DEVELOPMENT AND EVALUATION OF OPEN-SOURCE IEEE 1547.1 TEST SCRIPTS FOR IMPROVED SOLAR INTEGRATION

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ABSTRACT: Distributed Energy Resources (DERs) equipped with standardized, interoperable, grid-support functionality have the capability to provide a range of services for power system operators. These requirements have been recently codified in the 2018 revision of the American DER interconnection and interoperability standard, IEEE Std. 1547, as well as the revised Canadian interconnection standard, CSA C22.3 No. 9. Currently, the IEEE standards committee is drafting a new revision of the IEEE Std. 1547.1 test standard, which outlines the test procedures for certifying equipment compliant to IEEE Std. 1547. In addition, it is often referenced as a test standard in CSA C22.3 No. 9. This draft test standard has not been fully exercised yet to identify mistakes, redundancies, and/or implementation challenges. In this work, an international community of research laboratories developed open-source IEEE Std. 1547.1 test scripts. The scripts are used to evaluate grid-support functions – such as constant-power-factor, volt-var, volt-watt, and frequency-watt functions – of several DER devices to the draft standard, IEEE1547.1. Sample test results are presented and discussed, and recommendations are offered to improve the draft standard during the balloting process.

Keywords: distributed energy resources, advanced grid-support functions, interoperability, standards development, IEEE Std. 1547.1, smart grid, inverter.

1 INTRODUCTION

Distributed Energy Resources (DERs), such as photovoltaic (PV) inverters, are capable of positively influencing bulk and local power systems through the appropriate use of grid-support functions. These DER grid-support functions are now widely used in Europe and other regional jurisdictions [1-2] to support grid voltage, to respond to system faults, and to assist bulk system operation during frequency deviations. In USA, new interconnection standards in California [3] as well as the national interconnection standard, IEEE Std. 1547 [4], require DER devices to include standardized communication interfaces. Currently, the Canadian standard CSA C22.3 No. 9 is being revised and drafted to become the Canadian counterpart of IEEE 1547-2018. It defines the Canadian standard requirements for interconnection and grid-support functions for DER devices operating at voltage levels up to 50 kV [5].

Although some jurisdictions permit self-certification of DER devices meeting interconnection standards, USA and Canada require DER equipment to be certified by a Nationally Recognized Test Laboratory (NRTL). Accordingly, to certify any DER device, NRTLs must follow certification standards that outline the step-by-step procedures to assess whether the device meets the standard interconnection and interoperability requirements. If a DER passes the tests, the NRTL *lists* it to the standard, meaning that it is approved for sale in the jurisdiction requiring that interconnection standard.

American and Canadian PV inverter certifications are currently conducted based on UL 1741 [6] which references IEEE 1547.1 [7]. However, DERs will be certified based on the new IEEE 1547.1 test procedures once it is published. These test procedures are highly detailed with specifications for measurement and test equipment accuracy. Furthermore, they typically include dozens, if not hundreds, of measurement points for each of the grid-support functions. Therefore, it is critical to automate the certification process.

The SunSpec Alliance and the Smart Grid International Research Facility Network (SIRFN) – which is an Annex of the International Smart Grid Action Network (ISGAN) – have been collaborating for years to create a versatile open-source DER testing and certification platform that automatically executes test procedures for multiple certification standards. The group has developed draft standards for energy storage systems [8], evaluated grid-support functions in multiple DER devices [9-10], and created draft UL 1741 SA [11] test scripts.

These evaluations have used the SunSpec System Validation Platform (SVP) [12] to execute sequences of testing logic that change settings on the Device Under Test (DUT), grid simulator, PV simulator, and data acquisition system using Python scripts [13]. The SVP saves the results in the form of a manifest containing the test log, raw data, a summary of results with pass/fail results, and Microsoft Excel/python plots of the results.

