Optimization of Compliance Testing for Grid-supporting Inverter Functionalities

Siddhi Shrikant Kulkarni[1*], Gunter Arnold[1], Nils Schäfer[1]

[1] *Fraunhofer IEE, Kassel, Germany*
Corresponding author. Email: siddhi.kulkarni@iee.fraunhofer.de

ABSTRACT

Inverter based resources (IBRs) are capable of providing grid services to ensure system stability. Manufacturers of such IBRs are required to certify their products according to the testing procedures of each individual country to meet the grid connection requirements of the target markets. When various countries are targeted; time, effort and financial resources spent on the validation procedures increase with the number of targeted countries and need to be optimized. Hence, the importance of best practices for reducing testing effort becomes key. In this contribution the methodology and exemplary results for performing this optimization will be presented.

In this study, an approach is implemented for reducing the analysis and testing effort for battery energy storage systems (BESSs) covering various country specific regulations. Grid connection requirements and testing procedures for countries in Europe and outside Europe are analyzed to develop a holistic understanding of the common ranges for functionalities such as active power regulation based on frequency, active power regulation based on voltage and reactive power provision. Critical points are identified where certain country grid codes required exceptional criteria. The development of a harmonized testing procedure is an important further step in the reduction of measurement effort. Such a procedure will consider all grid connection requirements which need to be complied with according to the testing standards of all targeted countries.

Following, the developed harmonized testing procedures for the generalized compliance assessment are automated and tested in the laboratory environment with a BESS. Furthermore, possibilities for automation of such harmonized testing procedures are also discussed in order to improve the scalability of the laboratory testing using the harmonized grid testing procedures.

Keywords: *Battery energy storage systems, Inverter based resources, Grid connection requirements, Grid code compliance, Grid services*

1. INTRODUCTION AND MOTIVATION

A sharp rise in the number of BESS installations and the installed capacity has been observed in the past five years in Germany. This can be attributed especially to the stark increase in residential BESS installations [1,2].

The main application of residential BESS is for increasing self-consumption of households [3]. This has also found applications in peak-load reduction and self-consumption optimization for energy communities [4]. These activities have been driven by a reduction in feed-in-tariff, decrease in BESS prices and improvement in converter technology.

However, BESS which are inverter interfaced systems, have additional applications in ensuring grid stability via the provision of ancillary services which comes under the umbrella of grid services [5]. The economic benefit to households providing ancillary services using BESS has also been investigated in various studies e.g. [6].

Manufacturers of BESS which target multiple markets to sell their products need to test their products to comply with the grid connection requirements of the targeted countries before sending the products for type certification. This internal verification testing needs to be automated in order to expedite the verification of mass product lines. For BESS manufacturers to improve the time and resources spent on testing effort, a harmonized analysis and understanding of the grid connection requirements needs to be developed. Furthermore, harmonized and standardized testing procedures need to be developed which when used for testing the BESS

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ensure grid code compliance for all the targeted countries.

This can be explained using the following example. If Manufacturer A intends to sell his BESS in Germany, Switzerland and Austria; in order to internally verify the BESS, he should analyze the grid connection requirements of the three countries and develop a testing procedure incorporating the strictest requirements from the three countries in order to reduce measurement time and resources. This is more effective compared to individually testing according to the testing procedures of each of the three countries.

As part of this study conducted, power plants or power generating modules consisting of a BESS up to 1 MW connected to low voltage (LV) and medium voltage (MV) grid are considered. A harmonized grid code analysis and testing procedure development for 15 countries is conducted with respect to grid service provision by BESS for four grid services, namely: Limited frequency sensitive mode (LFSM-O and LFSM-U), Q(U), cosphi(P) and P(U). The 15 countries considered are: Germany [7,8], Belgium [9], the Netherlands [10,11], Switzerland [12], Austria [13,14], Spain [15], Portugal [16], Italy [17], Sweden [18], UK [19], Ireland [20], Finland [21], Poland [10,11], Australia and New Zealand [22].

Section 2 presents a review of the state of the art literature which is relevant for our study and highlights the research gap that is filled by our study.

2. LITERATURE REVIEW

The NC RfG 2016/631 released in 2016 [23] has fundamentally transformed the landscape of European nation grid codes by providing a harmonized EU-wide parental document stating exhaustive and non-exhaustive as well as mandatory and non-mandatory requirements for connection to the grid [24]. The respective national implementation documents came into force in 2019 and have been in operation and use for four years which has provided sufficient time to implement the country specific documents in grid code compliance testing studies.

It is important to state that NC RfG does not cover storage devices except for pump-storage power generating modules in the application scope. A new version of the RfG is currently under development, which will also contain additions for energy storage and electric vehicles. However, it is observed that certain (e.g. VDE-AR-N 4105:2018-11[7], CEI 0-21 2022-03[17] for BESS ≥ 11 kW) national implementation documents have used the NC RfG and extended the requirements to storage systems and also to include other requirements beyond what the NC RfG prescribes as mandatory. For example, the RfG prescribes LFSM-O as a mandatory requirement for power generating modules ≤ 1 MW. However, the provided examples [7] and [17] also require storage systems to include LFSM-U, Q(U) and cosphi(P) with [17] also requiring P(U) for BESS ≥ 11 kW which are part of the scope of the conducted study. Therefore, although the NC RfG provides a reference point and parental guidelines for the grid connection requirements in Europe, a manufacturer must conduct individual grid connection requirement analysis according to country specific documents. Furthermore, the NC RfG does not apply for countries not in the synchronous area of Europe therefore this literature gap remains even more pertinent in such cases.

The Monitoring report published by the ENTSO-E [25] provides an overview on the status of the country specific implementation of NC RfG with regards to the different grid services required. This source provides a strong basis for the harmonized grid connection requirements analysis with respect to frequency, fault ride through (FRT), voltage ranges and reconnection requirements after tripping and disconnection. However, a discussion on the reactive power provision and voltage dependent active power provision is not present in this source.

The [26] which also goes into detail with the country specific implementation of the NC RfG, released two years after [25] provides an even more detailed insight and analysis via an in-depth categorization of the various grid connection requirements. Here also reactive power provision is discussed in detail. Since [25] and [26] concern country specific NC RfG implementations, no approaches are used or suggested for including other countries outside of the scope of the NC RfG. This presents a drawback for the manufacturers.

An analysis which would include other 50 Hz markets presents challenging considering that a natural overlap in description of the grid connection requirements is not found. For example, the grid connection requirements document for Australia and New Zealand [22] does not describe the LFSM-O/-U (as given in the NC RfG) with the same terminology and also does not state a default or range of droop values, although the described grid service is the same as LFSM-O/-U. Instead for BESS, frequency values are mentioned for where the charging or the discharging power level is zero. Also, frequency values for where the power level is minimum (overfrequency) and maximum (underfrequency) are mentioned.

The [27] presents a review by using the EU Network Code [28] as a basis for checking the compatibility of the Australia [29] and Iran [30] grid connection code to the EU Network Code. A comparison of the active power controllability, reactive power capability and the fault ride through requirements is provided. Even though this literature provides a strong reference point to define criteria to conduct comparisons, it is eight years old and therefore lacks the relevance with respect to current available grid connection requirements documents.

With respect to the harmonized/standardized testing procedures, few literatures have studied this topic in detail. For example, EN 50549-10 [11] published in October 2022 is a European Standard which can be used as a basis for compliance type testing where no country specific testing procedure document is available. However, this document presents testing to check for conformity assessment with respect to the EN 50549-1 [10] and EN 50549-2 [31] respectively, and not the country specific documents. Therefore, one must conduct a holistic analysis of the country specific testing documentation to ensure that no testing conditions are missed.

