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Smart Inverter Functionality Testing for Battery Energy Storage Systems

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Abstract

Variable distributed energy resources (DERs) such as photovoltaic (PV) systems and wind power systems require additional power resources to control the balance between supply and demand. Battery energy storage systems (BESSs) are one such possible resource for providing grid stability. It has been proposed that decentralized BESSs could help support microgrids (MGs) with intelligent control when advanced functionalities are implemented with variable DERs. One key challenge is developing and testing smart inverter controls for DERs. This paper presents a standardized method to test the interoperability and functionality of BESSs. First, a survey of grid-support standards prevalent in several countries was conducted. Then, the following four interoperability functions defined in IEC TR 61850-90-7 were tested: the specified active power from storage test (INV4), the var-priority Volt/VAR test (VV) and the specified power factor test (INV3) and frequency-watt control (FW). This study then outlines the remaining technical issues related to basic BESS smart inverter test protocols.

Keywords

Battery Energy Storage Systems, Distributed Energy Resources, Smart Inverter Controls, Grid-Support Standards, Test Protocols, Interoperability

1. Introduction

Microgrids composed of distributed power from fluctuating renewable energy, such as photovoltaic (PV) system and wind power generation system, have raised concerns about the quality of the power that they produce owing to factors such as frequency and voltage fluctuations. Therefore, grid support functions that help guarantee a reliable supply of distributed power are in demand

[1] [2] [3] [4]. A wide variety of studies are being conducted in many countries on the introduction of grid support functions for PV inverters [2] [5]-[18]. In Japan, the implementation of some of these functions, such as fault ride throughs (FRTs) and output curtailment control functions, is making headway, but other functions standardization efforts have typically faced delays. Because there is little agreement on influence for the mature existing power grid system. However, battery energy storage systems (BESSs) are expected to serve as regulated power supplies that mitigate fluctuations in renewable energy power sources [19] [20]. Demonstrations of large-scale BESSs being installed to serve this purpose are increasing around the world. The functional requirements for the next-generation DERs, particularly with regard to their control protocols, are defined in IEC 61850-90-7 [21]. However, the requirements of grid connection regulations differ from one country to another, as do the testing methods and grid support function installation conditions. Therefore, unified international standards of the grid connection have not existed yet.

Japan's National Institute of Advanced Industrial Science and Technology (AIST) has joined the International Energy Agency's Implementing Smart Grid Action Network's (IEA-ISGAN)*1 affiliated Smart Grid International Research Facility Network (SIRFN)*2. Together with the network's main members, these organizations are developing testing methods for next-generation inverters (smart/advanced inverters) that conform to international standards. SIRFN is an international network of smart grid research facilities with 15 participating countries. It consists of four subgroups [22]:

- Smart Grid Distribution Automation
- Advanced Laboratory Testing Methods
- Power System Testing
- Test Protocols for Advanced Inverter Functions

The AIST takes part in planning the activities of the Test Protocols for Advanced Inverter Functions subgroup; it develops and verifies interoperable testing standards based on international compliance and consensus for next-generation distributed energy resources (DERs) using smart inverters. The goal is to move toward the development of international standards and certifications based on the testing methods developed here [23]. The initial results of these efforts have been posted on the ISGAN homepage [24].

This study will introduce the AIST's work regarding smart inverters stemming from SIRFN activities. It will also report on tests and testing results regarding the functions that allow battery smart inverters to support microgrid power quality (re: voltage & frequency control).

※1 *ISGAN* (*the International Smart Grid Action Network*) *is an IEA implementation agreement framework* and *aims to improve the understanding of smart grid technologies, practices, and systems and to promote adoption of related enabling government policies.*

※2 *SIRFN*: *Smart Grid Research Facility Network.*

2. Global Trends for Smart Inverters

BESSs have so far focused on smoothing fluctuations and shifting peaks in renewable energy. Some discussions have ensued regarding grid stabilization functions (advanced functions) such as voltage and frequency support functions [3] [15] [16] [17] [18] [25] [26] [27] and grid protection functionality.

