New York State Energy Research Development Authority (NYSERDA)

200888 NYSERDA O&R Challenge

PON 4128 Contract Number 149165

Rensselaer Polytechnic Institute Inverter Demonstration Report

By:	Smarter Grid Solutions Inc.
Date issued:	12/09/2022
Document Number:	200888 14A

Document Issue Control

Document name: Rensselaer Polytechnic Institute Inverter Demonstration Report

Document number: 200888 14A

Version	Issue Date	Author	Reviewed by	Approved by	Description	DUR
A	12/09/2021	Yusef Orest	Jack Rodman	Rachael Cornick	Initial release	6552

Contact:

Name: Stuart McMahon

Job Title: Delivery Architect

Email: smcmahon@smartergridsolutions.com

Smarter Grid Solutions, Inc.

335 Madison Avenue

4th Floor

New York, NY 10017

200888 NYSERDA O&R Challenge

Smarter Inverter and Advanced Distribution Management System (ADMS) Integration Project

Supported by
New York State Energy Research and Development Agency (NYSERDA)
PON 4128 - NYSERDA Agreement No: 149165

Report B
"Power Hardware-in-the-Loop Experimental Smart Inverter Testing Environment at RPI"

Rensselaer Polytechnic Institute
110 8th Street
Troy, NY 12180-3590

December 9, 2022

Authors:
Hao Chang, Prof. Luigi Vanfretti
ALSET Lab,
Electrical, Computer and Systems Engineering Department

RPI Principal Investigator/Project Manager: Luigi Vanfretti
Telephone: 518-276-2378, Email: vanfrl@rpi.edu

NYSERDA Project Manager
Michael Razanousky

SGS Project Manager
Yusef Orest

Introduction

This report contains a detailed description of the test results obtained in the NYSERDA PON4128 project, entitled “Power Hardware-in-the-Loop Experimental Smart Inverter Testing Environment at RPI”, performed by Rensselaer Polytechnic Institute. The project is supported by New York State Energy Research and Development Authority (NYSERDA), New York Power Authority (NYPA) and New York Independent System Operator (NYISO). The experiments conducted in this report follows “IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces” standardized testing procedures.

To verify the correct installation of the equipment and configuration of the SMA smart inverter, there were six separate tests conducted and documented in the following sections: Constant Power Factor; Constant Reactive Power; Voltage Var; Voltage Watt; Voltage Ride Through and Return to Service. Passing these tests will validate the capabilities of the testing environment setup for the next phase of this project which requires more sophisticated control logic with SGS’s Distributed Energy Resource Management System (DERMS) platform, Strata Grid. For more detailed information about the testing environment please refer to RPI Report A – “Power Hardware-in-the-Loop Experimental Smart Inverter Testing Environment at RPI”.

The experiments conducted in this report follow the “IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces,” i.e., the IEEE 1547.1-2020 standard.

To verify the correct installation of testing equipment and the configuration of the SMA smart inverter, there are six separate tests conducted and documented in the following sections, which correspond to the smart inverter control functionalities under test:

- Constant Power Factor
- Constant Reactive Power
- Voltage Var
- Voltage Watt
- Voltage Ride Through
- Return to Service

Carrying out these tests allows for validating the capabilities of the testing environment setup and the smart inverter functionalities. With the successful test results documented herein, the next phase, testing the integration of the smart inverter with SGS’s DERMS system, will begin.

For more detailed information about the testing environment please refer to Report A.

1. General Equipment Setup

In this section, the user interfaces for the equipment used in all testing experiments are introduced. The following four equipment types were used as control devices and laboratory observations were made to verify the functionality of the SMA inverter.

1.1. OP1400 Power Amplifier

For this project the OP1400 amplifier is emulating the power grid that the inverter is connected to. The user interface below shows the control panel of the OP1400 power amplifier running in parallel with a real-time simulator to control and monitor the status of the amplifier.

Listed below are the OP1400 User Interface inputs and outputs shown on Figure 1.

1. 3 Phase RMS Voltage Setpoint
2. Automated RMS Voltage Setpoint Adjustment
3. Slew Rate and Saturation Limiter
4. Current RMS Setpoint
5. Current RMS Voltage and Current for Each Phase

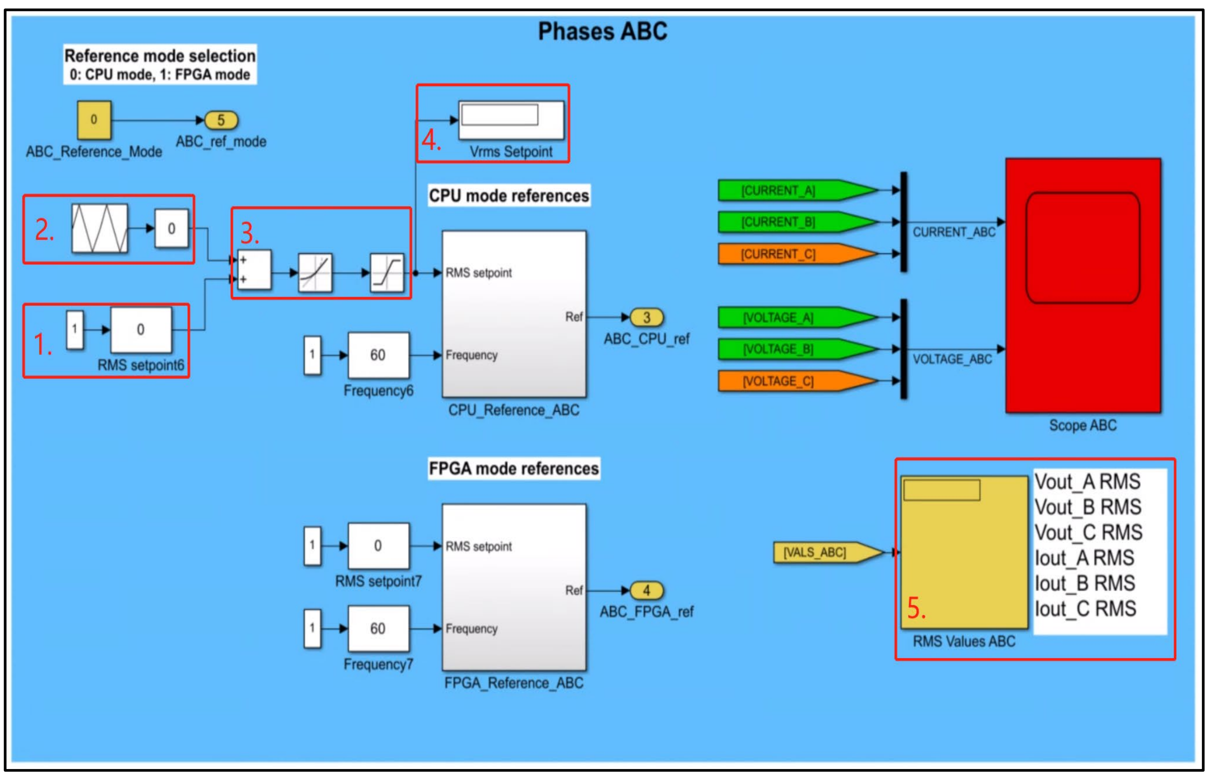


Figure 1 – OP1400 User Interface

In the following experiments, the 3 Phase RMS Voltage Setpoint is used to control the emulated grid voltage for the inverter to conduct High/Low voltage ride-through. The Automated RMS Voltage Setpoint Adjustment is used to automatically change the emulated grid voltage for the inverter to plot Volt-Watt and Volt-Var graphs. The Slew Rate limiter is necessary since during previous experiments a fast voltage change resulted in tripping the power amplifier due to autotransformer inrush current. The Saturation limiter avoids user input error exceeding the amplifier and inverter voltage limitations. The voltage saturates 160Vrms L-N. Thus, the voltage can reach 692V L-L on the high side of the autotransformer which is sufficient for the testing procedures.

1.2. DC Power Supply

The Photovoltaic Power Profile Emulation (PPPE) software automatically calculates solar array voltage and current profiles based on user-defined parameters. The figure below shows the user interface for MagnaDC PPPE software.

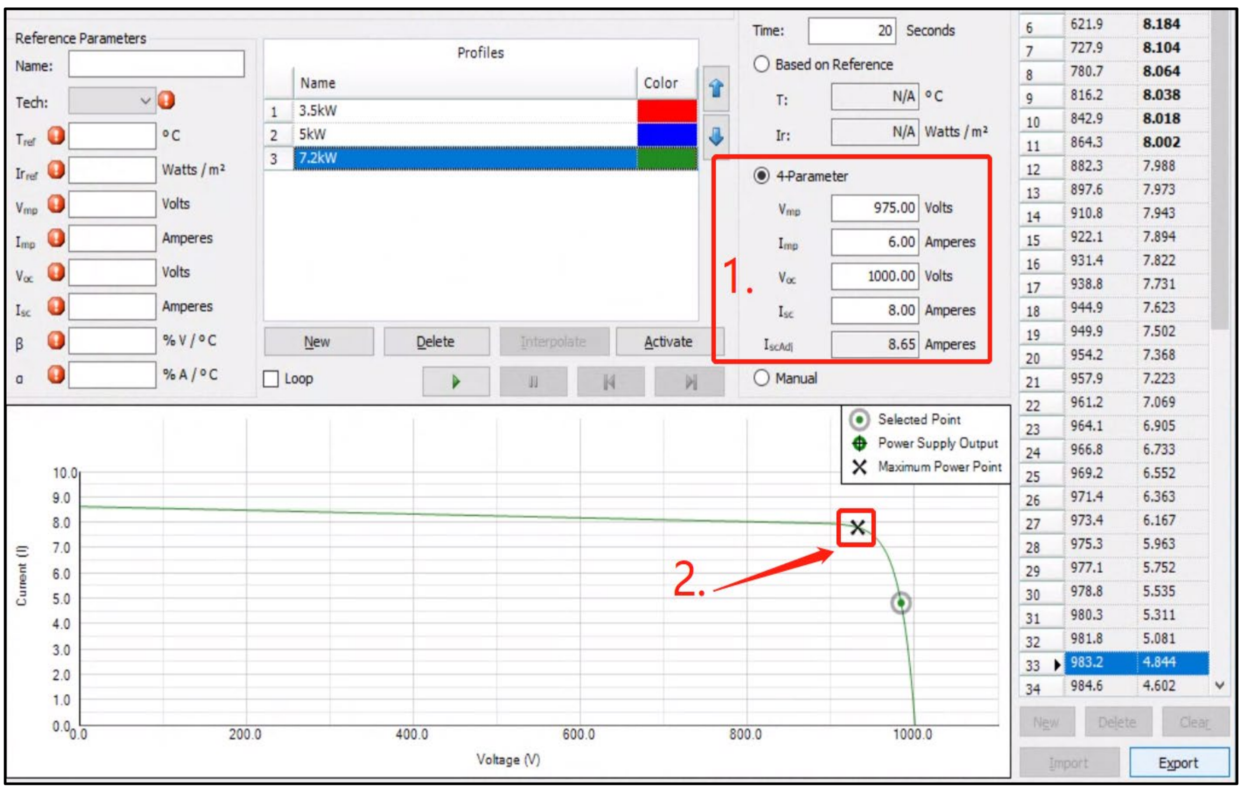


Figure 2 - MagnaDC PPPE User Interface

Since the experiments do not require change on the DC side and the maximum output real power of the inverter is set to 3kW, the profile in box 1 is sent to the DC power supply to have a maximum of 7.2kW (shown in box 2). MPP power profile for the solar panel is used in all the experiments.

