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ANNEX 5

SIRFN Draft Test Protocols for Advanced Battery Energy Storage System Interoperability Functions

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ISGAN Annex #5

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Disclaimer

Preface

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, with proper design and control, 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, supplying ancillary services such as voltage or frequency regulation.

New energy storage targets in Europe and California, energy storage regulations, 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, peak-shifting, and voltage support, while commercial and residential-scale systems are financially viable 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.

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)[1], 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." Widespread adoption of these functions could allow energy storage to remove some of the barriers to high penetration PV and wind power.

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 their product's 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 be used to 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.

[1] EPIA Policy and Communications Working Group: Position Paper on Self Consumption of PV Electricity, July 2013.

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 renewable energy sources. To accomplish this goal, the proposed SIRFN BESS protocol is inclusive of many technical rules and grid codes while being detailed enough for uniform results across laboratories, countries, and even, continents.

Acknowledgments

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 collaborated to integrate DERs into the electricity grid to accelerate the integration of higher penetrations of PV and other renewable energy resources.

RSE research was financed by the Research Fund for the Italian Electrical System under the Contract Agreement between RSE S.p.A. and the Ministry of Economic Development-General Directorate for Nuclear Energy, Renewable Energy and Energy Efficiency in compliance with the Decree of March 8, 2006.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. This work was funded by the US Department of Energy Office of Electricity and Office of International Affairs.

The participation of AIT within ISGAN-SIRFN is funded in the frame of the IEA Research Cooperation program by the Austrian Ministry for Transport, Innovation and Technology under contract no. FFG 839566.

AIST participation was supported by Japan Ministry of Economy, Trade and Industry (METI). National Institute of Advanced Industrial Science and Technology (AIST) established the Fukushima Renewable Energy Institute.

Abstract

In this report, SIRFN laboratories (Sandia, AIT, RSE and FREA) establish a harmonized Battery Energy Storage System (BESS) evaluation/certification protocol for advanced energy storage functions. The authors present this standardized protocol as an adoption or revision option for jurisdictions when creating or modifying certification testing requirements. To complete this process, each laboratory shared information on national, international, and jurisdictional grid codes and standards for BESS. Based on these requirements, and BESS testing and certification literature, a broad list of interoperability functions, use cases, storage capabilities, and requirements were compiled. This list was then consolidated to a unique set of BESS functions for inclusion in the certification procedure. Draft certification protocols for five initial functions were created by the SIRFN group in order to harmonize the international effort to establish a unified set of procedures for interoperability testing of BESS.

Executive Summary

Looking to the future, stakeholders are working on standards to make it possible to manage the potentially complex interactions between DER and the power system. The interconnection of DER to the grid is subject to performance and safety requirements that vary significantly between jurisdictions. Fulfilment of some of these requirements often requires that DER capabilities be certified by an independent testing entity. These codes and certification requirements are in a state of evolution worldwide, and the trend is toward expanding grid support features. To continue, this trend requires greater interoperability between DER and utility energy management systems.

The international standard IEC TR 61850-90-7[2], one example of a DER interoperability standard, was updated in February 2013 to incorporate advanced DER grid support functionality. All countries and jurisdictions do not necessarily conform to IEC TR 61850-90-7; and many regions do not have a defined certification procedure to validate the functionality of DER or energy storage devices. As a result, DER vendors must still create different versions of their software to be compliant with regional requirements. This adds cost and complexity to the design and certification processes. It also generates disparate testing methods as there is no common set of parameters that can be communicated to the DERs. If a single set of parameters was created that accounted for most or all the jurisdictional variations (e.g., a superset of the grid codes), a single procedure could validate all grid code requirements. The development of such as procedure is challenging because there are a large number of grid codes and technical rules—each with variations in the function definitions.

To address this challenge, the 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)—collaborated to create a concise set of test protocols for evaluating the Battery Energy Storage System (BESS)[3] interoperability and functionality. The approach taken by the SIRFN group was to create a test procedure which covers a superset of grid codes parameters, depicted in Figure 0-1. If a DER is to be tested to a regional grid code any superfluous parameters can be omitted. Similarly, if a DER is to be tested to many different regional grid codes redundant parameters can be omitted. Both of these cases result in more efficient and less costly certification and hence the potential

[2] IEC Technical Report IEC-61850-90-7 — Communication networks and systems for power utility automation – Part 90-7: Object models for power converters in distributed energy resources (DER) systems Edition 1.0 (Feb 2013).

[3] Note that this test protocol is primarily designed for inverter-based DERs, so not all ESSs may be tested with this protocol (e.g., pumped hydropower).

for a reduction in the overall cost of DER. This report includes interoperability test procedures for BESS beyond the original DER protocols created for IEC 61850-90-7 DER functions in the Sandia Interoperability Test Protocols[4,5]. This document will be expanded in the future to include additional functions.

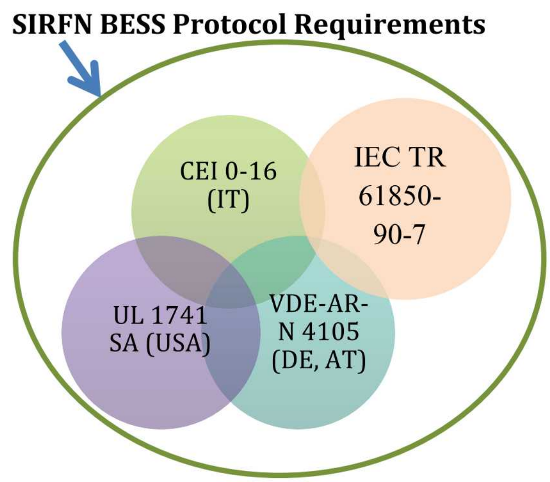

Figure 0-1: Visualization of integration method for SIRFN BESS Protocol.

The development of an inclusive set of tests for grid support functionality has the potential to open markets for energy storage providers. Harmonization and standardization of these advanced function tests would bolster the international market for energy storage systems and enable higher penetrations of renewable power. To accomplish this goal, the proposed SIRFN BESS protocol is inclusive of many technical rules and grid codes while being detailed enough for uniform results across laboratories, countries, and even, continents.

This protocol was developed so the testing parameters and procedures for all functions were effective and portable. 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. Initial

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[4] J. Johnson S. Gonzalez, M.E. Ralph, A. Ellis, and R. Broderick, "Test Protocols for Advanced Inverter Interoperability Functions – Main Document," Sandia Technical Report SAND2013- 9880, Nov. 2013.

[5] J. Johnson S. Gonzalez, M.E. Ralph, A. Ellis, and R. Broderick, "Test Protocols for Advanced Inverter Interoperability Functions – Appendices," Sandia Technical Report SAND2013-9875, Nov. 2013.

experimental results were presented at the 2015 European Photovoltaic Solar Energy Conference[6].

[6] D. Rosewater, J. Johnson, M. Verga, R. Lazzari, C. Messner, R. Bründlinger, K. Johannes, J. Hashimoto, K. Otani, International development of energy storage interoperability test protocols for renewable energy integration, EU PVSEC, Hamburg, Germany, 14-18 Sept, 2015.

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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[7,8], with proper design and control[9], 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[10,11,12], provide ancillary services[13,14], and be used for wide-area damping[15].

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

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[7] J. von Appen, M. Braun, T. Stetz, K. Diwold, D. Geibel, "Time in the Sun: The Challenge of High PV Penetration in the German Electric Grid," IEEE Power and Energy Magazine, vol.11, no.2, pp.55-64, March-April 2013.

[8] J. C. Boemer, et al "Overview of German Grid Issues and Retrofit of Photovoltaic Power Plants in Germany for the Prevention of Frequency Stability Problems in Abnormal System Conditions of the ENTSO-E Region Continental Europe," 1st international workshop on integration of solar power into power systems, Denmark, October 2011.

[9] R. Lazzari, et al "Enabling a flexible exchange of energy of a photovoltaic plant with the grid by means of a controlled storage system", International Journal of Control, vol. 88, no. 7, pp. 1353-1365, 2015

[10] J.W. Smith, W. Sunderman, R. Dugan, B. Seal, "Smart inverter volt/var control functions for high penetration of PV on distribution systems," Power Systems Conference and Exposition (PSCE), 2011 IEEE/PES , vol., no., pp.1,6, 20-23 March 2011.

[11] J. Seuss, M.J. Reno, R.J. Broderick, R.G. Harley, "Evaluation of reactive power control capabilities of residential PV in an unbalanced distribution feeder," 2014 IEEE 40th Photovoltaic Specialist Conference (PVSC), pp. 2094-2099, 8-13 June 2014.

[12] C. Winter, R. Schwalbe, M. Heidl, W. Pruggler, "Harnessing PV inverter controls for increased hosting capacities of smart low voltage grids: Recent results from Austrian research and demonstration projects." 4th International Workshop on Integration of Solar Power into Power Systems, Berlin, Germany, 10-11 Nov, 2014.

[13] A. Oudalov; D. Chartouni, C. Ohler, "Optimizing a Battery Energy Storage System for Primary Frequency Control," IEEE Transactions on Power Systems, vol.22, no.3, pp.1259-1266, Aug. 2007.

[14] A. Hoke, D. Maksimovic, "Active power control of photovoltaic power systems," 2013 1st IEEE Conference on Technologies for Sustainability (SusTech), pp.70-77, 1-2 Aug. 2013.

[15] J. Neely, J. Johnson, R. Bryne, R. T. Elliott, Structured optimization for parameter selection of frequency-watt grid support functions for wide-area damping, International Journal of Distributed Energy Resources and Smart Grids, DERlab/SIRFN Special Issue on Pre-standardisation Activities in Grid Integration of DER, 2015

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 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 1-1, and therefore includes all timing parameters needed. For example, in the case of testing according to specific requirements, additional and not requested 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. Similarly, if the full protocol is used a signal device may be tested for compliance to all of the jurisdictions surveyed[16].

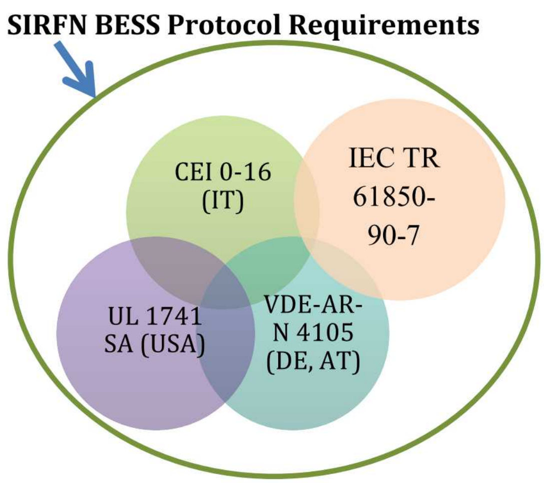

Figure 1-1: Visualization of integration method for SIRFN BESS Protocol.

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

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[16] It is important to note that this protocol need not include every test point required by every grid code and technical rule to provide an inclusive set of functional tests. Each code first defines the function and its requirements and then develops a test protocol to verify that a device meets these requirements. Instead of running every test defined in every code, this protocol surveys function requirements and then develops its own test protocol to verify functionality.

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 SIRFN BESS protocol is 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.

The development of the SIRFN BESS Protocol was the result of the following iterative process:

1. Review of appropriate grid codes, technical rules, standards, and BESS functions,
2. Consolidation of function requirements into draft protocol language,
3. Execution of draft protocol to BESS 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. The broad survey enabled the identification of any differences in requirements for the functions themselves. Once the differences in 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 and maintain the appropriate set-point and the time domain test to measure the BESS time response.

The SIRFN energy storage group has developed five test protocols for the evaluation by the larger group of SIRFN laboratories. Additional protocols will be added in the future and these draft protocols will be updated on an as-needed basis. The rest of this document is organized as follows. Section 1.1 covers the grid codes, technical rules, and standards reviewed in the development process for this report. Section 2 covers the general requirements for BESS laboratory testing and analysis. Section 3 covers preliminary test procedures to prepare for function testing. Sections 4 – 8 cover procedures for testing specific functions as specified by this protocol (Request Active Power from Storage, Request Reactive Power from Storage, Commanded Power Factor Frequency-Watt, and Volt-var).

1.1 ESS grid codes, technical rules, and standards

This protocol seeks to harmonize the certification procedures of a wide range of national and international grid codes, technical rules, and certification standards. In order to do this, a superset of requirements are included in the test procedures so that only the applicable experiments need to be performed, but all the tests are defined. For this reason, the same methodology is used for the experiments, including function descriptions, test sequences, and test points. The validation criteria is different for each requirement however, so the grid codes, technical rules, and standards must be consulted for the precise pass/fail criteria if they are not included in this report.

To create the functions, each interconnection code and technical rule was analyzed for similarities and differences in data requirements, specified curve shapes and default values. The following grid requirements and codes are applicable in different regions, though only a subset of these are integrated into each of the BESS functions, as described in each of the test protocols.

1. Italy
    a. CEI 0-21[17]
    b. CEI 0-16[18]
2. USA
    a. UL 1741 Supplement A[19]
    b. IEEE Standard 1547-2003[20]
    c. IEEE Standard 1547.1-2005[21]
    d. IEEE Standard 1547a-2014[22]
    e. California Electric Rule 21[23]
    f. Hawaii Rule 14H[24]
3. Germany
    a. VDE-AR-N 4105[25]
    b. VDE TAB 2007[26]

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[17] CEI Reference Technical Rules for the Connection of Active and Passive Users to the LV Electrical Utilities, CEI Reference 0-21-V1, December 2014.

[18] CEI Reference Technical Rules for the Connection of Active and Passive Consumers to the HV and MV Electrical Networks of Distribution Company, CEI 0-16-V1, December 2014.

[19] Underwriters Laboratories 1741 Supplement A, "Inverters, Converters, Controllers and Interconnection System Equipment for use with Distributed Energy Resources," (draft) Feb 2015.

[20] IEEE Standard 1547-2003, Standard for Interconnecting Distributed Resources with Electric Power Systems, 2003.

[21] IEEE Standard 1547.1-2005, Standard for Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems, 2005.

[22] IEEE Standard 1547a-2014, Standard for Interconnecting Distributed Resources with Electric Power Systems: Amendment 1, 2014.

[23] Pacific Gas and Electric Company, Electric Rule No. 21, Generating Facility Interconnections, Filed with the CPUC on 20 Jan, 2015.

[24] Hawaiian Public Utilities Commission Tariff Rule 14H, "Interconnection Of Distributed Generating Facilities Operating In Parallel with the Companies' Electric System" Filed 31 Mar 2015.

[25] VDE-AR-N 4105 "Technical requirements for the connection to and parallel operation with low-voltage distribution networks"

   c. FGW – TR3[27]
   d. FNN-Reference[28]
   e. BDEW MV Technical Guideline[29]
4. Austria
   a. TOR D4:2013[30]
   b. ÖVE/ÖNORM EN50438[31]
5. Japan
   a. METI Guideline[32]
   b. JEAC 9701[33]
   c. JEAC 9701 No. 2[34]
6. Spain
   a. P.O. 12.3:2006[35]

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[26] VDE-Reference TAB 2007, Technical conditions for connection to the low voltage network, 2007.

[27] Fördergesells chaft Windenergie und andere Erneuerbare Energien FGW e. V. TR3 "Bestimmung der Elektrischen Eigenschaften von Erzeugungseinheiten am Mittel-, Hoch- und Höchstspannungsnetz," (current status: Revision 23, 01/05/2013)

[28] FNN-Reference "Connecting and operating storage units in low voltage networks" Jun. 2013.

[29] BDEW MV Technical Guideline: "Generating plants connected to the medium-voltage network - Guideline for generating plants connection to and parallel operation with the medium-voltage network"

[30] TOR D4:2013 "Technical and organizational rules for network operators and users, Part D: Special technical rules, Parallel operation of generation facilities with distribution networks"

[31] EN 50438:2007 "Requirements for micro-generating plants to be connected in parallel with public low-voltage distribution networks" (Updated in 2013)

[32] Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI), Guideline of grid-interconnection technical requirement for power quality securement, 5 May, 2013.

[33] Grid-interconnection Code, JEAC 9701, The Japan Electric Association, 2012.

[34] Grid-interconnection Code, JEAC 9701, additional edition 2014 No.2, The Japan Electric Association, 2014.

