Power Hardware-in-the-Loop Smart Inverter Testing

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***Abstract*—This article presents the results of a series of laboratory experiments conducted to validate the performance and effectiveness of a solar photovoltaic (PV) inverter under different operating conditions and control modes. The experiments were conducted using a Power Hardware-In-the-loop (PHIL) facility, which consists of a power amplifier, an autotransformer, power quality meters, and a host computer running solar panel emulation software that drives a controllable DC supply. The experiments included testing the inverter's ability to maintain a constant power factor, deliver constant reactive power, regulate voltage using the voltage-var and voltage-watt modes, withstand voltage ride-through conditions, and return to service after a grid outage. The results show that the experimental facility is capable of performing tests that are intended to verify the industry requirements of PV inverters.**

***Index Terms*—PV inverter, power hardware-in-the-loop, real-time simulation, IEEE 1547**

I. Introduction

This paper summarizes the results of a project conducted by Rensselaer Polytechnic Institute (RPI) in collaboration with Smarter Grid Solutions to test smart inverter functionalities, which is supported by the New York State Energy and Research Development Authority (NYSERDA). The project established a Power Hardware-in-the-Loop (PHIL) experimental facility for smart inverter testing, with the goal of verifying its compliance with the IEEE 1547.1-2020 standard [1]. This paper briefly introduces the experimental facility (see more details in [2]) and reports the results of six tests carried out to validate the control functionalities of a smart inverter. The successful testing experience was critical for the next phase of the project, which involves testing the integration of the smart inverter with Smarter Grid Solutions' Distributed Energy Resources Management System (DERMS).

The remainder of this paper is organized as follows. Section II briefly describes the PHIL experimental facility and its main components. Section III presents and analyzes the six experiments conducted, while Section IV summarizes the main findings of this work.

II. PHIL Laboratory Experimental Facility

In this section, the equipment in Figure 1 and the user interfaces used in all the testing experiments are introduced. The PHIL experimental facility is made up of four major pieces of equipment that were used to perform and control the tests, and to make the observations necessary to verify the functionality of the SMA inverter. The user interfaces are crucial for conducting experiments and collecting accurate data. The PHIL equipment and interfaces, their functions, and how they were used in the experiments are described next.

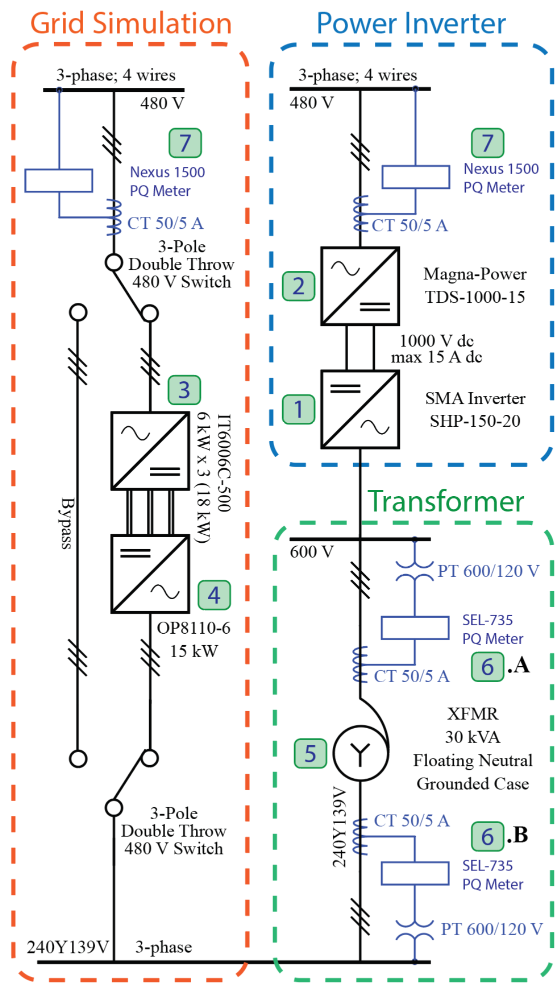

Fig. 1. PHIL Lab One Line Diagram

A. OP1400 Power Amplifier

The OP1400 power amplifier labeled 4 in Figure 1 is an essential component of the experimental platform, as it emulates the power grid to which the inverter is connected[1].