1.3. SMA Inverter

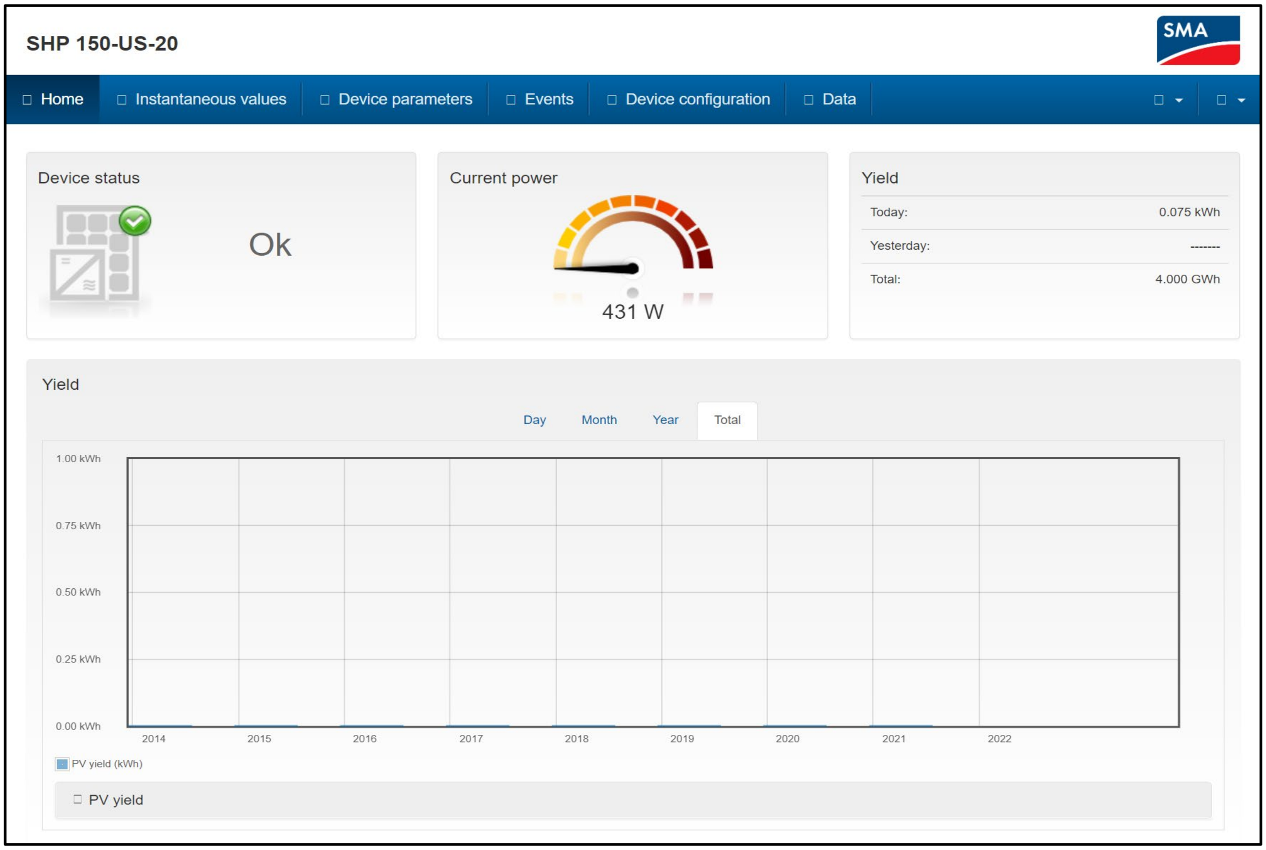


Figure 3 - SMA User Interface

The SMA inverter is the Equipment Under Test (EUT) used for all the tests completed in this inverter demonstration. The inverter is configured through its embedded web server user interface (UI) software shown in Figure 3 above. On the home page, the current output power and device status are displayed. The "Device parameters" tab is where all the configuration for the inverter is located. In the following experiments, the detailed settings are displayed and configured through the "Device parameters" tab on the home page.

1.4. METERING

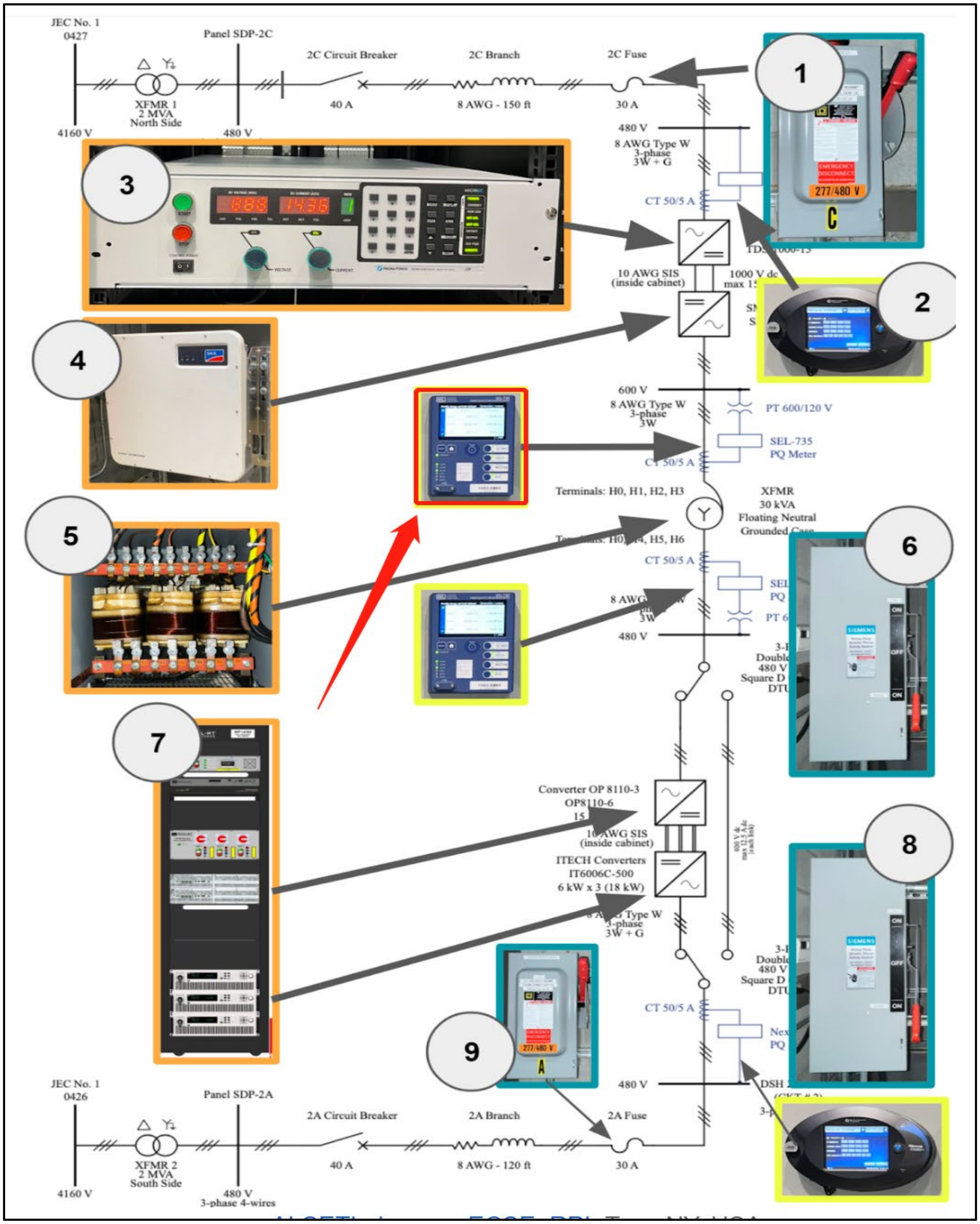


Figure 4 – Lab Single Line Wiring Diagram

To avoid any distortions introduced by the autotransformer, all the metering in this report is captured by the SEL-735 in the red box shown in Figure 4 above. The current transformer used by this meter has limited accuracy when measuring large current. The error causes nonlinear phase and amplitude error. Thus, when the meter is calibrated at high current, it tends to have more error at low current. The calibration process is documented at the end of this section.