In this work, Draft 9.5 of the IEEE Std. 1547.1 standard was used to create test scripts for the following DER grid-support function tests:

- Constant Power Factor
- Voltage-Reactive Power (volt-var) curve
- Voltage-Active Power (volt-watt) curve
- Frequency-Droop (frequency-power or frequency-watt) curve

The SIRFN team assessed multiple residential and commercial-scale PV inverters per the IEEE 1547.1 test standard in order to provide feedback to the standards development organization on areas that contain ambiguity and/or errors, and to provide other recommendations regarding the testing procedures.

2 SYSTEM VALIDATION PLATFORM

The SVP autonomously orchestrates interconnection and interoperability certification protocols. It automates the execution of tests/evaluations by communicating to laboratory equipment (i.e., grid simulator, PV simulator, and data acquisition system) as well as the Device under Test (DUT) in a laboratory test setup, as shown in Fig. 1. The user-selected parameters define the test sequence by selecting appropriate tests and configuring all equipment based on the DUT rating. The SVP uses abstraction layers to allow using the same scripts for different laboratory testbeds by merely changing the equipment drivers for each testbed. Therefore, the same script logic and commands (e.g., 'set grid voltage to 0.97 pu') is used in different test facilities, but the platform issues device-specific commands over the appropriate communication protocol and media depending on the defined device driver in this facility. This SVP architecture allows the test scripts to be completely portable to any power system testing laboratory in the world [13].

A screenshot of the graphical user interface (GUI) of SVP is shown in Fig. 2. One or more SVP Directories can be imported into the system, such as "C:\IEEE 1547.1" in Fig. 2. Within the directory, there are five subdirectories:

1. **Lib**: the library of abstraction layers and device drivers that communicates to the equipment. This directory is not shown in the GUI.
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. 2).
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.

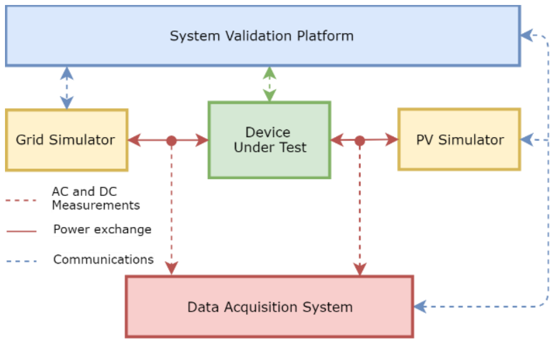

Figure 1: SVP generic laboratory configuration.

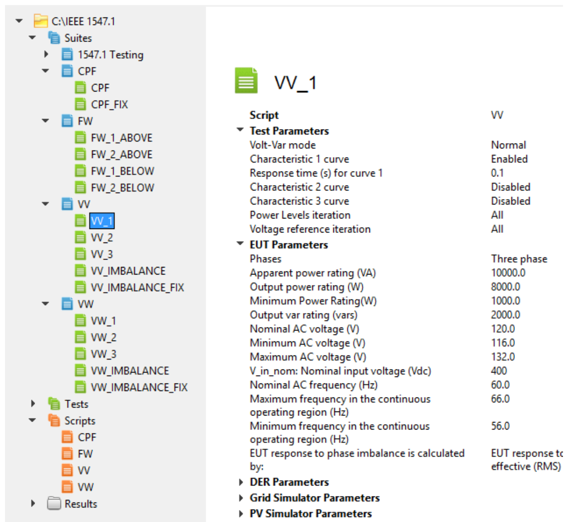

Figure 2 : Screenshot of the SVP with parameters for the specified test

3 LABORATORY TESTBEDS

SIRFN laboratories located in North America, Europe, Asia, and Australia collaborated to assess the DER equipment. Each laboratory used a testbed comprised of different equipment for the certification tests. Therefore, all laboratories implement the same generic testbed architecture of Fig. 1. Moreover, the same test logic is used at each laboratory using the SVP abstraction layers, as previously explained. Following are brief descriptions of the testbeds implemented in each laboratory.

The CanmetENERGY laboratory is located in Varennes, QC, Canada. The DER inverters can be assessed for both electrical and interoperability functions at the CanmetENERGY inverter test facility (INVERT). The test facility includes 120 kVA grid simulator, 120 kW/120 kVAR programmable RLC load bank, 4×15 kW Ametek TerraSAS PV simulators and three Zimmer LMG670 power analyzers. A 10 kW commercial three-phase solar inverter was used as a DUT.