[1]For detailed information on the OP1400 see: https://www.opal-rt.com/op1400-4-quadrant-power-amplifier/

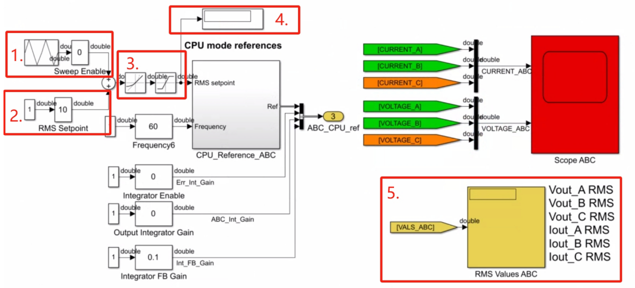

Fig. 2. OP1400 Power Amplifier UI

To control and monitor the amplifier, a user interface (UI) has been implemented; see Fig. 2. The UI serves as the control panel of the OP1400 power amplifier is executed using a real-time simulator. This interface is critical in ensuring the successful operation of the experimental platform during the testing experiments, as it allows the user to adjust parameters and observe the system's behavior in real-time.

In Figure 2, enclosed in red squares and numbered, are the different experiment control and monitoring functions used to carry out the tests:

1) Automated RMS Voltage Set-point Adjustment
2) Voltage Set-point Adjustment
3) Voltage Slew-rate Limiter
4) Voltage Set-point Display
5) RMS Voltage and Current for Each Phase (Monitoring)

In the following experiments, the 3-Phase RMS Voltage Set-Point is used to control the input voltage for the inverter to conduct High/Low voltage ride-through tests. The Automated RMS Voltage Set-Point Adjustment is used to automatically change the input voltage for the inverter to obtain the characteristic graphs of Volt-Watt and Volt-Var control mode operation. The Slew-Rate limiter is used to limit the impact of the autotransformer inrush current. This was necessary since during the coupling of the experimental platform it was observed that in experiments when the voltage was changed too quickly, the power amplifier's protections would trip because of the autotransformer's inrush current. The Saturation Limiter avoids user input errors that exceed the amplifier and inverter voltage limits. The voltage saturates at 160 Vrms L-N. Therefore, the voltage can reach 692 V L-L on the high side of the autotransformer, which is sufficient for all testing procedures within the scope of the experimental facility.

B. DC Power Supply

The DC power supply labeled as number 2 shown in Fig. 1 is used to emulate a Photovoltaic (PV) cell working under different conditions. The Photovoltaic Power Profile Emulation (PPPE) software automatically calculates the solar array voltage and current profiles based on user-defined parameters. The figure below shows the user interface for MagnaDC PPPE software.

Since the experiments do not require a change on the DC side and the maximum active power output of the inverter is set to 3 kW. Meanwhile, the profile in box 1 is sent to the DC

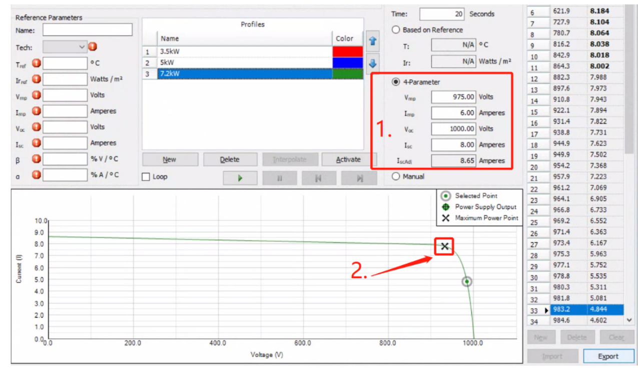

Fig. 3. DC Power Supply UI

power supply to have a maximum of 7.2 kW (shown in Fig.3 labeled 2), which allows the DC supply to operate following the characteristic of the emulated PV panel (see the green trace in Fig. 3). This power profile is used in all experiments.