In the U.S., various research institutions have performed comparative studies [25] based on reports from Sandia National Laboratories (SNL), a U.S. institution that has gathered testing methods for PV inverter grid support functions. Based on this data, the state of California in 2015 issued grid connection regulations (via CA Rule 21) covering some grid support functions [28] [29] [30]. The U.S. is also performing a full revision [31] of its DER grid connection regulations (IEEE 1547 and IEEE 1547.1). On September 7, 2016, the UL issued product safety standard UL 1741 SA [32], which covered inverter grid support testing methods. In conjunction, California required compliance with UL 1741 SA within one year from its issuance.

In Europe, the implementation of grid support functions began at an early stage. The status of smart inverter grid support functions is shown in **Table 1** and **Table 2** [4] [31]. With regard to low voltage (LV), Germany, Denmark, Italy, and Austria have been mandating grid support functions such as reactive power/power factor control and frequency control, FRTs, and active power control since 2012 (although reactor power control is not required in Denmark). As for medium voltage (MV), the same functions required by LV have been mandated since about 2008 in Germany, France, Italy, Austria, and Denmark. In addition, Spain, Portugal, England, the Czech Republic, Belgium, and other European countries have mandated some of these functions.

In Japan, the Fukushima Renewable Energy Institute, AIST (FREA) established two facilities related to smart grids and is pursuing research, development and standardization on smart inverters and other projects. FREA boasts a facility

Table 1. Grid support function requirements (LV), X: available, P: partial available.

Country	Germany	Italy	Austria	France	Spain	Europe (≤16 A)	Europe (>16 A)	U.S.	Japan
Function	2011	2012	2013	2013	2011/2014	2013	2014	(2018)	
Q control	X	X	X		N/A	X	X	X	N/A
PF control		X	P		N/A	X	X	X	N/A
Frequency control	X	X	X	X	N/A	X	X	X	N/A
Remote output control	X	X	X		N/A		X	X	P
LVRT		X			N/A		X	X	X
HVRT		X			N/A		X	X	N/A
Ref.	FGW TR3/VDE ARN4105	CEI 0-21	TOR D4	ERDF-NOI-RES_13E	RD1699/UNE206007-1	EN 50438	CLC/TS 50549-1	EEE1547Full revision	JEAC 9701

Table 2. Grid support function requirements (MV), X: available, P: partial available.

Country	Germany	Italy	Austria	France	Spain	EU	ENTSO-E	U.S.
Function	2008	2012	2013	2013	2010	2014	2013	(2018)
Q control	X	X	X	P		X	X	X
PF control	P	X	P	X	P	X	X	X
Frequency control	X	X	X			X	X	X
Remote output control	X	X	X		P	X	X	X
LVRT	X	X	X	P	P	X	X	X
HVRT		X				X	X	X
Ref.	FGW TR3/VDE ARN4120	CEI 0-16	TOR D4	DEVE 0808815A	P.O.12.3/P.O.12.2	CLC/TS 50549-2		IEEE1547Full revision

known as the DER System Lab. This lab features a 500 kVa simulated grid power source with a 300 kVa simulated load, a 600 kVA simulated DC source, and a 200 kVA simulated battery power source, rendering the facility capable of conducting a variety of DER system tests. The DER system testing platform at FREA is capable of conducting more complex tests through linking a combination of PV-battery system with a hydrogen mixed-combustion diesel engine generator. Furthermore, a new smart system research building opened at FREA in April 2016 (hereafter called FREA-G) and has approximately 10 times the testing facilities and equipment of the DER System Lab, with a 5 MVA simulated grid power source, a 3 MVA simulated load, and a 3 MVA simulated DC source. It also boasts a smart system testing platform capable of testing large-scale powered electronics devices. FREA-G is a world-class facility and is capable of using large-scale chambers to perform environmental testing and EMC testing, including grid connection tests.

These testing and development environments promote the continued research and development of microgrid technology aimed at putting distributed power and microgrid technology to use, to support ICT integration and the "smartification" of electric devices, with a focus on smart inverters. The goal is to build a smart system research platform that responds to various needs of research and development as well as certification.

