PI controller for the virtual-to-power interface	$K_p = 0.013775$
	$K_i = 0.38403$
Real-time simulation step	200 μ s

**Figure 12.** I–V characteristic curves of the PV generator at various irradiance levels obtained from both the real-time PV emulator (experimental results) and off-line simulations.

The experimentally measured current and voltage values were closely aligned with the off-line simulation results for each irradiance level presented in Figure 12. This scenario allows evaluating the performance of the PV emulator under various operating conditions, providing fundamental data for the validation of the proposed system.

To quantitatively evaluate the accuracy of the proposed real-time PV emulator, a comparative analysis between the offline simulation and the experimental results was conducted. Table 4 summarizes the electrical parameters extracted from the I–V curves for each irradiance level, alongside the Root Mean Square Error (RMSE) of the current. The experimental values for maximum power (P_{mpp}) and open-circuit voltage (V_{oc}) closely tracked the theoretical model. Furthermore, the RMSE remains below 0.06 A across all

tested irradiances, confirming the fidelity of the emulator in reproducing the PV generator behavior under steady-state conditions.

Table 4. Steady-state performance metrics and error comparison: Off-line simulation vs. Hardware-in-the-Loop (HIL).

Irradiance (W/m ²)	Environment	P_{mpp} (W)	V_{mpp} (V)	I_{mpp} (A)	V_{oc} (V)	Fill Factor	RMSE (A)
1000	Off-line	544.58	111.23	4.8958	131.86	0.7836	–
1000	HIL	549.00	113.16	4.8515	131.78	0.7949	0.0597
700	Off-line	375.38	110.79	3.3882	129.72	0.7870	–
700	HIL	370.50	112.59	3.2907	129.68	0.7843	0.0550
500	Off-line	261.32	109.56	2.3852	127.70	0.7826	–
500	HIL	260.90	107.49	2.4273	127.64	0.7773	0.0544
250	Off-line	119.20	106.18	1.1226	123.20	0.7516	–
250	HIL	121.10	103.99	1.1645	123.11	0.7290	0.0379

Evaluation of the Real-Time Execution Capability of the PV Emulator

To evaluate the real-time capability of the PV emulator, the execution-time performance of the TI LAUNCHXL-F28379D controller, which serves as the real-time digital simulator (RTDS), was assessed while executing both the PV generator mathematical model and the buck converter control algorithm. As described in Section 2.1.1, the PV model is solved using a Newton–Raphson iterative method with a convergence criterion based on an absolute current error threshold of 10^{-3} A and a maximum of 10 iterations per execution cycle. Both the real-time simulation and control tasks are executed with a sampling period of 200 μ s (5 kHz). Experimental measurements indicate that the combined execution time of the Newton–Raphson PV-model solver and the virtual-to-power interface controller is approximately 175 μ s on average. This execution time remains below the available computation window of 200 μ s, corresponding to a processor utilization of approximately 87.5%. These results confirm that the proposed implementation satisfies the real-time requirements of the platform without overruns, while still maintaining a computational margin for auxiliary functions such as data acquisition and monitoring.

4. Experimental Results for the Complete HIL Simulation Platform

This test focuses on evaluating the performance of the complete HIL simulation platform for grid-connected PV systems, with the HUT connected to the PV emulator according to the complete configuration illustrated in Figure 2. Table 5 presents the system parameters used in the test. As observed, the inverter switching frequency was set to 10 kHz, while both DC-DC converters operated at 20 kHz. In contrast, the MPPT algorithm was executed at 100 Hz, whereas the inverter control algorithm was set to operate at 5 kHz. Moreover, the same PV generator used in the previous test was considered, with its main parameters given in Table 3. This table also shows the parameters used for the PV emulator; however, different irradiance levels were considered for this test.

To provide a clearer description of the scenario, Figure 13 illustrates a timeline that details the initialization process of each component of the system along with the irradiance variations defined for each time interval. The system initialization occurred between 0 and 145 s, following a defined protocol that included the progressive activation of the control systems and the initial charging of both the inverter DC-link capacitors and the buck converter input capacitor. Regarding the irradiance profile, between 145 and 225 s the PV emulator started operating at an irradiance of 600 W/m², which subsequently increased

to 800 W/m^2 and finally to 1000 W/m^2 . From 225 to 325 s, the irradiance remained constant at 1000 W/m^2 . From 325 s onward, the irradiance level was progressively reduced in steps of 100 W/m^2 until it reached 400 W/m^2 .

