COLLABORATIVE DEVELOPMENT OF AUTOMATED ADVANCED INTEROPERABILITY CERTIFICATION TEST PROTOCOLS FOR PV SMART GRID INTEGRATION

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ABSTRACT: Photovoltaic (PV) systems and other Distributed Energy Resources (DERs) can provide voltage and frequency support to the electric grid through commanded and autonomous operating modes. These functions have been standardized in the International Electrotechnical Commission (IEC) Technical Report 61850-90-7 in 2013; and recently, in response to national and international requirements, are being added to PV inverters by the manufacturers. However there are currently large gaps in the certification standards for verifying the interoperability and functionality of the advanced DER functions. Sandia National Laboratories (SNL), the Austrian Institute of Technology (AIT), and TECNALIA—as part of a collaboration through the Smart Grid International Research Facility Network (SIRFN)—are designing and exercising test protocols to characterize the interoperability and advanced functionality of these devices. This paper discusses the ongoing development of a pre-certification standard protocol for testing advanced DER inverter interoperability functions and automation of the testing procedures in the U.S., Austria, and Spain. A non-dimensionalized comparison of the test results for a 3 kW single phase PV inverter at Sandia, a 20 kW three phase PV inverter at AIT, and a 5 kW single phase PV inverter at TECNALIA are provided.

Keywords: advanced inverter functions, advanced DER functions, interoperability, standards development, grid support, smart grid, photovoltaics

1 INTRODUCTION

As greater penetrations of variable renewable energy sources are connected to the electric power system, the ability of grid operators to perform voltage and frequency regulation and respond to grid disturbances with traditional power plants is being eroded. Technically, static converter-based distributed energy resources (DERs), such as PV inverters and energy storage systems (ESS), have the ability to assist grid operators control feeder voltages and system frequency. These capabilities are being added to DERs as more grid codes around the world require advanced functions [1]. These DER interoperability functions are defined generically in the International Electrotechnical Commission (IEC) Technical Report 61850-90-7 [2]. The functions include commanded modes as well as autonomous functions, which adjust active and reactive power to support locally-measured grid voltage and frequency.

Driven by new requirements in Europe [2] and proposed changes in California [3], inverter and power conditioning system (PCS) manufacturers are adding the advanced functionality to their devices. Large PV inverters and DER devices will likely be monitored and controlled with dedicated supervisory control and data acquisition (SCADA) controller, such as the prototype previously developed and tested by AIT [4]. In order for utilities to control large quantities of small DER devices, an aggregator, gateway, or translator will most likely act as an intermediary between the utility and DER [6]. To provide this functionality, the SunSpec Alliance, an industry consortium with many major inverter manufacturers, has developed specifications for DER Modbus mappings to allow utilities and third party interoperability devices (e.g., aggregators, gateways, etc.) to communicate to any SunSpec Alliance compliant advanced DER devices [7].

To guarantee the reliable and coordinated advanced interoperable functions in PV inverters and other DERs, harmonized national and international standards must be developed by the responsible bodies, such as Underwriters Laboratories (UL), IEC, CENELEC and national technical committees. To accelerate this process for UL 1741 [8] and other international standards, Sandia has drafted a first edition of testing protocols [9-10] to validate the functional capabilities of the DER with the help of laboratory tests. These initial protocols must be exercised to make improvements and verify their efficacy at certifying the functionality of the equipment under test (EUT).

