A Power Hardware-in-the-Loop Smart Inverter Testing Facility

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***Abstract*—This paper describes the authors' experience in the implementation of a Power Hardware-in-the-Loop (PHIL) laboratory facility designed to test smart inverters. PHIL testing offers significant advantages over traditional testing methods, such as purely simulated or hardware-only testing. This work aims to leverage such advantages and showcase a PHIL test bed designed to validate the cyber-and-physical performance of a 150kW power inverter under various operating conditions.**

The proposed PHIL laboratory facility incorporates essential equipment, including a 15kVA bi-directional power amplifier, a PV emulator, power supplies, a grid transformer, and PQ meters. By carefully selecting and configuring this equipment, the experimental setup closely resembles real-world implementation conditions, providing reliable and accurate testing results.

***Index Terms*—Inverter-based resources, power hardware-in-the-loop, real-time simulation, IEEE Std 1547**

I. Introduction

As renewable energy sources continue to play a crucial role in the global energy landscape, the integration of grid-connected photovoltaic (PV) inverters and other power electronics used in inverter-based resources (IBR) systems hinges in meeting specific requirements governed by various standards [1] and grid codes [2]. While a great number of efforts have been made for the assessment of IBR technologies when integrated to the grid, many aspects related to their dynamic performance cannot be fully assessed via conventional simulations, such as those performed for interconnection studies [3].

Fully assessing the cyber-and-physical performance of IBRs typically requires hardware-only tests, which are costly, time consuming and may lead to the possible destruction of the test specimen. A trade off to assess the "cyber" characteristics of similar devices, e.g., testing the control systems and communications of new technologies [4], is the use of real-time simulation with (Controller) Hardware-in-the-Loop (CHIL, HIL) [5]. CHIL means Controller Hardware-in-the-Loop (CHIL) testing, which means that the power stage of the inverter would be disconnected and modeled in a real-time simulator. Thus, CHIL allows for destructive tests to be performed to assess the performance of internal protections without resulting in damage of the test equipment [6]. While the real-time simulation approach is based entirely on simulation models, the other two methods (CHIL, HIL) involve hardware components. In the case of CHIL, it only involves the controller boards (low-voltage and low-power functions), and in the Power Hardware-in-the-Loop(PHIL) case, it involves the use of a bi-directional power amplifier capable of "emulating" the point of connection to the actual hardware inverter. This implies that there is an increase in complexity when going from RT, to CHIL and finally to PHIL. To complement CHIL and HIL testing the application of the PHIL testing method [7] provides a cost-effective and time-saving solution for evaluating the performance of power electronics systems under non-destructive real-world conditions.

In recent years, there has been a growing interest in PHIL testing for power electronics systems, including smart inverters. Several studies have demonstrated the benefits of PHIL testing over traditional testing methods, such as purely simulated or hardware-based testing. For example, [8] presented a PHIL testbed for grid-connected photovoltaic inverters, showing improved accuracy and reliability compared to purely simulated testing. In the paper [9], the author examined the stability of the inverter's power hardware-in-the-loop (PHIL) testing environment at a 100W scale.

This paper contributes to the efforts geared to improving the testing and development of power electronics systems, leading to more reliable, efficient, and safe utilization of smart inverters for renewable energy applications. In this work, the inverter has a power rating of 150 kW[1]. As a result, our experimental setup enables us to test the inverter in a configuration that closely resembles real-world implementation conditions, albeit at a lower capacity for the test specimen. In addition, the laboratory facility has been developed to test both "cyber" and physical performance, this paper mainly discusses aspects relevant to electrical performance; a future companion paper will discuss aspects of data communications and control.

The remainder of this paper is organized as follows. Section II summarizes the lab's design. Section III describes the individual components integrated into the test bed, while Section IV summarizes how they were integrated. Section V provides an example of how the platform can be used for a typical test, and Section VI summarizes the main conclusions

[1]However, we are currently limited to utilizing only 15 kW due to the constraints of the power amplifier (grid emulator)

of this work.