Table 5. Parameters used for testing the complete HIL simulation platform.

Parameter	Value
Inverter DC bus reference voltage	150 V
Peak phase voltage of the electrical grid at the PCC	60 V
Frequency of the electrical grid at the PCC	60 Hz
Boost converter switching frequency	20 kHz
Inverter switching frequency	10 kHz
Operating frequency for the MPPT algorithm	100 Hz
Operating frequency for the inverter control algorithm	5 kHz
PR regulator for the current controller	$K_{pr} = 10.36$ $K_{ir} = 11701$
PI controller for the DC bus voltage	$K_P = 0.1$ $K_I = 4$

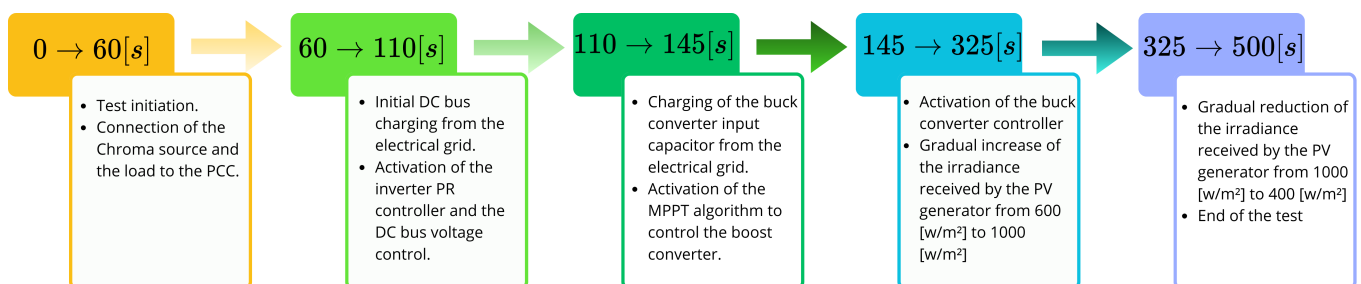


Figure 13. Timeline of the full-system experimental test.

The experimental results of the current delivered by the PV generator and its corresponding emulator reference current are presented in Figure 14, while the active power supplied by the PV generator is depicted in Figure 15. The output voltage of the PV emulator is presented in Figure 16 and the voltage in the DC bus of the power inverter during the test interval is illustrated in Figure 17. As can be observed, the activation of the buck converter at 145 s enables the photovoltaic emulator.

The results indicate that the PV generator current closely tracks the reference current after reaching steady state, demonstrating proper and stable system operation. A dynamic evaluation of the step responses in Figure 14 reveals a settling time (t_s) ranging from 10 to 15 s to reach the steady-state error band after each irradiance variation. Furthermore, the transient response exhibits a maximum dynamic overshoot of approximately 0.7 A during the steepest ascending steps (e.g., at $t \approx 210$ s), which is effectively damped by the control loops without causing instability. Minor fluctuations are observed in the current and power signals once steady state is reached, primarily due to the switching behavior of the three power electronic converters and the interaction among the multiple control loops implemented in the system.

The plots also show the correct MPP tracking under irradiance variations, both in the interval from 145 to 325 s (irradiance increased from 600 W/m^2 to 800 W/m^2 and then to 1000 W/m^2 , holding this final irradiance level constant over the last part of this interval) and in the interval from 325 to 500 s (decreasing steps of 100 W/m^2 until reaching 400 W/m^2). The PV generator operates at the maximum power point after reaching steady

state as a result of the control algorithm implemented for the boost converter, which verifies the proper operation of this control loop.

