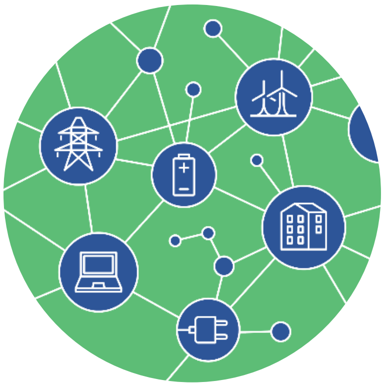
OSMOSE

OPTIMAL SYSTEM-MIX OF FLEXIBILITY SOLUTIONS FOR EUROPEAN ELECTRICITY

Real operation evaluation results of WP4 demonstration

D4.5



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Executive summary

The OSMOSE project aims to identify and develop the optimal mix of flexibilities for the European power system to enable the Energy Transition. To achieve this ambitious objective the project incorporates four large-scale demonstrations. One of these demonstrators has been developed under Work Package 4 to provide multiple flexibility services to the power system by developing a new Multi-Component Flexibility System (MCFS). The MCFS is composed of a Hybrid Flexibility Device equipped with a new design – it integrates modular multilevel static compensator, high voltage lithium-ion battery and supercapacitors – and a novel control system – formed by local control and a Master Control (for more details, see previous deliverables from this Work Package). The demonstrator of the MCFS was installed in CENER facilities in Navarra region (Spain) to evaluate its performance under real operation.

This deliverable presents the results obtained from real operation of the Hybrid Flexibility Device. Multiple tests under different operation modes and conditions have been conducted in order to evaluate and validate the different functionalities and capabilities that the device can provide. In this deliverable, the characteristics of the functionalities are introduced, the conducted tests are described and the obtained results are presented and discussed.

The conducted tests have been classified in different categories according to the group of functionalities they are referred to; namely, requirements, first, second and third level functionalities and combined functionalities. Requirements tests have been conducted to validate the capabilities of the Hybrid Flexibility Device to operate at different voltage and frequency levels and to provide the required active and reactive power.

First level control functionalities are responsible for maintaining grid stability under grid disturbances. This category comprises functionalities providing a fast response, such as inertia emulation, fast reactive current injection, power-frequency regulation under perturbed operation regime, and trapezoidal response. These functionalities were successfully evaluated during this project. In particular, the fast response in power provision has demonstrated to contribute significantly to maintaining grid stability.

Second level control functionalities are defined as those responsible to manage frequency and control once the grid stability has been managed by the first level control. The test conducted showed the capability of power-frequency regulation functionality to manage the grid frequency and the voltage and reactive power functionalities to manage grid voltage.

Third level control functionalities are responsible to optimally manage the flexibility devices, taking into account their nature and characteristics of the managed devices. The results demonstrate that the required setpoints satisfied the grid operation requirements.

Whilst the operation is managed by the Master Control, the setpoints generated for each flexibility device satisfied the grid operation requirements and optimized battery lifetime.

Finally, combined tests were also carried out to evaluate the simultaneous operation of different functionalities. The obtained results illustrate the appropriate implementation of those functionalities enabling to prioritize some functionalities over the others. Furthermore, the ability of the MCFS to provide multiple services to the grid at the same time under specific grid conditions has been proved.

List of acronyms and abbreviations

In the following table are listed the acronyms and abbreviations used in this document.

Acronym	Meaning
BESS	Battery Energy Storage System
D	Deliverable
DC	Direct Current
EMS	Energy Management System
ESS	Energy Storage System
FACT	Flexible AC Transmission Systems
HFD	Hybrid Flexibility Device
HMI	Human Machine Interface
HW	Hardware
MC	Master Control
MCFS	Multi-Component Flexibility Solution
P	Active Power
PCC	Point of Common Connexion
PLC	Programmable Logic Controller
PMG	Program management
PFR	Power Frequency Regulation
PPC	Power Control System Installed in the HFD
Q	Reactive Power
RES	Renewable Energy System
SAT	Service Acceptance Tests
SFD	Single Flexibility Device
SC	Supercapacitor
SCADA	Supervisory Control And Data Acquisition
SOC	State Of Charge
SPT	Setpoint Tracking
SSR	Safety SOC Range
STATCOM	Static compensator
SW	Software
TSO	Transmission System Operator
WP	Work Package

1. Introduction

The WP4 demonstration within OSMOSE project aims to provide multiple flexibility services to the power system by developing and testing a new hybrid flexibility device equipped with advanced control strategies. Figure 1 shows the main parts that constitute the demonstrator. One of them is the Hybrid Flexibility Device (HFD) specifically developed in the project and that has been connected to a 20 kV grid. This HFD integrates a modular multilevel static compensator (STATCOM), a high voltage lithium-ion battery and supercapacitors. The monitoring and operation of these different equipment that constitutes the HFD are done by using novel Master Control and SCADA developed in the project.

The demonstrator also incorporates an already existing microgrid equipped with different energy storage technologies that has been used mainly to evaluate the extended capabilities of the Master Control to coordinate different energy storage devices. Further information related to HFD and Master Control can be found at deliverable *D4.3 Hybrid Flexibility Device Implementation* and *D4.4 Master Control Strategies*[1].

Figure 1: Overview of demonstration with OSMOSE WP4

The demonstrator was installed in CENER facilities located in Sangüesa (Navarra, Spain) by September 2021. The device has been in real operation there where multiple tests have been conducted in order to test and evaluate its performance and functionalities.

This deliverable provides the results and conclusions obtained from the real operation tests carried out on WP4 demonstration. The tests have been specifically designed and conducted in order to validate the performance and required functionalities of the new developments

[1] Deliverable available at OSMOSE Resource Center *available at* https://www.osmose-h2020.eu/resource-center/

within WP4 as per defined in Deliverable *D4.1 Functionalities and services for the power system*[2].

In this report, in Section 3 the tests conducted to evaluate the performance of WP4 demonstration are described. Section 4 contains the explanation required to understand the real operation obtained results that are described later in Section 5. Simulations tools developed in the framework of the demonstrator and obtained results from simulations are described in Section 6. Finally, conclusions are presented in Section 7.

[2] Deliverable available at OSMOSE Resource Center *available at* https://www.osmose-h2020.eu/resource-center/

2. Tests definition

This section describes the real operation tests conducted to evaluate the performance of WP4 demonstrator. These tests are classified in 4 categories named as Requirements, functionalities of first, second and third control levels and combined functionalities.

Requirement's category tests aim to verify the fulfilment of a set of minimal requirements for voltage, frequency, and power management.

Test for validation of first, second and third control levels functionalities refer to the different control layers that incorporates the implemented system and the different functionalities provided by each control level. Control level 1 includes those functionalities that are applied to maintain the grid stability, control level 2 aggregates those functionalities that help to manage voltage and frequency once grid is stable, and control level 3 incorporates those functionalities implemented to optimally manage and coordinate the different energy storage devices of the demonstrator. More details of these control levels can be found in deliverable D4.4 Master Control Strategies.

Combined functionalities tests aim to validate the correct and coordinated performance of functionalities that can operate simultaneously under specific conditions.

2.1. Requirements

Before describing the functionalities, the implemented system has to provide a set of minimum nominal operating requirements in terms of voltage, frequency and power performance. These requirements are:

1. Voltage Stability: the device remains connected to the grid for specified times depending on the PCC voltage. At the same time, it is also capable of remaining connected to the grid during a variety of faults.
2. Frequency Stability: the device remains connected to the grid for specified times depending on the frequency of the grid and its derivative.
3. Reactive current capability as a function of voltage: the device has the ability to provide an inductive or capacitive reactive current as a function of voltage up to its rated value.
4. P-Q Capability: the device can simultaneously provide the rated active and reactive power.

2.2. Level-1 functionalities

The first level functionalities will provide services to support the stability of the grid. Given that an extremely fast response is needed in these functionalities, they are implemented as low-level controllers in the HFD itself. These services are inertia emulation, power-frequency regulation, fast reactive current injection and trapezoidal response. Level-1 functionalities a are defined below.

2.2.1. Inertia Emulation

The HFD will provide frequency control based on the inertia emulation of a synchronous generator. To emulate this inertial response, the HFD will generate an increase in active power proportional to the derivative of the frequency variation with a parameterizable inertia ‘H’.

2.2.2. Power-Frequency Regulation

The HFD will provide a Power-Frequency (P-f) control, which will inject or absorb increases in active power for frequency variations measured at the PCC.

In case of over-frequency, the HFD will decrease its active power injection to the grid until the setpoint indicated by the control is achieved. On the contrary, for frequency values below the setpoint (underfrequency), the system will increase its injected active power until the frequency reaches its reference value.

2.2.3. Fast reactive current injection

During and after a disturbance in the grid that affects the voltage, a fast and continuous control, by means of a change in reactive current, is required with the purpose of reducing voltage dips and overvoltage during fault clearing.

2.2.4. Trapezoidal Response

In addition to inertial control and P-f regulation, the storage will discharge and charge active power based on a trapezoidal response as illustrated in the figure below.

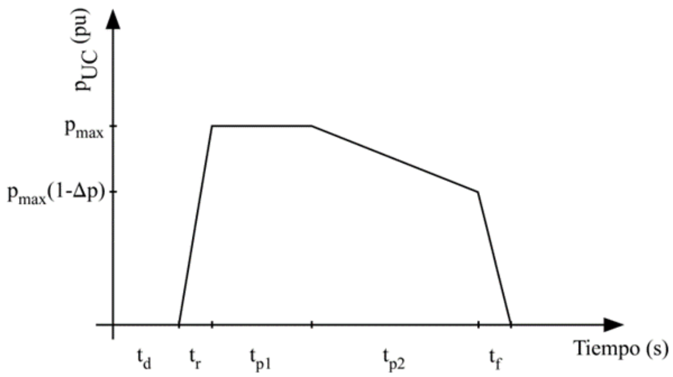

Figure 2: Trapezoidal Response profile

The trapezoidal control must be used as an alternative to the inertial and P-f controls, so this control cannot operate simultaneously with the inertial control and P-f regulation.

2.3. Level-2 functionalities

Second level functionalities will provide voltage and frequency control services once the grid stability is guaranteed. They have been implemented both in the HFD itself and also in the MC that involves the MCFS, so they can be performed by either one or the other. These functionalities are described next.

For a disturbed operating regime, level 1 operation will take effect, whose response and settling times are more restrictive (on the order of 10 times) than level 2. The normal and disturbed operating regimes are defined on the basis of the following values.

- Frequency
  - Nominal operating regime:
    - 49.75 Hz ≤ f ≤ 50.25 Hz

        - |df/dt| ≤ 0.5 Hz
    - Disturbed regime: either of the above two conditions is not met.
- Voltage
    - Normal operating regime:
        - 0.85 pu < VPCC < 1.15 pu
        - |ΔV| < 0.1 pu, measured in 1 cycle grid.
    - Disturbed regime: either of the above two conditions is not met.

2.3.1. Power-frequency Regulation (nominal operating mode)

As defined in Section 2.2.2, the HFD or MCFS, depending on the application case, will provide P-f control, which will inject or absorb active power increments for frequency variations measured at the PCC. The difference with level 1 P-f control is the operating regime of the equipment.

2.3.2. Voltage control with voltage setpoint

In this control mode, the HFD or MCFS, depending on the application case, must perform three-phase voltage control based on the error and a Q-V slope. The voltage error is calculated as the difference between the voltage reference and the voltage at the PCC.

2.3.3. Voltage control with reactive setpoint

In this control mode, the reactive power injected or absorbed by the HFD or MCFS, depending on the application case, must be controlled directly by the operator. The operator must set a reactive reference, and this value must be adjustable within the rated ranges of the equipment.

2.4. Level-3 functionalities

Level-3 functionalities are in charge of delivering reference values for different devices and controllers according to a program or as a response to system variables. These are high-level functionalities that enable the TSO to develop operation strategies, so they are implemented in the MC. In this section, level-3 functionalities are described.

2.4.1. Setpoint tracking

In this functionality, the charge/discharge process of the different flexibility devices that constitute the MCFS, can be managed by a setpoint signal. The setpoint may be changed continuously.

2.4.2. Program Management

This functionality enables the TSO to set a charge/discharge program that will be followed by the MCFS. This profile is specified in terms of charge/discharge power, starting time-point and duration time.

2.4.3. Congestion management

This functionality is designed to ensure that renewable energy production does not exceed a defined power limit in the node of interest. The MCFS will use its storage capacity to compensate the RES generation, supplying or absorbing active power so as to ensure the desired power at the reference bus. In the instant in which the production exceeds the power limit defined in the bus, the charging of the battery is initialized. In the discharge mode, the discharge may be "free", meaning that the devices are enabled to discharge at any time, or “programmed”, which only allows the discharge at certain periods of time.

2.5. Combined functionalities

Combined functionalities are different combinations of the previously presented functionalities to highlight the priority and effective coordination of services to provide the grid requirements. In this section, different combinations of functionalities are described:

2.5.1. Power frequency regulation and Program Management

The combination of these two functionalities enables the TSO to set a charge/discharge program at the same time that the power-frequency control is enabled. In case of unexpected frequency changes, the system may inject or absorb active power in response, taking into account that frequency regulation must be prioritised.

2.5.2. Power frequency regulation and Congestion management

The combination of these two functionalities enables the TSO to limit the active power in a certain node and reduce the effect of variability of renewable energy generation. At the same time, in case of unexpected frequency changes, the system may inject or absorb active power in response, taking into account that frequency regulation must be prioritised.

2.5.3. Power frequency regulation and Voltage control with reactive setpoint

The combination of these two functionalities enables the TSO to set a reactive power reference to control reactive power at PCC. At the same time that, in case of unexpected frequency changes, the system may inject or absorb active power in response, taking into account that frequency regulation must be prioritised.

2.5.4. Voltage control with reactive setpoint and Program management

The combination of these two functionalities enables the TSO to set a charge/discharge program along with a reactive power reference to control reactive power at PCC.

2.5.5. Inertia emulation control & Power-frequency Regulation. Perturbed Regime (INE-PFR)

The combination of these two functionalities enables the TSO to set an increase of active power as a function of frequency derivative, while it also responds to the rapid variations of the power exchanged with the grid, measuring frequency at the PCC.

2.5.6. Fast Frequency Response & Power-frequency Regulation. Nominal Regime (FFR-PFR)

The combination of these two functionalities enables the TSO to set active power as a function of frequency variations, while it also responds to the rapid variations of the power exchanged with the grid, measuring frequency at the PCC. This combination combines a level-1 functionality (FFR) and a level-2 functionality (PFR), which operate at the perturbed regime and normal operation, respectively.

2.5.7. Inertia emulation control & Power-frequency Regulation. Nominal Regime & Voltage Control based on Voltage Setpoint (INE-PFR-VCV)

The combination of these three functionalities enables the TSO the capability of simultaneously setting active and reactive power setpoints. Active power, as previously explained, is set as a function of frequency variations, operating at the disturbed operating regime and normal operation regime. The reactive power is set as a function of the voltage measurement and the defined control parameters.

2.5.8. Inertia emulation control & Power-frequency Regulation. Nominal Regime & Voltage Control based on Voltage Setpoint & Fast Reactive Current injection (INE-PFR-VCV-FRC)

The combination of these functionalities allows the TSO to set active and reactive power as a function of frequency and voltage variation, taking into account both control algorithms. The device response is fast since these controls operate at the disturbed operating regime and the normal operation regime.

3. Description of testing location and procedures

The real operation of the demonstrator has been carried out at CENER facilities, in the LEA centre (Wind Turbine Laboratory) in Sangüesa (Navarra), location where the WP4 demonstrator was installed. In this location, the OSMOSE project equipment was connected to the power grid by a 20/0.69 kV 2.5 MVA transformer and in parallel to CENER's Atenea microgrid, which has storage systems (lead-acid, lithium-ion and redox-flow) and PV generation. The complete system is schematically detailed in the following figure.

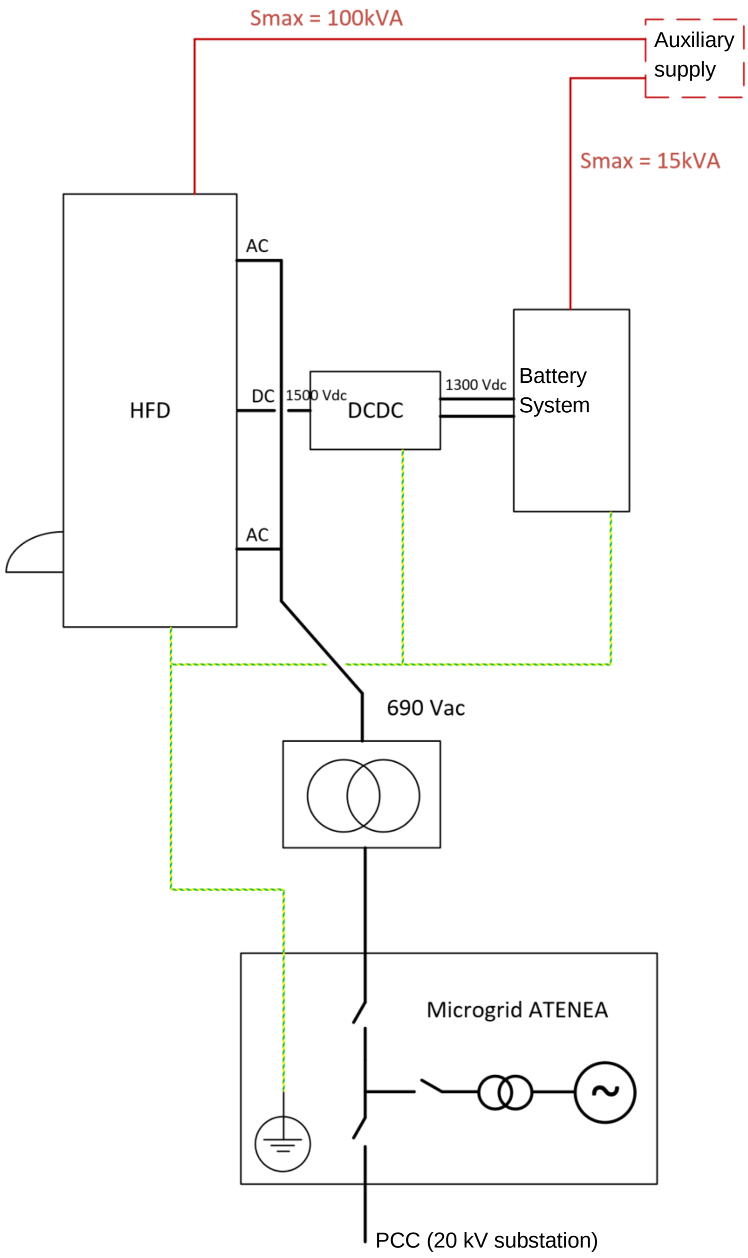

Figure 3: Simplified OSMOSE project schematic

3.1. Overall operation

The PCC is located at 20kV level, the substation is place upstream and downstream there are two transformers in parallel, one for connected the HFD and the other for Atenea microgrid.

Atenea microgrid is connected to a transformer of 20/0.42kV and 160KVA. Downstream this transformer the three participating devices are connected in parallel, which are a lead-acid battery, a lithium-ion battery and a redox-flow battery.

The HFD is directly connected to a transformer of 20/0.69 kV and 2.5MVA.

The HFD container consists of two multilevel topology converters each fed at 690V AC from the transformer. These AC-DC converters are capable of modulating a DC voltage on their neutrals, which are connected to a DC-DC converter high DC bus.

At the same time, the ultracapacitors are located in parallel, which serve as a sink and reservoir of active power when required. The DC-DC converter is responsible for boosting the voltage coming from the high voltage battery system from 1000-1200V to 1500V, which will be the active power source for the hybrid solution of the STATCOM.

3.2. Description of measurement equipment

All measurement data will be recorded on a synchronised time base and logged for reporting, but also to compare the measurement systems with internal (control) measurements.

The following calibrated measurement transducers will be used at the measurement positions defined in the set-up diagram.

Tag	Transducer	Rating	#	Type
Vac1, Vac2	Voltage LV	6.4 kV	4	LEM LV 200-AW/2/6400
Iac1, Iac2	Current LV	2 kA	6	LEM HAX 2000-S
Vdc	Voltage LV	2 kV	2	LEM DVL 2000
Idc, IBAT	Current LV	2 kA	2	LEM HAX 2000-S
V_{UC}	Voltage LV	2 kV	2	LEM DVL 2000
I_{UC}	Current LV	2 kA	1	LEM HAX 2000-S

Table 1. Calibrated measurement transducers

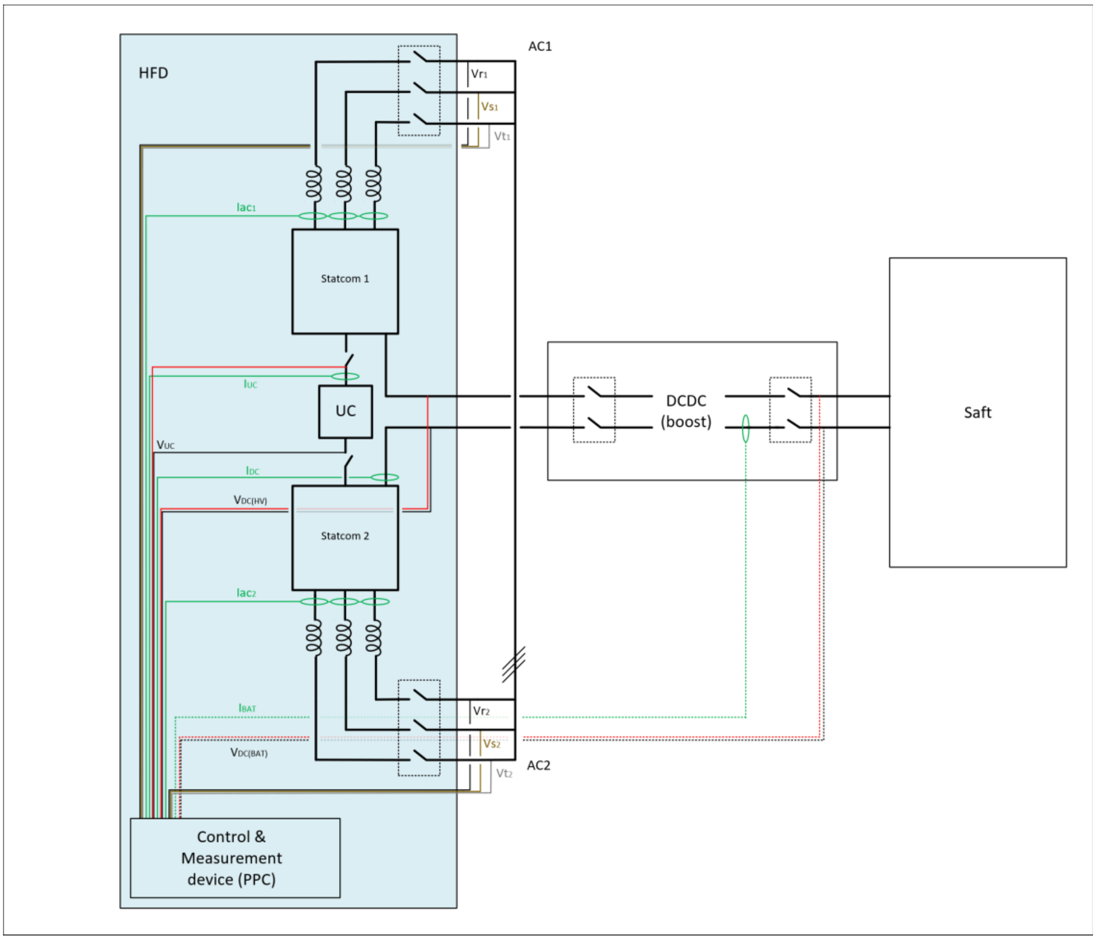

Figure 4: Detailed diagram of measurement points

3.3. Activation of demonstrator functionalities

The demonstrator operates activated by the operator or in response to specific events or disturbances that occur in the grid to mitigate their effect. However, depending on the specific events that occur in the grid, it may be possible that some functionalities could not be tested under stressing grid conditions. For these cases, the demonstrator incorporates the capability of emulating grid states and events using input data as a measurement. In doing so, it is possible to reproduce conditions that may not be found in the connected grid during the evaluation period (e.g., extreme overvoltage / undervoltage and over-frequency / underfrequency) but that allow the evaluation of all the demonstrator functionalities. This emulation tool consists of a DSP software that incorporates a virtual profile launching tool which allows to introduce previously determined values of voltage and frequency as an emulated value in the HFD terminals.

The “Virtual Profile” tool is written in python and it is based on the same proprietary protocol as the rest of the control software: TCP/IP socket communication protocol.

Therefore, this “Virtual Profile” tool inserts frames of voltage and frequency measurements previously defined by the user, replacing the real measurements read by the HFD. The definition of these values is done with the following table.

Pos. Seq. voltage, $|V_1|$ (p.u.)	Neg. Seq. voltage, $|V_2|$ (p.u.)	Frequency (p.u.)	Time interval (s)
1	0	1	1
0.05	0	1	0.001
0.05	0	1	0.26
1	0	1	0.001
1	0	0.96	5
1	0	0.96	0.4
1	0	1	0.001
1	0	1	0.4

Table 2. Virtual profiles values definition

The first two columns correspond to voltage values. These values are defined as the absolute value of the positive and negative sequence voltage. Thus, both symmetrical and asymmetrical faults can be emulated at the device terminals. The third column corresponds to frequency values. All these values are presented in p.u. values over the defined nominal.

The last column defines the times for each interval. Minimum time interval is 1 µs. There is no upper limit for time intervals. If voltage or frequency values are modified from one interval to another, the time considered would correspond to the rate of change (ramp) of those values.

An example is shown in Figure 5, considering Table 2 values.

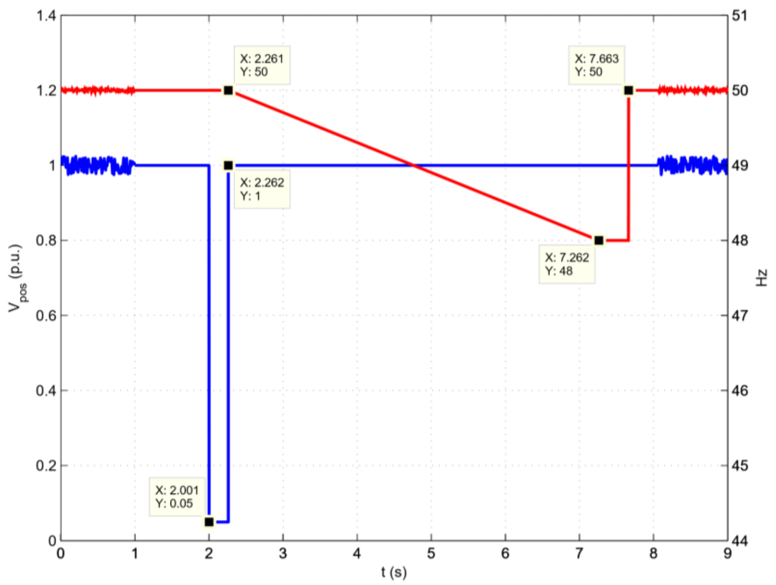

Figure 5: Virtual profiles values definition

The graph shows the voltage (blue curve) and frequency (red curve) profile as well as the times set by the tool. Once all the times defined in the last column have been consumed, the HFD receives as inputs the real values read in the PCC without modifications.

3.4. Calculation of frequency derivative

The direct calculation of the grid frequency is based on a Frequency-Locked Loop, which is a simpler PLL-derived grid synchronization technology that is decoupled from the phase angle and without trigonometric calculations, having a form similar to a PI controller.

The input to this FLL is αβ-reference voltage after applying a 16 kHz resonant filter to it. With a 2 kHz control interruption, the frequency value is obtained. The derivative calculation consists of the increment of this value in 10ms periods, enough time to filter possible peaks of the slope value.

3.5. Results representation

As briefly mentioned in section 3.2, the HFD has its own data acquisition software, which stores all the measurements and control variables within the HFD+DCDC system. This acquisition system stores historical data of all these variables, with a sampling rate of 100ms, giving the possibility of visualizing plots and saving data in .csv format. This tool has been used by GPTech to represent and described the different test results.

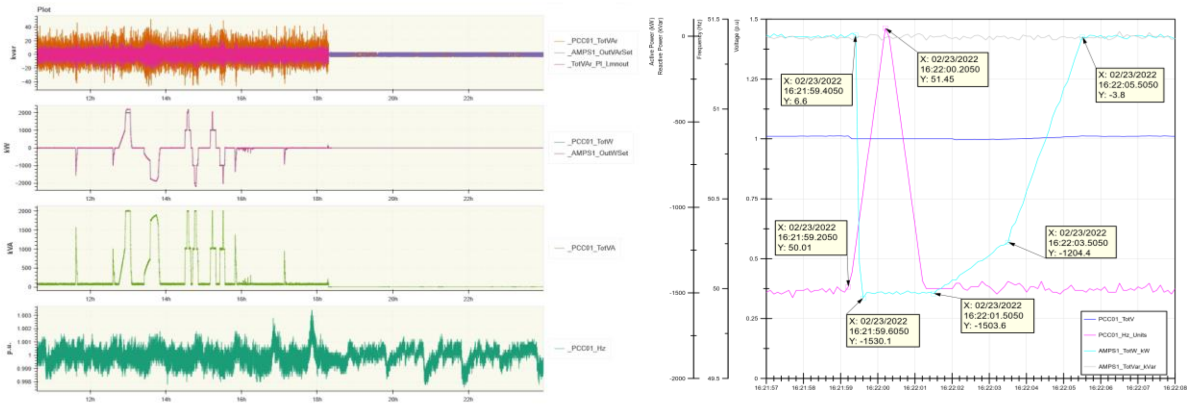

Figure 6: Example of data display and representation of stored .csv with PPC[3]

Due to the limitation of the sampling rate, the results from some tests may have been shown poorly. In these cases, a second data acquisition method, implemented in the innermost control layer and running on the DSP installed in the HFD, was be used. This tool allows finer sampling rates, up to 500 µs, with the possibility of storing up to 200 samples in .m format.

[3] *The acronym AMPS in the figure legends corresponds to Advanced multiport power station, GPTech name for this kind of control systems.*

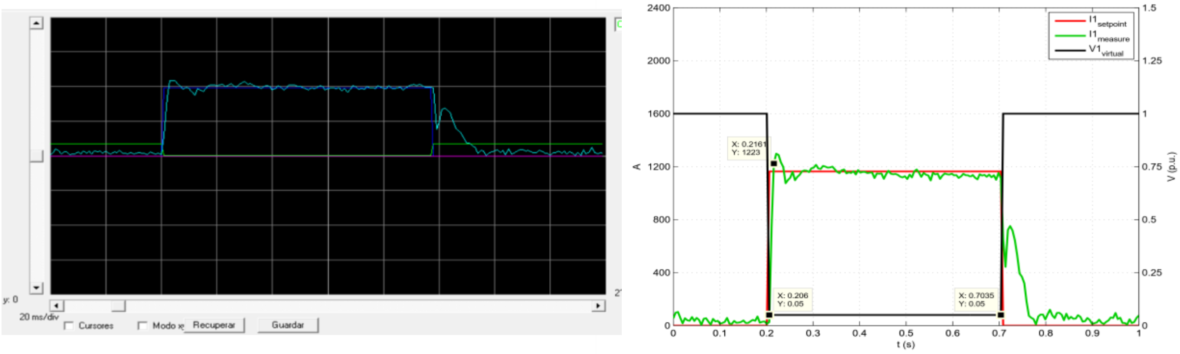

Figure 7: Example of data display and representation of stored .m with DSP

However, 200 samples are a restrictive factor, limiting the width of the sampling window. For example, for the case of a sampling period of 500 µs, a window of 100ms would be obtained, which is useful for transients or ramps, but not for complete test response. This means that a higher sampling rate (10-20ms) should be selected for the representation of results.

Regarding the test where the MCFS is tested, which implies to do measurements from PCC and all the flexibility devices, renewable generation and intermediate buses, CENER use a dedicated SCADA with a sample acquisition time of 500ms.

The main data acquired are electrical setpoints and measurements at PCC and devices, that for those the main data are status, electrical setpoints and measurements, alarms and SOC.

Along the different MCFS tests, the represented data will be:

- Status Functionalities
- V measured at PCC
- frequency at PCC
- P measured at PCC
- Q measured at PCC
- P setpoint
- Q setpoint
- SOC of the involved devices in the test

3.6. Constants

So as to provide an adequate response, the controllers need to be provided with certain constants, which describe physical charasteristics of the demonstrator. Table 3 shows the nominal power values of the MCFS and HFD used as parameters in the control of the system. Also, nomenclature used for the electrical variables (voltage, frequency and active and reactive power) is defined in Table 4.

Constant	Description	Value
Pn_BAT	Nominal power of the battery	2 MW
Qn	Nominal reactive power for the MCFS	2 MVAr
Pn_BAT+Pn_UC	Nominal active power of the battery plus supercapacitors	2 MW
Pn	Nominal active power for the MCFS	2 MW
Qn_HFD	Nominal reactive power defined for the HFD control	2 MVAr
Q_MCFS	Nominal reactive power defined for the MCFS	2 MVAr
F_PCC	Frequency measurement at PCC	measurement
V_PCC	Voltage measurement at PCC	measurement

Table 3. HFD and MCFS parameters values

Graph name	Description	Unit
ToTV	Voltage at the PCC	Per unit
Hz_Units	Frequency at the PCC	Per unit
ToTVar_KVar	Reactive Power Output at the HFD	KVAr
ToTW_kW	Active Power Output at the HFD	kW

Table 4. Graphs Values

3.7. Acceptance criteria HFD

Different acceptance criteria are established for validation of the demonstrator functionalities depending on the type of functionalities. The first group of criteria refers to functionalities managed by the low-level local control of the HFD. Thus, it was used in the test related to the requirements and Level-1 and Level-2 functionalities. The second set of acceptance criteria refers to level 2 and level-3 functionalities, managed by the Master Control. Therefore, the structure of Section 4 has slight differences according to these two groups of criteria.

3.7.1. Acceptance criteria for Requirements, Level1 and Level 2 control functionalities managed by the low-level control of the HFD

For the validation of the different functionalities, the following conditions are taken as acceptance criteria:

- The response time must be less than or equal to (≤) the response time established as a parameter in the project for each functionality (t_r).
- The concept of deviation (D) is defined as the relation between the obtained result [4] and the expected value:

$$D\ (\%) = \frac{|\Delta \boldsymbol{X}|(result)}{|\Delta \boldsymbol{X}|(planned)} \cdot 100\%$$

[4] *For Deviation calculation, measurement noises are not taken into account in the result values*

Where X represents the reference value for the tested functionality, previously defined for each test.

The acceptance criteria for Deviation (D) are as follows:

- ✓ **Validated: 0%** ≤ D (%) ≤ **10%**. Performance is within acceptable limits for verification of correct operation.
- ✓ **Suboptimal: 10%** ≤ D (%) ≤ **15%**. Performance requires a review of its operation to refine the response, with the possibility of repetition. Performance is considered valid if the response times of the functionality are met.
- × **Unacceptable: 15%** ≤ D (%). Invalid functionality. Review and repetition are mandatory.

3.7.2. Acceptance criteria for Level 2 and Level 3 control functionalities managed by the Master Control

For the validation of the different functionalities, the following conditions are taken as acceptance criteria:

- The rise time must be less than or equal to (≤) the defined for each functionality (t_r).
- The settling time must be less than or equal to (≤) the defined for each functionality (t_s).
- The overshoot must be less than or equal to (≤) the defined for each functionality (ov).
- The tolerance must be less than or equal to 5% of the setpoint

The acceptance criteria are as follows:

- ✓ **Validated:** Performance is within acceptable limits for verification of correct operation.
- × **Not validated:** Performance requires a review of its operation to refine the response, with the possibility of repetition.

For the combined functionalities, the acceptance criteria and the format of the results presentation will depend on the priority type of the functionalities that integrates the combined tests.

4. Real Operation Results Description

In the following section, the results obtained after execution of the tests described in Section 2. These have been grouped in four sets of tests as defined in that previous section: results from requirements tests are presented first, then results obtained from execution of first, second and third control level functionalities, and finally those results extracted from the combined operation of different functionalities.

For each set of results, the initial conditions of the tests, the acceptance criteria and the obtained results (graphs and tables) are presented and analysed.

4.1. Requirements

In order to ensure the proper and secure operation of the equipment, the fulfilment of the technical voltage, frequency and power requirements of the HFD is evaluated here. The capabilities of the equipment in terms of voltage and frequency stability and active and reactive power capabilities are verified next.

4.1.1. Voltage Stability (VST-1 & VST-2)

Two different sets of tests have been carried out to validate the voltage stability capabilities of the equipment. VST-1 tests are intended to ensure that the HFD is able to remain working at different voltage levels. VST-2 test are intended to validate that the HFD is able to withstand voltage dips according to its requirements.

Conditions for VST-1 test

The device must remain connected to the grid for the PCC voltage values and time frames specified in Table 5. In addition, the device must be injecting or absorbing reactive power according to the voltage scenario: over-voltage or under-voltage.

	V_PCC	Minimum time working	Q_HFD	P_HFD
VST-1 (a)	V_{PCC} = 1.48 p.u.	0 s	Q_{HFD} = -Qn (inductive)	P_{HFD} = 0.8 * Pn_BAT
VST-1 (b)	V_{PCC} = 1.399 p.u.	>= 1.5 s	Q_{HFD} = -Qn (inductive)	P_{HFD} = 0.8 * Pn_BAT
VST-1 (c)	V_{PCC} = 1.2 p.u.	>= 15 s	Q_{HFD} = -Qn (inductive)	P_{HFD} = 0.8 * Pn_BAT
VST-1 (d)	V_{PCC} = 1.12 p.u.	>= 60 min	Q_{HFD} = -Qn (inductive)	P_{HFD} = 0.8 * Pn_BAT
VST-1 (e-1)	V_{PCC} = 1.05 p.u.	>= 90 min	Q_{HFD} = -Qn (inductive)	P_{HFD} = 0.8 * Pn_BAT
VST-1 (e-2)	V_{PCC} = 0.95 p.u.	>= 90 min	Q_{HFD} = Qn (capacitive)	P_{HFD} = 0.8 * Pn_BAT
VST-1 (f)	V_{PCC} = 0.86 p.u.	>= 60 min	Q_{HFD} = Qn (capacitive)	P_{HFD} = 0.8 * Pn_BAT

Table 5. values for VST-1 test

Graph results for VST-1 test

The results of all the VST-1 tests are presented in Annex 7.1. In each figure, the voltage profile and the active and reactive power output are represented.