[35] Procedimientos de operación (P.O.) 12.3:2006 "Requisitos de respuesta frente a huecos de tensión de las instalaciones eólicas" (Procedure for verification validation and certification of the requirements of the PO 12.3 on the response of wind farms and photovoltaic plants in the event of voltage dips)

    b. P.O. 12.2:2005[36]
    c. Royal Decree 1565/2010[37]
    d. Royal Decree 1699/2011[38]
    e. UNE 206007-1 IN[39]
7. France
    a. ERDF-NOI-RES 13E[40]
8. International protocols
    a. CLC/TS 50549-1:2015-01 [41]
    b. CLC/TS 50549-2:2015-01[42]
    c. IEC 61850-90-7 and the Sandia Test Protocols for IEC 61850-90-7
    d. RfG:2013[43]

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. grid-connected inverters >6 kW), so not all requirements are applicable to each device under test.

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[36] Procedimientos de operación (P.O.) 12.2:2005 "Instalaciones conectadas a la red de transporte: requisitos mínimos de diseño, equipamiento, funcionamiento y seguridad y puesta en servicio" (Installations connected to the transport network: minimum requirements for design, equipment, operation and safety and commissioning)

[37] Royal Decree 1565/2010, of 19 November, by which regulates and modifies certain aspects relating to the activity of production of electrical energy in special regime.

[38] Royal Decree 1699/2011, of November 18, by which the connection is regulated a network of facilities for production of electricity from small power.

[39] UNE 206007-1 IN "Requisitos de conexión a la red eléctrica. Parte1: Inversores para conexión a la red de distribución" (Requirements for connection to the mains. Part 1: Inverters for connection to the grid.)

[40] ERDF-NOI-RES_13E v5 "Protections des installations de production raccordées au réseau public de distribution" (Protections for production facilities connected to the public distribution network)

[41] CLC/TS 50549-1:2015-01 "Requirements for the connection of a generating plant to a distribution system - Part 1: Connection to a LV distribution system and above 16A"

[42] CLC/TS 50549-2:2015-01"Requirements for the connection of a generating plant to a distribution system - Part 2: Connection to a MV distribution system"

[43] European Network Code Requirements for Generators (RfG):2013 "ENTSO-E Network Code for Requirements for Grid Connection Applicable to all Generators"

2 TEST REQUIREMENTS

The following interoperability tests have a number of requirements for the experimental test configuration, data acquisition system, and communications.

2.1 Test Configuration

This section provides general guidelines of the test setup and test equipment requirements to verify BESS functional interoperability. The specific testing requirements may vary widely depending on the purpose of the test (i.e., which set of advanced functions are being tested). The minimum test setup requirements to perform the experiments are shown below in Figure 2-1. The Equipment Under Test (EUT), also referred to at the Device Under Test (DUT) is connected to a storage element that is either a battery or a battery simulator and a grid simulator.

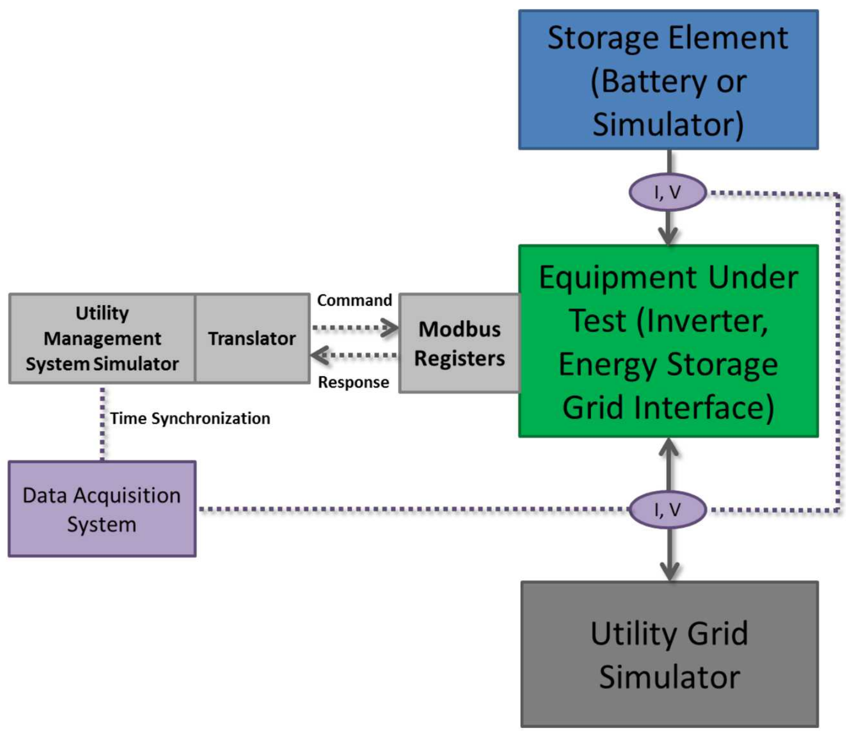

Figure 2-1: Laboratory Setup for Energy Storage Grid Support Testing.

A typical laboratory setup for the Equipment Under Test (EUT) should include the following:

- A **Utility Grid Simulator or grid connection**, which provides a power source or a sink to the DER. In some experiments it is possible to use the utility grid as long as the voltage and frequency are within the test tolerances. However, precise grid voltage and frequency changes are necessary for many of the functions. Therefore, a grid simulator will usually be more appropriate for the test setup than a connection to the actual grid. Note an optional **RLC Load Bank** may be used with the Utility Grid Simulator if it does not have regenerative (bidirectional real power) capabilities.

- A **Utility Management System Simulator**, which provides, using the proper communication protocols, utility-generated signals, information, commands and requests. The Utility Management System Simulator will be used to send commands to the EUT, as well as to change the parameters that govern the actions and responses of the EUT. The commands will be typically formatted according to IEC TR 61850-90-7 and implemented in a suitable communications protocol, unless otherwise required for the experiment. The Utility Management System Simulator will be configured to send commands formatted to IEC TR 61850-90-7, using a suitable communications protocol (such as Modbus or IEEE 2030.5 "SEP 2.0"). Since some inverters may not be compatible with the communications protocol used by the Utility Management System Simulator, a protocol translator may be required to convert commands. An Energy Management System, meter or other translator may be used to interface the Utility Management System Simulator with the DER inverter.

- The **Equipment Under Test** (EUT), which includes, at minimum, the inverter and controls. Since some EUTs may include an integrated energy storage element or other energy sources, the boundary of the EUT can be defined in a variety of ways including:
    - BESS inverter
    - BESS inverter + battery
    - Multimode inverter with PV + battery
    - Multimode inverter with PV
    - Multimode inverter with wind turbine + battery
    - Multimode inverter with wind turbine

  Testing will call for positive and negative real power flows so it is desired to use a battery simulator when possible to ensure that battery state-of-charge limits do not disrupt the experiments. The EUT is shown as separate from the battery in Figure 2-1 to identify the necessary data collection points. The EUT may or may not include a battery as integrated equipment. BESS often provide backup power to critical loads in addition to the services they supply to the grid. A critical load bus, as well as sensors for non-critical local loads, may also be included within the boundaries of the EUT.

- Optional **Sources for Local Inputs to the DER,** which could include a meter, an EMS, or other controls or sensors. Inputs such as temperature and time could be provided by the Utility Management Simulator, the Utility Grid Simulator, and/or local sensors or signal generators connected directly to inputs of the EUT. The EUT is required to have communication capabilities for all the interoperability tests described in this document.

Note that the EUT can be connected to either a stable utility grid or to a Utility Grid Simulator that allows the real and reactive power outputs of the DER to be controlled in response to grid voltage and frequency variations, local loads' or resources' energy inputs or outputs (real and reactive), and local voltage levels, depending on the test requirements. Power levels identified in this test protocol may need to be reduced due to power limitations of the utility grid, simulators, PV, and/or storage.

2.2 Data Acquisition Requirements

For each test, the following will be logged:

- Interoperability (Communication) Data
  - message sent
  - response received
  - status reports generated and transmitted by the DER
  - commands received (and responses) logged
- Electrical Response (Behavior)
  - time-synchronized data of relevant electrical behavior
- Temporal Information
  - Time the command is sent
  - Time the response is received
  - Time of any alarms

The status reporting and data logging will be completed with the Utility Management System Simulator. However, it might be desirable to use a faster sampling rate than possible through utility-issued commands; that will be accomplished by directly monitoring the outputs of the EUT with appropriate instrumentation and data loggers.

EUT input and output voltages, currents, reactive power, apparent power, and active power will be measured to observe the action taken in response to the commands. Sufficient electrical measurements should be taken to fully characterize the electrical response or behavior of the EUT at the electrical connection point (ECP)—as opposed to the point of common coupling (PCC) because local loads may influence the measurements at the PCC. The sampling rate and test duration should be adequate according to the nature of the electrical behavior being evaluated. Points to be measured include:

- AC voltage at the point of connection
- AC current out of the EUT
- Frequency at the point of connection
- Active and Reactive power at the point of connection
- DC voltage of the energy storage device
- Current in to and out of the energy storage
- DC voltage of the BESS or BESS simulator
- DC current out of the BESS array or BESS simulator

Required sampling rates and data accuracies are defined by the technical grid interconnection rule/ code/standard that is being tested, via IEC 61557-12 or IEC 61000-4-30, or—if not specified—Table 2-1 shows maximum acceptable data acquisition measurement tolerances to be used.

Parameter	Units	Maximum Tolerance of Measurement
Voltage (dc)	Volts	+/- 2%
Voltage (ac)	Volts rms	+/- 1%
Current (dc)	Amps	+/- 3%
Current (ac)	Amps rms	+/- 2%
Active Power	Watts	+/- 4%
Reactive Power	VAr	+/- 1%
Apparent Power	VA	+/- 2%
Power Factor	Displacement Power Factor	+/- 3%
Frequency	Hz	+/- 0.05 Hz
Time	Seconds	+/- 2%
Temperature	Degrees C	+/- 3°C

Table 2-1: Requirements for Data Acquisition Accuracy[44].

Test sequences may be repeated as needed to verify response to external variables (temperature effects, power disturbances, etc.). Additionally, some commands such as power level are not binary; therefore, it may be appropriate to verify interoperability and performance at several power levels.

2.3 Test Procedures

For each functions the procedure will be characterized by:

- Function definition
- Parameters
- Function Capability Table
- Function Test Definition
- Function Test Sequence
- Acceptance Criteria

Most of the defined advanced functions have optional parameters, tables, or definitions. Some manufacturers may choose to implement the functions in a particular way, or not to implement

[44] Adopted from draft UL 1741 SA, Feb 2016.

some of the functions at all. The test procedures are designed to take into account equipment limitations, such as different equipment ratings and avoiding conflict with voltage and frequency protection. The EUT's source(s) of input signals or locally sensed conditions should be enumerated to ensure the test engineer can account for these considerations. Furthermore, based on the jurisdictional requirements (sometimes referred to as the "source requirements document"), the number of tests and test points may be reduced as these procedures are designed to represent a superset of all requirements.

The test engineer should have knowledge of which of the possible options or capabilities for the functions are implemented in their EUT. A list of tables, modes, default parameters, curves, schedules, control logic, and permissible ranges of parameters should also be provided by the inverter manufacturer. The hierarchy among command functions and the conditions for switching from one mode to another should also be provided. If the EUT technical specifications are insufficient to setup the interoperability test, the manufacturer should be consulted. These capabilities and options are recorded in a Function Capabilities Table (FCT) in order to define the specific tests, and the parameters of those tests, to be conducted.

For each function being tested, the general test procedure is as follows:

- Review manufacturer specifications related to the implementation of standard functions and review communications interface requirements. Prepare a FCT and tailor the test setup and the test sequence accordingly.
- EUT is connected to the sources and sinks under normal operating conditions and for a period of 5 minutes. This is in order to verify that the EUT is operational and stable.
- Verification of communications compatibility. This can be done by issuing a status request to the EUT.
- Test communications functionality. This is performed by issuing a command to the EUT. The purpose is to establish how the EUT implements the function command.
- Test the electrical behavior to determine if the DER successfully executed the communicated command.
- Analysis of the test results.

3 PRELIMINARY SYSTEM CHARACTERIZATION TEST

In order to quantify the performance of equipment used in the experiments, the data acquisition system, grid simulator, and, if applicable, the DC Battery simulator accuracies must be determined.

3.1 DAS, Grid Simulator, and Battery Simulator Accuracies

The accuracies of the data acquisition system shall be determined using calibration techniques from IEEE, IEC, or equivalent standards. Once the data acquisition system (DAS) has been calibrated, the accuracies of the grid simulator voltage and frequency are determined. The battery simulator current and voltage behavior will also be quantified.

3.2 EUT Capabilities and Operating Limits

The EUT manufacturers are responsible for reporting the accuracies of their devices. Unless otherwise specified, Table 3-1 should be used for the minimum required EUT measurement accuracy.

	Minimum Measurement Accuracy	Sensing Speed	Range	Minimum Measurement Accuracy	Sensing Speed	Range
Voltage	±2% V_{nom}	10 cycles	85% to 110%	±2% V_{nom}	5 cycles	30% to 120%
Apparent Current	±2% I_{max}	10 cycles	0% to 110%	±2% I_{max}	10 cycles	0% to 110%
Frequency[45]	±0.016%	10 cycles	78.33% to 110%	±0.16%	5 cycles	78.33% to 110%
Active Power	±5% P_{rated}	10 cycles	20% < P < 100%	N/A	N/A	N/A
Reactive Power	±5% Q_{rated}	10 cycles	20% < Q < 100%	N/A	N/A	N/A
Power Factor	±5% PF_{rated}	10 cycles	P > 50%	N/A	N/A	N/A

Table 3-1: Minimum Requirements for Manufacturers Stated Measurement Accuracy[46].

If the manufacturer does not report (or know) the limits of the EUT, it may be necessary to determine the limits of the equipment. Standard reporting values are provided in each of the functions below but often cover the EUT limits, such as:

1. AC operational voltage range of the EUT and/or the programmed L/H VRT curves.
2. AC operational frequency range of the EUT and/or the programmed L/H FRT curves.
3. DC operational voltage range of the EUT
4. DC maximum current

[45] CLC/TS 50549 requires ±0.02% frequency accuracy for measurements between 94% and 104% of nominal.

[46] Adopted from draft UL 1741 SA, Feb 2016.

5. Chemistry designation of batteries (e.g. Lithium-Iron-Phosphate)
6. Battery maximum energy capacity (e.g. at maximum open-circuit voltage)
7. Battery nominal energy
8. Active power limits of the EUT
9. Reactive power limits of the EUT
10. Power factor (displacement, cosϕ) limits of the EUT.
11. The P-Q operational limits of the EUT. This region is often (semi)circular, but could be elliptical for certain EUTs. (See example in Figure 3-1)
12. Range of SOC limits the EUT can perform each of the grid-support functions.

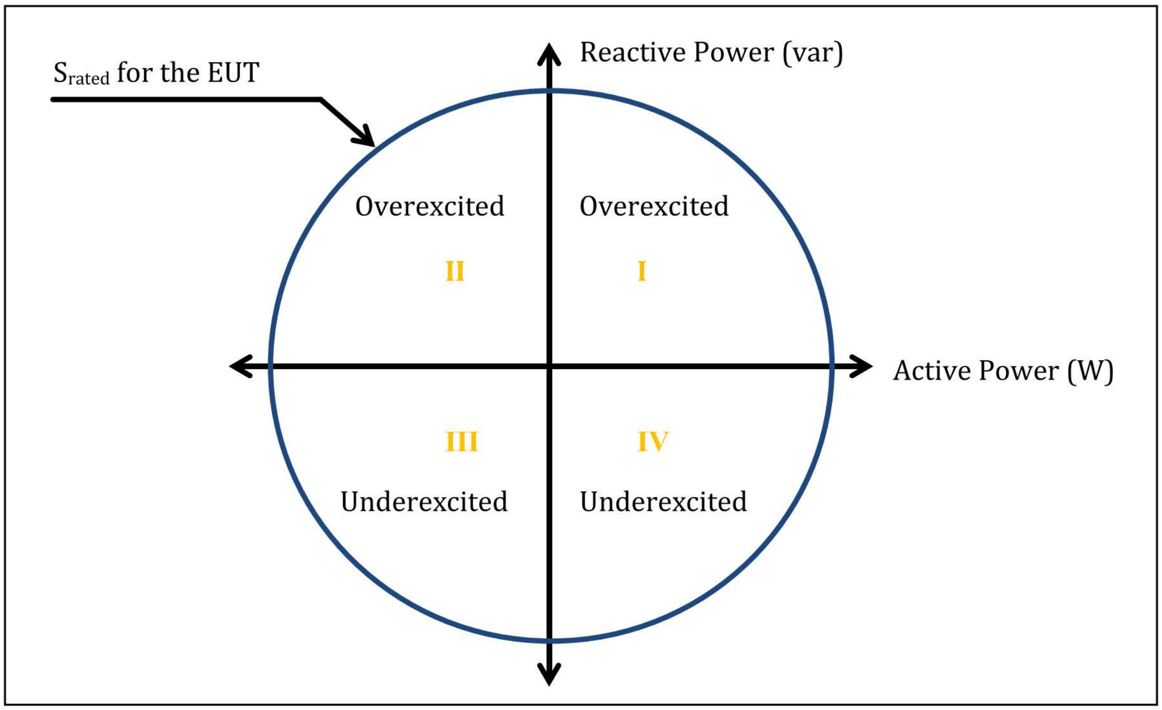

Figure 3-1: Example EUT P-Q Operational Limits.

