Automating the Sandia Advanced Interoperability Test Protocols

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***Abstract* — As the penetration of non-dispatchable renewable energy increases around the world, there is greater need to have smart power electronics interfaces to stabilize the electricity grid. Distributed Energy Resources (DERs) with advanced grid functionality and utility communication capabilities have the ability to assist grid operators with frequency and voltage regulation. As a result, the California Public Utilities Commission (CPUC) is considering updating Electric Rule 21 to require advanced functions on all newly interconnected PV inverters for Investor Owned Utilities (IOUs). One hurdle to installing PV inverters with the new functionality is certifying the DERs for advanced interoperability grid functionality defined in the International Electrotechnical Commission (IEC) Technical Report 61850-90-7. In November 2013, Sandia National Laboratories published testing protocols for advanced grid functions as a precursor to an international or updated Underwriters Laboratories (UL) 1741 certification standard. To accelerate this process, Sandia and an international collaborative of research laboratories began exercising the test protocols to improve the procedure and test parameters for the different advanced functions. This paper describes the process of automating the testing process with the SunSpec Alliance System Validation Platform and python scripting methodology. Results from four automated interoperability functions for a 3 kW residential-scale photovoltaic inverter are included.**

***Index Terms* — advanced inverter functionality, advanced grid functions, smart grid, voltage support, frequency support, photovoltaic systems, PV reliability.**

I. Introduction

Higher penetrations of variable renewable energy generation on electricity grids are displacing traditional power plants and eroding the utility and grid operators' ability to regulate grid voltage and frequency [1]. Fortunately, distributed generators connected to the grid with power electronics, such as photovoltaic (PV), battery, and wind resources, can provide grid stabilizing functionality like traditional spinning generation [2-3]. The internationally recognized set of the advanced interoperability functions and communications requirements are described in the International Electrotechnical Commission (IEC) Technical Report (TR) 61850-90-7 [4].

Sandia National Laboratories has created a test protocol for the IEC 61850-90-7 advanced DER functions [5-6], commonly referred to as the Sandia Test Protocols (STPs). These documents have been shared with stakeholders around the world with the ultimate goal of collaborating to create a consensus set of test protocols [7] which can be incorporated into an IEC, IEEE, and/or the UL 1741 certification standard [8]. The STPs were designed to verify DER (primarily PV inverters and energy storage systems) interoperability and electrical behavior functionality as specified by the IEC technical report. While the combinations of the parameters for each function in the STPs were selected to minimize the total testing time and effort, each function still requires extensive testing in order to fully verify the functionality of the equipment under test (EUT). As a result, Sandia and Loggerware, a contractor to the SunSpec Alliance, have collaborated to establish a method for automating the advanced functionality tests.

In this report, we describe a method for quickly and accurately testing DER functions and report results from several advanced inverter tests. The testing automation is performed using the SunSpec Alliance System Validation Platform, which runs Python test scripts that Loggerware and Sandia National Labs developed. The test scripts use the SunSpec Python package which utilizes the SunSpec XML model definitions for the advanced functions. The SunSpec System Validation Platform was used to characterize the communications and electrical behavior of a SunSpec-compliant 3 kW PV inverter for connect/disconnect (INV1), adjust maximum output power (INV2), set constant power factor (INV3), and volt-var mode (VV11). The goal of the tests was to demonstrate and improve the functionality of the System Validation Platform and exercise the Sandia Test Protocols, not to characterize the performance of the EUT, so a detailed discussion of results is not included in this document. By performing the work according to the current version of the STPs, Sandia was able to identify revisions needed to the test procedures and settings and suggest improvements to the test protocols for inclusion in certification standards. Once the SunSpec System Validation Platform has been designed and vetted, it will be available to DER manufacturers who wish to test their products and Nationally Recognized Testing Laboratories (NRTLs), e.g., UL, who wish to perform DER certification testing with an intuitive graphical user interface.