As an example, VST-1 (f) results are shown in next figure:

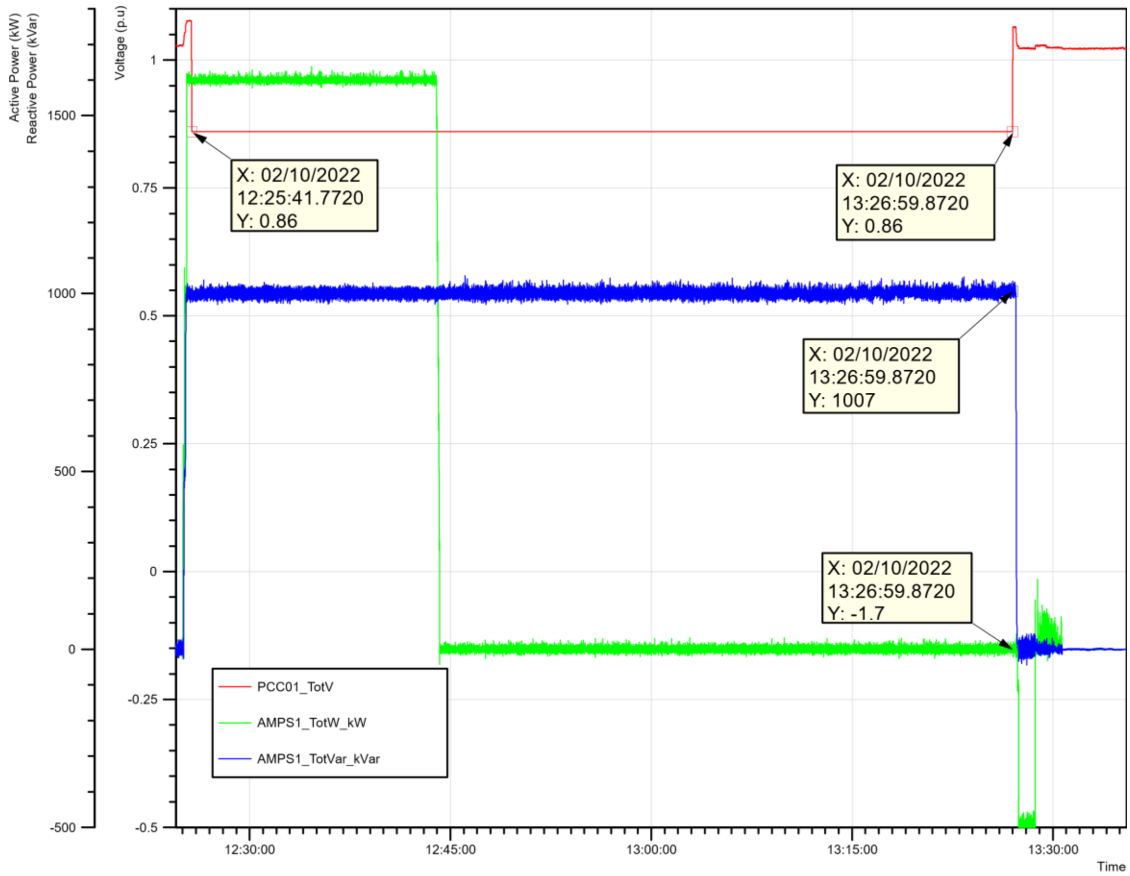

Figure 8: VST-1 (f) results

Table of results of VST-1 test

A summary of the previous results can be found in the following table, where the active and reactive power output, as well as the initial and final SoC of the batteries are included. The time the HFD continued working after the perturbation and the fulfilment of the acceptance criteria are also specified.

	Q_HFD	P_HFD	Initial SoC	Final SoC	Time working	Acceptance
VST-1 (a)	Q_{HFD} = -1 Mvar	P_{HFD} = 1.6 MW	90.67 %	90.67 %	0 s	✓
VST-1 (b)	Q_{HFD} = -1 Mvar	P_{HFD} = 1.6 MW	85.89 %	85.89 %	1.5 s	✓
VST-1 (c)	Q_{HFD} = -1 Mvar	P_{HFD} = 1.6 MW	81.11 %	80.98 %	15 s	✓
VST-1 (d)	Q_{HFD} = -1 Mvar	P_{HFD} = 1.6 MW	91.22 %	5.7 % (*)	> 3600 s	✓
VST-1 (e-1)	Q_{HFD} = -1 Mvar	P_{HFD} = 1.6 MW	94.33 %	6.56 % (*)	> 5400 s	✓
VST-1 (e-2)	Q_{HFD} = 1 Mvar	P_{HFD} = 1.6 MW	96.33 %	6.88 % (*)	> 5400 s	✓
VST-1 (f)	Q_{HFD} = 1 Mvar	P_{HFD} = 1.6 MW	88.89 %	5.22 % (*)	> 3600 s	✓

Table 6. Results values for VST-1

** SoC reached during the test*

At the power level required for this test (1.6 MW) the current is approximately 1500 A. If losses and tolerances are included, the current can reach up to 1750A. Taking into account that the nominal capacity of the battery is 580 Ah, the battery gets completely discharged in approximately 1520 minutes. This situation can be observed in the curves VST-1(d), (e) and (f). In those tests, the active power output initially matches the required value. When the battery discharges, the current is reduced due to low SoC.

As explained in section 3.5, for VST-1 (a), DSP acquisition software was used.

Conditions for VST-2 test

For VST-2 tests, the device must withstand both symmetrical and asymmetrical faults. For this purpose, the equipment monitors voltage obtained by direct measurement. To distinguish between faults, the device internally calculates using a second order generalized integrator (SOGI). The modulus of the positive and negative sequence voltages, and the tripping thresholds are defined; being the same for symmetrical and asymmetrical faults.

During a voltage failure, either symmetrical or asymmetrical, and if it is operated within the defined operating limits, the inverter continues to inject the current that was present at the instant prior to the fault, so that the power factor stays constant. But, if there was inductive current injection during a low voltage event, this inductive current would be fixed to 0 during the fault. If the fault exceeds the defined operating limits, the device stops current injection and disconnects from the grid in less than 10ms.

The tripping profile for the operating limits is shown below.

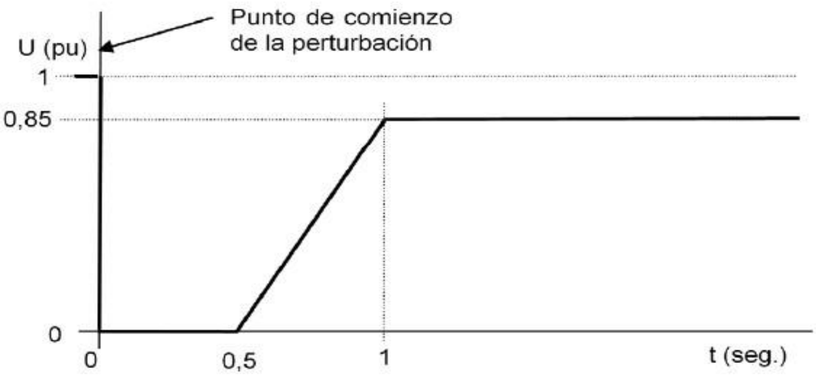

Figure 9: Dip voltage profile

	V_PCC during the voltage dip	Dip time	P_HFD
VST-2 (a)	0% Vn (±5%, Three-phase)	500 ms	P_{HFD} = 0.8 * Pn_BAT
VST-2 (b)	0% Vn (±5%, Two-phase)	500 ms	P_{HFD} = 0.8 * Pn_BAT
VST-2 (c)	0% Vn (±5%, Single-phase)	500 ms	P_{HFD} = 0.8 * Pn_BAT
VST-2 (d)	20% Vn (±5%, Three-phase)	620 ms	P_{HFD} = 0.8 * Pn_BAT
VST-2 (e)	20% Vn (±5%, Two-phase)	620 ms	P_{HFD} = 0.8 * Pn_BAT
VST-2 (f)	20% Vn (±5%, Single-phase)	620 ms	P_{HFD} = 0.8 * Pn_BAT
VST-2 (g)	75% Vn (±5%, Three-phase)	945 ms	P_{HFD} = 0.8 * Pn_BAT
VST-2 (h)	75% Vn (±5%, Two-phase)	945 ms	P_{HFD} = 0.8 * Pn_BAT
VST-2 (i)	75% Vn (±5%, Single-phase)	945 ms	P_{HFD} = 0.8 * Pn_BAT

Table 7. Dip voltage profile values

For the simulation of asymmetrical faults, the virtual profiles will take the norm value of the positive and negative sequences of the three-phase voltage. Simulation and calculation software are used to calculate norm values, setting the reference for the virtual profile. The values obtained with the software are employed during the test as shown Figure 10.

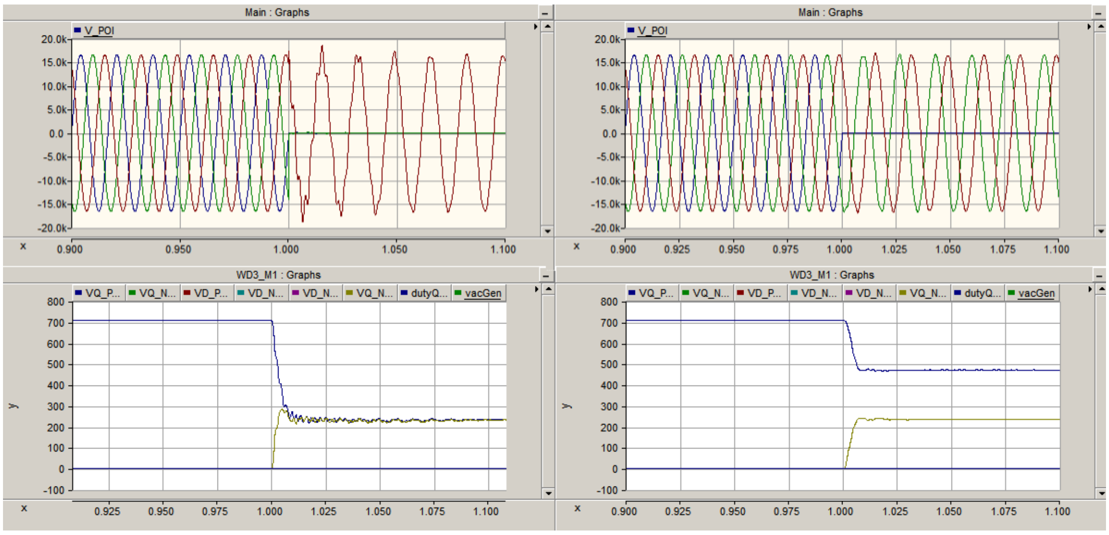

Figure 10: Asymmetrical faults in PSCAD

Results from PSCAD simulation for the single-phase and two-phase earth faults cases are shown in the Figure 10. Similar graphs and validation are obtained for different scenarios, obtaining the input values for the "Virtual profile" tool.

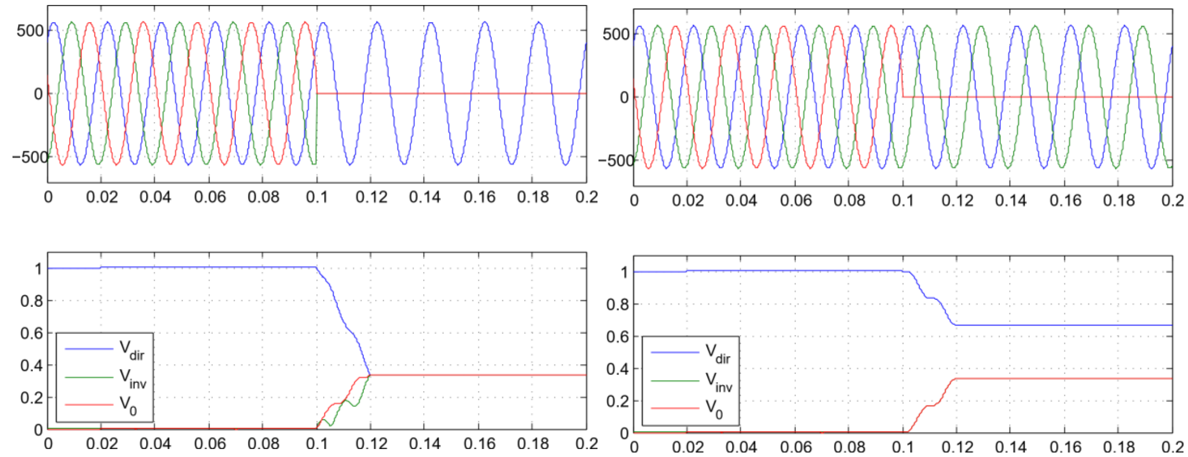

Figure 11: 0% Vn Two-phase and single-phase faults

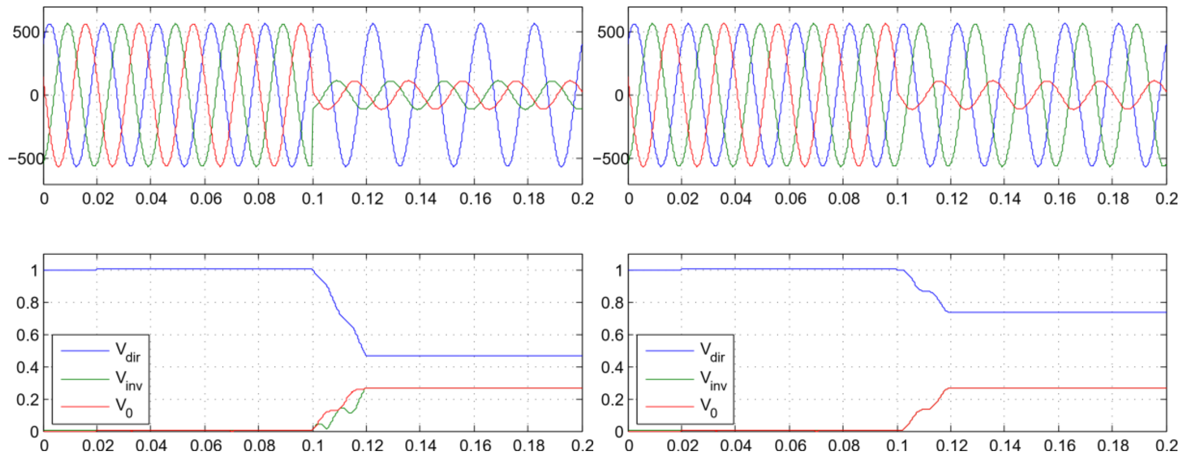

Figure 12: 20% Vn Two-phase and single-phase faults

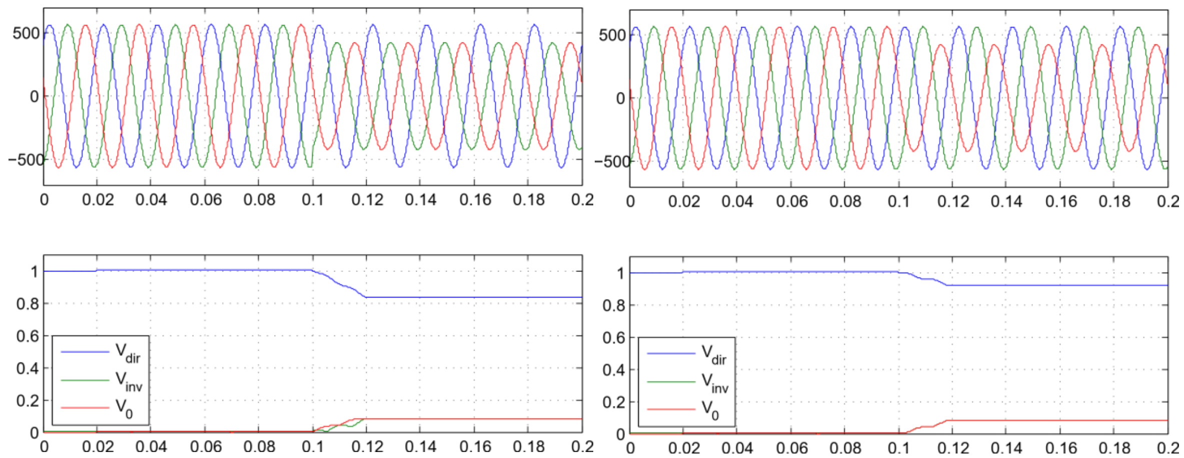

Figure 13: 75% Vn Two-phase and single-phase faults

The positive and negative sequence values for asymmetrical faults are summarized in Table 8.

V_PCC	V_positive	V_negative
0% Vn (Two-phase)	0.333 p.u	0.333 p.u
0% Vn (Single phase)	0.666 p.u	0.333 p.u
0% Vn (Two-phase)	0.466 p.u	0.266 p.u
0% Vn (Single phase)	0.733 p.u	0.266 p.u
0% Vn (Two-phase)	0.833 p.u	0.083 p.u
0% Vn (Single phase)	0.916 p.u	0.083 p.u

Table 8. Positive and negative sequence values for asymmetrical faults

Graph results for VST-2 test

The results of all the VST-2 tests are presented in Annex 7.1. In each figure, the voltage profile and the active and reactive power output are represented.

Every graph shows:

- Positive (V1) and negative (V2) sequence voltage at HFD input,
- Active power (P) injected by the HFD
- Machine tripping curve. For the case of the negative sequence voltage, this limit is considered with the inverse logic, i.e., it is defined at 0 in normal operation, and the same tripping profile for values greater than 0.

Minimum operating time limit of the device, as an example, VST-1 (f) results are shown in next figure

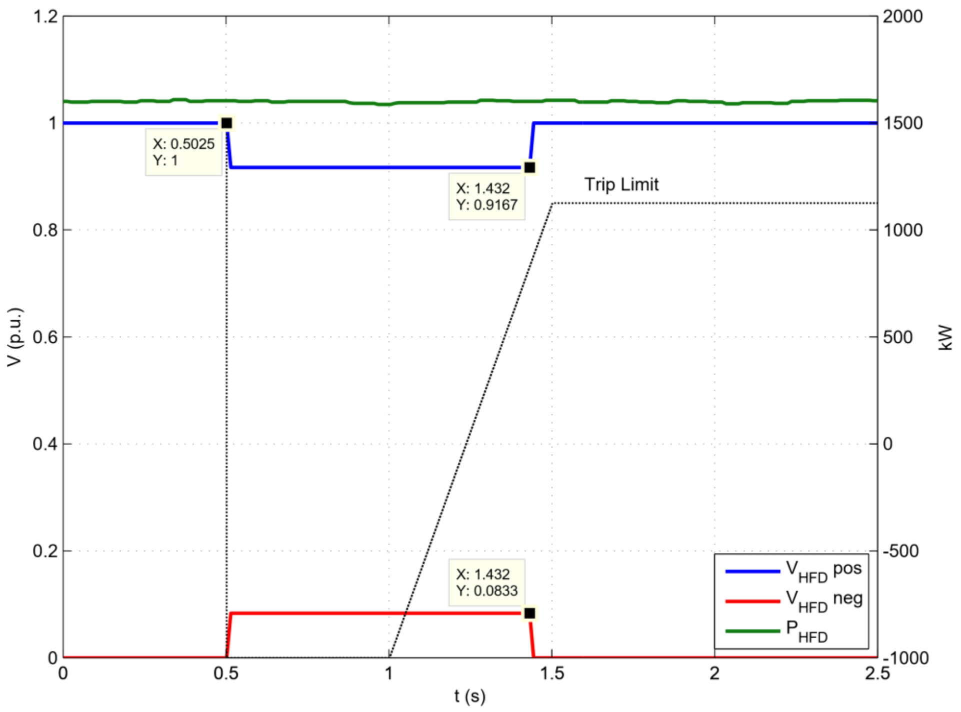

Figure 14: VST-2 (i)

Table of results of VST-2 test

A summary of the previous results can be found in the following table, where the active and reactive power output, as well as the input direct and inverse sequence voltages are included. The time the HFD continued working after the perturbation and the fulfilment of the acceptance criteria are also specified, showing HFD has met the defined criteria.

	Q_HFD	P_HFD	V_1	V_2	Time working	Acceptance
VST-2 (a)	Q_{HFD} = 0 Mvar	P_{HFD} = 1.6 MW	0.001 p.u	0 p.u	500 ms	✓
VST-2 (b)	Q_{HFD} = 0 Mvar	P_{HFD} = 1.6 MW	0.333 p.u	0.333 p.u	500 ms	✓
VST-2 (c)	Q_{HFD} = 0 Mvar	P_{HFD} = 1.6 MW	0.666 p.u	0.333 p.u	500 ms	✓
VST-2 (d)	Q_{HFD} = 0 Mvar	P_{HFD} = 1.6 MW	0.2 p.u	0 p.u	620 ms	✓
VST-2 (e)	Q_{HFD} = 0 Mvar	P_{HFD} = 1.6 MW	0.466 p.u	0.266 p.u	625 ms	✓
VST-2 (f)	Q_{HFD} = 0 Mvar	P_{HFD} = 1.6 MW	0.733 p.u	0.266 p.u	625 ms	✓
VST-2 (g)	Q_{HFD} = 0 Mvar	P_{HFD} = 1.6 MW	0.75 p.u	0 p.u	945 ms	✓
VST-2 (h)	Q_{HFD} = 0 Mvar	P_{HFD} = 1.6 MW	0.833 p.u	0.083 p.u	950 ms	✓
VST-2 (i)	Q_{HFD} = 0 Mvar	P_{HFD} = 1.6 MW	0.916 p.u	0.083 p.u	950 ms	✓

Table 9. Results values for VST-2

4.1.2. Frequency Stability (FST-1 & FST-2)

Two different sets of tests have been carried out to validate the frequency stability capabilities of the equipment. FST-1 tests are intended to ensure that the HFD is able to remain working at different frequency levels. FST-2 test are intended to validate that the HFD is able to withstand perturbations of the frequency according to its requirements.

Conditions for FST-1 test

For FST-1 tests, the device must remain connected to the grid for the times specified in the table depending on the frequency at the PCC.

	F_PCC	Minimum time working	Q_HFD	P_HFD
FST-1 (a)	f_{PCC} = 47.25 Hz	>= 3 s	Q_{HFD} = 0	P_{HFD} = 0
FST-1 (b)	f_{PCC} = 47.75 Hz	>= 60 min	Q_{HFD} = 0	P_{HFD} = 0
FST-1 (c-1)	f_{PCC} = 48.25 Hz	>= 90 min	Q_{HFD} = 0	P_{HFD} = 0
FST-1 (c-2)	f_{PCC} = 50.5 Hz	>= 90 min	Q_{HFD} = 0	P_{HFD} = 0
FST-1 (d)	f_{PCC} = 51.5 Hz	>= 60 min	Q_{HFD} = 0	P_{HFD} = 0

Table 10. Values for FST-1 test

Graph Results for FST-1 tests

The results of the FST-1 tests are presented in section 7.1.3. Figures shows frequency, voltage and total active and reactive power output of the HFD, all of them measured at the PCC.

As an example, graph of test FST-1 (d) is shown:

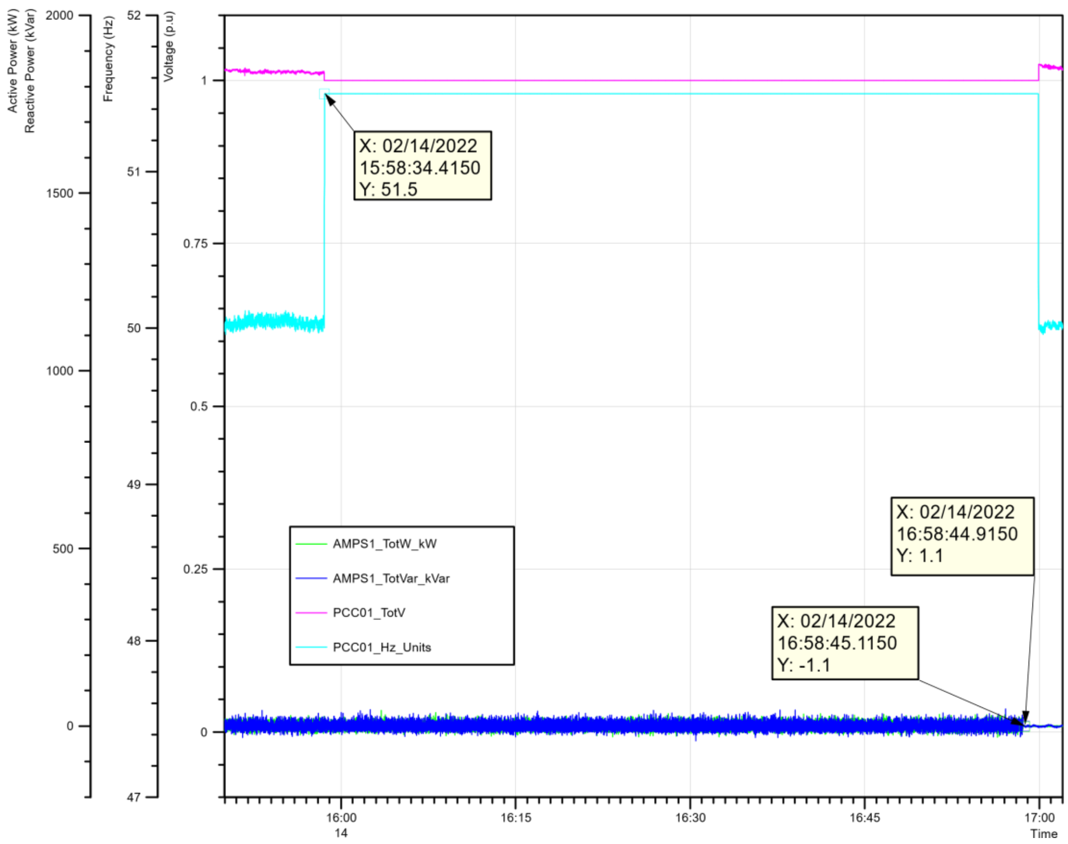

Figure 15: FST-1 (d)

Table of results of FST-1 test

A summary of the previous results can be found in the following table, where the active and reactive power output are included. The time the HFD continued working after the perturbation and the fulfilment of the acceptance criteria are also specified.

	Q_HFD	P_HFD	Time working	Acceptance
FST-1 (a)	Q_{HFD} = 0 Mvar	P_{HFD} = 0 MW	3.01 s	✓
FST-1 (b)	Q_{HFD} = 0 Mvar	P_{HFD} = 0 MW	3601 s	✓
FST-1 (c-1)	Q_{HFD} = 0 Mvar	P_{HFD} = 0 MW	> 5401 s	✓
FST-1 (c-2)	Q_{HFD} = 0 Mvar	P_{HFD} = 0 MW	> 5400 s	✓
FST-1 (d)	Q_{HFD} = 0 Mvar	P_{HFD} = 0 MW	3601 s	✓

Table 11. Results values for FST-1

It should be noted that FST-1 tests were performed at zero power. Thus, power signal consists only of the switching noise measurement. This ripple disappears when the equipment is disconnected, being useful to check when the device stops.

Regarding the results in Table 11, it should be reminded that the response time limits (t_r) defined for the project are:

- **47.0 Hz** ≤ f ≤ **47.5 Hz**: 3 seconds
- **47.5 Hz** ≤ f ≤ **48.0 Hz**: 1 hour (3.600 secs)
- **48.0 Hz** ≤ f ≤ **51.0 Hz**: continuous operation without restrictions
- **51.0 Hz** ≤ f ≤ **52.0 Hz**: 1 hour (3.600 secs)

In view of the limits, tests (a), (b) and (d) are validated since the protections cause the disconnection of the HFD within the t_r; while the HFD keeps its operation during tests (c).

Conditions for FST-2 test

For FST-2, the HFD must remain connected up to a frequency derivative of 2 Hz/s, as shown in the table below. The calculation of the frequency derivative has already been outlined in section 3.4.

	df/dt	Minimum time working	Q_HFD	P_HFD
FST-2 (a)	- 2 Hz/s	>= 750 ms	Q_{HFD} = 0	P_{HFD} = 0
FST-2 (b)	+ 2 Hz/s	>= 750 ms	Q_{HFD} = 0	P_{HFD} = 0

Table 12. Values in FST-2 test

Graph results for FST-2 test

In the following figures, the results of the FST-2 tests are presented. For each test, a frequency profile between those in the table above has been used. In the figures, frequency, voltage and total active and reactive power output of the HFD, all of them measured at the PCC, are represented.

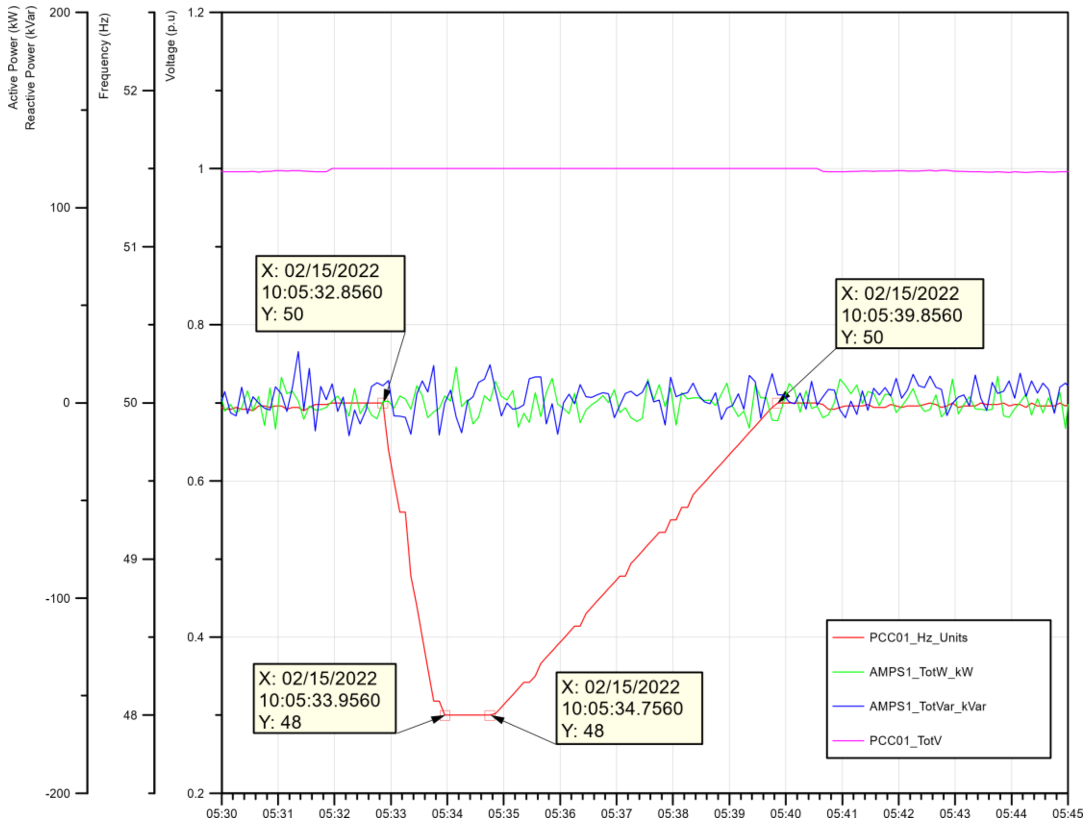

Figure 16: FST-2 (a)

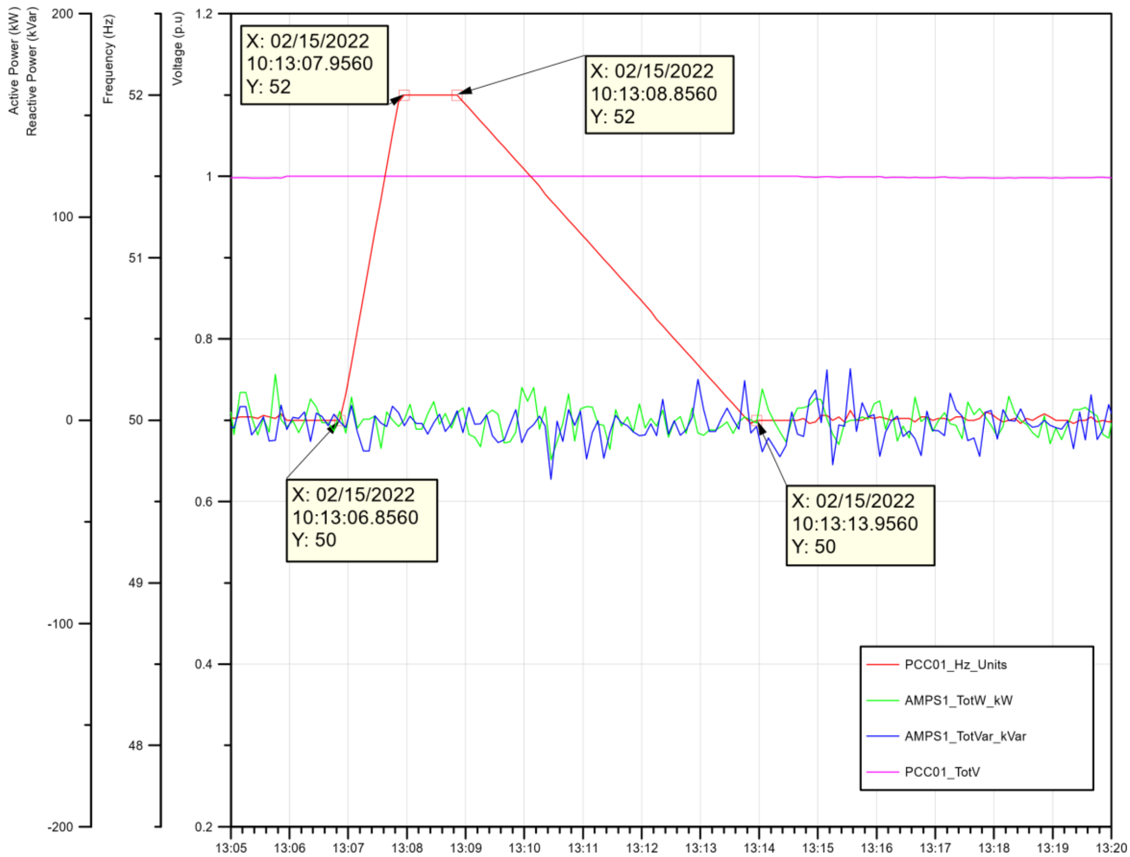

Figure 17: FST-2 (b)

Table of results of FST-2 test

In the following table, a summary of the previous results can be found. The time the HFD continued working after the perturbation and the fulfilment of the acceptance criteria are specified. At the same time, the active and reactive power output of the HFD have been included.

	Q_HFD	P_HFD	Time working	Acceptance
FST-2 (a)	Q_{HFD} = 0 Mvar	P_{HFD} = 0 MW	> 1 s	✓
FST-2 (b)	Q_{HFD} = 0 Mvar	P_{HFD} = 0 MW	> 1 s	✓

Table 13. Results for FST-2 test

As described for FST-1 tests, by observing the ripple in the power measurement, it can be extrapolated that the equipment did not disconnect in none of the tests. Therefore, the HFD passed FST-2, meaning it is robust against frequency derivatives of 2 Hz/s. This achievement is key for future tests, taking into consideration that higher levels functionalities operate under those conditions.

4.1.3. Reactive power Capability (Q = Q(V))

A set of tests has been carried out to ensure that the HFD is able to provide the desired reactive power at different voltage levels. In this sense, the device must provide an inductive or capacitive reactive current as a function of voltage.

Conditions for Q = Q(V) test

The device shall provide an inductive or capacitive reactive current as a function of voltage, up to its nominal value for at least 0.4 seconds, as indicated in the Table 14.

	V_PCC	Minimum time working	Q_HFD	P_HFD
Q = Q(V) (a)	0,30 pu	>= 400 ms	Q_{HFD} = Qn (capacitive)	P_{HFD} = 0.8 * Pn_BAT
Q = Q(V) (b)	0,30 pu	>= 400 ms	Q_{HFD} = 0	P_{HFD} = 0.8 * Pn_BAT
Q = Q(V) (c)	0,95 pu	>= 400 ms	Q_{HFD} = Qn (capacitive)	P_{HFD} = 0.8 * Pn_BAT
Q = Q(V) (d)	0,95 pu	>= 400 ms	Q_{HFD} = -Qn (inductive)	P_{HFD} = 0.8 * Pn_BAT
Q = Q(V) (e)	1,00 pu	>= 400 ms	Q_{HFD} = Qn (capacitive)	P_{HFD} = 0.8 * Pn_BAT
Q = Q(V) (f)	1,00 pu	>= 400 ms	Q_{HFD} = -Qn (inductive	P_{HFD} = 0.8 * Pn_BAT
Q = Q(V) (g)	1,05 pu	>= 400 ms	Q_{HFD} = Qn (capacitive)	P_{HFD} = 0.8 * Pn_BAT
Q = Q(V) (h)	1,05 pu	>= 400 ms	Q_{HFD} = -Qn (inductive)	P_{HFD} = 0.8 * Pn_BAT
Q = Q(V) (i)	1,20 pu	>= 400 ms	0	P_{HFD} = 0.8 * Pn_BAT
Q = Q(V) (j)	1,20 pu	>= 400 ms	Q_{HFD} = -Qn (inductive)	P_{HFD} = 0.8 * Pn_BAT

Table 14. Values for Q = Q(V)) tests

Two tests shall be launched in such a way that all profiles are tested. Therefore, for tests (a), (c), (e), (g) and (i), the voltage at the PCC will vary according to the values in the Table

14. The HFD will inject the capacitive nominal power indicated in the setpoint. The same will be done for the rest of the tests with an inductive rated power setpoint.

Graph Results for Q = Q(V) test

In the following figure, the results of the test performed to validate the capacitive reactive power capabilities of the HFD are presented. A single time series has been used to represent profiles a, c, e, g and i. Active and reactive power output, output current and voltage at the PCC are represented.