The paper [32] presents a generic grid code to conduct the assessment of grid code compliance for fault ride through and frequency events. The approach of implementing a generic grid code using a parametrized mathematical model and block diagrams and equations is innovative and very practical for researchers and engineers to implement. Additionally, the described generic grid code presents the importance of using the strictest requirements for the compliance testing. However, a detailed description of steps to be performed during laboratory testing is not provided. Also, a framework for developing a testing procedure is not given.

Section 3 of this paper delves deep into creating a harmonized analysis of the grid code connection requirements (henceforth termed as 'Harmonized Grid Code'). Furthermore, a guideline on developing harmonized testing procedures is provided for four grid services (henceforth termed as 'Harmonized Testing Procedure'). Section 4 presents the various possibilities for automated testing and presents the experimental results for laboratory tests conducted during the development of a harmonized testing procedure.

3. DEVELOPMENT OF THE HARMONIZED GRID CODE AND THE HARMONIZED TESTING PROCEDURE

The methodology for developing of a harmonized grid code is to derive from all the studied countries which have a country-specific grid code the strictest requirements or characteristics. The methodology for developing a harmonized testing procedure is to derive either the strictest or the maximum and minimum values based on the country-specific testing documents. The goal of developing the harmonized test procedures is to derive set test routines and a set matrix of starting conditions which can be run in an iterative manner. This will be elaborated in the upcoming sections.

3.1. Limited Frequency Sensitive Mode (LFSM)

LFSM as described in the NC RfG [23] is the regulation of active power with respect to frequency which takes place after the provision of frequency sensitive mode (FSM) is exhausted and proven unsuccessful in regulating the grid frequency. This terminology is not used by Australia and New Zealand however the functionality described under LFSM is utilized in these countries, therefore this terminology is further used in this paper. LFSM operation is characterized by decrease / increase of active power according to a set droop and enters operation for overfrequency / underfrequency (LFSM-O / LFSM-U). The relationship between the frequency, active power and droop can be characterized by the following equation.

$$s = \frac{\Delta f}{fn} * \frac{Pmax}{\Delta P} \tag{1}$$

Where s is the droop, Δf is the observed change in frequency, fn is the nominal frequency, Pmax is the maximum charging or discharging power of the battery and ΔP is the change in active power.

3.1.1. Harmonized Grid Code

First, criteria are developed in order to characterize the LFSM-O and LFSM-U characteristics. The values provided below are only for LFSM-O, however values for LFSM-U are derived in a similar manner. The criteria are:

- Threshold values: This defines the frequency value at which the LFSM-O/-U event begins. The values obtained from the European countries are 50.2 Hz – 50.5 Hz. However, since Australia and New Zealand [22] have a range of 50.1 Hz – 50.5 Hz, the final range of threshold values for the harmonized grid code considered is 50.1 Hz – 50.5 Hz.
- Droop range: The default and standard droop values are noted here. A range with a maximum and minimum droop values obtained after the analysis of the country-specific grid connection requirements is 2-12%. Italy [17] displays a testing procedure with a maximum droop of 1.3%, therefore the final range for the considered droops is 1.3-12%
- Other criteria which are important are:
- Strict operation range: Frequency range in which the LFSM-O/-U takes place. It is the range between the threshold value and the over/underfrequency protection limit. Overfrequency protection limits are between 51.5 Hz and 55 Hz.

3.1.2. Harmonized Testing Procedure

With this as a basis, the development of a framework for a harmonized testing procedure was conducted. After a thorough analysis of the testing procedure documentation available for the studied countries, the following steps are derived. These steps are used for developing the harmonized testing procedures for all the grid services that were analyzed as part of this study.

- Test setup description
    - General conditions for simulating signals
    - Environmental conditions for conducting the test
    - Power factor setting
    - Equipment Under Test (EUT)
    - Protection settings
    - Measurement Signals
        - Accuracy and uncertainty
        - Sampling rate
        - Measurement interval
- Test procedure description
    - What behavior should the tests show?
    - Definition of start settings
    - Procedure description
- Assessment procedure and criteria

As observed, the initial section deals with the test environment setup and the equipment setup. Then to prepare the test, the measurement signals should be recorded with the derived accuracy and sampling rate values. The values for these criteria are derived using the strictest values from the country-specific testing documents. For example, between a necessary frequency measurement accuracy of 50 mHz and 10 mHz, a measurement accuracy of 10 mHz is chosen. The values derived for measurement signals for the LFSM-O and LFSM-U are as follows in Table 1 and Table 2.

Table 1. Sampling rate for the measurement signals

Voltage and current signals	Additional Signals (e.g. battery state of charge etc.)
≥ 3 kHz [8,11]	≥ 1 Hz [8,11]

Table 2. Measurement accuracy for the measurement signals

Magnitude	Value
Maximum error in frequency measurement	±10 mHz [7,8,15,17,21]
Maximum error in current measurement	±0.5% In [11,15]
Measurement error in voltage measurement	±0.5% Un [11,15]

The second step of the harmonized testing procedure development framework deals with the requirements of a harmonized test. What behavior such a harmonized test should show is derived from the various testing requirements of the analyzed countries. Following, the LFSM-O requirements will be described; the LFSM-U requirements are derived in a similar manner.

- Travelling down and up the droop also known as travelling along the curve. This characteristic describes the phenomenon where active power decreases when the frequency crosses the LFSM-O threshold value according to the droop and the active power decreases along the droop when the frequency recovers.

- Travelling down and at constant power using fstop limitation: This behavior describes the phenomenon where for overfrequency the resultant active power is given by a negative droop. However, during recovery to nominal frequency, the active power stays constant at the value before recovery. A set fstop frequency value is considered. Then, according to a given reference 'tstop' time, when the frequency is below the fstop value for a tstop time, the active power is allowed to recover from the value before recovery to the value before the overfrequency event takes place.

- Return to setpoint and removal of power limitation: Traditionally, when the testing is conducted with the starting active power at a value below the maximum primary energy available (e.g. 60%Pmax [8]), when the frequency at the end of the test routine recovers to the nominal frequency, the active power is 60% Pmax. If the limitation on the active power is then removed, the active power goes up to the maximum primary energy available.

- Disconnection from the grid and recovery: When the frequency crosses the overfrequency protection limit, the generating unit should separate itself from the grid due to system and mains protection tripping. In order to bring the generating unit back into operation, the frequency should recover back to nominal frequency and a tolerance region for a certain minimum time period, after which the device will reconnect and first return to the active power value before the overfrequency transient event took place.

Once the desired behavior to be described by the testing procedure is derived from the analyzed documents, the start conditions for the test routines are defined.

Based on the different combinations of start parameters the following matrix was created as displayed in Table 3. The first column of the table represents the threshold frequency value. The second column represents the threshold values. Therefore, the threshold values 50.1 Hz and 50.5 Hz should be tested with droop 1.3% and 12% each. Following, for every threshold and the respective droop value, the combination of implementing the fstop characteristic with and without delay is considered and then the combination of no fstop characteristic implementation with and without delay. Furthermore, the starting power values are stated in brackets based on the analyzed documents and mentioned as a percentage of the maximum active power of the battery storage system.

