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INTERNATIONAL DEVELOPMENT OF ENERGY STORAGE INTEROPERABILITY TEST PROTOCOLS FOR PHOTOVOLTAIC INTEGRATION

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ABSTRACT: As variable, non-dispatchable photovoltaic power continues to displace traditional generation assets, additional resources are needed to control bulk and local power systems. One highly versatile option for providing frequency and voltage stability is to incorporate Energy Storage Systems (ESSs) at the distribution-level. Deployment of these technologies is expected to increase rapidly as time-of-use pricing and self-consumption requirements become wide-spread and provide greater financial incentives. Japanese, European and American stakeholders are working on the standardization of interoperability certification protocols for many grid support functions to validate the Distributed Energy Resource (DER) operations and communications within the power system. Specifically, in this project, Smart Grid International Research Facility Network (SIRFN) laboratories—Sandia National Laboratories (SNL), Austrian Institute of Technology (AIT), Ricerca sul Sistema Energetico (RSE), and National Institute of Advanced Industrial Science and Technology (AIST) Fukushima Renewable Energy Institute (FREA)—are collaborating to create a concise set of test protocols for evaluating the ESS interoperability and functionality. First, a survey of grid-support standards and use cases from several countries was completed. Then the grid support functions were condensed to the unique set of ESS capabilities and organized by function, control signal requirements, and response requirements. From this list, draft certification protocols were written to enable advanced interoperable ESSs covering this range of capabilities to better support photovoltaic and renewable energy integration. An overview of the protocol development process along with preliminary ESS test results for four initial functions (active power, fixed power factor, volt-var, and frequency-watt) is presented. This work is expected to provide the basis of an international testing standard for ESS grid-support functions in the future.

Keywords: energy storage systems, advanced inverter functions, advanced DER functions, interoperability, standards development, grid support, smart grid

1 INTRODUCTION

Distributed Energy Resources (DERs) such as energy storage systems (ESS) when deployed at a large scale are capable of significantly influencing bulk and local power systems. While in many cases the negative effects of uncoordinated DER have caused local and system-level challenges [1-2], with proper design and control [3], DER can effectively support the electric grid. DER with advanced control features have been shown to increase hosting capacity by providing voltage support in distribution circuits [4-6], provide ancillary services [7-8], and be used for wide-area damping [9].

New energy storage targets in Europe [10] and California [11], energy storage regulations [12], along with new storage technologies are providing the foundation for massive deployment of energy storage resources. Large-scale storage is common for renewable energy smoothing [13, 14], peak-shifting [14], and voltage support [15], while commercial and residential-scale systems are financially lucrative in many jurisdictions due to grid codes and other regulations. For instance, electricity prices in Germany are high enough that storing solar energy for use during peak price periods has made home ESS cost effective [16].

Further, the combination of PV and energy storage can generate additional value when interoperable grid-support ("advanced grid") functions allow for intelligent control. In a position paper issued by the European Photovoltaic Industry Association (EPIA), decentralized storage and the ability for those devices to respond to commanded signals will "help support distribution grids operation - and even sometimes avoid costly grid reinforcements [17]." Widespread adoption of these functions could allow energy storage to remove some of the barriers to high penetration PV.

Advanced DER grid functions are not the same across all countries and jurisdictions; and many regions do not have a defined certification procedure to validate the functionality of these devices. As a result, DER system vendors create different versions of the software to be compliant with regional requirements. This adds cost and complexity to the design and certification processes. It also generates disparate testing methods and there is no common set of parameters that can be communicated to the DERs. If a single procedure was created that accounted for all the jurisdictional variations (e.g., a superset of the grid code discrepancies), a single document and procedure could validate all grid code requirements. This is challenging because there are a large number of grid codes and technical rules—each with variations in the function definitions. For instance, the IEC TR 61850-90-7 [18] defines a ramp time and timeout period for frequency watt (FW), but this is not included in the Italian technical rule (other timing parameters are requested for the re-entry condition). The approach taken by the SIRFN group was to create a test procedure which covers a superset of these parameters, depicted in Figure 1, and therefore includes the ramp time and timeout period. For example, in the case of testing to the Italian requirements, the additional parameters are omitted. Thus, a single testing procedure can be used for all the grid codes (and rules) by employing a subset of the test parameters, an abbreviated test procedure, and different pass/fail criteria.

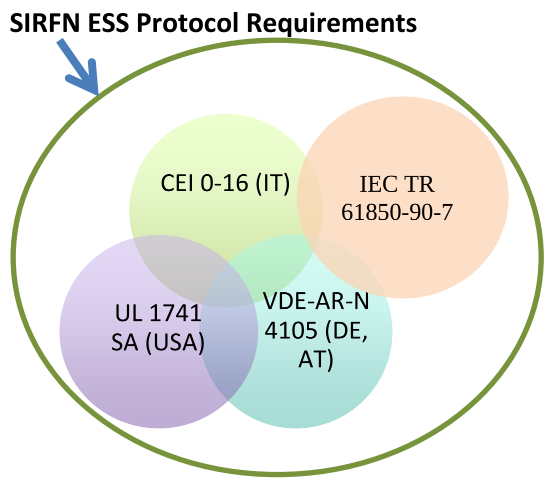

Figure 1: Visualization of integration method for SIRFN ESS Protocol

The development of an inclusive set of tests for grid support functionality has the potential to open markets for energy storage providers. Data collection redundancies are removed as well, thereby further reducing the overall cost of certification and deployment. Hence, harmonization and standardization of these advanced function tests would bolster the international market for energy storage systems and enable higher penetrations of solar. To accomplish this, the proposed SIRFN ESS protocol needed to be inclusive of many technical rules and grid codes while being detailed enough for uniform results across laboratories, countries, and even, continents. This paper presents the approach and progress of SIRFN to develop such a protocol.