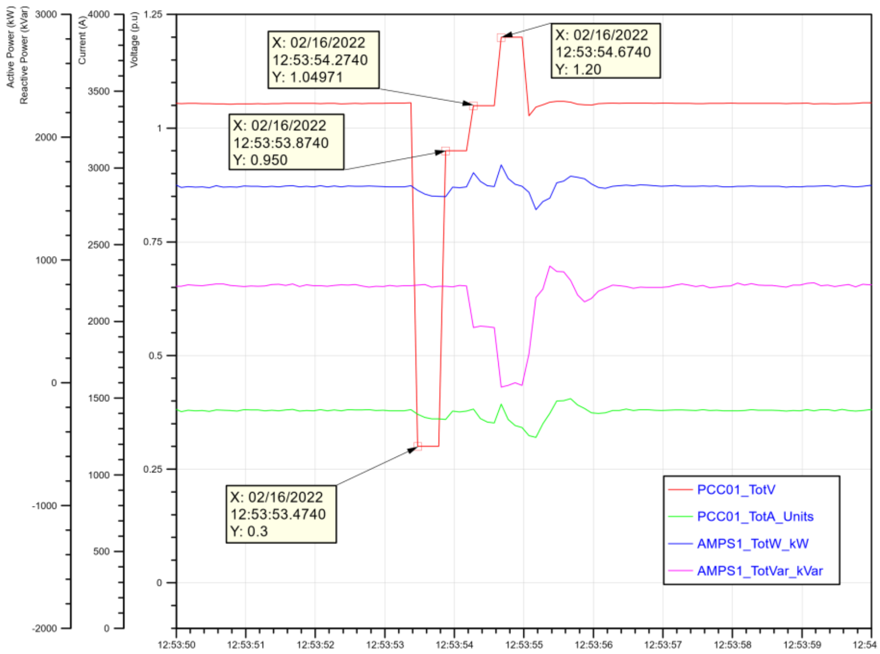

Figure 18: Q=Q(V) (a,c,e,g,i)

A value of 800 kVAr is defined for the first test, while the real voltage value is set to 1.05 p.u. Although the reactive power for the test is defined as the nominal, for a value of 1200 kVAr capacitive, the real voltage at the PCC would exceed 1.05 p.u. Therefore, it would start to saturate its value due to the limits defined in the project and represented below (Figure 19).

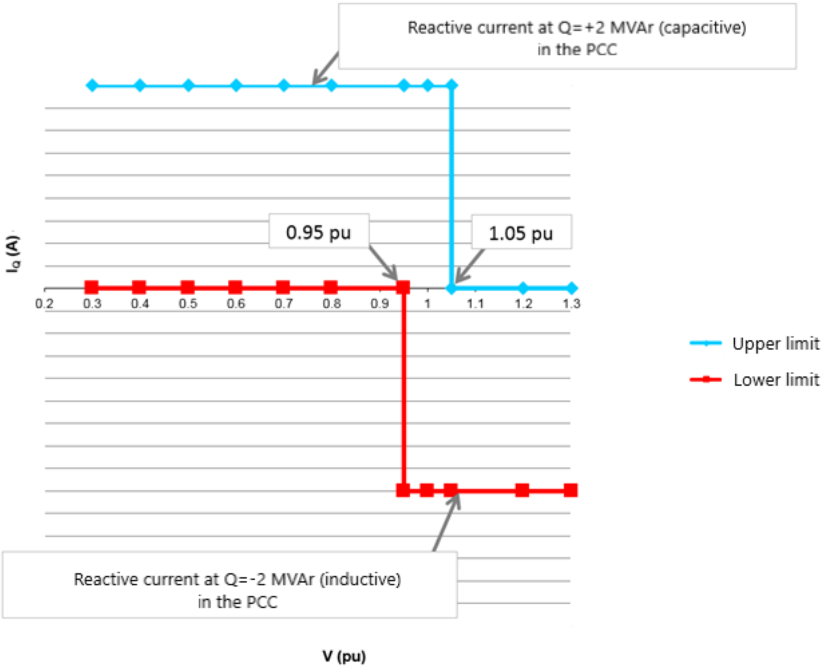

Figure 19: Saturation limits for reactive power

Regarding this limit value, a saturation ramp is implemented from 1.04 p.u. to 1.06 p.u. Through the ramp, the device would limit the capacitive reactive power to 0 kVar to avoid a bang-bang response in the power. Similar action is done for the lower limit, in this case, with the inductive reactive power, for a value of 0.94 p.u.

Because of this ramp, the equipment will set intermediate values at the limits of 1.05 p.u. and 0.95 p.u.

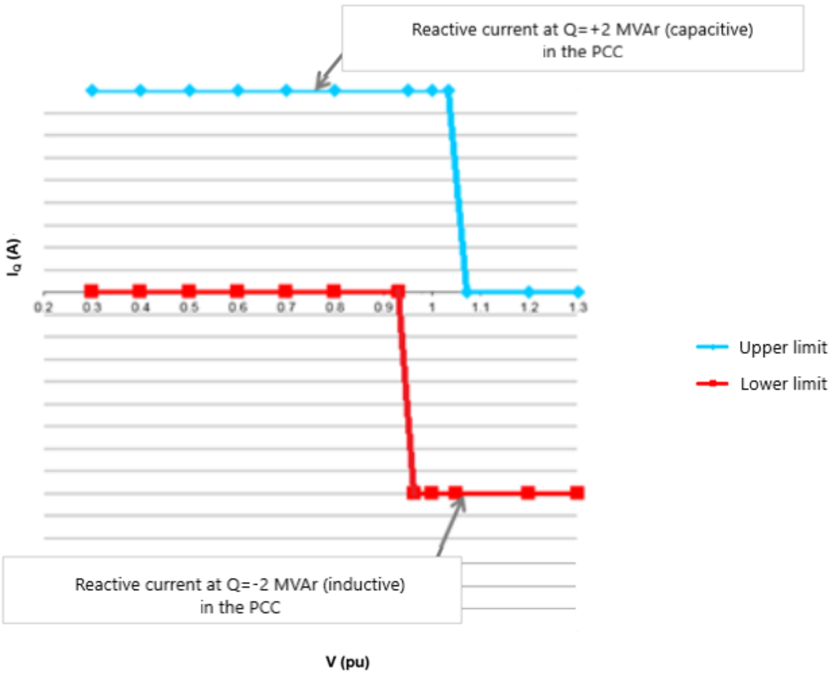

Figure 20: Adjusted saturation limits for reactive power

In the following figure, the results of the test performed to validate the inductive reactive power capabilities of the HFD are presented. A single time series has been used to represent profiles b, d, f, h and j. Active and reactive power output, output current and voltage at the PCC are represented.

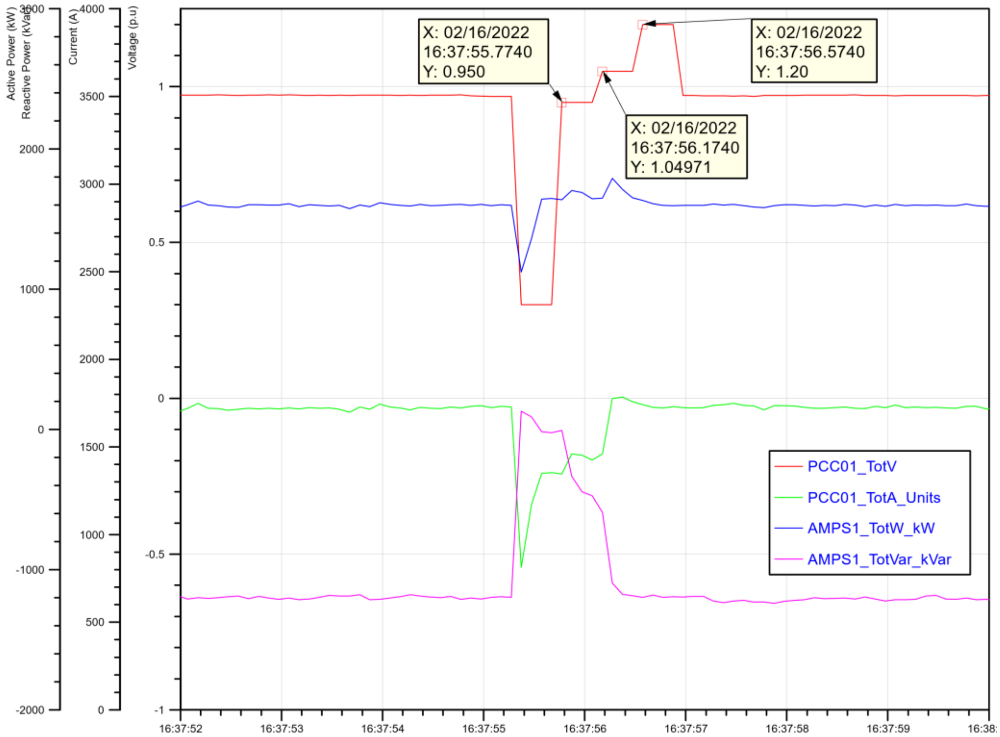

Figure 21: Q=Q(V) (b,d,f,h,j)

Table of results for Q = Q(V) test

The results of the above-mentioned test are summarized in the following table, where voltage at the PCC and the active and reactive power output of the HFD are included. The time the HFD continued providing the desired amount of power and the fulfilment of the acceptance criteria are also specified.

	V_PCC	Q_HFD	P_HFD	Time working	Acceptance
Q = Q(V) (a)	0,30 pu	Q_{HFD} = 0.8 Mvar	P_{HFD} = 1.6 MW	400 ms	✓
Q = Q(V) (c)	0,95 pu	Q_{HFD} = 0.8 Mvar	P_{HFD} = 1.5 MW	400 ms	✓
Q = Q(V) (e)	1,00 pu	Q_{HFD} = 0.8 Mvar	P_{HFD} = 1.6 MW	20 ms	✓
Q = Q(V) (g)	1,05 pu	Q_{HFD} = 0.5 Mvar	P_{HFD} = 1.6 MW	400 ms	✓
Q = Q(V) (i)	1,20 pu	Q_{HFD} = 0 Mvar	P_{HFD} = 1.6 MW	400 ms	✓
Q = Q(V) (b)	0,30 pu	Q_{HFD} = 0 Mvar	P_{HFD} = 1.6 MW	400 ms	✓
Q = Q(V) (d)	0,95 pu	Q_{HFD} = - 0.4 Mvar	P_{HFD} = 1.6 MW	400 ms	✓
Q = Q(V) (f)	1,00 pu	Q_{HFD} = - 1.2 Mvar	P_{HFD} = 1.6 MW	20 ms	✓
Q = Q(V) (h)	1,05 pu	Q_{HFD} = - 1.2 Mvar	P_{HFD} = 1.6 MW	400 ms	✓
Q = Q(V) (j)	1,20 pu	Q_{HFD} = - 1.2 Mvar	P_{HFD} = 1.6 MW	400 ms	✓

Table 15. Results for Q=Q(V) test

4.1.4. P-Q Capability

Finally, it is needed to ensure that the HFD can provide its rated apparent power at any power factor value. The following tests are aimed at evaluating the performance of the equipment under different output conditions.

Conditions for P-Q Capability tests

In these tests the device shall provide the active and reactive powers in the quadrant of the nominal apparent power. The tests are summarized in the four scenarios presented in Table 16. A ramp of 1 MVA/min is set for change between references.

	Q_HFD	P_HFD
P-Q (a)	Q_{HFD} = Qn (capacitive)	P_{HFD} = Pn_BAT
P-Q (b)	Q_{HFD} = - Qn (inductive)	P_{HFD} = Pn_BAT
P-Q (c)	Q_{HFD} = - Qn (inductive)	P_{HFD} = - Pn_BAT
P-Q (d)	Q_{HFD} = Qn (capacitive)	P_{HFD} = - Pn_BAT

Table 16. Values for Q=Q(V) test

However, a single test has been carried out running through the four quadrants of the P-Q curve. To ensure that the nominal power –2 MVA–is not exceeded, the next values of active and reactive power are taken as nominal references:

$$S^2 = P^2 + Q^2 = \left(\sqrt{2}\,[MW]\right)^2 + \left(\sqrt{2}\,[Mvar]\right)^2 \rightarrow S = 2\ MVA$$

Graph results for P-Q Capability test

The result of the P-Q capability evaluation, which have been condensed in a single test, are presented next. The following figures represent results obtained from the same test but comprising different data. In the first figure, the whole set of data of voltage, apparent current and active and reactive power is presented. In the next figures, the results shown are referred to reactive and active power respectively.

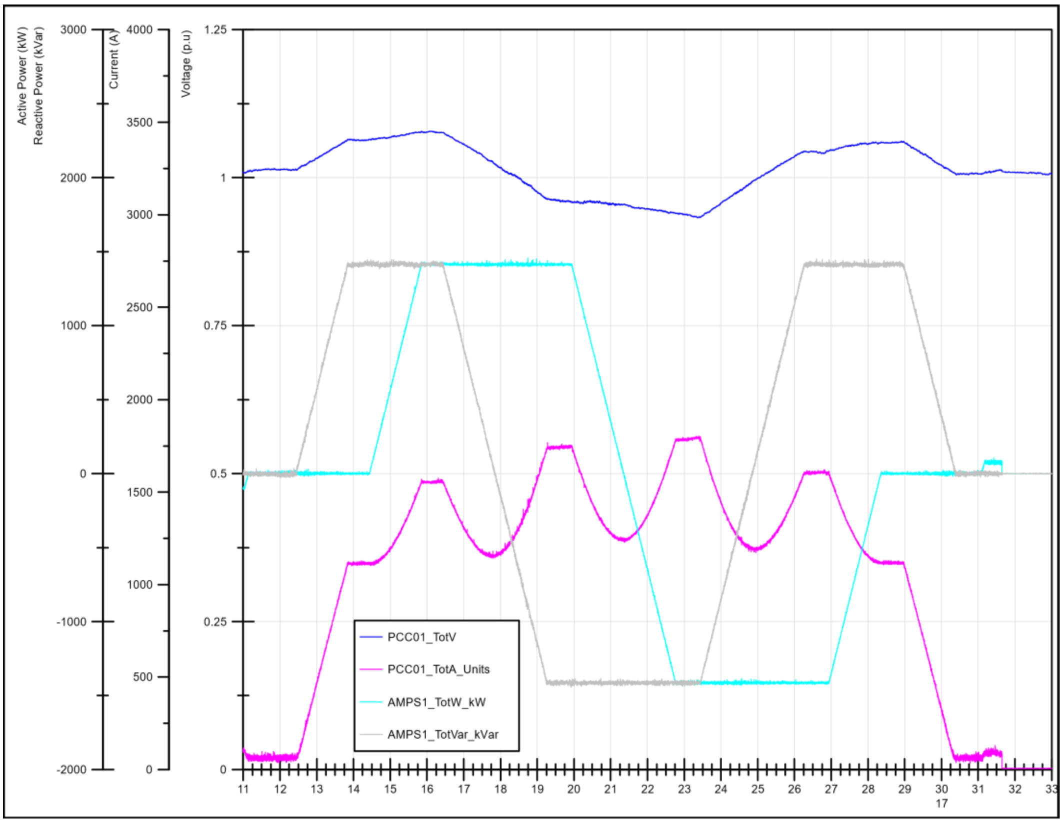

Figure 22: PQ Capability

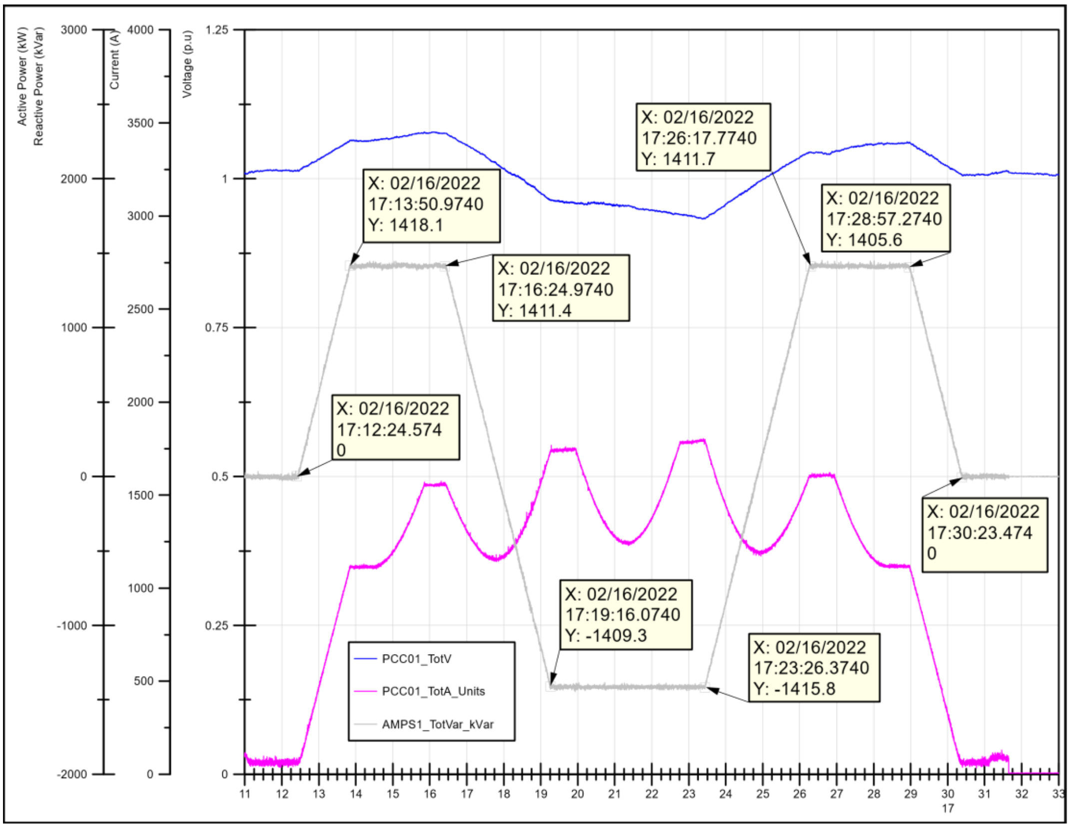

Figure 23: PQ Capability, reactive power measures

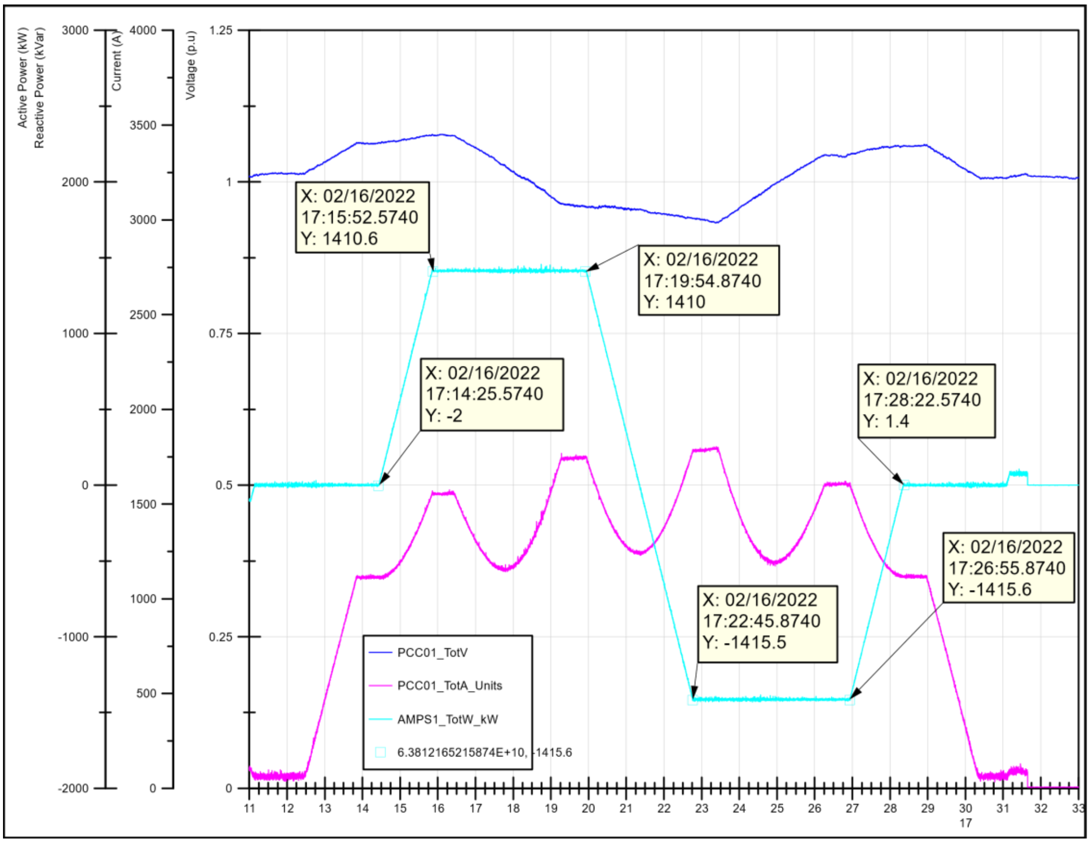

Figure 24: PQ Capability, active power measures

Table of results for P-Q test

In the following table, a summary of the previous results can be found. The active, reactive and apparent power outputs of the HFD are presented and the fulfilment of the acceptance criteria is specified. The ramp time, the time that HFD took to reach the consign value, is also included.

	Q_HFD	P_HFD	Ramp time	S_HFD (after ramp)	Acceptance
P-Q (a)	Q_{HFD} = 1414.21 kvar	P_{HFD} = 1414.21 kW	85 s	2 MVA	✓
P-Q (b)	Q_{HFD} = - 1414.21 kvar	P_{HFD} = 1414.21 kW	165 s	2 MVA	✓
P-Q (c)	Q_{HFD} = - 1414.21 kvar	P_{HFD} = - 1414.21 kW	165 s	2 MVA	✓
P-Q (d)	Q_{HFD} = 1414.21 kvar	P_{HFD} = - 1414.21 kW	165 s	2 MVA	✓

Table 17. Results for P-Q test

The device run all the tests in ramps of 0.5 p.u./min (1 MVA/min), keeping an apparent power of 2 MVA for about 1 min.

Regarding the inductive current injection, it should be noted that the HFD injects up to 200A more capacitive current than capacitive current. This is due to the fact that the voltage at the PCC drops when inductive current is supplied at the output, requiring additional current to keep the power at 2MVA.

4.2. Level-1 functionalities

In this section, the performance of the equipment regarding Level-1 functionalities is evaluated. These functionalities are performed by low-level controls intended to provide fast response to transient disturbances. The functionalities are inertia emulation, fast frequency response, power frequency regulation under perturbated operation, fast reactive current injection, and trapezoidal response.

4.2.1. Inertia emulation control (INE-0 & INE-1)

In the inertia emulation mode, the HFD must provide an active power response proportional to the frequency derivative. In the following tests, data series representing disturbances of different frequency derivative are used to test the HFD performance.

Conditions for Inertia emulation control tests

The device must vary its active power as a function of the frequency derivative, as fast as possible, for different inertia and derivatives values represented in the table.

	df/dt	INE_H	P_HFD_pretest
INE-0 (a)	- 2 Hz/s	0 s	P_{HFD} = 0.3 * Pn_BAT
INE-0 (b)	2 Hz/s	0 s	P_{HFD} = 0.3 * Pn_BAT
INE-1 (a)	- 0.4 Hz/s	6 s	P_{HFD} = 0.3 * Pn_BAT
INE-1 (b)	- 1.5 Hz/s	1 s	P_{HFD} = 0.3 * Pn_BAT
INE-1 (c)	- 1.5 Hz/s	6 s	P_{HFD} = 0.3 * Pn_BAT
INE-1 (d)	- 1.5 Hz/s	20 s	P_{HFD} = 0.3 * Pn_BAT
INE-1 (e)	- 3 Hz/s	1 s	P_{HFD} = 0.3 * Pn_BAT
INE-1 (f)	- 3 Hz/s	6 s	P_{HFD} = 0.3 * Pn_BAT
INE-1 (g)	- 3 Hz/s	20 s	P_{HFD} = 0.3 * Pn_BAT
INE-1 (h)	0.4 Hz/s	6 s	P_{HFD} = 0.3 * Pn_BAT
INE-1 (i)	1.5 Hz/s	1 s	P_{HFD} = 0.3 * Pn_BAT
INE-1 (j)	1.5 Hz/s	6 s	P_{HFD} = 0.3 * Pn_BAT
INE-1 (k)	1.5 Hz/s	20 s	P_{HFD} = 0.3 * Pn_BAT
INE-1 (l)	3 Hz/s	1 s	P_{HFD} = 0.3 * Pn_BAT
INE-1 (m)	3 Hz/s	6 s	P_{HFD} = 0.3 * Pn_BAT
INE-1 (n)	3 Hz/s	20 s	P_{HFD} = 0.3 * Pn_BAT

Table 18. Values for INE-0 & INE-1 tests

The tests will be implemented with a dead band of ± 0.5 Hz/s, and the maximum variation will be limited to ± 1500 kW, this being a configurable parameter, as well as the maximum saturation of the power will also be ± 1500 kW.

For the calculation of the inertia emulation, the classical formula of the frequency behavior versus load of a generator is used:

$$\frac{\partial f}{\partial \mathrm{t}} = \frac{\Delta \mathrm{P}}{2\mathrm{H}}$$

Thus, the inertia (H) must have dimensions of W· s/Hz. Aiming at correctly scale the inertia, the power and frequency terms must correspond to the nominal values of the device. At the firmware level, the nominal power of the device is 2800 kW, so the scaled value of the inertia would be as follows:

$$\overline{H} = H[s] \cdot \frac{2800\ [kW]}{50\ [Hz]}$$

Given the above, the final form of the calculation of the power variation by the emulated inertia is:

$$\Delta P = 2 \cdot \overline{H} \cdot \frac{\partial f}{\partial \mathrm{t}}$$

With this formula, it is possible to calculate the target values for the programmed tests in the next table:

	df/dt	INE_H	ΔP_HFD (planned)
INE-0 (a)	- 2 Hz/s	0 s	**0 kW**
INE-0 (b)	2 Hz/s	0 s	**0 kW**
INE-1 (a)	- 0.4 Hz/s	6 s	**0 kW**
INE-1 (b)	- 1.5 Hz/s	1 s	**168 kW**
INE-1 (c)	- 1.5 Hz/s	6 s	**1008 kW**
INE-1 (d)	- 1.5 Hz/s	20 s	**1500 kW ***
INE-1 (e)	- 3 Hz/s	1 s	**336 kW**
INE-1 (f)	- 3 Hz/s	6 s	**1500 kW ***
INE-1 (g)	- 3 Hz/s	20 s	**1500 kW ***
INE-1 (h)	0.4 Hz/s	6 s	**0 kW**
INE-1 (i)	1.5 Hz/s	1 s	**- 168 kW**
INE-1 (j)	1.5 Hz/s	6 s	**- 1008 kW**
INE-1 (k)	1.5 Hz/s	20 s	**- 1500 kW ***
INE-1 (l)	3 Hz/s	1 s	**- 336 kW**
INE-1 (m)	3 Hz/s	6 s	**- 1500 kW ***
INE-1 (n)	3 Hz/s	20 s	**- 1500 kW ***

**: Saturated performance due to maximum actuation value of 1500 kW*

Graph results for INE-0 & INE-1test

The results of the different test performed to validate the inertia emulation control are presented in this section. In the following figures and those presented in Annex 7.1.4, frequency and voltage data series are represented, as well as active and reactive power output.

The Figure 25 shows the results of the first two tests, which are intended to evaluate the performance of the equipment when the inertia emulation is disabled (INE-0 (a) and INE-0 (b)). The profiles representing negative and positive frequency deviations (a and b), have been evaluated in a single test. Similarly, the response of the HFD to a frequency deviation whose frequency derivative does not reach the dead band of the control (INE-1(a)) is represented.

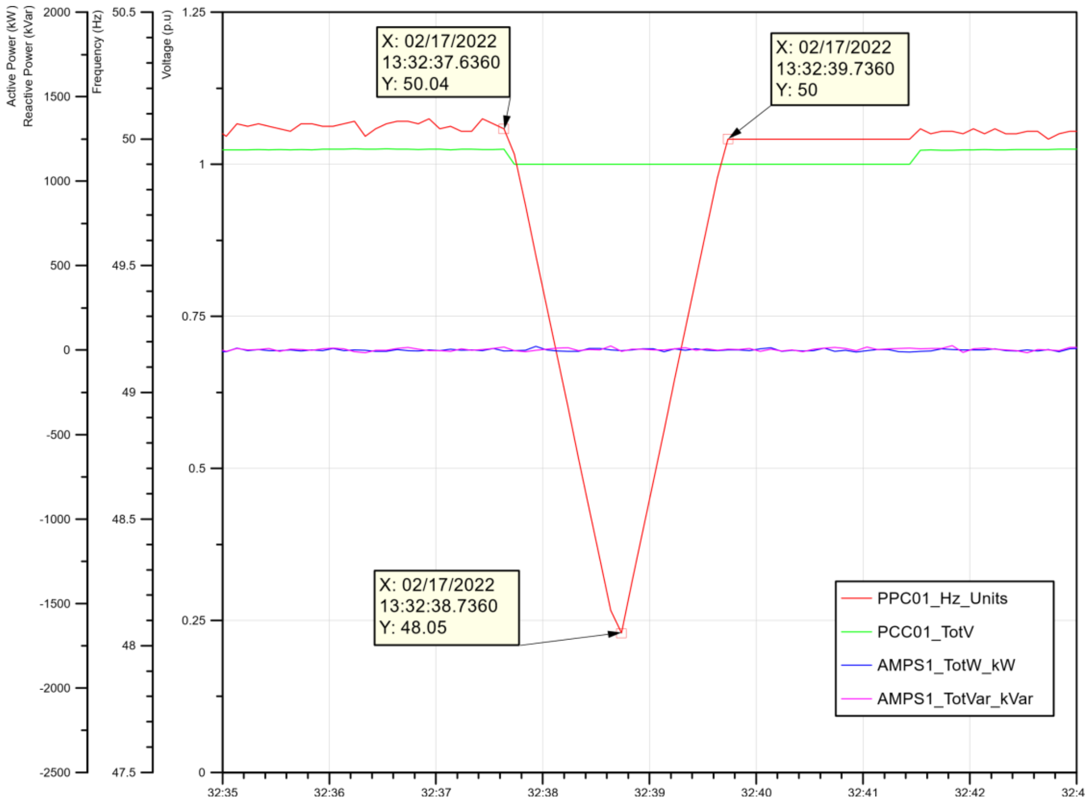

Figure 25: INE-0 (a,b)

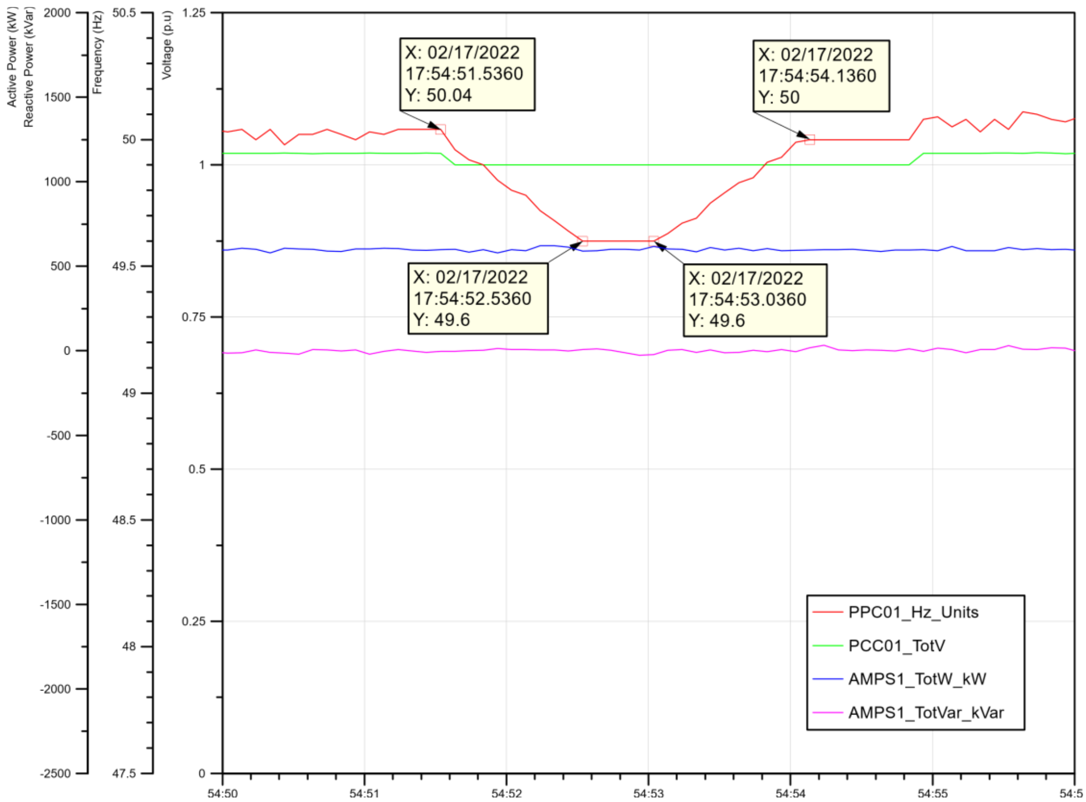

Figure 26: INE-1 (a,h)

The rest of the test are shown in Annex 7.1.4, where the figures show the results of the tests performed to validate the performance of the inertia emulation control (INE-1).

Disturbances with different values of frequency derivative have been recreated and different values of inertia have been set (profiles c to i) for these tests.

Table of Results for Inertia emulation control tests

The results of the above-mentioned tests are summarized in the following table, where the amount of power delivered before and after the change of the frequency, as well as the difference between them, are included. The value of the derivative of the frequency in each test and the fulfilment of the acceptance criteria are also specified.

	df/dt	P_HFD_pretest	P_HFD_final	ΔP_HFD	Deviation (%)	Acceptance
INE-0 (a)	- 2 Hz/s	P_{HFD} = 600 kW	P_{HFD} = 600 kW	**0 kW**	**0 %**	✓
INE-0 (b)	2 Hz/s	P_{HFD} = 600 kW	P_{HFD} = 600 kW	**0 kW**	**0 %**	✓
INE-1 (a)	- 0.4 Hz/s	P_{HFD} = 600 kW	P_{HFD} = 600 kW	**0 kW**	**0 %**	✓
INE-1 (b)	- 1.5 Hz/s	P_{HFD} = 600 kW	P_{HFD} = 766.4 kW	**166.4 kW**	**0.95 %**	✓
INE-1 (c)	- 1.5 Hz/s	P_{HFD} = 600 kW	P_{HFD} = 1500.7 kW	**900.7 kW ***	*	✓
INE-1 (d)	- 1.5 Hz/s	P_{HFD} = 600 kW	P_{HFD} = 1512.9 kW	**912.9 kW ***	*	✓
INE-1 (e)	- 3 Hz/s	P_{HFD} = 600 kW	P_{HFD} = 927.9 kW	**327.9 kW**	**2.41 %**	✓
INE-1 (f)	- 3 Hz/s	P_{HFD} = 600 kW	P_{HFD} = 1503.7 kW	**903.7 kW ***	*	✓
INE-1 (g)	- 3 Hz/s	P_{HFD} = 600 kW	P_{HFD} = 1500 kW	**900 kW ***	*	✓
INE-1 (h)	0.4 Hz/s	P_{HFD} = 600 kW	P_{HFD} = 600 kW	**0 kW**	**0 %**	✓
INE-1 (i)	1.5 Hz/s	P_{HFD} = 600 kW	P_{HFD} = 437.4 kW	**- 162.6 kW**	**3.21 %**	✓
INE-1 (j)	1.5 Hz/s	P_{HFD} = 600 kW	P_{HFD} = - 364.5 kW	**- 964.5 kW**	**4.31 %**	✓
INE-1 (k)	1.5 Hz/s	P_{HFD} = 600 kW	P_{HFD} = - 832 kW	**- 1432 kW**	**4.54 %**	✓
INE-1 (l)	3 Hz/s	P_{HFD} = 600 kW	P_{HFD} = 265.6 kW	**- 334.4 kW**	**0.48 %**	✓
INE-1 (m)	3 Hz/s	P_{HFD} = 600 kW	P_{HFD} = - 874 kW	**- 1474 kW**	**1.73 %**	✓
INE-1 (n)	3 Hz/s	P_{HFD} = 600 kW	P_{HFD} = - 865 kW	**- 1465 kW**	**2.33 %**	✓

Table 19. Results for Inertia emulation control test

*: *Saturated performance due to maximum power value of 1500 kW*

For the test of the 3 Hz/s profiles, a 1.5 Hz dip (or surge) in 500ms is simulated. Otherwise, the operating limits defined for the project would be exceeded and the device would be triggered to disconnect.

From the result graphs, it can be noticed that the inertia functionality easily meets the maximum response time of 500ms, and the maximum deviation from the expected value is less than 5% for all tests, which validates the successful performance of the inertia emulation.

INE-0 and INE-1(a,h) tests show that the performance is 0 due to deactivation of the functionality or due to a frequency derivative within the dead band.

INE-1 (c,d,f,g) tests show that the power increase is only 900kW because this performance is saturated at 1500kW by the parameter described previously, because of project conditions. In cases with transient, the mean of the initial and final values is taken as the action value.

4.2.2. Fast Frequency Response (FFR-0 & FFR-1)

In the Fast Frequency Response mode, the HFD must provide fast active power regulation in response to frequency disturbances as a function of frequency deviation. So as to test this functionality, the FFR controller has been provided with frequency data series representing disturbances of different frequency deviation rates.