The Austrian Institute of Technology (AIT), located in Vienna, Austria, performs experiments on DER at the Smart Electricity Systems and Technologies (SmartEST) inverter test laboratory. There are two testbeds available for equipment up to 30 kVA as well as for utility scale units up to 1 MVA. AIT configured the 30 kVA test lab to implement the SIRFN ESS test protocol and run automated tests of the advanced interoperability functions. An illustration of the testing setup is shown in Fig. 3. The testbed consists of multi-string PV array simulators, a controllable 30 kVA grid simulator and a simulated utility SCADA system which allows interoperability tests on a variety of inverters and DERs. AIT conducted experiments on the 34.5 kW three-phase AIT Smart Grid Converter (ASGC) connected to a controller hardware-in-the-loop (CHIL). Details of the CHIL setup can be found in [10] and [11].

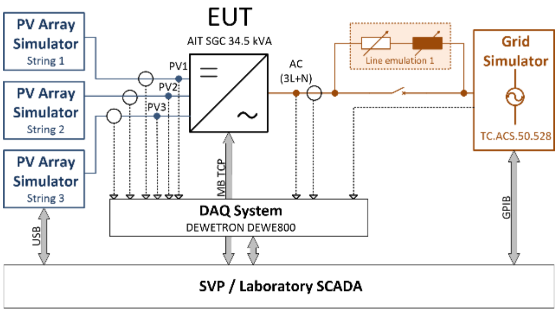

Figure 3 : AIT Smart Electricity Systems and Technologies (SmartEST) PV inverter test laboratory.

Sandia National Laboratories, located in Albuquerque, New Mexico, USA, performs DER experiments at the Distributed Energy Technologies Laboratory (DETL). The DETL testbed consists of a 200 kW PV simulator, a controllable 180 kVA Ametek grid simulator and LabVIEW data acquisition system. Sandia conducted experiments using the ASGC system (Similar to AIT) using the same configuration.

Fukushima Renewable Energy Institute, AIST (FREA), located in Fukushima, Japan, is the branch facility of AIST. FREA has two different DER testing facilities. The DER System Lab consists of a 500 kVA SanRex grid simulator, a 300 kVA SanRex controllable load, a 600 kVA SanRex PV simulator, and a 200 kVA Myway battery simulator with Yokogawa data acquisition system. The other facility called Smart System Research Facility (FREA-G) has approximately 10 times the testing capability than DER System Lab, with a 5 MVA SanRex grid simulator, a 3 MVA SanRex controllable load, and a 3 MVA SanRex bi-directional DC source with HIOKI data acquisition system. FREA conducted experiments on a 50 kW battery energy storage system with a 16.5 kWh Super Charge Ion Battery (SCiB) Li-ion battery.

Korea Electrotechnology Research Institute (KERI), located in Changwon, Korea, is a government funded research institute which engaged in R&D and the dissemination of industrial original technology. KERI also provides testing & certification services in various electricity-related fields. The test facility includes 60 kVA Chroma 61860 grid simulator, 4×15 kW Chroma 62150 PV simulator, and Yokogawa WT3000 power analyzer as a DAS. A 12 kW commercial three-phase solar inverter was used as a DUT.

4 EXPERIMENTAL RESULTS

Experiments were conducted with the SVP to assess the grid-support functions of PV inverters following the draft test standard, IEEE 1547.1. Sample results from CanmetENERGY, Sandia, AIT, KERI and FREA for four grid-support functions are compiled and presented in the following subsections. Note that the compiled results are labeled to identify the result-sets of each laboratory. Additionally, presented results in each subsection is followed by comments and recommendations to improve the test standard.