C. SMA Inverter

The SMA inverter is the EUT (equipment under test) for all tests carried out and documented next. The inverter is configured through its embedded server user interface, shown in Figure 4. In the UI's main screen (i.e., the Web Server's home page), the current output power and device status are displayed. The "Device Parameters" tab is where the configuration and settings for the inverter are displayed and can be modified. In the following experiments, the detailed settings are all displayed and configured through this tab.

III. Experiments

A. Constant Power Factor Mode

Understanding how an inverter interacts with the grid under constant power factor conditions is crucial for the integration of renewable energy sources, as it affects the stability and efficiency of the grid [3] [4]. In the following test, the constant power factor (pf) mode of the inverter will be tested with a 0.95 lagging power factor. From the UI introduced in Section II-C, the power factor is set to be constant at 0.95. Measurement data were recorded after the inverter finished adjusting the output power (i.e., when it reached a "steady state"). These

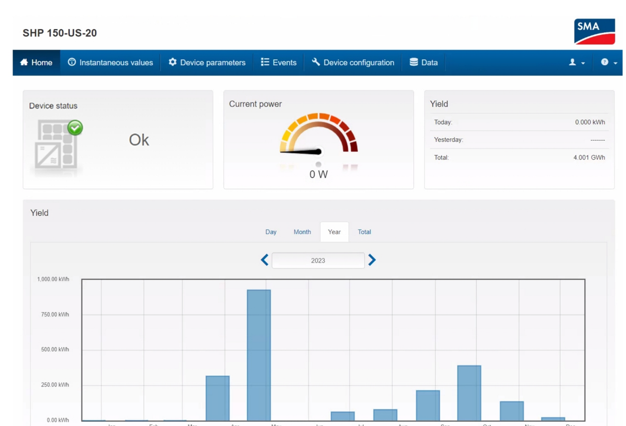

Fig. 4. SMA Inverter UI

TABLE I
0.95 LEADING CONSTANT POWER FACTOR TEST RESULTS

Power	Desired	Measured	Error
Real	3000W	2747W	8.4%
Apparent	3162VA	2916VA	7.8%
Reactive	986Var	977Var	0.9%
P.f.	0.95	0.94	1%

recordings are used to verify whether the inverter is outputting and maintaining the desired active and reactive power.

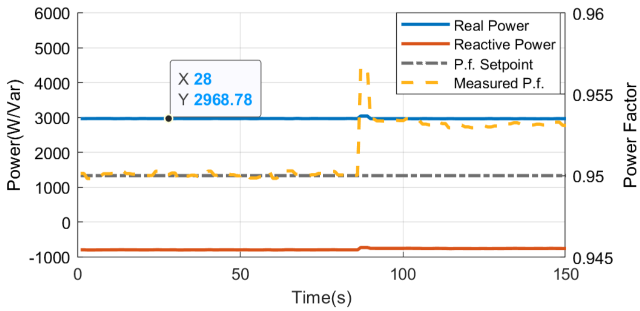

Fig. 5. SEL-735 Meter Measurements under 0.95 Lagging Power Factor

Figure 5 shows the inverter generating 3 kW and the power factor is 0.95, as expected. Since the SMA inverter is capable of generating 150 kW, 30.67 W of error is within tolerance.

The oscilloscope is used to verify the lag angle. From the measurement, the time lag is 827 microseconds. In terms of angle, this corresponds to $\hat{\phi} = 17.8^o$. The desired angle is $\phi = 18.2^o$. The measured lag angle is close to the desired angle. Noting that the waveforms are slightly distorted, the angle error can be attributed to instrumentation issues. However, the error is low and within tolerance.

The experiment is repeated for an Overexcited (Leading) power factor of 0.95, and the results are shown in Table I, with similar results as in the previous test.