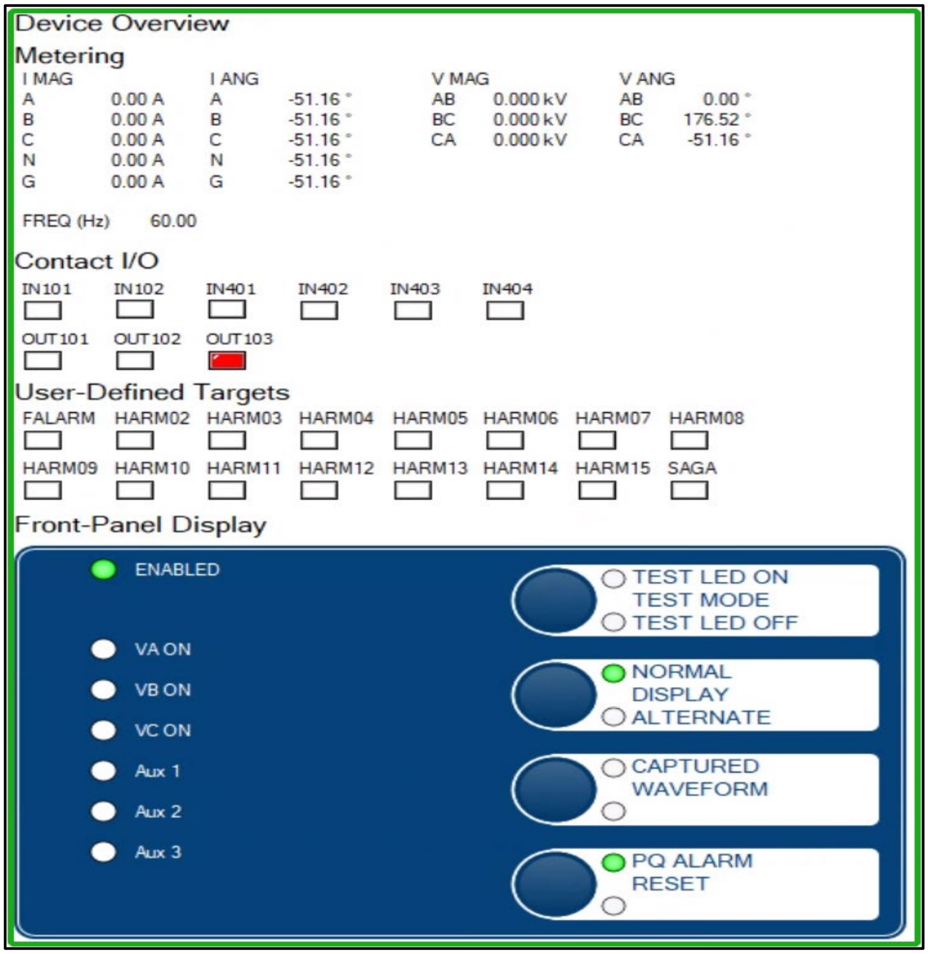


Figure 5 - SEL User Interface

Figure 5 above shows the screenshot of the meter's graphical interface including meter measurements. All of the testing meter measurement screenshots for each test reported in this document are directly taken from the meter through SEL's software to avoid delay and synchronization issues in data acquisition. An example of such screenshots is shown below.

	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		

Figure 6 - SEL Metering Result Example

In this report, the meter measurements will be presented in the format shown in Figure 6 above. The current, voltage, real power, apparent power, reactive power, and power factor are displayed to evaluate the status of the inverter. In the following segment, the meter calibration steps are introduced.

In the sequence, the meter calibration steps are introduced. The process is started by configuring the inverter through its graphical interface (homepage).

The inverter is energized (see figure below)

Manual setting

Active power	3,000 W	(0 W … 150,000 W)
Standardized active power	100 %	(0 % … 100 %)

Figure 7 - Inverter Output Display

1. Power on the inverter and set the output power for the inverter to 3kW. Since the amplifier is capable of going up to 5kVA, 3kW is chosen to leave some room for reactive power. Verify the reactive power stabilization is set to off.
2. Next, we verify the power output is displayed on the inverter's web server user interface. The power output is 2,910W±10W.

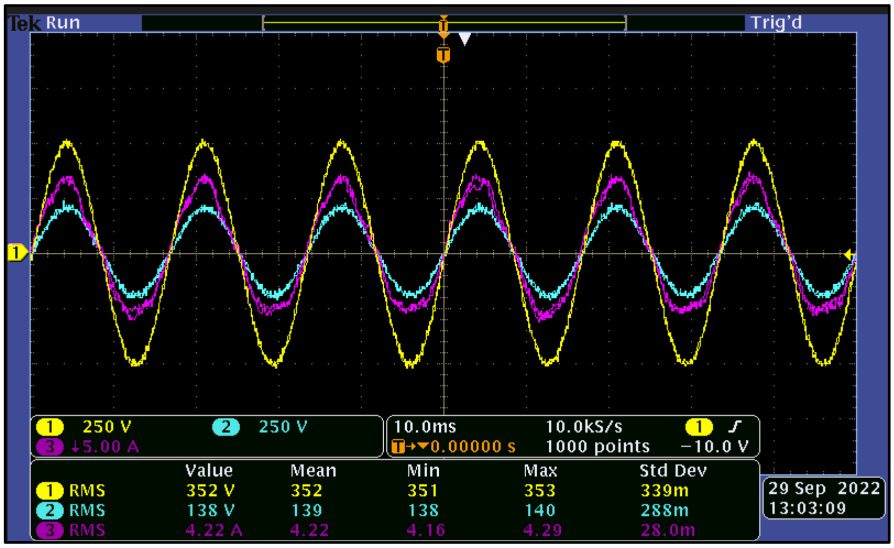


Figure 8 - Tek Oscilloscope Display (Yellow-Transformer Highside Voltage Blue-TF Lowside V Pink-Inverter Current)

3. A Tek oscilloscope is used to verify the phase of the voltage and output current. In Figure 8 above, the current is in phase with voltage which verifies the inverter is outputting zero reactive power.
4. In the SEL meter setting, the angle correction for the current transformer is adjusted until the true power factor reaches 1.

	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		

Figure 9 – SEL Metering Power Factor Display

5. From Figure 9 we can verify the meter is calibrated at high current working conditions.

2. Constant Power Factor

"This test verifies the EUT'S operation at a fixed power factor is compliant with 5.3.2 of IEEE Std 1547-2018. This test verifies the EUT's response to changes in voltage magnitude and power when connected to an ac test source." (IEEE-SASB Coordinating Committees)

2.1. Objective

In the following test, the Constant P.F. mode of the inverter will be tested. From the web SMA UI introduced in section 1.3., the power factor is set to be constant. The meter reading will be recorded after the inverter finishes adjusting the output power (reach steady state). With the observation, we can verify if the inverter is outputting and maintaining the desired active and reactive power.

2.2. Setup and Procedure

The setting of the inverter from the web server is introduced to document any configuration change.

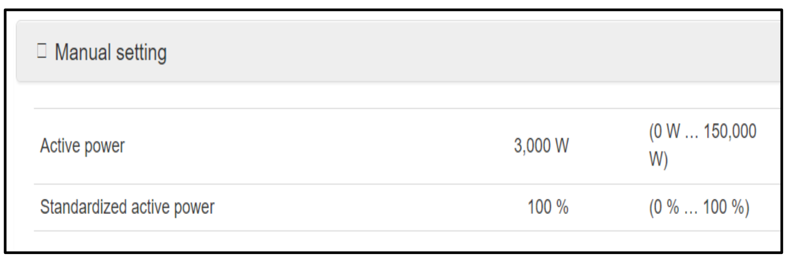


Figure 10 - Constant Active Power 3kW

In Figure 10 above, the inverter is set to output constant active power at 3kW – this is how the inverter is configured in the User Interface.

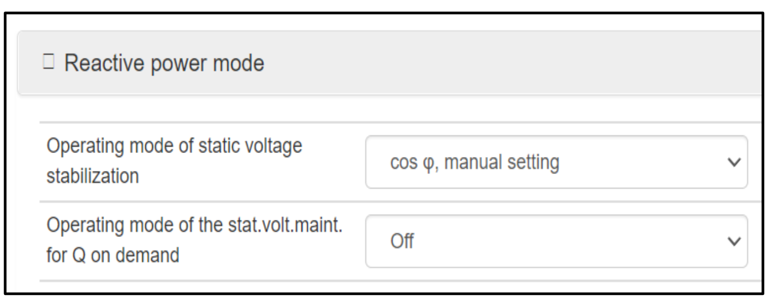


Figure 11 - Reactive Power Mode Display

The reactive power mode of the inverter is set to constant cos(phi) which is the power factor.

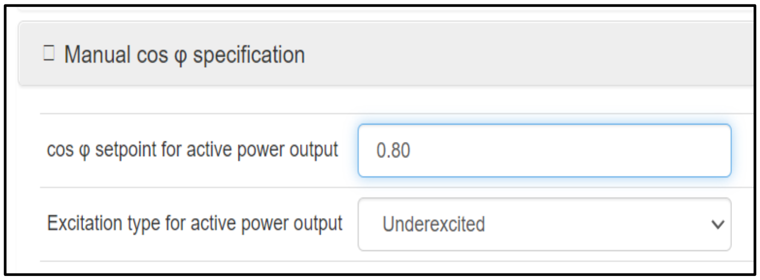


Figure 12 – Manual Power Factor Adjustment Display

For the following test, the cos(phi) and excitation type are adjusted according to different test requirements. In total 5 different combinations are documented in this report.

2.3. Result

The test results are presented in the following section: Unity P.F., Overexcited 0.95, Overexcited 0.9, Underexcited 0.95, Underexcited 0.9

2.3.1. Unity Power Factor

The inverter is configured to have a Unity power factor.

$$cos(\varphi) = 1$$

	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		

Figure 13 – SEL Metering Unity Power Factor Display

Figure 13 above shows the inverter generating around 3kW and the power factor is 1 as was expected. Since the SMA inverter is capable of generating 150kW, 158W of error is within the tolerance.