Sandia, AIT, and TECNALIA are collaborating to improve the test protocols and test parameters, share test-bed designs, and compare results from the testing through

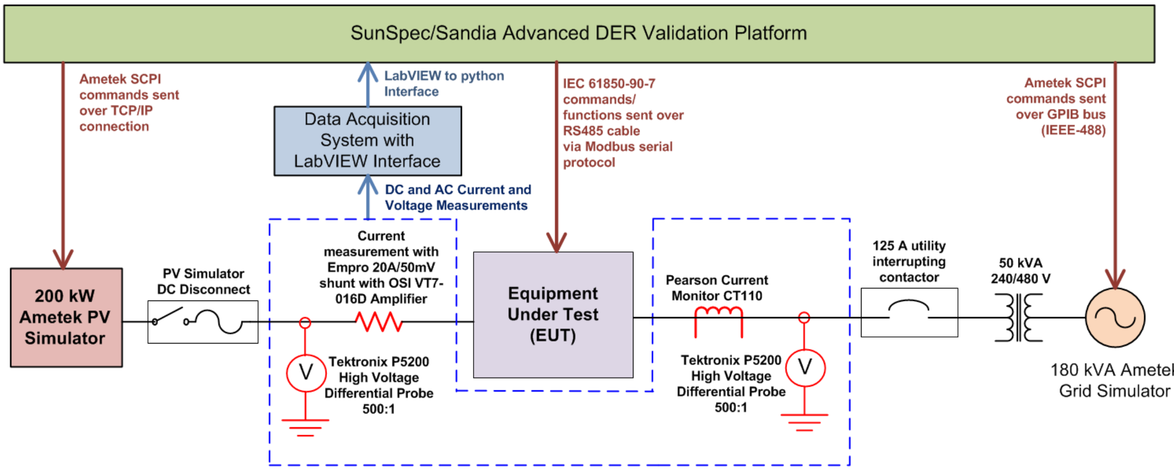

Figure 1: Sandia National Labs advanced DER interoperability test-bed at the Distributed Energy Technologies Laboratory (DETL).

the DERlab[1]-operated Smart Grid International Research Facility Network (SIRFN), under the auspices of the International Smart Grid Action Network (ISGAN). Currently 12 countries are participating in the SIRFN program which includes projects on advanced inverter/DER testing, cyber security, smart distribution, storage, forecasting, and other topics involving renewable energy integration.

In order to quickly test the large number of functions and parameter sets in the Sandia Test Protocols, SIRFN laboratories are automating the testing process. Sandia is creating python scripts which access the SunSpec Inverter Controls in order to automate the testing procedure [11]. The Austrian Institute of Technology has developed Matlab objects which interact directly with the EUT using the SunSpec models, test instruments, and data acquisition (DAQ) system. TECNALIA created python scripts using proprietary Modbus registers and uses a time server to synchronize the control scripts and the measurement instruments. This paper compares the different approaches to automating the test protocols, presents the results from testing a 3 kW, 60 Hz, 240 V split-phase PV inverter at Sandia, a 20 kW, 50 Hz, 230 V 3-phase PV inverter at AIT, and a 5 kW, 50 Hz, 230 V single-phase PV inverter at TECNALIA, and discusses improvements to the protocols based on these tests.

2 ADVANCED INVERTER TEST-BEDS

2.1 Sandia DER Interoperability Test Lab

The Distributed Energy Technologies Laboratory (DETL) at Sandia National Laboratories has been configured for performing advanced PV inverter interoperability and functionality testing. The test-bed consists of a 200 kW PV simulator, 180 kVA grid simulator, the interoperability interface with serial communication capability, data acquisition system, and equipment under test, as shown in Figure 1. A 3 kW PV inverter was selected for the EUT and the SunSpec Inverter Control Tool was used to update and enable the advanced function parameters. Sandia created test scripts in python to automatically run through the parameter sets for the connect/disconnect (INV1), adjust maximum output power (INV2), and set constant power factor (INV3) modes.

Sandia has partnered with the SunSpec Alliance to develop an inverter test platform [11]. Within the graphical user interface, the types of functions and associated parameter sets are selected which reference python scripts parameter set databases. The parameter sets, such as those in the Sandia Test Protocol test matrices, are then run sequentially for each of the functions via a serial communication link to the EUT. This method of automating the advance interoperability testing process will allow recognized testing labs to quickly and efficiently certify equipment to the standard.