II. Advanced Inverter Functions and Test Protocols

Advanced inverter functions (also known as advanced grid functions) are designed to provide methods for utilities to control DER and to provide autonomous grid stability through voltage and frequency support [4]. These functions,

enumerated in Table 1, will be enabled and modified through direct communications (e.g., DNP3 [9]) or via an aggregator which is capable of communicating with a fleet of DERs.

Each of the advanced inverter functions include parameters that define the behavior of the device in the mode, along with optional parameters, such as:

- Time window - an option in which the command is executed after a delay. The delay will be a random time uniformly distributed between zero and the time window value. If the time window is zero, the command executes immediately.
- 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 each of the advanced DER functions, the Sandia Test Protocols require the Utility Management System (UMS) Simulator to establish communications with the device and update the parameters of interest for the test. This is repeated a number of times for different parameter sets to verify the functionality of the EUT. As an example, the seven tests recommended by the STPs for the connect/disconnect function (INV1) are shown in Table II.

TABLE I. FUNCTIONS DEFINED IEC TR 61850-90-7.

Command/Function		General Category
INV1	Connect/disconnect	Immediate control functions
INV2	Adjust max generation level	
INV3	Adjust power factor	
INV4	Request active power (from storage)	
INV5	Signal for charge/discharge action	
VV11	Volt-Var mode 11 (watt priority)	Volt-var management modes
VV12	Volt-Var mode 12 (var priority)	
VV13	Volt-Var mode 13 (static mode)	
VV14	Volt-Var mode 14 (no var support)	
FW21	Set max power based on grid frequency	Frequency-Watt management modes
FW22	Set max power input/output based on grid frequency	
TV31	Dynamic reactive current support	
L/HVRT	Connect/disconnect settings for Low/High Voltage Ride-through (VRT)	"must disconnect" and "must remain connected" regions for freq. and voltage
L/HFRT*	Connect/disconnect settings for Low/High Frequency Ride-through (FRT)	
WP41	Feed-in power adjust power factor	Watt-triggered behavior modes
WP42	Feed-in power adjust power factor	
VW51	Adjust power output to smooth voltage	Voltage-Watt management modes
VW52	Adjust power input/output to smooth voltage	
TMP	Temperature mode behavior	
PS	Signal mode behavior	
DS91	Modify DER settings	Parameter setting and reporting
DS92	Log alarms and events/retrieve logs	
DS93	Status reporting	
DS94	Time synchronization	
* Low/High Frequency Ride Through is not included in IEC TR 61850-90-7 but is being considered by some jurisdictions, like California [10].		

TABLE II. TEST MATRIX FOR INV1 IN THE SANDIA TEST PROTOCOLS.

Test	EUT Initial Operating State	Command	Time Window (sec)	Timeout Period (sec)
1	>50% rated power, unity power factor	Disconnect 1	Default (e.g., 0)	Default (e.g., 0)
2	Inverter off	Connect 1	Default (e.g., 0)	Default (e.g., 0)
3	>50% rated power, unity power factor	Disconnect 2	0	Default (e.g., 0)
4	Inverter off	Connect 2	0	Default (e.g., 0)
5	>50% rated power, unity power factor	Disconnect 3	90	30
6	>50% rated power, unity power factor	Disconnect 4	60	0 (No Timeout)
7	Inverter off	Connect 4	60	0 (No Timeout)

III. SUNSPEC PYTHON PACKAGE

Based on the IEC technical report and high potential for new advanced inverter requirements from the CPUC [10], the SunSpec Alliance created an inverter interoperability specification for PV inverters [11-12], which defined the data models and Modbus register mappings for SunSpec-compliant devices. These models include many Modbus mappings, such as:

- Device nameplate information – manufacturer, model number, power rating, etc.
- Device status - current, voltage, power, frequency, power factor, etc.
- Immediate Controls – connect/disconnect (INV1), adjust maximum output power (INV2), set constant power factor (INV3), etc.
- Volt-Var – defines Volt-Var arrays and enables the functions (VV11, etc.)
- Frequency-Watt – defines settings and activation of the frequency-watt functions (FW21, FW22)
- Dynamic reactive current – set and enable (TV31)
- Low/High Voltage Ride-Through – set and enable L/HVRT functions

Loggerware was contracted by the SunSpec Alliance to create a Python-based framework that provides communications, testing, and automation capabilities for SunSpec-compliant devices. Python provides the flexibility to support different levels of contribution to the SunSpec framework. Developers with more experience can create new packages that provide objects implementing new sets of functionality. Those only interested in creating test scripts can take advantage of the packages already created and implement fully functional tests quickly with a limited amount of Python knowledge. A key objective of the SunSpec framework is to keep test script writing as simple as possible. The initial release of the SunSpec Python core package (`sunspec.core`, version 1.0.3, released in Jan 2014) provides communication capability and high-level objects designed for ease of scripting. The package allows interaction with the DER over

Remote Terminal Unit (RTU) or Transmission Control Protocol (TCP) communications using a user-friendly, object-oriented mapping scheme. It allows simple Python scripts to be created using high-level objects that expose all the capabilities provided by the SunSpec model definitions.

A. Python scripting for interoperability automation

Using the SunSpec Python core package, Sandia created a number of stand-alone Python scripts for automating the operation of the advanced DER function tests described in the Sandia Test Protocol test matrices [6]. These scripts were built with a main program that calls a function with the specific parameters. For instance, the pseudo-code describing the hardcoded INV2 function tests looks like:

```
Establish communications with EUT
#Test 1
INV2(power_level, ramp_time, time_window, timeout)
"Run PV simulator profile, enter 'c' to continue"
#Test 2
INV2(power_level, ramp_time, time_window, timeout)
"Run PV simulator profile, enter 'c' to continue"
#Test 3
INV2(power_level, ramp_time, time_window, timeout)
"Run PV simulator profile, enter 'c' to continue"
…
Return EUT to default operation
```

where the INV2 function pseudo-code is:

```
Verify DER is initialized. If not, correct.
Request and record the initial status of the EUT
Set power_level
Set ramp_time
Set time_window
Set timeout_period
Set enable_function to ON
Write data to EUT
Verify write command
```

While this approach allowed the user to enable the fixed parameter sets for each STP test quickly, the operator needed to manual start the PV simulator irradiance profile for each test. The irradiance (DC power available) profile for INV2 is 6 minutes long in order to capture slow ramps up and down, quick irradiance jumps, and a period of cloud enhancement. As a result, the operator must monitor to PV profile progress to determine when the Python script could continue and change the EUT parameters and begin the next profile. Automating this process with the SunSpec System Validation Platform greatly increased testing ease and freed up personnel time by removing the human from the procedure.

B. SunSpec System Validation Platform

Loggerware and Sandia have automated portions of the testing process and improved the ease of operation by creating a System Validation Platform that allows test grouping, execution control, and interaction with other elements in the test harness. The System Validation Platform can be accessed through an integrated graphical user interface (GUI) or from the command line for programmatic interaction. The System Validation Platform has the following capabilities:

1. Create parameterized test scripts that allow multiple tests to be created based on the script. Parameter settings are exposed through the GUI interface for ease of test creation.
2. Communicate with the PV simulator and grid simulator to run PV, voltage, and frequency profiles for the different tests.
3. Create suites of tests (and suites of suites) that can be run sequentially in a completely automated fashion. For instance, with proper System Validation Platform communications to the EUT, and PV and grid simulators interfaces, INV1, INV2, and INV3 can be run back-to-back autonomously.
4. Perform post-processing grading of the data acquired during the testing sequence, and utilize the data to apply pass/fail criteria to the EUT results.