B. Constant Reactive Power Mode

Inverters operating in constant reactive power mode serve a crucial function in supporting grid voltage. By absorbing or supplying reactive power as needed, they help maintain voltage stability within the grid, which is important in systems with fluctuating loads. Several studies on the use of the constant

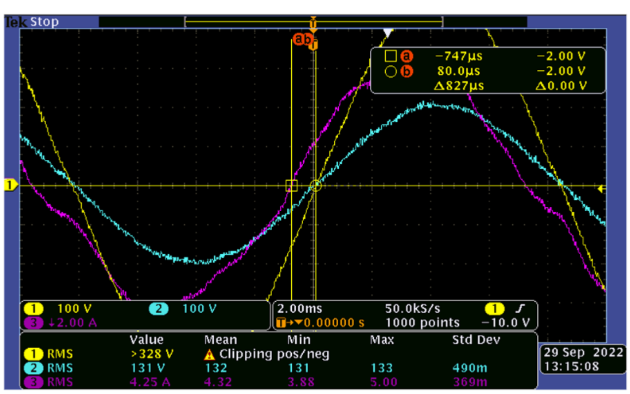

Fig. 6. Yellow: Transformer Voltage Measured at the HV Side, Blue: Transformer Voltage Measured at the LV Side, Pink:Inverter Current

TABLE II
CONSTANT REACTIVE POWER MODE TESTING RESULTS

Power	Desired	Measured	Error
Real	3000W	2769W	7.7%
Apparent	3092VA	2879VA	6.9%
Reactive	750Var	789Var	5.2%

reactive power control mode have been carried out in the literature. In paper [5] this control method was studied and in [6] its application was investigated in the Vestfol and Telemark region of Norway. These studies set the stage for practical application, where the effectiveness of the constant reactive power mode in real-world scenarios can be exploited.

In the following test, the constant reactive power mode of the inverter will be tested. From the UI introduced in Section II-C, the reactive power is set to be constant at 750 VAR, and the real power is set to 3 kW. A set of sample measurements taken during the experiment is shown in Fig. 7, from which we can verify if the inverter is outputting and maintaining the reactive power.

The desired and measured active, apparent, and reactive power shown in Table II is expected and within a reasonable tolerance.

C. Voltage-Var Mode

Inverters with Voltage-Var Mode can respond to voltage fluctuations by adjusting their reactive power output, thus helping to stabilize the voltage within the grid. This is particularly useful in managing voltage levels in distribution networks where there are significant variations in load or generation [7]. This dynamic voltage regulation, previously dependent on apparatus such as capacitor banks, paves the way for advanced application scenarios using smart inverters [8].

In the following test, the voltage-var functionality is tested. From the UI introduced in Section II-C, the active power is set to be constant. The expected reactive power output is shown in Figure 8. In the OP1400 power amplifier's UI (see Fig. 2), the desired 3-phase voltage is set to vary between 560 V to 640 V RMS at a rate of $< 0.2\,V/s$ to test how the inverter reacts to voltage changes. The measured volt-var curve is shown in Figure 8 with data collected from the meter.

The overall performance of the volt-var mode observed in Fig. 8 is consistent with our expectations as we compare the