4.1 Test for voltage-reactive power (volt-var VV) normal mode

Draft 9.5 of the IEEE 1547.1 standard – also referred to as D9.5 – requires evaluation of the voltage-reactive power function – also referred to as volt-var (VV) – with three different characteristics (i.e., VV curve parameter settings and response times) at different power levels. The three characteristics are defined for three reference voltages (1.00 pu, 1.05 pu, and 0.95 pu) with different response times. Tests of each characteristic include 243 test points (17 steps × 3 power levels × 3 voltage references). The SVP executes automated test sequences for the VV function, collects measurements (i.e., time, voltage and reactive power), and generates plots with pass/fail boundaries. The normal VV test was performed on different DUTs at different labs. Experimental results for VV characteristic 1 at 100% power level with reactive power rating set to 44% of available apparent rating of DUT are shown in Fig. 4. The test results reveal that the tested inverters remain within the passing band provided by the Annex C of D9.5 test criteria formulas. The pass-fail band for VV functions is defined by the equations below, where MRA stands for minimum required accuracy. Similar pass/fail formulas are also used for the other grid-support functions. It should be noted that the minimum and maximum values of the VV voltage range for the ASGC system was set to 0.85 pu and 1.15 pu respectively. Therefore, two points appear outside the VV characteristic region.

$$Q_{max} = Q(V_{meas} + 1.5 \times MRA(V)) - 1.5 \times MRA(Q)$$
$$Q_{min} = Q(V_{meas} - 1.5 \times MRA(V)) + 1.5 \times MRA(Q)$$

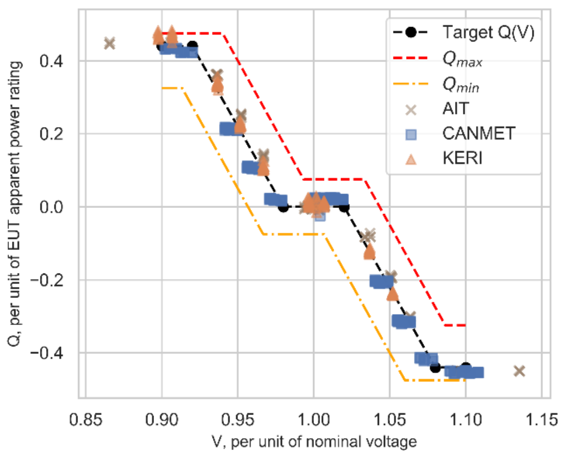

Figure 4 : Volt-Var test results for characteristic 1.

Comments: In the current version of VV tests, a number of steps were missing or misleading. Appropriate corrections have been suggested to the IEEE 1547.1 working group accordingly. Besides, D9.5 requires VV function test with imbalanced grid voltages for three phase PV inverters. However, it only provides magnitude values of the applied three phase voltages, while voltage phase angles remain undefined. Experimental results reveal that DUTs respond differently under different unbalanced three-phase voltage phase angles. Therefore, this point needs to be clarified in the standard.

4.2 Test for frequency-droop (frequency-power or frequency-watt FW) capability – above nominal frequency

This test evaluates the DUT's response to changes in the ac grid's frequency when it exceeds the nominal value. This grid-support function is also referred to as frequency-power or frequency-watt (FW). The test is done by setting the frequency trip settings to the widest setting and disabling all reactive/active power control functions. The draft standard also requires to test this function for two different characteristics with different deadbands, slopes and settling times. The characteristics should also be evaluated at three different power levels of 100%, 66% and 20%. Fig. 5 presents the test results at 100% power level for characteristic 1. A zoomed version is also added in Fig. 5 to show the test results around the deadband area of the FW characteristic. It is observed that the DUT reduces its output power as the frequency increases. The output power starts to decrease when frequency exceeds the threshold/deadband (60.036 Hz) and drops to zero for frequencies above 63 Hz. D9.5 states that there is no lower bound (P_{min}) for the acceptable active power output in the FW curve. Hence, Fig. 5 does not show a lower bound for the FW function.