The generated combinations were checked again with the testing requirements in the analyzed countries in order to remove redundancies (striked out when redundant in Table 3). Here it was found that the cases without fstop and with delay were not described in the testing procedure for any country. Therefore, these combinations are removed from consideration. Additionally, for the purpose of verification testing it is emphasized that the battery be tested only once with the starting power in charging mode (-50%Pmax) and once in discharging mode (100%Pmax). The redundant power values are therefore eliminated and red marked in the table.

The next step after the starting conditions have been defined, is the description of an exemplary testing procedure. For this purpose, Test 1 from Table 3 is described in detail. The test steps for Test 1 are tabulated in Table 4.

The Test 1 is conducted with 50.1 Hz as the threshold frequency, 1.3% droop, with a set delay= 1 s and with an fstop frequency of 50.05 Hz and a tstop time= 600 s at starting active power value 100% of Pmax and -50%Pmax.

In Table 4, the first column describes the test step, the second column describes the frequency value for that particular step, the third column describes the frequency at the end of the respective step which is the same as the frequency at the next step. The fourth column entails the expected change in active power. The fifth column encompasses the duration for which the step should be conducted respectively.

Table 3. Matrix of the starting conditions for LFSM-O

Starting conditions				Test no.
Active power Threshold	Droop	Start setting	Active power at start of the test	
50.1 Hz	1.3%	Fstop, delay	(100, ~~50~~, -50) %Pmax	Test 1
		Fstop, without delay	(100, ~~50~~, -50) %Pmax	Test 2
		~~No fstop, delay~~	~~(100, 50, -50) %Pmax~~	-
		No fstop, without delay	(100, ~~50~~, -50) %Pmax	Test 3
	12%	Fstop, delay	(100, ~~50~~, -50) %Pmax	Test 4
		Fstop, without delay	(100, ~~50~~, -50) %Pmax	Test 5
		~~No fstop, delay~~	~~(100, 50, -50) %Pmax~~	-
		No fstop, without delay	(100, ~~50~~, -50) %Pmax	Test 6
50.5 Hz	1.3%	Fstop, delay	(100, ~~50~~, -50) %Pmax	Test 7
		Fstop, without delay	(100, ~~50~~, -50) %Pmax	Test 8
		~~No fstop, delay~~	~~(100, 50, -50) %Pmax~~	-
		No fstop, without delay	(100, ~~50~~, -50) %Pmax	Test 9
	12%	Fstop, delay	(100, ~~50~~, -50)%Pmax	Test 10
		Fstop, without delay	(100, ~~50~~, -50)%Pmax	Test 11
		~~No fstop, delay~~	~~(100, 50, -50)%Pmax~~	-
		No fstop, without delay	(100, ~~50~~, -50)%Pmax	Test 12

Table 4. Testing procedure steps for Test 1 as described in Table 1

No. of test point	f0 (Hz)	fend (Hz)	ΔPtest expected (%Pmax)	Time duration each step
1	50.00	50.06	0%	2 min
2	50.06	50.70	0%	2 min
3	50.70	51.20	-60%	2 min
4	51.20	50.60	-50%	2 min
5	50.60	50.04	0%	2 min
6	50.04	51.00	0%	Tstop (600 s)+ Ramp time (5 min)
7	51.00	55.10	-90%	2 min
8	55.10	50.00	-	2 min
9	50.00	50.00	-	10 min
10	50.00	50.00	Return to starting setpoint and then 100%Pmax	Gradient time

Each step is conducted for a period of 2 minutes unless otherwise described. Additionally, each frequency change is performed using a rate of change of frequency (RoCoF) of 1 Hz/s unless stated otherwise. Each row of the last column (Time duration) refers to the frequency value in that row. For the tests in Table 4 the change in active power in Step 2 is the change observed when the frequency goes from 50.00 Hz to 50.06 Hz from Step 1 to Step 2.

It can be observed that while the frequency increases from 50.00 Hz to 50.06 Hz from Step 1 to Step 2, the active power does not change. This is because the frequency is still below the threshold value in Step 2, therefore the active power does not change from its starting power value. From Step 2 to Step 3 and Step 3 to Step 4, there is a change in the active power according to the droop because the active power decreases after crossing the 50.1 Hz threshold. However, while the frequency decreases from Step 4 to Step 5 and Step 5 to Step 6, the active power does not change and stays at the value achieved in Step 4.

At Step 6, the frequency is at 50.04 Hz, which is below the set fstop value. This step should be carried out for tstop time (600 s) after which the active power should ramp to the active power at the beginning of Step 1 (value before the overfrequency transient). This ramp should take a maximum of 5 minutes.

From Step 6 to Step 7, a frequency jump is tested with a RoCoF ≥ 4 Hz/s in order to check the immunity of the EUT to perform high RoCoF active power jumps as a reaction to frequency jumps. This is due to the testing procedure from Australia and New Zealand [22] requiring a step to verify the 4 Hz/s RoCoF.

From Step 7 to Step 8, the disconnection of the device from the grid is tested. Since the frequency crosses a value for overfrequency protection for all the analyzed countries at a frequency of 55.1 Hz, the generating unit should separate from the grid. At Step 9, the frequency is brought back to nominal frequency i.e. 50 Hz and after the frequency has been at 50 Hz for 10 minutes, the device connects back to the grid. Therefore Step 9 is conducted for a period of 10 minutes. Here, if the equipment under test was being operated at a reduced power using de-rating or curtailment, then this limiting of the available active power should be removed once in at the end of Step 9. In Step 10, after the EUT connects back to the grid and a ramp in the active power first to the active power value before the event took place and then to the maximum active power value is observed.

Once the test step description is completed, the evaluation conditions for the test are defined. These are also defined using strict criteria as obtained from the country-specific testing procedure documents.

3.2. Reactive power provision as a function of voltage Q(U)

Reactive power provision based on grid voltage is a voltage control technique which is a requirement for generating units connected to distribution networks and especially on the low voltage level.

3.2.1. Harmonized Grid Code

For the development of a harmonized grid code the default Q(U) characteristics provided by the country specific documents are plotted in Figure 1. Based on the variation between the provided characteristics, i.e. the voltage deadband and the various Q versus U slopes it is challenging to determine one harmonized characteristic. This variation can be attributed to the varying levels of renewable energy penetration on the distribution network level in the analyzed countries. The development of a harmonized grid code will be addressed in the next section as part of the discussion of which behavior the tests should show.

3.2.2. Harmonized Testing Procedure

The harmonized testing procedure is developed with the same framework as introduced in Section 3.1.2. The test setup and setting up of the measurement signals should be conducted in the same manner as described previously for LFSM-O. The following paragraphs will