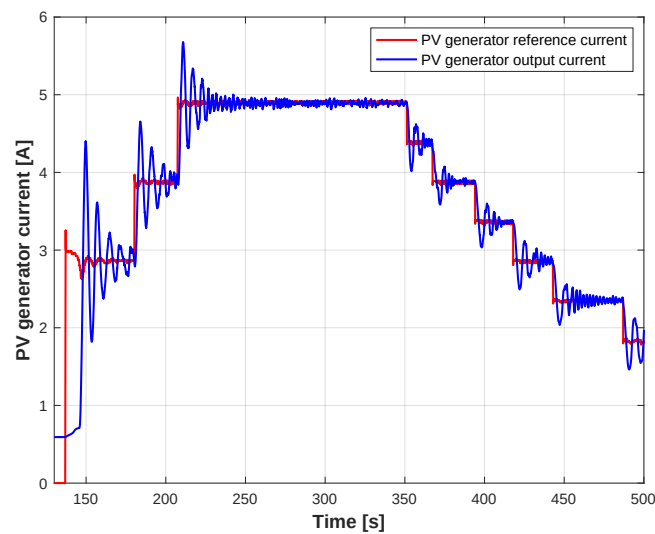


Figure 14. Output current vs. reference current of the PV emulator—Experimental results.

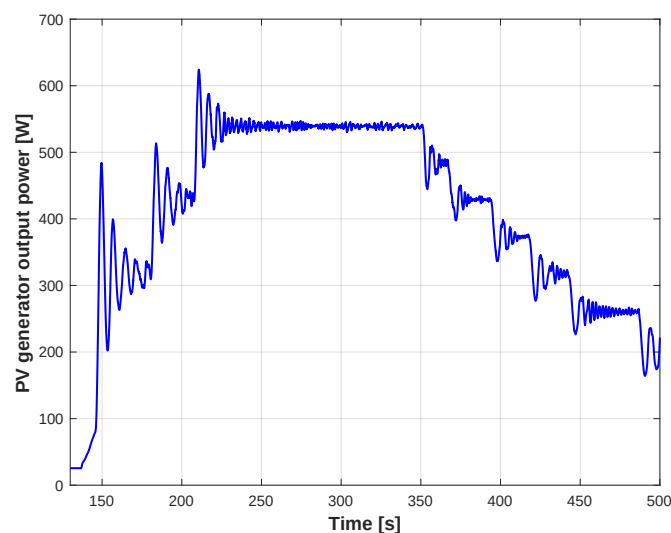


Figure 15. Output power supplied by the PV emulator—Experimental results.

The DC bus voltage of the power inverter tracks its reference value of 150 V, confirming the proper operation of the PI controller, as illustrated in Figure 17. Despite the abrupt power steps introduced by the irradiance changes, the DC-link voltage demonstrates a robust dynamic regulation. The maximum voltage deviation during the most severe transient is restricted to approximately 25 V (amounting to a 16.6% overshoot), with a recovery time of less than 15 s to return to the nominal 150 V reference. Under steady-state conditions, the peak-to-peak voltage ripple remains bounded within an acceptable margin.

Figure 18 presents the voltage measured at the PCC and the current injected by the power inverter into the grid both for phase a , whereas Figure 19 depicts the inverter reference currents in the α - and β -axes (red) compared with the currents injected into the grid (sensed currents) in the same axes (blue). These results confirm the proper operation of the control system, demonstrating that the reference current generation stage provides the appropriate grid-synchronized currents at the PCC and that the PR current controller

ensures accurate tracking of the reference current. To quantitatively assess the AC tracking performance and power quality, a steady-state waveform analysis was conducted on the $\alpha - \beta$ currents. As depicted in Figure 19, the injected currents exhibit highly accurate tracking with negligible phase shift relative to the reference signals. The minor deviations observed correspond predominantly to the high-frequency switching ripple of the inverter, yielding a measured Root Mean Square Error (RMSE) of 0.2961 A and 0.3375 A for the α and β axes, respectively. Furthermore, the Total Harmonic Distortion (THD) of the injected current (i_α) was calculated to be 3.72%, which is well below the 5% limit stipulated by international grid interconnection standards such as IEEE 1547. This low harmonic content confirms that the Proportional-Resonant (PR) controller, alongside the output filter, effectively ensures a high power quality injection into the electrical grid.

This level of performance is considered sufficiently accurate for the intended application, ensuring reliable operation under typical grid-connected conditions.