2 LABORATORY COLLABORATION

Under the auspices of the multi-lateral International Energy Association (IEA) International Smart Grid Action Network (ISGAN), 15 SIRFN laboratories in 13 countries in North America, Europe, and Asia collaborate to integrate DERs into the electricity grid to accelerate the integration of higher penetrations of PV and other renewable energy resources. In addition to this project, the SIRFN network conducts research in areas of Smart Grid Distribution Automation, Advanced Laboratory Testing Methods, and Power Systems Testing.

In February 2013, a set of standardized interoperability functions were defined for DERs in IEC TR 61850-90-7 [18]. Sandia National Laboratories established a testing protocol for these functions in November 2013 [19-20]. The first results from three PV inverters executing connect/disconnect (INV1), curtail active power (INV2), and fixed power factor (INV3) functions were presented in September 2014 by SIRFN labs SNL, AIT and TECNALIA [21]. The IEC report and Sandia test protocols were primarily tailored to photovoltaic DER resources. In this project SIRFN is expanding the testing protocols to energy storage systems. This work involves collaborative development of the test protocol, multiple laboratory experiments with the protocol to find areas to improve its precision and usability, and lastly the pursuance of wide-spread adoption through international standards-making bodies.

In this project, SIRFN laboratories (Sandia, AIT, RSE and FREA) are defining a harmonized ESS evaluation/certification protocol for advanced energy storage functions and providing this standardized protocol as an adoption option for jurisdictions when new requirements are added. To complete this process, each laboratory shared information on national, international, and jurisdictional grid codes and standards for ESS. Based on these requirements, and ESS testing and certification literature, a broad list of interoperability functions, use cases, storage capabilities, and requirements were being compiled. This list was then consolidated to a unique set of ESS functions for inclusion in the certification procedure. Draft certification protocols for four functions were created by the SIRFN group to start in order to harmonize the international effort to establish a unified set of procedures for characterizing storage systems. To ensure the repeatability and robustness of these protocols, interoperability test beds were constructed at each SIRFN lab to evaluate the effectiveness and portability of the test protocols with different hardware and different grid parameters.

3 ESS GRID CODES, TECHNICAL RULES AND STANDARDS ACTIVITIES

A harmonized national and international approach must be taken to guarantee the wide-spread applicability of the advanced interoperable functions for ESSs. Often code making bodies operate independently and there are separate certification procedures for each jurisdiction, which increase the barriers to enter multiple markets. To begin understanding the status of global ESS grid codes, each SIRFN laboratory discussed their respective national or regional requirements.

In the United States, there are no grid codes specifically for energy storage systems. All DERs interconnected to the U.S. electricity grid must be compliant to IEEE 1547-2003 [22] (interconnection requirements) and IEEE 1547.1 [23] (testing requirements). These standards are currently undergoing a revision to include advanced grid-support functions and interoperability requirements, but they are not expected for years. As a stopgap measure, the IEEE 1547a-2014 amendment [24] was adopted which allowed DERs to participate in voltage and frequency support with the agreement of the Area Electric Power System. This allowed local jurisdictions to create their own requirements for ESSs and DERs. Most notably, the California Public Utilities Commission (CPUC) passed the first set of "smart" inverter-based DER functions in January 2015 to provide greater grid support in Electric Rule 21. The new interconnection rules require ESS to limit their ramp rates, contain reactive power controls, and perform voltage and frequency ride-throughs [25]. Two additional phases have been outlined by stakeholders in the Smart Inverter Working Group which specify additional advanced DER functions and interoperability requirements, along with a proposed timeline for the adoption of these new capabilities [26].

In the U.S., Nationally Recognized Test Laboratories (NRTLs) independently verify products to safety and functional standards. PV inverters are certified to Underwriters Laboratories (UL) Standard 1741 [27]. However, new advanced inverter functions described in Electric Rule 21 are not included in this standard, so the UL 1741 Standards Technical Panel has been quickly developing new protocols for the certification of the seven CPUC functions in UL 1741 Supplemental A (UL 1741 SA), expected by the end of 2015.

Italy has defined technical rules regarding connection, prescription and grid support functions for energy storage systems. Requirements include advanced grid services including Freq/Watt, Volt/VAR, automated reactive power control following a $\cos(\phi)=f(P)$ and $Q=f(V)$ curve, centralized active and reactive power control, L/HVRT (low and high voltage ride through). These requirements are based on technical rules CEI 0-16 [28], for medium and high voltage, and CEI 0-21 [29], for low voltage. In addition, technical rules give detailed information about testing procedure for the different grid support functions.

In Japan, DER must follow the guideline of grid-interconnection technical requirements for power quality securement [30]. Japanese Grid-interconnection Code JEAC 9701 defines the technical requirements [31-32], which states all ESS must provide fault ride-through (FRT) functions. Other required functions, including interactive communications, have been discussed in a number of technical demonstration projects but are currently not required.

Germany and Austria have standardized some but not all of the advanced inverter functions for energy storage. The operating modes of storage system connected to the Low Voltage distribution grid are separated into "energy consumption" and "energy supply" mode [33]. In the energy supply mode, the storage is discharged to the public grid or PV-power is fed in directly. In this case the regulatory framework VDE-AR-N 4105 applies [34]. The grid operator can require a fixed displacement factor set point (fixed power factor) or a displacement factor which is a function of active power (watt-power factor), depending on the rated capacity of the plant. The ESS is required to reduce active power in the case of overfrequency (frequency-watt). However, there is no procedure to supply the grid with active or reactive power in case of underfrequency or undervoltage. When the ESS is charging, energy consumption mode [33], the regulatory framework "Technical conditions for connection to the low voltage network" applies [35]. Germany also has a subsidy program for ESS which is contingent on its ability to supply grid support functions [36]. In the subsidy program ESS manufacturers implement an open interface for grid support functions, which allows the parametrization of frequency-watt and volt-var characteristic curves and the ability for grid operators to remotely update active and reactive power set points.