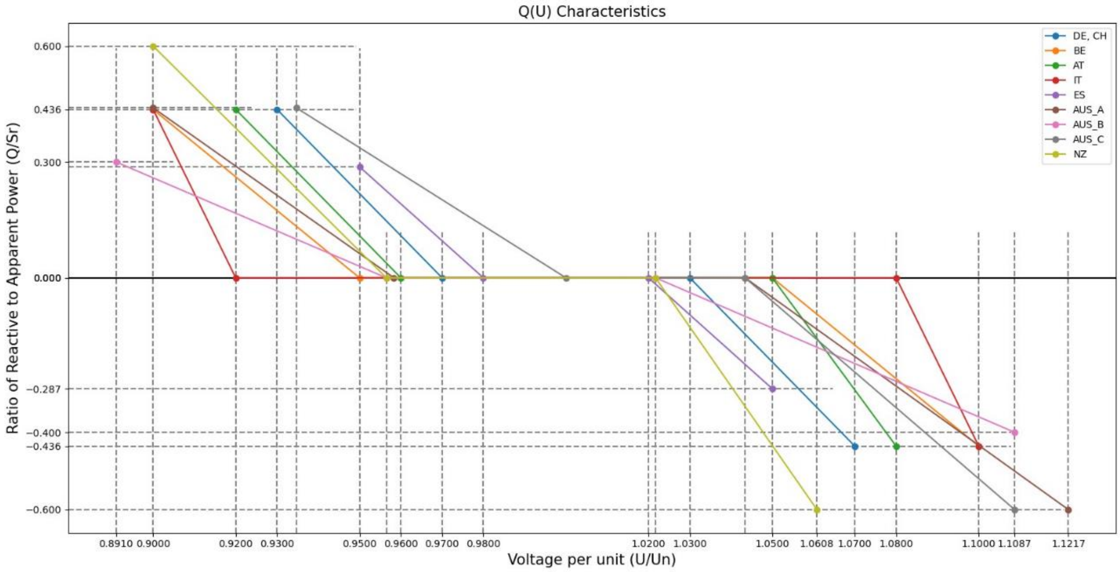

Figure 1 Overview of grid connection requirements for the Q(U) characteristic

address the description of what behavior the tests should show.

Based on the analyzed documents, Q(U) testing can be classically divided into:

- Static test: This test checks whether for the specified Q(U) characteristic (depending on which country), the required reactive power value is supplied or absorbed with a specified accuracy for the voltage level measured by the EUT in the simulated grid.
- Dynamic test: This test primarily checks whether the Q setpoint value for the detected voltage (U) value is reached within the time specified (a first order characteristic is also required and checked by many countries in their testing procedures).

In addition to this, the testing requirements in some countries (documents) describe additional functionalities which if implemented can be tested. These additional functionalities involve activating the characteristic using a minimum power factor or a lock-in (deactivating using lock-out) active power value. This is done in order to limit the reactive power amount at low active power levels. These characteristics are tested together with the static test or the dynamic test.

The lock-in/lock-out condition is directly connected to the active power supplied by the device. If the active power is higher than the lock-in value, Q(U) characteristic is activated. If it is lower than the lock-out value then the Q(U) characteristic is switched off. When the lock-out value is lower than the lock-in value, the characteristic has a hysteresis behavior. This is presented in Figure 2.

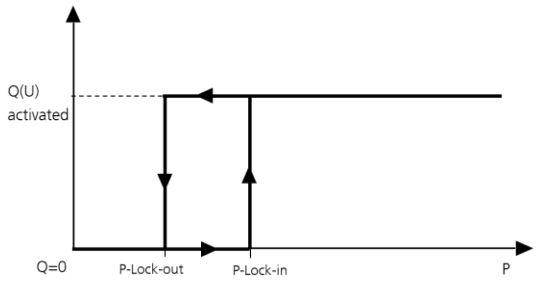

Figure 2 Lock-in and lock-out behavior of the Q(U) characteristic

The minimum power factor (cosphi) condition means that regardless of the active power currently supplied by the device, the device should supply or absorb reactive power according to its designed capacity and the grid voltage.

A summary of the requirements is provided in Table 5. Countries which are analyzed as part of this study but not included in the table do not have any Q(U) testing described in the country-specific documents.

Based on the information in Table 5, it is decided that a harmonized testing procedure will entail a static test and a dynamic test. The special characteristics of the minimum power factor and the lock-in/lock-out characteristic are tested via the dynamic testing procedure. For the purpose of conciseness, only one part of the static testing procedure will be described in depth in this paper.

The static testing procedure is divided into: a) a procedure with deadband, b) a procedure without using a deadband and c) a PQU procedure. This is because some the analyzed documents have provided a Q(U) characteristic with deadband, some have described a Q(U) characteristic without deadband and some have also described a PQU test which is used checking the impact of the capability curve on the reactive power provision.

a) Procedure with deadband

Based on the maximum and minimum deadband, as well as the steep and flat slope observed from the characteristics in Figure 1 , the following deadband characteristics are developed for the Q(U) static testing procedure (Figure 3, Figure 4, Figure 5). Since Italy (CEI021:2022-03 [17]) requires Q(U) testing for storage systems ≥ 11.08 kW rated capacity whereas other countries do not present this categorization, this needs to be taken into consideration.

Table 5. Testing characteristics for the analyzed countries

Country	Static test	Dynamic test
Germany [8]	Classic static (no additional functionality tested)	Classic dynamic (no additional functionality tested)
EN 50549-10 [11]	Classic static (with and without deadband) (with lock-in & lock out for both)	Classic dynamic (with lock-in & lock out)
Italy [17]	Static test with Q nonzero consideration (lock-in and lock-out)	-
Austria [13,14]	Classic static, static test (PQU)	Dynamic test with P(U) and Q(U) working together
Spain [15]	Classic static (without deadband)	-
Australia and New Zealand [22]	Static test	-

In summary the derived deadband characteristics can be described as follows:

- Maximum Deadband 1: Similarly, the maximum deadband of ±6%Un should be tested with a steep slope and a flat slope. This is performed only for devices ≤11.08 kW rated capacity.
- Maximum Deadband 2: Similarly, the maximum deadband of ±8%Un should be tested with a steep slope and a flat slope. This is performed only for devices ≥11.08 kW rated capacity.
- Minimum Deadband: The minimum deadband of ±3%Un should be tested with a steep slope and a flat slope. This is performed for all devices, regardless of active power rating.

Therefore based on the analyzed countries, for a BESS with rated capacity ≤11.08 kW, the Minimum Deadband and Maximum Deadband 1 should be tested (steep and flat slope for each) whereas for a BESS with rated capacity ≥11.08 kW, the Minimum Deadband and Maximum Deadband 2 should be tested (steep and flat slope for each).

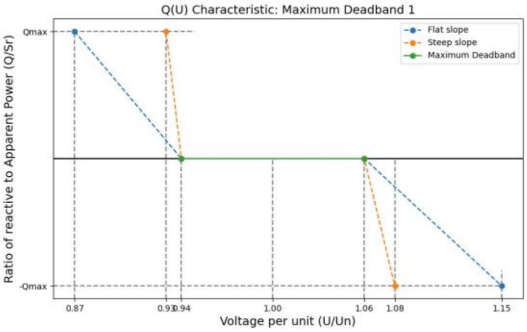

Figure 3 Q(U) Characteristic Maximum Deadband 1

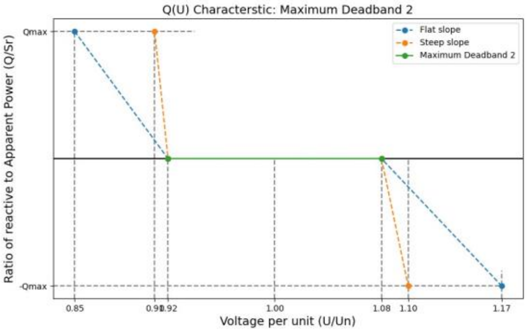

Figure 4 Q(U) Characteristic Maximum Deadband 2

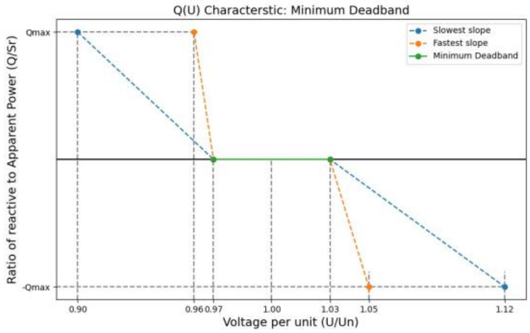

Figure 5 Q(U) Characteristic Minimum Deadband

After the harmonized grid characteristics are derived, the key values for carrying out the test are described. These are the stepsize for the voltage change, the voltage (both over and undervoltage) upto which the voltage step change should be conducted and the active power level with which the test should be started. These values are derived based on the strictest or maximum and minimum limit values obtained from the analyzed documents.