II. PHIL Lab Design & Setup

A. Overall Design

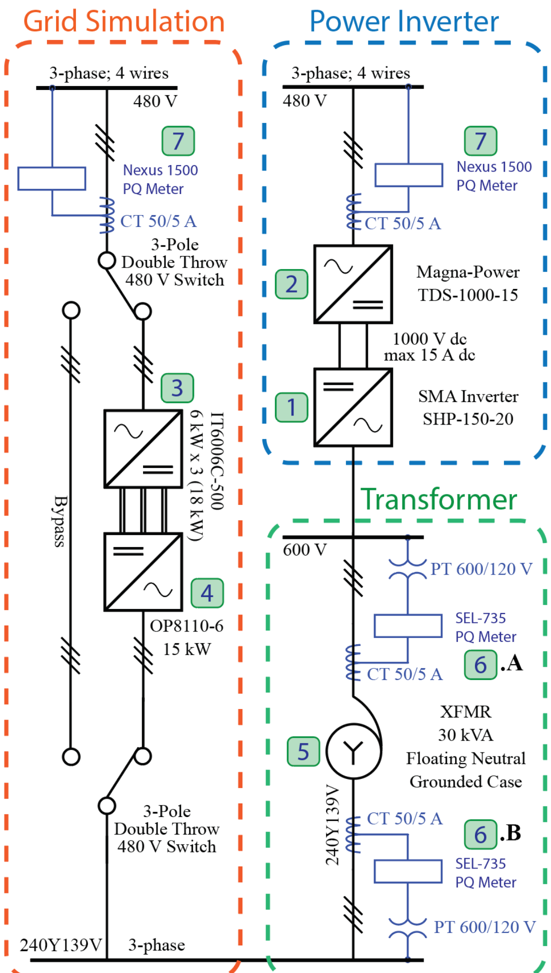


Fig. 1. Overall PHIL Lab. Design Schematic

TABLE I
Table of Main Test-Bench Equipment

Label	Equipment	Description
1	SHP-150-20	SMA Inverter
2	TDS-1000-15	PV Emulator
3	IT6006C-500	Power Amp. DC Power
4	OP8110-6 and -3	Power Amplifiers
5	AUT-MIT-114	Grid Transformer
6.A/B	SEL-735	PQ Meter
7	Nexus 1500	PQ Meter

The primary objective of the facility is to exert full control over the input and output voltages and currents of the smart inverter while operating in various modes, including voltage-var, voltage-watt, and fixed power factor. Figure 1 depicts the electrical design schematic of the overall laboratory setup at ALSET Lab, Rensselaer Polytechnic Institute, along with the model numbers and brief descriptions of each component, which are listed in Table I. In Fig. 1, the power flow in the lab setup starts from the "Power Inverter" (blue dashed square), to the "Transformer" (green dashed square), and to the grid emulation (red dashed square) sub-systems. To keep the design within budget, the main design constraint was the capacity of the power amplifier that could be purchased. This led to the choice of a 15 kW bi-directional power amplifier, the OP1400 comprised of two key devices labeled with 8 in Fig. 1.

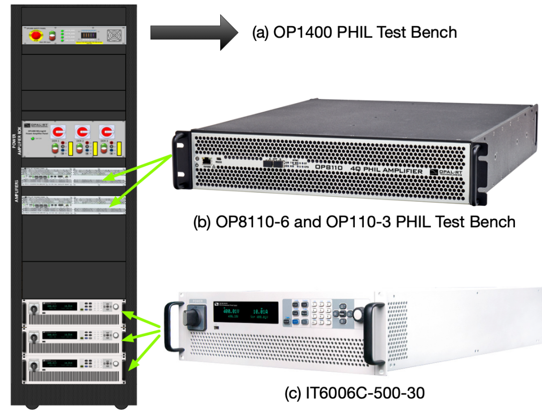


Fig. 2. OP1400 PHIL Test Bench and its Key Components.

The result of this choice determined all subsequent choices for other equipment, and the result is that the current test specimen, SMA's SHP-150-20 smart inverter, can only be tested at 12% of its nameplate capacity. Although this choice did not impact the ability to carry out tests, it does imply that the tests would be conducted at a maximum of 10% of the inverter's nameplate capacity.

III. Main Components

In this section, all the individual components used in the test bed are introduced.

A. OP1400 PHIL Test Bench

In the [10], the utilization of a switching converter as a power amplifier is presented for testing the Hardware Under Test (HUT). [10] introduces an effective approach for establishing a connection between simulation and real-world HUT.

Such capabilities are streamlined in the OP1400 PHIL Test Bench labeled with 4 in Fig. 1, and in Fig. 2(a). This test bench is comprised of several individual components, of which the OP8110 (4Q power amplifier, Fig. 2(b)) and the IT6006C-500 (bi-directional power supply, Fig.2(c)) are described next[2].