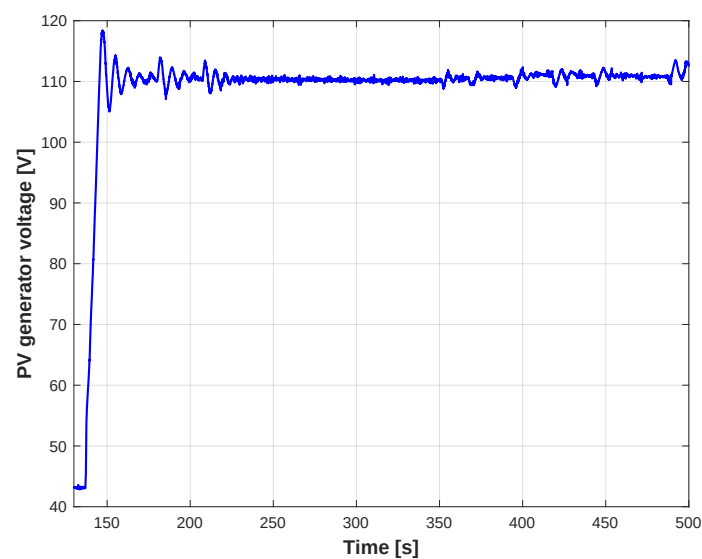


Figure 16. PV emulator output voltage—Experimental results.

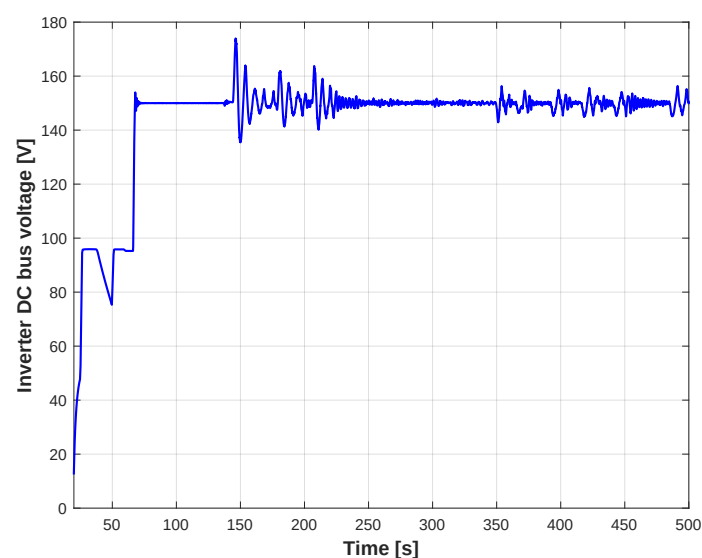


Figure 17. Inverter DC-link voltage—Experimental results.

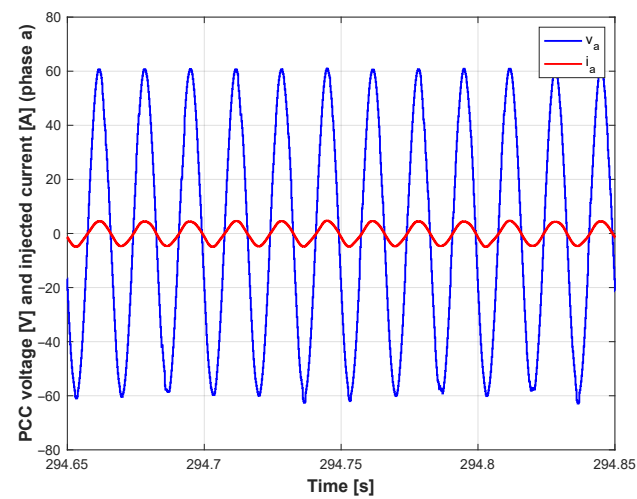
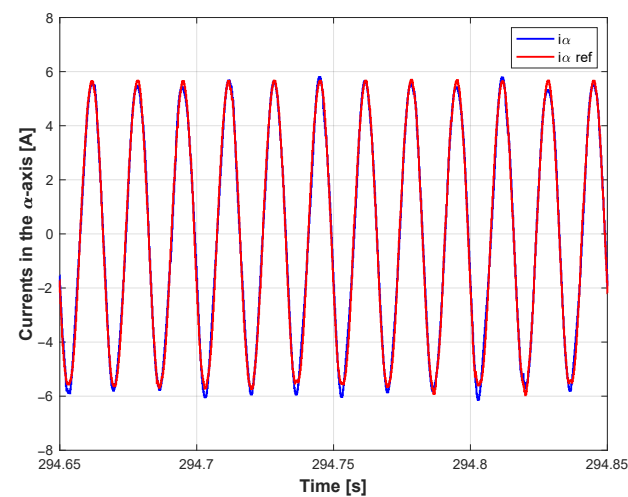
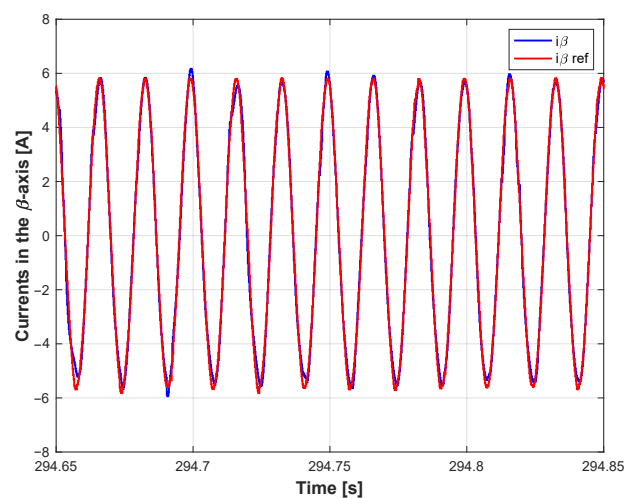