In certain testing situations, the test engineer may perform preliminary experiments to validate the manufacturer's stated capabilities in order to verify the experiments will run without unexpected outcomes, e.g., high/low voltage tripping.

One common challenge in testing BESS power electronics components is the reliance on the battery to provide the full range of capacities of the EUT. For instance, at high and low states-of-charge, the active power limits of the EUT become restricted and therefore the manufacturer-stated limits of the EUT are not valid in those cases. For this reason, it is advisable to use battery simulators. Without the simulator, reliance on the battery capacities are necessary, which can be effected by SOC, temperature, chemistry, etc. To avoid problems, artificially limiting the operation of the EUT, the experiments should be conducted near the 50% of SOC of the battery, at room temperature, using a battery chemistry which the EUT has been designed.

Further, if certain battery parameters (SOC) are known to change the settings listed above, the manufacturer should provide these limits/capabilities as functions of the battery parameter. If this effect is unknown, although it is time-intensive, the test engineer may determine these limits experimentally prior to running the grid-support functions listed in the sections below.

3.3 Validating Reported EUT Capabilities

Each of the functions in this report are designed to validate the capabilities of the EUTs. In some cases, if the EUT is not performing according to the manufacturer-states limits/capabilities, additional experiments may be necessary to understand the limitations of the EUT to provide feedback to the manufacturer. The design and execution of these additional experiments are left to the test engineer to design and execute.

3.4 ESS Interoperability Characterization

Prior to executing the interoperability grid-support experiments the communications capabilities of the EUT must be validated and all the parameters to be tested demonstrate the read/write permissions with the Utility Management System Simulator. This can be performed also by a 3rd party47 or another test fixture.

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[47] The SunSpec Alliance is capable of validating the communication capabilities of SunSpec-compliant EUTs using a testing tool.

4 REQUEST ACTIVE POWER FROM STORAGE TEST (INV4)

4.1 Function definition

This function requests the energy storage system to either charge or discharge as a percentage of the storage system's charge and discharge capacity. A battery simulator may be used in the test to reduce the time needed for the test by reducing charge and/or discharge times. It should be noted that charge/discharge requests are always subject to the state of charge, temperature, ramp rate limits, and other constraints imposed by the battery. Therefore, the INV4 function should be executed only to the extent that the request is feasible, as determined by the local energy storage control system.

This test procedure evaluates the functionality required in:

- CEI 0-21
- CEI 0-16
- IEC 61850-90-7

The differences in the grid codes for each of the INV4 functions is provided in Table 4-1.

Country/ Grid Code	Data Requirements	Test Points	Time parameters
Italy/CEI 0-21: 2014-12 (LV) **and** **Italy/CEI 0-16: 2014-12(MV)**	P, Q, P_{dc}, cosφ measured (sample time 1s, data averaged at 1 min)	Active power from W_{MAXch} to W_{MAXdch} every 20% (11 test points)	Time Delay, Ramp Rate fixed to 20% W_{MAXch}/min and 20% W_{MAXdch}/min
International / IEC 61850-90-7 [48]	P measured (1 s average), communications recorded	Active power at W_{MAXch}, $W_{MAXch}/2$, $W_{MAXch}/4$, W_{MAXdch}, $W_{MAXdch}/2$, $W_{MAXdch}/4$	Ramp Rate, Time Delay, Timeout

Table 4-1: Review of Grid Codes for the INV4 function.

4.2 Parameters

Before starting the INV4 test, the following parameters will be determined by the manufacturer and test engineer for use in the procedure.

[48] Evaluated with the Sandia Interoperability Test Protocols

Parameter	Notes
P_{BESS}	Requested real power output of the BESS device, expressed as a percentage of the BESS output power capacity (W_{MAXdch}). If negative, this represents real power absorbed by the BESS device, expressed as a percentage of the BESS charge power capacity (W_{MAXch}).
t_W	Time window is an optional parameter in which the function is enabled after a delay. The delay can be random or fixed. If the time delay is zero, the command will execute immediately.
r_R	Requested ramp rate ($\%P_{rated}/s$) is an optional parameter defining the slope the EUT must move from the current set point to the new set point. The corresponding requested ramp time $t_R=1/r_R$ expresses the time for a change of $100\%P_{rated}$.
t_{out}	Timeout period is an optional parameter that defines the time after which the EUT will reset the INV4 function and set the active power to a default value. The default timeout period is indefinite (timeout period = 0 – Not Enable).
ChgGrid	Boolean that defines whether the storage system can be charged from the grid.

Table 4-2: INV4 Parameters.

Parameter	Notes
W_{MAXch}	Maximum charge active power rating (W), negative value
W_{MAXdch}	Maximum discharge active power rating (W), positive value[49]
$Q_{MAXover}$	Maximum over excited reactive power rating (var), positive value[50]
$Q_{MAXunder}$	Maximum under excited reactive power rating (var), negative value
MSA_w[51]	Output Power accuracy (W or %W)
MSA_t	Accuracy of response time (s)
SOC_{opMAX}	Maximum operative state of charge at maximum charge power (%) [52]
SOC_{opMIN}	Minimum operative state of charge at maximum discharge power (%)
[t_{W_min}, t_{W_max}]	Adjustment range of time window (s). t_{W_min} will be 0 for most EUTs.

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[49] Grid-centric nomenclature from IEC 61850-90-7 is adopted here.

[50] This test follows the IEEE Std-1459-2000 reactive power sign convention, in which an overexcited power factor is positive and an underexcited power factor is negative.

[51] The manufacturer's stated accuracy is necessary for some of the pass/fail criteria in certain grid codes, e.g., UL 1741 SA. It is also used for general acceptance criteria.

[52] This information can also be provided in tabular or function formats with active power limits vs SOC level.

$[r_{R\_min}, r_{R\_max}]$	Adjustment range of the ramp rate ($\%P_{rated}$/s).
$[t_{out\_min}, t_{out\_max}]$	Adjustment range of timeout period (s). t_{out_min} will be 0 for most EUTs.
t_S	Settling time (s)

Table 4-3: Manufacturer parameters.

4.3 Function Capability Table (FCT)

The INV4 function will be tested according to the present protocol. The Function Capability Table (FCT) should be filled out based on the capabilities of the EUT. If the EUT has the capability of acting on any of the optional parameters, then additional tests of those capabilities shall be performed, as indicated in the FCT.

Test Type	***ChgGrid***	*Timing*	*Tests to Include*
INV4 domain	No	Default	Test 2 in Table 4-5
	Yes	Default	Tests 1 and 2 in Table 4-5
Time domain	Yes	t_R Enabled	Tests 3, 4, 9, and 10 in Table 4-6
	Yes	t_W Enabled	Tests 5, 6, 11 and 12 in Table 4-6
	Yes	t_{out} Enabled	Tests 7, 8, 13 and 14 in Table 4-6

Table 4-4: INV4 Function Capability Table.

4.4 INV4 Function Test Definitions

Table 4-5 and Table 4-6 suggests possible combinations of parameters to be tested. Performing all possible combinations may not be feasible. If an inverter does not have a particular capability, then those tests are run without configuring that function. All the tests must be performed in active power priority.

4.4.1 INV4 Test

The Request Active Power tests consist of in active power steps from zero active power to W_{MAXch} and from zero active power to W_{MAXdch} with active power steps about $5\%*W_{MAXch}$ or $5\%*W_{MAXdch}$. These tests should be repeated with reactive power set to $100\%*Q_{MAXover}$ to $20\%*Q_{MAXover}$ in steps of $20\%*Q_{MAXover}$ and $100\%*Q_{MAXunder}$ to $20\%*Q_{MAXunder}$ in steps of $20\%*Q_{MAXunder}$. Each power level must be held for the greater of 5 seconds and $2\cdot t_S$.

#	**P_{BESS}**	Ramp time, t_R (s)	Time window, t_W (s)	Timeout, t_{out} (s)
1	$0\%*W_{MAXch}$ to $100\%*W_{MAXch}$ in steps of $5\%*W_{MAXch}$	0	0	0

2	0%*W_{MAXdch} to 100%*W_{MAXdch} in steps of 5%*W_{MAXdch}	0	0	0

Table 4-5: INV4 Test Matrix.

4.4.2 INV4 Timing Test

The Request Active Power timing tests consist of two steps from zero active power to the maximum charge power W_{MAXch} and back to zero active power and from zero active power to the maximum discharge power W_{MAXdch} and back to zero active power. Each power step is held for a minimum test duration (timing interval) equal to the greater of 5 seconds and $2\cdot(t_R + t_W + t_{out})$ or $2\cdot t_S$. The ramp times are calculated from the ramp rates using $t_R = 1/r_R$. If the maximum ramp time or maximum time window defined by the manufacturer exceeds 5 minutes, they may be changed to 5 minutes in order to complete the tests in a reasonable amount of time.

#	Ramp time, t_R (s)	Time window, t_W (s)	Timeout, t_{out} (s)
Default	0	0	0
t1	$t_{R\_max}/2$	0	0
t2	t_{r_max}	0	0
t3	0	$t_{W\_max}/2$	0
t4	0	t_{W_max}	0
t5	0	0	$t_{out\_max}/2$
t6	0	0	t_{out_max}

Table 4-6: INV4 timing setting test matrix.

4.5 INV4 Function Test Sequence

The Request Active Power from Storage test shall be carried out as follows:

Step 1: Prepare the EUT according to the following:

- Configure EUT and energy storage element according to Section 2.1.
- Connect to Utility Simulator with operation within nominal voltage range for a minimum of 5 minutes.
- Verify EUT is powered on to a level required to receive the command.
- Verify energy storage state of charge (SOC) will not interfere with INV4 tests. If the SOC is near SOC_{opMAX} or SOC_{opMIN}, charge or discharge the BESS system until close to: $(SOC_{opMAX} + SOC_{opMIN})/2$.
- Establish communication to EUT with Utility Management System Simulator.

- Record EUT output (e.g., voltage, current, power) with data acquisition system according to Section 2.2.
- Set Active and Reactive Power to zero.

Step 2: Request status from EUT and record the EUT parameters.

Step 3: Send default timing parameters to EUT according to Table 4-6.

Step 4: Confirm timing parameters are updated in the EUT.

Step 5: Send INV4 command according to Table 4-5.

Step 6: Record EUT response for the test duration, where the test duration is defined as the greater of 5 seconds and $2 \cdot t_S$.

Step 7: Repeat Steps 5-6 according to tests defined in Table 4-5 based on the FCT (INV4 domain tests).

Step 8: Set Active Power to zero.

Step 9: Step the commanded active power through the sequence: 0, W_{MAXch}, 0, W_{MAXdch}, 0 according to Section 4.4.2.

Step 10: Repeat Steps 8-9 with new the timing parameters based on the FCT (Timing tests).

Step 11. Repeat steps 3-10 with reactive power set to 100%*$Q_{MAXover}$ to 20%*$Q_{MAXover}$ in steps of 20%*$Q_{MAXover}$ and 100%*$Q_{MAXunder}$ to 20%*$Q_{MAXunder}$ in steps of 20%*$Q_{MAXunder}$.

Step 11: Analyze performance data.

4.6 Acceptance criteria

Acceptance criteria are determined using the definitions provided in the grid code.

4.6.1 Default requirements – generic test case

The maximum difference between the programmed power and response is less than or equal the manufacturer's stated power accuracy (MSA_P) plus the DAQ active power accuracy and the maximum difference between the programmed response time and actual response is less or equal than the manufacturer's stated time accuracy (MSA_t) plus the DAQ time accuracy.

4.6.2 Italian technical rule[53]

The maximum difference between the measured power and the set power is less than ±2.5% of Wmax.

[53] As of now, only the Italian grid code requirements are available for this function.

5 REQUEST REACTIVE POWER (*VV13*)

5.1 Function definition

This function requests the energy storage system to either sink or source reactive power as a percentage of the storage system's reactive power capacity. A battery simulator may be used in the test to reduce the time needed for the test by reducing charge and/or discharge times. It should be noted that charge/discharge requests are always subject to the state of charge, temperature, ramp rate limits, and other conditions of the battery. Therefore, the VV13 function should be executed only to the extent that the request is feasible, as determined by the local energy storage control system.

This test procedure evaluates the functionality required in:

- CEI 0-21
- CEI 0-16
- EN 50438:2013
- CLC/TS 50549
- IEC 61850-90-7

The differences in the grid codes for each of the VV13 functions is provided in Table 5-1.

Country/ Grid Code	Data Requirements	Test Points	Time parameters
Italy/CEI 0-21: 2014-12 (LV) **and** **Italy/CEI 0-16: 2014-12(MV)**	P, Q, $P_{dc,}$ cosφ measured (sample time 1s, data averaged at 1 min)	$Q_{MAXover}$, 0 and $Q_{MAXunder}$ with active power from W_{MAXch} to W_{MAXdch} every 20% (33 test points)	No Time parameter
EN 50438:2013	P, Q, Vrms (Sample time 200ms, data averaged at 1 min).	$Q_{MAXover}$, 0 and $Q_{MAXunder}$ at active power output W_{MAXdch} at 50 % P_n	No Time parameters
International / IEC 61850-90-7[54]	P, Q, V_{rms} measured (1 s average), communications recorded	VArMaxPct = 30, 50, 75, 100% of max VArs (only for $Q_{MAXover}$) with Active Power Output = 50, 90, 100% $WMax_{dch}$	Ramp Rate, Time Delay, Timeout

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[54] Evaluated with the Sandia Interoperability Test Protocols.

Table 5-1: Review of Grid Codes for the VV13 Function.

5.2 Parameters

Before starting the VV13 test, the following parameters will be determined by the manufacturer and test engineer for use in the procedure.

Parameter	Notes
Q_{BESS}	Requested reactive power output of the BESS device, expressed as a percentage of the BESS maximum reactive power capacity
t_W	Time window is an optional parameter in which the function is enabled after a delay. The delay can be random or fixed. If the time delay is zero, the command will execute immediately.
r_R	Requested ramp rate ($\%Q_{rated}/s$) is an optional parameter defining the slope the EUT must move from the current set point to the new set point. The corresponding requested ramp time $t_R=1/r_R$ expresses the time for full execution.
t_{out}	Timeout period is an optional parameter that defines the time after which the EUT will reset the VV13 function and set the reactive power to a default value. The default timeout period is indefinite (timeout period = 0 – Not Enable).

Table 5-2: VV13 Parameters.

Parameter	Notes
W_{MAXch}	Maximum charge active power rating (W), negative value
W_{MAXdch}	Maximum discharge active power rating (W), positive value[55]
$Q_{MAXover}$	Maximum over excited reactive power rating (var), positive value[56]
$Q_{MAXunder}$	Maximum under excited reactive power rating (var), negative value
MSA_Q[57]	Output reactive power accuracy (var or %var)
MSA_t	Accuracy of response time (s)

---

[55] Grid-centric nomenclature from IEC 61850-90-7 is adopted here.

[56] This test follows the IEEE Std-1459-2000 reactive power sign convention, in which an overexcited power factor is positive and an underexcited power factor is negative.

[57] The manufacturer's stated accuracy is necessary for some of the pass/fail criteria in certain grid codes, e.g., UL 1741 SA. It is also used for general acceptance criteria.

SOC_{opMAX}	Maximum operative state of charge at maximum reactive power (%) [58]
SOC_{opMIN}	Minimum operative state of charge at maximum reactive power (%)
[t_{W_min}, t_{W_max}]	Adjustment range of time window (s). t_{W_min} will be 0 for most EUTs.
[r_{R_min}, r_{R_max}]	Adjustment range of the ramp rate ($\%Q_{rated}/s$)
[t_{out_min}, t_{out_max}]	Adjustment range of timeout period (s). t_{out_min} will be 0 for most EUTs.
t_S	Settling time (s)

Table 5-3: Manufacturer parameters.

