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International Development of a Distributed Energy Resource Test Platform for Electrical and Interoperability Certification

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***Abstract* — Several international research laboratories are collaborating under a Smart Grid International Research Facility Network (SIRFN) project to develop certification procedures for advanced distributed energy resources (DER). To effectively evaluate interoperability and grid-support functionality in DER equipment, test permutations across the full range of modes and parameters are required. It is impractical to complete these experiments manually so the project team is working to develop a software tool, associated abstraction layers, and hardware drivers to execute the experiments autonomously using the same open-source test logic. This software can then be programmed to complete interoperable DER certification experiments at DER vendor facilities, certification laboratories, or research institutions. By sharing the codebase with all institutions, barriers to adoption steadily decrease. To demonstrate the approach, Underwriters Laboratories 1741 Supplement A volt-var and specified power factor test results from multiple laboratories are presented and compared.**

***Index Terms* — interoperability, grid-support functions, certification protocols, DER testing, smart grid**

I. Introduction

In the last decade, grid codes around the world have been changing to require photovoltaic systems and other distributed energy resources (DER) to provide grid services through autonomous and commanded control functions [1]-[3]. These functions provide grid operators with methods to provide voltage regulation [4], bulk system services [5], power system visibility [6], and other grid services [7]—thereby, increasing the renewable energy hosting capacity of the power system. As these new requirements go into place, there is growing need to evaluate the functionality of these devices to the electrical requirements and verify the communications capabilities provide the desired behavior [8].

The Smart Grid International Research Facility Network (SIRFN) operates as an International Energy Association (IEA) International Smart Grid Action Network (ISGAN) research program with multiple research areas. One of the research programs is focused on the development and evaluations of interoperable DER certification protocols. The ultimate goal of the effort is to enable greater penetrations of renewables by accelerating the adoption of smart grid converter technologies. Technical challenges that prevent greater deployment of renewable technologies can be mitigated with advanced DER technologies, but DER vendors will not interconnect products with these capabilities unless grid code requirements exist. In many cases, equipment being installed already have the hardware and software components required to provide this functionality—because it is required in other jurisdictions—but it is disabled because these functions are disallowed or not required. Therefore, in cases where SIRFN laboratories are operating in regions without DER grid-support requirements or certification protocols (such as in Mexico or India), executing interoperability DER experiments can help (a) advise DER interconnection and communication requirements by demonstrating DER grid-support capabilities and (b) accelerate the development of certification procedures by rapidly iterating and exercising draft test sequences.

Previously, the team developed test protocols for the IEC 61850-90-7 functions [9]-[10] and test protocols for energy storage systems [11]. Experimental results from these protocols as well as national requirements—i.e., the US DER

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certification protocol, UL 1741 [12]—have been presented for residential and commercial scale devices [8], [13] and a 34.5 kW smart grid converter deployed in a controller hardware-in-the-loop environment [10], [14]. To execute these experiments, each research laboratory developed their own DER testbeds with unique data acquisition systems and test equipment (PV simulators, grid simulators, etc.). Differences in the results between laboratories highlighted the need to have a common set of test logic that would be executed in the same way at all the labs. This would minimize the human element in the experiments; although some variance will inherently exist in the results due to differences in test equipment, data acquisition systems, and the devices under test.

In 2014, the SunSpec Alliance and Sandia began a joint project to automate the test protocols by creating a software tool, called the SunSpec System Validation Platform (SVP), which orchestrated test sequences by communicating to data acquisition systems, power equipment, and devices under test [15]. Ultimately, the ability to full automate steady-state test sequences were developed [16] and the capability to work with other lab equipment over a range of protocols and media was created using abstraction layers and device drivers [17]. This tool remains in development but as the open-source repository of test code and device drivers grows (see [18]), new laboratories come up to speed much quicker. Gradually, more SIRFN laboratories have become interested in participating in the project and contributing to the SVP development.

This paper describes the SIRFN collaboration, SVP development, and presents test results generated from multiple laboratories using the same test scripts. The results show the benefits of working within an open community, the speed and consistency of the SVP, and the reactive and active power grid-support function capabilities of PV inverters.