In addition to existing national grid codes, it is important to recognize the grid supporting functions of energy storage which are not formally codified. There are many groups around the world working to advance the state of the art in DER integration and performance testing: the DOE Electricity Storage Handbook through Sandia, Electric Power Research Institute (EPRI) and the National Rural Electric Cooperative Association (NRECA), IEEE P2030.2 working group, IEC TC120 international integration working group, Rule 21 Smart Inverter Working Group (SIWG) and the Smart Grid Interoperability Panel (SGIP) to name a few. This effort connects the work of these discrete groups in an effort to find commonality and produce broadly applicable test protocols. While these groups have focused on the services provided to the electric grid (e.g. frequency regulation) this new work simplifies these services into basic control functions that can be adapted to meet the needs of a given jurisdiction. This offers a device-centric perspective beneficial to developers and test laboratories. Table 1 shows one example of the kind of commonality that can be found. While each organization has a different name for changing power output with respect to measured voltage, the device functionality (based on control signal and required action) is the same and so only one test is needed.

4 PROTOCOL DEVELOPMENT

Development of the SIRFN ESS Protocol is the result of the following iterative process:

1. Review of appropriate grid codes, technical rules, standards, and ESS functions,
2. Consolidation of function requirements into draft protocol language,
3. Execution of draft protocol to ESS with equipment units at SIRFN laboratories, and
4. Updating draft protocols to improve usability and to generate better results.

In this process, the first step was to survey national and international grid codes and rules to understand the range of capabilities that would need to be tested in order to cover the superset of requirements. Table 1 shows a representative sample of grid codes reviewed for the volt-var function. Characteristics such as the data requirements, specified curve, and default values were recorded for each code and analyzed for their similarities and differences. Surveyed countries/codes included but were not limited to: Italy (per CEI 0-21:2014-12 (LV)), USA (per California Rule 21), Germany (Optional testing per FGW - TR3 Rev23), Austria (TOR D4:2013 - ÖVE/ÖNORM EN50438–optional Voltage/Var function), and the present state of international protocols (IEC 61850-90-7 VV11). Note that the surveyed codes apply at a variety of locations in the power system (e.g. Medium Voltage), and to a variety of devices (e.g. gird connected inverters > 6kW).

Table I: Review of Grid Codes for the Volt / VAR function

Country/ Grid Code	Data Requirements	Specified Curve	Default Values
Italy/CEI 0-21:2014-12 (LV)	P, Q, V_{ac} measured (1 s average) , Q awaited, Q error	V_{1i}= under voltage at the left edge of the deadband V_{2i}= under voltage at max capacitive reactive power V_{1s}= over voltage at the right edge of the deadband V_{2s}= over voltage at max inductive reactive power Q_{1i}=reactive power at V_{1i} Q_{2i}=reactive power at V_{2i} Q_{1s}=reactive power at V_{1s} Q_{2s}=reactive power at V_{2s} $Q_{max,cap}$ and $Q_{max,ind}$ from capability curve	V_{1i} = 0.92 V_n, Q_{1i} = 0 V_{2i} = 0.9 V_n, Q_{2i} = $Q_{max,cap}$ V_{1s} =1.08 V_n, Q_{1s} = 0 V_{2s} = 1.1 V_n, Q_{2s} = $Q_{max,ind}$
US (California)/ UL 1741 SA: 2015	AC and DC current and voltage. The minimum measurement accuracy shall be 1% or less of rated EUT nominal output voltage and 1% or less of rated EUT output current.	• Q_1 = maximum capacitive reactive power setting • Q_2 = reactive power setting at the left edge of the deadband • Q_3 = reactive power setting at the right edge of the deadband • Q_4 = maximum inductive reactive power setting • V_1 = voltage at Q_1 • V_2 = voltage at Q_2 • V_3 = voltage at Q_3 • V_4 = voltage at Q_4	$V_1 = V_2 - Q_1/KVAR_{max}$, Q_1 = $Q_{max,cap}$ $V_2 = V_n - Deadband_{min}/2$, Q_2 = 0 $V_3 = V_n + Deadband_{min}/2$, Q_3 = 0 $V_4 = Q_4/KVAR_{max} + V_3$, Q_4 = $Q_{max,ind}$
Germany/ FGW - TR3 Rev23 (optional test)	Displacement factor, P, Q, and V useing a 0.2s (min) sliding average. The settling time shall be determined on the basis of ±5% rated active power.	Aditional tests are carried out for PGUs with reactive power control with Q(U) caricteristic curve. The voltage steps start at the lowest voltage to the highest voltage and vice vcersa.	none
Austria ÖVE/ÖNORM EN50438 (optional - in accordance with DSO, e.g. function used by local DSO - -Vorarlberg Netz)	Displacement factor, P, Q, and V using a 0.2s (min) sliding average. The settling time shall be determined on the basis of ±5% rated active power.	V_{1i}= under voltage at the left edge of the deadband V_{2i}= under voltage at max capacitive reactive power V_{1s}= over voltage at the right edge of the deadband V_{2s}= over voltage at max inductive reactive power Q_{1i}=reactive power at V_{1i} Q_{2i}=reactive power at V_{2i} Q_{1s}=reactive power at V_{1s} Q_{2s}=reactive power at V_{2s} $Q_{max,cap}$ and $Q_{max,ind}$ from capability curve	For grid operator (Vorarlberg Netz) V_{1i} = 1.02 V_n, Q_{1i} = 0 V_{2i} = 0.99 V_n, Q_{2i} = $Q_{max,cap}$ V_{1s} =1.05 V_n, Q_{1s} = 0 V_{2s} = 1.08 V_n, Q_{2s} = $Q_{max,ind}$
International / IEC 61850-90-7 VV11	Monitor and record electrical output of EUT. • Voltage • Active power • Reactive power	Pointwise definition with (V_1, Q_1) through (V_x, Q_x) points. • Q_x = Desired reactive power setting at V_x • V_x = Voltage setting at Q_x.	No default. Example settings are: V_1 = 0.97 V_n, Q_1 = 50% $Q_{max,overexcited}$ V_2 = 0.99 V_n, Q_2 = 0 V_3 = 1.01 V_n, Q_3 = 0 V_4 = 1.03 V_n, Q_4 = 50% $Q_{max,underexcited}$

While the goal of the function is common between the countries, there are many differences in terminology and default values. All three regional rules specify four voltage and reactive power pairs while the IEC standard generalizes its curve by specifying any number of pointwise voltage-reactive power pairs. Further, substantive differences exist between the data collection requirements for each case, in order to satisfy all rules and standards, a laboratory must collect data on AC and DC voltage and current, and active and reactive power.