2.2 AIT SmartEST PV Inverter Test Lab

AIT has configured its PV inverter test lab to implement the test protocol and run automated tests of the advanced interoperability functions, shown in Fig. 2. The test bed consists of multi-string PV array simulators, a highly dynamic grid simulator and a configurable grid and a simulated utility SCADA system and allows tests on PV inverters up to the 30 kVA range.

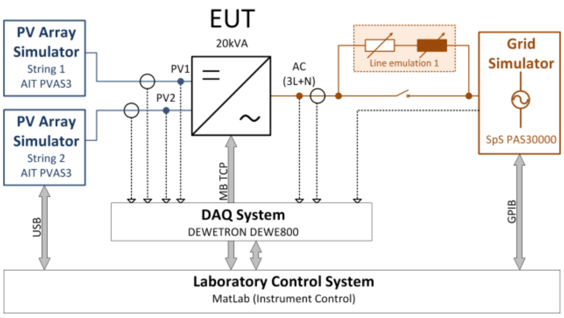

Figure 2: AIT Smart Electricity Systems and Technologies (SmartEST) PV inverter test laboratory.

In order to run automated tests, AIT has developed a set of MATLAB® control objects, which control the PV and grid simulators as well as the EUT via dedicated interfaces. The control signals are provided by an IEC 61850 based distribution management SCADA system and are then sent to a gateway, which maps the commands to the SunSpec models.

[1] European Network of DER laboratories and pre-standardisation, http://www.der-lab.net

A 20 kVA 3-phase PV inverter was selected as the equipment under test (EUT) for the development and verification of the automation system at AIT. During the first tests, direct control functions specified in IEC 61850-90-7, including INV1, INV2 and INV3 were addressed.

2.3 TECNALIA Microgrid Laboratory

TECNALIA has started to arrange an advanced DER testing laboratory according to IEC 61850-10 [12] and 61850-90-7 [2]. The Fig. 3 shows the general test setup of the TECNALIA microgrid. The microgrid has a PV simulator, a line emulator, a variable load and a programmable AC source. Ethernet and serial ports are the physical links between the test master computer and the controllable devices. A Network Time Protocol (NTP) server was used to synchronize the test master computer and the Ethernet meter.

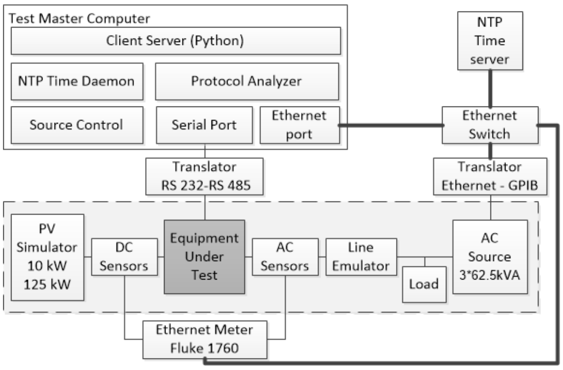

Figure 3: TECNALIA advanced PV inverter test-bed

A 5 kVA single-phase PV inverter (not SunSpec compliant) was selected as EUT. The EUT has the INV1, INV2 and INV3 modes through proprietary Modbus commands. TECNALIA created client server scripts in Python to run direct control functions of IEC TR 61850-90-7 from the test master serial port following the Sandia Test Protocol [9-10]. A serial protocol analyzer was used to record serial port communications. Electrical variables and communication signals were logged during the test sequences.

3 ADVANCED FUNCTIONALITY TESTING

The test protocols are an evolving set of recommendations for characterizing the behavior of EUT devices that have advanced interoperability functions. The procedures were originally drafted by Sandia National Laboratories in November 2013, but the document is continuously updated based on research and certification laboratory feedback as the protocols are exercised. SIRFN in particular has initiated a round-robin testing plan that will circulate the protocols to gather suggestions for improving the test procedures. This way, as different advanced functions become required in different jurisdictions around the world, there will be a starting place for the certification standard.