A test procedure description for plants with a BESS ≤ 11.08 kW rated capacity is presented in the following manner. The active power value of the BESS inverter is set and the grid voltage is increased in a stepwise manner up to the maximum voltage shown in the characteristic curve for the Minimum Deadband in Figure *5*. Then, the voltage is decreased in a stepwise manner to the minimum voltage shown in the characteristic curve for the Minimum Deadband in Figure *5*. The same is then repeated with the Maximum Deadband 1 shown in Figure 3.

The test procedure description for plants with a BESS ≥ 11.08 kW rated capacity is conducted in a similar manner, except that the Minimum Deadband and the Maximum Deadband 2 characteristic are tested.

Furthermore, the development of a test procedure without a deadband is conducted in a similar way. Based on grid connection requirements for countries requiring a zero deadband characteristic, a harmonized grid characteristic is developed. Then, the methodology for conducting the test is defined.

The PQU test focuses on the generation capability curve of the inverter interfacing the battery. For inverter capability curves, there is a region below a set power level, where the P-Q relation can be defined freely by the manufacturer of the inverter and does not need to comply with the P-Q requirement of the country. Inverters which are able to regulate their power below this set power level can be tested to check the dependency of the freely designed region of the P-Q characteristic on the reactive power provision according to grid voltage.

Finally, the dynamic testing procedure is described where also the functionalities of the lock-in and lock-out are tested. Here the interplay between the P(U) characteristic and the Q(U) characteristic can also be observed. Therefore, for the purpose of this study the dynamic testing procedure was designed using the P(U) and Q(U) characteristics of Austria. The steps are designed so as to check the provision of reactive power with an activated Q(U) characteristic when the active power provision is affected due to the P(U) characteristic. For example, at a grid voltage (overvoltage) where the P(U) characteristic regulates the active power to zero, the reactive power provision will also be zero even though the Q(U) is active for this overvoltage condition. In the same procedure, the P(U) can be deactivated for undervoltage conditions and the lock-in and lock-out characteristic can be tested by varying the active power between set lock-in/lock-out active power values. The entire above mentioned dynamic testing procedure procedure can be repeated with the step for the lock-in/lock-out replaced by reducing the active power to a minimum active power value where the provision of reactive power will depend on the P-Q curve of the inverter (testing of minimum cosphi)

3.3. Power factor regulation as a function of active power (cosphi(P))

This characteristic is provided as a possible requirement by various countries and can be requested by the distribution system operator as an alternative to the Q(U) and other modes for reactive power provision. Various countries provide a characteristic and testing procedure for the cosphi(P) functionality (Table 6). In addition to this the testing is provided in the form of a static test and a dynamic test wherein the static test is conducted via slow gradual change of the supplied active power and dynamic test is conducted with active power steps (jumps). Furthermore, a lock-in and lock-out voltage (grid voltage) is used to activate or deactivate the cosphi(P) characteristic (similar to Figure 2). This means that only when the grid voltage is greater than the lock-in value, reactive power provision or absorption can take place. This can then be deactivated when the grid voltage drops below the lock-out grid voltage value.

Table 6. Summary of countries with cosphi(P) characteristic and the type of testing procedure

Country	Default characteristic	Testing procedure present	Type of testing procedure
Germany [7,8]	Provided (underexcited)	Provided	Static test

Austria [13,14]	Provided (underexcited)	Provided	Static and dynamic test
Italy [17]	Provided (overexcited)	Provided	Static and dynamic test
EN 50549-10 [11]	Not provided by the EN 50549-1	Provided (3 characteristics tested)	Static and dynamic test
Switzerland [12]	Provided	Not provided	-

3.3.1. Harmonized Grid Code

Germany, Austria and Italy provide a cosphi(P) characteristic wherein the power factor is 1 between 0%Pn and 50%Pn (based on nominal power of inverter interfacing battery with the electrical grid). Beyond 50%Pn, the power factor is regulated linearly either in the capacitive (Italy [17]) or the inductive direction (Germany [7,8] and Austria [13,14]). However, it is observed that the EN 50549-10 [11] here provides various other cosphi(P) characteristics (30% deadband around 50%Pn followed by power factor regulation, no deadband wherein power factor is linearly regulated below and above 50%Pn) which should also be considered.

The following characteristics are developed for the harmonized grid code.

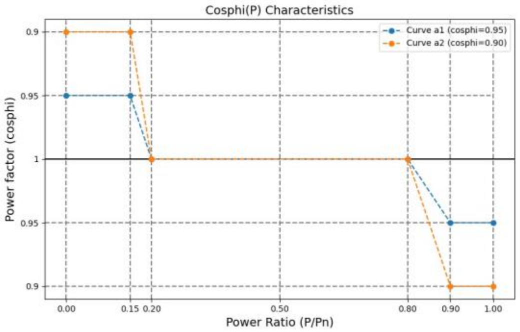

Figure 6 Type (a) curves (a1,a2) for the cosphi(P) characteristic

The Type (a) characteristic (Figure 6) developed ensures that cosphi= 0.95 (capacitive and inductive) (a1) and cosphi= 0.90 (capacitive and inductive) (a2) can be tested as compared to the EN 50549-10 wherein only the cosphi= 0.95 (capacitive and inductive) are tested.

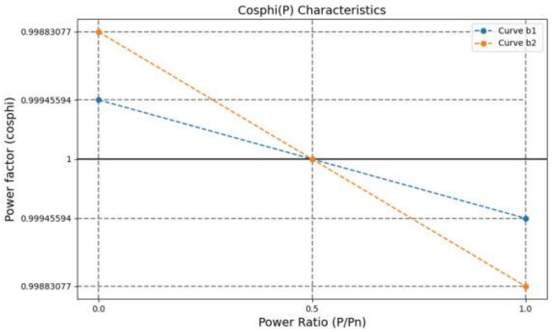

Figure 7 Type (b) curves (b1,b2) for the cosphi(P) characteristic

The Type (b) characteristic which is also developed based on the EN 50549-10 and considers no deadband and maximum regulation according to 10%Qmax where Qmax is arrived at 0.33 (cosphi=0.95 capacitive and inductive) and 0.436 (cosphi=0.90 capacitive and inductive). Therefore, cosphi values for 0.033 and 0.0436 (capacitive and inductive) are plotted in the Type (b) characteristic in Figure 7. This takes into consideration both power factor values in comparison to the EN 50549-10 which only considers a Qmax=0.33 (cosphi=0.95).

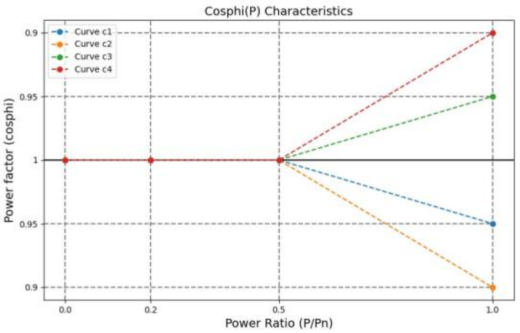

Figure 8 Type c curves (c1, c2, c3,c4) for the cosphi(P) characteristic

The Type (c) characteristic (Figure 8) ensures that cosphi= 0.95 inductive (c1), 0.90 inductive (c2) and cosphi= 0.95 capacitive (c3), 0.90 capacitive (c4) as well as can be tested as compared to the EN 50549-10 wherein only the cosphi= 0.95 (inductive) are tested.