Once these requirements were identified, draft protocol language was developed to evaluate the equipment under test (EUT). Generally, two different sets of tests were created for each function: an operational domain test to evaluate the accuracy of the function to reach the appropriate setpoints and the time domain test to measure the ESS time response. As an example, Figure 2 shows the grid frequency-active power operational domain test points to evaluate the frequency-watt function. FW Curves 1-4 show the upper and lower active power limits of the function, the “tie-line” indicates if and when the DER must track to the power maximum in quadrant II and the power minimum in quadrant IV, and the hysteresis reset curves (not shown) describe how the EUT returns to the original ESS active power setting. Beyond the maximum and minimum frequencies of the FW Curves the system will eventually disconnect and the power output will drop to zero. To verify the EUT maintains the proper power level until this point, the EUT is tested at grid frequencies up to the disconnection limits, Hz_{min} and Hz_{max}.

The test procedure foreseen seven different FW curve variations to be tested at 35 test points at five commanded powers of W_{MAXch}, 50% W_{MAXch}, 0, 50% W_{MAXdch}, W_{MAXdch}; in addition, time domain test must be performed with different timing parameters (up to 11 different settings of ramp time, recovery time delay, etc.) at five commanded power. Consequently, the complete frequency-watt procedure includes over 1300 measurement test points; but when testing to specific national or international requirements, only a small subsection of these experiments are required. To further accelerate the test process, automated interoperability testing platforms are being developed, such as the SunSpec Alliance System Validation Platform [37-38].

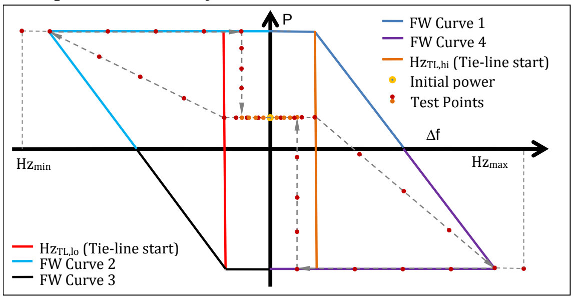

Figure 2: Frequency test points required for FW Domain tests. The points are traced with the grid simulator to reach the hysteresis values

4 ADVANCED INVERTER TEST-BEDS

There are many advantages to performing data-driving protocol development with multiple laboratories across the world. The range of testing equipment, data acquisition systems, and equipment under test ensure the testing protocols are grid and hardware agnostic and the procedure can be clarified if there are points of confusion. Further, by comparing results from multiple laboratories, discrepancies in results and data reporting indicate areas of refinement in the protocols.

4.1 SNL Distributed Energy Technologies Laboratory

Sandia National Laboratories, located in Albuquerque, New Mexico, performs experiments on DER at the Distributed Energy Technologies Laboratory (DETL) [39]. Sandia has configured the DETL residential 10-node test system to implement the SIRFN ESS advanced interoperability test protocol. An illustration of the testing setup is shown in Fig. 3. The test bed consists of a 200 kW PV simulator, a controllable 180 kVA grid simulator and the controller for interoperability tests on verity of inverters and DER. Sandia tested a 4.5 kVA Schneider Electric Conext XW+ 5548 NA connected to a 48 V nominal, 380 Ah lead acid battery system with specialized chemistry for microcycling. The EUT parameters were change through proprietary research software, XDT, through a USB-to-Xanbus Conext Combox gateway.

In addition to the test bed, the Energy Storage Test Pad (ESTP) located at the corner of the corner of the DETL facility is capable of testing 1 MW grid-tied ESS systems in cargo container form factors [40]. In July of 2014 the TransPower GridSaver, a 1MW rated lithium-ion battery based ESS, was installed at the ESTP for independent analysis. A range of experiments was performed on this EUT including capacity testing, response rate testing, and signal tracking accuracy testing [41].