Beyond the post-processed pass/fail grading, the System Validation Platform includes basic constructs for screening procedures for determining if the EUT has failed a test in real-time. This can be helpful to operators if the test bed is incorrectly configured (e.g., a communication wire is disconnected, the parameters in a test are outside the limits of the EUT, etc.). Once the UL 1741 standards technical panel (STP) or other certification technical panels define passing and failing results for the tests, better automation of the EUT screening and post-processing grading can be included in the System Validation Platform. However, for now, post-processing analysis by hand would be necessary to assign pass/fail evaluations.

Two Python packages have been added to the base sunspec package: `sunspec.testtool` and `sunspec.dashboard`. The `testtool` package implements all the functionality associated with defining, grouping, and executing tests and suites. The dashboard package provides a graphical user interface for SunSpec based functionality including the System Validation Platform. This architecture provides the capability for all the System Validation Platform functionality to be invoked from the command line as well as the GUI allowing tests and suites to be executed from other test frameworks or based on some automated criteria.

Test scripts written for the System Validation Platform framework utilize a test script object that provides an abstraction layer allowing the script to be run in multiple environments. The test script object provides a number of standard interface functions such as parameter acquisition, prompting for additional input, event logging, and results reporting. The three execution environments currently supported are: standalone, System Validation Platform command line, and GUI interface. Standalone execution is used to create and debug the script in any of the many Python development tools. Once the script is tested, it can then be added to the desired testing group for use within the System Validation Platform.

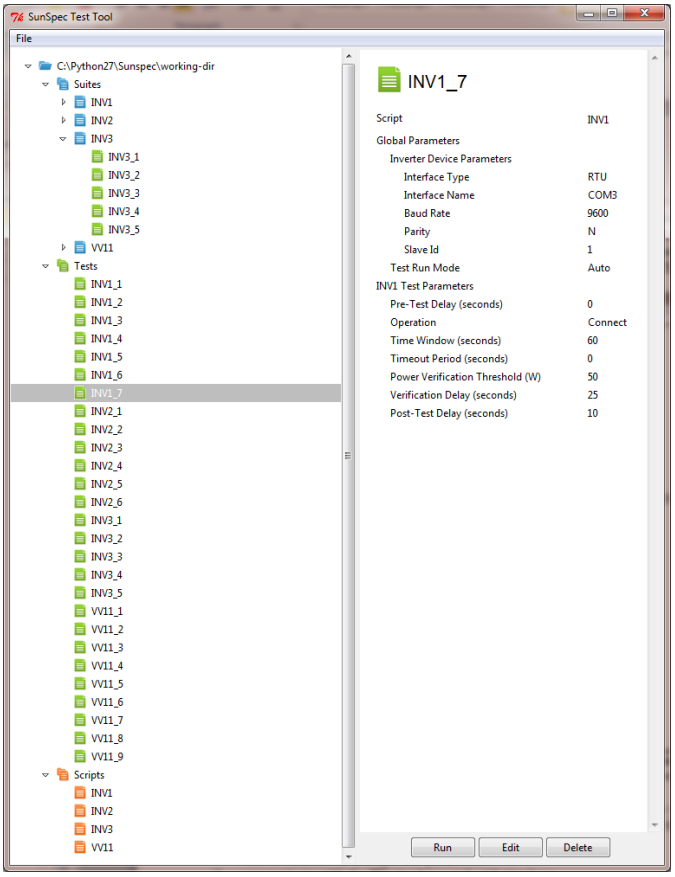

Fig. 1. Screenshot of the prototype SunSpec System Validation Platform operating on Window 7 with INV1, INV2, INV3, and VV11 tests and suites.

Script parameters are defined within the script itself using functionality provided by the test script object. This method of script parameter definition allows arbitrary parameter sets and groupings. The GUI interface exposes the parameter set for inspection and update.

To enable automated testing, additional packages such as PV simulation, grid simulation, and results dataset management are undergoing continuous development. It is possible to add support for any new components or functionality by the development of new packages.