In this initial study, INV1, INV2, and INV3 were tested at three laboratories to compare the testing methodology, PV and grid simulator responses, and data acquisition systems (DASs). The results were compared to determine the influence of the test equipment, DASs, PV inverter nameplate sizes, firmware versions, and EUT designs on the test effectiveness. Further, by comparing international results from multiple labs verified the test protocols are grid impartial, i.e., effective at testing EUTs connected to different grid voltages and frequencies.

3.1 Connect/Disconnect (INV1) Tests

The Sandia, AIT, and TECNALIA INV1 test results for Tests 1-5 (see Table I) are shown in Figures 4 and 5. Each advanced inverter function includes optional parameters, such as:

- Time window – a desynchronizing option which executes the function after a delay randomly between zero and the time window value.
- Timeout period – an option that defines the time after which the EUT will revert to its default status.
- Ramp time – an option defining the time the EUT must move from the current set point to the new set point.

For all the advanced DER tests the default values for ramp rate, time window, and timeout period are 0 (disabled). Test 1 and 3 results in Fig. 4 show the inverter power dropping to zero when the disconnect command is issued for all three laboratories. Similarly, the inverter comes back on when the connection command is issued. This is completed by disabling the standby mode Modbus register in the EUTs via serial communication at Sandia and TECNALIA, and a TCP connection at AIT. AIT provided greater than 100% rated DC power to the EUT during the test, SNL provided exactly 100% rated power at the PV simulator maximum power point, and TECNALIA chose to provide 60% of the EUT rating. This explains the difference in operating power in the INV1 results.

Table I: INV1 test matrix [10].

Test	**EUT Initial Operating State**	**Connect/ Disconnect Command**	**Time Window** (seconds)	**Timeout Period** (seconds)
1	>50% rated power, unity PF	Disconnect	Default	Default
2	Inverter off	Connect	Default	Default
3	>50% rated power, unity PF	Disconnect	0 (None)	Default
4	Inverter off	Connect	0 (None)	Default
5	>50% rated power, unity PF	Disconnect	90	30 AIT:180
6	>50% rated power, unity PF	Disconnect	60	0 (None)
7	Inverter off	Connect	60	0 (None)

In Fig. 4, the disconnection process is consistent for the three laboratories, however the connection power profiles for the three EUTs were not the same due to the maximum power point training (MPPT) algorithms of each of the PV inverters. Another small difference in the data is SNL collected 1 Hz data, whereas AIT and TECNALIA collected 200 ms data; yet both data collection rates provide a clear indication of the execution of the INV1 command. This explains why the Sandia disconnect data appears to contain a fast downward ramp.

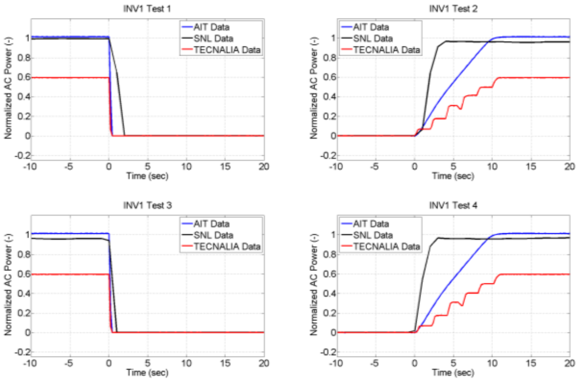

Figure 4: Connect/disconnect (INV1) results at AIT, Sandia, and TECNALIA.

INV1 Test 5 utilizes both a randomization time window and a timeout period. To illustrate the differences in the time period response of the three EUTs, the disconnect was aligned in Fig. 5. The Sandia EUT returned for full operation at around 40 seconds because the timeout period was 30 seconds and the reconnection time was reduced from the typical American requirement of 5 minutes to 10 seconds. The TECNALIA and AIT inverters reconnected after approximately 122 and 245 sec. This is because the reconnection process for these devices was much longer (91 sec for TECNALIA and 84 sec for AIT based on the response from the connect command). The additional time for the AIT EUT connection was due to a 180 sec reconnection time command during the test sequence indicated in Table I. The randomization window for test 5 was 90 seconds so the device should randomly disconnect within a 0-90 second window once the command is sent (i.e., written to the Modbus registers). The disconnect operation occurred after 47 sec at AIT, 55 sec at SNL, and 19 sec at TECNALIA.