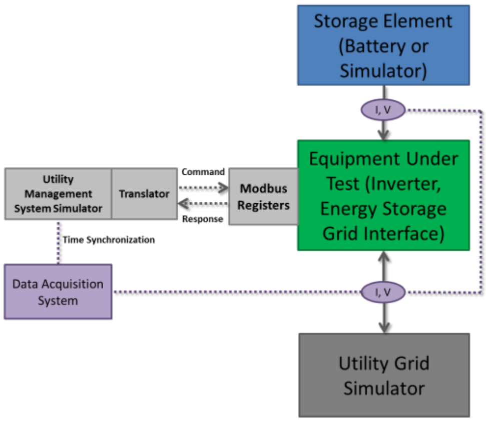

Figure 3: DETL Setup for Energy Storage Grid Support Testing

4.2 AIT SmartEST PV Inverter Test Lab

The Austrian Institute of Technology, located in Vienna Austria, performs experiments on DER at the Smart Electricity Systems and Technologies (SmartEST) PV inverter test laboratory [42], which consists of a certification and a research test bed. AIT configured the research test bed to implement the SIRFN ESS test protocol and run automated tests of the advanced interoperability functions. The tests at AIT were performed with two small-scale storage systems, designed for an increased self consumption and an increased degree of self-sufficiency in a household. The first system, used for Frequency/Watt and Request Active Power tests was a single phase DC-coupled Lithium-Ion storage system. This topology has the battery directly connected to the DC-Link of the PV-Inverter Unit. This system was configured by the manufacturer in that way that it shall be compliant to the Italian grid requirements (CEI-0-21:2014-12). Theoretically the Power Conversion System (PCS) of the ESS is able to charge from- and discharge energy into the public grid (bidirectional operation) For the Frequency/Watt function the bidirectional operation mode is not a mandatory requirement in the Italian grid code. The manufacturer did not implement this function at this time. Therefore Frequency/Watt tests were only possible at PV injection or battery discharge conditions into the public grid. Furthermore the device had no Voltage/Var function implemented because it is only required for ESS in Italy, with an output power, higher than 6 kW. The second system was a single-phase AC-coupled system, parametrized by the manufacturer to fulfill the German grid requirements. For the tests a Lead Acid battery was used. The maximum constant charge current was about 30 A (~1.5 kW) the maximum constant discharge current was about 50 A (~2.4 kW). For testing the Request Power Factor (INV3) function, the storage system was controlled over Modbus TCP/IP. Setting the power factor was only possible under discharging conditions, because of restrictions set by the applicable grid codes. An illustration of the testing setup for the AC-coupled system is shown in Fig. 4. The test bed consists of multi-string PV array simulators, a controllable 30 kVA grid simulator and a simulated utility SCADA system which allows interoperability tests on verity of inverters and DER.

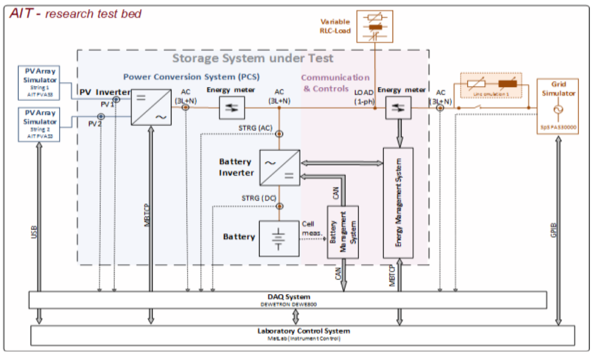

Figure 4: AIT Smart Electricity Systems and Technologies (SmartEST) Research Test Bed

4.3 RSE ESS Test Labs

Ricerca sul Sistema Energetico, located in Milan, Italy, performs experiments on DER in a number of laboratories including a battery laboratory, inverter laboratory, and DC and AC microgrid laboratories [43]. The RSE Inverter Test Laboratory consists of multi-string PV array simulators, a controllable grid simulator and a simulated utility SCADA system that allows interoperability tests on verity of inverters and DER. A second lab, used for testing larger systems up to 200 kVA, is an AC microgrid with different DER connected that allows also system testing at nominal and different frequency and voltage. An illustration of the testing setup is shown in Fig. 5.

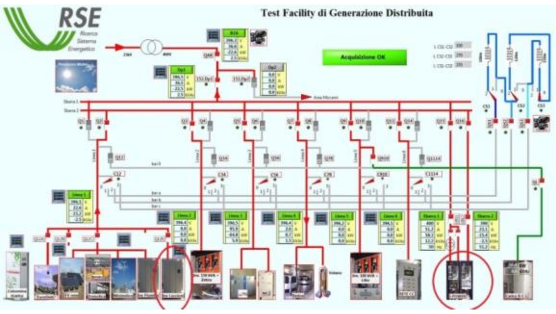

Figure 5: RSE DER Test Facility with grid simulator

The RSE tests were performed with a 30 kW, 32 kWh Li-Ion Battery ESS manufactured by Loccioni Group connected to a 200 kVA grid simulator capable of voltage adjustments in the range of 300-440 V and frequency control in the range 45-65 Hz. The ESS had no grid support functions implemented but the active and reactive power can be controlled independently. In order to test protocol functions, a software tool that incorporates automated test sequence management and grid support control functions was designed by RSE. The four protocol functions were implemented and additional ones could be easily designed for future testing activities. The RSE test set-up with this control structure is illustrated in Fig. 6.

Once the function control software was enabled, the test sequence was started and grid simulator was configured for the corresponding voltage or frequency setpoints. From electrical measurements at the ESS terminals, the software calculated the ESS active and reactive setpoints to emulate the advanced grid-support functions. Once that test conditions are stabilized, electrical data was acquired and recorded for the required time interval. All data communication to the ESS was performed with a Modbus TCP/IP connection. One drawback of the software control method was a slight increase in ESS settling time, but it is extensible to any system typology, grid-support function, and could be easily transferred to other test laboratories.

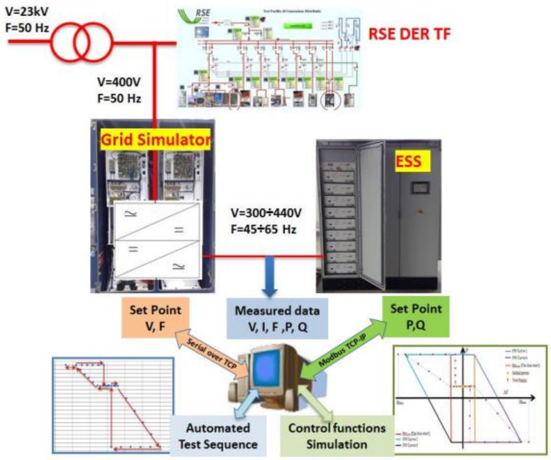

Figure 6: RSE Inverter Test Laboratory

4.4 FREA Smart DER Research Facility

The Fukushima Renewable Energy Institute, located in Fukushima, Japan, performs experiments on DER at their Smart DER Research Facility for testing of grid-connected inverters and energy storage systems [44]. FREA has configured the facility 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. 7. The facility consists of Bi-directional DC (PV and Storage) simulators, a controllable 500 kVA grid simulator (to be expanded to 5000kVA in 2016) and a simulated utility SCADA system which allows interoperability tests on verity of inverters and DER.