Conditions for Fast Frequency Response tests

The device must vary its active power as a function of the frequency variation, as fast as possible, for different under and over frequency scenarios, and operate according to the parameters described in the table below.

	f	FFR_Droop	FFR_PmaxRange	FFR_DeadBand	P_HFD_pretest
FFR-0 (a)	49 Hz	0 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	P_{HFD} = 0.3 * Pn_BAT
FFR-0 (b)	51.5 Hz	0 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	P_{HFD} = 0.3 * Pn_BAT
FFR-1 (a)	49 Hz	4 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	P_{HFD} = 0.3 * Pn_BAT
FFR-1 (b)	48 Hz	1 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	P_{HFD} = 0.3 * Pn_BAT
FFR-1 (c)	48 Hz	4 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	P_{HFD} = 0.3 * Pn_BAT
FFR-1 (d)	48 Hz	12 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	P_{HFD} = 0.3 * Pn_BAT
FFR-1 (e)	48 Hz	1 %	[-100 %; +100 %]	[-0,03 Hz; +0,03 Hz]	P_{HFD} = 0.3 * Pn_BAT
FFR-1 (f)	48 Hz	4 %	[-100 %; +100 %]	[-0,03 Hz; +0,03 Hz]	P_{HFD} = 0.3 * Pn_BAT
FFR-1 (g)	48 Hz	12 %	[-100 %; +100 %]	[-0,03 Hz; +0,03 Hz]	P_{HFD} = 0.3 * Pn_BAT
FFR-1 (h)	48 Hz	4 %	[-50 %; +50 %]	[-0,03 Hz; +0,03 Hz]	P_{HFD} = 0.3 * Pn_BAT
FFR-1 (i)	51.5 Hz	1 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	P_{HFD} = 0.3 * Pn_BAT
FFR-1 (j)	51.5 Hz	4 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	P_{HFD} = 0.3 * Pn_BAT
FFR-1 (k)	51.5 Hz	12 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	P_{HFD} = 0.3 * Pn_BAT
FFR-1 (l)	51.5 Hz	1 %	[-100 %; +100 %]	[-0,03 Hz; +0,03 Hz]	P_{HFD} = 0.3 * Pn_BAT
FFR-1 (m)	51.5 Hz	4 %	[-100 %; +100 %]	[-0,03 Hz; +0,03 Hz]	P_{HFD} = 0.3 * Pn_BAT
FFR-1 (n)	51.5 Hz	12 %	[-100 %; +100 %]	[-0,03 Hz; +0,03 Hz]	P_{HFD} = 0.3 * Pn_BAT

Table 20. Parameters and scenario for FFR-0 & FFR-1 tests

The curve describing the control of this functionality is shown in Figure 27.

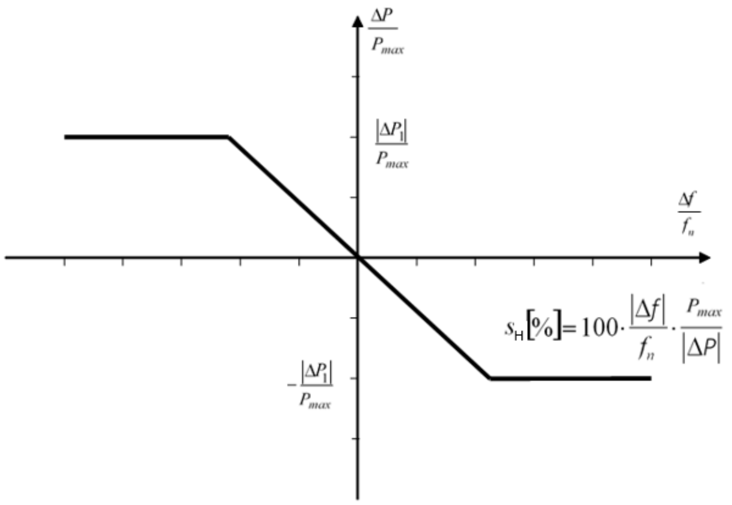

Figure 27. FFR control curve

Where SH represents the value of FFR_Droop and Pmax is set at 1500 kW. With this curve and the formula shown in Figure 27, it is possible to calculate the target values for the programmed tests, as can be observed in Table 21.

	Δf	FFR_Droop	FFR_PmaxRange	FFR_DeadBand	ΔP_HFD (planned)
FFR-0 (a)	- 1 Hz	0 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	**0 kW**
FFR-0 (b)	1.5 Hz	0 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	**0 kW**
FFR-1 (a)	- 1 Hz	4 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	**562.5 kW**
FFR-1 (b)	- 2 Hz	1 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	**1500 kW***
FFR-1 (c)	- 2 Hz	4 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	**1312.5 kW**
FFR-1 (d)	- 2 Hz	12 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	**437.5 kW**
FFR-1 (e)	- 2 Hz	1 %	[-100 %; +100 %]	[-0,03 Hz; +0,03 Hz]	**1500 kW***
FFR-1 (f)	- 2 Hz	4 %	[-100 %; +100 %]	[-0,03 Hz; +0,03 Hz]	**1477.5 kW**
FFR-1 (g)	- 2 Hz	12 %	[-100 %; +100 %]	[-0,03 Hz; +0,03 Hz]	**492.5 kW**
FFR-1 (h)	- 2 Hz	4 %	[-50 %; +50 %]	[-0,03 Hz; +0,03 Hz]	**738.75 kW**
FFR-1 (i)	1.5 Hz	1 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	**- 1500 kW***
FFR-1 (j)	1.5 Hz	4 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	**- 937.5 kW**
FFR-1 (k)	1.5 Hz	12 %	[-100 %; +100 %]	[-0,25 Hz; +0,25 Hz]	**- 312.5 kW**
FFR-1 (l)	1.5 Hz	1 %	[-100 %; +100 %]	[-0,03 Hz; +0,03 Hz]	**- 1500 kW***
FFR-1 (m)	1.5 Hz	4 %	[-100 %; +100 %]	[-0,03 Hz; +0,03 Hz]	**- 1102.5 kW**
FFR-1 (n)	1.5 Hz	12 %	[-100 %; +100 %]	[-0,03 Hz; +0,03 Hz]	**- 367.5 kW**

Table 21. Values for FFR-0 & FFR-1 tests

**: Saturated performance due to parameter Pmax*

Graph Results for FFR-0 & FFR-1 tests

The results of the different test performed to validate the Fast Frequency Response control are presented in Annex 7.1.5.

The figures show:

- FR-0(a) and FFR-0(b): Evaluation of the performance of the equipment when the FFR functionality is disabled. The profiles representing negative and positive frequency deviations (a and b), have been evaluated in a single test.
- The rest figures show the results of the tests performed to validate the performance of the FFR control (FFR-1). Disturbances with different values of frequency deviation have been recreated and different configurations of the controller have been set (profiles c to n) for these tests.

As an example, profile n is shown in next figure:

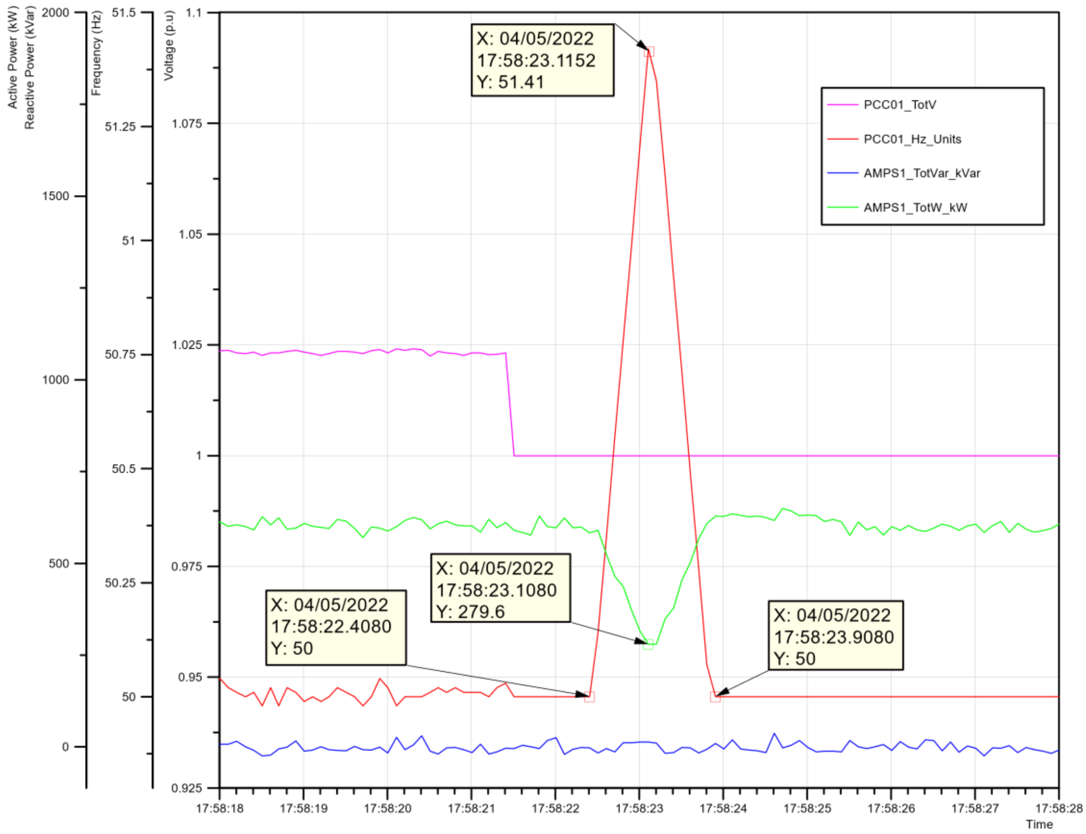

Figure 28: FFR-1 (n)

The disturbances consist of up and down ramps of 750ms. Therefore, ramps with up to 2.66 Hz/s would be contemplated, enough to check a fast response speed of the performance.

As explained in section 3.5, for FFR-0 and FFR-1 tests, DSP acquisition software was used.

Table of Results for FFR-0 & FFR-1 tests

In the following table, a summary the results of the tests conducted to evaluate this functionality can be found. In the table, the amount of power delivered before and after the change of the frequency, as well as the difference between them, are included. The value of the variation of the frequency in each test and the fulfilment of the acceptance criteria are also specified.

	Δf	P_HFD_pretest	P_HFD_final	ΔP_HFD	Deviation (%)	Acceptance
FFR-0 (a)	- 1 Hz	P_{HFD} = 600 kW	P_{HFD} = 600 kW	0 kW	**0 %**	✓
FFR-0 (b)	1.5 Hz	P_{HFD} = 600 kW	P_{HFD} = 600 kW	0 kW	**0 %**	✓
FFR-1 (a)	- 1 Hz	P_{HFD} = 600 kW	P_{HFD} = 1121.2 kW	521.2 kW	**7.34 %**	✓
FFR-1 (b)	- 2 Hz	P_{HFD} = 600 kW	P_{HFD} = 1492.4 kW	892.4 kW*	*	✓
FFR-1 (c)	- 2 Hz	P_{HFD} = 600 kW	P_{HFD} = 1498.8 kW	898.8 kW*	*	✓
FFR-1 (d)	- 2 Hz	P_{HFD} = 600 kW	P_{HFD} = 1009 kW	409 kW	**6.51 %**	✓
FFR-1 (e)	- 2 Hz	P_{HFD} = 600 kW	P_{HFD} = 1489.2 kW	889.2 kW*	*	✓
FFR-1 (f)	- 2 Hz	P_{HFD} = 600 kW	P_{HFD} = 1495.4 kW	895.4 kW*	*	✓
FFR-1 (g)	- 2 Hz	P_{HFD} = 600 kW	P_{HFD} = 1042.9 kW	442.9 kW	**10.07 %**	✓
FFR-1 (h)	- 2 Hz	P_{HFD} = 600 kW	P_{HFD} = 748.6 kW	148.6 kW*	*	✓
FFR-1 (i)	1.5 Hz	P_{HFD} = 600 kW	P_{HFD} = - 890.6 kW	- 1490.6 kW	**0.63 %**	✓
FFR-1 (j)	1.5 Hz	P_{HFD} = 600 kW	P_{HFD} = - 244.1 kW	- 844.1 kW	**9.96 %**	✓
FFR-1 (k)	1.5 Hz	P_{HFD} = 600 kW	P_{HFD} = 312.1 kW	- 287.9 kW	**7.87 %**	✓
FFR-1 (l)	1.5 Hz	P_{HFD} = 600 kW	P_{HFD} = - 897.8 kW	- 1497.8 kW	**0.15 %**	✓
FFR-1 (m)	1.5 Hz	P_{HFD} = 600 kW	P_{HFD} = - 390.4 kW	- 990.4 kW	**10.17 %**	✓
FFR-1 (n)	1.5 Hz	P_{HFD} = 600 kW	P_{HFD} = 279.6 kW	- 320.4 kW	**12.82 %**	✓

Table 22. Results for Inertia emulation control test

*: *Saturated performance due to parameter Pmax*

As it can be observed, all FFR scenarios begin with positive active power setpoint. From that pre-test conditions, the power varies up to the maximum value with 1% and 4% droop, similar to the inertia emulation tests.

It should be noted that, in the test (h), Pmax is modified to 50% of the power defined as maximum (=1500 kW).

Regarding the response ramp, it can be seen that it is aligned with the slope defined in the frequency profile (Table 20). So, the performance is fast enough to follow frequency increment without oscillations or additional overshoots, even for the most aggressive droop tests with 1%: FFR-1 (b), (e), (i), (l).

Finally, it should be noted that the deviation is slightly higher than expected in some of the test: FFR-1 (g), (m), (n). Although the response time can be accepted, improvements are required to perfect the final response, as already stated in section 3.6.

4.2.3. Power-frequency Regulation. Perturbed regime (PFR-p)

In the power-frequency regulation mode, for the perturbed regime, the HFD must provide fast active power regulation with respect to variations in frequency. To evaluate this functionality, different frequency profiles have been tested and combined with different values of the droop of the controller.

Conditions for Power-frequency Regulation tests

The HFD must vary its active power as a function of the frequency variation, as fast as possible and for different droop values. Inertia emulation and fast-frequency response controls should be disable.

	f	PFR_Droop	P_HFD_pretest
PFR-p (a)	48.05 Hz	1 %	P_{HFD} = 0.3 * Pn_BAT
PFR-p (b)	48.05 Hz	4 %	P_{HFD} = 0.3 * Pn_BAT
PFR-p (c)	48.05 Hz	12 %	P_{HFD} = 0.3 * Pn_BAT
PFR-p (d)	51.5 Hz	1 %	P_{HFD} = 0.3 * Pn_BAT
PFR-p (e)	51.5 Hz	4 %	P_{HFD} = 0.3 * Pn_BAT
PFR-p (f)	51.5 Hz	12 %	P_{HFD} = 0.3 * Pn_BAT

Table 23. Parameters and scenario for PFR-p tests

The characteristic curve of this control is analogous to the FFR (see Figure 27). With a dead band of ± 0.03 Hz and a Pmax range of 1500 kW, the expected values for the different tests are generated, as can be observed in Table 24.

	Δf	PFR_Droop	ΔP_HFD (planned)
PFR-p (a)	- 1.95 Hz	1 %	**1500 kW***
PFR-p (b)	- 1.95 Hz	4 %	**1440 kW**
PFR-p (c)	- 1.95 Hz	12 %	**480 kW**
PFR-p (d)	1.5 Hz	1 %	**- 1500 kW***
PFR-p (e)	1.5 Hz	4 %	**- 1102.5 kW**
PFR-p (f)	1.5 Hz	12 %	**- 367.5 kW**

Table 24. Values for PFR-p tests

**: Saturated performance due to parameter Pmax*

Graph Results for PFR-p tests

The results of the different test performed to validate the power-frequency response in the perturbed regime are presented in Annex 7.1.6. The figures show voltage, frequency, active power output and reactive power output for the different frequency profiles and control configurations (tests from a to f).

As an example, results for PFR-p (f) are shown in next figure:

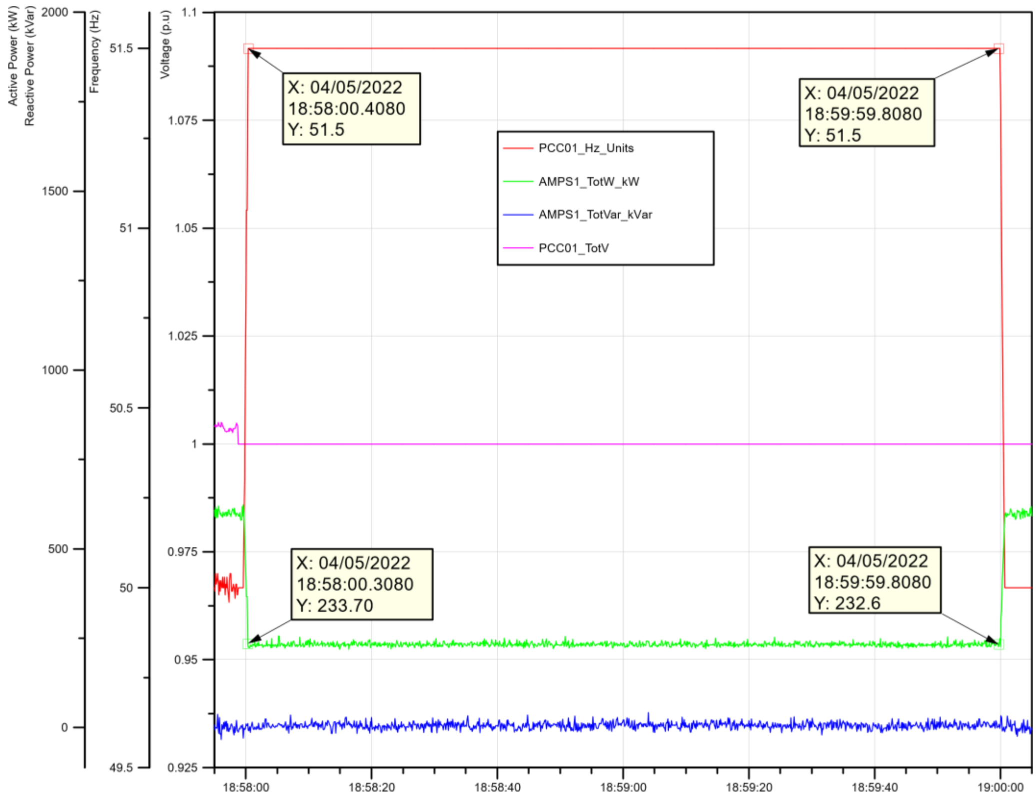

Figure 29: PFR-p (f)

Table of Results for PFR-p tests

The results of the above-mentioned tests are summarized in the following table, where the amount of power delivered before and after the change of the frequency, as well as the difference between them, are included. The value of the variation of the frequency in each test and the fulfilment of the acceptance criteria are also specified.

	Δf	P_HFD_pretest	P_HFD_final	ΔP_HFD	Deviation (%)	Acceptance
PFR-p (a)	- 1.95 Hz	P_{HFD} = 600 kW	P_{HFD} = 1504.1 kW	904.1 kW*	*	✓
PFR-p (b)	- 1.95 Hz	P_{HFD} = 600 kW	P_{HFD} = 1498.5 kW	898.5 kW*	*	✓
PFR-p (c)	- 1.95 Hz	P_{HFD} = 600 kW	P_{HFD} = 1082.1 kW	482.1 kW	**0.44 %**	✓
PFR-p (d)	1.5 Hz	P_{HFD} = 600 kW	P_{HFD} = - 898.3 kW	- 1498.3 kW*	*	✓
PFR-p (e)	1.5 Hz	P_{HFD} = 600 kW	P_{HFD} = - 496.5 kW	- 1096.5 kW	**0.54 %**	✓
PFR-p (f)	1.5 Hz	P_{HFD} = 600 kW	P_{HFD} = 233.2 kW	- 366.8 kW	**0.19 %**	✓

Table 25. Results for PFR-p test

*: *Saturated performance due to parameter Pmax*

As in FFR tests, the length of the ramps are 750ms, while the reference is held for 2 min. The response time is similar to FFR test results. This is consistent assuming that the characteristic curve and the droop are the same as in the FFR tests.

As a first conclusion, with a very fast response to frequency increases, PFR-p has the same behavior that FFR has. Both performances are fed by the same PI, whose dynamics govern the response time of both.

However, regarding to the final value, a difference is observed with respect to FFR, a deviation lower than 1%. This is explained by the duration of the tests. PFR-p test lasts longer than FFR tests, so final output value can reach the expected level in the steady state.

4.2.4. Fast Reactive Current injection (FRC-0 & FRC-1)

In the Fast Reactive Current injection mode, the HFD must provide fast reactive power regulation in response to voltage disturbances as a function of voltage deviation. So as to test this functionality, the FRC controller has been provided with voltage data series representing different disturbances.

Conditions for FRC tests

The device must inject the necessary reactive current against pre-defined test faults, with the parameters shown in Table 26.

	V_PCC	t_fault	FRC_K1	FRC_I1_LimU	Control Activation
FRC-0 (a)	0 p.u (±5%, Three Phase)	250 ms	0	0.9 p.u	Exceed VMIN <= V <= VMAX
FRC-0 (b)	1.3 p.u.	1000 ms	0	0.9 p.u	Exceed VMIN <= V <= VMAX
FRC-1 (a)	0 p.u (±5%, Three Phase)	250 ms	3.5	0.9 p.u	Exceed VMIN <= V <= VMAX
FRC-1 (b)	0 p.u (±5%, Three Phase)	250 ms	6	0.9 p.u	Exceed VMIN <= V <= VMAX
FRC-1 (c)	0 p.u (±5%, Three Phase)	500 ms	3.5	0.9 p.u	Exceed VMIN <= V <= VMAX
FRC-1 (d)	0 p.u (±5%, Three Phase)	500 ms	3.5	0.5 p.u	Exceed VMIN <= V <= VMAX
FRC-1 (e)	0 p.u (±5%, Three Phase)	250 ms	3.5	0.9 p.u	Exceed ΔVi >= FRC_│ΔVi│
FRC-1 (f)	0 p.u (±5%, Two-Phase)	250 ms	3.5	0.9 p.u	Exceed VMIN <= V <= VMAX
FRC-1 (g)	1.3 p.u	1000 ms	3.5	0.9 p.u	Exceed VMIN <= V <= VMAX

Table 26. Parameters and scenario for FRC tests

For the above tests, the following parameters are set:

- FRC_VMAX = 1,15 p.u.
- FRC_VMIN = 0,85 p.u.
- FRC_│ΔVi│ = 0,10 p.u.
- FRC_K2 = -3,5
- FRC_I1_LimL = -0,9 p.u.

The initial project specifications state that, during and after a disturbance in the transmission grid affecting the voltage, a continuous and fast control is required during perturbations. This is done through changes in the reactive current, aiming at reducing the depth of the voltage dips and the surges during the clearance of the fault. Such performance should be governed by the following equation:

$$\Delta I_{1,2} = K_{1,2} \cdot \Delta U_{1,2}$$

Consisting of injection/absorption of additional required reactive current, the value ‘ΔI’ is based on the increase in voltage ‘ΔU’ multiplied by a gain K. Subscripts 1 and 2 correspond to the positive and negative sequence, respectively.

At the firmware level, the HFD performs power control. It is therefore necessary to rewrite the above equation to suit the device control calculations. The calculation of the required reactive power increment is:

$$\frac{\Delta Q}{U_n \cdot S_n} = K_{1,2} \cdot \Delta U_{1,2}$$

$$\Delta Q = K_{1,2} \cdot U_n \cdot S_n \cdot \left(U_{DB} - U_{1,2}\right)$$

- 'Un' is the nominal value of the voltage module in p.u. (1 p.u).
- Sn is the nominal value of the power. It should be noted that Sn at firmware level is 2.8 MVA, something to be taken into account when calculating the reference current.
- 'U_DB' corresponds to the maximum and minimum values at which the fast current injection starts to act ('FRC_VMAX _VMIN').

Therefore, the reference current (to be injected/absorbed) of the HFD will be defined by:

$$I_{1,2} = \frac{\Delta Q}{\sqrt{3} \cdot U_n} \cdot I_{lim1,2}$$

- With '*I*_lim1,2': the parameter corresponding to the limitation of injection/absorption of total reactive current (FRC_I_Lim).

Once the equations have been defined, the current required for each test was obtained:

	V_PCC	t_fault	FRC_K1	FRC_I1_LimU	ΔI_1 (planned)	ΔI_2 (planned)
FRC-0 (a)	0 p.u (±5%, Three Phase)	250 ms	0	0.9 p.u	**0 A**	**0 A**
FRC-0 (b)	1.3 p.u.	1000 ms	0	0.9 p.u	**0 A**	**0 A**
FRC-1 (a)	0 p.u (±5%, Three Phase)	250 ms	3.5	0.9 p.u	**1163.94 A**	**0 A**
FRC-1 (b)	0 p.u (±5%, Three Phase)	250 ms	6	0.9 p.u	**1995.32 A**	**0 A**
FRC-1 (c)	0 p.u (±5%, Three Phase)	500 ms	3.5	0.9 p.u	**1163.94 A**	**0 A**
FRC-1 (d)	0 p.u (±5%, Three Phase)	500 ms	3.5	0.2 p.u	**831.38 A**	**0 A**
FRC-1 (e)	0 p.u (±5%, Three Phase)	250 ms	3.5	0.9 p.u	**1382.18 A(1)** **1050.45 A(2)**	**0 A**
FRC-1 (f)	0 p.u (±5%, Two-Phase)	250 ms	3.5	0.9 p.u	**751.75 A**	**- 266.69 A**
FRC-1 (g)	1.3 p.u	1000 ms	3.5	0.9 p.u	**- 218.24 A**	**0 A**

Table 27: Values for FRC tests

(1),(2): initial and final value of the current setpoint.

For the activation of the control by a voltage surge, the variation of the voltage value at the PCC (rms) with respect to a 50-cycle moving average of this value is measured. When this value is higher than 10% of the nominal value (FRC_|ΔVi|= 0.10 p.u.), the fast current injection is activated due to abrupt voltage change. This control activation is mutually exclusive from the one triggered by exceeding upper or lower limits.

Since the voltage dip is kept constant during the time of the fault, the moving average voltage will be decreasing, therefore the current reference will be decreasing accordingly. Once the fault is cleared and the voltage value returns within the set limits, current injection ceases in order to avoid a bang-bang response of the system.

Graph results for FRC tests

The results of the different test performed to validate the FRC functionality are presented in Annex 7.1.7. The figures show the positive and negative sequence of the setpoint, and output currents are plotted for the different frequency profiles and control configurations (tests from a to g). The voltage profile is also represented.

As an example, results for test FRC (g) are shown in next figure:

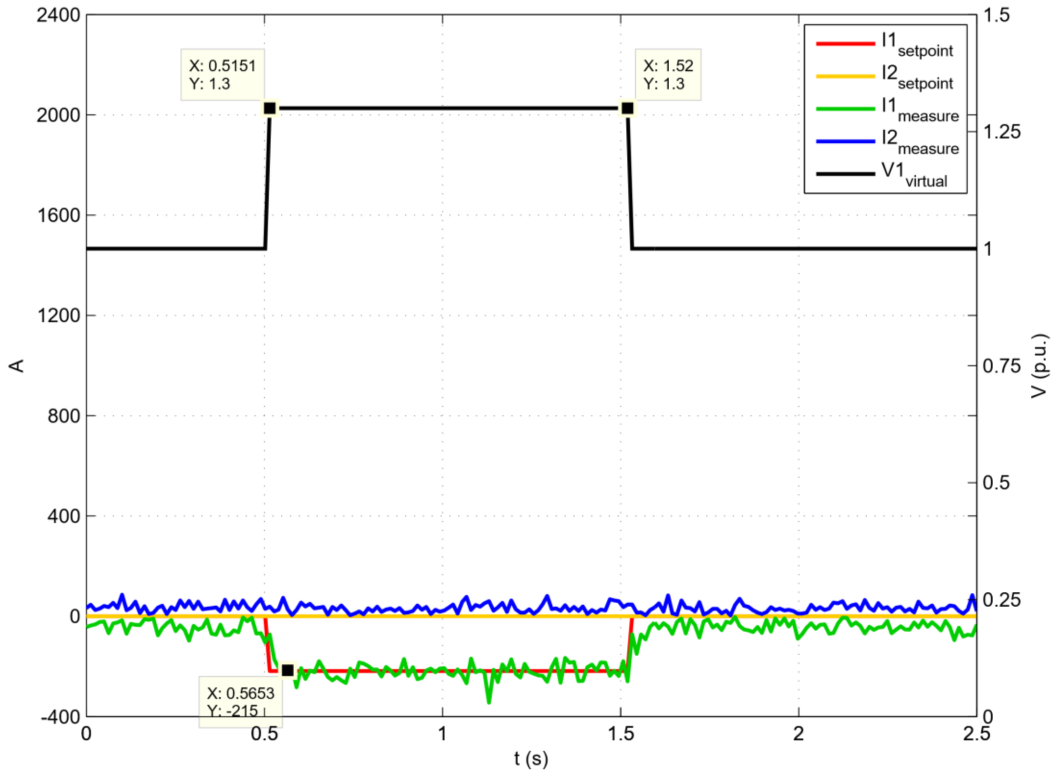

Figure 30: FRC-1 (g)

Table of Results for FRC tests

In the following table, a summary the results of the tests conducted to evaluate this functionality can be found. In the table, the direct and inverse sequence output current and voltage (measured at the PCC) are presented. The current deviation as a percentage, as well as the acceptance criteria are also included.

	V1_PCC	V2_PCC	I_1	I_2	Deviation I_1 (%)[5]	Deviation I_2 (%)5	Acceptance
FRC-0 (a)	0.05 p.u.	0 p.u.	< 30 A	< 30 A	**0 %**	**0 %**	✓
FRC-0 (b)	1.3 p.u.	0 p.u.	< 30 A	< 30 A	**0 %**	**0 %**	✓
FRC-1 (a)	0.05 p.u.	0 p.u.	1292 A	< 30 A	**11 %**	**0 %**	✓
FRC-1 (b)	0.05 p.u.	0 p.u.	2189 A	< 30 A	**9.71 %**	**0 %**	✓
FRC-1 (c)	0.05 p.u.	0 p.u.	1297.8 A	< 30 A	**11.5 %**	**0 %**	✓
FRC-1 (d)	0.05 p.u.	0 p.u.	927.3 A	< 30 A	**11.54 %**	**0 %**	✓
FRC-1 (e)	0.05 p.u.	0.0 p.u.	1552 A 1058.1 A	< 30 A	**12.29 %** **0.72 %**	**0 %**	✓
FRC-1 (f)	0.333 p.u.	0.333 p.u.	942.4 A	- 262.5 A	**25.37 %**	**1.57 %**	✓
FRC-1 (g)	1.3 p.u	0 p.u.	- 215 A	< 30 A	**1.48 %**	**0 %**	✓

Table 28. Results for FRC test

The existence of small current in some of the measurement (< 30A), when there is no power injection, is caused by the HFD no-load state. In this state, the HFD requires small current for DC-link balancing and for the switching losses.

Observing the results, current response is very fast, in the order of 10-15ms; even for those cases reaching the nominal current of the HFD (see test FRC-1 (b)).

For the case of current injection by abrupt voltage change, test (e), it is observed that the current reference is reduced over time. As stated before, this is due to the fact that the average of the last 50 cycles is decreasing until the total clearing of the fault that restarts the counting.

4.2.5. Trapezoidal Response (TRP)

The Trapezoidal Response is intended to provide a fast pre-programmed active power response to a frequency disturbance. So as to test this functionality, the controller has been provided with frequency data series representing different disturbances.

Conditions for TRP tests

The device must vary its active power according to the programmed response.

[5] *As can be seen in the graphs, the deviation is calculated on the peak value. In the table, the overshoot is represented, which was set at 20% as an acceptable value in the project. The current value is aligned with the setpoint value in the permanent regime for all the tests.*

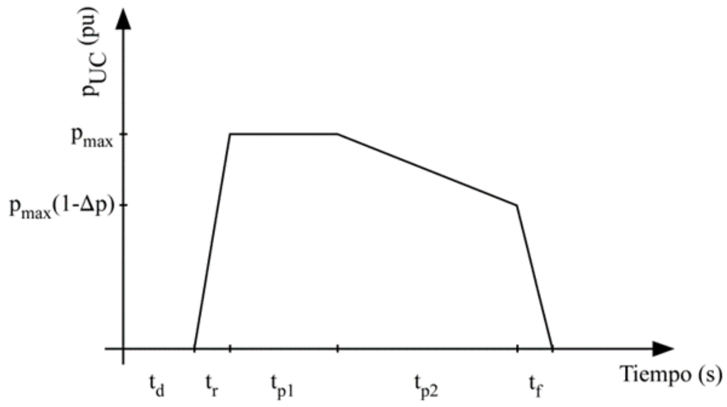

Figure 31: TRP profile

The following parameters are set:

- TRP_Pmax = 1.5 MW
- TRP_td <= 0,05 s
- TRP_tr <= 0,1 s
- TRP_ΔP = 300 kW
- TRP_f_trigger_U = 49,85 Hz
- TRP_f_trigger_O = 50,15 Hz

The other parameters will vary depending on the test according to the Table 29:

	F_PCC	TRP_Status	TRP_tp1	TRP_tp2	TRP_tf
TRP (a)	48 Hz	0	10 s	10 s	10 s
TRP (b)	48 Hz	1	10 s	10 s	10 s
TRP (c)	48 Hz	1	2 s	2 s	2 s
TRP (d)	51,5 Hz	1	10 s	10 s	10 s
TRP (e)	51,5 Hz	1	2 s	2 s	2 s

Table 29. Parameters and scenario for TRP tests

Therefore, for the trapezoidal discharge profile, there is no equation governing the behaviour of the discharge. The functionality is defined by the desired instants and power values.

Thus, the predicted values are trivial to know and would be as shown in the Table 30.

	F_PCC	ΔP (tp1, planned)	ΔP (tp2, planned)	ΔP (tf, planned)
TRP (a)	48 Hz.	**0 kW**	**0 kW**	**0 kW**
TRP (b)	48 Hz	**1500 kW**	**1200 kW**	**0 kW**
TRP (c)	48 Hz	**1500 kW**	**1200 kW**	**0 kW**
TRP (d)	51.5 Hz	**-1500 kW**	**-1200 kW**	**0 kW**
TRP (e)	51.5 Hz	**-1500 kW**	**-1200 kW**	**0 kW**

Table 30: Values for TRP tests

The discharge profile will start as soon as the frequency exceeds any of the lower or upper limits defined for the tests (TRP_f_trigger). It will perform the entire profile regardless of whether the frequency returns to a value within the limits. This behaviour could be modified.

Graph Results for TRP tests

The results of the different test performed to validate the TRP functionality are presented in Annex 7.1.8. The figures show voltage, frequency, active power output and reactive power output are represented for the different frequency profiles and control configurations (tests from a to e).

As an example, results from TRP (e) test are shown in next figure:

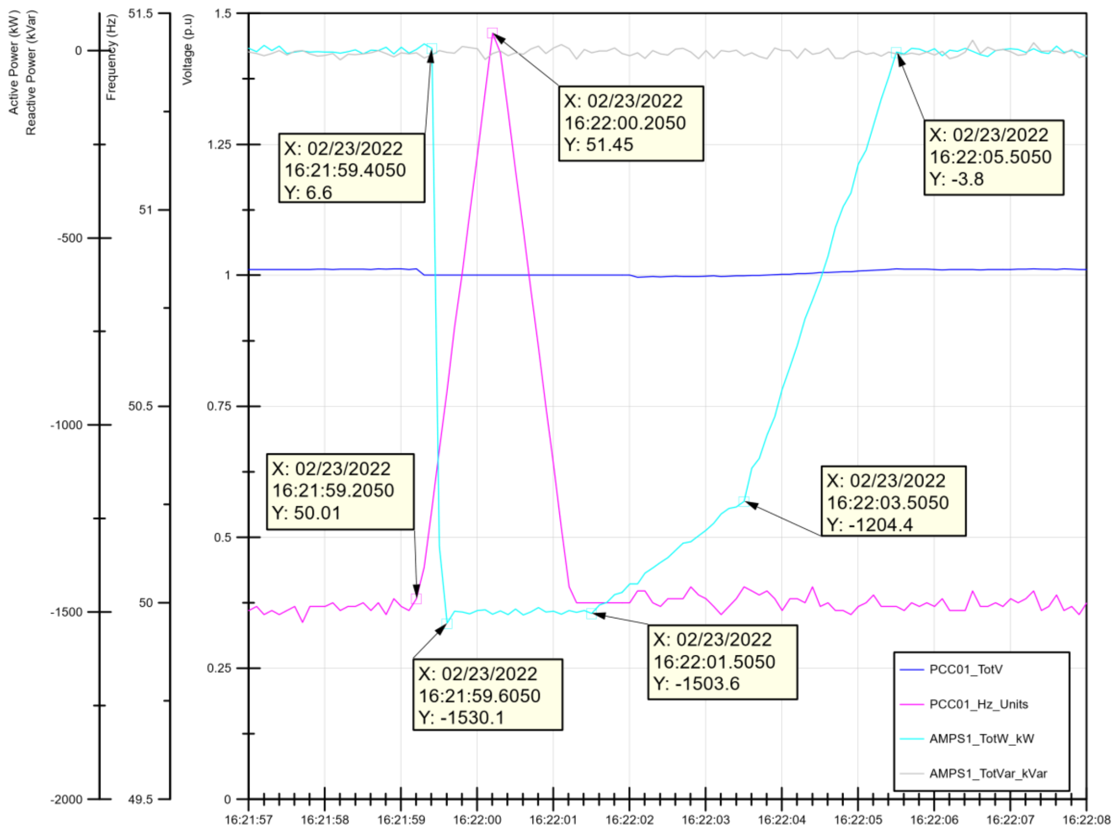

Figure 32: TRP (e)

Table of Results for TRP tests

The results of the above-mentioned tests are summarized in the following table, where the amount of power delivered, as well as the deviation from the setpoint, are included. The value of the variation of the frequency in each test and the fulfilment of the acceptance criteria are also specified.

	F_PCC	P_HFD (tp1)	P_HFD (tp2)	P_HFD (tf)	Deviation (tp1)	Deviation (tp2)	Deviation (tf)	Acceptance
TRP (a)	48 Hz.	0 kW	0 kW	0 kW	**0 %**	**0 %**	**0 %**	✓
TRP (b)	48 Hz	1493 kW	1211.7 kW	-3.7 kW	**0.47 %**	**0.97 %**	**0 %**	✓
TRP (c)	48 Hz	1488 kW	1203.2 kW	-4.9 kW	**0.8 %**	**0.27 %**	**0 %**	✓
TRP (d)	51.5 Hz	-1499.7 kW	-1193.8 kW	-2.3 kW	**0.02 %**	**0.52 %**	**0 %**	✓
TRP (e)	51.5 Hz	-1503.6 kW	-1204.4 kW	-3.8 kW	**0.24 %**	**0.37 %**	**0 %**	✓

Table 31. Table of results for TRP tests

For the calculation of the deviation, the considered power are the values reached in the permanent regime.