Figure 18. PCC voltage (phase a) and current injected into the electrical grid (phase a)—Experimental results.



(a) Currents in the α -axis



(b) Currents in the β -axis

Figure 19. Injected vs. reference currents in the α - β frame—Experimental results.

5. Training Strategies

The HIL simulation platform for grid-connected PV systems will allow the Department of Electrical, Electronic, and Telecommunications Engineering of the Industrial University of Santander (Colombia) to have a versatile and safe tool to carry out laboratory practices where undergraduate and graduate students can gain hands-on experience and a practical understanding of PV systems. The main training strategy will involve the development of guided laboratory practices. In these practices, learning objectives are defined, while general instructions are given, stimulating creativity and autonomous experimentation. Table 6 summarizes the difficulty level, target audience, and main assessment indicators associated with each practice. Graduate students are expected to engage more deeply with the analytical and design aspects of each activity, while undergraduate students focus on observation, configuration, and interpretation of results.

Table 6. Summary of laboratory practices.

Practice	Difficulty Level	Target Audience	Assessment Indicators
(1) Introduction to the HIL platform	Basic	Undergrad.	Component identification quiz; safe startup protocol checklist
(2) PV emulator basic model	Basic/Intermediate	Undergrad.	Correct I-V and P-V curves obtained; parameter configuration report
(3) MPPT controller operation	Intermediate	Undergrad./Graduate	Efficiency comparison between algorithms; MPP tracking time and ripple analysis
(4) Complete system in normal operation	Intermediate	Undergrad./Graduate	Power flow monitoring report; steady-state error quantification
(5) PV shading modeling	Intermediate/Advanced	Graduate	Multiple-peak P-V curve identification; power loss quantification under shading patterns
(6) Abnormal grid conditions	Advanced	Graduate	THD and power quality metrics; comparison with baseline; critical analysis of state-of-the-art strategies

The main practices that will be carried out with the PV simulator are the following. These are organized in increasing order of complexity, from basic instrumentation and system familiarization to advanced control and grid interaction studies. Practices 1 and 2 are intended for undergraduate students in power electronics or renewable energy courses, where the emphasis is on system identification and experimental observation. Practices 3 and 4 are suitable for both undergraduate and graduate levels, requiring deeper understanding of control algorithms and system dynamics. Practices 5 and 6 are primarily targeted at graduate students, involving analytical tasks such as shading pattern modeling and power quality assessment under abnormal grid conditions. Assessment is based on lab reports, experimental data analysis, and comparison with theoretical or simulated results, with graduate students additionally required to critically review state-of-the-art strategies related to each topic.

5.1. Introduction to the Use of the HIL Simulation Platform and Its Components

Objective: Familiarize with the basic components and operation of the HIL simulation platform.