The System Validation Platform GUI is shown in Fig. 1 with INV1, INV2, INV3, and VV11 *scripts*, *tests*, and *suites*. The *scripts* contain the parameterized Python scripts in a working directory. Each script has parameters declared within the script that include the different advanced inverter settings and communication values for RTU or TCP connections to the EUT. A specific set of parameter values associated with a script is called a *test*. For instance, the 7th test of INV1 shown in Table II, is a connection operation with 60 second time window and no timeout period. These settings are shown in Fig. 1 for the INV1_7 test. There are additional adjustable delays included in the prototype INV1 script before and after the test, and there is a basic pass/fail screening criteria of 50 W after 25 seconds for the INV1_7 test. This means that if the power level is above 50 W after 25 seconds has passed since the command was sent to the EUT, the EUT passes the screen. This capability provides the operator a quick indication of the status of the testing. In the future, NRTLs or other certification organizations can code more rigorous logic into the scripts to perform pass/fail evaluations based on the final result dataset.

The tests can be organized into *suites* consisting of a series of tests that will execute sequentially. In the future, the entire set of tests for all required advanced functions will be run with a single click—and with appropriate instrumentation, data acquisition systems, and pass/fail criteria, the EUT can be fully certified for all the required advanced functionality.

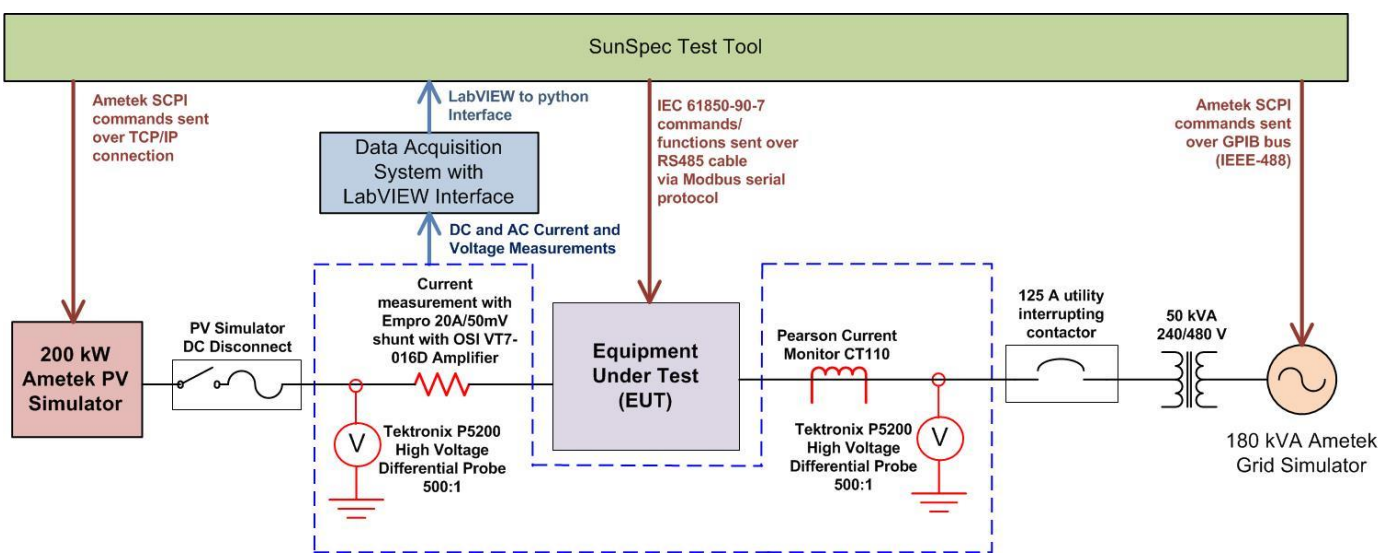

Fig. 2. Advanced Inverter Experimental Testbed at DETL.