3. Smart Inverter Function Testing

The SIRFN advanced inverter function test protocol subgroup is working together with Western research institutions (SNL in the US, AIT in Austria, and RES in Italy) to develop testing methods that are consistent across international borders for control protocols for PV inverter and battery inverter grid support functions. Here, the goal is to comply with the various standards of the US, Austria, and Italy and to apply these methods to inverter control for the PV systems and battery energy storage systems in each country. At the same time, control protocol interoperability between research facilities will be verified, and reviews will be conducted of the inverter function testing methods used in each country.

In this section, the conditions used in the new analyses of battery inverter grid support functions will be explained. The testing methods are inspected to ensure that they are comprehensive, consistent, and as uniform as possible. These requirements are based on the technical requirements and grid connection regulations relating to grid support functions that are required for each country's distributed power sources in the present or that will be required in the future.

The items performed in these tests are the four items taken from the testing method plan formulated by SIRFN (hereafter, the SIRFN draft):

1) Specified power factor control (INV3)
2) Specified active power control (INV4)
3) Voltage/reactive power control (VV)
4) Frequency/active power control (FW)

4. Smart Inverter Testing Method Inspection Results

The configuration of the DER system testing room used in these battery smart inverter tests is depicted in **Figure 1**. Each power source and measurement instrument (DAS) is semi-automatically controlled as testing is conducted. The target test items must presume an extremely wide range of cases. Moving forward, there will be a need for complete automation using a testing platform such as Sunspec. Furthermore, the smart inverter testing unit (equipment under test, or EUT) was made at a SanRex machinery factory (a special-order remodeled product) with a rated value of 49.9 kW; external control was performed using special software from SanRex. In all testing, measurements were taken at a sampling rate of 50 milliseconds.

4.1. Specified Power Factor Control (INV3)

The IEC 61850-90-7 and CA Rule 21/UL 1741 SA standards were assumed for INV3 testing. However, while IEC 61850-90-7 defines timing parameters (ramp rate, time window, timeout, etc.), UL 1741 SA does not. Furthermore, the equipment under test (EUT) does not support power factor/active power priority modes. Consequently, discussion on these modes as well as timing parameters are out of scope of this work. The battery State of Charge (SOC) at the time of testing did not impact the INV3 test results, so in cases where the SOC fell close to the upper or lower limits, BESS were charged and/or discharged to bring SOC to a value in the midrange.

The test conditions took into account the capacity of Li-ion batteries and used active power at 15 different output levels (−80%, −75%, −50%, −30%, −20%, −10%, −5%, 0%, 5%, 10%, 20%, 30%, 50%, 75%, and 100%) with five specified power factors (PFs): −0.8, −0.9, 1, 0.9, and 0.8. Positive values of active power were defined as electrical discharges; negative values were defined as electrical charges. Positive values of reactive power were deemed delay compensations.

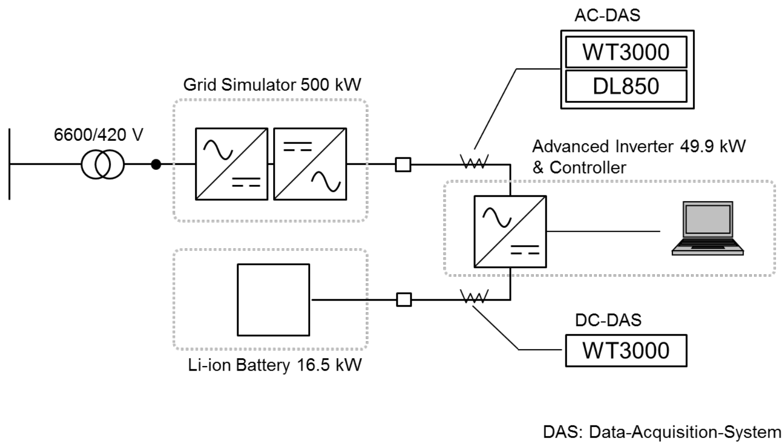

Figure 1. FREA testing facility (DER system lab) structure.