If the initial values were used, the overshoot would be obtained. In that case, the test with the highest overshoot would be the TRP (e) with 2%, well below from the maximum 20% accepted for the project.

Taking into account that the sampling rate in the data acquisition is 100ms and the response starts from the dead band (+-0.15Hz), it is difficult to verify that the response time is less than 100ms. Nevertheless, from the FRC tests, it was obtained that the device is capable of providing up to 2.000 kW of power in 20ms. So, that information could be extrapolated to those tests acquired with DSP software.

4.3. Level-2 functionalities managed by HFD

Level-2 functionalities provide control on system variables once grid stability is ensured. As previously mentioned, these functionalities have been implemented both in the HFD itself and in the MC. In this section, the performance of the equipment regarding Level-2 functionalities implemented in the HFD is evaluated.

4.3.1. Power-frequency Regulation. Nominal regime (PFR-n)

In the power-frequency regulation mode, for the normal regime, the HFD must provide active power regulation with respect to variations in frequency in accordance with its specifications. To evaluate this functionality, different frequency profiles have been tested and combined with different values of the droop of the controller.

Conditions for PFR-n tests

The device must vary its active power according to changes in frequency.

	f	PFR_Status
PFR-n (a)	50,25 Hz	0
PFR-n (b)	50,25 Hz	1
PFR-n (c)	49,75 Hz	1

Table 32. PFR-n test conditions

The following parameters are set:

- P_HFD initial = 0.3 Pn
- PFR_PmaxRange = [-100%; +100%] = [-2MW ; 2MW]
- PFR_DeadBand = [-0,05Hz; +0,05Hz]
- Droop 4%

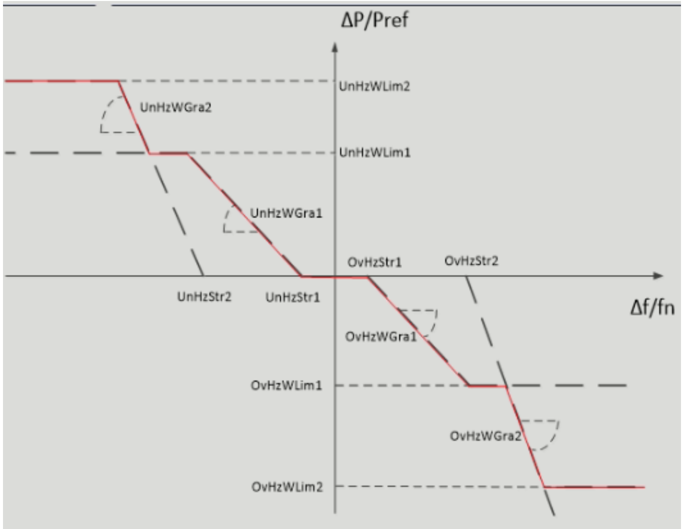

Figure 33. PPC Frequency response configuration

The parameters configurated in the PPC to achieve the proper frequency response are described next:

- UnHzStr1 and OvHzStr1 that represent the dead band. These parameters are set to 0.05Hz.
- UnHzWGra1 and OvHzWGra1 represent the droop. The configurated droop was of 4%.
- UnHzWLim1 and OvHzWLim1 represent the maximum active power (PFR_PmaxRange). These are set to +/- 2MW.
- All other parameters are not set because a second frequency response ramp is not required.

Graph Results for PFR-n

The results of the different test performed to validate the power-frequency response in the perturbed regime are presented next. In the following figures, voltage, frequency, active power output and reactive power output are represented for the different frequency profiles and control configurations (tests a, b and c).

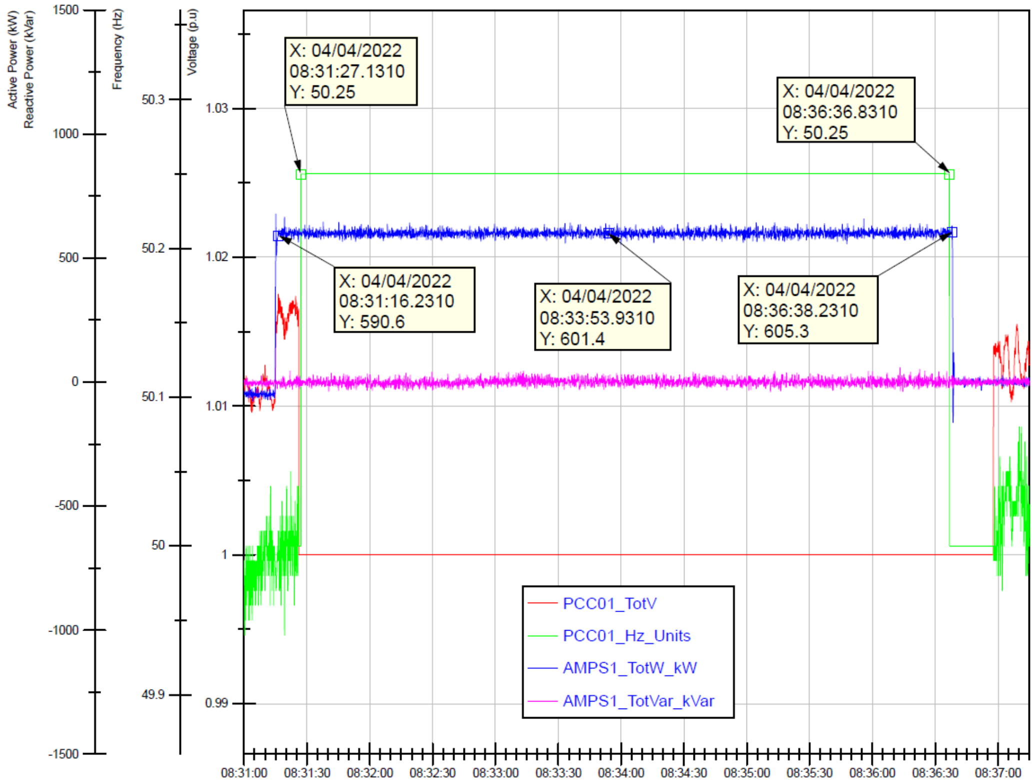

Figure 34. PFR-n (a)

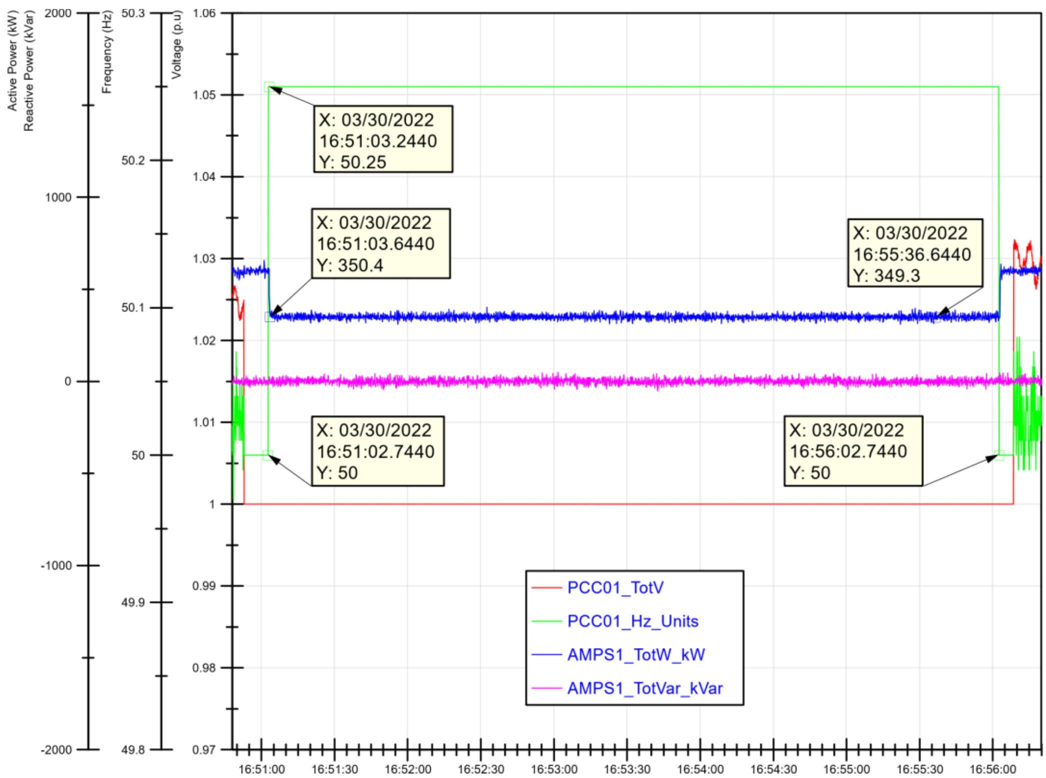

Figure 35. PFR-n (b)

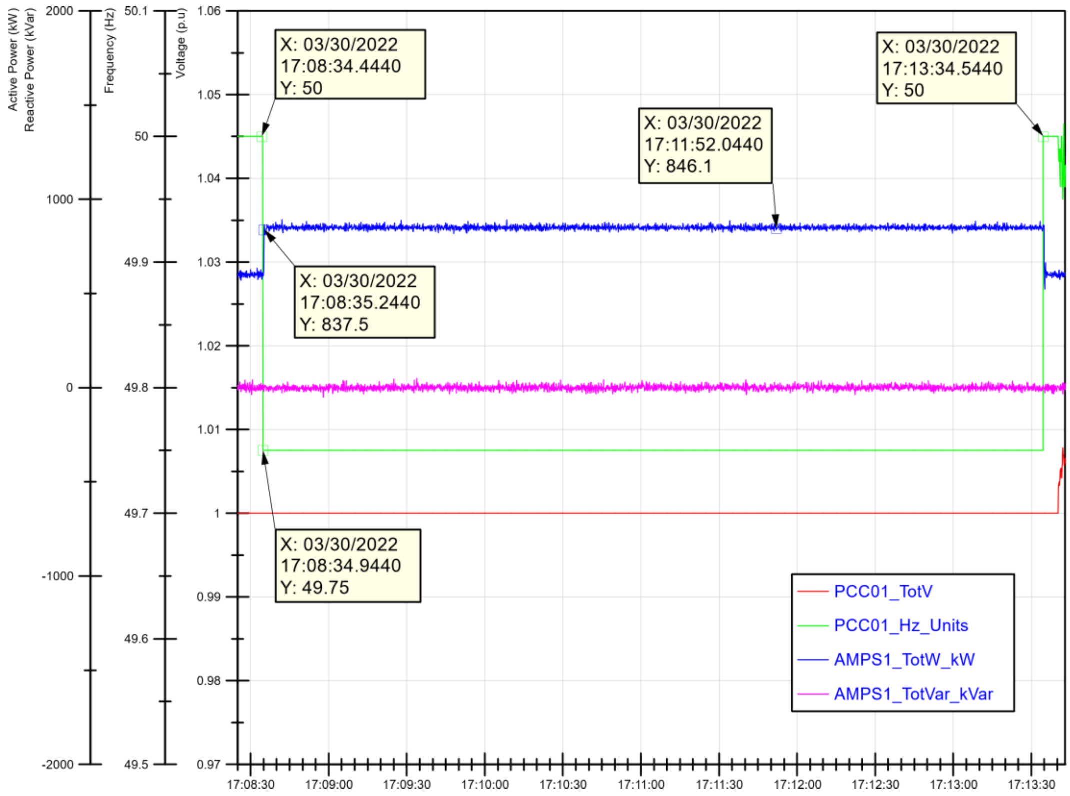

Figure 36. PFR-n (c)

Table of Results for PFR-n tests

The results of the above-mentioned tests are summarized in the following table, where the amount of power delivered before and after the change of the frequency, as well as the difference between them, are included. The value of the variation of the frequency in each test and the fulfilment of the acceptance criteria are also specified.

	f	P_HFD init	P_HFD final	Expected |ΔP|	PFR_Status	Acceptance
PFR-n (a)	50,25 Hz	590,6 kW	605,3 kW	0 kW	0	✓
PFR-n (b)	50,25 Hz	599,1 kW	341,1 kW	-250 kW	1	✓
PFR-n (c)	49,75 Hz	594,3 kW	839,9 kW	+250 kW	1	✓

Table 33. PFR-n test results

The expected response is met within the acceptance criteria. The expected values can be calculated as follows:

$$S_H[\%] = 100 \cdot \frac{|\Delta f|}{f_n} \cdot \frac{P_{max}}{|\Delta P|} \rightarrow |\Delta P| = 100 \cdot \frac{|\Delta f|}{f_n} \cdot \frac{P_{max}}{S_H[\%]}$$

It is observed in the charts that the PFR_tr and PFR_te (0.5s and 1.5s respectively) are met, observing response time under the 400ms.

4.3.2. Voltage Control based on Voltage Setpoint (VCV)

In the VCV functionality, the HFD must provide control on the voltage of the controlled node, in response to the voltage setpoint. So as to validate this functionality, different voltage setpoint values and control configurations have been tested.

Conditions for VCV tests

The device must vary its reactive power according to the voltage measure on the PCC, voltage setpoint and control parameters.

	VCV_Status	VCV_OutVSet	VCV_Kv	VCV_RAMP_Status	V_PCC
VCV (a)	0	1,1 p.u.	75	0	1,0 p.u.
VCV (b)	1	1,1 p.u.	2	0	1,0 p.u.
VCV (c)	1	1,1 p.u.	75	0	1,0 p.u.
VCV (d)	1	1,1 p.u.	2	1	1,0 p.u.
VCV (e)	1	0,9 p.u.	0,8	0	1,0 p.u.
VCV (f)	1	0,9 p.u.	75	0	1,0 p.u.
VCV (g)	1	0,95 p.u.	2	0	1,05 p.u.
VCV (h)	1	1,05 p.u.	2	0	0,95 p.u.

Table 34. VCV test conditions

The following parameters are set for these tests:

- VCV_DeadBand = [-0,025; +0,025]
- VCV_Lim_Q1 = 0 p.u
- VCV_Lim_V1 = 0,95 p.u
- VCV_Lim_Q2 = -1 p.u
- VCV_Lim_V2 = 0,98 p.u
- VCV_Lim_Q3 = 1 p.u
- VCV_Lim_V3 = 1,03 p.u
- VCV_Lim_Q4 = 0 p.u
- VCV_Lim_V4 = 1,05 p.u
- VCV_Q_LimMAX = Qn_HFD (capacitive) = 2MVAr
- VCV_Q_LimMIN = Qn_HFD (inductive) = -2MVAr
- VCV_Ramp = 2 kV/min

The curve configuration on the PPC side is described below.

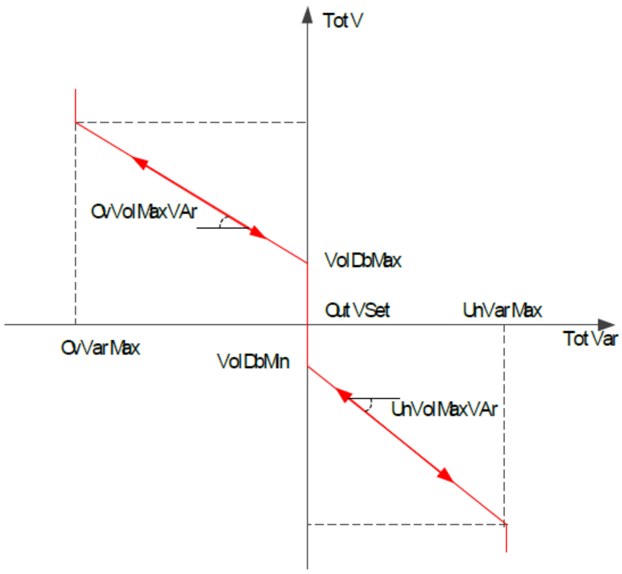

Figure 37. Voltage reference control curve

The parameters configurated set in the PPC are:

- VolDbMax and VolDbMin are the deadband limits. These parameters are set to 0.025 p.u (VCV_DeadBand).
- OvVolMaxVAr and UnVolMaxVAr are the slope values. These are configurated according to VCV_K_V (OvVolMaxVar = 1/VCV_Kv)
- OvVArMax and UnVArMax are the reactive power limits. These are set to +/- 2MVAr.

In addition, a Q-V curve is defined and configurated in the PPC. The graphical representation of this curve is shown in the following figure:

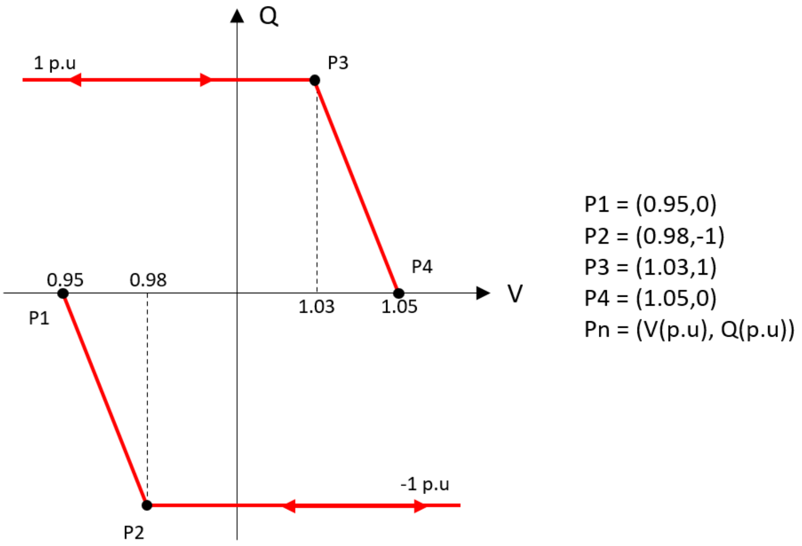

Figure 38. Q-V curve configuration

Graph Results for VCV tests

The results of the different test performed to validate the VCV functionality are presented in Annex 7.1.9. The figures show active and reactive power output, as well as the voltage setpoint profile and the output voltage, are represented for the different voltage setpoints and control configurations (tests from a to h).

As an example, results for VDV (h) tests are shown in next figure:

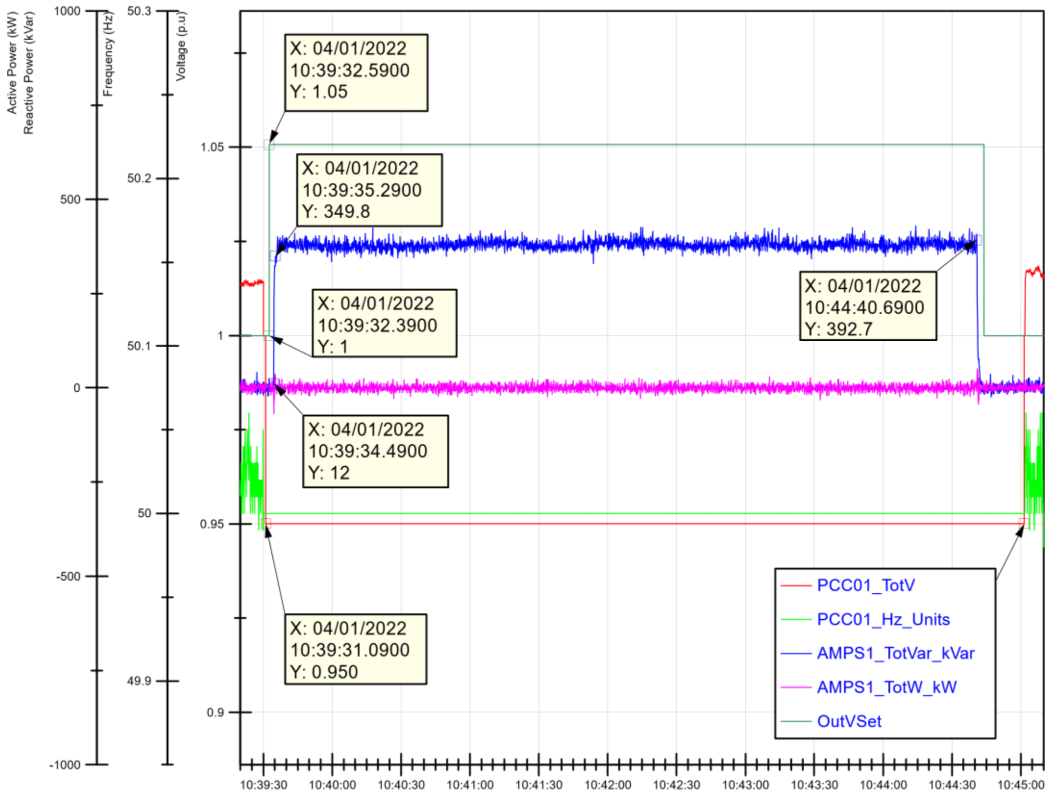

Figure 39. VCV (h)

Table of Results for VCV tests

The results of the above-mentioned tests are summarized in the following table, where the expected and measured change in the reactive power output, as well as the voltage setpoint, are included. The percentage of the variation of the reactive power in each test and the fulfilment of the acceptance criteria are also specified.

	VCV_Status	VCV_VOutVSet	V_PCC	Expected |ΔQ|	Q Measure	Deviation (%)	Acceptance
VCV (a)	0	1,1 p.u.	1,0 p.u.	0 kVAr	0 kVAr	-	✓
VCV (b)	1	1,1 p.u.	1,0 p.u.	400 kVAr	394,8 kVAr	1,3%	✓
VCV (c)	1	1,1 p.u.	1,0 p.u.	2 MVAr*[6]	1995,6 kVAr	0,22%	✓
VCV (d)	1	1,1 p.u.	1,0 p.u.	400 kVAr	401,4 kVAr	0,35%	✓
VCV (e)	1	0,9 p.u.	1,0 p.u.	-160 kVAr	-163,7 kVAr	2,31%	✓
VCV (f)	1	0,9 p.u.	1,0 p.u.	-2 MVAr*	-1997,8 kVAr	0,11%	✓
VCV (g)	1	0,95 p.u.	1,05 p.u.	-400 kVAr	-401,0 kVAr	0,25%	✓
VCV (h)	1	1,05 p.u.	0,95 p.u.	400 kVAr	392,7 kVAr	1,82%	✓

Table 35. VCV test results

[6] The reactive response is limited by the parameter OvVArMax and UnVArMax, set to +/- 2MVAr

The expected response of the frequency response can be calculated as follows:

$$Slope\ K_v = \frac{Q/_{Q_n}}{\Delta V/_{V_n}}\ with\ \Delta V = V_{OUTVSET} - V_{PCC}$$

Therefore, if we deduct $Q/_{Q_n}$ we have that:

$$\frac{Q}{Q_n} = K_v \cdot \frac{\Delta V}{V_n}$$

With this equation, the expected reactive power response can be calculated as a function of the voltage measured in the PCC and the voltage set point. The relative error can be calculated from the expected values and actual measurements. These errors can be seen in the 'Deviation' column.

The validation of this functionality is as follows:

1. A constant PCC voltage is set using the virtual profiles tool.
2. Once the profile is launched, a reference is established (OutVSet) that will be maintained for the test duration, previously defined. This ensures a constant reference for the VCV performance, avoiding response fluctuations.

It is important to clarify the following points that can be deduced from the charts:

- The virtual voltage profiles are more than 5 minutes long to be able to enable the control and modify the voltage setpoint.
- In Figure 235 the reactive response does not start till the voltage setpoint is changed.
- In Figure 240, it can be observed a reactive response to the variation from 1p.u to 1.05p.u in the PCC voltage. After that, the voltage setpoint is changed to 0.95p.u., observing an additional reactive injection.
- In all the graphs, the expected response is observed and confirmed, with some minor oscillations caused by switching noise.
- For tests (g) and (h), a characteristic behaviour is observed, which differs from the rest due to the test conditions.
- For case (g), the control is activated (VCV_Status = 1) before the change in the setpoint (OutVSet). As a consequence, the voltage at the PCC rises to 1.05 and the functionality starts to operate before setting the setpoint. Therefore, a first step is caused before the final response is observed.
- On the other hand, for case (h), the opposite operation is performed. The setpoint is sent and then the functionality is activated, avoiding the initial step observed in the previous test (g). This action creates a delay between the setpoint sent and the start of the response.

As a conclusion, it is observed in all the charts above that the reactive injection and response times are aligned with the expected objectives shown in the Table 35. The time constants VCV_tr and VCV_te (1s and 5s) are also met.

4.3.3. Voltage Control based on Reactive Power Setpoint (VCQ)

In the VCQ functionality, the HFD must provide control on the voltage of the controlled node, in response to the reactive power setpoint. So as to validate this functionality, different reactive power setpoint values and control configurations have been tested.

Conditions for VCQ tests

The device must vary its reactive power according to the setpoint and control parameters.

	VCQ_Status	VCQ_Consigna	VCQ_Ramp	VCQ_RAMP_Status
VCQ (a)	0	+Qn_HFD (capacitive)	2 Mvar/min	0
VCQ (b)	1	+Qn_HFD (capacitive)	2 Mvar/min	0
VCQ (c)	1	+0,5*Qn_HFD (capacitive)	2 Mvar/min	0
VCQ (d)	1	-Qn_HFD (inductive)	2 Mvar/min	0
VCQ (e)	1	-Qn_HFD (inductive)	-5 Mvar/min	1

Table 36. VCQ test conditions

The tests are summarized in a single test that will run through all the different ramps and setpoints.

Graphs Results for VCQ tests

The results of the different test performed to validate the VCQ functionality are presented next. In the following figures, active and reactive power output, as well as the voltage and frequency at the PCC, are represented for the different voltage setpoints and control configurations (tests from a to e).

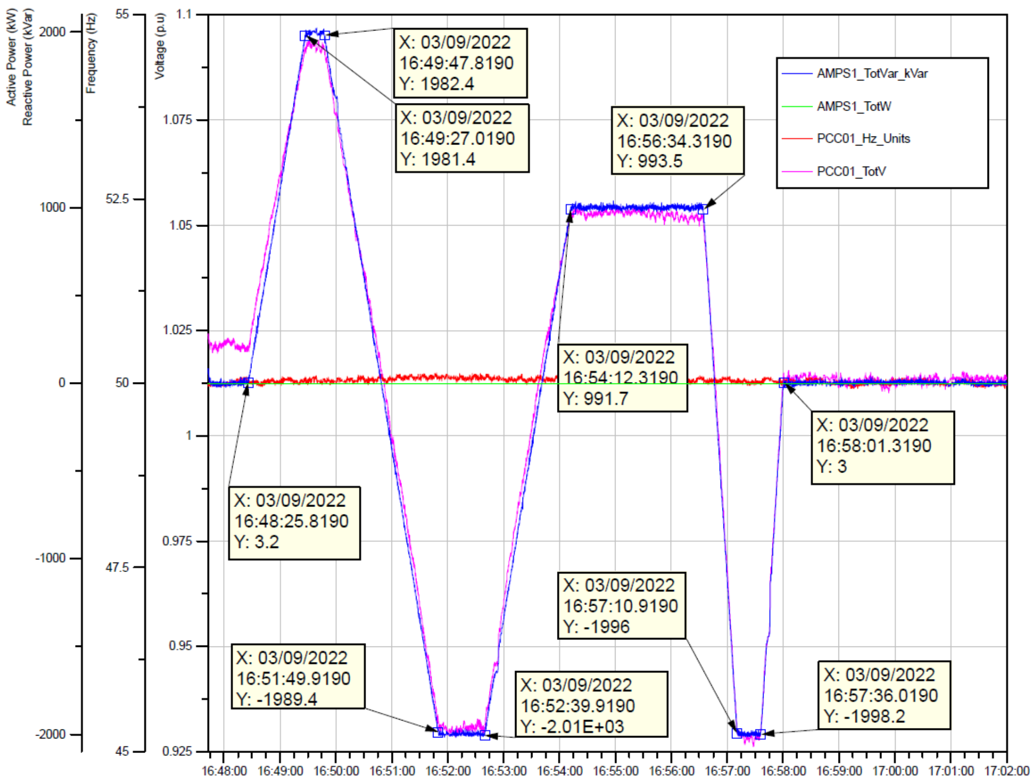

Figure 40. VCQ all ramps

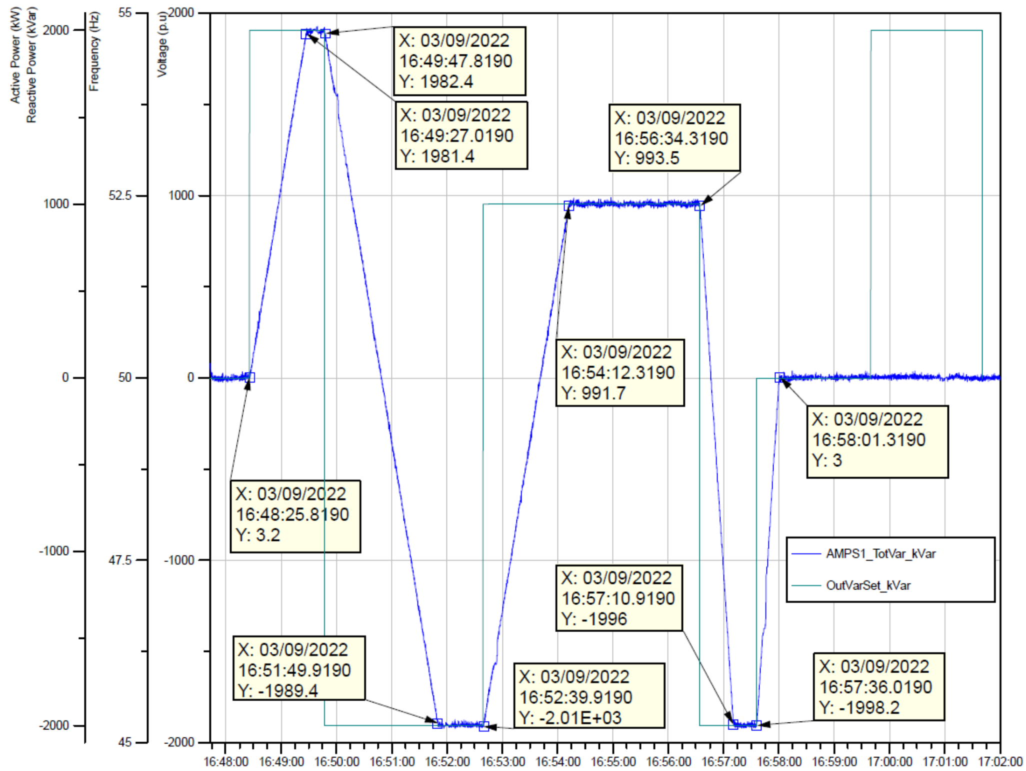

Figure 41. VCQ with setpoint and labels

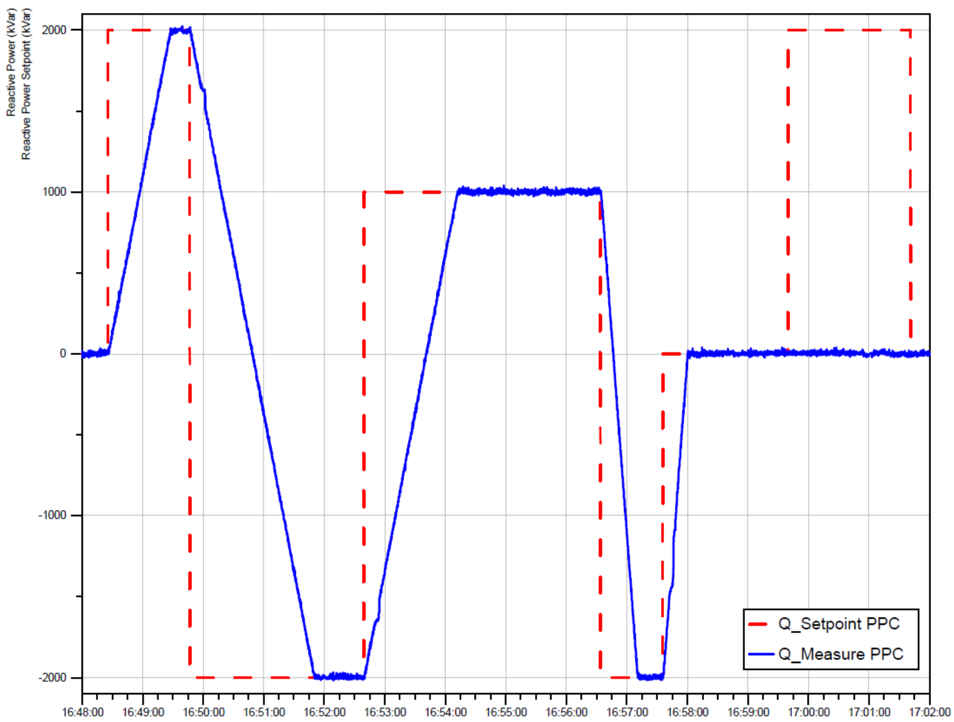

Figure 42. VCQ with setpoint

Table of Results for VCQ tests

The results of the above-mentioned tests are summarized in the following table, where the initial and final reactive power output, as well as the initial and final time, are included. The ramp time, the control error, and the fulfilment of the acceptance criteria are also specified.

	Q_HFD init	Q_HFD final	Init time	Final time	Ramp time	Error	Acceptance
VCQ (b)	3,2 kVAr	1991,4 kVAr	16:48:25.8190	16:49:27.0190	61,2s	2%	✓
VCQ (d)	1982,4 kVAr	-1996,7 kVAr	16:49:47.8190	16:51:49.9190	61,05s	1,75%	✓
VCQ (c)	-2003,2 kVAr	998,9 kVAr	16:52:39.9190	16:54:12.3190	30,8s	2,6%	✓
VCQ (e)	999,0 kVAr	-1989,7 kVAr	16:56:34.3190	16:57:10,9190	12,2s	1,6%	✓
VCQ (a)	0 kVAr	0 kVAr	-	-	-	-	✓

Table 37. VCQ test results

In order to have all the tests collected in a single chart, the following order of execution was followed:

1. Ramp from 0MVAr to 2MVAr with 2MVAr/min (VCQ (b))
2. Ramp from 2MVAr to -2MVAr with -2MVAr/min (VCQ (d))
3. Ramp from –2MVAr to 1MVAr with 2MVAr/min (VCQ (c))
4. Ramp from 1MVAr to -2MVAr with -5MVAr/min VCQ (e))
5. Ramp from 0MVAr to 2MVAr with 2MVAr/min and control disabled VCQ (a))

It should be noted that the time calculated in ‘Ramp time’ column is not the time between init time and final time, but the time required to follow the ramp corresponding to each test. For example, for the test case d, the ramp was executed between 2MVAr and -2MVAr but we are interested in the time between 0Mvar and -2MVAr. The reference values are reached within the acceptance criteria and the ramp limit is followed.

4.4. Level-2 functionalities managed by the Master Control

As previously mentioned, level-2 functionalities have been implemented both in the HFD itself and in the Master Control (MC). The following tests concern 2nd level functionalities that are controlled by the MC.

For this level 2 results section, and also for Level 3, the structure for reporting the results obtained from testing each functionality includes a fist sub-section for tests conditions definition, which provides information to understand the tests applied, and a second subsection with the obtained results and their analysis. In turn, the test implementation definition subsection contains the following information:

- Purpose of the test (as complement description done in Section 2)
- Existing conditions at the initiation of each test
- The methodology applied
- Variables that are measured
- Acceptance criteria explanation for the test
- Obtained results illustration and evaluation

Nomenclature for parameters and variables used in this section is as defined in Table 71.

4.4.1. Power-frequency Regulation. Nominal regime (PFR-n)

In the power-frequency regulation mode, for the normal regime, the HFD must provide active power regulation with respect to variations in frequency in accordance with its specifications.

To evaluate this functionality, different frequency profiles have been tested and combined with different values of the droop of the controller.

4.4.1.1. Test conditions definition

Purpose

Evaluate the active power response with respect to variations in frequency.

Pre-test conditions

Pre-test conditions and parameters for the test:

- Level-1 functionalities disabled
- Level-2 functionalities disabled except PFR
- Level-3 functionalities disabled except SPT
- F_PPC = 50 Hz
- V_PPC = 1 p.u.
- Lp= 59%
- Le = 60%
- Eta = 0 MWh
- SOCinicial = 50%
- t_pre=10s

Methodology

The devices that take part along PFR-n tests are the HFD and a redox-flow battery from ATENEA microgrid.

Cause a frequency disturbance in the grid. The next parameters must be set:

- PFR_PmaxRange = [-100 % ; +100 %]
- PFR_DeadBand = [-0,05 Hz ; +0,05 Hz]
- PFR_tr = 5 s
- PFR_te = 15 s

For each test, the frequency variation must be set at values according to Table 38.

	f	PFR_Status	SPT_P_setpoint	SPT_tr
PFR-n (a)	50,25 Hz	0	800 kW	1
PFR-n (b)	50,25 Hz	1	800 kW	1
PFR-n (c)	49,75 Hz	1	800 kW	1

Table 38 f_PCC frequency profiles for PFR-n

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its P as a function of the frequency variation.

4.4.1.2. Test results

PFR_n (a):

The continuous PFR that is classified as 2nd level functionality and it is controlled by the MC. Following the methodology and with verified pre-test conditions, the signals measured at PCC during 8 minutes with a sampling rate of 1 second are shown in Figure 43:

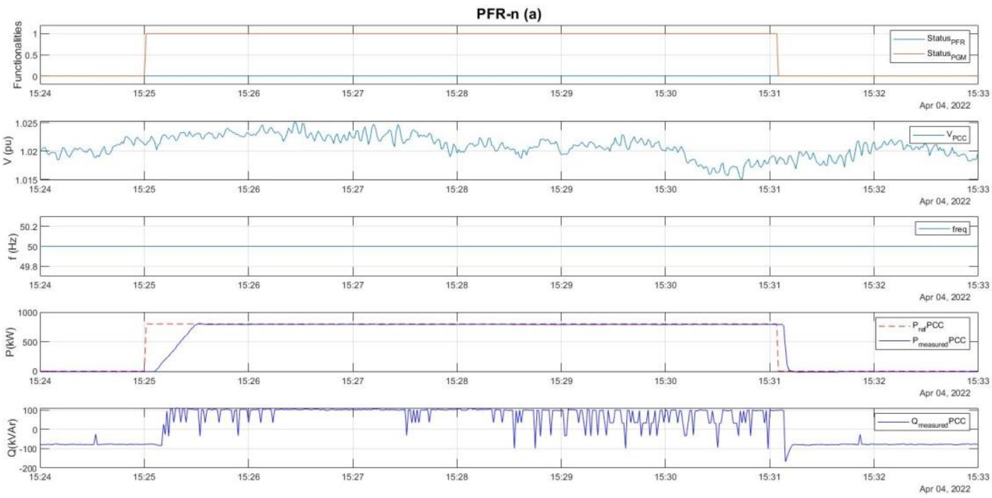

Figure 43: PFR-n (a) signals measured at PCC

Active power response at PCC, reference signals and acceptance limits are indicated in Figure 44.