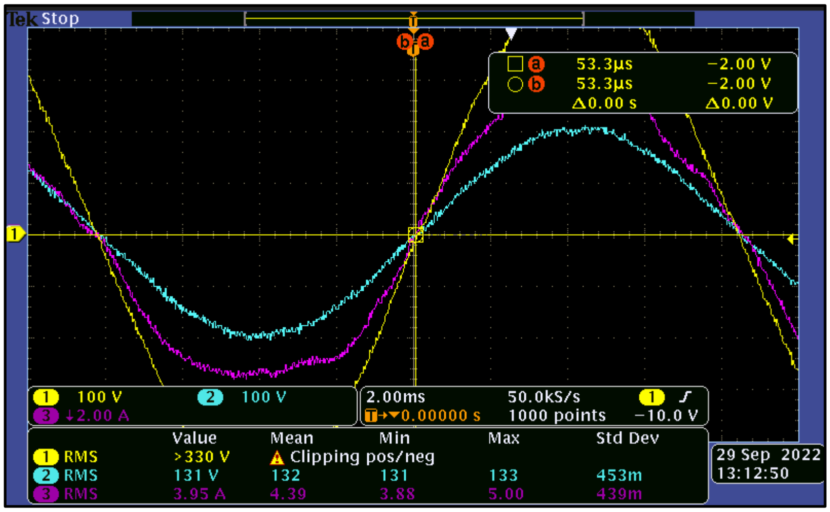


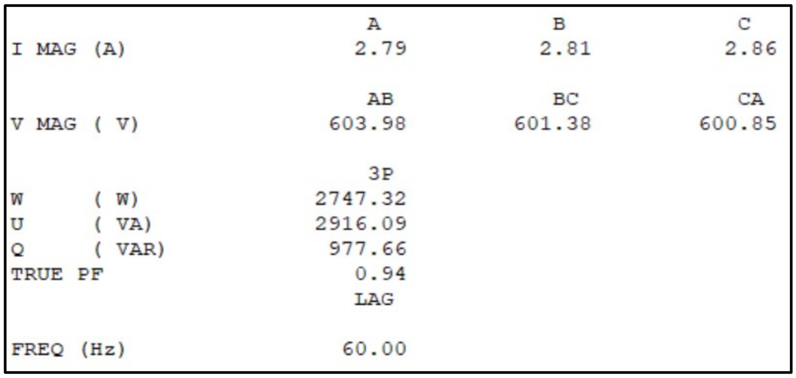
Figure 14 - Oscilloscope Unity Power Factor Display (Yellow-Transformer Highside Voltage Blue-TF Lowside V Pink-Inverter Current)

The oscilloscope shows the current is in phase with the voltage which indicates a unity power factor.

2.3.2. Overexcited Power Factor 0.95

The inverter is configured to have lagging 0.95 P.F.

$$cos(\varphi) = 0.95$$



	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		

Figure 15 - SEL Metering Overexcited Power Factor 0.95 Display

$$cos(\varphi) = 0.95$$

$$\varphi = 18.2^o$$

$$W_{Real} = 3000W$$

$$Q_{Reactive} = tan(18.2^o) * W_{Real} = 986Var$$

$$U_{\ Apparent} = \sqrt{W^2{}_{Real} + Q^2{}_{Reactive}} = 3157VA$$

Table 1 - Overexcited Power Factor 0.95 Results

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

From the above calculations, the measured real, apparent and reactive power are as expected and within reasonable tolerance, shown in Table 1.

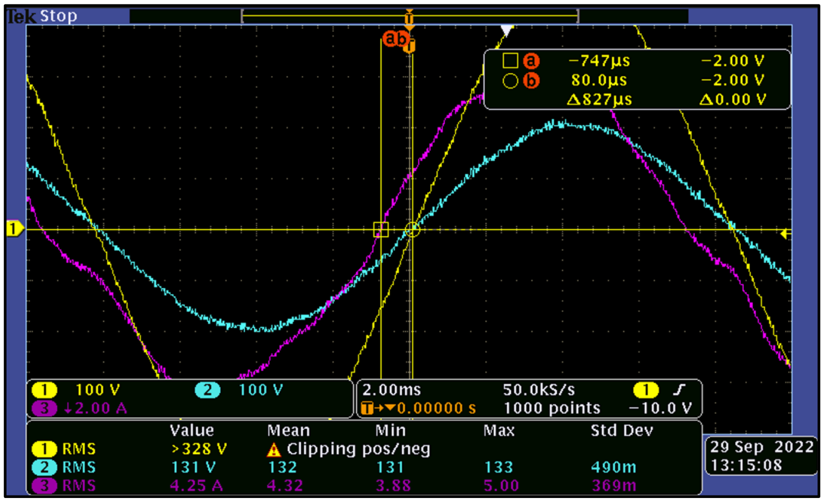


Figure 16 - Oscilloscope Overexcited Power Factor 0.95 Display (Yellow-Transformer Highside Voltage Blue-TF Lowside V Pink-Inverter Current)

The oscilloscope is used to verify the lag angle. From the measurement, the time lag is 827 microseconds.

$$\varphi = 360 * 0.827ms * 60Hz = 17.8^o$$

The measured lag angle is close to the desired angle. The error could be introduced by measurement error since the current waveform is slightly distorted. The measurement here is to cross check the measurement from the meter.

2.3.3. Overexcited Power Factor 0.9

The inverter is configured to have lagging 0.9 P.F.

$$cos(\varphi) = 0.9$$

	A	B	C
I MAG (A)	2.92	2.93	2.98
	AB	BC	CA
V MAG (V)	604.82	602.20	601.60
	3P		
W (W)	2697.12		
U (VA)	3011.06		
Q (VAR)	1338.67		
TRUE PF	0.90		
	LAG		
FREQ (Hz)	60.00		

Figure 17 – SEL Metering Overexcited Power Factor 0.9 Display

$$cos(\varphi) = 0.9$$

$$\varphi = 26.8^o$$

$$W_{Real} = 3000W$$

$$Q_{Reactive} = tan(25.8^o) * W_{Real} = 1450Var$$

$$U_{\ Apparent} = \sqrt{W^2{}_{Real} + Q^2{}_{Reactive}} = 3332VA$$

Table 2 – Overexcited Power Factor 0.9 Results

Power	Desired	Measured	Error
Real	3000W	2697W	10.1%
Apparent	3332VA	3011 VA	9.6%
Reactive	1450Var	1338Var	7.7%
P.F..	0.9	0.9	0%

From the above calculations, the measured real, apparent and reactive power are as expected and within reasonable tolerance. The measured power factor is 0.9.

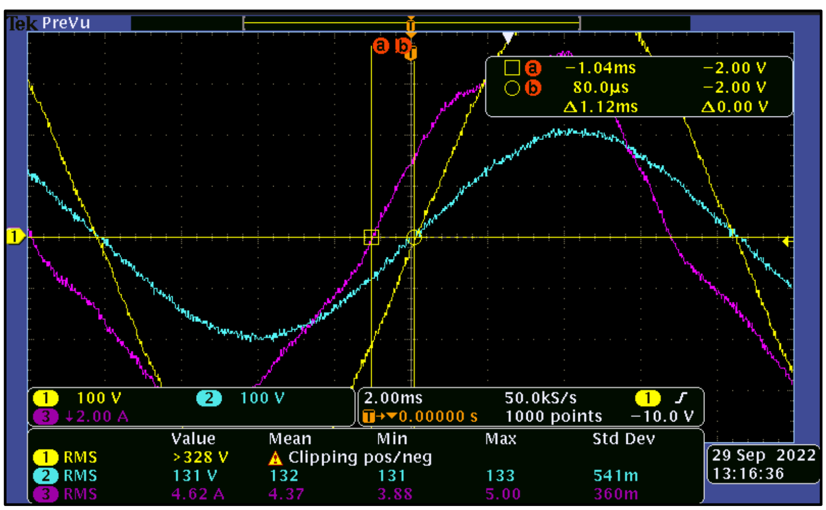


Figure 18 – Oscilloscope Overexcited Power Factor 0.9 Display (Yellow-Transformer Highside Voltage Blue-TF Lowside V Pink-Inverter Current)

The oscilloscope is used to verify the lag angle. From the measurement, the time lag is 1.12 millisecond.

$$\varphi = 360 * 1.12ms * 60Hz = 24^{o}$$

The measured lag angle is close to the desired angle.

2.3.4. Underexcited Power Factor 0.95

The inverter is configured to have leading 0.95 P.F.

$$cos(\varphi) = -0.95$$

	A	B	C
I MAG (A)	2.93	2.99	3.02
	AB	BC	CA
V MAG (V)	600.52	597.90	597.64
	3P		
W (W)	2963.22		
U (VA)	3073.29		
Q (VAR)	-815.13		
TRUE PF	0.96		
	LEAD		
FREQ (Hz)	60.00		

Figure 19 – SEL Metering Underexcited Power Factor 0.95 Display

$$cos(\varphi) = -0.95$$

$$\varphi = -18.2^{o}$$

$$W_{Real} = 3000W$$

$$Q_{Reactive} = tan(-18.2^{o}) * W_{Real} = -986Var$$

$$U_{\ Apparent} = \sqrt{W^2{}_{Real} + Q^2{}_{Reactive}} = 3157VA$$

Table 3 – Underexcited Power Factor 0.95 Results

Power	Desired	Measured	Error
Real	3000W	2747 W	8.4%
Apparent	3162 VA	2916 VA	7.8%
Reactive	-986Var	-815Var	17%
P.F..	0.95	0.96	1%

From the above calculations, the measured real, apparent and reactive power are as expected and within reasonable tolerance.

Figure 20 – Oscilloscope Underexcited Power Factor 0.95 Display (Yellow-Transformer Highside Voltage Blue-TF Lowside V Pink-Inverter Current)

The oscilloscope is used to verify the lead angle. From the measurement, the time lead is 667 microseconds.

$$\varphi = 360 * 0.667ms * 60Hz = 14^o$$

The measured lag angle is not close to the desired angle. From the figure above we can see the current waveform is much more distorted than the lagging case. From the scope measurement, simply the zero-crossing point is taken as the reference point when calculating the time lead, which is not an effective way to estimate phase shift when the wave is heavily distorted. We can conclude from the above measurement that either the inverter is not an effective reactive absorber, or the autotransformer caused the nonlinearity in the current waveform.

2.3.5. Underexcited Power Factor 0.9

The inverter is configured to have leading 0.9 P.F.

$$cos(\varphi) = -0.9$$

```
                                 A              B              C
I MAG (A)                     3.16           3.22           3.25

                                AB             BC             CA
V MAG ( V)                  599.58         596.94         596.79

                                3P
W       ( W)               3028.85
U       ( VA)              3294.27
Q       ( VAR)            -1295.48
TRUE PF                       0.92
                              LEAD

FREQ (Hz)                    60.00
```

Figure 21 – SEL Metering Underexcited Power Factor 0.9 Display

$$cos(\varphi) = -0.9$$

$$\varphi = -26.8^o$$

$$W_{Real} = 3000W$$

$$Q_{Reactive} = tan(25.8^o) * W_{Real} = -1450Var$$

$$U\ _{Apparent} = \sqrt{W^2{}_{Real} + Q^2{}_{Reactive}} = 3332VA$$

Table 4 – Underexcited Power Factor 0.9 Results

Power	Desired	Measured	Error
Real	3000W	2697W	10.1%
Apparent	3332VA	3011 VA	9.6%
Reactive	-1450Var	-1295Var	10.7%
P.F..	0.9	0.92	2%

From the above calculations, the measured real, apparent and reactive power are as expected and within reasonable tolerance. The measured power factor is 0.92.