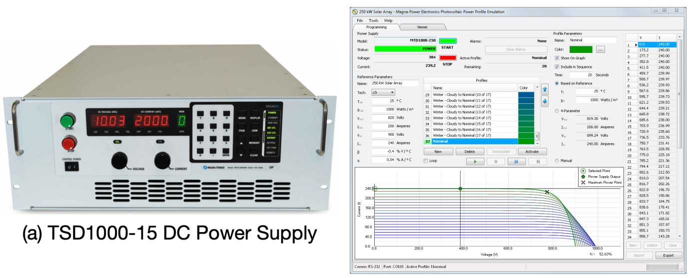
1) OP8110 4-quadrant Power Amplifier: In our laboratory setup, we utilize the OP8100 4-Quadrant power amplifier, depicted in Figure 2, which has the capability to inject/absorb 15 kVA of power. In this setup, the amplifier functions as an emulator for the power grid that the PV inverter is connected to. Being a 4-quadrant amplifier, it allows us to absorb power from the inverter under test. During operation, the amplifiers generate a controlled 277/480 Vrms 3-phase voltage to simulate normal grid conditions. Observe that the output voltage and frequency are adjustable, enabling us to conduct both Low/High-frequency ride-through and Low/High Voltage ride-through tests for the inverter by controlling it through a

[2]See https://tinyurl.com/OP1400 for detailed information.

real-time simulator (OP5031 and OP4520, not shown in the figures).

2) IT6006C-500 Power Supply: The OP1400 test benches shown in Fig. 2(a) are fitted with three ITECH IT6000C series bi-directional DC power supplies, shown in Fig. Fig. 2(c). These power supplies offer a consistent 500V DC input voltage to the OP8110 4-Quadrant amplifiers and enable them to inject/absorb power from/to the 3-phase mains input.

B. TSD1000-15 DC Power Supply



(a) TSD1000-15 DC Power Supply

(b) Solar Array Emulation Software

Fig. 3. TSD 1000-15 DC Power Supply and Solar Array Emulation Software.

To provide DC voltage/current to the smart inverter and perform the emulation of photovoltaic (PV) array behavior a DC power supply is a widely employed technique in equipment testing. In articles [11] and [12], the Newton-Raphson Method is introduced as a means to replicate the power curve of a PV panel. Notably, the method proposed in [11] exhibits superior performance in terms of settling time when compared to programmable power supplies. However, considering our specific application in this test-bed, the required power rating surpasses the capacity of our laboratory setup. Hence, we have implemented the Magna-Power programmable DC power supply shown in Fig. 3(a), which features programmable voltage, current, and protection settings, as well as high-accuracy measurements. This power supply utilizes high-frequency IGBT-based power processing in a current-fed topology, providing enhanced control and system protection compared to the conventional voltage-fed topology. This topology includes an additional stage, which ensures self-protection of the power supply even under fault conditions, eliminating the risk of fast-rising current spikes and magnetic core saturation. The Photovoltaic Power Profile Emulation(PPPE) software, shown in Fig. 3(b), automatically calculates solar array voltage and current profiles based on user-defined parameters. These profiles can be sent sequentially to the Magna-Power power supply, which emulates the defined characteristics. The software allows us to define an unlimited number of profiles to be emulated and sequenced over a given time period, enabling us to evaluate the performance of the inverter through repeatable and controllable experiments.

C. SMA SHP 150-US-20 Inverter

The SMA SHP 150-US-20 inverter serves as the primary test object or HUT in this experimental setup. One of the key features of the SMA inverter is its ability to operate in different control modes depending on the specific requirements from the grid operator. For instance, in fixed power mode, the inverter ensures that the generated power output remains constant, even if the irradiance or temperature conditions change. In Volt/Var mode, the inverter adjusts the voltage and reactive power output to maintain a specific power factor at the grid connection point. In Frequency-watt mode, the inverter adjusts the active power output to maintain the grid frequency within a certain range. By testing the inverter's performance in these different modes, we can ensure that it will operate effectively and efficiently in a variety of real-world conditions.

D. PQ Meters

In order to obtain accurate measurements from the experiments, our setup includes two types of PQ meters - the Nexus 1500+ and SEL-735. These meters are strategically placed throughout the system (see Fig.1, numbers 6.A/B and 7), allowing us to obtain precise readings of voltage, current, real power, reactive power, and other important variables.

E. Autotransformer

The autotransformer used in our setup plays a critical role in ensuring that the experiment is conducted within the required specifications. As mentioned earlier, the power amplifier that emulates the grid behavior has a voltage rating of only up to 277L-N, which is significantly lower than the inverter's voltage rating of 346V L-N. To bridge this gap, we have incorporated a 30 kVA Maddox three phase dry type autotransformer in the middle of the system to step up the amplifier output to match the inverter's voltage rating.