IV. Automated Advanced Inverter Testing

A. Laboratory Configuration

The SunSpec System Validation Platform was used to run the automated advanced DER function tests at the Distributed Energy Technologies Laboratory (DETL) at Sandia National Labs with a 3 kW SunSpec-compliant PV inverter. The laboratory test setup is shown in Fig. 2. The Equipment Under Test was connected to a 200 kW PV simulator and a 180 kVA grid simulator. The testbed and simulators are capable of testing much larger PV inverters, but initial testing used a residential device in order to minimize safety concerns when developing the commands from the System Validation Platform to the simulators.

The SunSpec System Validation Platform communicated with the PV simulator using IEEE 488.2 Standard Commands for Programmable Instruments (SCPI) [13] with a TCP/IP connection over CAT5 Ethernet cable. The System Validation Platform is capable of configuring simulated PV I-V curves, creating and running irradiance profiles, and turning on and off the power to the PV simulator. Similarly, the AC grid simulator was manipulated using Ametek SCPI commands. These commands were sent over IEEE 488 General Purpose Interface Bus (GPIB) to read and write nominal voltage and frequency, voltage and frequency sag/surge profiles, and energization settings.

The IEC 61850-90-7 communications to the inverter uses the SunSpec Modbus interface over RS-485. The SunSpec System Validation Platform was configured for Modbus interface communication to the EUT. In this case, a Remote Terminal Unit (RTU) connection is established on a Universal Serial Bus (USB) port and connected to a Modbus card in the EUT. This configuration allowed the SunSpec System Validation Platform to be able to read and manipulate the Modbus registers that control the advanced inverter functions of the EUT.

Data was collected with a National Instruments (NI) PXIe system at 24 kHz. The measured data channels (e.g., DC current/voltage, AC current/voltage) and calculated channels (e.g., frequency, AC power, AC reactive power, RMS AC current/voltage, etc.) were displayed in real time to the user with a Sandia-developed NI LabVIEW program at a 1 seconds update rate. An update to the LabVIEW program that provides an interface to the SunSpec Python code is in development in order to enhance the logic of assigning pass/fail criteria.

Through the UL 1741 Standard Technical Panel or other certification standards organizations the development of a common data set should be associated with each function. The data set definitions would specify the data channels, sampling rates, reporting formats, and pre- and post-test capture periods to standardize the evaluation methodology and establish means of sharing and distributing of results. To begin this process, the Smart Grid International Research Facility Network (SIRFN), under the International Energy Association (IEA) International Smart Grid Action Network (ISGAN) is performing round-robin testing of advanced PV inverters to develop methods of sharing and comparing results from multiple laboratories [14].

B. SunSpec System Validation Platform Experience

The automated testing process drastically increased the number of experiments that could be performed in a day. This testing technique could be deployed by manufacturers and certification laboratories to reduce the cost and time for internal and UL 1741 certification testing. Once the laboratory is configured and the communication interfaces established with the System Validation Platform, a single click of the mouse can run the all the advanced test protocols. An example of running suites of INV1, INV2, INV3, and VV11 function suites for is shown in Fig. 3. In the screenshot, the "All Tests" suite is running through the suites for each of the functions. It is currently at the INV1_6 test, shown on the left, with indications provided for the pass/fail screening process for each of the previous INV1 tests. The right side of the System Validation Platform displays more detailed information about each of the tests. For instance, test INV1_5 includes a 90 second randomization time window and a 30 second timeout period, shown in Table II. For this test, the EUT disconnected after 55 seconds (within the time window) and reconnected after 44 seconds—which includes the mandatory delay before reconnection and time required for resynchronizing the inverter with the grid. Since the 44 second reconnection was within the 30 second timeout period plus the verification delay the test passed the screen. The 25 second verification delay can be adjusted based on the EUT to provide more specific screening information to the test operator.