The oscilloscope image was not shown since due to current distortion. Simply measuring the zero-crossing point is no longer a valid method for measuring phase shift for this test.

2.4. CONCLUSION

The overall constant power factor performance is consistent with our expectation. The errors in the experiment are mainly caused by nonlinear behavior of the autotransformer and measurement inaccuracy.

3. Constant Reactive Power

"This test verifies the EUT'S operation at a constant reactive power setting is compliant with 5.3.5 of IEEE Std 1547-2018 and the reactive power capabilities of the EUT defined in5.2 of IEEE Std 1527-2018. This test verifies the EUT's response to changes in voltage magnitude and power when connected to an ac test source." (IEEE-SASB Coordinating Committees)

3.1. Objective

In the following test, the constant reactive power mode of the inverter will be tested from the web UI introduced in section 1.3. The reactive power is set to be constant. The meter reading will be recorded after the inverter finishes adjusting the output power and reaches steady state. With the observation, we can verify if the inverter is outputting and maintaining the desired active and reactive power.

3.2. Setup and Procedure

The setting of the inverter from the web server is introduced to document any configuration change.

Figure 22 - Active Power 3kW Setting Display

In Figure 22, the inverter is set to output constant active power at 3kW.

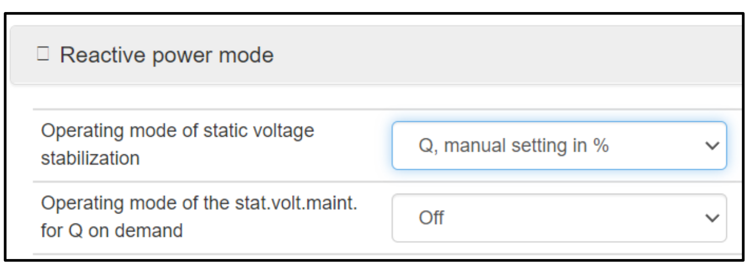


Figure 23 – Voltage Stabilization Setting Display

The Operating mode of static voltage stabilization is set to manual control Q.

☐ Manual reactive power setting for active power output	
Reactive power	0.5 %

Figure 24 - Reactive Power Setting Display

For the following test, the percentage of reactive power is adjusted according to different test requirements. In total six different combinations are documented in this report.

Maximum active power	150,000 W
RCD adjustment	Off
Maximum active power output	150,000 W
Currently set apparent power limit	150,000 VA
Maximum apparent power	150,000 VA

Figure 25 - Reactive Power Test Settings

The maximum apparent power is 150kVA. Since we are only able to set the reactive power as a percentage in web UI, the 0.5%, 1%, 1.5%, -0.5%, -1% and -1.5% are chosen to test the constant reactive power mode of the inverter.

3.3. Result

3.3.1. Underexcited 750Var

$$Q_{Reactive} = -0.5\% * 150kVA = -750Var$$

	A	B	C
I MAG (A)	2.85	2.90	2.94
	AB	BC	CA
V MAG (V)	600.77	598.11	597.89
	3P		
W (W)	2932.20		
U (VA)	2995.88		
Q (VAR)	-614.41		
TRUE PF	0.98		
	LEAD		
FREQ (Hz)	60.00		

Figure 26 - SEL Metering Underexcited 750 Var Display

From the above figure, the measured reactive power is -614Var.

Table 5 - Underexcited 750 Var Results

Power	Desired	Measured	Error
Real	3000W	2932W	2.2%
Apparent	3092VA	2995 VA	3.1%
Reactive	-750Var	-614Var	18.1%

Note: Error causes and impacts prefaced in section 2.3.4.

From the above calculations, the measured real, apparent and reactive power are as expected and within reasonable tolerance. The error of the reactive power is analyzed in section 2.3.4.

3.3.2. Underexcited 1500W

$$Q_{Reactive} = -1\% * 150kVA = -1500Var$$

```
                               A              B              C
I MAG (A)                   3.16           3.22           3.25

                              AB             BC             CA
V MAG ( V)                599.58         596.94         596.79

                              3P
W      ( W)              3028.85
U      ( VA)             3294.27
Q      ( VAR)           -1295.48
TRUE PF                     0.92
                            LEAD

FREQ (Hz)                  60.00
```

Figure 27 - SEL Metering Underexcited 1500W Display

From the above figure, the measured reactive power is -1295Var.

Table 6 - Underexcited 1500WResults

Power	Desired	Measured	Error
Real	3000W	3028W	1%
Apparent	3354VA	3294VA	1.7%
Reactive	-1500Var	-1295Var	13.6%

From the above calculations, the measured real, apparent and reactive power are as expected and within reasonable tolerance.

3.3.3. Underexcited 2250W

$$Q_{Reactive} = -1.5\% * 150kVA = -2250Var$$

```
                          A            B            C
I MAG (A)              3.56         3.64         3.66

                         AB           BC           CA
V MAG ( V)           598.40       595.83       595.75

                         3P
W      ( W)         3116.50
U      ( VA)        3776.99
Q      ( VAR)      -2133.80
TRUE PF                0.83
                       LEAD

FREQ (Hz)             60.00
```

Figure 28 - SEL Metering Underexcited 2250W Display

From the above figure, the measured reactive power is -2133Var.

Table 7 - Underexcited 2250W Results

Power	Desired	Measured	Error
Real	3000W	3116W	3.9%
Apparent	3750VA	3776 VA	0.7%
Reactive	-2250Var	-2133Var	5.2%

From the above calculations, the measured real, apparent and reactive power are as expected and within reasonable tolerance.

3.3.4. Overexcited 750W

$$Q_{Reactive} = 0.5\% * 150kVA = 750Var$$

	A	B	C
I MAG (A)	2.75	2.77	2.82
	AB	BC	CA
V MAG (V)	603.40	600.80	600.45
	3P		
W (W)	2769.26		
U (VA)	2879.55		
Q (VAR)	789.33		
TRUE PF	0.96		
	LAG		
FREQ (Hz)	60.00		

Figure 29 - SEL Metering Overexcited 750W Display

From the above figure, the measured reactive power is 789Var.

Table 8 - Overexcited 750W Results

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

From the above calculations, the measured real, apparent and reactive power are as expected and within reasonable tolerance.

3.3.5. Overexcited 1500W

$$Q_{Reactive} = -1\% * 150kVA = -1500Var$$

```
                          A          B          C
I MAG (A)              2.94       2.96       3.01

                         AB         BC         CA
V MAG ( V)           604.82     602.22     601.70

                         3P
W      ( W)         2684.28
U      ( VA)        3003.73
Q      ( VAR)       1347.98
TRUE PF                0.89
                        LAG

FREQ (Hz)             60.00
```

Figure 30 - SEL Metering Overexcited 1500W Display

From the above figure, the measured reactive power is 1347 Var.

Table 9 - Overexcited 1500W Results

Power	Desired	Measured	Error
Real	3000W	2684W	10.5%
Apparent	3354VA	3003 VA	10.4%
Reactive	1500Var	1347 Var	10.2%

From the above calculations, the measured real, apparent and reactive power are as expected and within reasonable tolerance.

3.3.6. Overexcited 2250W

$$Q_{Reactive} = -1.5\% * 150kVA = -2250Var$$

```
                          A          B          C
I MAG (A)              3.27       3.27       3.32

                         AB         BC         CA
V MAG ( V)           606.24     603.57     602.95

                         3P
W      ( W)         2590.64
U      ( VA)        3452.05
Q      ( VAR)       2281.49
TRUE PF                0.75
                        LAG

FREQ (Hz)             60.00
```

Figure 31 - SEL Metering Overexcited 2250W Display

From the above figure, the measured reactive power is 2281Var.

Table 10 - Overexcited 2250W Results

Power	Desired	Measured	Error
Real	3000W	2590W	13.6%
Apparent	3750VA	3452VA	8.0%
Reactive	2250Var	2281Var	1.3%

From the above calculations, the measured real, apparent and reactive power are as expected and within reasonable tolerance.

4. Voltage-Var

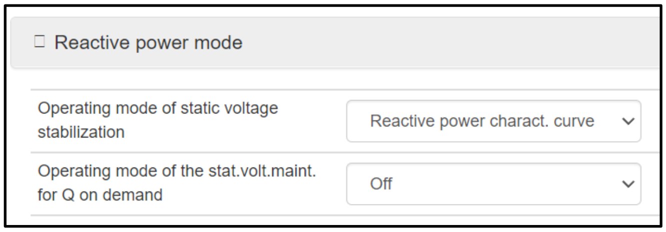
"This test verifies the EUT's operation with voltage-reactive power (volt-var) mode enabled is compliant with 5.3.3 of IEEE Std 1547-2018 during voltage disturbances within the continuous operation range defined in 6.4.2.2 of IEEE Std 1547-2018 with an imbalanced grid (i.e., with a nonzero negative sequence component). This test verifies the EUT's response to changes in voltage magnitude when connected to an ac test source with a fixed VRef." (IEEE-SASB Coordinating Committees)

4.1. Objective

In the following test, the Volt-Var mode of the inverter will be tested. From the web UI introduced in section 1.3., the active power is set to be constant. The meter reading will be recorded after the inverter finishes adjusting the output power (reach steady state) and transmitted through Modbus protocol to MATLAB Simulink to plot Volt vs. Reactive power plot automatically.