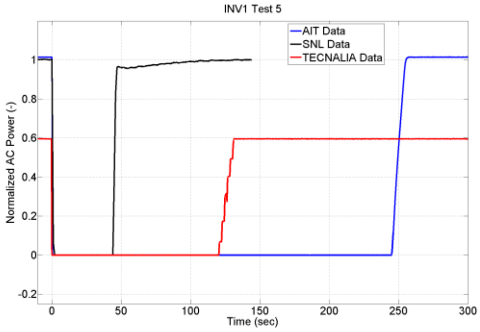

Figure 5: INV1 Test 5 with timeout.

3.2 Real Power Curtailment (INV2) Tests

The INV2 function is used to limit the maximum real power output of the inverter to a watt max (WMax) value as a percentage of nameplate active power. In order to determine the response of the device for different irradiance events—e.g., morning/afternoon ramps and fast moving clouds—an irradiance profile is run with the PV simulators to change the available DC power to the

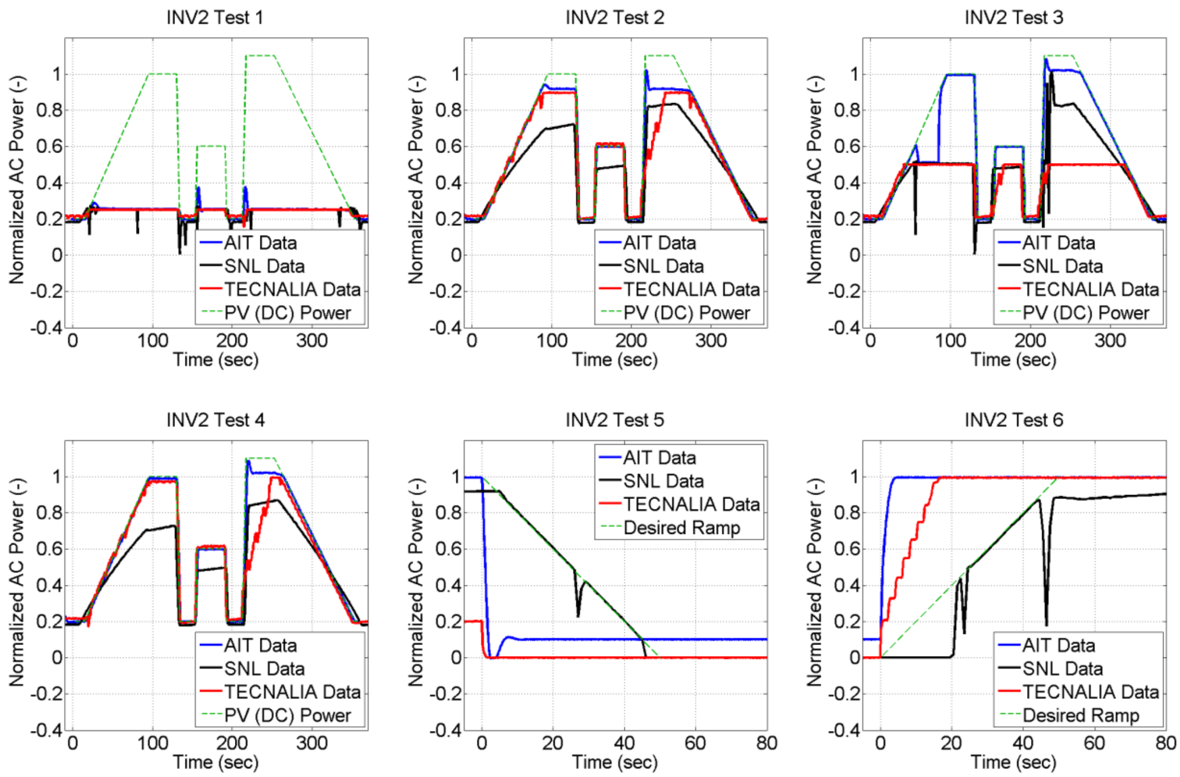

Figure 6: Test results for real power curtailment (INV2) at AIT, SNL, and TECNALIA.