5.3 Function Capability Table (FCT)

The VV13 function will be tested according to the present protocol. The Function Capability Table (FCT) (Table 5-4) should be filled out based on the capabilities of the EUT. If the EUT has the capabilities of acting on any of the optional parameters, then additional tests of those capabilities shall be performed, as indicated in the FCT.

Test Type	*Timing*	*Tests to Include*
VV13 domain	Default	Tests 1 and 2 in Table 5-5
Time domain	t_R Enabled	Tests 3, 4, 9, and 10 in Table 5-6
	t_W Enabled	Tests 5, 6, 11 and 12 in Table 5-6
	t_{out} Enabled	Tests 7, 8, 13 and 14 in Table 5-6

Table 5-4: VV13 Function Capability Table.

5.4 VV13 Function Test Definitions

Table 5-5 and Table 5-6 provides possible combinations of parameters to be tested. Performing all possible combinations may not be feasible. If the EUT does not have a particular capability, then those tests are run without configuring that function. All the tests must be performed in reactive power priority.

5.4.1 VV13 Test

The Request Reactive Power tests consist of in reactive power steps from zero reactive power to $Q_{MAXover}$ and from zero reactive power to $Q_{MAXunder}$ with reactive power steps about $5\%*Q_{MAXover}$ or $5\%*Q_{MAXunder}$. These tests should be repeated with active power set to

[58] This information can also be provided in tabular or function formats with reactive power limits vs SOC level.

100%*W_{MAXch} to 0 watts in steps of 20%*W_{MAXch} and 100%*W_{MAXdch} to 20%*W_{MAXdch} in steps of 20%*W_{MAXdch}. Each power level must be held for the greater of 5 seconds and $2 \cdot t_S$.

#	Q_{BESS}	Ramp time, t_R (s)	Time window, t_W (s)	Timeout, t_{out} (s)
1	0%*$Q_{MAXover}$ to 100%*$Q_{MAXover}$ in steps of 5%*$Q_{MAXover}$	0	0	0
2	0%*$Q_{MAXunder}$ to 100%*$Q_{MAXunder}$ in steps of 5%*$Q_{MAXunder}$	0	0	0

Table 5-5: VV13 Test Matrix.

5.4.2 VV13 Timing Test

The Request Reactive Power timing tests consist of two steps from zero reactive power to the maximum overexcited reactive power $Q_{MAXover}$ and back to zero reactive power and from zero reactive power to the maximum underexcited power $Q_{MAXunder}$ and back to zero reactive power. Each power step is held for a minimum test duration (timing interval) equal to the greater of 5 seconds, $2 \cdot (t_R + t_W + t_{out})$, and $2 \cdot t_S$. The ramp times are calculated from the ramp rates using $t_R = 1/r_R$. If the maximum ramp time or maximum time window defined by the manufacturer exceeds 5 minutes, they may be changed to 5 minutes in order to complete the tests in a reasonable amount of time.

#	Ramp time, t_R (s)	Time window, t_W (s)	Timeout, t_{out} (s)
Default	**0**	**0**	**0**
t1	$t_{R\_max}/2$	0	0
t2	t_{r_max}	0	0
t3	0	$t_{W\_max}/2$	0
t4	0	t_{W_max}	0
t5	0	0	$t_{out\_max}/2$
t6	0	0	t_{out_max}

Table 5-6: VV13 timing setting test matrix.

5.5 VV13 Function test sequence

The Request Reactive Power from Storage test shall be carried out as follows:

Step 1: Prepare the EUT according to the following.

- Configure EUT and energy storage element according to Section 2.
- Connect to Utility Simulator with operation within nominal voltage range for a minimum of 5 minutes.

- Verify EUT is powered on to a level required to receive the command.
- Verify energy storage state of charge (SOC) will not interfere with VV13 tests. If the SOC is near SOC_{opMAX} or SOC_{opMIN}, charge or discharge the BESS system until close to: $(SOC_{opMAX} + SOC_{opMIN})/2$.
- Establish communication to EUT with Utility Management System (UMS).
- Record EUT output (e.g., voltage, current, power) with data acquisition system according to Section 2.2.
- Set Active and Reactive Power to zero.

Step 2: Request status from EUT and record the EUT parameters.

Step 3: Send default timing parameters to EUT according to Table 5-6.

Step 4: Confirm timing parameters are updated in the EUT.

Step 5: Send VV13 command according to Table 5-5 based on the FCT.

Step 6: Record EUT response for the test duration, where the test duration is defined as the greater of 5 seconds and $2 \cdot t_S$.

Step 7: Repeat Steps 5-6 according to the tests defined in Table 5-5 (VV13 domain tests).

Step 8: Set Reactive Power to zero

Step 9: Step the commanded reactive power through the sequence 0, $Q_{MAXover}$, 0, $Q_{MAXunder}$, 0 according to Section 5.4.2.

Step 10: Repeat Steps 8-9 with new the timing parameters based on the FCT (Timing tests).

Step 11: Repeat steps 3-9, with reactive power set to $100\%*W_{MAXch}$ to $20\%*W_{MAXch}$ in steps of $20\%*W_{MAXch}$ and $100\%*W_{MAXdch}$ to $20\%*W_{MAXdch}$ in steps of $20\%*W_{MAXdch}$.

Step 12: Analyze performance data.

5.6 Acceptance Criteria

Acceptance criteria are determined using the definitions provided in the grid code.

5.6.1 Default requirements – generic test case

The maximum difference between the programmed reactive power and response is less or equal than the manufacturer's stated power accuracy (MSA_Q) plus DAQ reactive power accuracy and the maximum difference between the programmed response time and actual response is less or equal than the manufacturer's stated time accuracy (MSA_t) plus DAQ time accuracy.

5.6.2 Italian technical rules

The maximum difference between the measured reactive power and the set reactive power is less than ±5% of the EUT nameplate apparent power and the Power Factor deviation is less than ±0.02.

5.6.3 EN 50438:2013

The maximum difference between the measured reactive power and the set reactive power is less than $\Delta Q < \pm 5\%$ of the EUT nameplate active power

5.6.4 CLC/TS 50549

The maximum difference between the measured reactive power and the set reactive power is less than $\Delta Q < \pm 2\%$ of the EUT nameplate apparent power in the range 10% - 100% of nameplate apparent power

6 COMMANDED POWER FACTOR TEST (INV3)

6.1 Function definition

This function sets the power factor (i.e., Displacement Factor, cosϕ) angle in response to a command from the utility controller or a combination of local conditions, modes, schedules, etc. A ramp rate and a delay time before starting may also be included. A timeout period may be included for reverting to the default state of the EUT.

This test procedure evaluates the functionality required in:

- IEC 61850-90-7
- California Rule 21/UL 1741 SA

The differences in the grid codes for each of the VV13 functions is provided in Table 6-1.

Country/ Grid Code	Data Requirements	Test points	Time parameters
California/ UL 1741 SA: 2016	P, Q measured, cosφ calculated	- 1.0 - $PF_{min,ind}$ - $PF_{mid,ind}$ - $PF_{min,cap}$ - $PF_{mid,cap}$	No timing parameters
International / IEC 61850-90-7[59]	P, Q measured (1 s average), communications recorded	- 1.00 (default) - MinPFOverAval (e.g., 0.80 Overexcited) - MinPFUnderAvail (e.g., 0.80 Underexcited) - MinPFOverAval/2 + 0.5(e.g., 0.90 Overexcited) - MinPFUnderAvail/2 + 0.5 (e.g., 0.90 Underexcited)	Ramp Rate, Time Delay, Timeout

Table 6-1: Review of Grid Codes for the INV3 function.

6.2 Parameters

Before starting the PF test, the following parameters will be determined by the manufacturer and test engineer for use in the procedure.

[59] Evaluated with the Sandia Interoperability Test Protocols

Parameter	Notes
PF_{BESS}	Requested power factor of the BESS device, expressed as a number between 0 and 1.
t_W	Time window is an optional parameter in which the function is enabled after a delay. The delay can be random or fixed. If the time delay is zero, the command will execute immediately.
r_R	Requested ramp rate (%Prated/s) is an optional parameter defining the slope the EUT must move from the current set point to the new set point. The corresponding Requested ramp time t_R express the time for action completion.
t_{out}	Timeout period is an optional parameter that defines the time after which the EUT will reset the commanded power function and set the power factor to a default value. The default timeout period is indefinite (timeout period = 0 – Not Enable).

Table 6-2: INV3 Function Capability Table.

Parameter	Notes
W_{MAXch}	Maximum charge active power rating (W), negative value
W_{MAXdch}	Maximum discharge active power rating (W), positive value[60]
$Q_{MAXover}$	Maximum over excited reactive power rating (var), positive value[61]
$Q_{MAXunder}$	Maximum under excited reactive power rating (var), negative value
MSA_t[62]	Accuracy of time (s)
MSA_{PF}	Power Factor Accuracy
SOC_{opMAX}	Maximum operative state of charge at maximum charge power (%)[63]
SOC_{opMIN}	Minimum operative state of charge at maximum discharge power (%)

[60] Grid-centric nomenclature from IEC 61850-90-7 is adopted here.

[61] This test follows the IEEE Std-1459-2000 reactive power sign convention, in which an overexcited power factor is positive and an underexcited power factor is negative.

[62] The manufacturer's stated accuracy is necessary for some of the pass/fail criteria in certain grid codes, e.g., UL 1741 SA. It is also used for general acceptance criteria.

[63] This information can also be provided in tabular or function formats with active power limits vs SOC level.

[t_{W_min}, t_{W_max}]	Adjustment range of time window (s).
[r_{R_min}, r_{R_max}]	Adjustment range of the ramp rate (PF/s)
[t_{out_min}, t_{out_max}]	Adjustment range of timeout period (s)
t_S	Settling time (s)
$PF_{minunder}$	Minimum Underexcited Power Factor[64]
$PF_{minover}$	Minimum Overexcited Power Factor

Table 6-3: Manufacturer parameters.

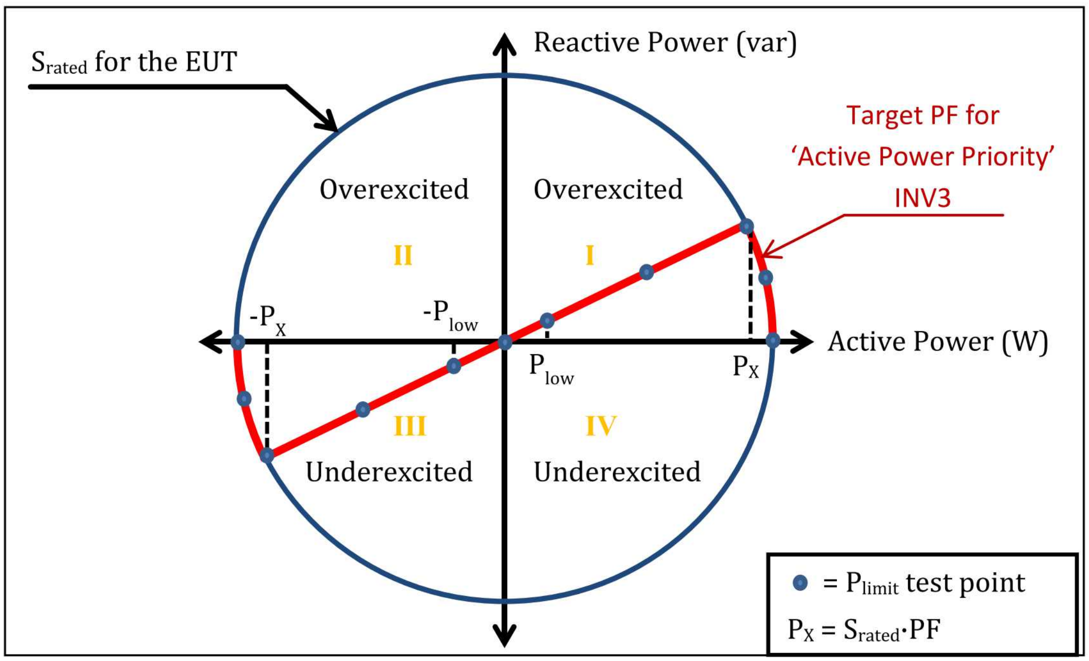

Figure 6-1: Example target PF for an EUT with 'Active Power Priority' enabled.

Additionally the following parameters will be calculated:

[64] This test follows the concepts of reactive power sign convention in which a capacitive, overexcited power factor is positive and an inductive, underexcited power factor is negative.

- $P_X = S_{rated} \cdot PF$ is the maximum active power which an 'Active Power Priority' mode maintains the PF command. Active power ratings above this value in 'Active Power Priority' will result in PF values closer to unity.
- $P_{low} = 0.2 \cdot S_{rated}$ unless stated otherwise by the equipment manufacturer.
- $PF_{midover} = (1 - PF_{minover})/2$, half the EUT overexcited range.
- $PF_{midunder} = (1 - PF_{minunder})/2$, half the EUT underexcited range.

6.3 Function Capability Table (FCT)

The INV3 function will be tested according to the EUT capabilities. The Function Capability Table (FCT) (Table 6-4) should be filled out based on the capabilities of the EUT. If the EUT has the capabilities of acting on any of the optional parameters, then additional tests of those capabilities shall be performed, as indicated in the FCT.

Test Type	*Timing*	*Tests to Include*
INV3 domain	Default	Tests 1 and 2 in Table 5-5
Time domain	t_R Enabled	Tests 3, 4, 9, and 10 in Table 5-6
	t_W Enabled	Tests 5, 6, 11 and 12 in Table 5-6
	t_{out} Enabled	Tests 7, 8, 13 and 14 in Table 5-6

Table 6-4: INV3 Function Capability Table.

6.4 INV3 Function Test Definition

Table 6-5 and Table 6-6 provides possible combinations of parameters to be tested. Performing all possible combinations may not be feasible. If the EUT does not have a particular capability, then those tests are run without configuring that function. All the tests must be performed in active power priority.

6.4.1 INV3 Test

The Commanded Power Factor tests consist in active power steps $-W_{MAXch}$, $-(W_{MAXch}+P_X)/2$, $-P_X$, $-(P_X+P_{low})/2$, $-P_{low}$, 0, P_{low}, $(P_X+P_{low})/2$, P_X, $(W_{MAXdch}+P_X)/2$ and W_{MAXdch}, executed with different values of Power Factor, in accordance with Table 6-5. Each power level must be held for the greater of 5 seconds and $2 \cdot t_S$.

#	PF_{BESS}	Ramp time, t_R (s)	Time window, t_W (s)	Timeout, t_{out} (s)
1	1	0	0	0
2	$PF_{midover}$	0	0	0
3	$PF_{minover}$	0	0	0

4	$PF_{midunder}$	0	0	0
5	$PF_{minunder}$	0	0	0

Table 6-5: INV3 Test Matrix.

6.4.2 INV3 Timing Test

The Commanded Power Factor timing tests consist of two steps from power factor equal to unity to the minimum overexcited power factor $PF_{minover}$ and back to unity and from power factor equal to unity to the minimum underexcited power factor $PF_{minunder}$ and back to unity, performed with active power set to P_X and $-P_X$. Each power step is held for a minimum test duration (timing interval) equal to the greater of 5 seconds and $2 \cdot (t_R + t_W + t_{out})$ or $2 \cdot t_S$. The ramp times are calculated from the ramp rates using $t_R = 1/r_R$. If the maximum ramp time or maximum time window defined by the manufacturer exceeds 5 minutes, they may be changed to 5 minutes in order to complete the tests in a reasonable amount of time.

#	Ramp time, t_R (s)	Time window, t_W (s)	Timeout, t_{out} (s)
Default	0	0	0
t1	$t_{R\_max}/2$	0	0
t2	t_{r_max}	0	0
t3	0	$t_{W\_max}/2$	0
t4	0	t_{W_max}	0
t5	0	0	$t_{out\_max}/2$
t6	0	0	t_{out_max}

Table 6-6: INV3 timing setting test matrix.

6.5 INV3 Function test sequence

The commanded power factor test shall be carried out as follows:

Step 1: Prepare the EUT according to the following.

- Configure EUT and energy storage element according to Section 2.
- Connect to Utility Simulator with operation within nominal voltage range for a minimum of 5 minutes.
- Verify EUT is powered on to a level required to receive the command.
- Verify energy storage state of charge (SOC) will not interfere with VV13 tests. If the SOC is near SOC_{opMAX} or SOC_{opMIN}, charge or discharge the BESS system until close to: $(SOC_{opMAX} + SOC_{opMIN})/2$.
- Establish communication to EUT with Utility Management System (UMS).

- Record EUT output (e.g., voltage, current, power) with data acquisition system according to Section 2.2.
- Set Active and Reactive Power to zero.

Step 2: Request status from EUT and record the EUT parameters.