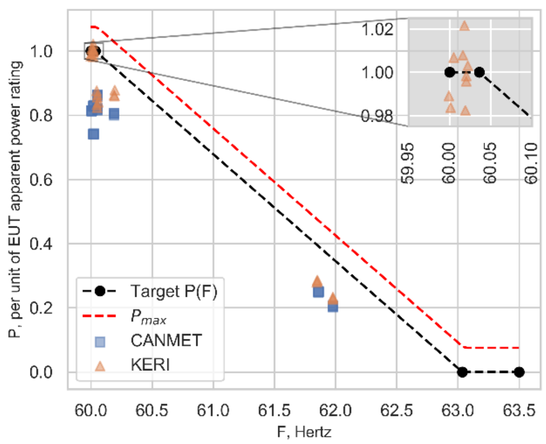

Figure 5: Frequency-droop test results of characteristic 1.

Comments: D9.5 was not considering the frequency accuracy when ramping to the maximum frequency range (step k in the test FW procedure). It is observed that following the current procedure of the FW test results in test points around the beginning of the droop curve (at nominal frequency) and other points at the zero-power line (frequencies above 63 Hz in this case) if the DUT parameter f_H is set to 65 Hz for steps k) and l) of the FW test. Subsequently, it is difficult to verify the droop curve. To address this issue in this work, f_H was set to 62 Hz to provides an insight about the droop characteristic. The standard needs to address this issue so that the droop characteristic can be verified. The same issue applies to the FW test with operation below the nominal frequency.

4.3 Test for constant power factor (PF) mode

This test verifies the DUT's operation at a fixed power factor (PF). The DUT is subjected to changes in ac voltage magnitudes at different power levels, and it is required to follow the commanded fixed PF. The tests are conducted for four different PF values: minimum and medium values for each PF with reactive power injection and absorption. In addition, three phase units are tested with imbalanced voltages. The test results from four labs are presented in Fig. 6. Some of the DUTs follow the target PF for all operation points. The DUTs from CanmetENERGY and AIT passed the test. For one of the DUTs, it was difficult to follow the PF command at low active power value.

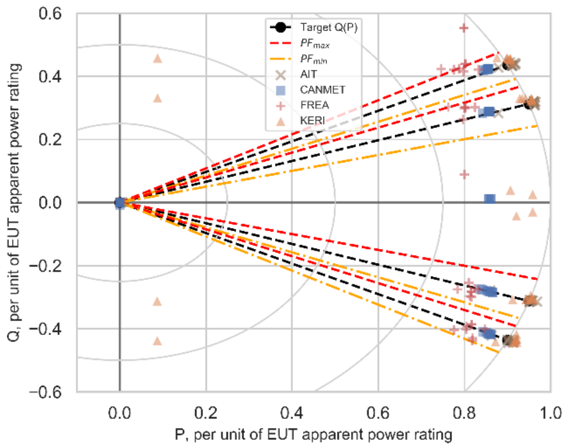

Figure 6: Constant power factor test results.

Comments: For three-phase units, before applying the imbalanced voltages, the DUT should operate at the nominal voltage, rather than the minimum voltage of the function. Therefore, a step needs to be added in the test procedure to address this point. Furthermore, the three-phase unbalanced voltage phase angles need to be defined, as previously recommended for the VV test.

4.4 Test for voltage-active power (volt-watt VW) normal mode

This test verifies the DUT's active power response to changes in the ac voltage magnitude. This grid-support function is also referred to as volt-watt (VW). The test is conducted by setting the voltage trip settings to the widest setting and disabling all other reactive/active power control functions. The standard requires this test to be performed for three different characteristics of the VW function at three different power levels. Fig. 7 shows the test results at 100% power level for characteristic 1 of the VW function. The PV inverter reduces its active power as the ac voltage magnitude increases beyond 1.06 pu. Similar to the FW test, D9.5 does not define a lower boundary for the output active power for assessing this function. It is worth noting that ASGC uses a voltage range of 0.85 to 1.15 for this function, leading to few result points appearing outside the range of this function.

Comments: Some of the test procedures cannot be executed if the second voltage point of the VW characteristic is greater than or equal to the maximum voltage of the DUT. In this case, some steps need to be skipped. Besides, tests at different power levels should be started with the rated voltage, which needs to be incorporated as a step in the current test procedure.