EUT. The six tests with the associated parameters are shown in Table II. In the first four tests, the curtailment for the EUTs are maintained by the devices except for some overshoot experienced by the AIT and SNL inverters in Test 3 after the timeout period, shown in Fig. 6. The SNL EUT MPPT algorithm did not quickly return the device to the INV2 power limit, but the INV2 function prevented it from exceeding the curtailment value, shown in Test 1. The timeout period in Test 3 does not appear after 30 seconds for any of the laboratories but a reversion to the default parameters is seen in AIT after ~80 sec and SNL after ~215 sec.

In Test 5 and Test 6, the ramp rate capabilities of the device were verified. The 2% nameplate watts/sec ramp rate is designed to produce a change from 100% output to 0% in 50 seconds for Test 5 and 0% to 100% AC output in Test 6. The SNL EUT was the only inverter to display this functionality, shown in Fig. 6; although this EUT does have difficulty maintaining the slope throughout the DC power range, especially at low power when the inverter shuts off. The other two devices stepped down or up to the target curtailment instantaneously without the ramp. Also note that the long reconnection time for the AIT EUT was onerous for the operators, so the curtailment was set to 10%, not 0%. This feedback was provided to SNL and will be changed in future versions of the Sandia Test Protocols.

Table II: INV2 test matrix.

Test	***WMax*** (% nameplate)	**Ramp Rate** (% nameplate watts/sec)	**Time Window** (sec)	**Timeout Period** (sec)	**PV Power Profile**
Test 1	25	0	0	0	Fig. A2- 1 [10]
Test 2	90	0	300	0 AIT:60	Fig. A2- 1 [10]
Test 3	50	20	60	30 AIT:60	Fig. A2- 1 [10]
Test 4	100	0	0	0	Fig. A2- 1 [10]
Test 5	0 AIT:10	2	0	0	Constant at nameplate
Test 6	100	2	0	0	Constant at nameplate

3.3 Fixed Power Factor (INV3) Tests

The INV3 data show the accuracy of the fixed power factor (PF) control for multiple PF (cosφ) settings. The same irradiance profile used for the INV2 tests is run for each INV3 test to adjust the maximum available DC power to the inverter. The results from the 5 tests in Table III are shown in Fig. 7 with the target power factors for all the labs indicated with dashed lines. The first test is at unity power factor and the results closely align for each EUT device. For tests 2-5, the power factor value is dependent on the minimum overexcited and underexcited power factor capabilities of the EUT. The minimum PF was 0.85 capacitive (overexcited) and inductive (underexcited) for the AIT and SNL EUTs, and 0.80 for the TECNALIA EUT. The displacement PF was calculated using the fundamental components of the active and apparent power at all three laboratories [13]. The total power factor (which included the contribution of harmonics to the apparent power) was also calculated at Sandia, to determine the influence of harmonic distortion on the power factor results. The maximum total harmonic distortion (THD) was 7.63%, which resulted in a 0.3% difference in the fundamental and total power factor; however, these calculated values could deviate more significantly for other EUTs so it is important to specify a standardized data analysis method for all calculated test-bed channels. Additionally, the SNL data acquisition system calculated the absolute value of reactive power, so the sign of the reactive power was reversed in tests 3 and 5 to provide a direct comparison with the European laboratory results.