Step 3: Send default timing parameters to EUT according to Table 6-6.

Step 4: Confirm timing parameters are updated in the EUT.

Step 5: Set the EUT active power to required power level (starting value 0).

Step 6: Send INV3 Power Factor settings according to the test required in Table 6-5.

Step 7: Record EUT response for the test duration, where the test duration is defined as the greater of 5 seconds and $2 \cdot t_S$.

Step 8: Repeat Steps 3-7 with the EUT active power set to $-W_{MAXch}$, $-(W_{MAXch}+P_X)/2$, $-P_X$, $-(P_X+P_{low})/2$, $-P_{low}$, 0, P_{low}, $(P_X+P_{low})/2$, P_X, $(W_{MAXdch}+P_X)/2$ and W_{MAXdch}.

Step 9: Repeat Steps 3-8 according to the tests defined in Table 6-5 (INV3 domain tests).

Step 10: Set Active Power to P_X or to $-P_X$.

Step 11: Step the commanded Power Factor through the sequence: unity, $PF_{minover}$, unity, $PF_{minunder}$, unity according to Section 6.4.2.

Step 12: Repeat Steps 10-11 with new the timing parameters based on the FCT (Timing tests).

Step 13: Analyze performance data.

6.6 Acceptance criteria

Acceptance criteria are determined using the definitions provided in the grid code.

6.6.1 Default criteria

The maximum difference between the measured power factor and the PF setting must be less than MSA_{PF} plus the DAS PF accuracy. The maximum difference between the measured time response and the time response settings must be less than MSA_t plus the DAS time accuracy.

7 FREQUENCY/WATT "P(F)" TEST (FW)

7.1 Function definition

FW function enables the inverter to have multiple curves which describe limits placed on power production/absorption based on frequency changes; one or more frequency-watt curves are used to *control* active power generation and charging (in the case of a storage system). If frequency increases, power generation is reduced (and, if requested, also charging is enabled) to maintain nominal grid frequency. If frequency falls, storage charging rates are limited (and if requested also discharge and power generation is activated) to maintain nominal grid frequency.

Frequency-triggered management is used to mitigate grid frequency deviations by increasing or decreasing power supplied by the DER. Such actions may be taken during emergency conditions, or this capability may be used during normal operations to "smooth" minor frequency variations, such as in a microgrid.

This function is defined for a general case applicable to all codes or rules. Parameter and test matrixes definition takes into account specific national requirements. In particular the test procedure evaluates the functionality required in:

- CEI 0-21
- CEI 0-16
- IEC 61850-90-7
- UL 1741 SA
- VDE-AR-N 4105
- CLC/TS 50549

Country/ Grid Code	Data Requirements	Specified Curve	Time Parameters
Italy/CEI 0-21: 2014-12 (LV) **and** **Italy/CEI 0-16: 2014-12(MV)**	P, f measured (0.2 s average)	The external FW profile is: (50 Hz, W_{MAXdch}); (50.3 Hz, W_{MAXdch}); (51.5 Hz, W_{MAXch}); (50 Hz, W_{MAXch}); (49.7 Hz, W_{MAXch}); (47.5 Hz , W_{MAXdch}) Hysteresis Enable, Tie Line Enable, QuadExit Enable	Time window, Recovery ramp rate, Recovery delay
International /	P, f_{rms} measured	Multiple curves, e.g., Test 1:	Ramp Rate, Time Delay,

IEC 61850-90-7[65]	(1 s average), communications recorded	F_1 = 100.3%, PG_1 = 0% F_2 = 101.7%, PG_2 = -15% F_3 = 104.0%, PG_3 = -80%	Timeout
US California/ UL 1741 SA: 2016	P, f measured	Multiple curves F_1 = fstart_min, $PG_1 = W_{MAXdch}$ F_2 = fstart_min + 100%$P_{rated}/K_{Power\text{-}Freq}$, PG_2 = 0%	

Table 7-1: Review of Grid Codes for the Freq-Watt function.

7.2 Parameters

Before starting the FW test, the following parameters will be determined by the manufacturer and test engineer for use in the procedure.

Parameter	Notes
FW Curve y[66]	Arrays of $(F_x,P_x)_y$ pairs where x is the point number and y is the FW quadrant.
FW Curve yh	Arrays of $(F_x,P_x)_{yh}$ pairs where x is the point number, y is the FW quadrant, and h indicates a hysteresis curve.
TL	Tie-line setting: when the tie-line is enabled the EUT must follow a line from the EUT power at F_{n-1} to (F_n, P_n) for curve 1 and must follow a line from the EUT power at F_2 to (F_1, P_1) for curve 3. See Figure 7-4 for an illustrative example of operation with tie-lines enabled.
$Hz_{TL,hi}$	AC over-frequency where tie-line effect begins (Hz)
$Hz_{TL,lo}$	AC under-frequency where tie-line effect begins (Hz)
QuadExit	When enabled, the EUT is required to reverse the active power flow to compensate for the frequency deviation.
Hys_{enable}	Turn on/off Hysteresis
t_W	Time window is an optional parameter in which the function is enabled after a delay. The delay can be random or fixed. If the time delay is zero, the command will execute immediately.

65 Evaluated with the Sandia Interoperability Test Protocols

66 While it is possible for FW function reference parameters to be specified in a number of ways in the grid code or EUT, for this protocol, the FW curves will be defined with (F, P) points.

r_R	Requested ramp rate (%P_{rated}/s) is an optional parameter defining the slope the EUT must move from the current set point to the new set point. The corresponding Requested ramp time $t_R=1/r_R$ expresses the time for full execution.
t_{RD}	Recovery delay is an optional parameter expressing the minimum waiting time during the recovery phase.
r_{Rec}	Recovery ramp rate (%P_{rated}/s) is an optional parameter defining how quickly the EUT output returns to normal (default) values after frequency reenters into the no-regulation range. The corresponding recovery ramp time, $t_{Rec}=1/r_{Rec}$ expresses the time for full execution.
t_{out}	Timeout period is an optional parameter that defines the time after which the EUT will reset the frequency-watt function and set the active power to a default value. The default timeout period is indefinite (timeout period = 0 – Not Enable).

Table 7-2: FW parameters.

Parameter	Notes
W_{MAXch}	Maximum charge active power rating (W), negative value
W_{MAXdch}	Maximum discharge active power rating (W), positive value[67]
[Hz_{min}, Hz_{max}]	AC frequency allowed operating range (Hz)
Hz_{nom}	AC nominal frequency (Hz)
MSA_{Hz}[68]	AC frequency accuracy (Hz or %Hz)
MSA_w	Output Power accuracy (W or %W)
MSA_t	Accuracy of time (s)

[67] Grid-centric nomenclature from IEC 61850-90-7 is adopted here.

[68] The manufacturer's stated accuracy is necessary for some of the pass/fail criteria in certain grid codes, e.g., UL 1741 SA. It is also used for general acceptance criteria.

SOC_{opMAX}	Maximum operative state of charge at maximum charge power (%)[69]
SOC_{opMIN}	Minimum operative state of charge at maximum discharge power (%)
$[t_{W\_min}, t_{W\_max}]$	Adjustment range of time window (s). t_{W_min} will be 0 for most EUTs.
$[r_{R\_min}, r_{R\_max}]$	Adjustment range of the ramp rate ($\%P_{rated}$/s)
$[t_{RD\_min}, t_{RD\_max}]$	Adjustment range of recovery delay time (s). t_{RD_min} will be 0 for most EUTs.
$[r_{Rec\_min}, r_{Rec\_max}]$	Adjustment range of the rate of return to normal operation ($\%P_{rated}$/s)
$[t_{out\_min}, t_{out\_max}]$	Adjustment range of timeout period (s). t_{out_min} will be 0 for most EUTs.
t_S	Settling time (s)

Table 7-3: Manufacturer parameters.

FW allows more than one frequency-watt curve to be specified. Furthermore, frequency-watt settings may be different in under or over frequency conditions. In order to define FW inverter response, set-up parameters must be configured in the EUT.

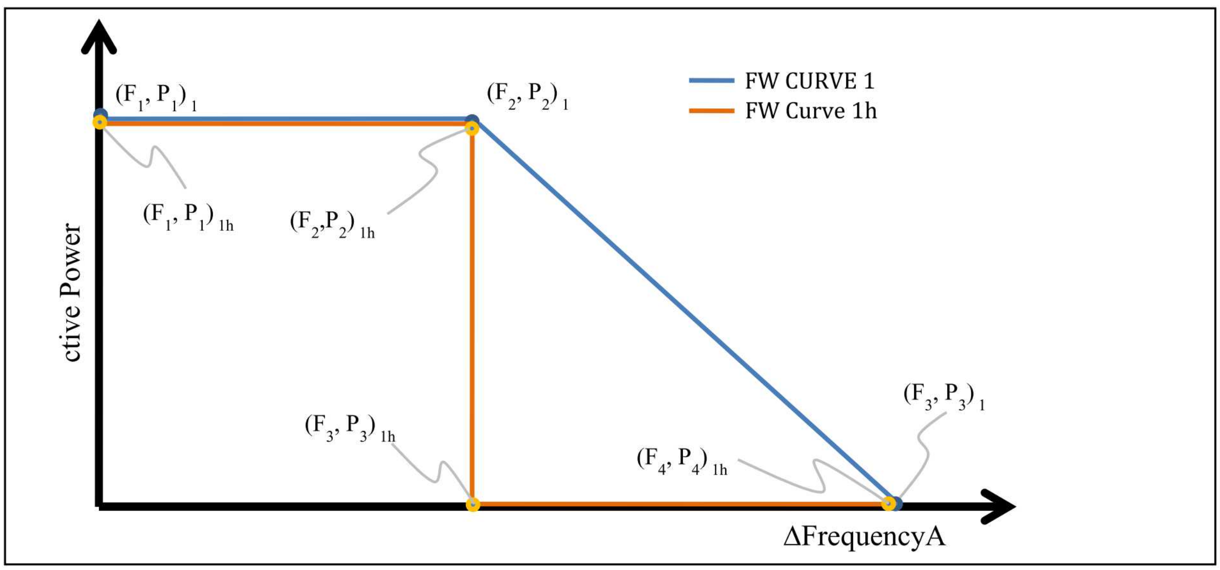

Figure 7-1: Example FW points definition.

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[69] This information can also be provided in tabular or function formats with active power limits vs SOC level.

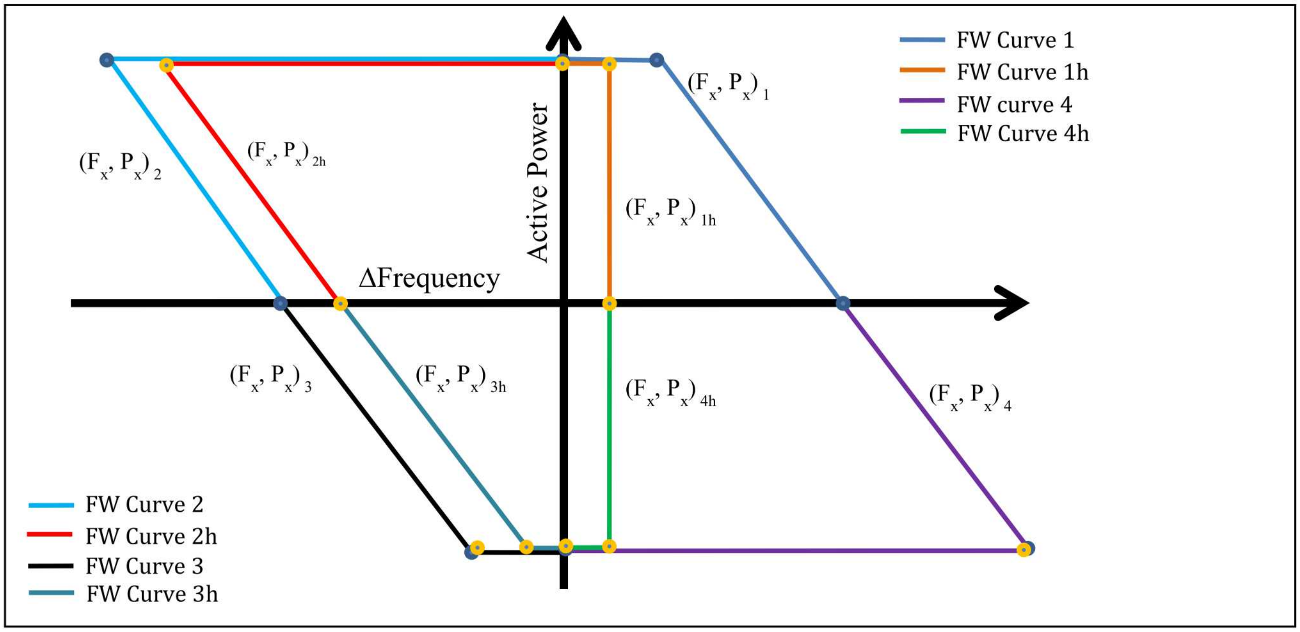

Figure 7-2: Example FW curves. In quadrants 1 and 4 there is an example of asymmetric hysteresis and in quadrants 2 and 3 there is an example of symmetric hysteresis.

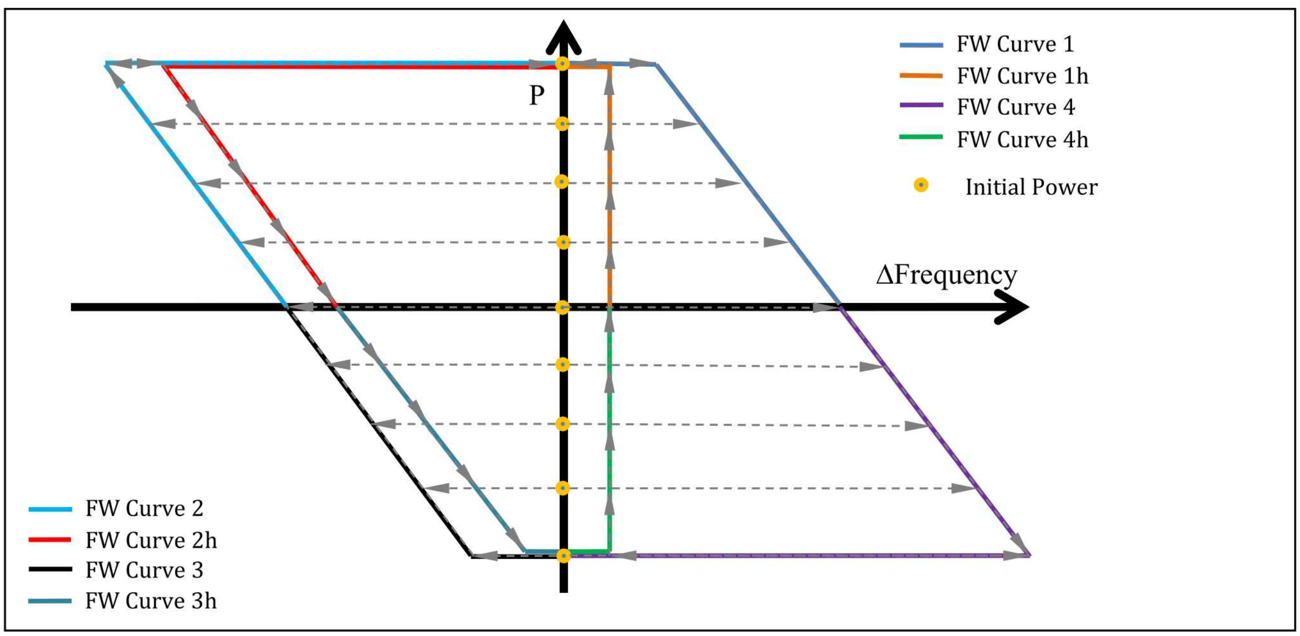

Figure 7-3: Example FW response with hysteresis, QuadExit = 1, and TL = 0.