4.2. Setup and procedure

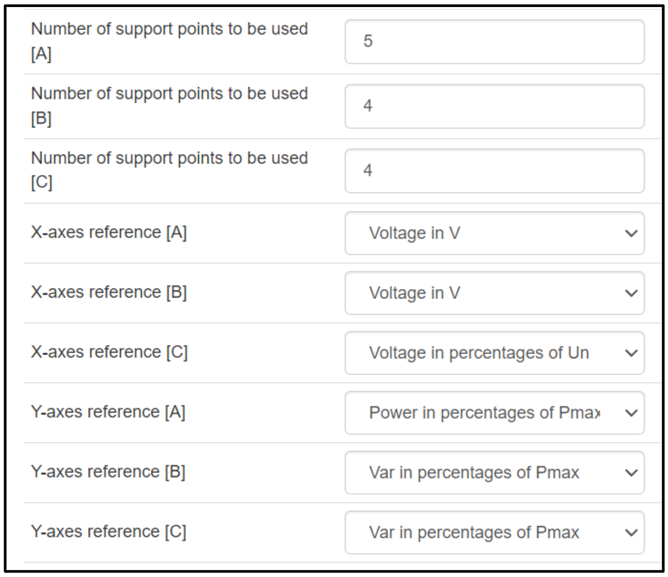
On the RT-Lab console mentioned in section 1.1, the desired 3 phase voltage is set to slowly oscillate between 560V to 640V RMS (<0.2V/s) to test how the inverter reacts to change of voltage.



☐ Reactive power mode	
Operating mode of static voltage stabilization	Reactive power charact. curve
Operating mode of the stat.volt.maint. for Q on demand	Off

Figure 32 – Volt-Var Characteristic Curve Setting Display

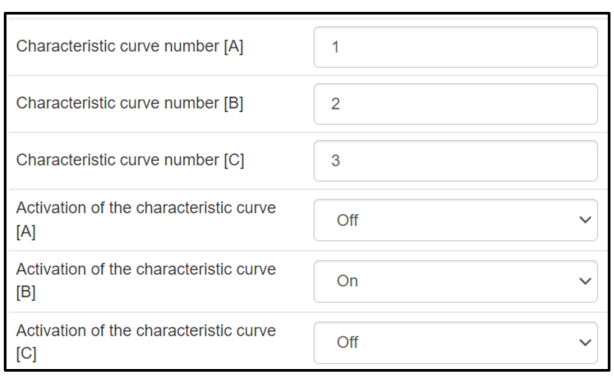
The Operating mode of static voltage stabilization is set to the Reactive power characteristic curve.



Number of support points to be used [A]	5
Number of support points to be used [B]	4
Number of support points to be used [C]	4
X-axes reference [A]	Voltage in V
X-axes reference [B]	Voltage in V
X-axes reference [C]	Voltage in percentages of Un
Y-axes reference [A]	Power in percentages of Pmax
Y-axes reference [B]	Var in percentages of Pmax
Y-axes reference [C]	Var in percentages of Pmax

Figure 33 - Operating Mode Volt-Var Characteristic Curve Setting Display

The curve B is used to set the Volt-Var curve, The desired volt-var curve has 4 points in the plot. Thus, the number of points used is set to 4. The X-axes reference is set to voltage and Y-axes reference is set to Var in percentage of Pmax.



Characteristic curve number [A]	1
Characteristic curve number [B]	2
Characteristic curve number [C]	3
Activation of the characteristic curve [A]	Off
Activation of the characteristic curve [B]	On
Activation of the characteristic curve [C]	Off

Figure 34 – Curve B Characteristic Curve Setting Display

The Curve number 2 is selected to be characteristic Curve B and only the activation for Curve B is turned on.

Supporting points of the characteristic curve 2

X value [A]	585.000	(-1,000.000 ... 1,000.000)
X value [B]	595.000	(-1,000.000 ... 1,000.000)
X value [C]	605.000	(-1,000.000 ... 1,000.000)
X value [D]	615.000	(-1,000.000 ... 1,000.000)
X value [E]	100.000	(-1,000.000 ... 1,000.000)
X value [F]	100.000	(-1,000.000 ... 1,000.000)
X value [G]	100.000	(-1,000.000 ... 1,000.000)
X value [H]	100.000	(-1,000.000 ... 1,000.000)
Y value [A]	1.000	(-100.000 ... 100.000)
Y value [B]	0.000	(-100.000 ... 100.000)
Y value [C]	0.000	(-100.000 ... 100.000)
Y value [D]	-1.000	(-100.000 ... 100.000)
Y value [E]	100.000	(-100.000 ... 100.000)
Y value [F]	100.000	(-100.000 ... 100.000)
Y value [G]	100.000	(-100.000 ... 100.000)
Y value [H]	100.000	(-100.000 ... 100.000)

Figure 35 - Curve 2 and Curve B Characteristic Curve Setting Display

Since only 4 points are used, only the first 4 points for X and Y values are set.

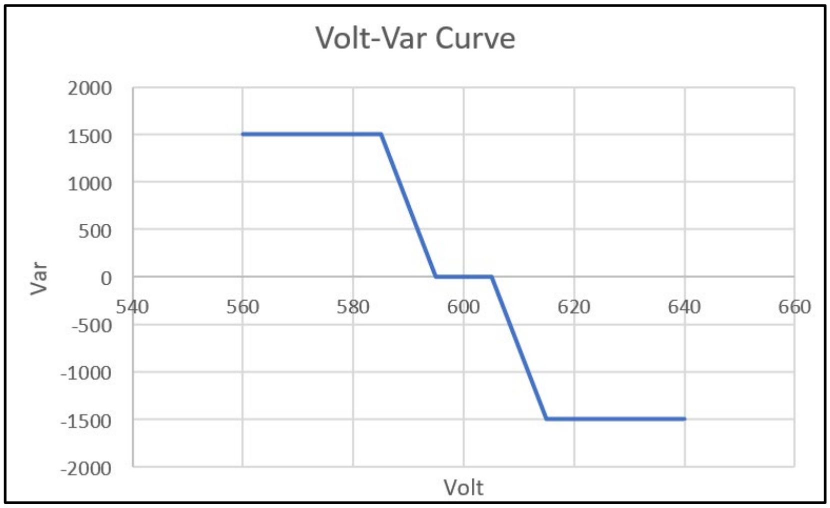


Figure 36 - Volt-Var Curve Behavior Display

The curve shown in Figure 36 is set as the volt-var behavior when the inverter detects a change in voltage.

4.3. RESULT

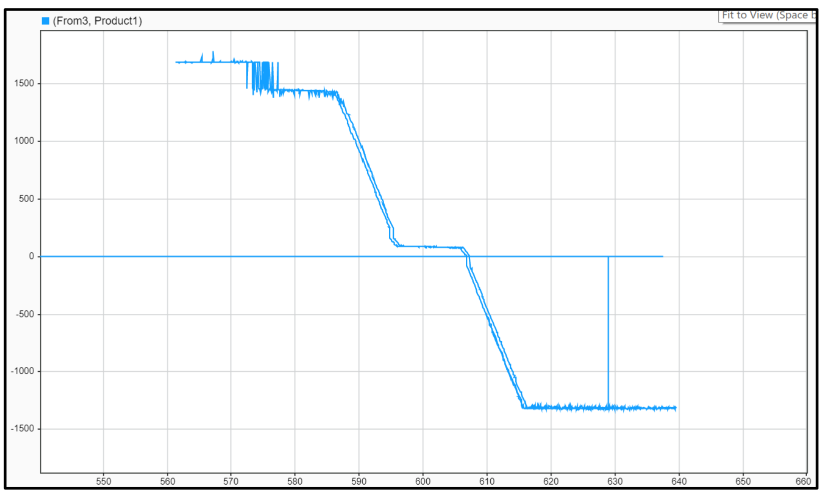


Figure 37 - Volt-Var Meter Data Plot

Figure 37 above is plotted in MATLAB with data collected from the meter. The overall vol-var mode performance is consistent with our expectation as we compare the measured volt-var curve to desired. The reactive power is zero when the voltage swings between 595V to 600V. This is expected since the meter errors always exist in the experiments. The power instability when voltage swings between 570V to 590V is caused by coupling between the DC power supply and the inverter which needs to be investigated further.

5. Voltage-Watt

"This test verifies the EUT's operation with voltage-active power (volt-watt) mode enabled is compliant with 5.4.2 of IEEE Std 1547-2018. This test verifies the EUT's response to changes in voltage magnitude when connected to an ac test source. This test is optional for Category A equipment." (IEEE-SASB Coordinating Committees)

5.1. Objective

In the following test, the Volt-Watt mode of the inverter will be tested. From the web UI introduced in section 1.3, the reactive power is set to zero. The meter reading will be recorded after the inverter finishes adjusting the output power (reach steady state) and transmitted through Modbus protocol to MATLAB Simulink to plot Volt vs. Active power figure automatically.

5.2. Setup and procedure

On the RT-Lab console mentioned in section 1.1, the desired 3 phase voltage is set to oscillate between 578V to 631V RMS slowly(<0.2V/s) to test how the inverter reacts to change of voltage.

Number of support points to be used [A]	5
Number of support points to be used [B]	4
Number of support points to be used [C]	4
X-axes reference [A]	Voltage in V
X-axes reference [B]	Voltage in V
X-axes reference [C]	Voltage in percentages of Un
Y-axes reference [A]	Power in percentages of Pmax
Y-axes reference [B]	Var in percentages of Pmax
Y-axes reference [C]	Var in percentages of Pmax

Figure 38 - Operating Mode Volt-Watt Characteristic Curve Setting Display

The curve A is used to set the Volt-Watt curve, The desired volt-var curve has 5 points in the plot. Thus, the number of pints used is set to 5. The X-axes reference is set to voltage and Y-axes reference is set to power in percentage of Pmax.

Characteristic curve number [A]	1
Characteristic curve number [B]	2
Characteristic curve number [C]	3
Activation of the characteristic curve [A]	Off (Off / On)
Activation of the characteristic curve [B]	
Activation of the characteristic curve [C]	Off

Figure 39 - Curve A Characteristic Curve Setting Display

The curve number 1 is selected to be characteristic Curve A and only the activation for Curve A is turned on.

Supporting points of the characteristic curve 1	
X value [A]	590.000
X value [B]	595.000
X value [C]	600.000
X value [D]	605.000
X value [E]	615.000
X value [F]	100.000
X value [G]	100.000
X value [H]	100.000
Y value [A]	3.000
Y value [B]	3.000
Y value [C]	3.000
Y value [D]	2.000
Y value [E]	0.500
Y value [F]	100.000
Y value [G]	100.000
Y value [H]	100.000

Figure 40 - Curve 1 and Curve a Characteristic Curve Setting Display

Since only 5 points are used, only the first 5 point of X and Y values are set.