Figure 2 provides the results of the INV3 test. The specified reactive power at each specified PF is represented by a solid line. The solid circle represents the EUT's installed capacity; the dotted circle represents the EUT's upper limit. UL 1741 SA requires that there are four power factor conditions and three active power conditions (at the minimum output or 20%, at 33% to 60%, and at 100%). However, there were cases during this test where the test unit could not be tested at its rated values (100%) owing to the battery rating. In these cases, it was necessary to relax the active power conditions as well as the testing methods using simulated battery power. In addition, the relationship between the active power output levels and the reactive power is not necessarily linear; therefore, it is necessary in some cases to test multiple output levels. Caution must be taken here, however, as this leads to an increase in required testing hours.

4.2. Specified Active Power Control (INV4)

The IEC 61850-90-7 and CEI 0-21/CEI 0-16 standards were assumed for INV4 testing. The SOC during testing was the same as INV3 testing. SIRFN draft testing conditions specify that tests are to be performed with active power from the maximum charge output to the maximum discharge at 5% intervals, and for reactive power to decrease from 100% to 20%, then increase from 20% to 100% at 20% intervals. Owing to the limitations of the test unit, however, active power was limited to a maximum of 80% in both output and discharge; reactive power ranged from 100% to 80%, then 80% to 100%. As for timing parameters, only ramp time was inspected.

The testing results reviewed the following test items:

1) Reduction in active power/reactive power requirements

2) Definition of timing parameters

3) Inspection methods for timing parameters

Clear differences of different active power level were not confirmed in the test unit. In addition, as the range of reactive power is specified, the impact of reactive power on active power is limited. Therefore, it is possible to decrease the

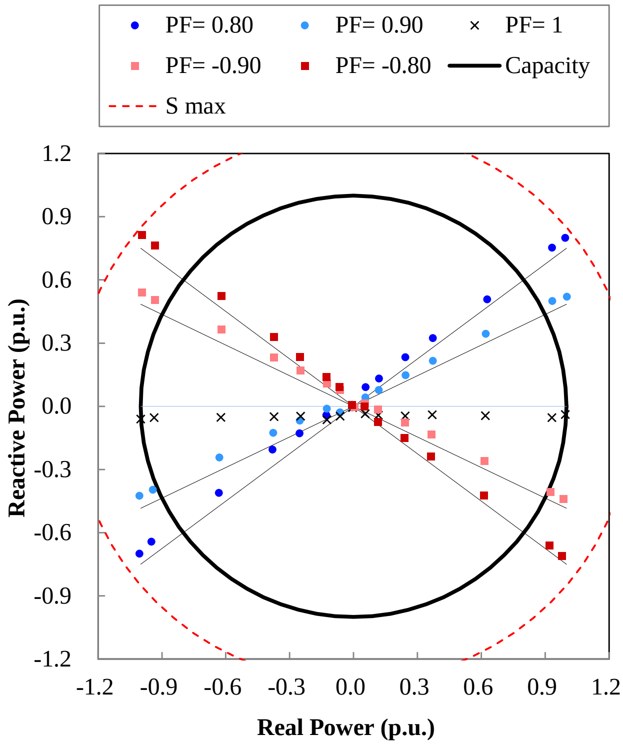

Figure 2. Specified power factor control (INV3) testing result example.

range of active-power conditions to three values each for charge and discharge as with the INV3 tests, and the range of reactive power to a single set level. In this fashion, measurement time may be decreased as well.

While the timing parameter in the SIRFN draft was defined as ramp time (s), the test unit required the ramp rate (%s). It was therefore necessary to change the testing conditions. In the cases where the ramp rate was converted to ramp time, the values differed according to the active power in the test conditions, which complicated matters. In addition, the definitions of timing parameters differ depending on the testing standards. It would therefore be desirable to establish uniform definitions or a conversion table for support. Moreover, when timing parameter tests are conducted, a measurement environment boasting a trigger method and an index to evaluate the ramp rate or ramp time is required. Timing parameter testing reaffirmed the importance not only of the testing methods but also of common sense in the design of testing standards.