II. System Validation Platform

The SVP was developed under a Cooperative Research and Development Agreement (CRADA) between Sandia National Laboratories and the SunSpec Alliance to autonomously orchestrate interconnection and interoperability certification protocols. The SVP completes these evaluations by communicating to laboratory equipment and equipment under test (EUT), as shown in Fig. 1. Python scripts are developed with user-defined parameters that are exposed to the user through a graphical user interface (GUI). The user-selected parameters define the test sequence by:

- selecting which types of tests should be executed,
- setting the power, voltage, current, etc. levels based on the EUT ratings, and
- configuring battery simulators, data acquisition systems (DASs), equipment under test (EUT), grid simulators, PV or DC simulators, hardware-in-the-loop systems, and resistive, capacitive or inductive load banks.

Abstraction layers are employed to select equipment drivers for a given laboratory testbed—i.e., the same script logic (e.g., 'set grid voltage to 0.97 pu') will send device-specific commands over the appropriate communication protocol and media. A representation of the abstraction layers pointing to specific devices is shown in Fig. 2. By architecting the SVP in this manner, the test scripts are completely portable to any power system testing laboratory in the world. In the rare cases, that equipment does not include communication interfaces, the user is prompted to make the appropriate change to the test equipment or EUT.

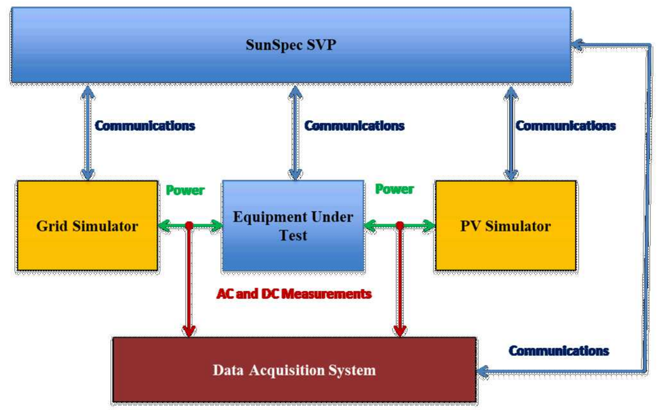


Fig. 1. SVP interaction with laboratory equipment.

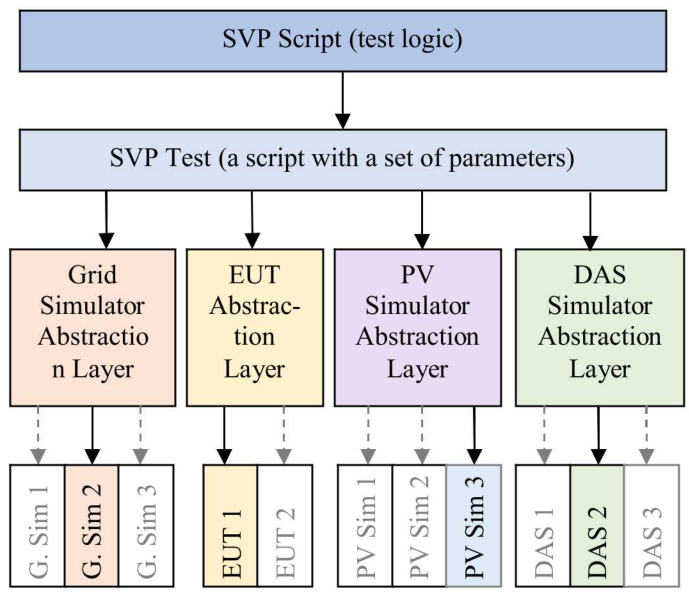


Fig. 2. SVP code structure.