3.3.2. Harmonized Testing Procedure

The point at which the power factor regulation is started is considered the threshold point. Therefore, in the Type (a) curve the threshold point is 0.20Pn and 0.80Pn. In the Type (c) curve, the threshold point is 0.5Pn. The Type (b) curve has a threshold point for 50%Pn, however for the purpose of testing, 0.20Pn and 0.80Pn are considered the threshold points. A static procedure and a dynamic procedure are designed. The procedure should performed for all the harmonized grid codes obtained (Type (a), Type (b) and Type (c)). Essentially, each of the sub-curves should also be tested with the static testing procedure and the dynamic testing procedure.

The principle of the designed harmonized testing procedure involves checking the activation of the characteristic using the threshold points and simultaneously testing the lock-in and lock-out characteristic.

For the static testing procedure, the lock-in and lock-out grid voltage values are first set (with the lock-out voltage < lock-in voltage as in Figure 2). The test is started below the lock-in voltage and the active power is set to a value below the threshold and increased in a stepwise manner to a value above the threshold. Since the grid voltage is below the lock-in voltage, no reactive power provision is observed. The grid voltage is then increased to a value greater than the lock-in voltage after which, reactive power provision is observed according to the characteristic curve. After this, the active power is increased to maximum nominal power (100%Pn) and the voltage is decreased to a value between the lock-in and lock-out voltage. The reactive power provision is observed according to the characteristic curve. In the final step, the grid voltage is reduced to a value below the lock-out voltage upon which the cosphi(P) characteristic will be deactivated and the reactive power provision will decrease to 0.

For the dynamic testing procedure, the lock-in/lock-out voltage characteristic is deactivated and not tested since it is already tested using the static testing procedure. Instead, the active power is varied from below the threshold value in a stepwise jump manner to the maximum nominal power and verified using tolerance values for a first order characteristic.

3.4. Active power regulation as a function of voltage (P(U))

The P(U) testing procedure is developed in order to enable active power curtailment in case of high voltages. This characteristic is useful for low voltage distribution networks wherein a strong relationship between the active power and the voltage is observed in contrast to transmission networks due to the high R/X ratio of distribution networks. The P(U) characteristic can be displayed according to the characteristic in Figure 9.

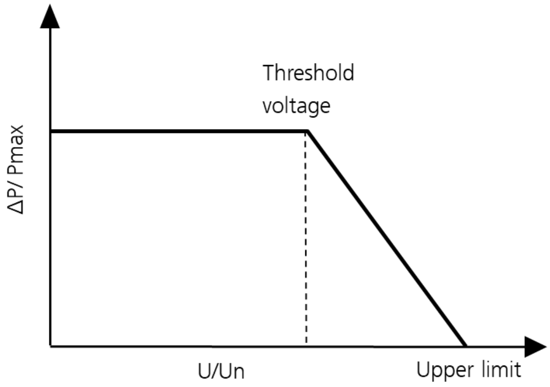

Figure 9 Sample P(U) characteristic

3.4.1. Harmonized Grid Code

A first analysis is conducted for understanding what behavior must be displayed according to the testing procedures described for every country. It is observed that although some countries have presented a default P(U) characteristic, no testing procedure was described. The vice versa was also observed i.e. no default characteristic presented, however information regarding the testing procedures was provided. Additionally, as also observed in the analysis of reactive power provision according to voltage, the testing documents provide a static or a dynamic testing procedure or both. This information is also summarized in Table 7. Countries which are not mentioned in the table and part of this study have not provided either and are therefore considered as not having any P(U) requirements.

Table 7. Summary on P(U) characteristic and testing information availability

Country	Default characteristic	Testing procedure present	Type of testing procedure
Belgium [9]	Provided	Not provided	-
Austria [13,14]	Provided	Provided	Static and dynamic
Italy [17]	Not provided	Provided	Static test
Switzerland [12]	Provided	Not provided	-
EN 50549-10 [11]	Not provided	Provided	Static and dynamic
Australia and New Zealand [22]	Provided	Provided	Static test

Based on the information in Table 7, the following harmonized grid characteristic is obtained.

Table 8. P(U) characteristic 1

Country	Threshold voltage value	Upper limit value
Australia and New Zealand [22]	235 V	240 V
	235 V	265 V
	255 V	265 V

Table 9. P(U) Characteristic 2

Country	Threshold voltage value	Upper limit value
Belgium [9]	1.08 Un	1.13 Un
Austria [13] and Switzerland [12]	1.1 Un	1.12 Un

Since the P(U) characteristics for Australia and New Zealand are presented with respect to the active power output level as a percentage of the apparent power, the characteristic is presented in the following manner (Table 8). This is based on the allowed range described in the AS 4777.2:2020.

The P(U) characteristic 2, includes countries which describe the characteristic based on the ratio of current active power to rated active power (Table 9).

3.4.2. Harmonized Testing Procedure

In order to develop a time efficient testing procedure, instead of conducting two separate tests, static and dynamic, a single test routine will be used to test the behaviors that are tested in the static test and the dynamic test. The proposed testing procedure (explained in the following paragraphs) describes conducting a static test from Un (nominal grid voltage) up to the threshold voltage value and then a dynamic test from the threshold voltage value to the upper limit value.

The testing procedure is designed in the following manner. Starting at the nominal grid voltage, the voltage should be increased using certain voltage steps (value for voltage steps is derived according to minimum value present in testing procedure documentation). The voltage is increased up to a value just below the threshold voltage (U1). The voltage is then increased to a value just beyond the threshold voltage to check whether the P(U) characteristic is activated (U2). The voltage is then brought down to a value below the threshold voltage due to which the P(U) characteristic will be deactivated (U1). This concludes the static aspect of the testing procedure. Finally, a voltage jump is performed from the voltage just below the threshold voltage (U1) to a value beyond the upper limit value (U3) to test the dynamic part of the harmonized grid testing procedure.

The values for the voltage steps for the static testing procedure, the values of U1, U2 and U3 are determined using strict values obtained from testing procedure documentation available for P(U) (column 3 of Table 7). Additionally, the values for the time constant and the activation times for the dynamic aspect of the testing procedure are also obtained based on the principle of maximum and minimum values from the documentation available for the dynamic testing procedure from the analyzed countries.

One aspect observed during the analysis and design was the possible interplay between the Q(U) and the P(U) characteristics. The regulation of active power based on voltage according to P(U) could position the active power at such a point on the inverter capability curve that the desired reactive power provision could be restricted. This impacts the Q(U) characteristic, however, has no effect on the P(U) characteristic.

4. EXPERIMENTAL VERIFICATION

This section discusses the possibilities for automated testing. Exemplary results of automated laboratory tests performed at the Fraunhofer IEE test centre SysTec with a rooftop PV battery storage system are presented for the two functionalities LFSM-O and Q(U).