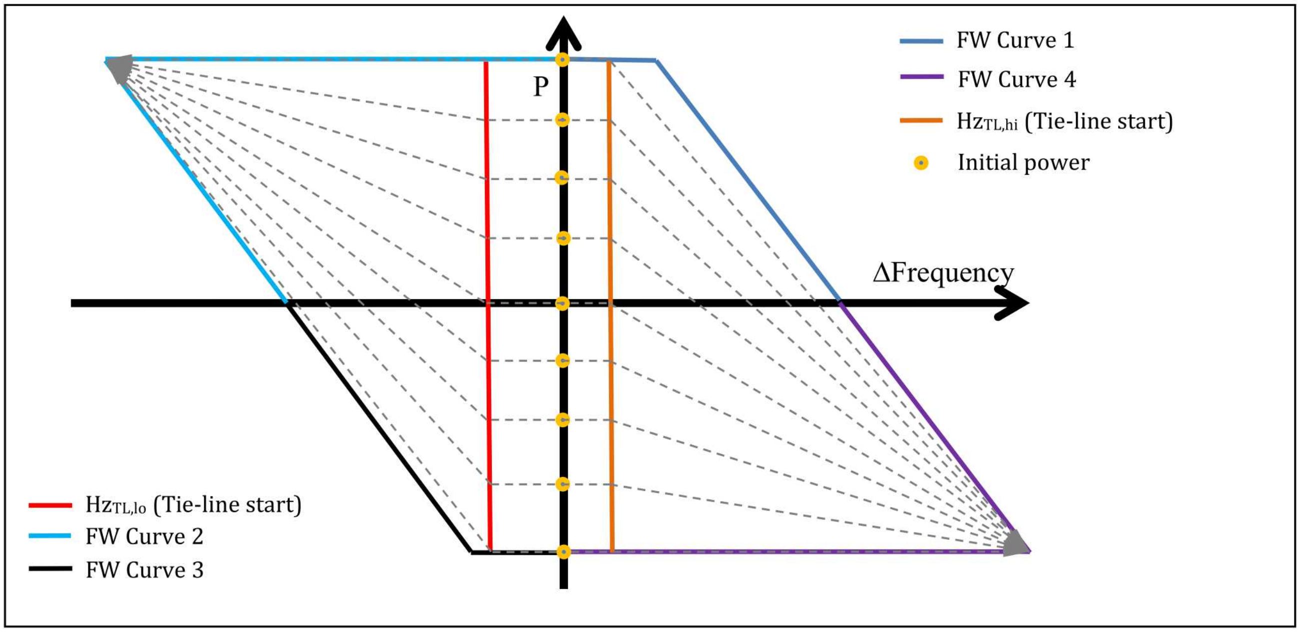

Figure 7-4: Example FW response with no hysteresis, QuadExit = 1, and TL = 1.

Depending on grid code, timing parameters can assume different values. The following figures show the FW function time domain behavior in under-frequency and in over-frequency. Examples with and without hysteresis are included. Also the timing response of the FW function with timing parameters set to zero is shown.

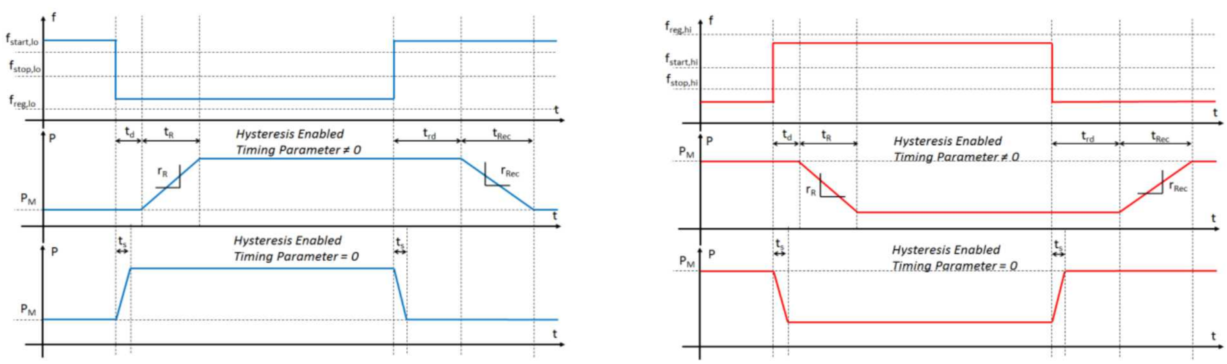

Figure 7-5 Time domain FW function – Asymmetric Hysteresis Enabled in under-frequency (left side) and in over-frequency (right side).

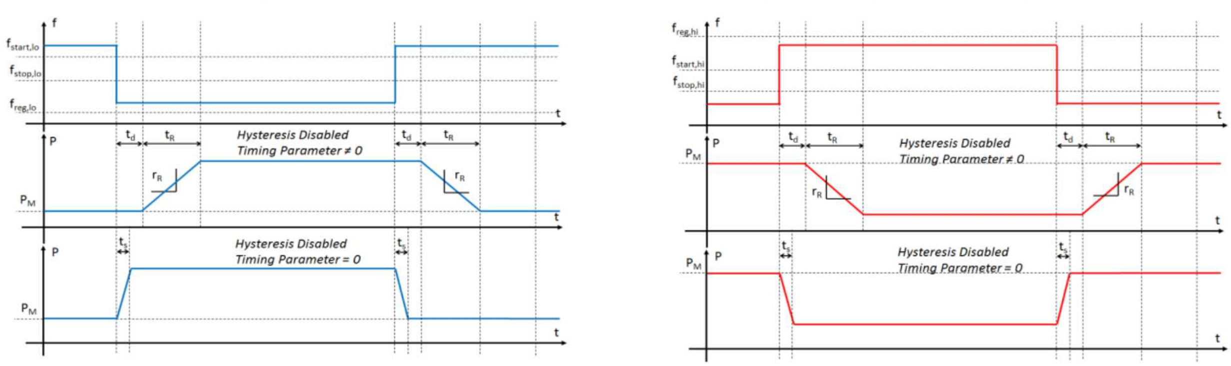

Figure 7-6 Time domain FW function – Asymmetric Hysteresis Disabled in under-frequency (left side) and in over-frequency (right side).

7.3 Function Capability Table (FCT)

The FCT should be filled out based on the capabilities of the EUT. Two different tests are foreseen: FW Domain Test and Time Domain Test. The possible FW modes to be tested depend on:

- Tie-line setting
- QuadExit
- Hysteresis
- Timing parameters:
    - ramp time, t_R
    - recovery delay time, t_{RD}
    - recovery ramp time, t_{Rec}
    - time window, t_W
    - timeout, tout

For general test case FCT table is as follow; specific rules/codes test are also included in Table 7-6 and Table 7-7. Generally, not all test are required: depending on FW modes it is possible to choose the corresponding FW test curves.

Test Type	*Hysteresis*	*Quad Exit*	*Tie Line*	*FW test number*
FW domain	No	No	No	Test #1 in Table 7-7
	No	Yes	No	Test #2 in Table 7-7
	No	No	Yes	Test #3 in Table 7-7
	No	Yes	Yes	Test #4 in Table 7-7
	Yes	No	No	Test #5 in Table 7-7
	Yes	Yes	No	Test #6 in Table 7-7
	Yes	No	Yes	Test #7 in Table 7-7
	Yes	Yes	Yes	Test #8 in Table 7-7

Table 7-4 Function Capability Table for FW domain test.

Test Type	*Hysteresis*	*Time window & Ramp time*	*Timeout*	*Timing test number*
Time	No	No	No	Test #t1 default in Table 7-8
	No	Yes	No	Test #t2 and Test #t3 in Table 7-8

domain	Yes	No	No	Test #t4 and Test #t5 in Table 7-8
	Yes	Yes	No	Test #t6 and Test #t7 in Table 7-8
	No	No	Yes	Test #t8 and Test #t9 in Table 7-8

Table 7-5 Function Capability Table for FW timing test.

7.4 FW Function Test Definition

7.4.1 FW Domain Test

FW domain test verifies the EUT operation according to the required test condition as defined in FCT (Table 7-4). Test will be performed setting up the EUT on the basis of the FW test curves as in Table 7-7.

Each test is executed at eleven different starting active power levels ranging from W_{MAXch} and $W_{MAXdch,}$ with reactive power set to 0. For each power level, test is carried out at different frequency values adjusted, with a grid simulator, between Hz_{min}+Δf[70] and Hz_{max} -Δf in order to avoid the EUT disconnection at the frequency limits. Along each of the FW trajectory lines defined by FW test curves a minimum of 5 points[71] is required. Each point must be held for the greater of 5 seconds and $2 \cdot t_S$. Figure 7-7 shows an example of the frequency test points required.

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[70] Δf is calculated as the composed accuracy of the EUT frequency measurement accuracy and the grid simulator frequency setup accuracy. A typical value defined in codes/rules could be about 10 mHz.

[71] This can be adjusted if National Codes/Rules require a different number of points. A minimum of three frequency settings will be used, but additional test points maybe necessary. The frequency between points should be large enough to resolve the watt accuracy of the EUT for the function.

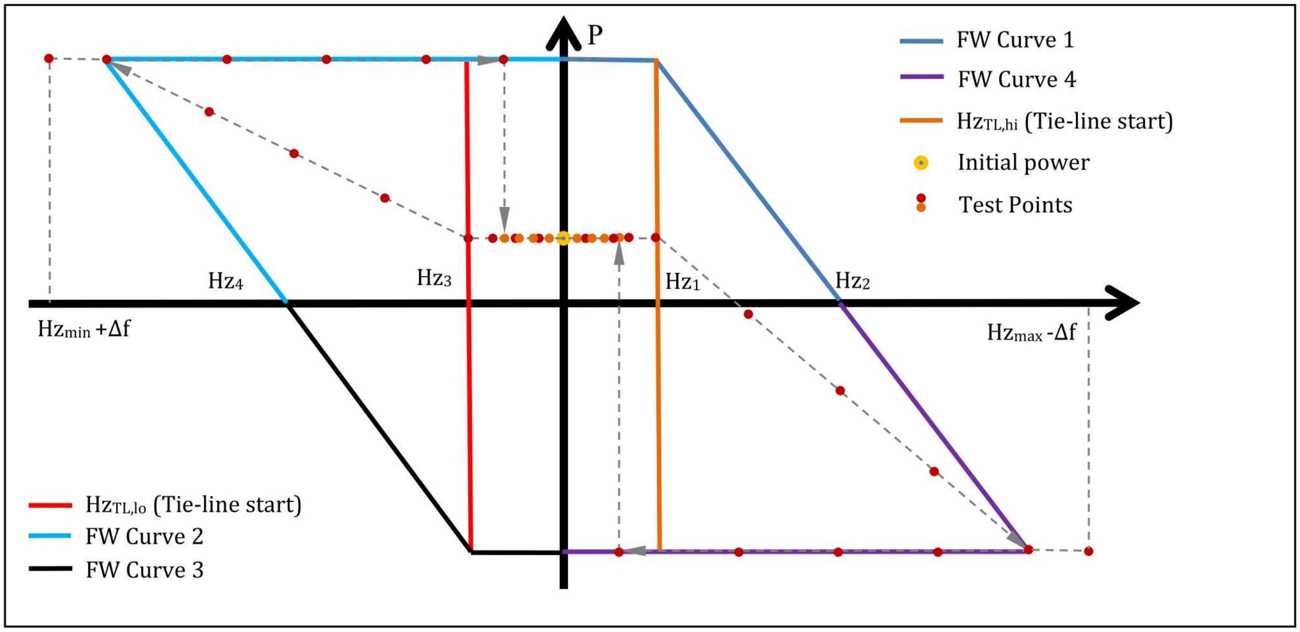

Figure 7-7: Frequency points required for FW Domain tests. The points are traced with the grid simulator to reach the hysteresis values.

Where the value Hz_1, Hz_2, Hz_3 and Hz_4 can be defined as follow:

$Hz_1 = Hz_{nom} + 0.3$[72] $\cdot (Hz_{Max} - Hz_{nom})$ (over-frequency regulation threshold)

$Hz_2 = Hz_1 + \frac{Hz_{Max} - Hz_1}{W_{MAXdch} - W_{MAXch}} \cdot W_{MAXdch}$ (over-frequency curve 1 and curve 4 intersection point)

$Hz_3 = Hz_{nom} - 0.3 \cdot (Hz_{nom} - Hz_{min})$ (under-frequency regulation threshold)

$Hz_4 = Hz_3 - \frac{Hz_3 - Hz_{Min}}{W_{MAXdch} - W_{MAXch}} \cdot -W_{MAXch}$ (under-frequency curve 2 and curve 3 intersection point)

[72] This value can be changed according to specific codes/rules request

		Format: $P(f) = [(f_x,P_x)_y]$ where y is the quadrant
Generic FW and Hysteresis Test Curves	FW Test Curve 1	Quadrant 1: $[(Hz_{nom},W_{MAXdch})_1; (Hz_1,W_{MAXdch})_1; (Hz_2,0)_1; (Hz_{max},0)_1]$ Quadrant 2: $[(Hz_{nom},W_{MAXdch})_2; (Hz_{min}, W_{MAXdch})_2; (Hz_{min},0)_2]$ Quadrant 3: $[(Hz_{nom},W_{MAXch})_3; (Hz_3,W_{MAXch})_3; (Hz_4,0)_3; (Hz_{min},0)_3]$ Quadrant 4: $[(Hz_{nom},W_{MAXch})_4; (Hz_{max},W_{MAXch})_4; (Hz_{max},0)_4]$
	FW Test Curve 2	Quadrant 1: $[(Hz_{nom},W_{MAXdch})_1; (Hz_1,W_{MAXdch})_1; (Hz_2,0)_1]$ Quadrant 2: $[(Hz_{nom},W_{MAXdch})_2; (Hz_{min}, W_{MAXdch})_2; (Hz_4,0)_2]$ Quadrant 3: $[(Hz_{nom},W_{MAXch})_3; (Hz_3,W_{MAXch})_3; (Hz_4,0)_3]$ Quadrant 4: $[(Hz_{nom},W_{MAXch})_4; (Hz_{max},W_{MAXch})_4; (Hz_2,0)_4]$
	Hysteresis Test Curve 1	Quadrant 1: $[(Hz_{max},0)_{1h1}; (Hz_2,0)_{1h1}; (Hz_{HysHi},0)_{1h1}; (Hz_{HysHi}, W_{MAXdch})_{1h1}; (Hz_{nom},W_{MAXdch})_{1h1}]$ Quadrant 2: $[(Hz_{min}, W_{MAXdch})_{2h}; (Hz_{HysLo}, W_{MAXdch})_{2h}; (Hz_{HysLo},0)_{2h}]$ Quadrant 3: $[(Hz_{min},0)_{3h}; (Hz_3,0)_{3h}; (Hz_{HysLo},0)_{3h}; (Hz_{HysLo}, W_{MAXch})_{3h}; (Hz_{nom},W_{MAXch})_{3h}]$ Quadrant 4: $[(Hz_{max},W_{MAXch})_{4h}; (Hz_{HysHi}, W_{MAXch})_{4h}; (Hz_{HysHi},0)_{4h}]$
	Hysteresis Test Curve 2	Quadrant 1: $[(Hz_{max},0)_{1h}; (Hz_{HysHi},0)_{1h}; (Hz_{HysHi}, W_{MAXdch})_{1h}; (Hz_2,W_{MAXdch})_{1h}]$ Quadrant 2: $[(Hz_{min}, W_{MAXdch})_{2h}; (Hz_{HysLo}, W_{MAXdch})_{2h}; (Hz_{HysLo},0)_{2h}]$ Quadrant 3: $[(Hz_4,0)_{3h}; (Hz_{HysLo},0)_{3h}; (Hz_{HysLo}, W_{MAXch})_{3h}; (Hz_{nom},W_{MAXch})_{3h}]$ Quadrant 4: $[(Hz_{max},W_{MAXch})_{4h}; (Hz_{HysHi}, W_{MAXch})_{4h}; (Hz_{HysHi},0)_{4h}]$
Grid Code Specific FW and Hysteresis Test Curves	CEI 0-16/21 FW Test Curve	Quadrant 1: $[(Hz_{nom},W_{MAXdch})_1; (100.6,W_{MAXdch})_1; (101.8,0)_1]$ Quadrant 2: $[(Hz_{nom},W_{MAXdch})_2; (98.2,W_{MAXdch})_2; (98.8,0)_2]$ Quadrant 3: $[(Hz_{nom},W_{MAXch})_3; (99.4,W_{MAXch})_3; (98.8,0)_3]$ Quadrant 4: $[(Hz_{nom},W_{MAXch})_4; (103,W_{MAXch})_4; (101.8,0)_4]$
	CEI 0-16/21 Hysteresis Test Curve	Quadrant 1: $[(Hz_{nom},W_{MAXdch})_{1h1}; (100.2,W_{MAXdch})_{1h1}; (100.2,0)_{1h1}]$ Quadrant 2: $[(98.2,W_{MAXdch})_{2h2}; (99.8,W_{MAXdch})_{2h2}; (99.8,0)_{2h2}]$ Quadrant 3: $[(Hz_{nom},W_{MAXch})_{3h3}; (99.8,W_{MAXch})_{3h3}; (99.8,0)_{3h3}]$ Quadrant 4: $[(103,W_{MAXch})_{4h4}; (100.2,W_{MAXch})_{4h4}; (100.2,0)_{4h4}]$
	VDE 4105 FW Test	Quadrant 1: $[(Hz_{nom},W_{MAXdch})_1; (100.4,W_{MAXdch})_1; (103, 0.52^* W_{MAXdch})_1;$

	Curve	$(103,0)_1]$ Quadrant 2: $[(97,W_{MAXdch})_2; (Hz_{nom},W_{MAXdch})_2;]$ Quadrant 3: $[(97,W_{MAXch})_3; (Hz_{nom},W_{MAXch})_3;]$ Quadrant 4: $[(Hz_{nom},W_{MAXch})_4; (103,W_{MAXch})_4;]$
	IEC 61850-90-7 FW Test Curve	Quadrant 1: $[(Hz_{nom},W_{MAXdch})_1; (100.3,W_{MAXdch})_1; (101.7,0.85*W_{MAXdch})_1; (104,0.2*W_{MAXdch})_1]$

Table 7-6: FW Test Curves.