A screenshot of the SVP is shown in Fig. 3. One or more SVP Directories can be imported into the system, such as "E:\UL1741 SA" shown in Fig. 3. Within the directory, there are five subdirectories:

1. Lib: the library of abstraction layers and device drivers that communicates to the equipment.
2. Scripts: the python code that represents the test logic

3. Tests: the set of parameters for a given script (e.g., values in the right pane of Fig. 3)
4. Suites: a collection of multiple tests or other suites that will execute sequentially
5. Results: the log and results from a test or suite

Except for the Lib subdirectory, everything is exposed to the user in the GUI. As shown in Fig. 3, the suites (blue) contain a collection of tests (green) and/or other suites; available scripts (orange) for VV and SPF are shown; and the results directory (gray) displays the results of an experiment where the "PF+VV for Typhoon HIL" suite was executed. Importantly, the SVP collects, saves, and plots time-domain data, as well as generating a summary of the test results and assembling all this data into an excel sheet for additional post-processing or inspection. Detailed pass/fail criteria are applied to each measurement and saved with the data.

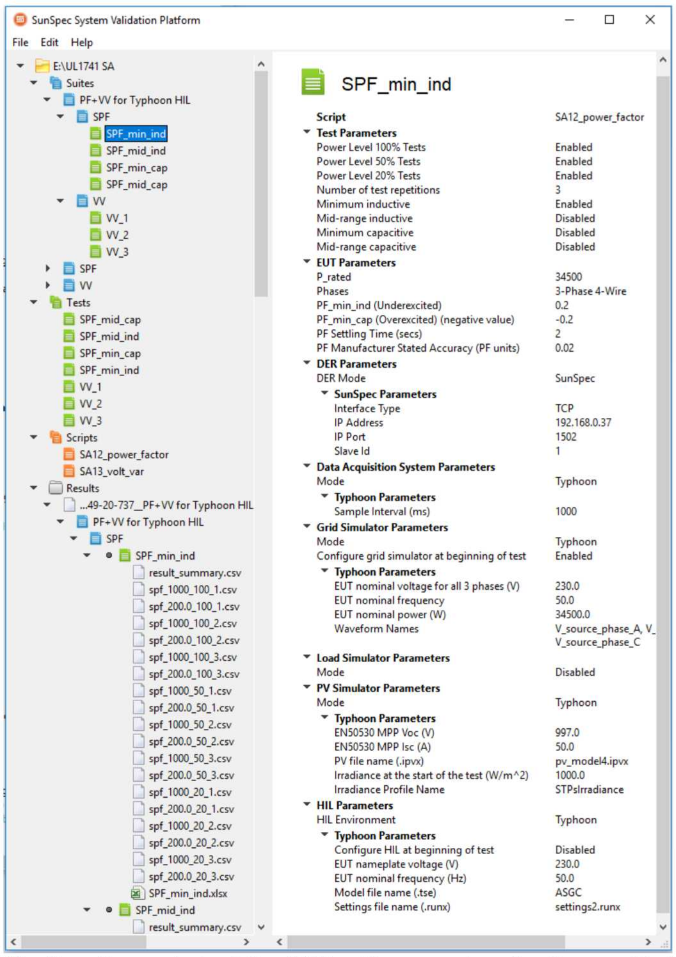


Fig. 3. Screenshot of the SVP with parameters for the specified power factor test shown in the right pane.

III. Experimental Results

Experiments were conducted with the SVP to evaluate DER interoperable grid-support functions (e.g., volt-var, fixed power factor) using the UL 1741 Supplement A certification protocol. Each SIRFN laboratory has different testing facilities, EUTs, and is at a different stage of SVP integration. Many of the laboratories only have a portion of the laboratory equipment connected to the SVP and cannot conduct fully-automated experiments yet. For this reason, results from a subset of the laboratories are presented here.

Sandia conducted experiments at the Distributed Energy Technologies Laboratory (DETL) in Albuquerque, NM, USA on a 3.0 kW split-phase solar inverter and on the 34.5 kW three-phase AIT Smart Grid Converter (ASGC) connected to a controller hardware-in-the-loop (CHIL). Details of the testing configuration for the 3.0 kW inverter are provided in [13] and [15] and details of the CHIL setup are in [8] and [14]. AIT conducted experiments using the ASGC system using this same configuration in Vienna.