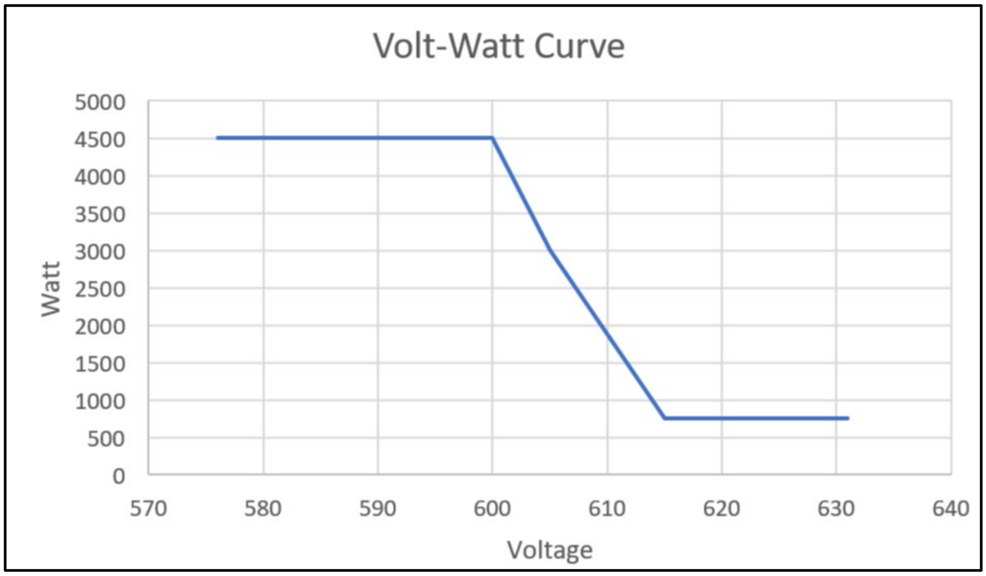


Figure 41 - Volt-Watt Curve Behavior Display

The above curve is set as the volt-watt behavior when the inverter detects a change in voltage.

5.3. Result

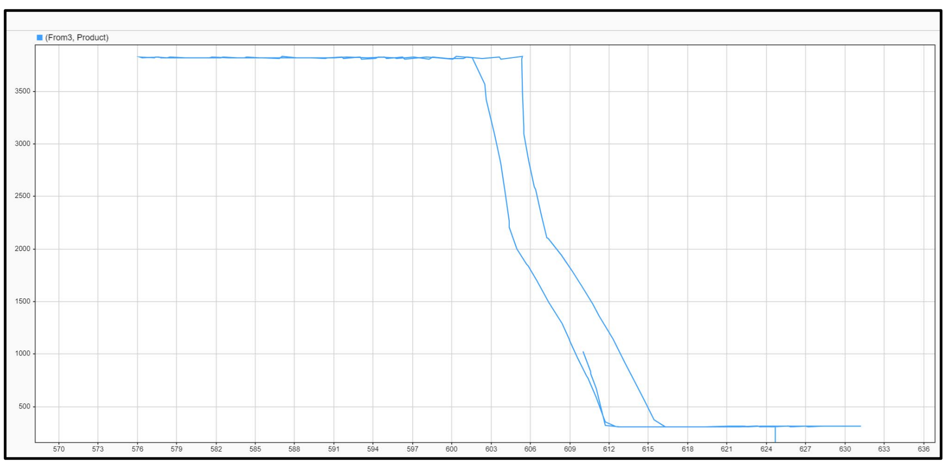


Figure 42 - Volt-Watt Meter Data Plot

Figure 42 above is plotted in MATLAB with data collected from the meter. The overall vol-watt mode performance is consistent with our expectation as we compare the measured volt-watt curve to desired. The hysteresis is noticeable in the above figure, which is not mentioned in the setting of the inverter. Further investigation is needed to find out the cause of this hysteresis.

6. Voltage Ride Through

"The low-voltage ride-through (LVRT) test verifies the ability of the EUT to ride through voltage sags without tripping in accordance with the requirements in 6.4.2 of IEEE Std 1547-2018." (IEEE-SASB Coordinating Committees)

6.1. Objective

In the following test, the High/Low voltage ride through of the inverter will be tested. From the web UI introduced in section 1.3., the active power is set to 3kW. The meter reading of real power will be recorded as an indicator of whether the inverter is running and transmitted through Modbus protocol to MATLAB Simulink to plot Watt vs. Time figure automatically. Due to equipment limitation, the power amplifier is only able to conduct experiments that has time scale over 5s. Thus, 20s of tripping time is chosen to have enough time for the power amplifier to increase and decrease voltage.

6.2. Setup and procedure

The return to service after grid fault is set to 60 seconds to reduce the time of waiting when inverter is tripped.

☐ Voltage monitoring		
Upper maximum threshold	1,040.00 V	(780.00 V ... 1,700.00 V)
Upper maximum threshold tripping time	0.312 ms	(0.100 ms ... 5.000 ms)
Median maximum threshold	720.00 V	(510.00 V ... 798.00 V)
Median maximum threshold tripping time	160 ms	(50 ms ... 59,000 ms)
Lower maximum threshold	640.00 V	(510.00 V ... 720.00 V)
Lower maximum threshold tripping time	20,000 ms	(100 ms ... 60,000 ms)
Upper minimum threshold	500.00 V	(270.00 V ... 600.00 V)
Upper minimum threshold tripping time	20,000 ms	(100 ms ... 60,000 ms)
Median minimum threshold	300.00 V	(270.00 V ... 600.00 V)
Median minimum threshold tripping time	160 ms	(100 ms ... 60,000 ms)
Upper maximum threshold as RMS value	720.00 V	(510.00 V ... 798.00 V)
Upper max.threshold as RMS value for tripping time	160 ms	(50 ms ... 59,000 ms)
Lower minimum threshold as RMS value	300.00 V	(270.00 V ... 600.00 V)
Lower min.threshold as RMS value for tripping time	160 ms	(100 ms ... 60,000 ms)
Voltage increase protection trigger time	10,000 ms	(40 ms ... 10,000 ms)
Voltage increase protection	720.00 V	(600.00 V ... 798.00 V)
Lower reconnection limit	530.00 V	(270.00 V ... 600.00 V)
Upper reconnection limit	635.00 V	(600.00 V ... 798.00 V)

Figure 43 - Voltage Ride Through Setup Display

The lower maximum threshold is set to 640V and the tripping time is set to 20s. If the voltage increases above 640V for less than 20s, the inverter should not trip. If the voltage increases above 640V for more than 20s, the inverter should trip. The upper minimum threshold is set to 500V and the tripping time is set to 20s. If the voltage decreases below 500V for less than 20s, the inverter should keep operating.

6.3. Result

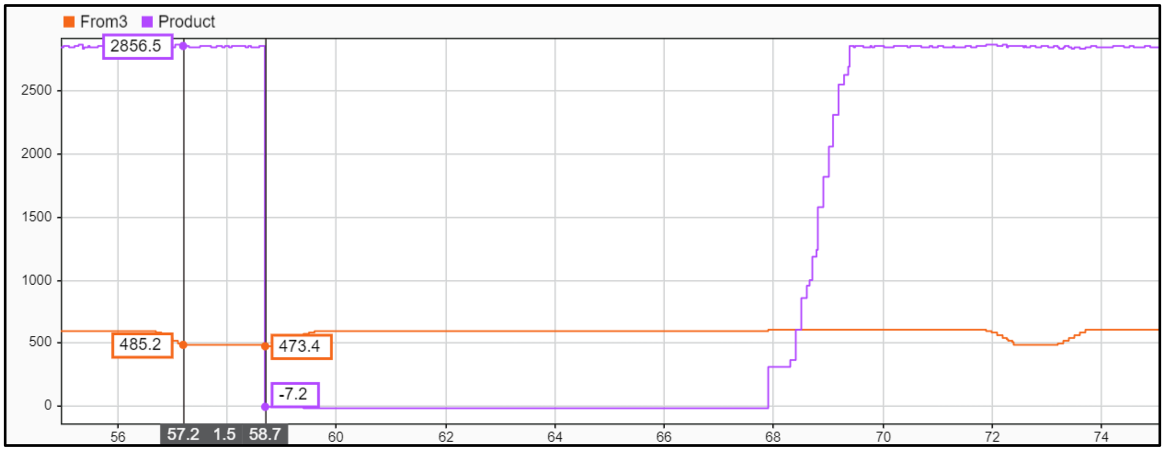


Figure 44 - Volt Ride Through Meter Data Plot (Purple line: Active Power; Orange Line: Voltage)

The console (MATLAB) to control the OPAL-RT is running on a laptop which does not process at the same speed at the simulator. Thus, plotting software in MATLAB is not in real-time with the simulator, instead, it is a routine that post-processes the results from the experiments. Consequently, the time axis in the measurements in the above figure needs to be scaled by a factor of 13.3 (one second in the above figure is 13.3s in real life). The voltage dropped under 500V at 57.2s and the inverter's power reduced to 0 at 58.7s. From the above figure, we can see the tripping time is 1.5*13.3=19.5s which is close to the expected value.

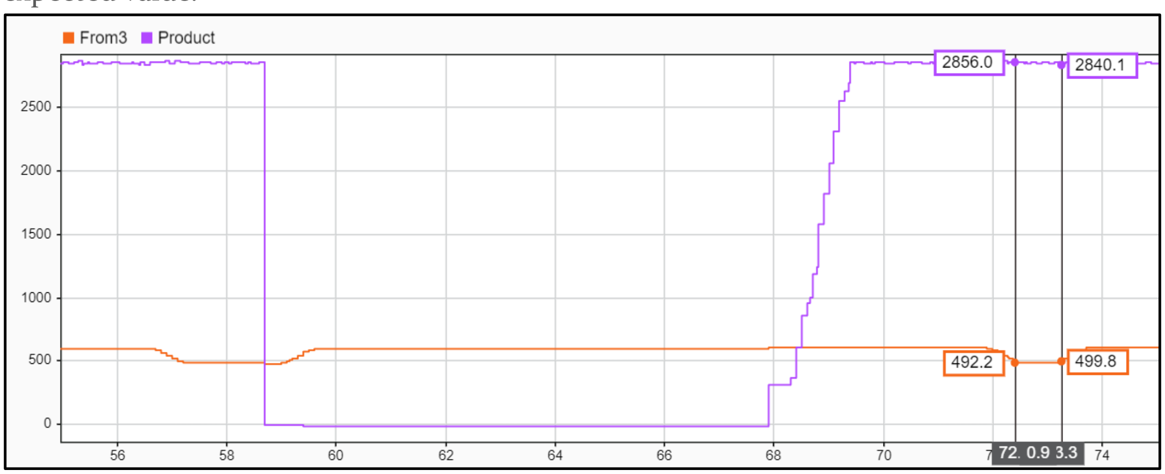


Figure 45 -Volt Ride Through Ramping Plot (Purple line: Active Power; Orange Line: Voltage)

Figure 45 above shows that the inverter starts ramping up power at 68s. The voltage dropped below 500V at 72s and increased above 500V after 12s and the inverter's power maintained at desired value.