	Test #	Curves		$Hz_{TL,hi}$	$Hz_{TL,lo}$
		FW Curve	*Hysteresis Curve*		
Generic FW and Hysteresis Test Curves	1	FW Test Curve 1			
	2	FW Test Curve 2			
	3	FW Test Curve 1		Hz_1	Hz_3
	4	FW Test Curve 2		Hz_1	Hz_3
	5	FW Test Curve 1	Hysteresis Test Curve 1		
	6	FW Test Curve 2	Hysteresis Test Curve 2		
	7	FW Test Curve 1	Hysteresis Test Curve 1	Hz_1	Hz_3
	8	FW Test Curve 2	Hysteresis Test Curve 2	Hz_1	Hz_3
Grid Code Specific FW and Hysteresis Test Curves	9	CEI 0-16/21 FW Test Curve	CEI 0-16/21 Hysteresis Test Curve	*100.6 (e.g., 50.3 Hz)*	*99.4 (e.g., 49.7 Hz)*
	10	VDE 4105 FW Test Curve			

	11	IEC 61850-90-7 FW Test Curve		100.3	

Table 7-7: FW Test Matrix; FW Test Curves are defined in Table 7-6.

7.4.2 FW Timing Test

The Frequency-Watt timing tests consist of two steps from the nominal frequency to $Hz_{min} + \Delta f$ and back to nominal frequency or from the nominal frequency to $Hz_{max} - \Delta f$ and back to nominal frequency. Each frequency step is held for a minimum test duration (timing interval) equal to the greater of 5 seconds and $2 \cdot (t_R + t_{RD} + t_{Rec} + t_W + t_{out})$ or $2 \cdot t_S$, as defined in Table 7-2 and in Figure 7-5 and Figure 7-6.

	Test #	Ramp time, t_R (s)	Recovery Delay time, t_{RD} (s)	Recovery ramp time, t_{Rec} (s)	Time window, t_W (s)	Timeout, t_{out} (s)
Generic FW and Hysteresis Test Curves	t1 DEFAULT	0	0	0	0	0
	t2	$t_{R\_max}/2$	0	0	$t_{W\_max}/2$	0
	t3	t_{R_max}	0	0	t_{W_max}	0
	t4	0	$t_{RD\_max}/2$	$t_{Rec\_max}/2$	0	0
	t5	0	t_{RD_max}	t_{Rec_max}	0	0
	t6	$t_{R\_max}/2$	$t_{RD\ max}/2$	$t_{Rec\_max}/2$	$t_{W\_max}/2$	0
	t7	t_{R_max}	t_{RD_max}	t_{Rec_max}	t_{W_max}	0
	t8	0	0	0	0	$t_{out\_max}/2$
	t9	0	0	0	0	t_{out_max}
Grid Code Specific FW and Hysteresis Test Curves	1 (CEI 0-16/21)	0	300	300	0	0
	2 (CEI 0-16/21)	0	300	300	1	0

Table 7-8: FW timing setting test matrix[73].

[73] The test must be repeated starting from different power levels; a minimum of five is necessary.

7.5 FW Function test sequence

The FW test shall be carried out as follows:

Step 1: Prepare the EUT according to the following:

- Configure EUT and energy storage element according to Section 2.1.
- Connect to Utility Simulator with operation within nominal voltage range for a minimum of 5 minutes.
- Verify EUT is powered on to a level required to receive the command.
- Verify energy storage state of charge (SOC) will not interfere with FW tests. If the SOC is near SOC_{opMAX} or SOC_{opMIN}, charge or discharge the BESS system until close to: $(SOC_{opMAX} + SOC_{opMIN})/2$.
- Establish communication to EUT with Utility Management System (UMS).
- Record EUT output (e.g., voltage, current, power) with data acquisition system according to Section 2.2.
- Set Reactive Power to zero.

Step 2: Request status from EUT and record the EUT parameters.

Step 3: Send FW (F, P) pairs according to required test as in Table 7-7.

Step 4: Confirm FW parameters are updated in the EUT.

Step 5: Send default timing parameters to EUT according to Table 7-8.

Step 6: Set the EUT power to required power level (starting value 0).

Step 7: Adjust the grid frequency to the required grid frequency points: 5 points per line including also line to $Hz_{min} + \Delta f$ and $Hz_{max} - \Delta f$ points. The tests will follow this sequence: Hz_{nom} to $Hz_{max} - \Delta f$ to Hz_{nom} to $Hz_{min} + \Delta f$ and to Hz_{nom}.

Step 8: Set the timing parameters according to Table 7-8.

Step 9: Step the grid frequency to $Hz_{min} + \Delta f$ and $Hz_{max} - \Delta f$ according to Section 7.4.2.

Step 10: Repeat Steps 8-9 new the timing parameters based on the FCT (Timing tests).

Step 11: Repeat Steps 5-10 with the EUT power set to 100%*W_{MAXch} to 20%*W_{MAXch} in steps of 20%*W_{MAXch} and 100%*W_{MAXdch} to 20%*W_{MAXdch} in steps of 20%*$W_{MAXdch.}$

Step 12: Repeat Steps 3-11 with FW new pairs based on the FCT (FW domain tests).

Step 13: Analyze performance data.

Note: if only FW domain is tested, steps 8-10 are skipped. If only time domain is tested, step 7 is skipped.

7.6 Acceptance criteria

Acceptance criteria are determined using the definitions provided in the grid code. The following sections contain different acceptance criteria.

7.6.1 Default requirements

The maximum difference between the programmed expected output and response is less or equal than the manufacturer's stated power accuracy (MSA_P) at any frequency defined by the region f_{test} ± (MSA_{Hz} plus the DAS frequency accuracy). The maximum difference between the programmed response time and actual response is less or equal than the manufacturer's stated time accuracy (MSA_t) plus the DAS time accuracy.

7.6.2 Italian technical rules

The EUT active power error is less than ±2.5% of the EUT nameplate apparent power.

7.6.3 UL 1741 SA Draft Criteria

For each frequency step, the EUT should remain within the stated accuracy of the P(f) characteristic except when the frequency is changing. The EUT shall obtain the P(f) characteristic within its stated accuracy within the stated settling time. For rising frequency (and for falling frequency with hysteresis disabled), the EUT shall be considered in compliance if, for each line cycle after the manufacturer's stated settling time t_s has passed following a frequency change (see Figure 7-8), the measured (f, P) data point falls within the boundaries shown in Figure 7-9 and Figure 7-10 below.

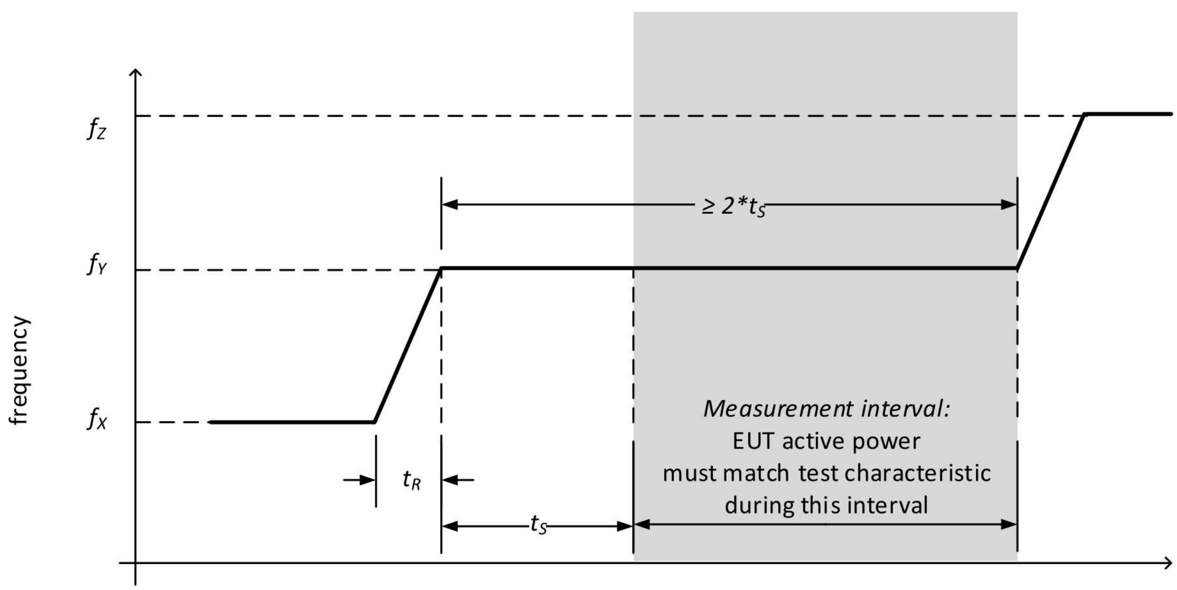

Figure 7-8: Frequency vs. time during a portion of the frequency-watt test.

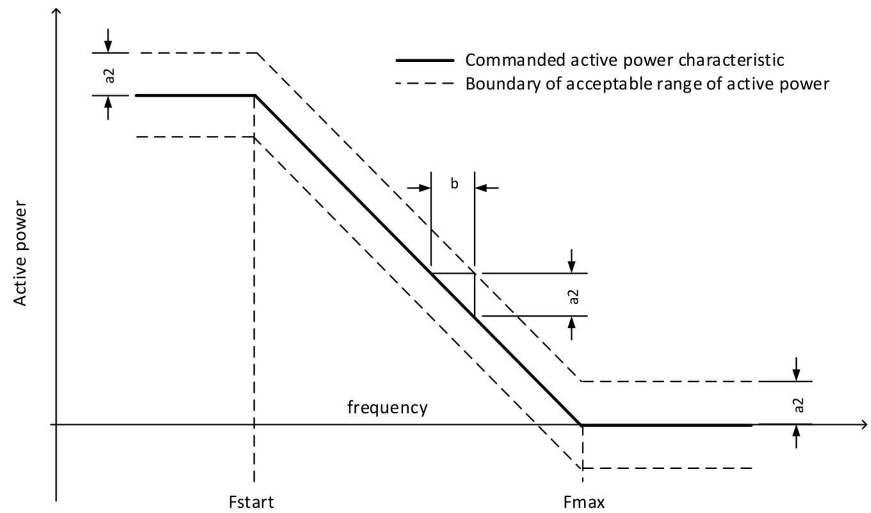

Figure 7-9: Frequency-Watt test criteria. $a_2 = MSA_P$, $b = MSA_{Hz}$.

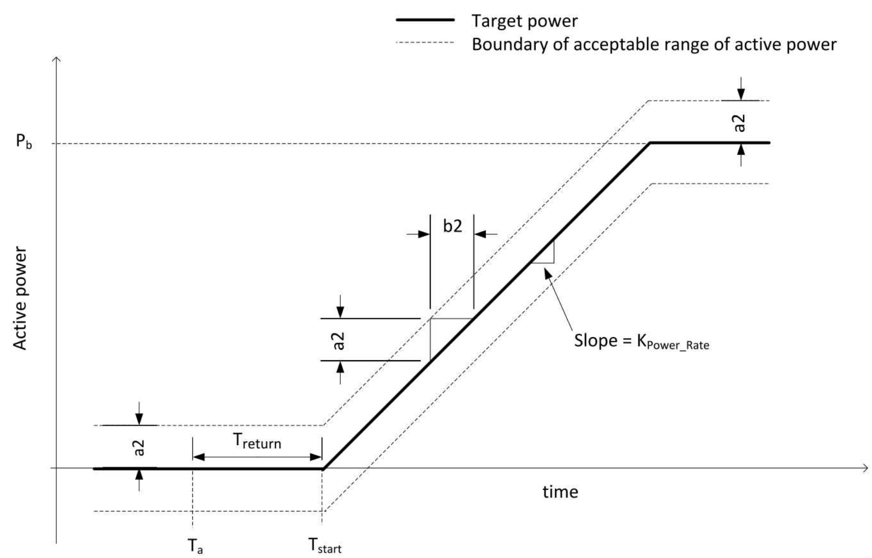

Figure 7-10: Frequency-Watt test criteria during return to nominal power with hysteresis enabled. T_a is the time the frequency reaches F_{stop}. $T_{start} = t_a + t_{return}$. $a_2 = MSA_P$. $b_2 = MSA_t$. P_b is the nominal power for the test.

8 VAR-PRIORITY VOLT-VAR "Q(V)" TEST (VV12)

In order to maintain a stable grid voltage, it is desired that inverters be able to source or sink reactive power. One way to achieve this is to have the inverter source or sink reactive power in response to fluctuations in grid voltage. This test verifies that the EUTs volt-var mode implements the reactive power response to fluctuations in grid voltage according to a stepwise Q(V) curve. The var-priority function is defined in IEC 61850-90-7 as VV12.

8.1 Function definition

This function defines how a BESS will provide reactive power support to the grid during a voltage deviation. This test procedure evaluates the functionality required in:

- CEI 0-21
- CEI 0-16
- IEC 61850-90-7
- VDE-AR-N 4105 Germany/FGW - TR3 Rev23 (optional test)
- CLC/TS 50549
- UL 1741 SA
- Austria ÖVE/ÖNORM EN50438 (optional - in accordance with DSO, e.g. function used by local DSO --Vorarlberg Netz)

Country/ Grid Code	Data Requirements	Specified Curve	Default Values
Italy/CEI 0-21: 2014-12 (LV) **and** **Italy/CEI 0-16: 2014-12(MV)**	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	• 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	$V_1 = V_2 - Q_1/KVAR_{max}$, $Q_1 = Q_{max,cap}$ $V_2 = V_n - Deadband_{min}/2$, $Q_2 = 0$ $V_3 = V_n + Deadband_{min}/2$, $Q_3 = 0$ $V_4 = Q_4/KVAR_{max} + V_3$, $Q_4 = Q_{max,ind}$

	output current.	• V_4 = voltage at Q_4	
Germany/ FGW - TR3 Rev23 (optional test)	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.	Additional tests are carried out for PGUs with reactive power control with Q(U) characteristic curve. The voltage steps start at the lowest voltage to the highest voltage and vice versa.	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 Additionally a dynamic of the response must be configurable. (Dynamic according first order filter with adjustable time constant between 3 s and 60 s. Duration until 95 % of the new set point after a voltage deviation is 3-times of the time constant.	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[74]	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% $Q_{MAXover}$ 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% $Q_{MAXunder}$

Table 8-1: Review of Grid Codes for the Volt-var Function

[74] Evaluated with the Sandia Interoperability Test Protocols

8.2 Parameters

Before starting the VV test, the following parameters will be determined by the manufacturer and test engineer for use in the procedure.

Parameter	Notes
VV Curve [75]	Arrays of (V_x,Q_x) pairs where x is the point number
VV Curve h	Arrays of $(V_x,Q_x)_h$ pairs where x is the point number and h indicates a hysteresis curve.
t_W	Time window is an optional parameter in which the function is enabled after a delay. The delay can be random or fixed. If the time delay is zero, the command will execute immediately.
r_R	Requested ramp rate ($\%Q_{rated}/s$) is an optional parameter defining the slope the EUT must move from the current set point to the new set point. The corresponding Requested ramp time $t_R=1/r_R$ express the time for full execution.
t_{RD}	Recovery delay is an optional parameter expressing the waiting time after the grid voltage reaches the hysteresis curve.
r_{Rec}	Recovery ramp rate ($\%Q_{rated}/s$) is an optional parameter defining how quickly the EUT output returns to normal (default) values after voltage reaches the hysteresis curve. The corresponding recovery ramp time $t_{Rec}=1/r_{Rec}$ expresses the time for full execution.
t_{out}	Timeout period is an optional parameter that defines the time after which the EUT will reset the volt-var function and set the reactive power to a default value. The default timeout period is indefinite (timeout period = 0 – Not Enable).