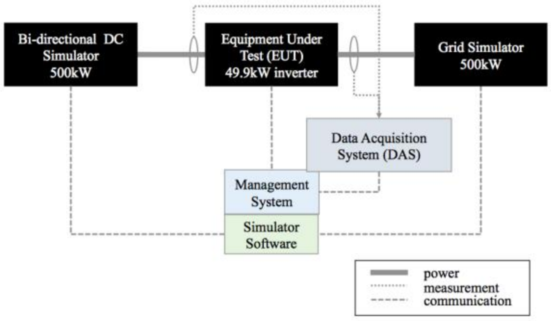

Figure 7: FREA Smart DER Research Facility

5 RESULTS

5.1 Frequency Watt (FW)

RSE and AIT performed experiments on the FW functionality of energy storage systems in their laboratories. Figure 8 shows an example course for this testing. Frequency starts at 1 p.u. and is adjusted down until the EUT increases its active power until reaching its rated power and the frequency reaches its lower limit. Frequency is then increased until the system returns to its nominal active power, either gradually or abruptly if hysteresis is active. This same process is then repeated for high frequency.

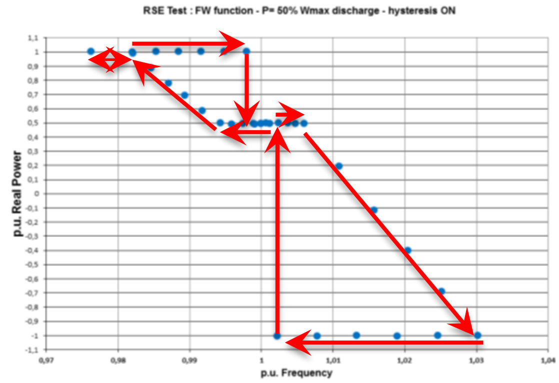

Figure 8: RSE test results for the Italian grid code FW curves without hysteresis

Figure 9 shows the data collected by RSE and AIT from these tests. During each test frequency was adjusted up and down and held to record the energy storage system's steady state response. All axes have been normalized to per-unit (p.u.) frequency and power for the local grid conditions of the lab and the energy storage system's rated power. RSE and AIT performed one of the tests in the protocol that matched the parameters in the Italian requirements. The primary difference in the results is because the ESS system at RSE allowed bi-directional flow and the AIT system was now permitted to charge from the grid. Five different initial power levels were set and the frequency-watt response was evaluated both with and without hysteresis, though only those results with hysteresis are presented here.

5.2 Request Active Power from Storage Test (ESS1)

All four laboratories performed experiments on the ESS1 functionality of energy storage systems in their laboratories. Figure 10 shows the data collected from RSE and Sandia. The vertical axis has been normalized to per-unit (p.u.) active power according to the energy storage system's rated power. Six tests were performed each starting from rest to full rated power charge, ½ rated power charge, ¼ rated power charge, ¼ rated power discharge, ½ rated power discharge, and full rated power discharge. RSE also performed the minimum and maximum ramp rate tests in accordance with the test procedure in Fig 11.