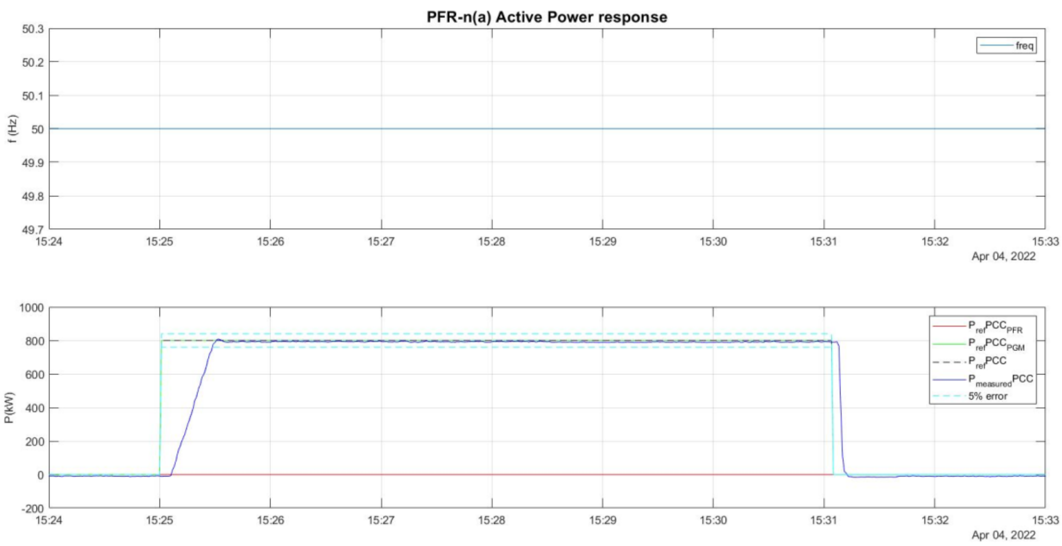

Figure 44: PFR-n (a) active power at PCC

On one hand, since PFR status is deactivated, no action due to frequency change is taken. On the other hand, as level-3-SPT functionality is activated, consequently a correct response is obtained following 800 kW active power setpoint. Therefore, this test passes the acceptance criteria.

PFR-n (b):

In this test, signals measured at PCC during 7 minutes are plotted separately in Figure 45.

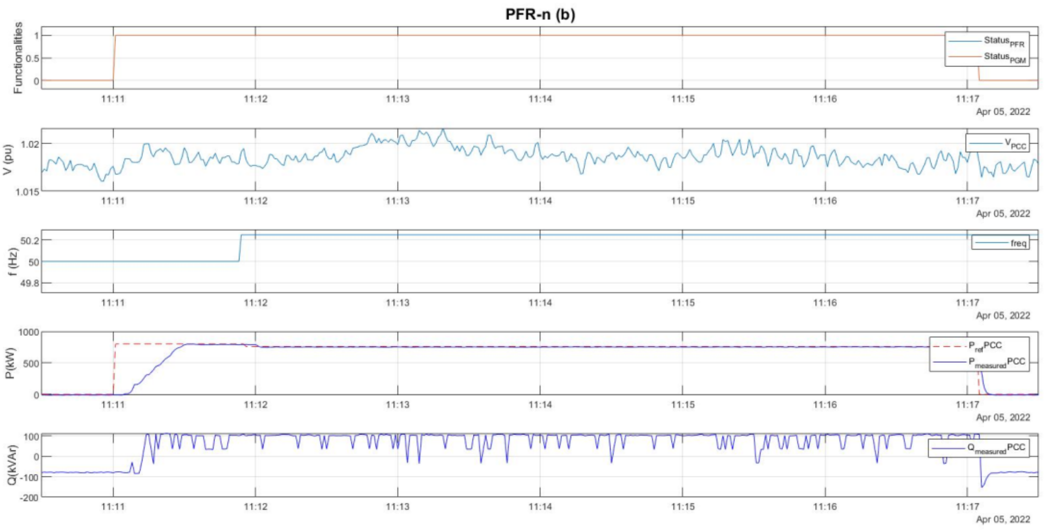

Figure 45: PFR-n (b) signals measured at PCC

In Figure 46, active power response at PCC is detailed with each reference signal, one for PFR_n and other for PGM functionalities. The allowed margins are also plotted to visually show the performance of the control. After pre-test conditions achieved with PGM functionality, the total P required at PCC taking into account pre-test conditions and power and energy reserves for second level functionalities, the set-point turns into P_{PCC}=760kW. For over-frequency values (50.25 Hz) the MCFS is able to decrease its active power injection to the grid from 800 kW to 760 kW achieving the reference set point within the set-point-range (5% error). Rise time is given by t_1-t_0.

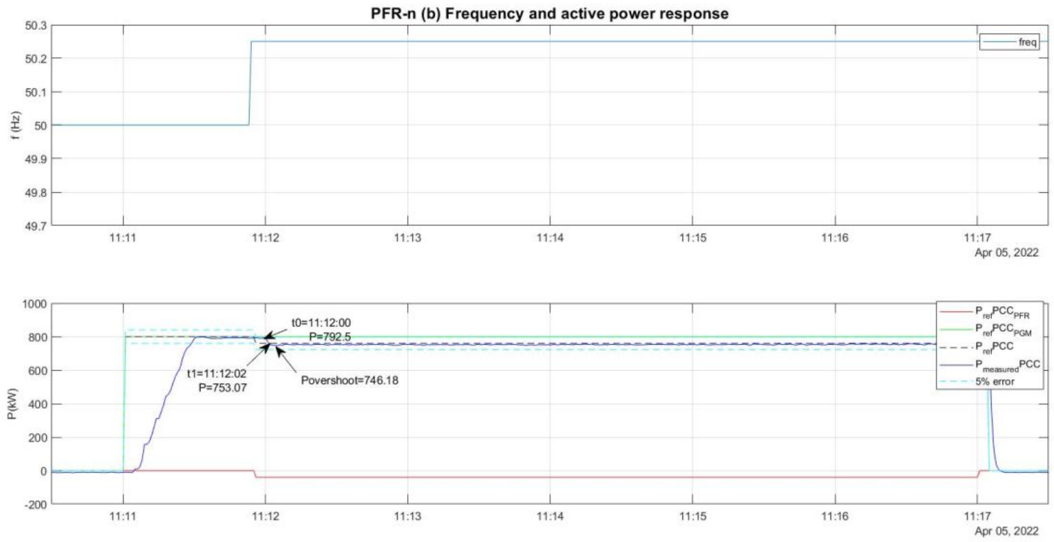

Figure 46: PFR-n (b) active power at PCC

PFR-n (c):

During testing procedures, signals were measured at PCC. These are graphically represented in Figure 47 for 7 minutes.

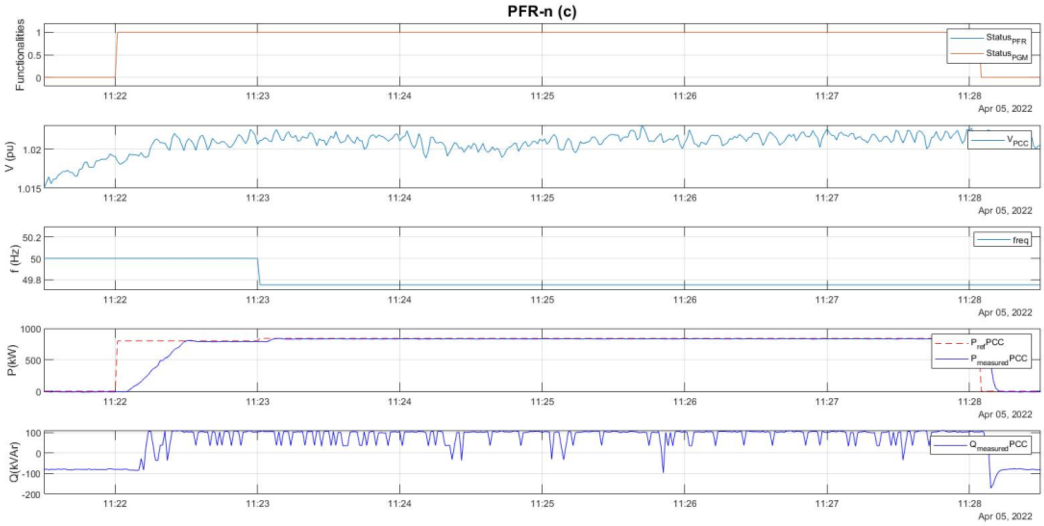

Figure 47: PFR-n (c) signals measured at PCC

Active power response at PCC is plotted in Figure 48. Reference signals and acceptance limits (5%) are also included.

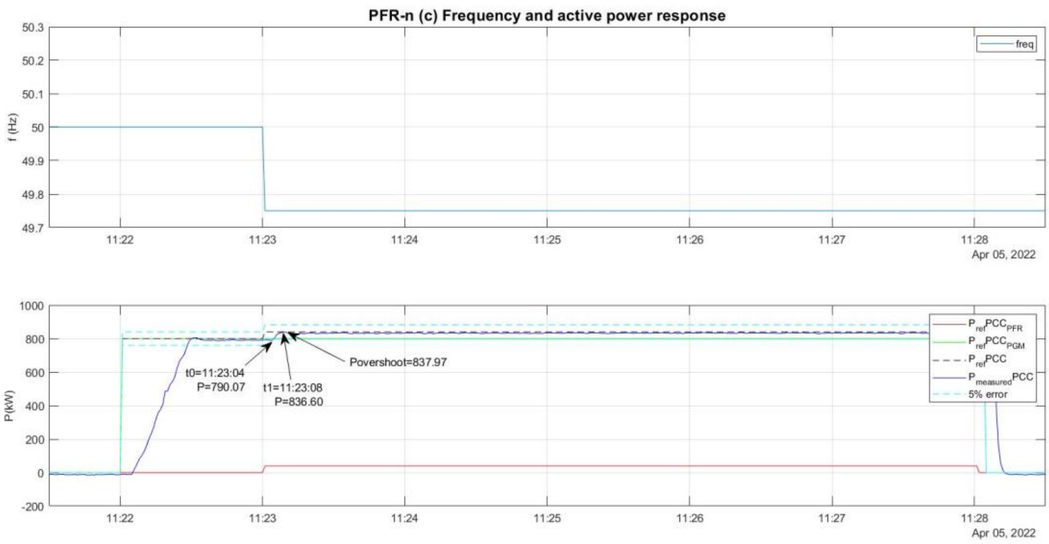

Figure 48: PFR-n (c) active power at PCC

For under-frequency values (49.75 Hz) the MCFS is able to increase its active power injection to the grid achieving the reference set point within the set-point-range (5% error). After pre-test conditions, the total P required at PCC taking into account pre-test conditions and power and energy reserves for second level functionalities, the set-point turns into P_{PCC}=840kW. Rise time is given by t_1-t_0.

Summary for PFR-n tests:

To sum up, the fulfilment of the acceptance criteria applied for PFR-n (b) and PFR-n (c) tests is shown in Table 39:

	Test condition	Test condition value	Test value	Acceptance
PFR-n (a)	Not follow PFR-n-set-point	From 800 kW to 760 kW	800 kW	✓
PFR-n (b)	tr (s)	5	2	✓
	te (s)	10	2	✓
PFR-n (c)	tr (s)	5	4	✓
	te (s)	10	4	✓

Table 39 Acceptance criteria for PFR-n

4.4.2. Voltage Control based on Voltage Setpoint (VCV)

In the VCV functionality, the HFD must provide control on the voltage of the controlled node, in response to the voltage setpoint. So as to validate this functionality, different voltage setpoint values and control configurations have been tested.

4.4.2.1. Test conditions definition

Purpose

Set several voltage instructions to verify the correct response of the control.

Pre-test conditions

Pre-test conditions and parameters for the test:

Table 3

- F_PCC = 50 Hz
- V_PCC = 1 p.u.
- t_pre=10s
- Level-1 functionalities disabled
- Level-2 functionalities disabled except VCV
- Level-3 functionalities disabled

Methodology

The device that takes part along VCQ tests is the HFD .

Modify the voltage setpoint for different control parameters. The next parameters must be set:

- VCV_DeadBand = [-0,025 pu ; +0,025 pu]
- VCV_Lim_Q1 = 0 pu
- VCV_Lim_V1 = 0.95 pu
- VCV_Lim_Q2 = -1 pu
- VCV_Lim_V2 = 0.98 pu
- VCV_Lim_Q3 = 1 pu
- VCV_Lim_V3 =1.03 pu
- VCV_Lim_Q4 = 0 pu
- VCV_Lim_V4 = 1,05 pu

- VCV_Q_LimMAX = Q_MCFS (capacitive)
- VCV_Q_LimMIN = Q_MCFS (inductive)
- VCV_RAMP = 2 kV/min
- VCV_tr = 2 s
- VCV_te = 5 s
- VCV_Qos = 1.2 pu

The control will be validated for different slope values, with and without ramp in the setpoint and for voltage disturbances in the PCC, according to Table 40.

	VCV_Status	VCV_Vconsigna	VCV_Kv	VCV_RAMP_Status	V_PCC
VCV (a)	0	1,1 p.u.	75	0	1,0 p.u.
VCV (b)	1	1,1 p.u.	2	0	1,0 p.u.
VCV (c)	1	1,1 p.u.	75	0	1,0 p.u.
VCV (d)	1	1,1 p.u.	2	1	1,0 p.u.
VCV (e)	1	0,9 p.u.	0,8	0	1,0 p.u.
VCV (f)	1	0,9 p.u.	75	0	1,0 p.u.
VCV (g)	1	0,95 p.u.	2	0	1,05 p.u.
VCV (h)	1	1,05 p.u.	2	0	0,95 p.u.

Table 40 Control Parameters profile for VCV

Signals to be measured

- V_PCC
- F_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its Q according to the voltage and the control parameters and reach the voltage setpoint.

4.4.2.2. Test results

VCV (a):

VCV is classified as a 2nd level functionality and it is controlled by the MC. Following the methodology and with verified pre-test conditions, the signals measured at PCC during 7 minutes with a sampling rate of 1 second are shown in Figure 49:

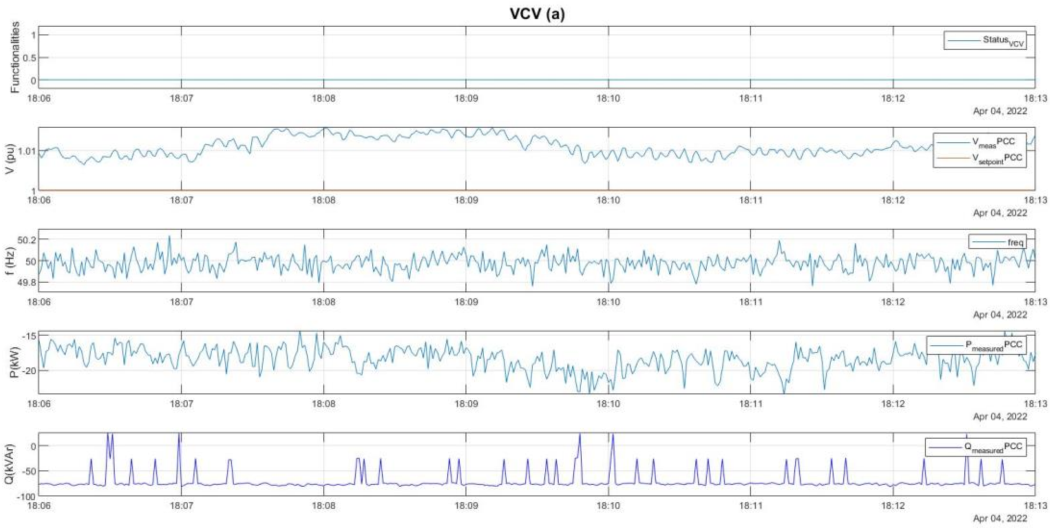

Figure 49: VCV (a) signals measured at PCC

Reactive power response at PCC, reference signals and acceptance limits are indicated in Figure 50:

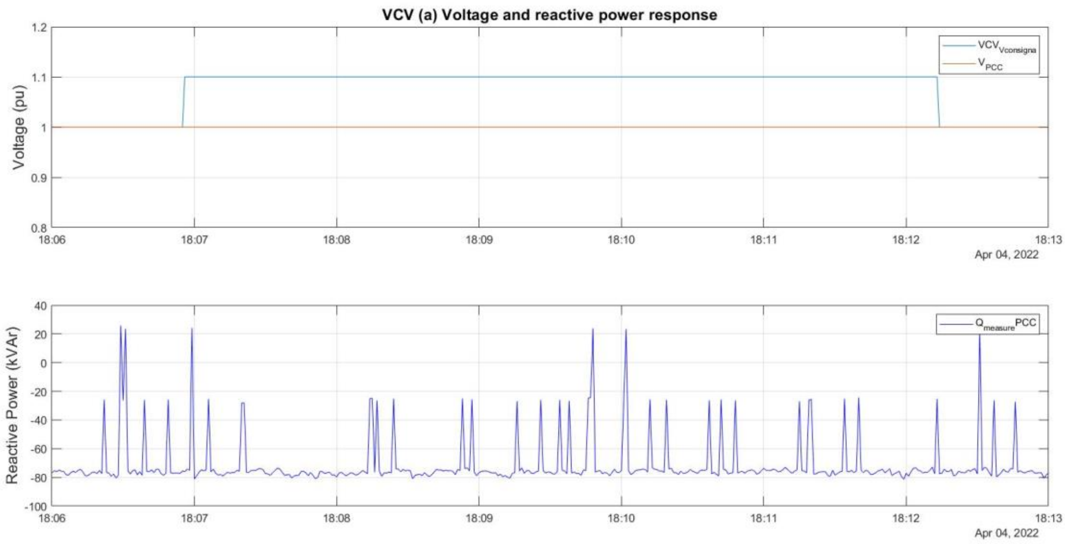

Figure 50: VCV (a) voltage and reactive power at PCC

On one hand, since VCV status is deactivated, no action due to voltage change is taken.

Therefore, this test passes the acceptance criteria.

VCV (b):

In this test, following the methodology and with verified pre-test conditions, the signals measured at PCC during 6 minutes with a sampling rate of 1 second are shown in Figure 51:

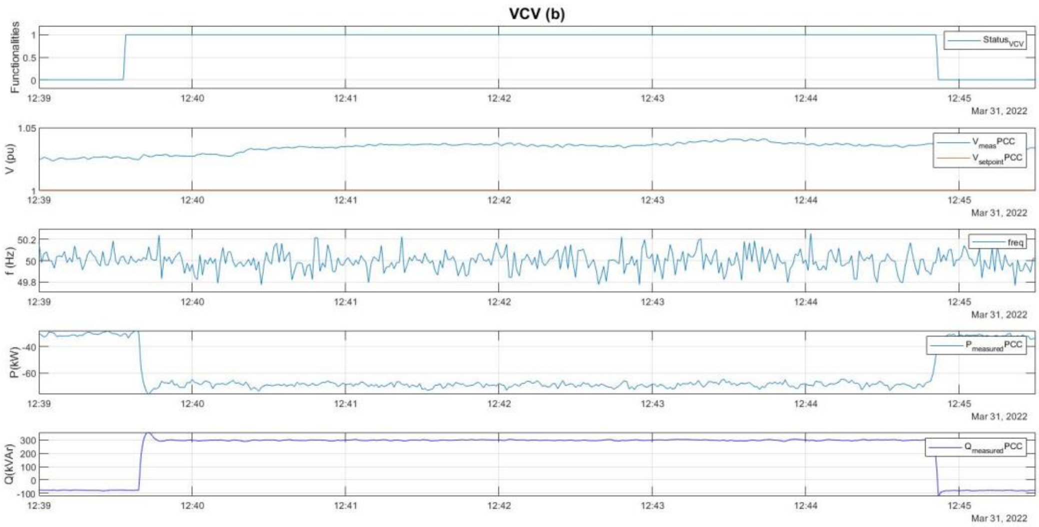

Figure 51: VCV (b) signals measured at PCC

Reactive power response at PCC, reference signals and acceptance limits are indicated in Figure 52.

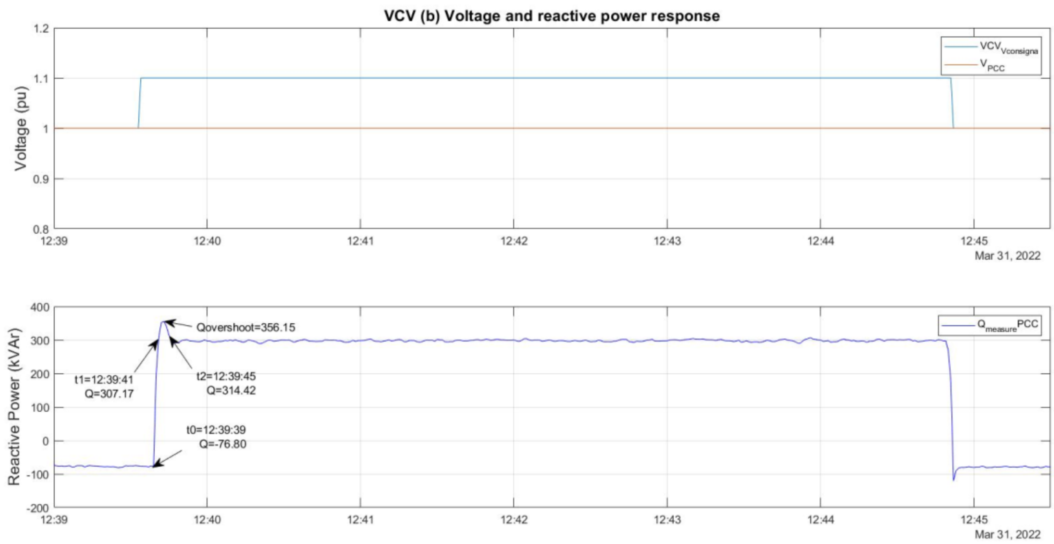

Figure 52: VCV (b) voltage and reactive power at PCC

For an increased voltage reference (1.1 pu) the MCFS is able to increase its reactive power injection to the grid achieving the reference set point within the set-point-range (5% error).The total Q required at PCC set-point turns into Q_{PCC}=300kVAr. Rise time is given by t_1-t_0 and settling time is given by t_2-t_0. As acceptance criteria is reported in Table 41, t_r and overshoot limits are accomplished, but not t_e requirement for the provision of this reactive power response during VCV (b) test.

VCV (c):

In this test, following the methodology and with verified pre-test conditions, between which a 75 kV/min voltage ramp is defined, the signals measured at PCC during 6 minutes with a sampling rate of 1 second are shown in Figure 53:

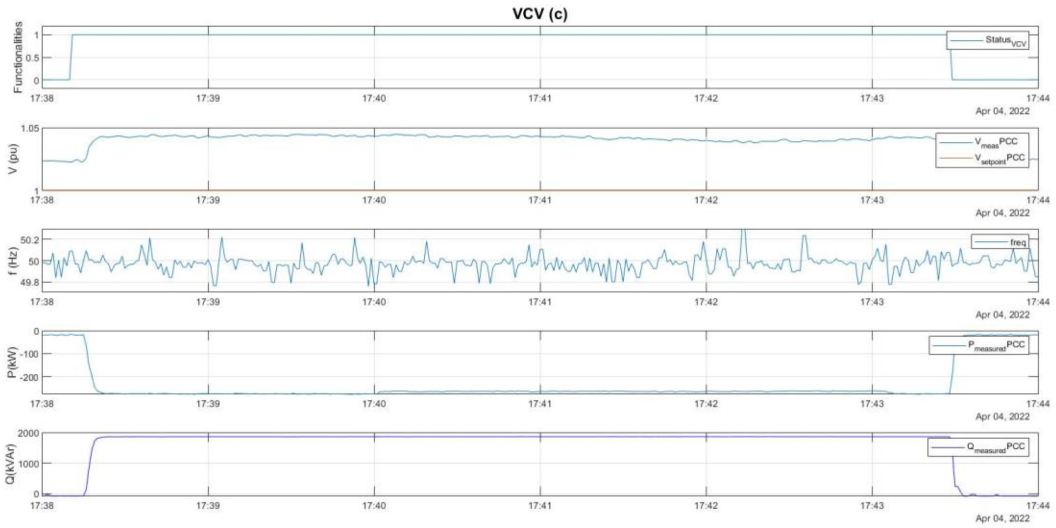

Figure 53: VCV (c) signals measured at PCC

Reactive power response at PCC, reference signals and acceptance limits are indicated in Figure 54:

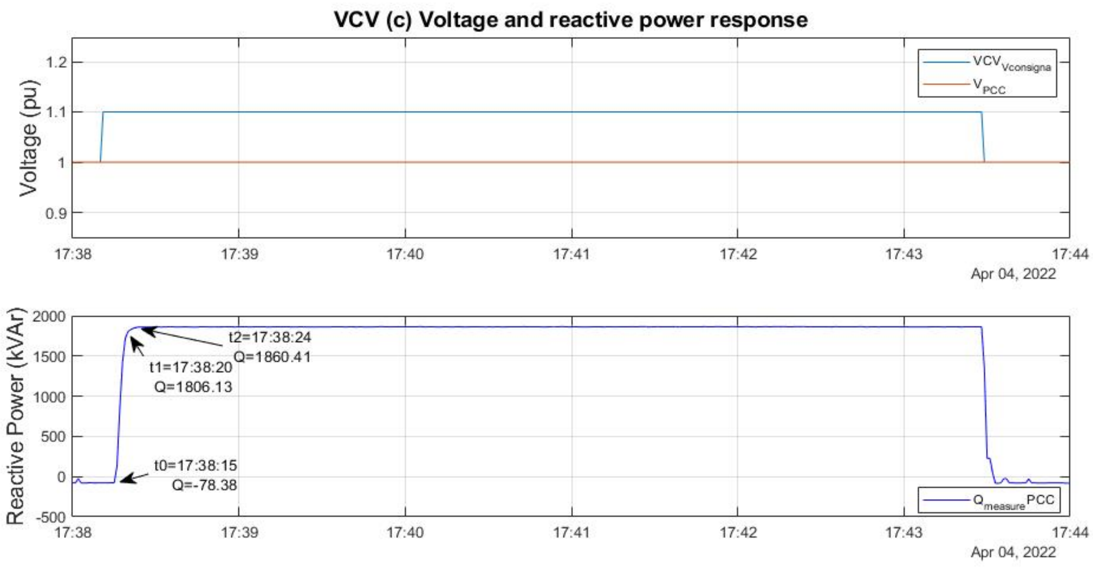

Figure 54: VCV (c) voltage and reactive power at PCC

For an increased voltage reference (1.1 pu) the MCFS is able to increase its reactive power injection to the grid achieving the reference set point within the set-point-range (5% error). The total Q required at PCC set-point turns into Q_{PCC}=2000kVAr, but the maximum reactive power measured at PCC is 1867kVAr due to inductive effect introduced by transformers and wirings of the installation.

VCV (d):

Following the methodology and with verified pre-test conditions, the signals measured at PCC during 6 minutes with a sampling rate of 1 second are shown in Figure 55:

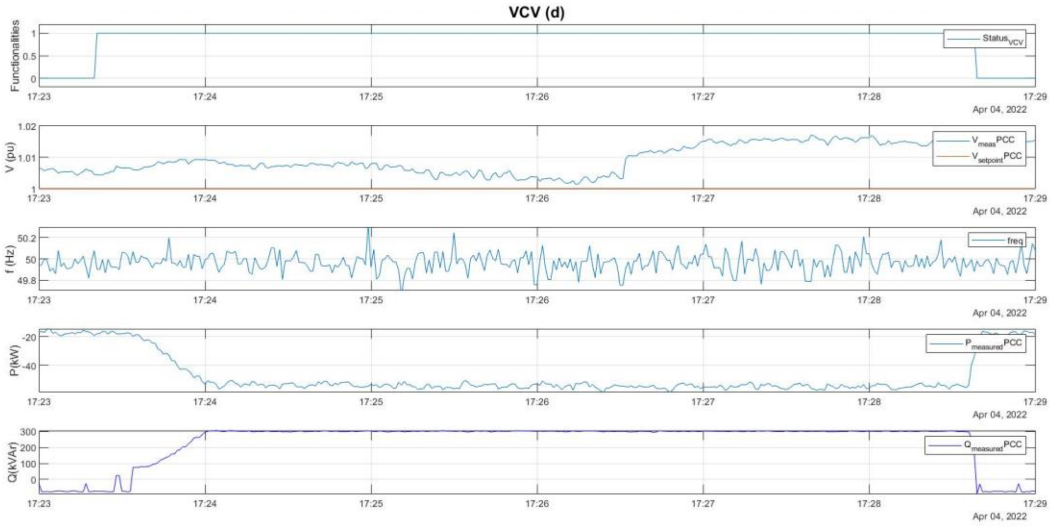

Figure 55: VCV (d) signals measured at PCC

Reactive power response at PCC, reference signals and acceptance limits are indicated in Figure 56.

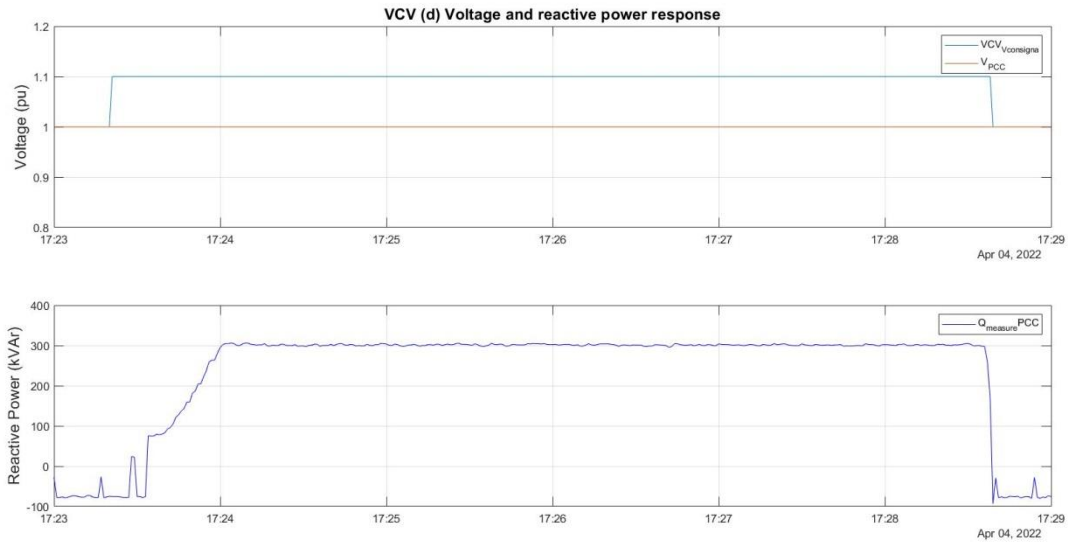

Figure 56: VCV (d) voltage and reactive power at PCC

For an increased voltage reference (1.1 pu) the MCFS is able to increase its reactive power injection to the grid achieving the reference set point. In this test, a voltage ramp of 2kV/min is defined and then the reactive power setpoint is also ramped. The total Q required at PCC set-point turns into Q_{PCC}=300kVAr and it is accomplished.

VCV (e):

In this test, following the methodology and with verified pre-test conditions, the signals measured at PCC during 7 minutes with a sampling rate of 1 second are shown in Figure 57:

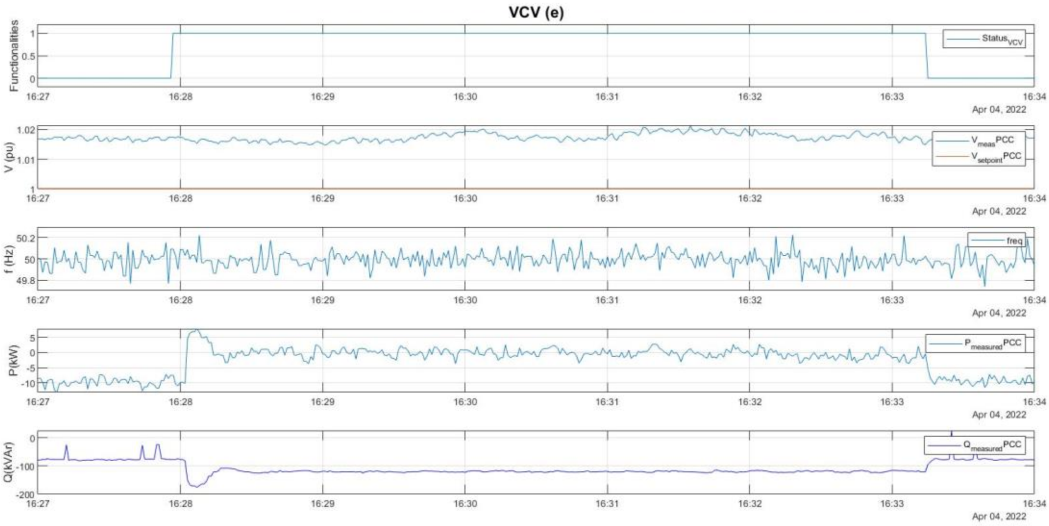

Figure 57: VCV (e) signals measured at PCC

Reactive power response at PCC, reference signals and acceptance limits are indicated in Figure 58.

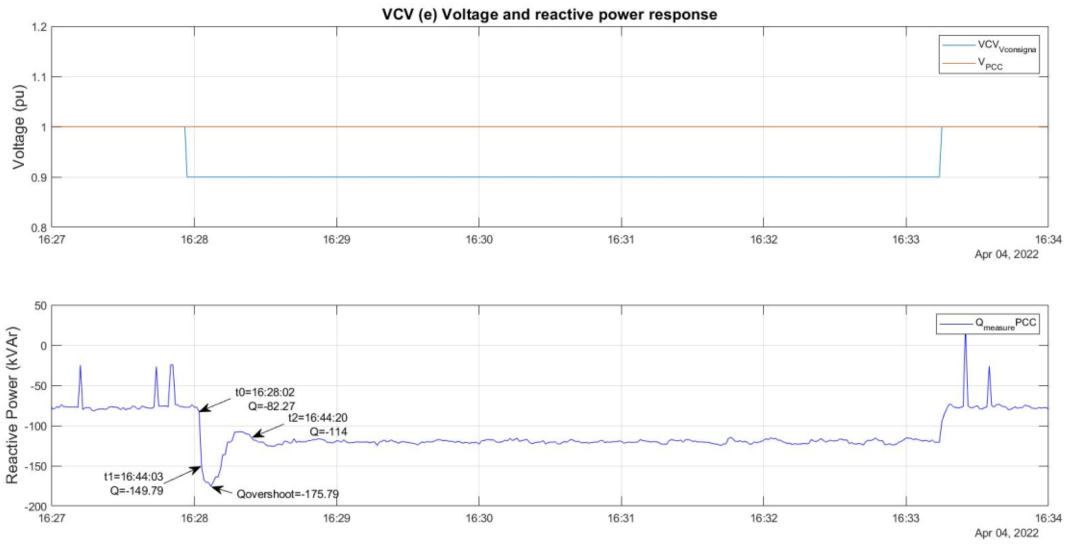

Figure 58: VCV (e) voltage and reactive power at PCC

For a decreased voltage reference (0.9 pu) the MCFS is able to decrease its reactive power injection to the grid achieving the reference set point within the set-point-range (5% error).The total Q required at PCC set-point turns into Q_{PCC}=-120kVAr. Rise time is given by

t_1-t_0 and settling time is given by t_2-t_0. As in Table 41, t_r limit is accomplished, but neither t_e nor overshoot requirement are fulfilled.

VCV (f):

In this test, following the methodology and with verified pre-test conditions, the signals measured at PCC during 7 minutes with a sampling rate of 1 second are shown in Figure 59:

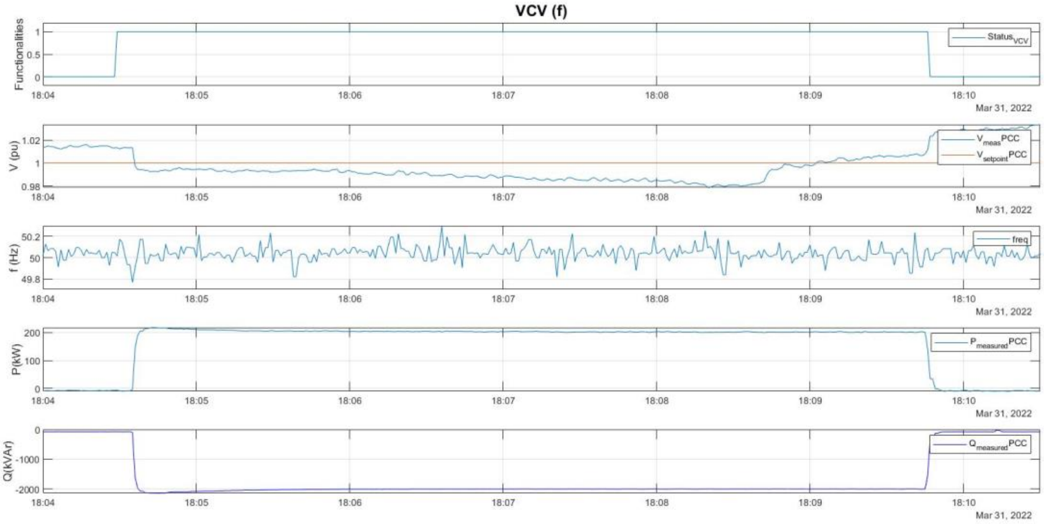

Figure 59: VCV (f) signals measured at PCC

Reactive power response at PCC, reference signals and acceptance limits are indicated in Figure 60.