In the first practice, introductory activities will be carried out to identify the components of the system and learn protocols for safe starting and use of the equipment. Basic instructions will be given for the use of cards such as the LAUNCHXL-F28379D Texas Instruments development tool, and guidelines will be provided on how to operate the programmable Chroma power supply. In addition, students will be introduced to the operation and configuration of power converter modules, the interconnections between control boards, the sensing devices, and the switching signals associated with the converters.

5.2. Developing a Basic Model with the PV Emulator

Objective: Learn how to integrate a model into the PV emulator.

In this practice, students will focus on learning how to operate the real-time PV emulator and its main components: the RTDS and the virtual-to-power interface. The session will begin with an explanation of the charging circuit used to initialize the DC bus. Next, a preconfigured mathematical model of the PV generator will be executed in the RTDS. Afterwards, the elements of the single-diode equivalent circuit with series and parallel resistances, as presented in Section 2.1.1, will be analyzed and configured. Finally, students will be required to obtain the I–V and P–V characteristics of the PV generator under standard test conditions, as well as under other selected operating conditions.

5.3. Operation of the MPPT Controller

Objective: Understand the operation of the Maximum Power Point Tracking (MPPT) controller.

In this practice, students will understand the logic of MPPT controllers. For this, different MPPT algorithms will be studied and implemented in the microcontroller, for example, the Perturb and Observe (P&O) method or the incremental conductance technique, among others. The results of the experiment will allow calculating the impact that these algorithms can have on the exploitation of the solar resource.

5.4. Integration of the Complete System in Normal Operation

Objective: Test the interaction of the grid-connected PV simulator in normal operation.

In this practice, students will understand how to configure the HIL simulation platform to emulate a grid-connected PV system in normal operation. The power flow to the grid will be monitored to evaluate the response of the system under various operating conditions, such as changes in irradiance and temperature.

5.5. Modeling of PV Shading

Objective: Analyze the impact of PV panel shading on power output.

In this practice, the students will analyze the impact of partial PV shading in power production. For this, some shading patterns will be mathematically modeled in the PV emulator, monitoring the impact on the PV power output and the system's response.

5.6. Operation Under Abnormal Grid Conditions and Their Impact on PV System Performance

Objective: Analyze how abnormal grid conditions influence the performance and energy production of a grid-connected PV system.

In this practice, the students will analyze the impact of abnormal grid conditions on PV energy production and power quality. To achieve this, the power grid emulator (Chroma 61511) will be programmed to reproduce scenarios such as voltage sags and unbalances. The resulting energy production and signal quality will be compared with a baseline case under normal grid conditions. As an additional task, students will study PV control strategies from the state of the art that are specifically designed for such operational scenarios.

6. Discussion

The HIL approach is recommended for both teaching and research in photovoltaic systems due to its ability to accurately emulate real operating conditions and its cost-effectiveness. This methodology provides a safe and controlled environment for experimentation, enhancing the learning process and supporting the development of emerging technologies.

The proposed HIL platform can be used in research to evaluate, validate, and analyze power converter controllers under near-realistic operating conditions. Its implementation enables the replication of field scenarios without the inherent risks associated with on-site testing, thereby providing a valuable tool for technological advancement.

An additional advantage of this system is its comparatively low cost relative to other available solutions, making it a practical option for institutions and projects with limited financial resources. Unlike previous studies, the use of a low-cost simulator has proven both efficient and practical, providing an accessible alternative for future research and educational applications in PV systems and related technologies, including other distributed energy resources. Table 7 summarizes the estimated hardware costs of each subsystem. The total estimated hardware cost of the complete platform is therefore approximately \$9360 USD (it should be noted that the P-HUT cost does not include the Chroma 61511 programmable AC power source, which is shared laboratory equipment not acquired exclusively for this platform). This figure contrasts sharply with commercial real-time simulation platforms such as OPAL-RT, dSPACE, or Typhoon HIL, whose acquisition costs typically range from \$20,000 to over \$100,000 USD, excluding software licenses and maintenance fees.

Table 7. Estimated hardware cost of the proposed HIL platform.