4.3. Voltage/Reactive Power Control (Voltage/Variance, VV12)

IEC 61850-90-7, CEI 0-21/CEI 0-16, VDE-AR-N 4105/ FGW-TR3, CLC/TS 50549, UL1741 SA, and Austria's OVE/ONORM EN50438 standards are assumed for voltage/variance testing. The SOC during testing was the same as INV3.

Testing conditions (Volt-Var curves) vary according to the regulations of each country. The SIRFN draft testing requirements comprehensively specify these conditions, but the test conditions for a sample case are provided here in Table 3. The requirement for active power is 80% (discharge).

Figure 3 shows the configuration values as a solid line; the measured values are shown as X marks. Actual UL certification requires testing voltage/variance under several conditions (e.g., differing active power and reactive power, priority modes, and timing parameters). Conducting these tests manually requires an enormous amount of time. Therefore, automation of testing and adjustments to test conditions and points of measurement, etc., becomes necessary. During this test, the points of measurement used were reviewed. Under test conditions where the reactive power was fixed (e.g., between sets 1 - 2, sets 3 - 4, and sets 5 - 6), it is considered possible to perform sufficient testing with several measurement points. However, in test conditions where the reactive power changes (e.g., between sets 2 - 3), it is necessary to have from three to five measurement points. In addition, for single-point measurements, voltage conditions are represented by the average value maintained over a 5-s period. It is also desirable to perform measurements at each set point.

4.4. Frequency/Active Power Control (FW)

IEC 61850-90-7, CEI 0-21/CEI 0-16, VDE-AR-N 4105, CLC/TS 50549, UL1741 SA, and EN50438 are taken as basis for FW testing. The SOC during testing was the same as INV3.

FW testing conditions are extremely complex, as regulations (e.g., tie-line conditions, hysteresis, and timing parameters) differ from one country to another. The SIRFN draft testing requirements comprehensively detail testing conditions. In the sample case offered here, there were three initial values for active power (0%, −40%, and 40%), no reactive power, hysteresis present, and all other conditions absent (no ramp rate, no recovery ramp rate, no time delay, no recovery time delay, and no tie lines).

Figures 4-6 show the results of FW testing. In Table 4, the configuration values are shown as solid lines; the measured values are shown as dot marks. Just as with the voltage/variance tests, it is required to conduct tests over multiple varying conditions (e.g., differing active power and reactive power, joint tests with

Table 3. Voltage/reactive power control (Volt/VAR) testing conditions.

Set Point	Curve 1	Curve 2
(p.u.)	(V, Q)	(V, Q)
Set 1	(0.88, 0.5)	(0.88, 0.125)
Set 2	(0.97, 0.5)	(0.97, 0.125)
Set 3	(0.99, 0)	(0.99, 0)
Set 4	(1.01, 0)	(1.01, 0)
Set 5	(1.03, −0.5)	(1.03, −0.125)
Set 6	(1.12, −0.5)	(1.12, −0.125)

Table 4. Frequency/Watt (FW) testing conditions.

Set Point	Curve
(p.u.)	(F, P)
Set 1	(50.0, 80%)
Set 2	(50.3, 80%)
Set 3	(50.97, 0%)
Set 4	(51.49, −80%)
Set 5	(49.25, −80%)
Set 6	(48.38, 0%)
Set 7	(47.51, 80%)
Set 8	(49.5, 80%)