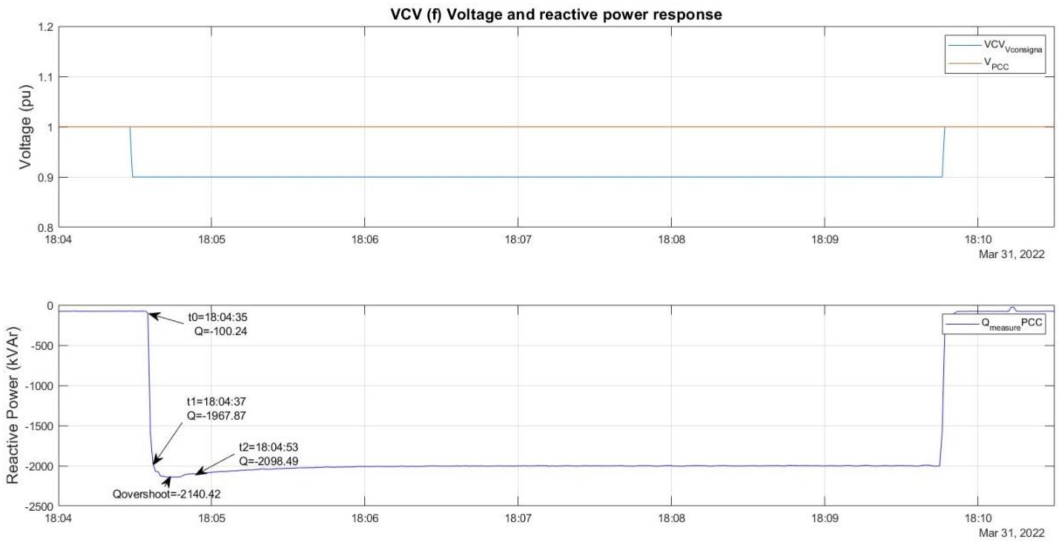

Figure 60: VCV (f) voltage and reactive power at PCC

For a decreased voltage reference (0.9 pu) the MCFS is able to decrease its reactive power injection to the grid achieving the reference set point within the set-point-range (5% error).The total Q required at PCC set-point turns into Q_{PCC}=-2000kVAr. Rise time is given by

t_1-t_0 and settling time is given by t_2-t_0. As in Table 41, t_r and overshoot limits are accomplished, but not t_e requirement.

VCV (g):

In this test, VCV is classified as 2nd level functionality and it is controlled by the MC. Following the methodology and with verified pre-test conditions, the signals measured at PCC during 7 minutes with a sampling rate of 1 second are shown in Figure 61:.

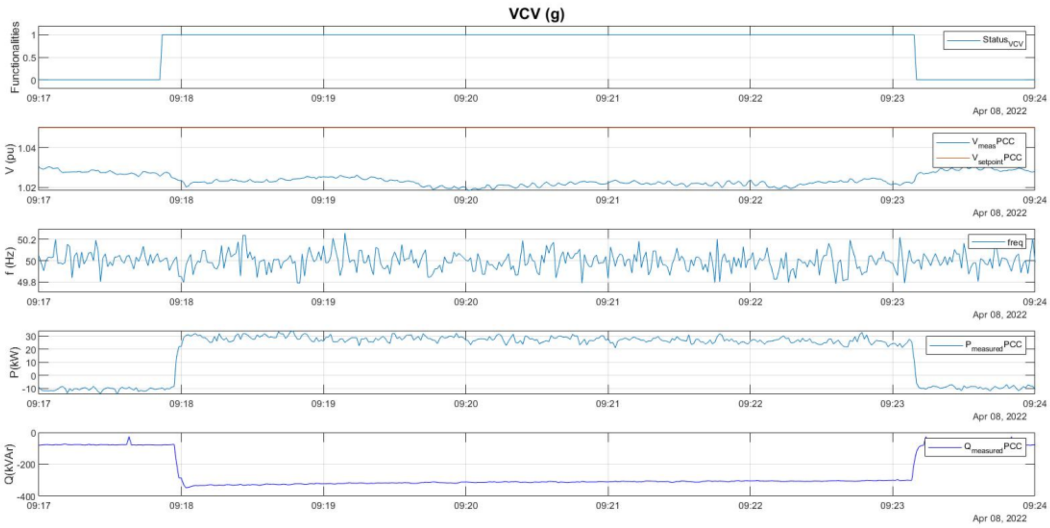

Figure 61: VCV (g) signals measured at PCC

Reactive power response at PCC, reference signals and acceptance limits are indicated in Figure 62.

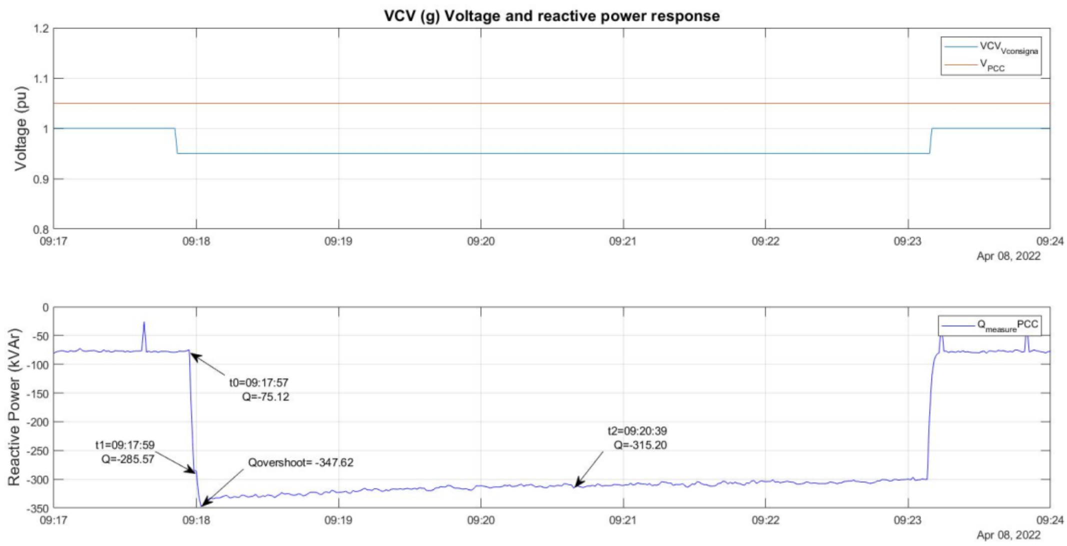

Figure 62: VCV (g) voltage and reactive power at PCC

For an increased voltage reference (1.05 pu) and Vsetpoint of 0.95 pu, the MCFS is able to decrease its reactive power injection to the grid achieving the reference set point within the set-point-range (5% error). The total Q required at PCC set-point turns into Q_{PCC}=-300kVAr.

Rise time is given by t_1-t_0 and settling time is given by t_2-t_0. As indicates Table 41, t_r and overshoot limits are accomplished, but not t_e requirement.

VCV (h):

In this test, following the methodology and with verified pre-test conditions, the signals measured at PCC during 7 minutes with a sampling rate of 1 second are shown in Figure 63:.

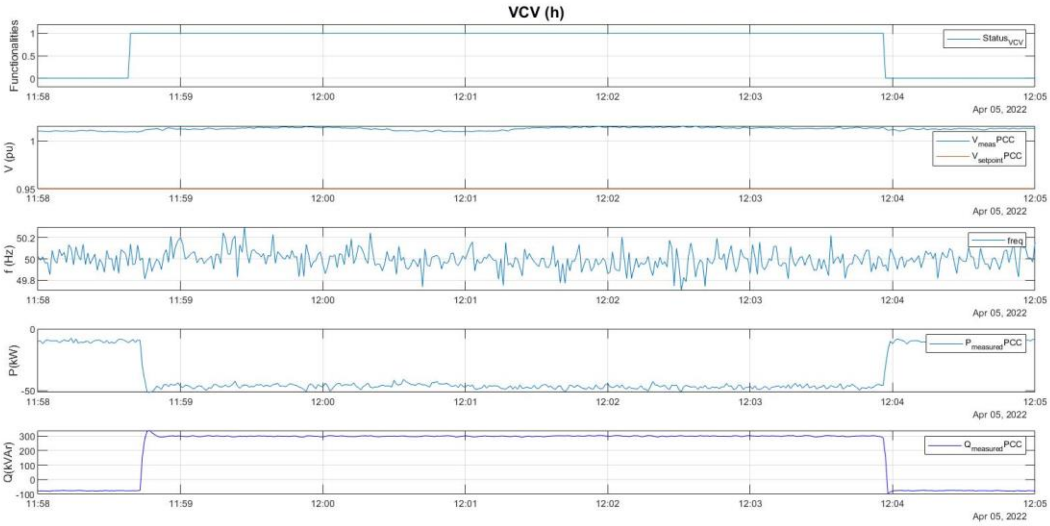

Figure 63: VCV (h) signals measured at PCC

Reactive power response at PCC, reference voltage signals and measurements are indicated in Figure 64.

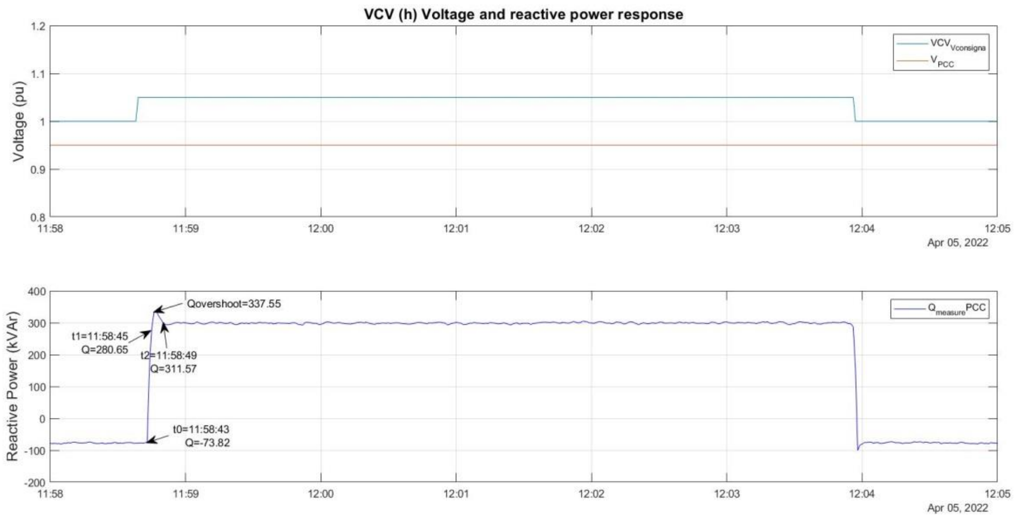

Figure 64: VCV (h) voltage and reactive power at PCC

For a decreased voltage reference (0.95 pu) and Vsetpoint of 1.05 pu, the MCFS is able to decrease its reactive power injection to the grid achieving the reference set point within the set-point-range (5% error). The total Q required at PCC set-point turns into Q_{PCC}=300kVAr.

Rise time is given by t_1-t_0 and settling time is given by t_2-t_0. As indicates Table 41, t_r and overshoot limits are accomplished, but not the t_e requirement.

Summary for VCV tests:

To sum up, the fulfilment of the acceptance criteria for VCV tests is shown in Table 41.

	Test condition	Test condition value	Test value	Acceptance
VCV (b)	tr (s)	2	2	✓
	te (s)	5	6	x
	overshoot	1.2	1.18	✓
VCV (c)	tr (s)	2	5	x
	te (s)	5	2	✓
	overshoot	1.2	0	✓
VCV (d)	Follow V-set-point	Q_{PCC}=300kVAr	Q_{PCC}=300kVAr	✓
VCV (e)	tr (s)	2	1	✓
	te (s)	5	18	x
	overshoot	1.2	1.46	x
VCV (f)	tr (s)	2	2	✓
	te (s)	5	18	x
	overshoot	1.2	1.07	✓
VCV (g)	tr (s)	2	2	✓
	te (s)	5	162	x
	overshoot	1.2	1.15	✓
VCV (h)	tr (s)	2	2	✓
	te (s)	5	6	x
	overshoot	1.2	1.12	✓

Table 41 Acceptance criteria for VCV

4.4.3. Voltage Control based on Reactive Power Setpoint (VCQ)

In the VCQ functionality, the HFD must provide control on the voltage of the controlled node, in response to the reactive power setpoint. So as to validate this functionality, different reactive power setpoint values and control configurations have been tested.

4.4.3.1. Test conditions definition

Purpose

Set several reactive power instructions to verify the correct response of the control.

Pre-test conditions

- Table 3Pre-test conditions and parameters for the test:F_PPC = 50 Hz
- V_PPC = 1 p.u.
- t_pre=10s
- Level-1 functionalities disabled
- Level-2 functionalities disabled except VCQ
- Level-3 functionalities disabled

Methodology

The device that takes part along VCQ tests is the HFD.

Modify the reactive setpoint for different control parameters. The next parameters must be set:

- VCQ_Q_LimMAX = Q_MCFS (capacitive)
- VCQ_Q_LimMIN = Q_MCFS (inductive)
- VCQ_VMAX = 1,05 pu
- VCQ_VMIN = 0,95 pu
- VCQ_tr= 5 s
- VCQ_te=10 s
- VCQ_Qos= 1,2 pu
- VCQ_tol= 0.05 pu

The control will be validated for different reactive setpoints, both capacitive and inductive, with and without ramp in the setpoint, according to Table 42.

	VCQ_Status	VCQ_Qconsigna	VCQ_RAMP	VCQ_RAMP_Status
VCQ (a)	0	+Q_MCFS (capacitive)	2 MVAr/min	0
VCQ (b)	1	+Q_ MCFS (capacitive)	2 MVAr/min	0
VCQ (c)	1	+0,5*Q_ MCFS (capacitive)	2 MVAr/min	0
VCQ (d)	1	-Q_ MCFS (inductive)	2 MVAr/min	0
VCQ (e)	1	-Q_ MCFS (inductive)	-5 MVAr/min	1

Table 42 Control Parameters profile for VCQ

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its Q according to the setpoint and control parameters.

4.4.3.2. Test results

<u>VCQ (a):</u>

Following the methodology and with verified pre-test conditions, the signals measured at PCC during 7 minutes with a sampling rate of 1 second are shown in Figure 65:

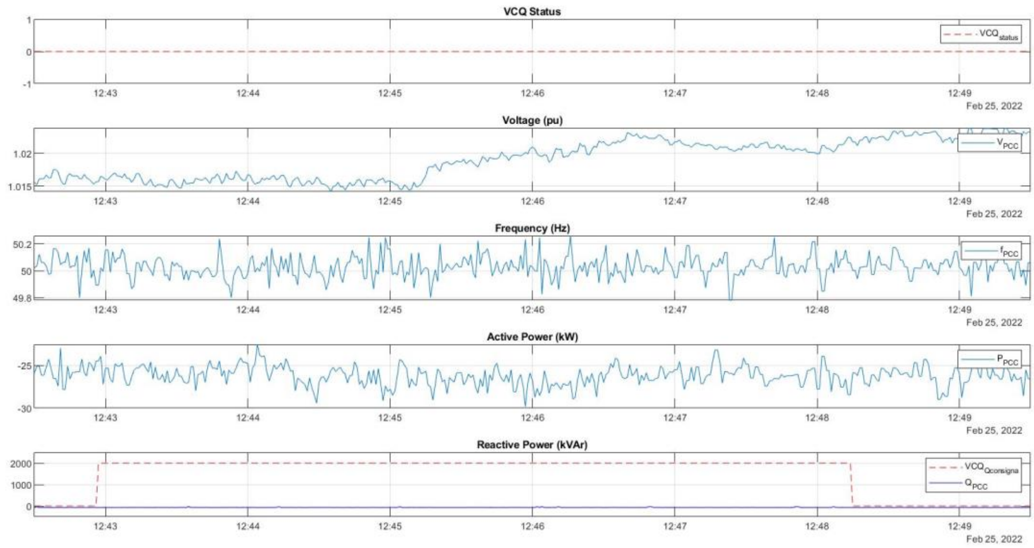

Figure 65: VCQ (a) signals measured at PCC

Since VCQ status is deactivated, no action due to reactive power setpoint is taken. Thus, an acceptance criterion is accomplished.

VCQ (b):

Signals measured at PCC during this test VCQ (b) are shown in Figure 66.

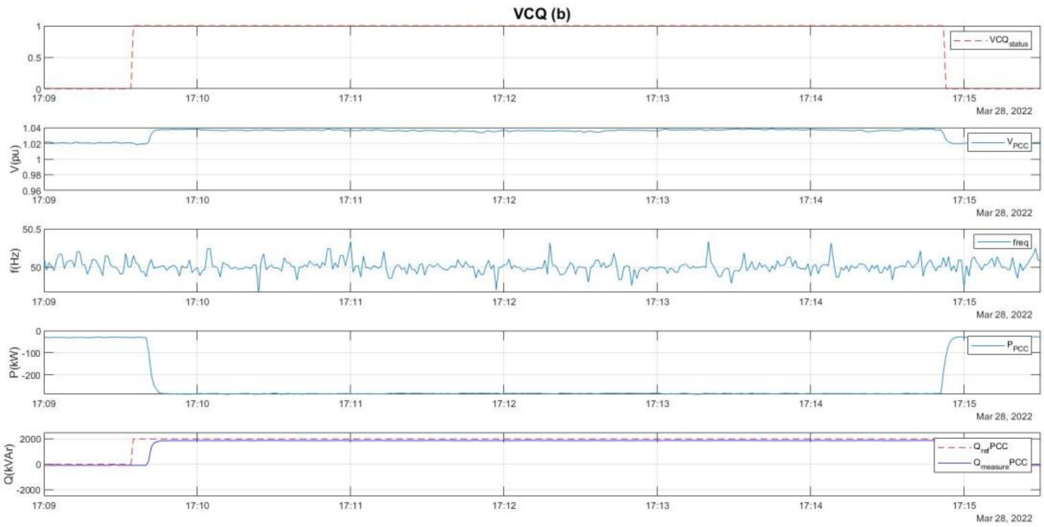

Figure 66: VCQ (b) signals measured at PCC

Reactive power response at PCC is presented in accordance with voltage response at PCC in Figure 67.

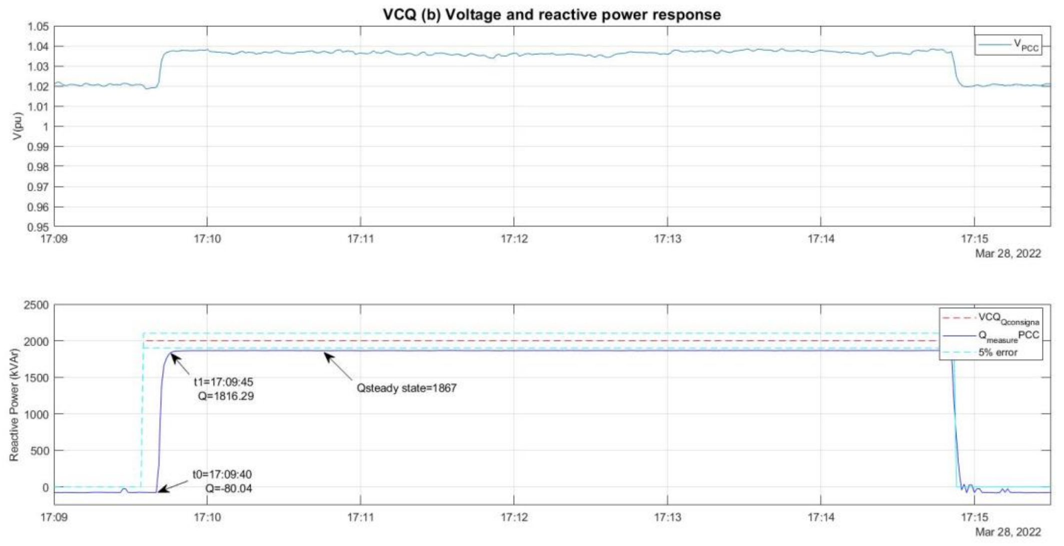

Figure 67: VCQ (b) voltage and reactive power at PCC

The reactive power setpoint at PCC is 2000kVAr, but the maximum reactive power measured at PCC is 1867kVAr due to inductive effect introduced by transformers and wirings of the installation.

The response profile of reactive power at PCC is partially fulfilled due to the mentioned inductance effect. To sum up, the response control point measured are reported in Table 43.

<u>VCQ (c):</u>

Signals measured at PCC:

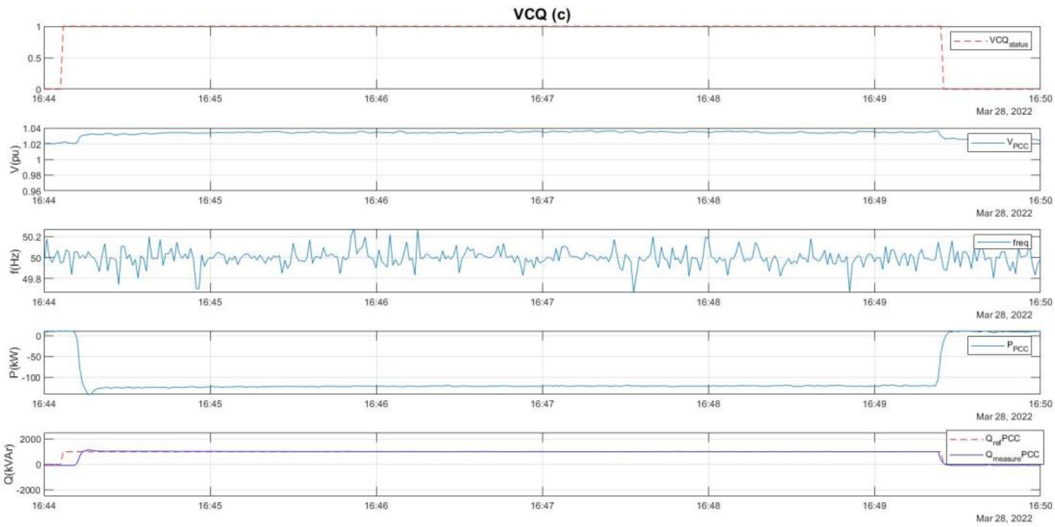

Figure 68: VCQ (c) signals measured at PCC

Reactive power response at PCC is shown in Figure 69.

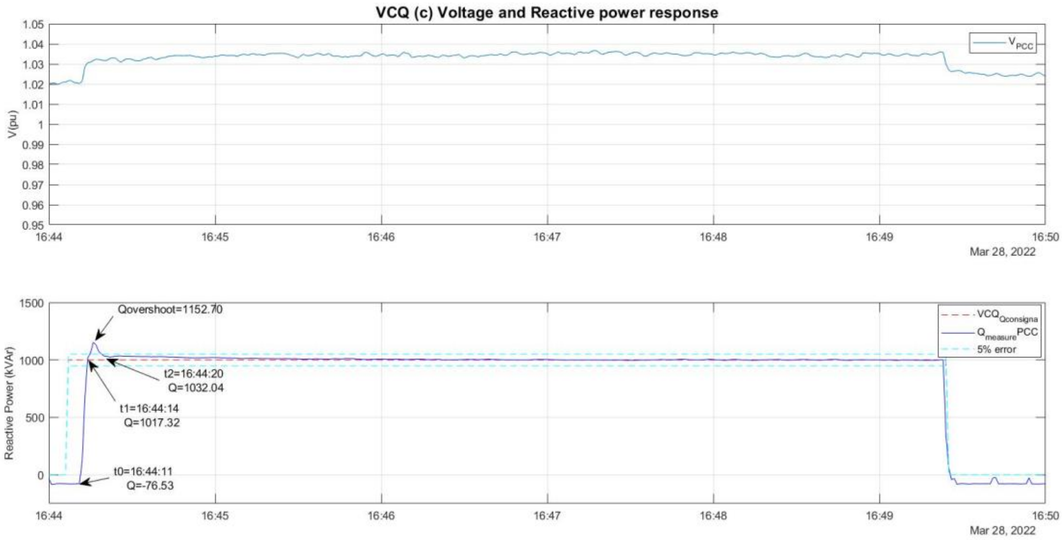

Figure 69: VCQ (c) voltage and reactive power at PCC

The reactive power setpoint at PCC is 1000kVAr and the measured response at PCC follows that setpoint, therefore the response fulfils with the requested time response, summarized in Table 38Table 43.

<u>VCQ (d):</u>

Signals measured at PCC for 6 minutes test attending to pre-test conditions and test methodology defined for VCQ (d) test are presented in Figure 70.

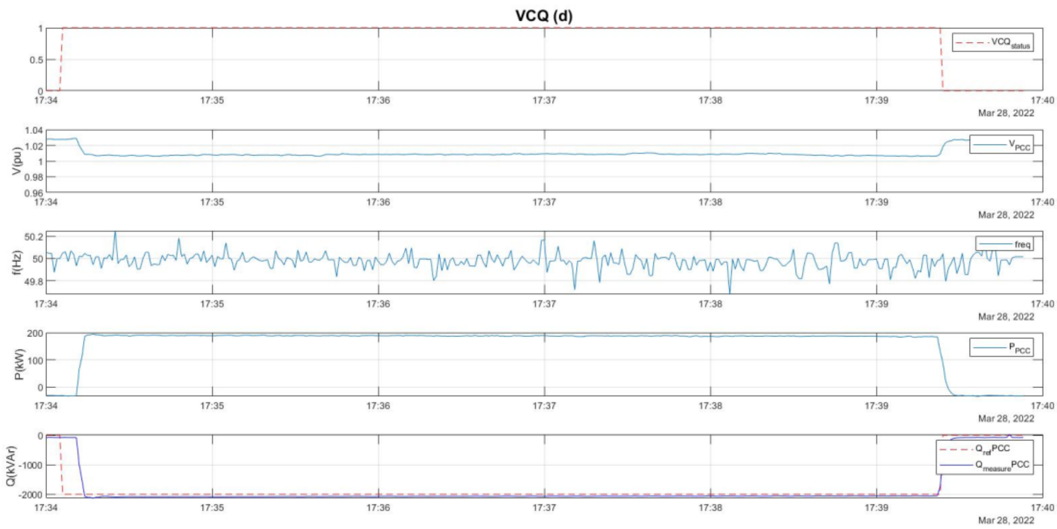

Figure 70: VCQ (d) signals measured at PCC

Reactive power response measured at PCC according to reference is given in Figure 71, as well as voltage at PCC.

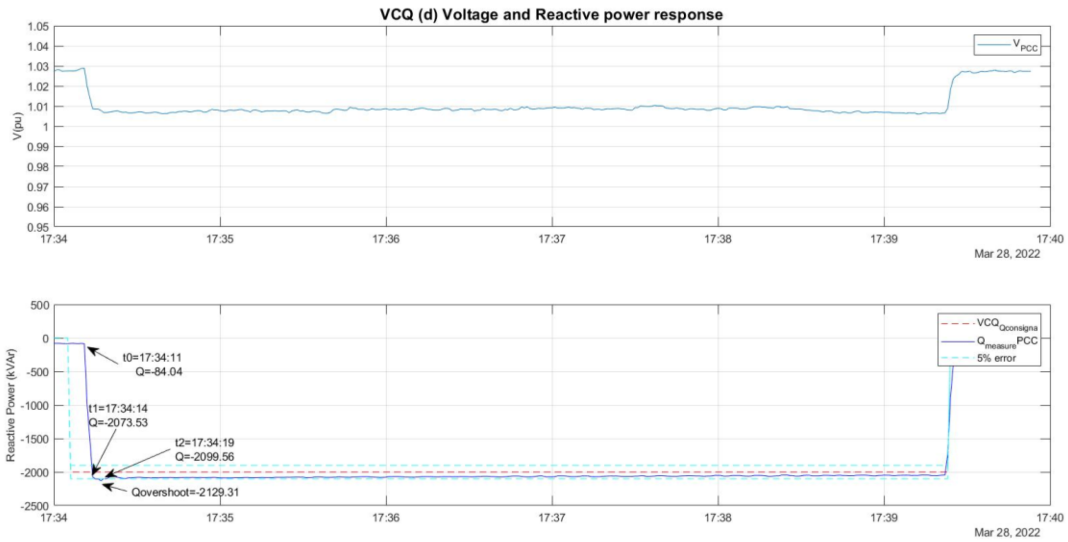

Figure 71: VCQ (d) voltage and reactive power at PCC

The reactive power setpoint at PCC is -2000kVAr and it can be seen that the measured response at PCC follow that setpoint, therefore the response perfectly complies with the requested time response.

VCQ (e):

Signals measured at PCC for 6 minutes test attending to pre-test conditions and test methodology defined for VCQ (d) test are presented in Figure 72.

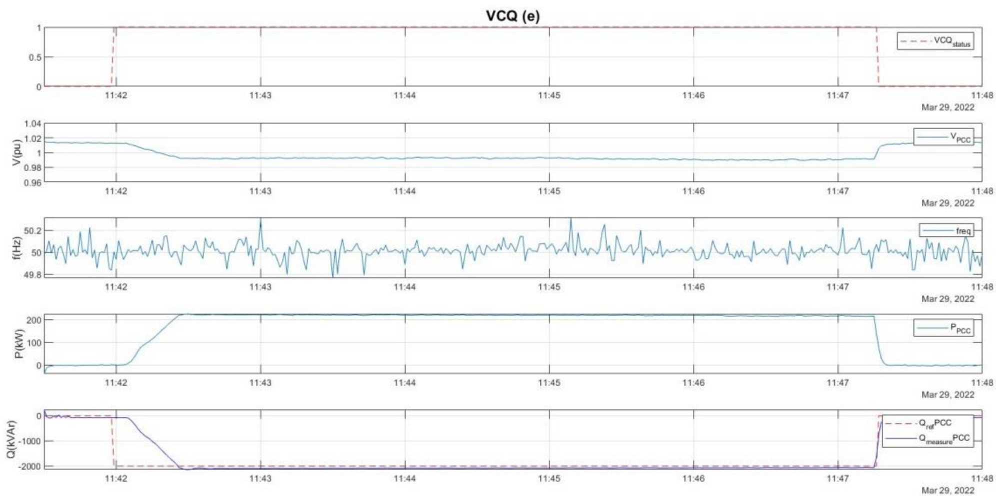

Figure 72: VCQ (e) signals measured at PCC

Reactive power response measured at PCC according to reference is given in Figure 73, as well as voltage at PCC.

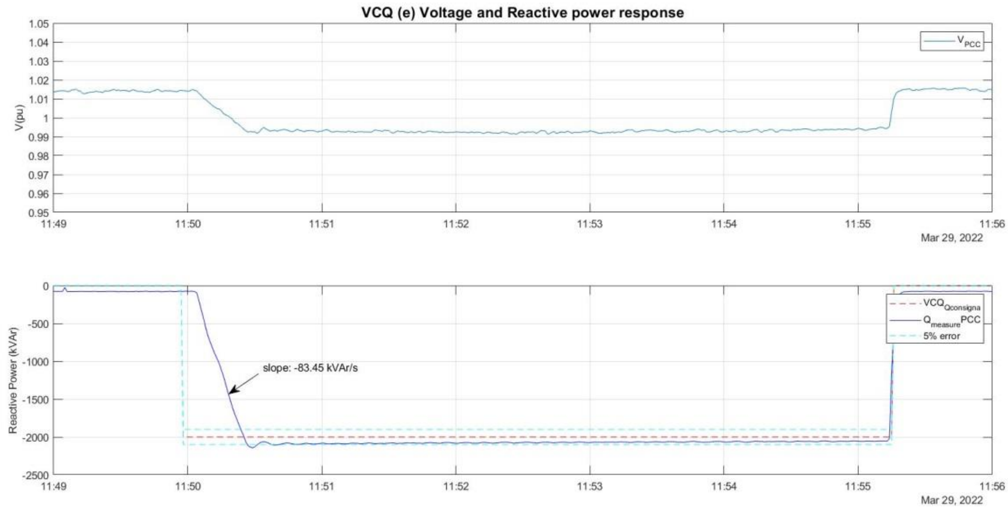

Figure 73: VCQ (e) voltage and reactive power at PCC

The reactive power setpoint at PCC is -2000kVAr reached following a ramp of -5MVAr/min. The measured response at PCC follows that ramped setpoint and the measured ramp at PCC results in -5 MVAr (-83.45 kVAr/s). Therefore, the acceptance criteria are fulfilled.

<u>Summary for VCQ tests:</u>

The test conditions are verified and thus acceptance criteria for VCQ tests results are summarized in Table 43.

	Test condition	Test condition value	Test value	Acceptance
VCQ (a)	Not follow Q-set-point	2000kVAr	0 kVAr	✓
VCQ (b)	tr (s)	5	5	✓
	te (s)	10	-	✓
	overshoot	1.2	1.18	✓
VCQ (c)	tr (s)	5	3	✓
	te (s)	10	9	✓
	overshoot	1.2	1.15	✓
VCQ (d)	tr (s)	5	3	✓
	te (s)	10	8	✓
	overshoot	1.2	1.06	✓
VCQ (e)	Follow Q-set-point	-2000kVAr	-2000kVAr	✓

Table 43 Acceptance criteria for VCQ tests

4.5. Level-3 functionalities

Level-3 functionalities are in charge of delivering reference values for different devices and controllers according to a program or as a response to system variables. These are high-level functionalities that enable the TSO to develop operation strategies, so they are implemented in the MC. In this section, the results obtained from the tests related to level-3 functionalities are shown.

Content of this section follows the same structure as defined in previous for Level-2 functionalities results. Nomenclature of parameters and variables is also defined in Table 71.

4.5.1. Setpoint Tracking (SPT-1)

In this functionality, the charge/discharge process of the different flexibility devices that constitute the MCFS, can be managed by a setpoint signal. The setpoint may be changed continuously.

4.5.1.1. Test conditions definition

Purpose

The main goal of this test is to verify that the system does not react to variations of active power setpoint when SPT_Status is deactivated.

Pre-test conditions

Pre-test conditions and parameters for the test:

- Table 3Setpoint tracking deactivated (SPT_Status = 0).
- SPT_P_Setpoint(1)= 10kW.
- SPT_P_Setpoint(2)= 20kW.
- Level-1 functionalities disabled
- Level-2 functionalities disabled
- Level-3 functionalities disabled except SPT
- F_PPC = 50 Hz
- V_PPC = 1 p.u.
- Lp= 0%
- Le = 0%
- Eta = 0 MWh
- SOCinicial = 50%
- SPT_RampUp = 2 MW/min
- SPT_RampDown = 2 MW/min

Methodology

The devices that take part along SPT-1 test are HFD, lead-acid battery and lithium-ion from ATENEA microgrid.

The main action performed is to track the active power setpoint for different control parameters.

For each test, the active power setpoint variation must be set as two consecutive changes with one minute apart according to Table 44.

	SPT_Status	SPT_P_setpoint	SPT_tr
SPT-1 (a)	0	[SPT_P_Setpoint(1), SPT_P_Setpoint(2), SPT_P_Setpoint(1)]	1
SPT-1 (b)	1	[SPT_P_Setpoint(1), SPT_P_Setpoint(2), SPT_P_Setpoint(1)]	1
SPT-1 (c)	1	[SPT_P_Setpoint(1), 0]	1

Table 44 P setpoint for SPT-1

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its active power response according to the active power setpoint variation and control parameters.

4.5.1.2. Test results

The SPT-1 is classified as a 3rd level functionality, which is controlled by the MC. Following the methodology, the signals measured at PCC during 8 minutes with a sampling rate of 1 second are shown in Figure 74.

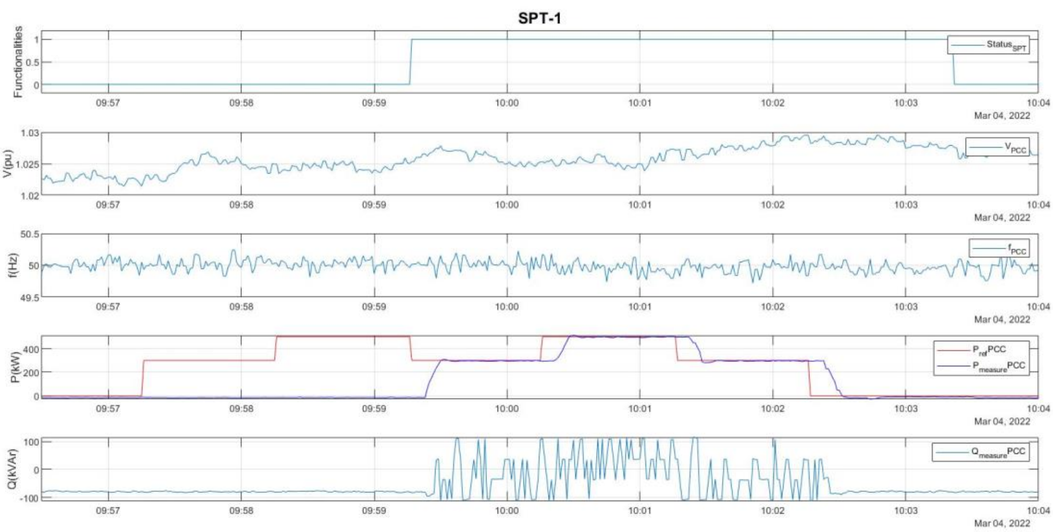

Figure 74: SPT-1 signals measured at PCC

Active power response at PCC, reference signals and SOC of the MCFS are indicated in Figure 75.