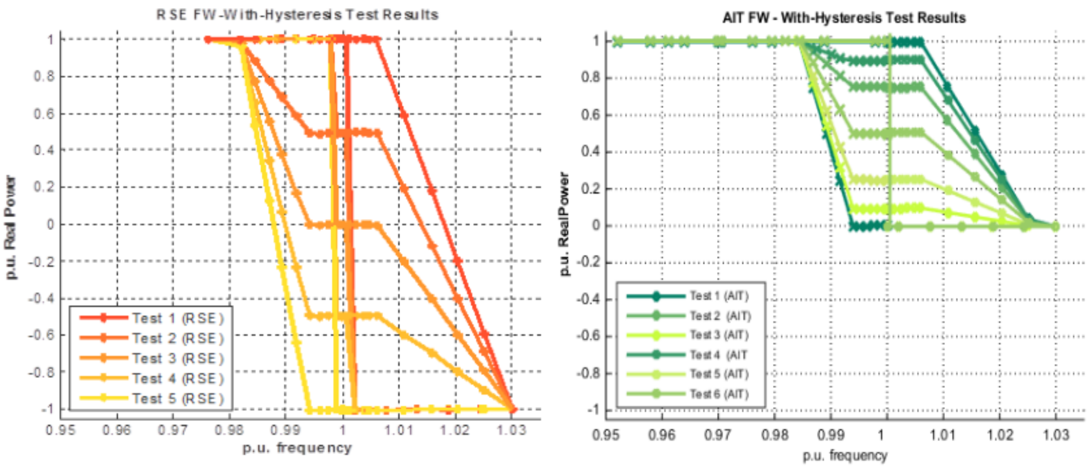

Figure 9: RSE and AIT Test Results for FW with hysteresis

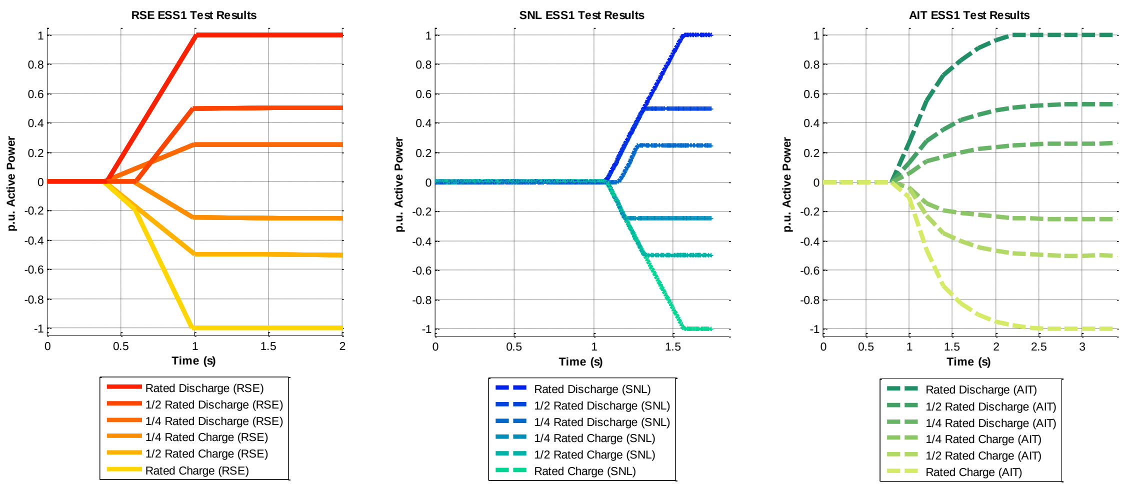

Figure 10: RSE, SANDIA, and AIT test results for ESS1 function

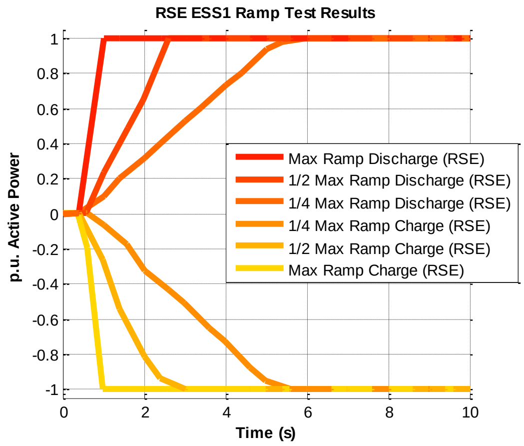

Figure 11: RSE test results for ESS1 function including different ramp rate

5.3 Volt-VAR "Q(V)" Test (VV)

RSE and FREA performed experiments on the VV functionality of an energy storage system in their laboratory. Figure 12 shows the data collected from a selected subset of RSE tests. The set points for Tests 1-3 are defined by the "set" curves, while the recorded data are shown as the "Measured" points. All three tests were performed at -1.0 p.u. active power charge (a), -0.5 p.u. active power charge (b), no. active power charge or discharge (c), 0.5 p.u. active power discharge (d), and 1.0 p.u. active power discharge (e). Presented here are the results of three profiles that were characterized at zero active power. Figure 13 shows the data collected from a selected subset of FREA tests. During each test, the grid voltage was adjusted through the voltage range of the EUT and held for 5 seconds before recording the ESS steady state response.

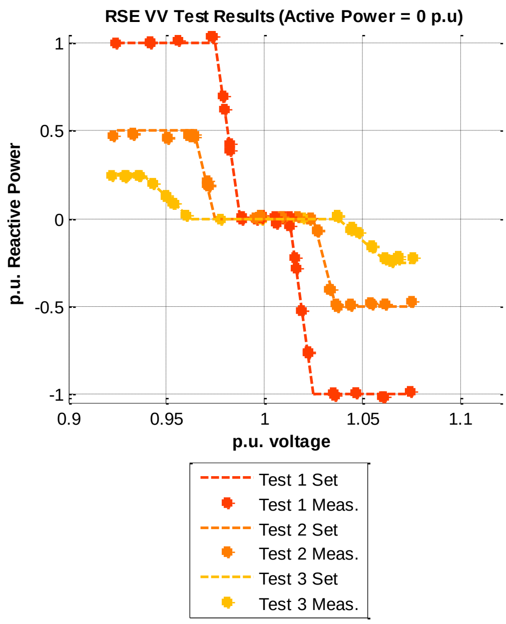

Figure 12: RSE test results for VV function (three test cases with no active power)

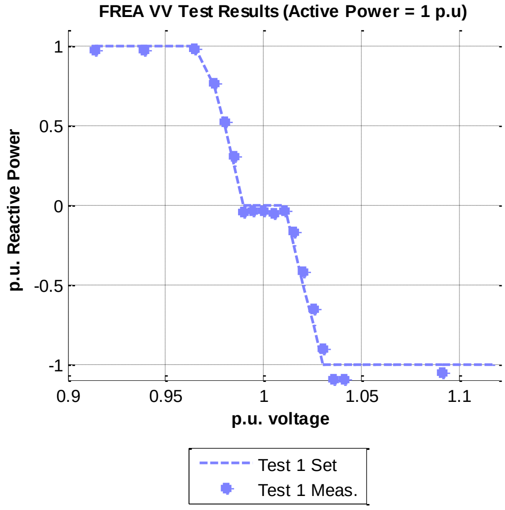

Figure 13: FREA test results for VV function (one test case at rated active power)

5.4 Commanded Power Factor Test (INV3)

RSE and FREA performed experiments on the INV3 functionality of energy storage systems in their laboratories. Figures 14 and 15 shows the data collected from these tests respectively to their originating labs. All axes have been normalized to per-unit (p.u.) active and reactive power according to the energy storage system rating. The apparent power limit is indicated by the nameplate capability. RSE performed 5 tests on their energy storage system: INV3 set to PF = 1.0, 0.2 underexcited, 0.6 underexcited, 0.2 overexcited and 0.6 overexcited. The excitation nomenclature [45] has been adopted to avoid confusion in reference frames when using leading/lagging or inductive/capacitive. During each test, the system was commanded to ten active power set points—five charging and five discharging levels from the grid. The dotted lines indicate the ideal curves given the commanded power factor. Note that this plotting method conceals overlapping points at -1 and 1 p.u. active power.

FREA's performed 9 tests on their energy storage system. As the EUT relied on input leading and lagging power factor these values are shown whereas the protocol prefers the use of terms overexcited and underexcited. Here too the dotted lines show the ideal curves given the setpoints entered. It can also be observed that the EUT is able to exceed its apparent power rating for the limited course of the test.