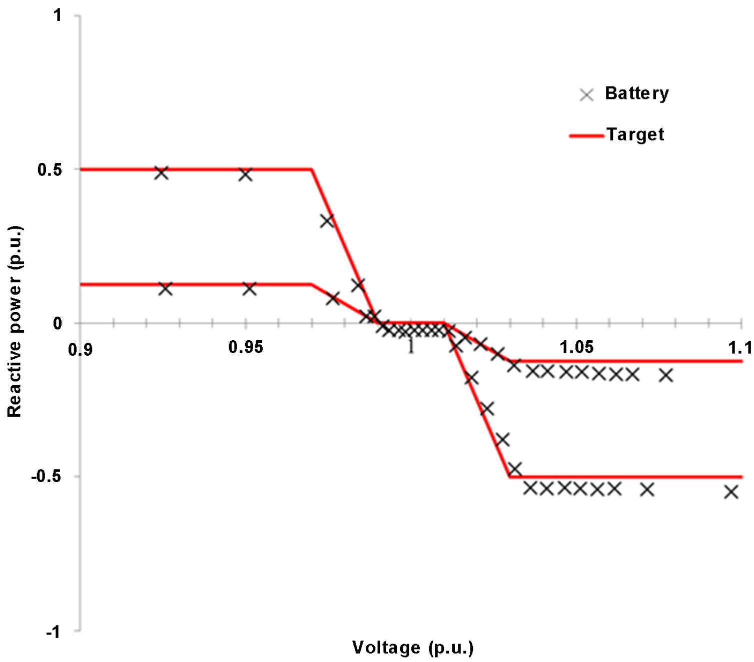

Figure 3. Specified power factor control (INV3) testing result example.

other grid support functions, and differing timing parameters). Conducting these tests manually requires an enormous amount of time. Therefore, automation of testing and adjustments to test conditions and points of measurement, etc., becomes necessary. During this test, the points of measurement used were reviewed. In test conditions where active power is fixed, it is considered possible to conduct sufficient testing with even three to five measurement points. In all conditions shown in Figure 5 and Figure 6, the measurement results for active power were stable compared to those of reactive power. However, at set points, junctions develop where active power is controlled; this makes clear measurements difficult. While this is outside the scope of this paper, further discussion regarding the number of measurement points and the measurement conditions

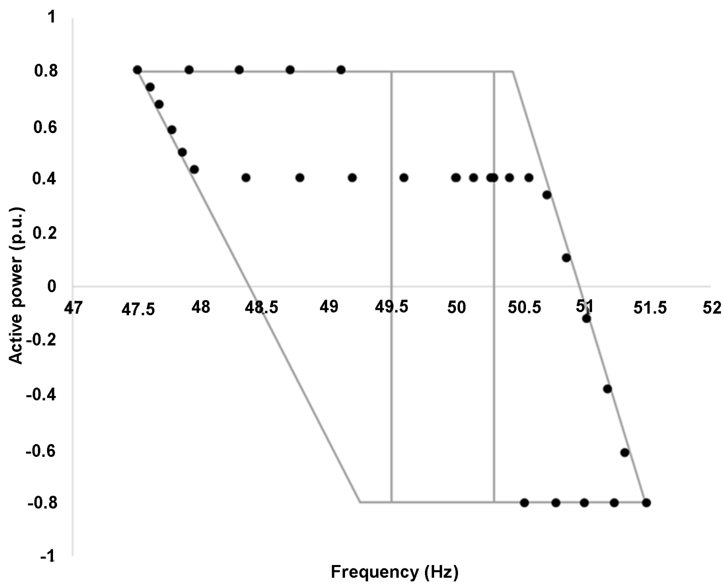

Figure 4. Frequency/Watt (FW) testing results (active power 40%).

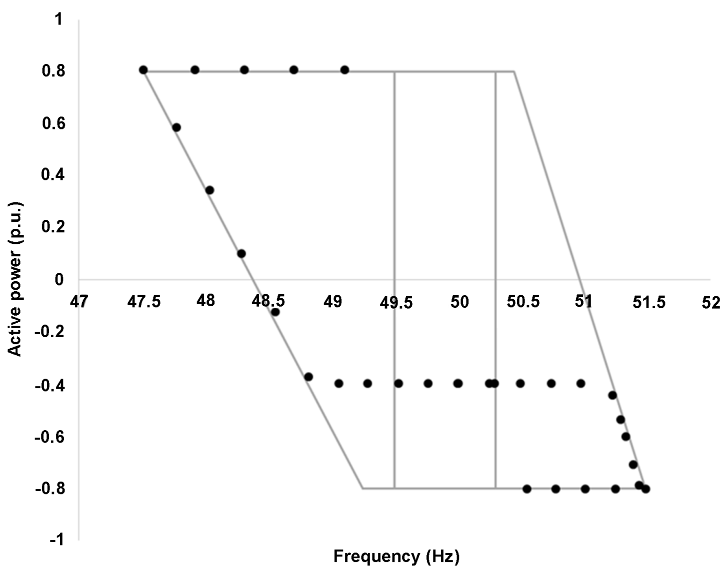

Figure 5. Frequency/Watt (FW) testing results (active power—40%).