4.1. General test setup

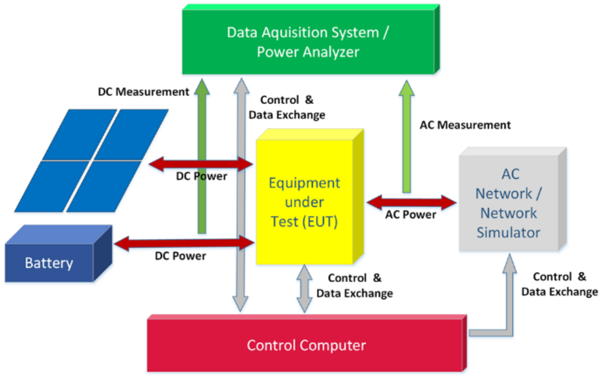

Figure 10 Test setup (rooftop PV battery storage system)

The test setup for a PV battery storage system consists of the following main components:

- Equipment Under Test
- AC network or AC network simulator
- DC power supply or real PV modules and battery
- Data acquisition system / power analyzer
- Control computer (supervision & data exchange)

When testing a PV battery storage system, the hybrid inverter represents the EUT. It converts the DC power received from the PV modules into AC power, while storing DC power to the battery (charging) or receiving DC power from the battery (discharging). In laboratory tests, the PV modules may be replaced by a DC source with suitable photovoltaic profile emulation. On the AC side the EUT is preferably connected to an AC network simulator. In case no suitable AC network simulator is available, tests could also be performed connected to the AC network with alteration of nominal values of system frequency or voltage set to the control of the EUT, thus emulating values differing from nominal values while the device is actually operating at nominal conditions.

4.2. Possibilities for automated testing

In this subsection at first some general statements regarding the automated testing are presented. In the second part the implemented automation measures in the shown test setup (Fig.7) are shortly described.

First of all, the main goals of automated testing are time and cost savings as well as safeguarding the quality of test results especially when the testing procedure or the testing campaign requires a considerable number of repetitions.

Without the knowledge of the specific test campaign including its frame conditions it is very difficult or nearly impossible to estimate the amount of time and cost savings.

Time and cost savings could not only be realized during the experiments itself, but also in the preparation phase and during the assessment of the test results and its documentation (e.g. in a standardized test report).

The following test automation possibilities should be considered in general.

First of all, the experimental setup and the selection of suitable test equipment with automation features and its communication & control capabilities play a key role. For example, the following possibilities could be implemented here:

- Test execution using pre-defined scripts for AC Network Simulator, Power Analyzer, EUT, PV-Simulator etc.
- Measurement data evaluation and test reporting using scripts and pre-defined templates.
- Using either digital trigger events or time-based synchronization of participating equipment for defining start and end point of testing as well as measurement data acquisition

Secondly, with respect to the testing infrastructure it is also important to consider the specific remote control and automation capabilities of the EUT such as:

- Automated Importing / Exporting of operational parameter (lists) such as various control settings
- Availability and type of (Remote) control interfaces (Analog & Digital) & Communication protocols (e.g. Modbus, CAN, IEC 61850, Sunspec)

Besides the above listed measures of course the impact of the test procedures itself should be taken into account, as it is thoroughly explained in the first part of this publication. In this context the following topics are relevant:

- Using standardized test procedures
- Simplicity of the test procedures
- Number of test runs / iterations

In the following two subsections, results of the laboratory tests performed with a rooftop PV battery storage system at the Fraunhofer IEE test center SysTec are presented. The considered EUT consists of a hybrid inverter with rated power of 5 kW and a battery with a capacity of approximately 5 kWh. The generated DC power comes from rooftop PV modules with a capacity of approx. 5 kW_{peak}. On the AC side, the EUT was connected to an AC network simulator with a power capacity of 90 kVA. Pre-defined scripts have been used in order to manipulate system frequency and voltage e.g. according to the harmonized testing procedure, for the testing of the functionalities LFSM-O and Q(U) respectively.

Before execution of the various tests, the EUT was “fed” with different parameter settings in order to activate the LFSM-O or Q(U) functions and to specify its particular characteristic and limiting values. These parameter lists have been exported to the control computer after execution not only for possible repetitions but also for documentation purposes. Furthermore, the power analyzer was prepared for the tests (measurement setup and test procedures) with the help of prepared setup files.

In the context of Grid Compliance testing, it is nearly always necessary to post-process the recorded measurement data for preparation of the test report. Such measures were also used during our measurement campaign e.g. for calculation of mean values (10 s and 60 s) as well as for the graphical representation of the test results using pre-defined diagrams.

4.3. Test performance and results – Limited Frequency Sensitive Mode in case of Overfrequency (LFSM-O)

Different LFSM-O tests with various settings and test procedures have been conducted. A test in which the following inverter settings were used is described in more detail below:

- f_Threshold = 50.20 Hz
- f_overprotect = 51.50 Hz
- f_stop = 50.10 Hz
- f-Droop (dP/df) = -40 % P_ref / Hz

A "stepwise" frequency variation with a 1 Hz/s RoCoF was conducted, applying the following frequency steps: 50.00 Hz, 50.06 Hz, 50.70 Hz, 51.20 Hz, 50.04 Hz, 55.10 Hz and back to 50.00 Hz.

Figure 11 shows the recorded 200-ms mean values of active power and the 2-s mean values of the network frequency, both plotted over time. The variation of solar irradiation due to time of day and more directly the phenomena of clouding due to cloud procession can be seen in the value of the active power.

Also visible from the diagram is the dip in active power approximately every 360 s; this is due to the local MPP optimization algorithm activated in the inverter control and set to be performed every 6 minutes. It is designed to optimize the PV yield in the event of partial shading and searches for a possibly new MPP point periodically at a user-defined time interval.

At the frequency step of 55.10 Hz the device switches off (active power permanently drops to zero). This is due to exceeding the overfrequency protection tripping value "f_overprotect" of 51.50 Hz. When the conditions for re-connection are met the EUT reconnects and ramps up active power, at first (up to about 25% of nominal power) with a rather steep active power gradient, followed by a brief pause and a renewed rise with a smaller ramp rate. A combined consideration of these two time intervals results in the reduced ramp rate being kept over the whole time span.

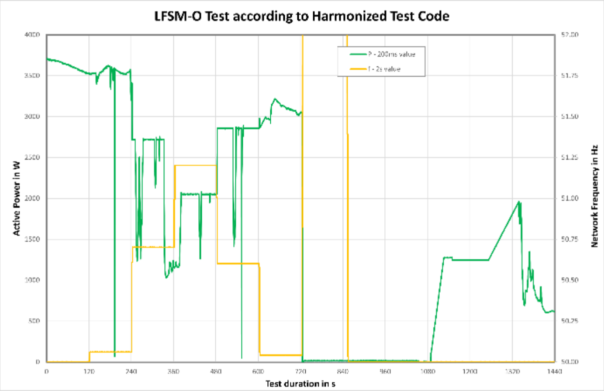

Figure 11 Measured active power and network frequency displayed over time for LFSM-O test according to developed harmonized testing procedure

By transferring the measured active power values to 10-s mean values and plotting them together with the LFSM-O characteristic curve, the diagram shown in Figure 12 is obtained. The active power values at the different frequency steps lie on / match well with the LFSM-O characteristic curve; the characteristic is not exceeded and the EUT follows the f-Droop as parameterized. The lower active power values occurring for each of the frequency steps are due to cloud procession as described for Figure 11. Two values at the frequencies of around 50.25 Hz and 51.05 Hz must be neglected, as they are the results of frequency transition periods.