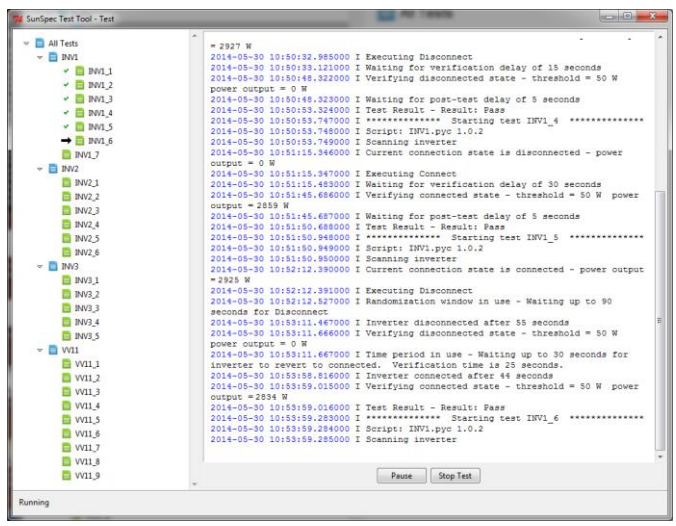

Fig. 3. Screenshot of the SunSpec System Validation Platform running the INV1, INV2, INV3, and VV11 suites. The green checkmarks indicate the results for the test has passed the screening. In this case, the first 5 tests for the INV1 function have passed the screen and INV1 Test 6 is currently running.

While communication between the SunSpec System Validation Platform and the simulators has been established, at this point Sandia engineers are still executing the AC voltage profile and PV irradiance profile operations by hand until all safety concerns have been addressed. Automated operation of power systems with prototype software must be carefully vetted for the safety of test personnel and laboratory hardware. This safety testing and check-off process will need to be addressed by each test facility before conducting fully automated testing.

C. Experimental Results

Once the tests have been completed, detailed post processing of the results is necessary to certify the interoperability and electrical functionality of the device for the functions. This is not the emphasis of this report, but exemplary results for the functions are included to identify data acquisition channels and sampling rates for each function. For INV1, INV2, INV3, and VV11, the test procedure and parameters in the Sandia Test Protocols [6] were followed and data storage rates for all the functions was set to 1 Hz in order to capture the quasi-steady-state operation of the EUT. If transient behavior of the device is of particular interest, higher sampling rates are necessary.

Connect/disconnect (INV1) results are presented in Fig. 4 for five different power factor set points. In the INV1 tests, the EUT disconnects and connects in accordance with the IEC 61850-90-7 parameters transferred to the local EUT Modbus registers.

Active power curtailment (INV2) results are shown in Figure 5. The INV2 test matrix contains four tests with a PV DC power profile (controlled by the PV simulator irradiance profile) and two tests (INV2_5 and INV2_6) with full DC power to verify the downward and upward power ramp rates.

Constant power factor (INV3) results for the first three tests are shown in Fig. 6. The irradiance profile is run once per test. As shown by the purple trace, the power factor (PF) is above the target level when the EUT is overexcited and undershoots the target PF when the EUT is underexcited. The Sandia LabVIEW program calculates the power factor in real-time and stores that as a parameter at 1 second intervals. This is believed to be sufficient for accessing EUT compliance with this function.

The first five watt-priority volt/var function tests are shown in Fig. 7. A grid voltage profile is run for each of the tests to determine EUT behavior as the local AC voltage changes. It should be noted that the reactive power is always recorded as positive regardless of the leading or lagging EUT currents.

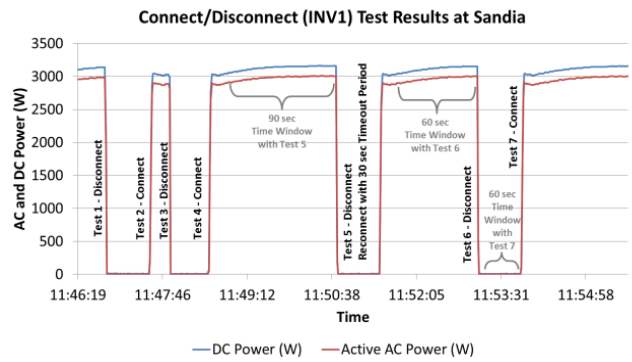

Fig. 4. Connect/disconnect (INV1) test results.