In Test 2 and 3, the AIT parameters deviated from the test matrix by including a 60 second timeout period. This returned the EUT to unity PF at the beginning of the PV profile. However, from the results in INV3 Tests 4 and 5, it is clear the 20 kW inverter at AIT can hold a much tighter PF tolerance compared to the EUTs at SNL and TECNALIA. The superior AIT EUT INV3 accuracy is believed to be from the three phase PF calculation which smoothest the power factor fluctuation per phase, and the AIT EUT has better dynamic performance because it is a larger unit. The influence of the available DC power is also more pronounced in the SNL and TECNALIA results as well. The stronger PF bias in the SNL results may be caused by the output filter in the residential-scale device.

One of the challenges of this testing is determining the time window because the communication signal must be logged in the data acquisition system that is also recording the electrical behavior of the device so the timestamps are synchronized. Each laboratory has approached this differently, but the accuracy of determining the timing parameters is believed to be within 10 ms for all the laboratories if the sampling rate on the data acquisition systems were increased. To the nearest second, the time window execution in Test 2 was completed after 13 sec at AIT, 34 sec at SNL, and 0 sec at TECNALIA (the EUT does not have time window parameter available).

At this time, there is no pass/fail criteria included in any of the Test Protocols because this will depend on the codes in each jurisdiction and the manufacturer’s stated accuracy. However, it is evident that these three EUTs are capable of providing voltage support through fixed power factor adjustment.

Table III: INV3 test matrix.

Test	**Power Factor (INV3)**	**Ramp Rate** (% nameplate watts/sec)	**Time Window** (seconds)	**Timeout Period** (seconds)
1	1.00 (default)	Default	0	Default
2	MinPFOverAval (e.g., 0.80 Overexcited)	Default	60	600
3	MinPFUnderAvail (e.g., 0.80 Underexcited)	Default	300	Default
4	0.5+MinPFOverAval/2 (e.g., 0.90 Overexcited)	10	Default	Default
5	0.5+MinPFUnderAvail/2 (e.g., 0.90 Underexcited)	Default	Default	1800

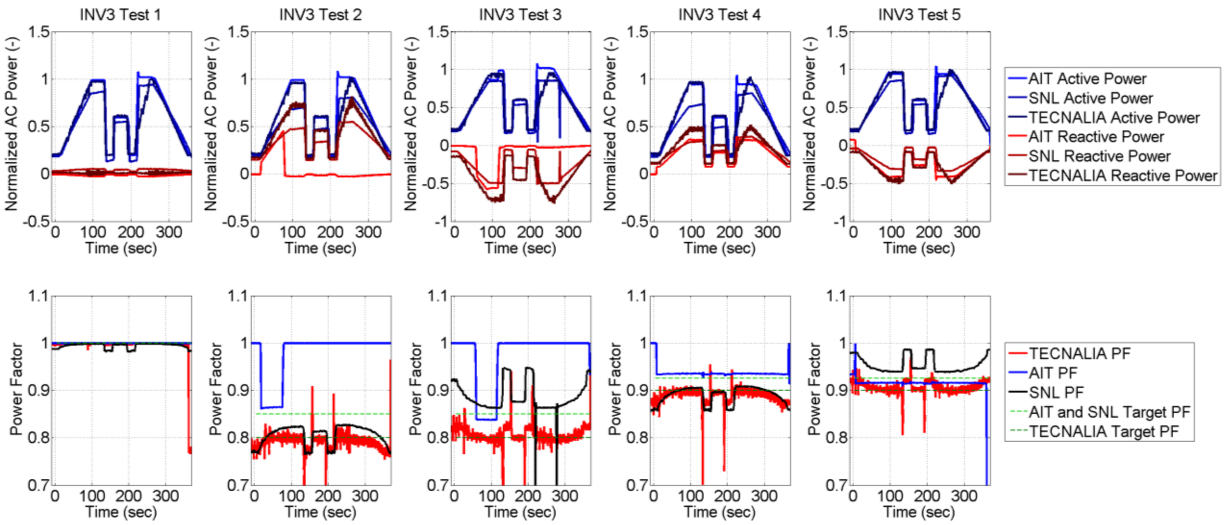

Figure 7: Test results for fixed power factor (INV3) at AIT, SNL, and TECNALIA.