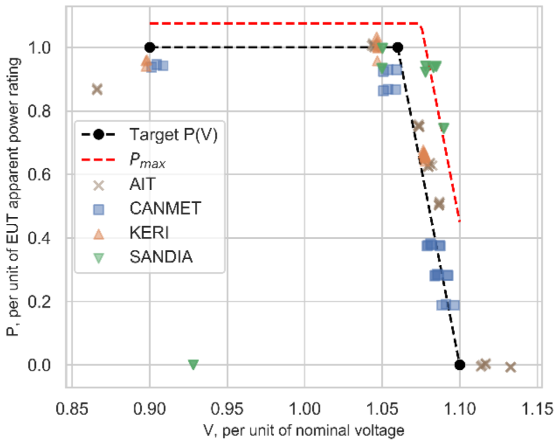

Figure 7: Volt-watt test results of characteristic 1.

4.5 Response time evaluation of grid support functions

Grid-support functions usually have a response time as a parameter that indicates the time required for the DER's controlled variable to reach at least 90% of its final steady-state value in respect to its initial value. IEEE 1547.1 D9.5 also requires verification of the response time for grid-support functions. This verification process for one of the grid-support functions are discussed below.

Fig. 8 shows a DUT's time domain response of the VW function for an entire test duration at 100% power level. The figure plots the active power response against changes in the grid voltage magnitude (average voltage magnitude over the three-phases). A zoomed version for evaluation of the time response is also added in the figure. In the zoomed part of the plot, the black dotted line indicates the 90% value, the red marker (►) indicates the initial value, the purple marker (♦) marks the value after one time-constant, and the green marker (◄) marks the value after four time-constants. In this case, the time constant is equal to the response time of the grid-support function. As per D9.5, the DUT's active power must reach at least 90% of its steady-state value after one time-constant. As seen in the figure, the DUT does not meet the response time requirement for the VW function.

To assess the final steady-state values for the different grid-support functions, the value at four time-constants is considered. Note that considering the time response characteristics of available commercial DERs, steady-state value assessment at two time-constants could be too strict. Accordingly, the results presented in earlier sections correspond to the time response values taken at two/four time-constants for each grid support function (as indicated by the green marker (◄) in the zoomed portion of Fig. 8).

Comments: If Y and Tr are output value of the function and response time respectively; then from D9.5, when the Y(initial) value is very close to Y(final), then then there is an ambiguity in assessing the final value due to the consideration of MRA (Y(final) ≈ Y(Tr) +/- Y_{MRA}). This should be addressed by the standard. Also not all grid support functions are testing these parameters and the standard should be updated to test them.

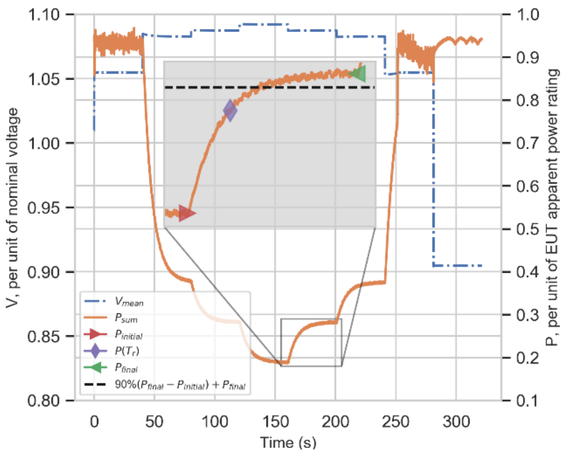

Figure 8: VW time domain test results with response time evaluation.

5 CONCLUSION

To encourage smooth and sustained deployment of PV at the distribution level around the world, grid codes are requiring DERs to incorporate grid-support functionalities as well as communication capabilities. An international collaboration within the Smart Grid International Facility Network (SIRFN) developed test scripts to automate the test procedures of draft 9.5 of the IEEE Std. 1547.1 test standard. The conducted tests and compiled rest results allowed the laboratories to provide feedback to the IEEE standards development organization to improve the balloted standard before formal adoption within the US and Canada.

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