The experiments at CanmetENERGY were performed at the inverter test facility (INVERT) in Varennes, QC, Canada on a 10 kW three-phase solar inverter. The EUT can operate in both active and reactive power priority mode and has a maximum reactive power capability of 53% of its nameplate rating. The architecture of test facility is similar to Fig. 1 which is equipped with 60 kW Ametek TerraSAS PV simulator and 120 kVA Ametek grid simulator. The test results were acquired with ZES Zimmer LMG670 data acquisition system.

CSIRO evaluated the power factor functionality of a 15.0 kW three-phase solar inverter at the Renewable Energy Integration Facility (REIF) lab. The SVP was connected to a Ametek ETS600X PV simulator, Elspec Blackbox data acquisition system, and the EUT. To evaluate the inverter, the device was connected to 5 kW of simulated PV from the Ametek TerraSAS and a 2 kW string of actual PV to ensure the inverter remained operational because the inverter would trip when connected to the solar simulator alone.

FREA conducted VV experiments on a 50 kW battery energy storage system with a 16.5 kWh Super Charge Ion Battery (SCiB) Li-ion battery using 500 kVA SanRex grid simulator and a Yokogawa WT3000 data acquisition system. The volt-var experiments were completed with zero active power.

A. Specified Power Factor (SPF) Results

Per UL 1741 SA, the SPF tests may be conducted with active or reactive power priority modes and consist of three repetitions of changing the EUT PF from unity to $PF_{min,ind}$, $PF_{mid,ind}$, $PF_{min,cap}$, and $PF_{mid,cap}$, at power levels of 20% P_{rated}, 100% P_{rated}, and between 33-66% P_{rated}, where:

Prated is the EUT output power rating
$PF_{min,ind}$ is the minimum inductive (underexcited) PF
$PF_{mid,ind}$ is the middle of the EUT inductive range
$PF_{min,cap}$ is the minimum capacitive (overexcited) PF
$PF_{mid,cap}$ is the middle of the EUT capacitive range

The SVP records, saves, and plots the time response of the EUT as the PF is changed from unity to the target power factor. After the manufacturer's specified settling time, the displacement factor is measured and the EUT response is evaluated for compliance by verifying the power factor is within the manufacturer's stated accuracy. The evaluation data is saved to a separate summary file. Using the PF and apparent power summary data, easy-to-visualize results were plotted for each of the devices on a P-Q plane.

As shown in Fig. 4(A), the results from the 34.5 kW ASGC system are quite accurate, with the unity power factor measurements all lying within 0.8% of nameplate power of the Q = 0 line and the PF measurements mostly falling within ±0.02 PF of the target, as indicated by the pass/fail boundary. The CHIL experiments at AIT used a different ASGC firmware and CHIL configuration. Results in Fig. 4(D) show the device accurately produced the specified PFs. However, it did not consistently produce P_{rated} power at unity PF, possibly from the oversized PV system used for the experiments; and, when the available PV power was adjusted at the start of each test, an overcurrent fault was experienced by the EUT which generated one result at the origin while the EUT reconnected.

In comparison of the accurate ASGC, the 3.0 kW system at Sandia experienced a negative reactive power bias of roughly -360 var at P_{rated}) that shifted all the results downward. This is likely due to the control software not compensating for the AC output filter of the inverter. This effect was previously characterized in more detail in [16]. It is also worth noting this is a legacy system that is no longer sold by the manufacturer.

The reactive power from the 10 kW system at CanmetENERGY was quite accurate for the reactive power priority PF experiments shown in Fig. 4(C). In the case of the active power priority experiments in Fig. 4(F), the equipment did not reach the ±0.85 PF targets for the 100% P_{rated} test cases because this would have curtailed EUT active power. Instead the EUT only transitioned to approximately 0.93 or -0.93 PF and remained there. The EUT output active power is limited to 92-93% of its rating during 100% P_{rated} operation. Therefore, even with active power priority the EUT achieves PF_{mid} target values at 100% P_{rated}. Lastly, in the case of the CSIRO results, since the EUT was powered by both a PV simulator and an uncontrollable 2 kW PV string, the active power settings were not set to precisely 20%, 50% and 100%, but rather three different P_{rating} levels.