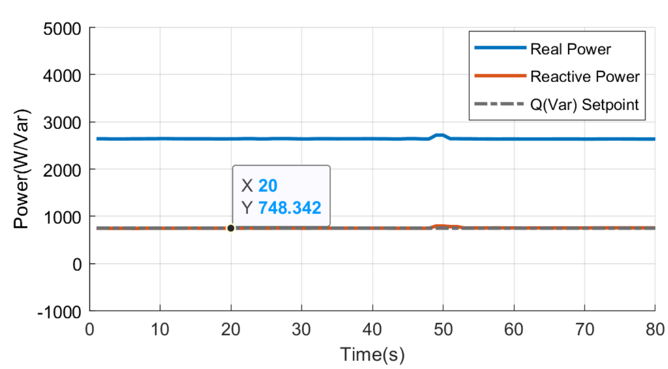

Fig. 7. SEL-735 Meter Measurements under Constant Reactive Power Mode

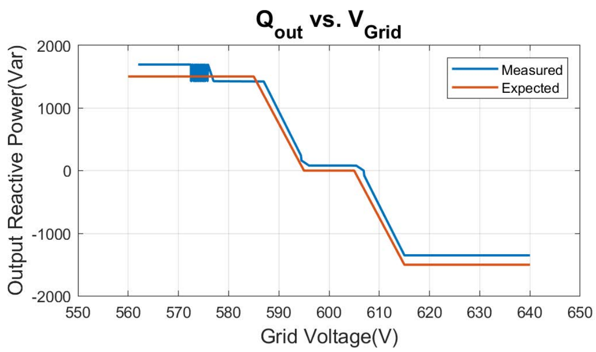

Fig. 8. Measured and Expected Volt-Var Curve

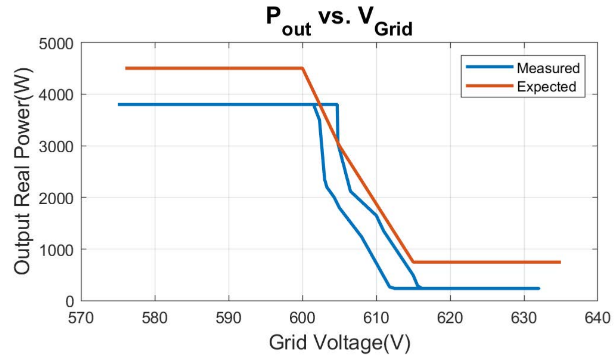

Fig. 9. Measured and Expected Volt-Watt Curve

measured volt-var characteristic curve (in blue) to the one specified within the inverter (in red). The reactive power is nonzero when the voltage changes between 595 V to 600 V. Note that this measurement is taken at the inverter's terminal, with the transformer energized. Another important behavior to note are the reactive power output oscillations observed when the voltage changes between 570 V and 590 V. The current hypothesis is that they are caused by the coupling between the DC power supply and the inverter; however, this needs to be studied further.

D. Voltage-Watt Mode

The voltage-watt mode is essential in scenarios with high penetration of photovoltaic (PV) systems. When solar generation is high, it can cause over-voltage issues in the grid. This mode enables inverters equipped with it to reduce their power output as the voltage of the network increases, minimizing the risks of overvoltage [9] [10]. The following test results illustrate how this mode functions under test conditions. The measured and expected volt-var curve is shown in Figure 9 with data collected from the power meter.

The test results shown in Fig. 9 show that the overall performance of the volt-watt mode is consistent with expectations. When comparing the measured volt-watt curve (in blue) with the desired curve (in red), we observe that the output power is significantly lower than the desired level. Note that during these tests, only a fraction of the inverter's 150 kW capacity is utilized. The current hypothesis is that the control system of this inverter allows a certain margin of error. Furthermore, hysteresis is evident in Fig. 9 (in blue), which is not expected. More studies are needed to determine the cause of this hysteresis.

E. Voltage Ride Through

Voltage Ride Through (VRT) is essential to maintain grid stability during transient voltage disturbances. It enables inverters to continue operating and supporting the grid even during short periods of under or over-voltage, which are common in power systems [11] [12].

In the following test, the High/Low VRT of the inverter will be tested. From the UI in Fig. 2, the active power is set to 3 kW. Due to equipment limitations, the power amplifier is only able to conduct experiments that have a time scale over 5 s (slew rate limit). Thus, 20 s of tripping time is chosen to allow the power amplifier enough time to increase and decrease the voltage. The lower maximum threshold is set to 640 V and the tripping time is set to 20 s. If the voltage increases above 640 V under 20 s the inverter should not trip and vice versa. The upper minimum threshold is set to 500 V and the tripping time is set to 20 s. If the voltage decreases below 500 V under 20 s, the inverter should continue to operate and vice versa.

In Figure 10, the voltage dropped below 500 V at 760.76 s. The inverter output power dropped to zero at 780 s. This is expected since the tripping time is set to 20 s. The voltage dropped below 500 V for 8 s at 962.92 s. The power output of the inverter is maintained at the desired value.

In Figure 11, the inverter tripped at 780 s since the grid voltage is higher than 640 V for longer than the tripping time of 20 s. The inverter maintains output power at 3 kW when the grid voltage is over 640 V for shorter than 20 s.

Thus, the results in Figs. 10 and 11 verify the VRT capabilities of the inverter.