IV. Test-bench System Integration

A. DC Power Supply Wiring

From the back of the power supply shown in Fig. 6, we can see the current transformer (Green Arrow) for measuring input 480V current and output Positive and Negative (Blue Arrow) DC power for the input of the inverter.

In addition Fig. 6, the RS-232 serial input for the solar panel emulation software on the host computer, indicated by the red arrow. Similarly, the yellow arrow points towards the Ethernet port connected to the central switch that facilitates the remote control of the DC power supply not only via the serial port but also through the Ethernet interface.

Fig. 4. SMA SHP 150-US-20 Inverter

Fig. 5. (a) SEL-735 and (b) Nexus 1500+ PQ and Revenue Meters.

TABLE II
TRANSFORMER SPECIFICATIONS

Voltage	Current	Connection Per Phase
600Y/346V	28.9	H0 H1 H2 H3
480Y/277V	36.1	H0 H4 H5 H6
400Y/231V	43.3	X0 X7 X8 X9
240Y/139V	72.2	X0 X4 X5 X6
208Y/120V	83.3	X0 X1 X2 X3

B. Inverter Wiring

Figure 7 highlights the various connections to integrate the inverter. The red arrow points towards the DC power input for the inverter, which is responsible for converting DC power generated by the solar panels to AC power. The blue arrow indicates the output of the inverter, which feeds AC power to the load. The green arrows indicate the potential transformer and current transformer for the SEL-735 PQ meter. Finally, the yellow arrow indicates the Ethernet port, which is connected to the central switch via an Ethernet cable. This connection allows the setup to communicate with the SGS Strata Distributed Energy Resource Management Software (DERMS) platform using the ModBus protocol, enabling remote control and monitoring of the system. More information about communications and DERMS integration will be discussed in a separate paper.

C. Transformer Wiring

As it can be observed in Fig. 1, the experimental setup can bypass the inverter and connect to the power grid. In this case, the autotransformer needs to have 480Y(H4 H5 H6) on the low side connected to the grid. When the power amplifier is used to emulate the grid, the amplifier is connected to 240Y(X4 X5 X6) (see Table II). The status of the connection needs to be manually verified before energizing the system.

From Figure 8, the inverter is connected to H1 H2 H3 terminals on the high side. The wires pointed by the red arrows are going to a 3-pole double-throw switch. Since the maximum

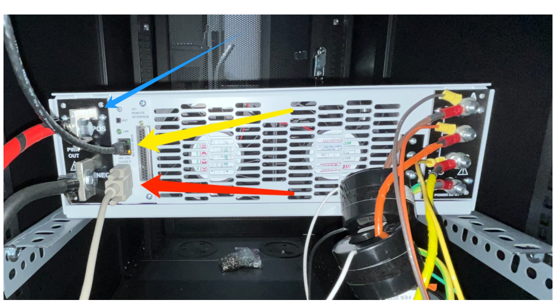


Fig. 6. TDS-1000-15 DC Power Supply Instrumentation and Comms. Wiring

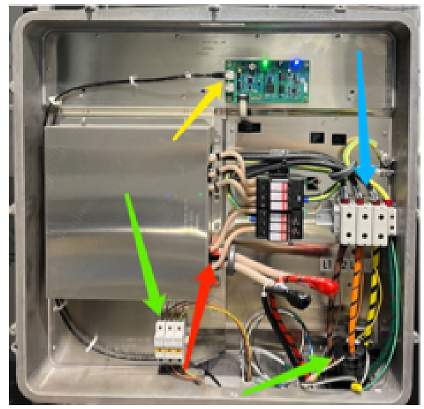


Fig. 7. SMA SHP-150-20 Inverter Wiring

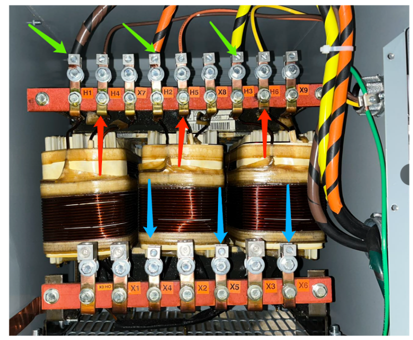


Fig. 8. Autotransformer Wiring

voltage of the power amplifier can't reach 480V L-L, it is necessary to change the transformer taps to change from the power grid connection to the power amplifier connection. In the configuration shown in Fig. 8, the transformer is wired to be connected directly to power grid H4 H5 H6, which is indicated by the red arrow. Three blue arrows are pointing at X4 X5 X6 terminals, which need to be connected to Opal-RT power amplifier where grid emulation is implemented.