may be required in situations where tests are conducted that include tie-line conditions and timing parameters. In addition, for single-point measurements, voltage conditions are represented by the average value maintained over a 5-s interval.

5. Conclusions

Four research institutions (SNL in the US, AIT in Austria, RES in Italy, and AIST in Japan) affiliated with the Smart Grid International Research Facility Network (SIRFN) jointly assembled battery smart inverter control protocols and an interoperability validation testing method draft based on the IEC TR61850-90-7 standard and conforming to the grid connection regulations of

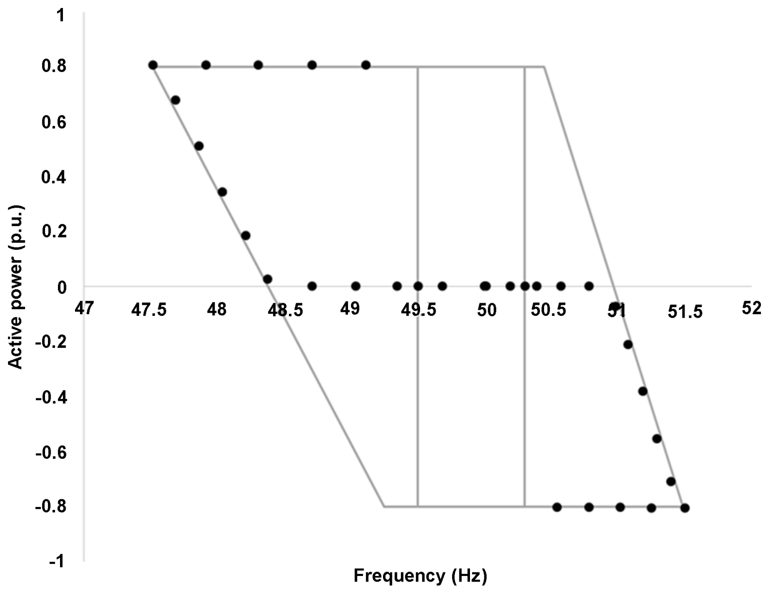

Figure 6. Frequency/Watt (FW) test results (active power 0%).

various countries. Based on the specified testing method, four grid support function tests (INV3, INV4, VV12, and FW) were conducted, and reviews were performed on the validity of the ensuing test results and the challenges posed. As a result of these efforts, valuable experience is acquired regarding standardized testing of the battery systems. Lessons learned from these endeavors can help next tests be conducted in a more efficient fashion. Furthermore, practical challenges encountered in the actual testing can be utilized to enhance design of testing facilities. In this respect, the work presented in this paper holds significant value towards creating a framework for standard testing of Smart Inverters and the practical consideration related to it.

A battery smart inverter with battery from SanRex was used as the test unit in all functions, but it was confirmed that it did not fulfill its intended purpose owing to cognition errors in the implementation methods. A reappraisal that includes revisions of the testing method draft will be required in the future. Through these tests, results were obtained that indicated the minimum number of measurement points required for verifying function validity. In all tests, a large number of measurement points were collected and the complete automation of testing was important. However, because of this, it was also confirmed that coordination and adjustments before measurements are also important.

In the future, testing will be required of timing parameters such as ramp rates and delay times that are important to control functions. However, as the definitions in each set of regulations regarding timing parameters differ, a decision on standardized definitions will be crucial. It will also be necessary to examine testing methods for functions not included in the current draft such as output control functions (VW) from voltage fluctuations based on the standard e.g. UL 1741 SA.

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