Table 8-2: VV Test Parameters.

Parameter	Notes
W_{MAXch}	Maximum charge active power rating (W) – negative value
W_{MAXdch}	Maximum discharge active power rating (W) – positive value[76]
$Q_{MAXunder}$	Maximum Underexcited Reactive Power[77]
$Q_{MAXover}$	Maximum Overexcited Reactive Power
$[V_{min}, V_{max}]$	AC voltage range with function enabled (V)

[75] While it is possible for VV function reference parameters to be specified in a variety of grid code or EUT, for this protocol, the VV curves will be defined with (V, Q) points.

[76] Grid-centric nomenclature from IEC 61850-90-7 is adopted here.

[77] This protocol follows the IEEE Std-1459-2000 reactive power sign convention, in which an overexcited power factor is positive and an underexcited power factor is negative.

V_{nom}	AC nominal voltage (V)
K_{VARmax}	Maximum Slope (var/V)
[$Deadband_{min}$, $Deadband_{max}$]	Deadband Range (V)
MSA_t[78]	Accuracy of time (s)
MSA_{VAR}	Reactive Power Accuracy (% or var)
MSA_{Vac}	AC voltage accuracy (V)
SOC_{opMAX}	Maximum operative state of charge at maximum reactive power (%)[79]
SOC_{opMIN}	Minimum operative state of charge at maximum reactive power (%)
[t_{W_min}, t_{W_max}]	Adjustment range of time window (s).
[r_{R_min}, r_{R_max}]	Adjustment range of the ramp rate (var/s)
[t_{RD_min}, t_{RD_max}]	Adjustment range of recovery delay time (s). t_{RD_min} will be 0 for most EUTs.
[r_{Rec_min}, r_{Rec_max}]	Adjustment range of the rate of return to normal operation (%Q_{rated}/s)
[t_{out_min}, t_{out_max}]	Adjustment range of timeout period (s)

Table 8-3: Manufacturer parameters.

VV12 allows more than one voltage-var curve to be specified. Furthermore, voltage-var settings may be different in under or over voltage conditions. In order to define VV12 inverter response, set-up parameters must be configured in the EUT.

[78] The manufacturer's stated accuracy is necessary for some of the pass/fail criteria in certain grid codes, e.g., UL 1741 SA. It is also used for general acceptance criteria.

[79] This information can also be provided in tabular or function formats with active power limits vs SOC level.

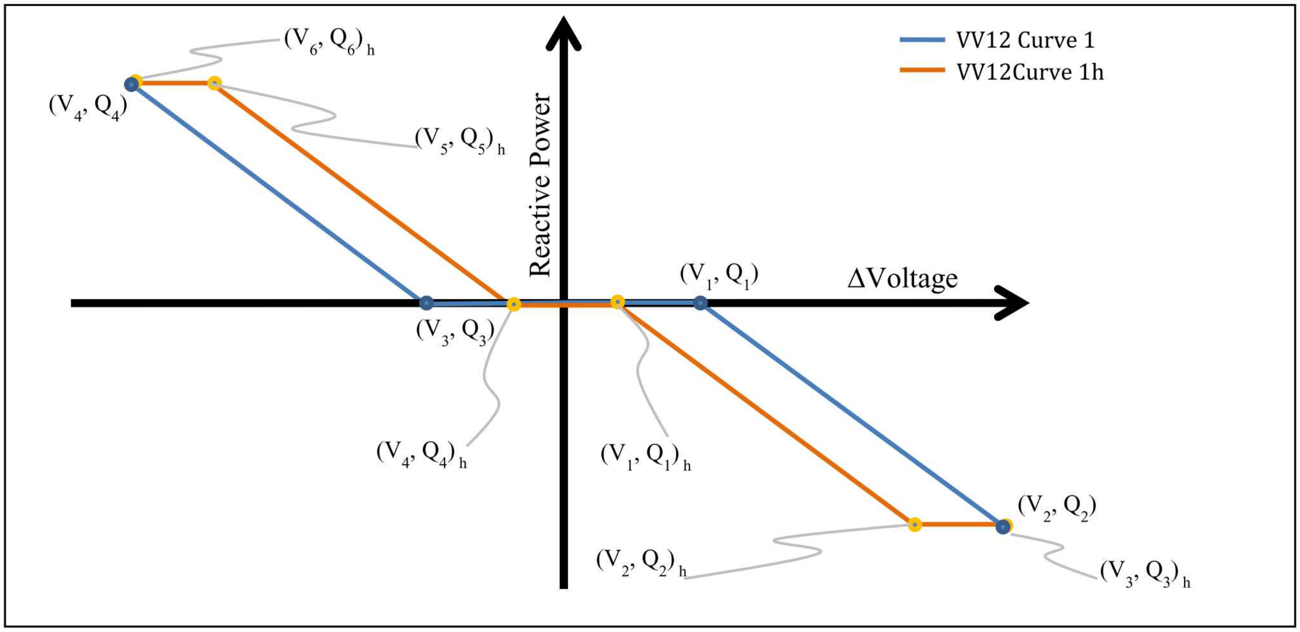

Figure 8-1: Example VV12 points definition

8.3 Function Capability Table (FCT)

The FCT should be filled out based on the capabilities of the EUT. Two different tests are undertaken: VV Domain Test and Time Domain Test. The possible VV modes to be tested depend on:

- Hysteresis
- Reactive Power Offset:
    - Overexcited
    - Underexcited
- Timing parameters:
    - ramp time, t_R
    - time window, t_W
    - timeout, t_{out}

Test Type	*Reactive Power Offset*	*Hysteresis*	*Timing*	*Tests*
VV domain	No	No	Default	Test #1 in Table 7-7
	No	Yes	Default	Test #2 in Table 7-7
	Overexcited	No	Default	Test #3 in Table 7-7
	Overexcited	Yes	Default	Test #4 in Table 7-7
	Underexcited	No	Default	Test #5 in Table 7-7
	Underexcited	Yes	Default	Test #6 in Table 7-7

Table 8-4: VV12 Function Capability Table for VV12 domain test.

Test Type	*Hysteresis*	*Time window & Ramp time*	*Timeout*	*Timing test number*
Time domain	No	No	No	Test #t1 default in Table 8-8
	No	Yes	No	Test #t2 and Test #t3 in Table 8-8
	Yes	No	No	Test #t4 and Test #t5 in Table 8-8
	Yes	Yes	No	Test #t6 and Test #t7 in Table 8-8
	No	No	Yes	Test #t8 and Test #t9 in Table 8-8

Table 8-5 Function Capability Table for VV12 timing test.

8.4 VV12 Function Test Definition

8.4.1 VV12 Domain Test

VV domain test verifies the EUT operation according to the required test condition as defined in FCT (Table 8-4). Test will be performed setting up the EUT on the basis of the VV test curves as in Table 8-6. All the timing parameters will be set to 0. Each test is executed at five different starting active power levels ranging from W_{MAXch} and W_{MAXdch}, with reactive power set to 0. For each power level, test is carried out at different voltage values adjusted, with a grid simulator, between $V_{min}+\Delta V$[80] and $V_{max}-\Delta V$ in order to avoid the EUT disconnection at the voltage limits. Along each of the VV trajectory lines defined by VV test curves a minimum of 3 points[81] is required. Each point must be held for the greater of 5 seconds and $2 \cdot t_S$.

		Format: $Q(V) = [(V_x, Q_x)]$
Generic VV12 and Hysteresis	VV12 Test Curve 1	$[(V_{max}, Q_{MAXunder}); (V_{nom} - Deadband_{min}/2, 0);$ $(V_{nom} + Deadband_{min}/2, 0); (V_{min}, Q_{MAXover})]$

[80] ΔV is calculated as the composed accuracy of the EUT voltage measurement accuracy and the grid simulator voltage setup accuracy. A typical value defined in codes/rules could be about +/-2% ofV_{nom}.

[81] This can be adjusted if National Codes/Rules require a different number of points. A minimum of three AC voltage settings will be used, but additional test points maybe necessary. The voltage between points should be large enough to resolve the var accuracy of the EUT for the function.

Test Curves		
	VV12 Test Curve 2	$[(V_{max},Q_{MAXunder}); (V_{nom} - Deadband_{min}/2,Q_{offset}); (V_{nom} + Deadband_{min}/2,Q_{offset}); (V_{min},Q_{MAXover})]$
	Hysteresis Test Curve 1	$[(V_{max},Q_{MAXunder}); (V_{max} - Deadband_{min}/4,Q_{MAXunder});$ $(V_{nom} + Deadband_{min}/4,0); (V_{nom} - Deadband_{min}/4,0);$ $(V_{min} + Deadband_{min}/4,Q_{MAXover}); (V_{min},Q_{MAXover})]$
	Hysteresis Test Curve 2	$[(V_{max},Q_{MAXunder}); (V_{max} - Deadband_{min}/4,Q_{MAXunder});$ $(V_{nom} + Deadband_{min}/4,Q_{offset}); (V_{nom} - Deadband_{min}/4,Q_{offset});$ $(V_{min} + Deadband_{min}/4,Q_{MAXover}); (V_{min},Q_{MAXover})]$
Grid Code Specific VV12 and Hysteresis Test Curves	CEC Rule 21[82] Curve "Most Aggressive"	$[(V_2 - Q_1/K_{VARmax},Q_{MAXunder}); (V_{nom} - Deadband_{min}/2,0); (V_{nom} + Deadband_{min}/2,0); (V_3 + Q_4/K_{VAR},Q_{MAXover})]$
	CEC Rule 21 Curve "Average"	$[(V_2 - Q_1/K_{VARavg},0.5Q_{MAXunder}); (V_{nom} - Deadband_{avg}/2,0); (V_{nom} + Deadband_{avg}/2,0); (V_3 + Q_4/K_{VARavg},0.5Q_{MAXover})]$
	CEC Rule 21 Curve "Least Aggressive"	$[(V_2 - Q_1/K_{VARmin},0.25Q_{MAXunder}); (V_{nom} - Deadband_{max}/2,0); (V_{nom} + Deadband_{max}/2,0); (V_3 + Q_4/K_{VARmin},0.25Q_{MAXover})]$

[82] The following parameters will be calculated:

- $V_{dev} = \min(V_{nom} - V_{min}, V_{max} - V_{nom})$, the minimum voltage deviation from V_{nom} which causes the EUT to stop volt-var operation
- $K_{VARmin} = (Q_{MAXunder}/4)/(V_{dev} - Deadband_{max}/2)$ or as specified by the Source Requirements Document
- $K_{VARavg} = (K_{VARmax} + K_{VARmin})/2$
- $Deadband_{avg} = (Deadband_{max} + Deadband_{min})/2$

	CEI 0-16/21 VV12 Test Curve	$[(1.1V_{nom}, Q_{MAXunder}); (1.08V_{nom}, 0); (0.92V_{nom}, 0); (0.9V_{nom}, Q_{MAXover})]$

Table 8-6: VV12 Test Curves.

	Test #	Curves		Q_{offset}
		VV12 Curve	*Hysteresis Curve*	
Generic VV12 and Hysteresis Test Curves	1	VV12 Test Curve 1		
	2	VV12 Test Curve 1	Hysteresis Test Curve 1	
	3	VV12 Test Curve 2		$0.05Q_{MAXover}$
	4	VV12 Test Curve 2	Hysteresis Test Curve 2	$0.05Q_{MAXover}$
	5	VV12 Test Curve 2		$0.05Q_{MAXunder}$
	6	VV12 Test Curve 2	Hysteresis Test Curve 2	$0.05Q_{MAXunder}$
Grid Code Specific VV12 and Hysteresis Test Curves	7	UL 1741 Curve "Most Aggressive"		
	8	UL 1741 Curve "Average"		
	9	UL 1741 Curve "Least Aggressive"		
	10	CEI 0-16/21 VV12 Test Curve		

Table 7-7: VV12 Test Matrix.

Note: These tests should be repeated with active power set from 0 to 100%W_{MAXch} in increments of 20%*W_{MAXch} and 0 to 100%*W_{MAXdch} in increments of 20%*W_{MAXdch}.

8.4.2 VV12 Timing Test

The volt-var timing tests consist of two steps from the nominal voltage to $V_{min} + \Delta V$ and back to nominal voltage then from the nominal frequency to $V_{max} - \Delta V$ and back to nominal voltage. Each voltage step is held for a minimum test duration (timing interval) equal to 2 times ($t_R + t_{window} + t_{out}$) according to Table 8-8 plus twice the EUT settling time (t_s).

	Test #	Ramp time, t_R (s)	Recovery Delay time, t_{RD} (s)	Recovery ramp time, t_{Rec} (s)	Time window, t_W (s)	Timeout, t_{out} (s)
Generic VV12 and Hysteresis Test Curves	t1 DEFAULT	0	0	0	0	0
	t2	$t_{R\_max}/2$	0	0	$t_{W\_max}/2$	0
	t3	t_{R_max}	0	0	t_{W_max}	0
	t4	0	$t_{RD\_max}/2$	$t_{Rec\_max}/2$	0	0
	t5	0	t_{RD_max}	t_{Rec_max}	0	0
	t6	$t_{R\_max}/2$	$t_{RD\ max}/2$	$t_{Rec\_max}/2$	$t_{W\_max}/2$	0
	t7	t_{R_max}	t_{RD_max}	t_{Rec_max}	t_{W_max}	0
	t8	0	0	0	0	$t_{out\_max}/2$
	t9	0	0	0	0	t_{out_max}
Grid Code Specific VV12 and Hysteresis Test Curves	1 (CLC/TS 50549)	9	0	0	0	0
	2 (CLC/TS 50549)	180	0	0	0	0

Table 8-8: VV12 Timing Test Matrix.

8.5 VV12 Function test sequence

The VV12 test shall be carried out as follows:

Step 1: Prepare the EUT according to the following:

- Configure EUT and energy storage element according to Section 2.1.
- Connect to Utility Simulator with operation within nominal voltage range for a minimum of 5 minutes.
- Verify EUT is powered on to a level required to receive the command.
- Verify energy storage state of charge (SOC) will not interfere with VV12 tests. If the SOC is near SOC_{opMAX} or SOC_{opMIN}, charge or discharge the BESS system until close to: $(SOC_{opMAX} + SOC_{opMIN})/2$
- Establish communication to EUT with Utility Management System (UMS).
- Record EUT output (e.g., voltage, current, power) with data acquisition system according to Section 2.2.

- Set Active and Reactive Power to zero.

Step 2: Request status from EUT and record the EUT parameters.

Step 3: Send VV12 (V, Q) pairs according to required test as in Table 7-7.

Step 4: Confirm VV12 parameters are updated in the EUT.

Step 5: Send default timing parameters to EUT according to Table 8-8.

Step 6: Set the EUT power to required power level (starting value 0).

Step 7: Adjust the grid voltage to the required grid voltage points: 5 points per line including also line to Hzmin +Δf and Hzmax-Δf points. The tests will follow this sequence: V_{nom} to V_{max}-ΔV to V_{nom} to V_{min} +ΔV and then back to V_{nom}.

Step 8: Set the timing parameters according to Table 8-8.

Step 9: Step the grid frequency to V_{min} +ΔV and V_{max}-ΔV according to Section 8.4.2.

Step 10: Repeat Steps 8-9 with new timing parameters based on the FCT (Timing tests).

Step 11: Repeat Steps 5-10 with the EUT power set to 100%*W_{MAXch} to 20%*W_{MAXch} in steps of 20%*W_{MAXch} and 100%*W_{MAXdch} to 20%*W_{MAXdch} in steps of 20%*W_{MAXdch}

Step 12: Repeat Steps 3-11 with VV12 new pairs based on the FCT (VV12 domain tests).

Step 13: Analyze performance data.

8.6 Acceptance criteria

Acceptance criteria are determined using the definitions provided in the grid code.

8.6.1 Default criteria

The maximum difference between the measured reactive power and the reactive power settings must be less than MSA_{VAR} at any voltage defined by the region V_{test} ± (MSA_{Vac} plus the DAQ V_{ac} accuracy). The maximum difference between the measured time response and the time response settings must be less than MSA_t plus the DAQ time accuracy.

8.6.2 Italian technical rules

The maximum difference between the measured reactive power and the reactive power output must be less than ±5% of S_n (nominal apparent power).

8.6.3 CLC/TS 50549

The maximum difference between the measured reactive power and the set reactive power is less than $\Delta Q < \pm 2\%$ of the EUT nameplate apparent power in the range 10% - 100% of nameplate apparent power