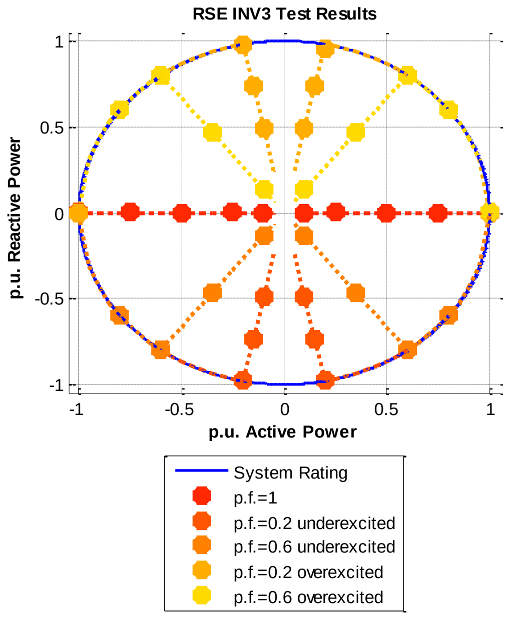

Figure 14: RSE test result for INV3 Function

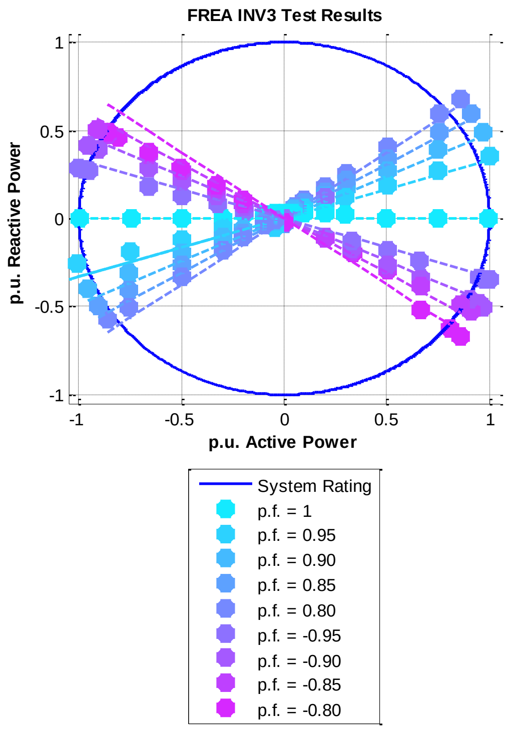

Figure 15: FREA test result for INV3 Function

6 DISCUSSION

The testing process and results presented here provided feedback to the protocol development process in terms of data collection consistency, clarity of the protocol, and other concerns. The most important factor when converting PV testing protocols to ESS protocol is the four quadrant capability (in particular active power bi-directionality); this implies that control functions defined for PV must be extended also to charge operations. Currently each national grid code or technical rule treats the functions differently related to the charge of the ESS (a typical example is FW function). So, as the procedure was developed, the different technical rules were considered such that a harmonized test protocol was generated.

Another important difference when converting PV testing protocols to ESS protocols is the energy-limited nature of energy storage system. While PV inverters can be tested to steady state input conditions, the initial condition of the energy storage element undergoing the test is a big concern. A balance must be struck between the importance of self-limiting functionality to protect system components and the standardization of tests to validate functionality. It was decided to separate the grid-support function tests from any self-limiting effects at the SOC limits. The low-level controls that protect the ESS will override grid support functions so these effects were intentionally avoided. For this reason, the each experiment is performed at an initial SOC which allows the systems to complete testing without encountering its energy limits.

Many specific lessons were learned from the use of draft procedures to produce the results in Section 5. For example, the original draft procedure for FW verification called for the collection of five data points on each line segment (see Figure 2). After applying the protocol it became clear that steady-state data cannot be collected on the vertical line segments when there is no recovery ramp when releasing from the hysteresis latch. This observation identified that additional clarification was needed in the protocol to ensure that consistent data would be collected. The most recent version now states that “energy storage system power should be recorded at each frequency defined by the test curve and at five intermediate frequencies during each frequency transition.” This change is indicative of the iterative protocol writing process described in Section 3.

While performing the INV3 tests, the laboratories noted inconsistency in terminology defining excitation and have corrected this issue by standardizing around the use of ‘overexcited’ and ‘underexcited’. A number of other issues regarding parameters, specific steps in the test procedure, and the test matrices were also corrected. As an example, in the ESS1 function, the power level was held for 2 times the timing parameters, but in cases where these timing parameters are zero, the test would have no duration specified. This has been corrected by adding 5 seconds to the equation.

7 CONCLUSION

To encourage sustained, smooth deployment of PV 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 Energy Storage Systems (ESS) as an extension of IEC TR 61850-90-7. Sandia, AIT, RSE, and FREA are working to develop the SIRFN ESS protocol for grid support functionality through an iterative process. First, the team reviewed the field of grid codes and grid support use cases. Then draft language was developed to meet the following criteria: inclusiveness and modularity, precision and standardization of results, and simplicity/ease of use. Each lab then used the daft protocol to collect data on ESS hardware. The process of obtaining the results (presented here) provided valuable feedback to improve the protocols. Through this iterative process, the protocols will be expanded and refined, with the hope that national and international standards organizations will adopt this harmonized ESS interoperability test protocol.

The results collected from this iteration of the protocol development process produced draft language for four grid-support functions: FW, VV, ESS1, and INV3. These functions require different procedures to validate from those used in PV inverters because they are four-quadrant devices and have different operating requirements, e.g., permission to charge from the grid, state of charge limitations, etc. SIRFN laboratories have performed validation testing for these functions on ESS. Feedback from these tests has improved the protocols and has provided an illustrative example of data-driving standards development processes. Work is ongoing to develop and refine common test protocols for additional grid-support functions.

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