While the range of results are expansive, it is important to

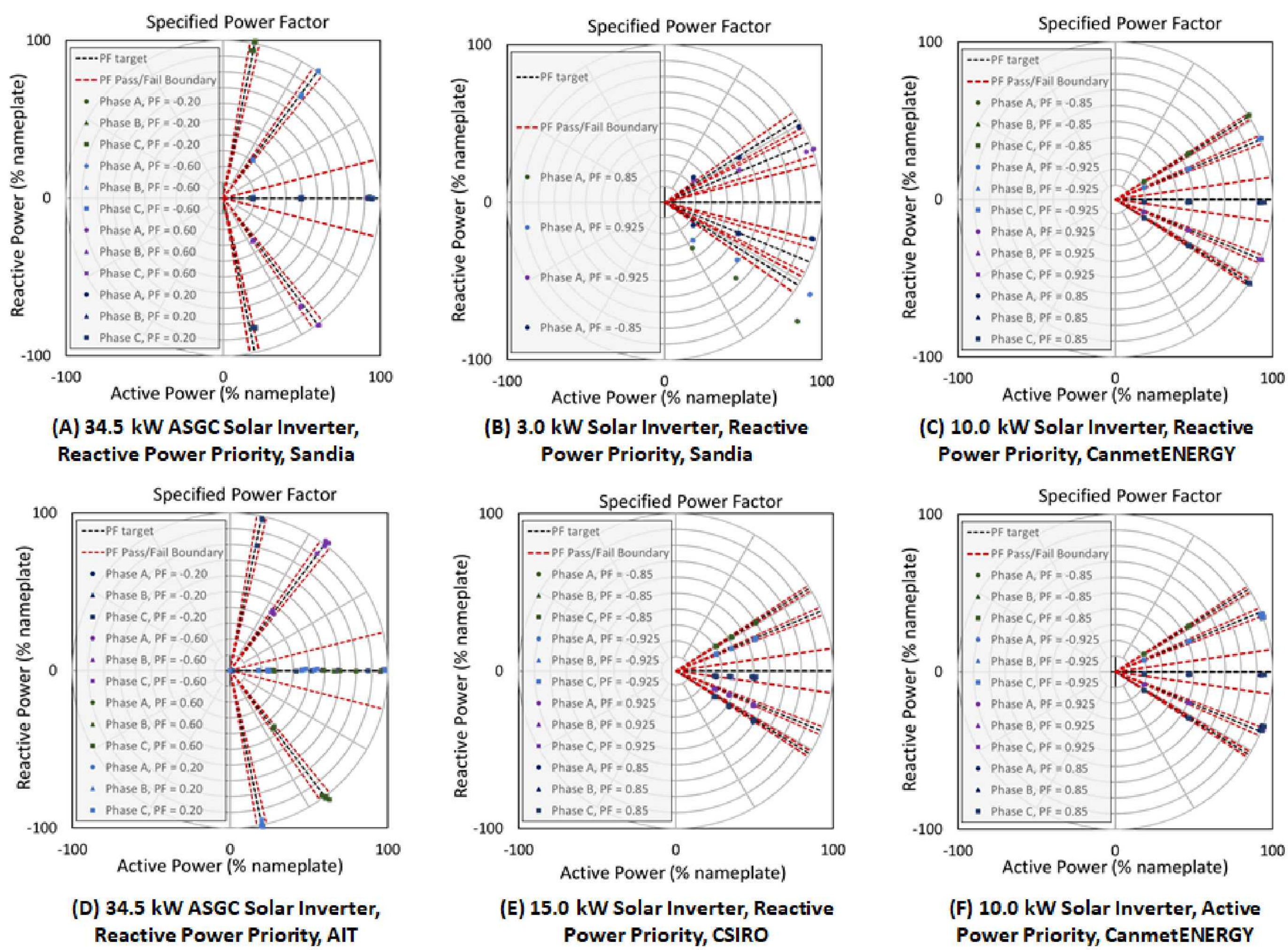


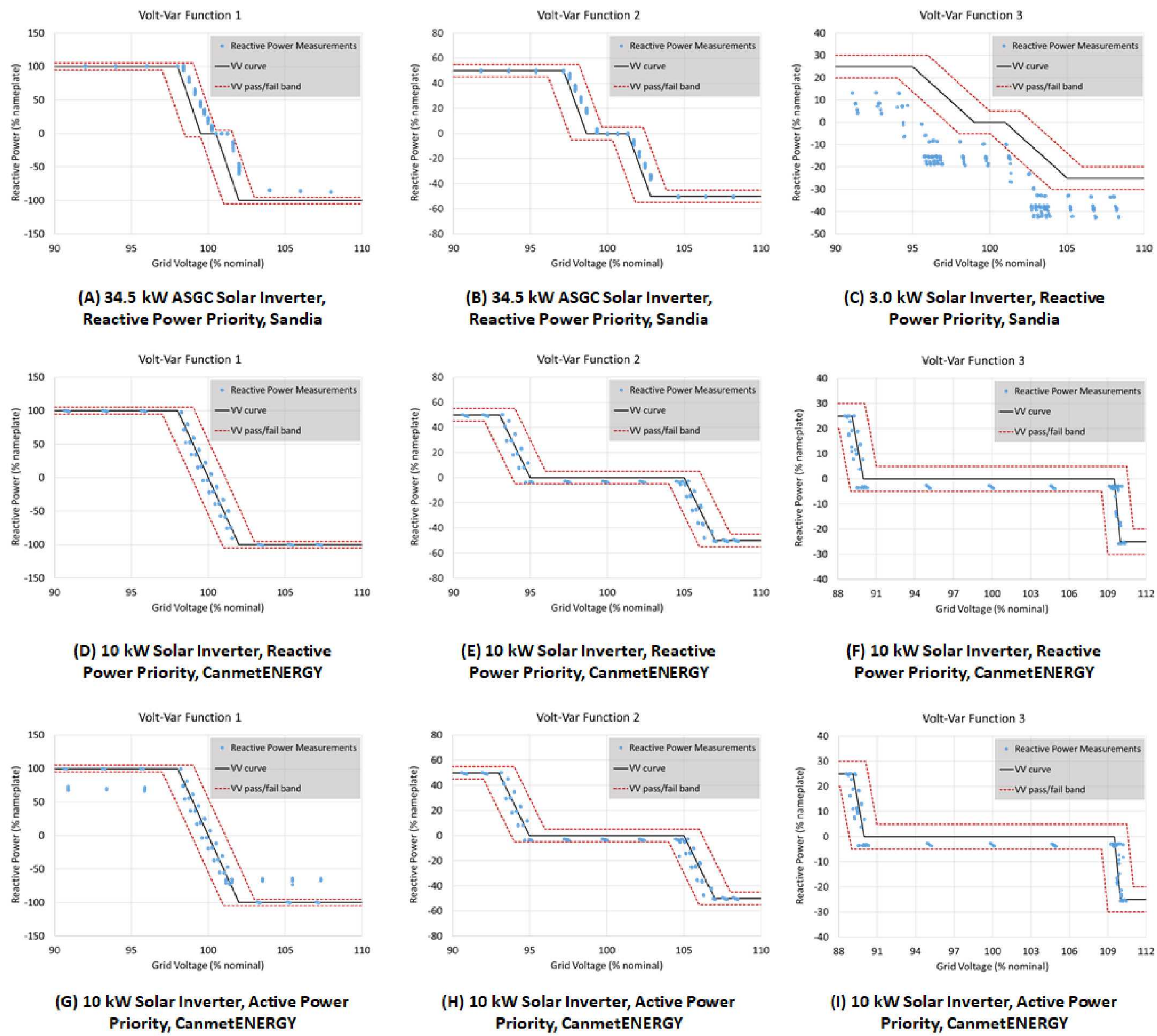
Fig. 4. Specified power factor results for multiple DER EUTs collected using the same SVP script at multiple laboratories. Unity PF measurements are plotted with each of the PF data sets.

note the same test logic was used to produce all the data. The SVP architecture allows for use in a range of environments (different data acquisition systems, grid simulator, and PV simulators) and EUTs (different topologies, nameplate ratings, ranges of adjustability, and manufacturer specified accuracies).