D. Power Amplifier Wiring

The 3-pole double-throw switch on the right shown in Fig. 9A is connected to the front panel of the OP1400 test bench. When the switch on the right is closed (up where the blue arrow is pointing) in Fig. 9A, the test bench is connected to the autotransformer. In Fig. 9B and 9C, the red arrow indicates where the banana plug is located. It is possible to easily change the wiring configuration and verify the voltage with a multimeter. The banana cables connect the power amplifier to the autotransformer. In our application, to maximize the performance of the power amplifier, the amplifier is configured in differential mode (see Fig. 9D). Since the inverter does not have a neutral connection, the amplifier, and the inverter are wired in a floating neutral scheme.

V. ILLUSTRATIVE TESTING EXAMPLES

The following section demonstrates two experiments of one of the tests that can be applied to an inverter using the testing facility described above.

1) Unity Power Factor Test. In this test, the amplifier is configured to emulate a grid with nominal condition 600V

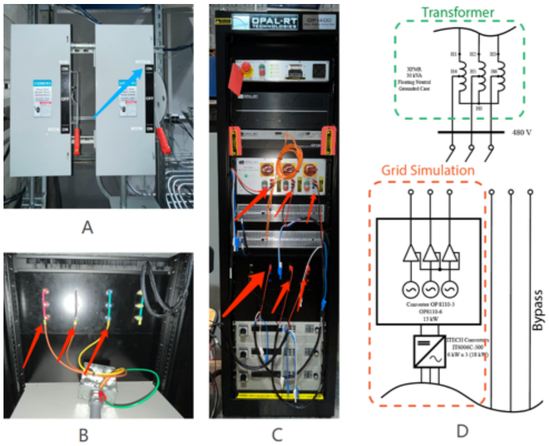


Fig. 9. SMA SHP-150-20 Inverter Wiring

	A	B	C
I MAG (A)	2.71	2.74	2.79
	AB	BC	CA
V MAG (V)	602.20	599.58	599.19
	3P		
W (W)	2842.06		
U (VA)	2843.36		
Q (VAR)	86.11		
TRUE PF	1.00 LAG		
FREQ (Hz)	60.00		

Fig. 10. SEL 735 Meter Reading for PF=1

Peak-Peak. The inverter is configured to generate 3kW with unity PF. The meter shown in Fig. 1 labeled as number 6.A is used to measure the power factor.

The test was conducted successfully as shown in Fig. 10, where it can be observed how the transformer high-side voltage waveform is in phase with the transformer current waveform, as expected.

2) 0.95 Power Factor Test. In this test, the inverter is configured to generate 3kW with 0.95 Lagging PF. The meter measurement is taken to validate the output. The result is shown in Fig. 11. The Power Factor (PF) has been recorded at 0.94, aligning closely with the anticipated value. An error margin of 0.1 is considered acceptable, given that the testing is conducted at merely 2% of the inverter's full capacity.

VI. Conclusion

The power hardware-in-the-loop (PHIL) testing method provides a powerful approach to validate of power electronics systems, as is the case in this paper for smart inverters. With the increasing demand for renewable energy sources, it has become essential to test the performance and functionalities of inverters used in solar power plants interconnected with the power grid. In this work, we have demonstrated how a PHIL test bench can be designed and utilized to test the performance of a solar inverter under various operating conditions.

Overall, this work demonstrates the importance of using PHIL testing to validate the performance of new power electronics systems. With the growing demand for renewable energy sources, it is essential to have reliable and efficient power conversion systems. The PHIL test bench offers a cost-effective and time-saving solution for testing the performance of inverters and other power electronics systems.

	A	B	C
I MAG (A)	2.79	2.81	2.86
	AB	BC	CA
V MAG (V)	603.98	601.38	600.85
	3P		
W (W)	2747.32		
U (VA)	2916.09		
Q (VAR)	977.66		
TRUE PF	0.94 LAG		
FREQ (Hz)	60.00		

Fig. 11. SEL 735 Meter Reading for PF=0.95 Overexcited

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This paper is dedicated to the memory of Jerry W. Dziuba, who was instrumental in the implementation of this laboratory and passed away before it was completed.

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