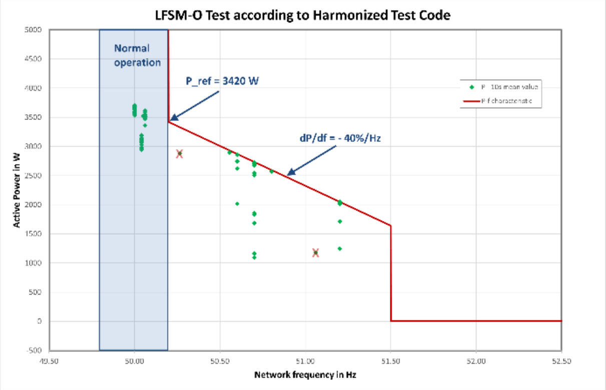

Figure 12 P(f) characteristic and measured 10-s mean values of active power for LFSM-O test according to developed harmonized testing procedure

4.4. Test performance and results – Reactive power provision as a function of voltage (Q(U))

Various Q(U) tests according to the new developed harmonized testing procedure have been executed. The test purpose is the determination of accuracy of reactive power provision as a function of voltage. A test in which the following inverter settings were used is described in more detail below:

- Q-U deadband = Un ± 1 %
- Q_max = ± 43.6 % Pnom
- Qmax @ ≤0.91 Un / -Qmax @ ≥1.09 Un

The test procedure involved a voltage variation with steps of 2 % Un and a duration of 60 s per step.

Figure 13 shows the recorded 200-ms mean values of both reactive power and phase-to-neutral voltage, both plotted over time. Like in the test case of LFSM-O presented in subsection 4.3, approximately every 360 s the local MPP optimization algorithm becomes active, which is also visible here in the reactive power supply.

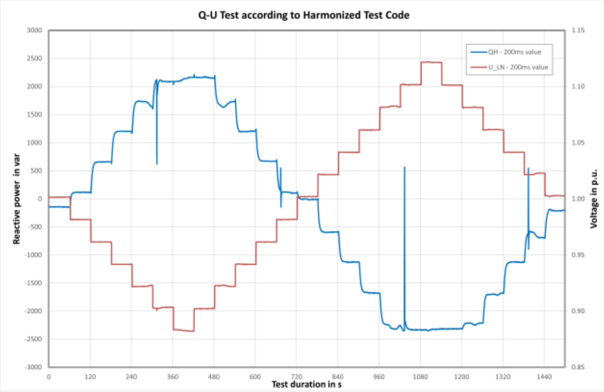

Figure 13 Measured reactive power and Ph-N voltage displayed over time for Q(U) test according to developed harmonized testing procedure

By transferring the measured reactive power values to 1-min mean values and plotting them together with the Q(U) characteristic curve, the diagram shown in Figure 14 is obtained. For the provision of reactive power a tolerance band of ±5 % Pnom is applied.

The observed reactive power provision follows the Q(U) characteristic, but a systematic deviation of approximately -150 to -300 var (or -3 to -6 % Pn) could be observed. This deviation is mainly caused by the measurement uncertainties of both involved devices (power analyser and EUT) and especially its different current sensors. Considering the Rogowski coil current probes used with the power analyser, taking into account an amplitude error of 1 % of the measured value (e.g. 5 A) and a phase angle error of 1 degree, a measurement uncertainty of approx. 120 var can be derived for this operating point, resulting from the current measurement alone. Added to this is the uncertainty resulting from the voltage measurement of the power analyser and of course the measurement uncertainties of the EUT.

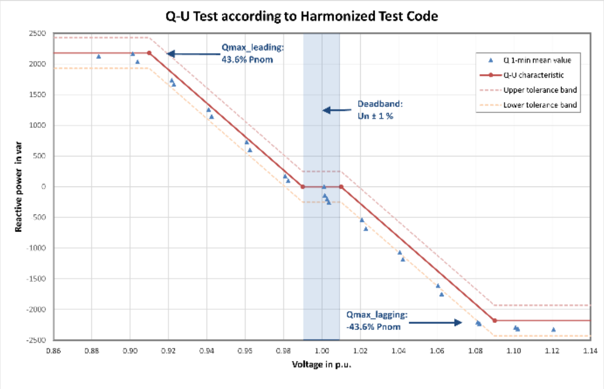

Figure 14 Q(U) characteristic and measured 1-min mean values of reactive power for Q(U) test according to developed harmonized testing procedure

5. CONCLUSION

The study described in this paper details the importance of conducting an analysis to develop a harmonized grid code and a harmonized testing procedure with respect to performing expedited internal verification of products by manufacturers to be sent for certification and before being sold to customers. The development of a harmonized grid code and harmonized testing procedure for four grid services with respect to 15 countries for battery storage system plants up to 1 MW is described. A framework with detailed steps for test setup, measurement of signals, inclusion of required test behaviors based on analyzed documents and conducting assessment of the test results is provided. This approach is essential for performing the tests in a systematic manner and conducting thorough documentation which also enables a high repeatability and reproducibility of the tests.

From the study, it is observed that most of the analyzed countries require and provide a LFSM-O characteristic (

). The cross (x) marks in the table mean: provided or available. In comparison to the LFSM-O fewer countries require the LFSM-U characteristic. This can be attributed to the mandatory requirements by the NC RfG wherein only LFSM-O is required for power generating modules with a maximum power level ≤ 1 MW. Even fewer countries require and provide testing documentation for reactive power provision grid services or active power regulation according to voltage. The reasoning for this is not clear however it certainly means an underutilization of inverter capability which has the possibility of performing various grid-supporting services.

Furthermore, it is also observed, that with respect to developing the harmonized grid code, in some cases the information needs to be derived from a testing procedure documentation of a country. Whereas it would be expected that the harmonized grid code is developed solely based on grid connection requirements documents. This was observed for LFSM-O where the droop for the harmonized grid code has to be expanded from 2-12% (obtained when only grid connection requirements are studied) to 1.3-12% (obtained after consideration to the testing procedure provided by Italy [17] for storage systems is given).

The advantages of time and resource saving resulting from development and application of harmonized testing procedures are obvious, especially if the tests are standardized and only the starting conditions need to be changed. Less different test cases and fewer iterations need to be conducted.

Table 10. Summary of Requirements and Testing Procedure Documentation for the analyzed countries *(GCR: Grid Connection Requirement, TP: Testing procedure)

Country	LFSM-O		LFSM-U		Q(U)		cosphi(P)		P(U)	
	GCR	TP	GCR	TP	GCR	TP	GCR	TP	GCR	TP
Germany [7,8]	x	x	x	x	x	x	x	x		
Austria [13,14]	x	x			x	x	x	x	x	x
Italy [17]	x	x	x	x	x	x	x	x		x
Spain [15]	x	x			x	x				
Belgium [9]	x		x						x	
Netherlands [10,11]	x	x	x	x		x		x		x
Poland [10,11]	x	x	x	x		x		x		x
Sweden [18]	x	x	x							
Switzerland [12]	x		x		x		x		x	
Finland [21]	x									
Portugal [16]	x		x							

An additional advantage is described in this paper on the various opportunities for automation, at the testing stage as well as the evaluation stage. The potential is immense especially with regard to the routine testing of commercial off-the-shelf products and the number of requested test iterations.

The test methods investigated in this paper using the example of a PV battery storage system can be performed with laboratory infrastructures and test facilities usually already existing from tests with grid following / grid supporting inverters.

AUTHORS' CONTRIBUTIONS

Siddhi Shrikant Kulkarni: Conceptualization, Methodology, Investigation, Visualization, Writing – original draft, Writing - review & editing. Gunter Arnold: Laboratory Measurements, Visualization, Writing – original draft, Writing-review and editing. Nils Schäfer: Laboratory Measurements, Writing – original draft, Writing-review and editing.

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