B. Volt-Var (VV) Results

The volt-var tests for UL 1741 SA are extensive. First, the EUT is tested to either active or reactive power priority. Then three VV curves are programmed into the EUT and the reactive power is measured at three or more points along each of the five segments of the VV curve. These measurements are taken increasing and decreasing the voltage three times at 100% P_{rated}, five times at between 50% and 95% P_{rated}, and three times at 20% P_{rated}. For each power priority mode, a minimum of 990 reactive power measurements are taken and validated to be within the manufacturer's specified reactive power accuracy, while accounting for the manufacturer's specified voltage accuracy.

Volt-var results were collected on multiple DER devices as shown in Fig. 5. The ASGC appears to incorrectly measure the grid voltage slightly (~0.5 V) because the VV points are shifted to the right in Fig. 5(A) and (B), although some of this inaccuracy could be from the CHIL system as well. Since, the manufacturer's specified accuracy of voltage was set to 1 V, the EUT passes the test for the 2nd ("average") VV curve. This was not the case for the 1st ("most aggressive") VV curve



(A) 34.5 kW ASGC Solar Inverter, Reactive Power Priority, Sandia

(B) 34.5 kW ASGC Solar Inverter, Reactive Power Priority, Sandia

(C) 3.0 kW Solar Inverter, Reactive Power Priority, Sandia

(D) 10 kW Solar Inverter, Reactive Power Priority, CanmetENERGY

(E) 10 kW Solar Inverter, Reactive Power Priority, CanmetENERGY

(F) 10 kW Solar Inverter, Reactive Power Priority, CanmetENERGY

(G) 10 kW Solar Inverter, Active Power Priority, CanmetENERGY

(H) 10 kW Solar Inverter, Active Power Priority, CanmetENERGY

(I) 10 kW Solar Inverter, Active Power Priority, CanmetENERGY

Fig. 5. Volt-var results for multiple DER EUTs collected using the same SVP script at multiple laboratories.

because at high voltages the EUT is unable to sink 100% of its reactive power capacity. In the case of the 3 kW single-phase device in Fig. 5(C), the same shift in the reactive power from the PF experiments is seen.

Fig 5(D)-(I) are the results from a single device in reactive and active power priority modes for the three volt-var curves. This EUT remains within the passing band, except for the 100% P_{rated} experiments for the "most aggressive" curve in Fig. 5(G), where the active power priority mode does not allow the EUT to reach the nameplate reactive power. In the case of active power priority UL 1741 SA ambiguously states the EUT must remain within the "manufacturer stated Q(V) characteristic," so it is likely this would be a passing test result at any Nationally Recognized Testing Laboratory (NRTL).

IV. Conclusions

Certification testing of DER equipment is necessary to verify power equipment interconnected to power systems around the world operate as intended. New grid codes in many countries now include advanced grid-support functions. Research laboratories in the Smart Grid International Research Facility Network (SIRFN) are working to create a common testing platform to quickly and accurately assess the communications and electrical performance of solar inverters, battery energy storage systems, and other DER to these grid codes. The device drivers, abstraction layers, and scripts are made publicly available on GitHub [18] to accelerate development and adoption. Results presented here demonstrate the portability of the scripts and SVP library to function in multiple laboratory environments. To date, the focus has been on creating the test scripts for UL 1741 SA, but the group plans to generate a range of test scripts for national and international requirements, and other test protocols like the ISGAN BESS test protocols [11] and Sandia IEC 61850-90-7 test protocols [9-10] in the future.

Acknowledgements

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