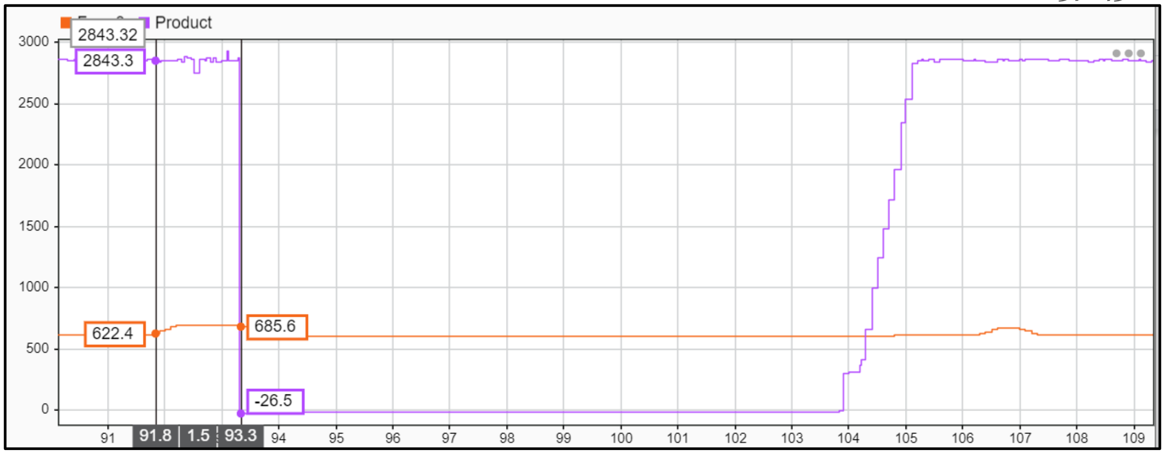


Figure 46 - Volt Ride Through Tripping Plot (Purple line: Active Power; Orange Line: Voltage)

The voltage increases over 640V at 92s and the inverter's power is reduced to 0 at 93.3s. In Figure46 above, we can see the tripping time is 1.3*13.3=17.3s which is close to desired value 20s.

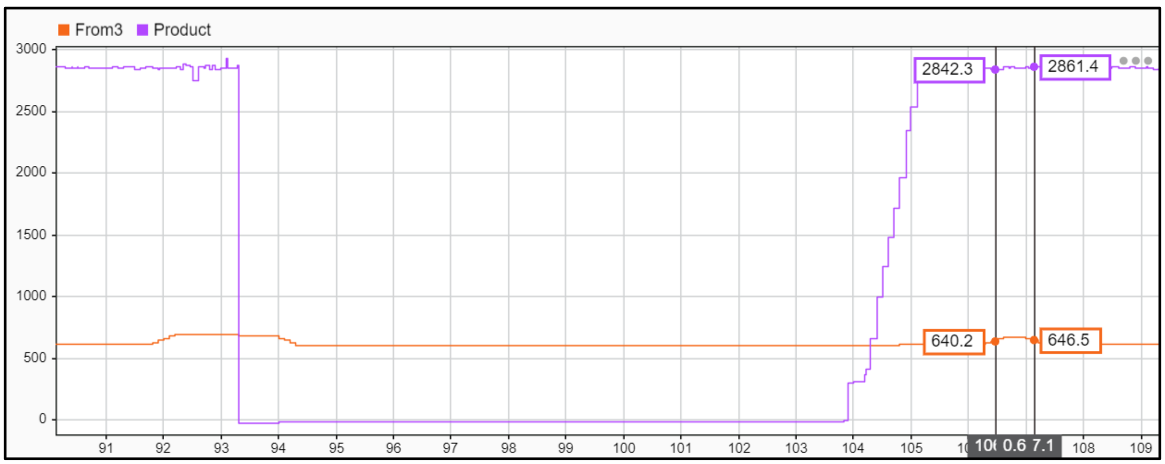


Figure 47 - Volt Ride Through Desired Value Ramping Plot (Purple line: Active Power; Orange Line: Voltage)

From the above figure, the inverter starts ramping up power at 104s. The voltage rises above 640V at 106.5s and decreases below 640V after 8s and the inverter's power is maintained at desired value.

7. Return to Service

7.1. Objective

According to IEEE Std 1547-2020, a 5 min wait after the inverter receives power is necessary to keep maintenance personnel's safety and overall power grid stability. In the following test, the amount of time that inverter waits after tripping due to low grid voltage is tested.

7.2. Setup and Procedure

In the following test, the return to service of the inverter will be tested. From the web UI introduced in section 1.3., the active power is set to 3kW. The meter reading of real power will be recorded as an indicator of whether the inverter is running and transmitted through Modbus protocol to MATLAB Simulink to plot Watt vs. Time figure automatically.

Country standard

Limitation to 4 reconnections (24 hrs) after exceeding continuous residual current	On	
Minimum insulation resistance	32.20 kOhm	(14.00 kOhm … 3,000.0 kOhm)
Maximum duration of a short interruption	3.000 s	(0.000 s … 6.67 min)
Reconnection time upon short interruption	5.00 min	(0.000 s … 26.67 min)
Reconnection time after grid fault	5.00 min	(0.000 s … 26.67 min)
Reconnection time upon restart	0.000 s	(0.000 s … 26.67 min)
Nominal voltage	600 V	(480 V … 690 V)
Nominal frequency	60.00 Hz	(44.00 Hz … 66.00 Hz)
Tripping threshold DC current monitoring	1.000 A	(0.020 A … 2.000 A)
Tripping time DC current monitoring	200 ms	(0 ms … 10,000 ms)
Disconnection limit for leakage current	1.500 A	(0.000 A … 1.500 A)
Disconnection limit for the lagging component of the leakage current	1.500 A	(0.000 A … 1.500 A)

Figure 48 – Return to Service Setup Display

The Reconnection time after grid fault is set to 5 min. The inverter should get back online 5 min after the inverter receives normal (600V) grid voltage reading.

7.3. RESULT

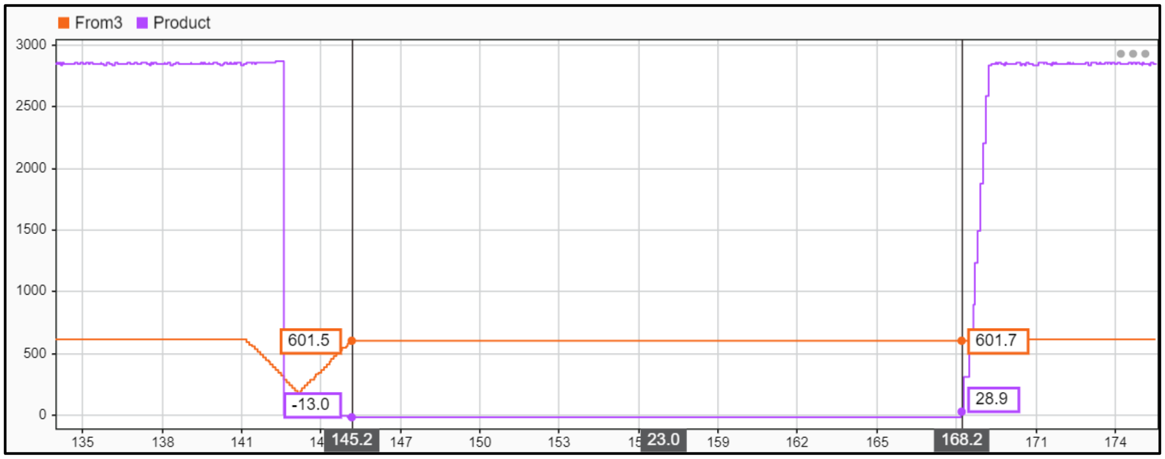


Figure 49 - Return to Service Meter Data Plot (Purple line: Active Power Orange Line: Voltage)

In Figure 49 above, the inverter receives nominal voltage at 145.2s and returns to service at 168.2s. The wait duration is 23*13.3=306s which is close to the desired value 300s.

8. Test Results

This report sought to present results for different operating modes of the SMA inverter. The operating modes tested were Constant Power Factor, Constant Reactive Power, Voltage-Var, Voltage-Watt, Voltage Ride Through, and Return to Service. All six tests were conducted and passed as illustrated in the Results section of each respective test.

Among all the experiments conducted, there was observed error which can mainly be attributed to nonlinear behavior of equipment and measuring devices. One limitation with the RPI Laboratory environment to be considered is the coupling oscillation between the DC power supply and the inverter, which caused instability in power output. Solely from observing the behavior of the inverter, the oscillation only started when the apparent power reached the upper limit of the power amplifier. According to Opal-RT's technical support team, the amplifier can be configured differently to reach 15kVA as initially designed. For future experiments, the configuration of the amplifier should be adjusted to adapt experiments that require higher power rating.

Accounting for the limitations of the lab environment, the intention of the report, to prove the various operating modes of the SMA inverter, has still been successfully executed and documented. With successful testing of these operating modes the project is now ready to move into phase two which involves integrating these tests into the Strata Grid system.

Bibliography - References

Korn, G. A., & Wait, J. V. (1978). *Digital continuous-system simulation*. Prentice-Hall.

IEEE-SASB Coordinating Committees. "IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces." *IEEE 1547.1-2020*, 2020, https://standards.ieee.org/ieee/1547.1/6039/.