F. Return to Service

After an event such as a fault in the grid or a power outage, the immediate return of the inverters to service helps to maintain local loads supplied. The "Return to Service Wait" period allows the utility to give inverter owners a value for the inverter to reconnect that can help ensure that when the inverter reconnects, it does so under stable conditions [1].

In the following test, the return to service of the inverter will be tested. The active power is set to 3 kW and the reconnection time after the grid fault is set to 2 min. The inverter

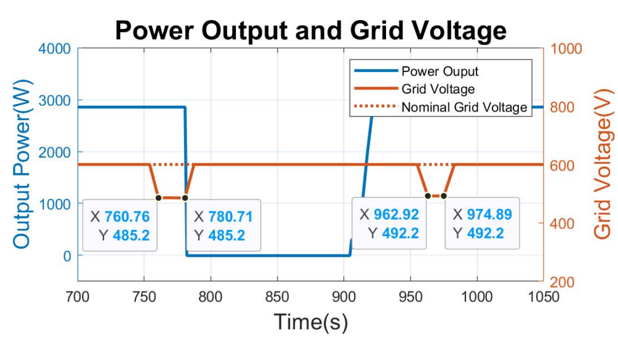

Fig. 10. Low Voltage Ride Through Test

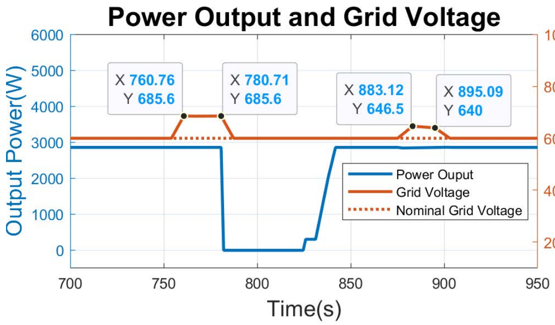

Fig. 11. High Voltage Voltage Right Through Test

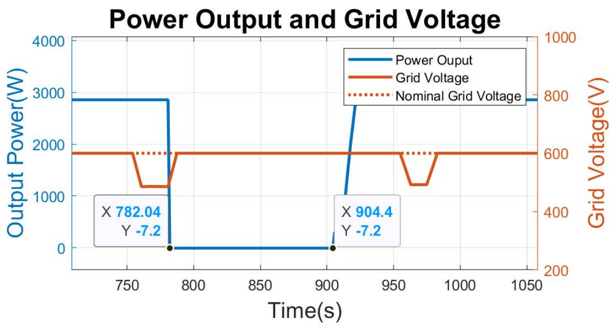

Fig. 12. Return to Service Test

should be back online in 2 min after the inverter measures a normal (600 V) grid voltage.

In Figure 12, the inverter receives a nominal voltage at 782.04 s and it starts raping up output power at 904.4 s. The waiting duration is 122.36 s, which is close to the expected value of 120 s, which verifies the return to service function of the inverter.

IV. Conclusion

The Power Hardware-in-the-Loop experimental facility for smart inverter testing implemented at Rensselaer Polytechnic Institute was successfully used to test the functionality of the SMA inverter in different operating conditions and control modes. The six experiments documented in this paper include the testing of the inverter operating in control modes: constant power factor, constant reactive power, voltage-var, voltage-watt, voltage ride through and return to service. Experiments were conducted in accordance with the IEEE 1547.1-2020 standard.

The results show that the testing environment is capable of validating the functionalities of the smart inverter. However, it is important to note that there were discrepancies between the expected output of the inverter and the measured values due to errors introduced by some of the instrumentation, primarily attributed to the non-linear behavior of the current and voltage transformers. Additionally, there exists a coupling oscillation between the DC power supply and the inverter that caused unexpected behavior in the output power and needs to be investigated further. To address this, the amplifier configuration should be adjusted to accommodate experiments that require a higher power rating. Despite these challenges, the results of the tests demonstrate the effectiveness of the testing environment and provide a foundation for the next phase of the project, which will involve testing the integration of the smart inverter with the SGS DERMS system.

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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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