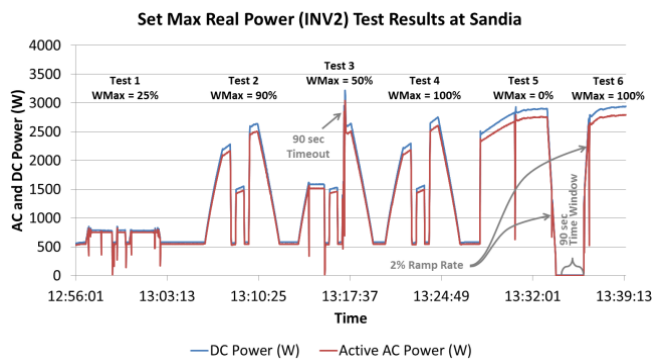

Fig. 5. Curtail active power (INV2) test results.

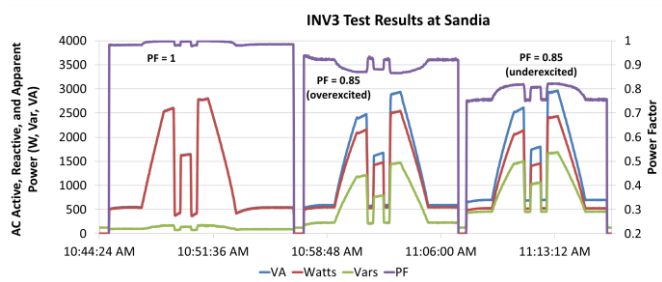

Fig. 6. Constant power factor (INV3) test results for the first three parameter sets.

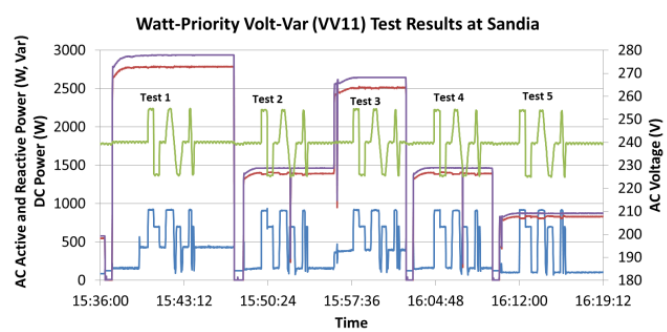

Fig. 7. Volt-var with watt priority (VV11) results for the first five tests.

V. Conclusions

International and domestic interconnection standards are requiring new functionality from distributed energy resources to help maintain grid voltage and frequency stability, and respond to grid disturbances. European grid codes and proposed changes to Rule 21 in California mandate advanced interoperability functions for all grid-tied PV inverters. In order to provide manufacturers and certification laboratories a user-friendly advanced inverter testing tool, Sandia National Laboratories, the SunSpec Alliance, and Loggerware are collaborating to create a graphical user interface for automating IEC 61850-90-7 advanced inverter function tests with SunSpec inverter models. The Sandia Test Protocols are being used as the basis for the testing parameters for each of the functions; and while they were designed to minimize the number of tests to verify the functionality of the equipment, testing requires extensive interaction with test equipment. The SunSpec System Validation Platform is designed to interact with all these devices to reduce testing time for manufacturers, test labs, and certification facilities; plus, in the future, offer automated pass/fail evaluations of the equipment with integration with a data acquisition system. In this report, we describe the design and operation of the SunSpec System Validation Platform at the Distributed Energy Technologies Laboratory (DETL) at Sandia National Labs and present results from using it to test four advanced inverter functions with a 3 kW residential PV inverter.

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