4 IMPROVING THE TEST PROTOCOLS

The comparison of the laboratory results revealed a number of issues with the test protocols. A number of redundancies, testing difficulties, and other limitations with the protocols were discovered. For example, here are some of the issues that were identified:

- Ambiguous statements lead to different interpretations of the testing instructions, e.g., at what point the irradiance profile should be initiated after the command was issued to the inverter.
- The timing parameters (time window, timeout period) are not fully characterized in INV1, INV2, or INV3. Particularly the time period in INV1 because the lengthy and manufacturer-specific inverter startup process and the timeout period in INV2 because the operation cannot be resolved in the data when the PV power profile is below the WMax power limit.
- When configuring the PV simulator, the max DC power was not defined as the PV inverter nameplate rating. This could lead to inconsistent results between labs and for different equipment.
- It is important to use common definitions of the measured and calculated data channels in order to achieve comparable results (e.g. different definitions for reactive power, frequency, and PF calculations may lead to large variations in results).
- Defining sampling and recording rates are necessary to guarantee repeatable test results between the laboratories.
- Since the performance of the EUT under dynamic input (PV power) leads to transients and fluctuations, it will be necessary provide tolerances for the measurements in order to verify compliance during the tests.

Based on the feedback from the three test laboratories, the testing protocols were updated with improved test matrices and more explicit procedures to verify the functionality of advanced inverters. As an example the updated INV2 test matrix is shown in Table IV. Two additional tests were added to the matrix to better characterize the ramp rate, time window, and timeout period independent of the maximum watt (WMax) limit which is characterized independently in Tests 1-4.

Table IV: Improved INV2 test matrix based on the collaboration.

Test	*WMax* (% nameplate)	**Ramp Rate** (% nameplate watts/sec)	**Time Window** (sec)	**Timeout Period** (sec)	**PV Power Profile**
1	25	0	0	0	Fig. A2- 1 [10]
2	90	0	0	0	Fig. A2- 1 [10]
3	50	0	0	0	Fig. A2- 1 [10]
4	100	0	0	0	Fig. A2- 1 [10]
5	10	2	0	0	Constant at nameplate
6	100	2	90	0	Constant at nameplate
7	10	10	20	45	Constant at nameplate
8	100	5	0	90	Constant at nameplate

5 CONCLUSION

To encourage sustained, smooth PV deployment at the distributed level around the world, an international collaboration within the Smart Grid International Facility Network (SIRFN) is accelerating the development and refinement of certification testing protocols for advanced interoperability functions defined in IEC TR 61850-90-7. Sandia National Laboratories, AIT Austrian Institute of Technology, and TECNALIA created advanced interoperability test-beds and completed an initial set of experiments using the first version the Sandia Test Protocols. These experiments employed 3, 5, and 20 kW PV inverters and a range of PV and grid simulation, and data acquisition equipment. The results from connect/ disconnect (INV1), adjust maximum output power (INV2), and fixed power factor (INV3) were compared for the three laboratories to identify challenges in the testing protocols and improve them. As SIRFN test laboratory participation increases and more advanced function procedures are validated, the Sandia Test Protocols will continue to improve. This living document will act as a starting place for certification standards as grid codes evolve in the world to require the distribution (and transmission) interconnected DER to have interoperability and advanced functionality.

Ultimately, the SIRFN group would like to provide experimentally-validated recommendations to establish and harmonize certification procedures from UL, IEEE, IEC, and other standards-making bodies. With conformance test procedures and associated certification schemes grid operators can rely on the coordinated and stable performance of advanced interoperability functionalities, and manufacturers can list their products once to gain access to multiple markets. These standardized DER capabilities provide the basis for the full integration of PV systems into a future Smart Grid slow dynamics control schemes. Eventually this allows the utility and grid operators to manage a large number of PV systems in a unified way and capture the potential benefits of inverter based DER.

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