Subsystem	Estimated Cost (USD)
RTDS (TI LAUNCHXL-F28379D)	~80
Virtual-to-power interface (initialization, transformers, rectifier, buck converter, sensors)	~2200
Controller Under Test—CUT (TI LAUNCHXL-F28379D)	~80
Power Hardware Under Test—P-HUT (boost converter, inverter, LCL filter, sensors, initialization, protections)	~7000
Total	~9360

However, this cost-effective approach also introduces certain limitations. In particular, the current prototype is rated at 1 kW, which is adequate for laboratory-scale training and research activities but may not fully represent the operating conditions, power levels, and scalability requirements of medium- and high-power commercial photovoltaic installations. In addition, the real-time simulation is executed on a TI LAUNCHXL-F28379D microcontroller, whose computational resources impose practical constraints on the complexity of the models, the achievable simulation time step, and the incorporation of additional real-time functions. Although the reported processor utilization of 87.5% confirms successful real-time operation, the remaining computational margin limits the integration of more detailed models or larger-scale system emulation.

Another characteristic of the proposed platform is its reliance on MATLAB/Simulink for model development, controller design, and automatic code generation. This approach offers significant advantages, including a user-friendly graphical programming environment, rapid prototyping capabilities, simplified implementation of control algorithms, and straightforward deployment to the TI LAUNCHXL-F28379D controller. These features make the platform particularly attractive for educational and research applications, as they

reduce development time and lower the programming expertise required from users. However, this dependence on proprietary software may limit accessibility in institutions where MATLAB/Simulink licenses are not available and may reduce portability to alternative development environments. In addition, the performance and scalability of the platform remain partially constrained by the capabilities and code-generation support provided by the software framework.

Compared with previous low-cost academic HIL platforms, the proposed system offers the advantage of integrating both CHIL and PHIL functionalities within a single educational framework; however, this is achieved at the expense of lower computational resources and scalability than those available in commercial real-time simulation systems.

The final implemented module demonstrated stable and appropriate behavior, thereby validating the operation of the proposed design previously verified through offline simulations. The results confirm that processing capability, system initialization procedures, and the quality of sensed signals are critical factors for achieving a successful real-time HIL implementation.

This work also validates the correct operation of the control algorithms designed for the power conditioning unit, with results demonstrating the satisfactory performance of the current controllers and the effectiveness of the reference signal generation algorithm. The ability to operate and modify the system in real time represents a key advantage, as it enables observation of the system's responses to disturbances and external factors, thereby providing deeper insight into the behavior of the control system.

This work paves the way for future research in which the developed module can be employed to evaluate advanced control strategies that enable the integration of ancillary services into PV systems, including load compensation, voltage and frequency regulation, inertia support, and fault ride-through capabilities.

7. Conclusions

This document presented the design and implementation of a platform based on the hardware-in-the-loop technique for the emulation of grid-connected PV systems, with real hardware devices incorporated into the simulation environment. The proposed platform integrates a real-time PV emulator with the physical systems under test. The developed emulator accurately reproduces the behavior of PV generators under varying parameters such as irradiance, temperature, and the number and type of PV panels. In addition, the platform provides a reliable environment for testing control algorithms on real-time microcontroller platforms and for evaluating the power conditioning unit of PV systems under near-realistic operating conditions. By emulating both the PV generator and the electrical grid, the system enables the recreation of various scenarios, including different weather conditions and grid disturbances, thereby offering a versatile tool not only for educational purposes, but also for research and validation.

The experimental tests successfully validated the operation of the system in accordance with the design specifications. The results indicate that the proposed HIL system constitutes an effective tool for emulation of PV systems. Moreover, the versatility of this platform facilitates advanced studies and experimental work, contributing to the progress of power electronics and fostering the development of more efficient and reliable energy systems.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

APC	Active Power Curtailment
CHIL	Controller Hardware-In-the-Loop
CUT	Controller Under Test
HIL	Hardware-In-the-Loop
HMI	Human–Machine Interface
HUT	Hardware Under Test
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
PCC	Point of Common Coupling
PHIL	Power Hardware-In-the-Loop
PI	Proportional–Integral
P-HUT	Power Hardware Under Test
PR	Proportional-Resonant
PV	Photovoltaic
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
RTDS	Real-Time Digital Simulator
RTS	Real-Time Simulation
STC	Standard Test Conditions

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