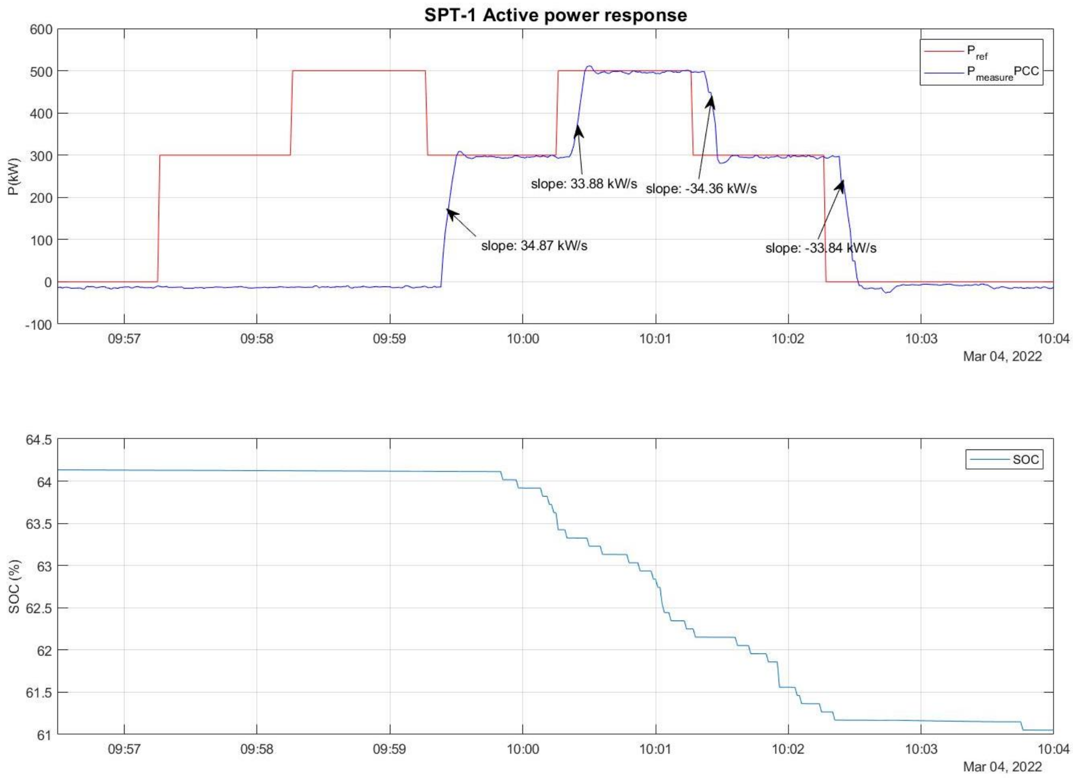

Figure 75: SPT-1 active power at PCC and SOC

At first, when SPT status is deactivated, no action due to active power setpoint is taken. Later, when SPT status is activated the active power setpoint is achieved.

Besides, the setpoint changes are achieved and established in less than one minute with the dedicated active power ramp up and down and the measurements at PCC are the following ones:

- The ramp up of the first change measured at PCC is 2.09MW/min (34.87kW/s).
- The ramp up of the second change measured at PCC is 2.03MW/min (33.88kW/s).
- The ramp down of the third change measured at PCC is -2.06MW/min (-34.36kW/s).
- The ramp down of the fourth change measured at PCC is -2.09MW/min (-33.84kW/s).

Therefore, this test passes the acceptance criteria.

4.5.2. Setpoint Tracking (SPT-2)

In this functionality, the charge/discharge process of the different flexibility devices that constitute the MCFS, can be managed by a setpoint signal. The setpoint may be changed continuously.

4.5.2.1. Test conditions definition

Purpose

Evaluate the active power response with respect to variations of active power setpoint according to the parameter SPT_tr settings.

Pre-test conditions

Pre-test conditions and parameters for the test:

- Setpoint tracking activated (SPT_Status = 1).
- SPT_P_Setpoint(1)=0 MW (SPT-2 (a))
- SPT_P_Setpoint(2)= -200 kW
- SPT_P_Setpoint(3)= 200 kW
- Level-1 functionalities disabled
- Level-2 functionalities disabled
- Level-3 functionalities disabled except SPT
- F_PPC = 50 Hz
- V_PPC = 1 p.u.
- Lp= 0%
- Le = 0%
- Eta = 0 MWh
- SOCinicial = 50%
- SPT_RampUp = 2 MW/min
- SPT_RampDown= 2 MW/min

Methodology

The devices that take part along SPT-2 test are HFD, lead-acid battery and lithium-ion from ATENEA microgrid.

The main action performed is to track the active power setpoint for different control parameters.

For each test, the active power setpoint variation must be set according to the next Table 45.

	SPT_P_setpoint	Minutes apart between changes	SPT_tr
SPT-2 (a)	[SPT_P_Setpoint(1), SPT_P_Setpoint(2), SPT_P_Setpoint(3), SPT_P_Setpoint(2)]	1	1
SPT-2 (b)	[SPT_P_Setpoint(3), SPT_P_Setpoint(2)]	1	5
SPT-2 (c)	[SPT_P_Setpoint(3), SPT_P_Setpoint(2), SPT_P_Setpoint(1)]	10	30

Table 45: P setpoints for SPT-2

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its active power response according to the active power setpoint variation and control parameters and must ignore setpoint changes that occur between two consecutive evaluation periods. The new setpoint must be reached within 1 minute.

4.5.2.2. Test results

The SPT is classified as a 3rd level functionality, which is controlled by the MC. Following the methodology, the signals measured at PCC during 70 minutes (SPT-2(a), SPT-2(b) and SPT-2(c) are performed in an orderly manner one after the other) with a sampling rate of 1 second are shown in Figure 76

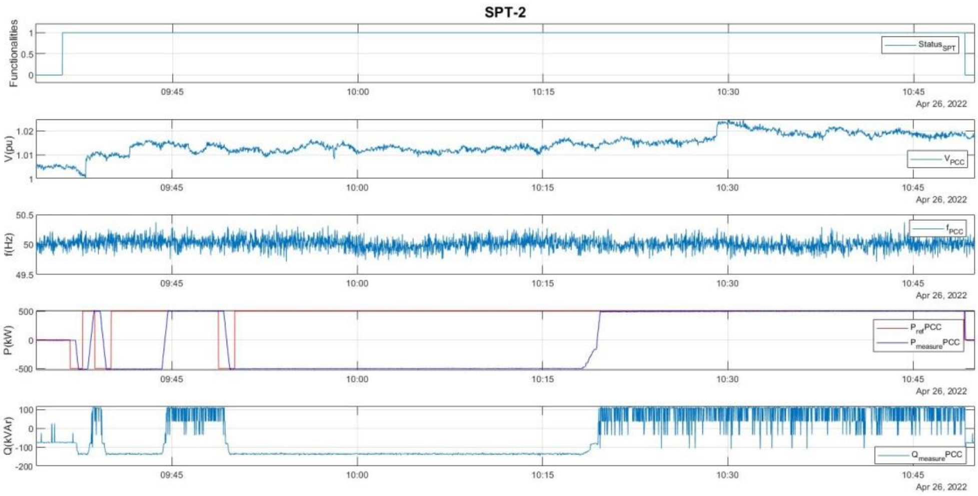

Figure 76: SPT-2 signals measured at PCC

In this test, the active power setpoints are defined at different time. Active power response at PCC, reference signals and SOC of the MCFS are indicated in Figure.

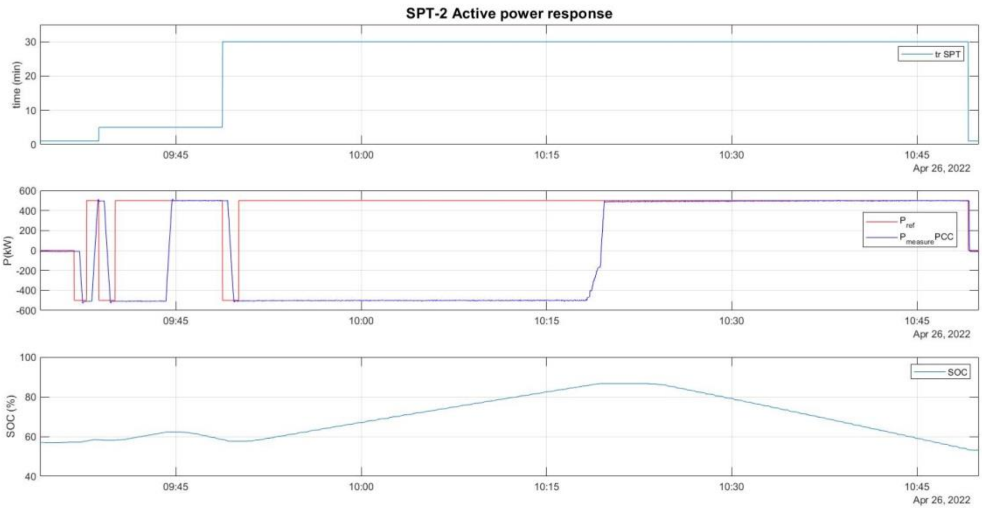

Figure 77: SPT-2 active power at PCC and SOC

The setpoint changes are achieved according to the configured value of SPT_tr variable, ignoring the setpoint changes introduced before the specified time defined in SPT_tr concludes.

As Figure 77shows, the response at PCC is fulfilled and follows the different setpoint changes according to the indicated evaluation time periods. That provides duration of each interval:

1. 0kW for 1 minute
2. -500kW for 1 minute
3. 500kW for 1 minute
4. -500kW for 5 minutes
5. 500kW for 5 minutes
6. -500kW for 30 minutes
7. 500kW for 30 minutes

All the transitions between changes are ramped and their rate of change is 2MW/min for the ramp_up case and –2MW/min for the ramp_down case. However, the transition from change 6 to 7 is not achieved in the first moments. This performance is explained by the SOC level since it was reaching its maximum value and the charging capacity is curtailed by the devices.

As a result, this test passes the acceptance criteria.

4.5.3. Setpoint Tracking (SPT-3)

In this functionality, the charge/discharge process of the different flexibility devices that constitute the MCFS, can be managed by a setpoint signal. The setpoint may be changed continuously.

4.5.3.1. Test conditions definition

Purpose

Evaluate the ramp (up and down) values and the time rate response limits of active power response with respect to variations of active power setpoint and ramp values.

Pre-test conditions

Pre-test conditions and parameters for the test:

- Table 3Setpoint tracking activated (SPT_Status = 1).
- Level-1 functionalities disabled
- Level-2 functionalities disabled
- Level-3 functionalities disabled except SPT
- F_PPC = 50 Hz
- V_PPC = 1 p.u.
- Lp= 0%
- Le = 0%
- Eta = 0 MWh
- SOCinicial = 50%
- SPT_P_Setpoint(1)= 2 MW

- SPT_tr = 1

Methodology

The devices that take part along SPT-3 test are HFD, lead-acid battery and lithium-ion from ATENEA microgrid.

The main action performed is to track the active power setpoint for different control parameters.

- SPT_P_Setpoint(2)= - SPT_P_Setpoint(1)

For each test, the active power setpoint variation must be set as two consecutive changes with one minute apart according to Table 46.

	SPT_P_setpoint	SPT_RampUp	SPT_RampDown	Minutes apart between changes
SPT-2 (a)	[SPT_P_Setpoint(1), SPT_P_Setpoint(2), SPT_P_Setpoint(1)]	0.1 MW/min	0.1 MW/min	23.33
SPT-2 (b)	[SPT_P_Setpoint(1), SPT_P_Setpoint(2), SPT_P_Setpoint(1)]	4 MW/min	4 MW/min	3.16
SPT-2 (c)	[SPT_P_Setpoint(1), SPT_P_Setpoint(2)]	100 MW/min	100 MW/min	1.93

Table 46 P setpoints for SPT-3

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its active power response according to the active power setpoint, ramp and control parameters.

4.5.3.2. Test results

The SPT is classified as a 3rd level functionality, which is controlled by the MC. Following the methodology, the signals measured at PCC during 70 minutes (SPT-2(a), SPT-2(b) and SPT-2(c) are performed in an orderly manner one after the other) with a sampling rate of 1 second are shown in Figure 78.

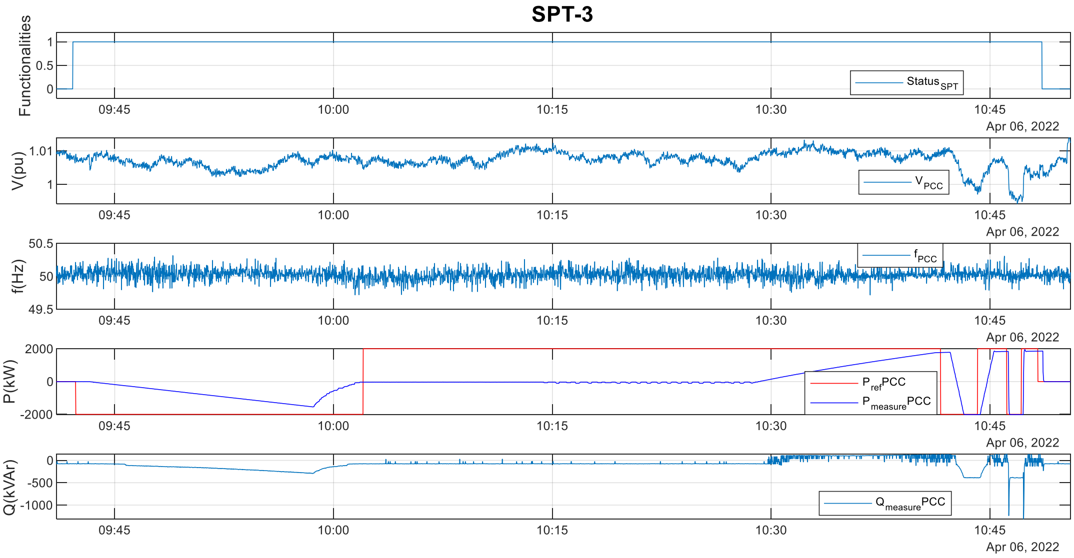

Figure 78: SPT-3 signals measured at PCC

In this test, the active power setpoints are defined with different ramp values. Active power response at PCC, reference signals, SOC of the MCFS and resulting ramp values are indicated in

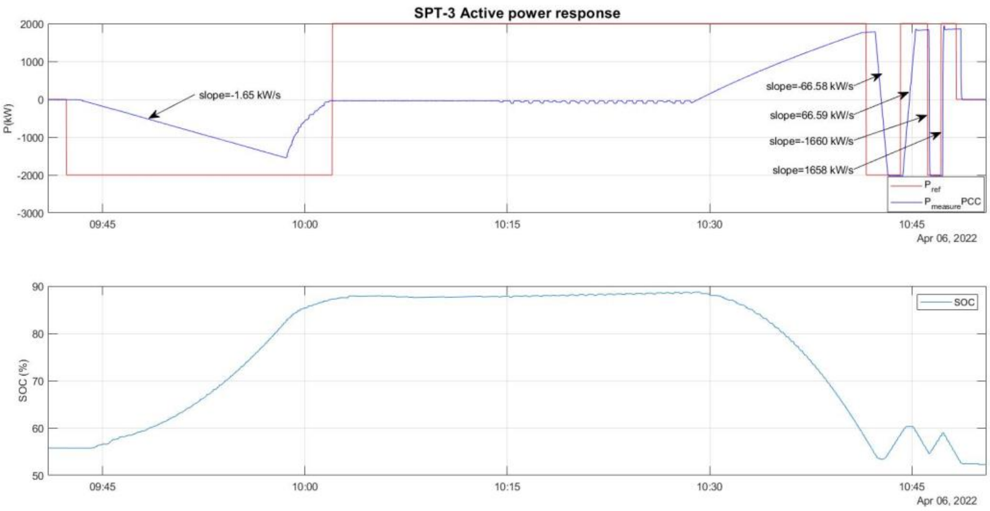

Figure 79.

Figure 79: SPT-3 Active power at PCC and SOC

The setpoint changes are achieved with the dedicated active power ramp up and down and the measurements at PCC are reported in an orderly manner:

- The ramp down of the first change measured at PCC is 0.099MW/min (-1.65kW/s).
- The ramp up of the second change is not achieved due to SOC limitation.
- The ramp down of the third change measured at PCC is -3.99MW/min (-66.58kW/s).
- The ramp up of the fourth change measured at PCC is 3.99MW/min (66.59kW/s).
- The ramp down of the fifth change measured at PCC is -99.6MW/min (-1660kW/s).
- The ramp up of the sixth change measured at PCC is 99.5MW/min (1658kW/s).

As


SPT-3 Active power response
slope=-1.65 kW/s
slope=-66.58 kW/s
slope=66.59 kW/s
slope=-1660 kW/s
slope=1658 kW/s
P(kW)
Apr 06, 2022
SOC (%)
SOC

Figure 79 shows, the response at PCC is fulfilled and follows the different ramp values as long as it is possible due to the SOC maximum and minimum values. Therefore, the first setpoints with slow ramp values (0.1MW/min) are followed until the SOC level reached its maximum. The succeeding setpoints can be achieved because the ramps are faster and the SOC limits are not reached.

As a result, this test passes the acceptance criteria.

4.5.4. Setpoint Tracking (SPT-4)

In this functionality, the charge/discharge process of the different flexibility devices that constitute the MCFS, can be managed by a setpoint signal. The setpoint may be changed continuously.

4.5.4.1. Test conditions definition

Purpose

Evaluate the capacity of following the active power setpoint at each minute for a long period of hours.

Pre-test conditions

Pre-test conditions and parameters for the test:

- Table 3Setpoint tracking activated (SPT_Status = 1).
- Level-1 functionalities disabled
- Level-2 functionalities disabled
- Level-3 functionalities disabled except SPT
- F_PPC = 50 Hz
- V_PPC = 1 p.u.
- Lp= 0%
- Le = 0%
- Eta = 0 MWh
- SOCinicial = 50%
- SPT_RampUp = 2 MW/min
- SPT_RampDown= 2 MW/min
- SPT_P_Setpoint(1)= 0 MW
- SPT_tr = 1

Methodology

The devices that take part along SPT-4 test are HFD, lead-acid battery and lithium-ion from ATENEA microgrid.

The main action performed is to track the active power setpoint for different control parameters.

- SPT_P_Setpoint(2)= 2 MW (Pmax)
- SPT_P_Setpoint(3)= -2 MW (-Pmax)

The active power setpoint variation must be set with changes of 0.1 MW each minute between the boundary values defined according to Table 47.

	SPT_P_setpoint	Minutes
SPT-4	[SPT_P_Setpoint(1), SPT_P_Setpoint(2), SPT_P_Setpoint(2), SPT_P_Setpoint(3), SPT_P_Setpoint(1), SPT_P_Setpoint(1)]	[0,108.5, 119.48, 207.50, 230.46,240]

Table 47 P setpoints and time for SPT-4

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its active power response according to the program times and ramp values.

4.5.4.2. Test results

Following the methodology, the SPT-4 test signal results measured at PCC are plotted in Figure 81.

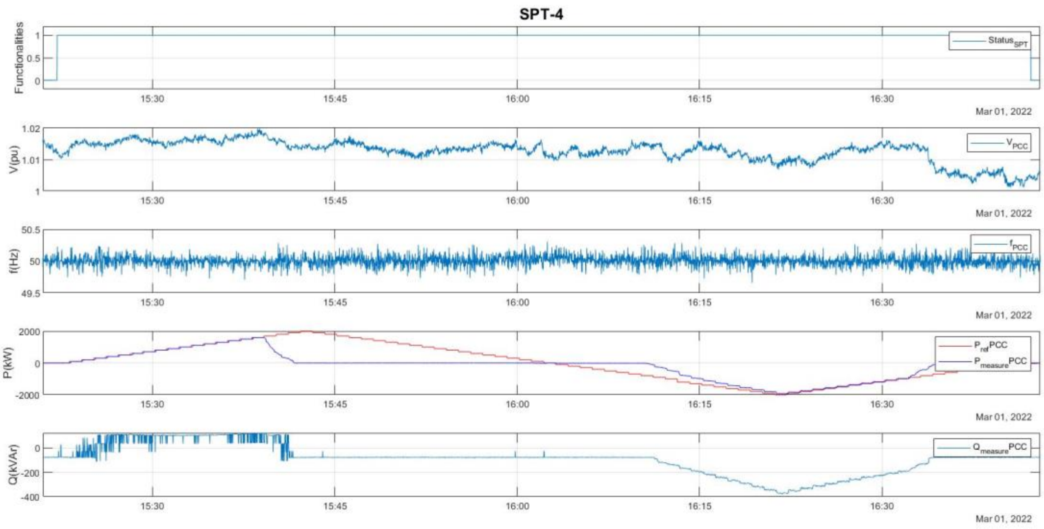

Figure 80: SPT-4 signals measured at PCC

Active power response at PCC and SOC of the MCFS are shown in Figure 81.

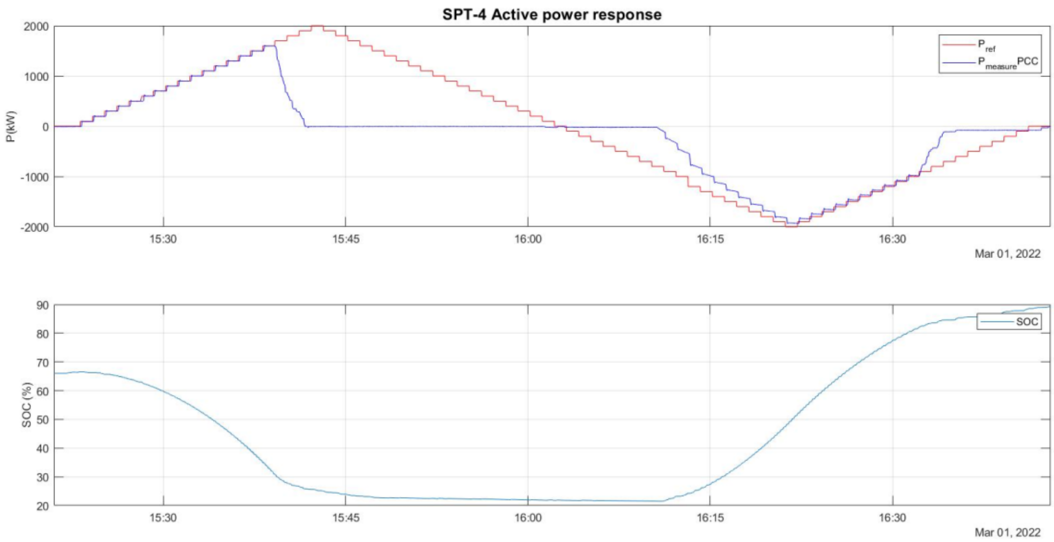

Figure 81: SPT-4 Active power at PCC and SOC

The active power response changes by 0.1 MW each minute, while SOC level allows to comply with the active power setpoint. Therefore, these steps are validated and this test passes the acceptance criteria.

4.5.5. Program management (PGM-1)

This functionality enables the TSO to set a charge/discharge program that will be followed by the MCFS. This profile is specified in terms of charge/discharge power, starting time-point and duration time.

4.5.5.1. Test conditions definition

Purpose

The main goal of this test is to verify that the system does not execute the program with variations of active power setpoint when PGM_Status is deactivated.

Pre-test conditions

Pre-test conditions and parameters for the test:

Table 3

- Program management activated (PGM_Status = 0).
- Level-1 functionalities disabled
- Level-2 functionalities disabled
- Level-3 functionalities disabled except PGM
- F_PPC = 50 Hz
- V_PPC = 1 p.u.
- Lp= 0%
- Le = 0%
- Eta = 0 MWh
- SOCinicial = 100%

Methodology

The devices that take part along PGM-1 test are HFD, lead-acid battery and lithium-ion from ATENEA microgrid.

The main action performed is to track the active power setpoint for each program according to Table 48.

	PGM_P_setpoint [MW]	SPT_RampUp [MW/min]	SPT_RampDown [MW/min]	PGM_Ti [min]
PGM-1	[0.1, 0.2, 0]	2	2	1

Table 48 P setpoints and times for PGM-1

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its active power response according to the program times and ramp values.

4.5.5.2. Test results

The PGM-1 is classified as a 3rd level functionality, which is controlled by the MC. Following the methodology and pre-tests conditions, the signals measured at PCC are reported in Figure 82.

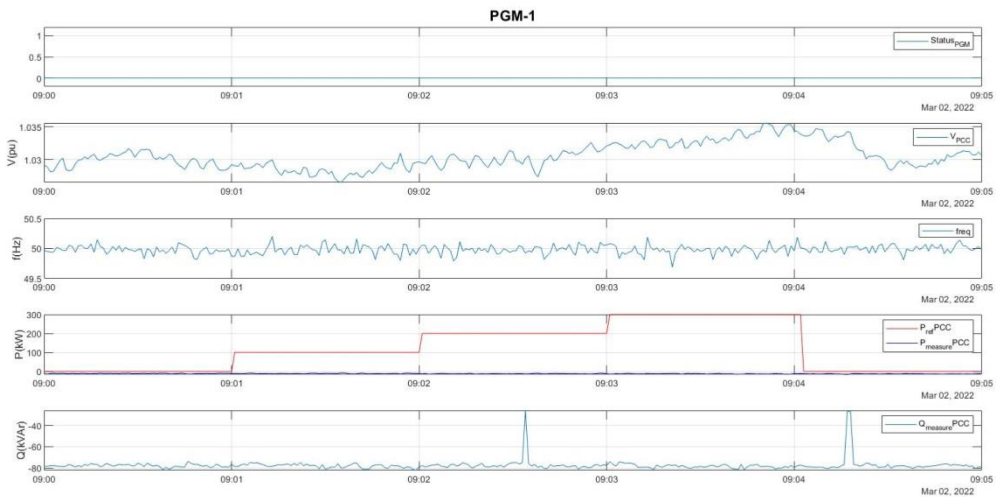

Figure 82: PGM-1 signals measured at PCC

In Figure 83 active power response, reference and SOC of the MCFS are presented.

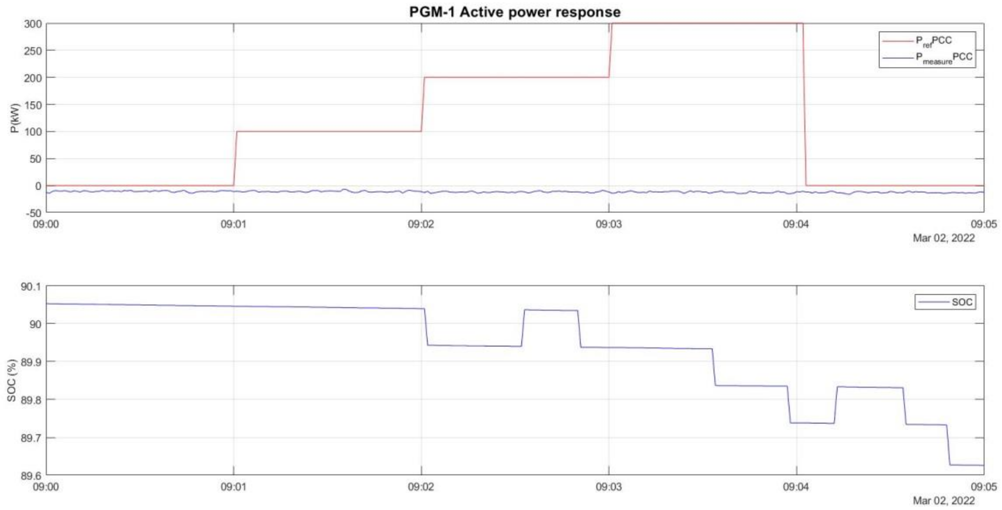

Figure 83: PGM-1 active power response at PCC and SOC

Since PGM status is deactivated during all test development, the MCFS do not vary its active power response following the program. As a consequence, the test is validated.

4.5.6. Program management (PGM-2, PGM-3, PGM-4)

This functionality enables the TSO to set a charge/discharge program that will be followed by the MCFS. This profile is specified in terms of charge/discharge power, starting time-point and duration time.

4.5.6.1. Test conditions definition

Purpose

The main goal of this test is to verify that the system executes the program with variations of active power setpoint when PGM_Status is activated.

Pre-test conditions

Pre-test conditions and parameters for the test:

- Table 3Program management activated (PGM_Status = 1).
- Level-1 functionalities disabled
- Level-2 functionalities disabled
- Level-3 functionalities disabled except PGM
- F_PPC = 50 Hz
- V_PPC = 1 p.u.
- Lp= 0%
- Le = 0%
- Eta = 0 MWh
- SOCinicial = 100%
- PGM_P_Setpoint = 2 MW

Methodology

The devices that take part along PGM-2, PGM-3 and PGM-4 tests are HFD, lead-acid battery and lithium-ion from ATENEA microgrid.

The main action performed is to track the active power setpoint for each program according to Table 49.

	PGM_P_setpoint [MW]	SPT_RampUp [MW/min]	SPT_RampDown [MW/min]	PGM_Ti [min]
PGM-2	[PGM_P_Setpoint/2, PGM_P_Setpoint, PGM_P_Setpoint/2, 0, -PGM_P_Setpoint/2, -PGM_P_Setpoint, -PGM_P_Setpoint/2, 0]	2	2	3
PGM-3	[PGM_P_Setpoint/2, PGM_P_Setpoint, PGM_P_Setpoint/2, 0, -PGM_P_Setpoint/2, -PGM_P_Setpoint, -PGM_P_Setpoint/2, 0]	2	2	[3, 1, 5, 6, 5, 1, 2, 6]
PGM-4	[PGM_P_Setpoint/2, PGM_P_Setpoint, PGM_P_Setpoint/2, 0, -PGM_P_Setpoint/2, -PGM_P_Setpoint, -PGM_P_Setpoint/2, 0]	[0.1; 1.0; 1.0; 1.0; 1.0; 2.0; 0.1]	[2.0; 2.0; 0.1; 1.0; 2.0; 2.0; 2.0]	10

Table 49 P setpoints and times for PGM-2, PGM-3 and PGM-4

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its active power response according to the program times and ramp values.

4.5.6.2. Test results

PGM-2:

For PGM-2 signals measured at PCC are reported in Figure 84, where power reference at PCC is plotted in red colour and the satisfactory active power response at PCC (blue) shows the demanded ramp.

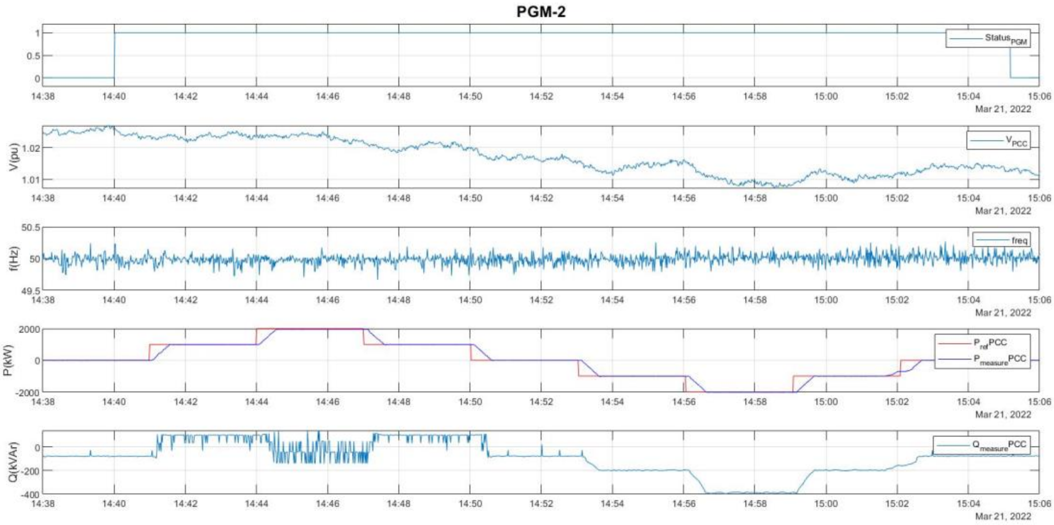

Figure 84: PGM-2 signals measured at PCC

In Figure 85 active power response at PCC and global SOC are presented.

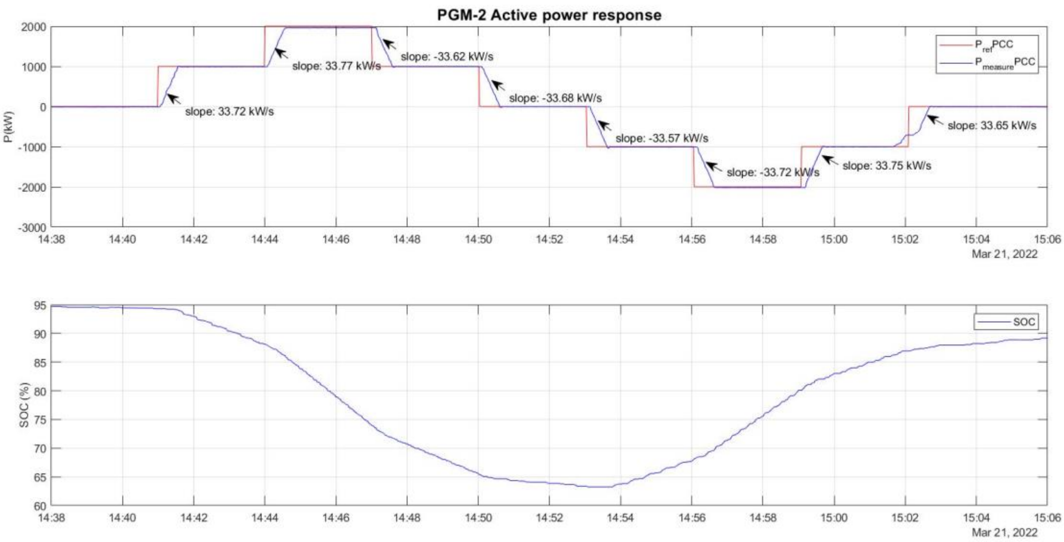

Figure 85: PGM-2 active power at PCC and SOC

The MCFS active power response fulfil with the programmed setpoint until the SOC limitation is reached. At each programmed time, the ramp achievement is reported. As a result, the acceptance criteria fulfilment is met:

- The ramp up of the first change measured at PCC is 2.02MW/min (33.72kW/s).
- The ramp up of the second change measured at PCC is 2.03MW/min (33.77kW/s).
- The ramp down of the third change measured at PCC is -2.01MW/min (-33.62kW/s).
- The ramp down of the fourth change measured at PCC is -2.02MW/min (-33.68kW/s).
- The ramp down of the fifth change measured at PCC is -2.01MW/min (-33.57kW/s).
- The ramp down of the sixth change measured at PCC is -2.02MW/min (-33.72kW/s).
- The ramp up of the seventh change measured at PCC is 2.02MW/min (33.75kW/s).
- The ramp up of the eighth change measured at PCC is 2.02MW/min (33.65kW/s).

PGM-3:

In Figure 86 signals measured at PCC may be seen according to PGM-3.

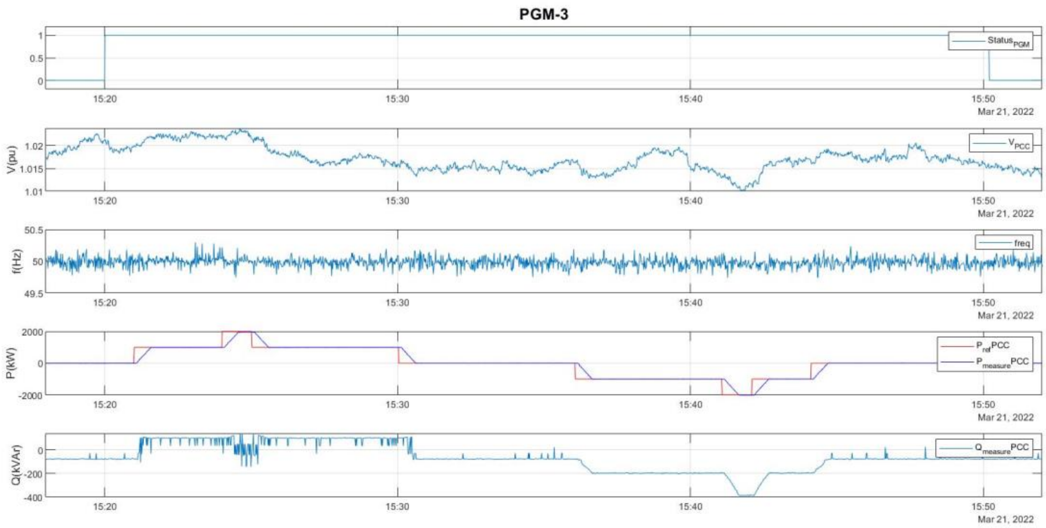

Figure 86: PGM-3 signals measured at PCC

Active power response at PCC with active power references and global SOC in PGM-3 are shown in Figure 87.

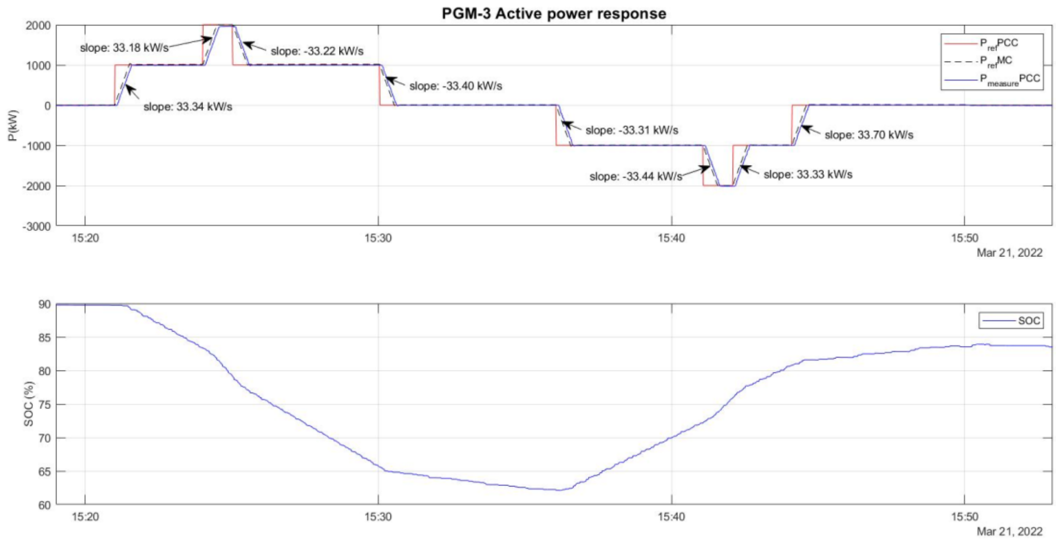

Figure 87: PGM-3 active power at PPC and SOC

The MCFS active power response fulfil with the programmed setpoint until the SOC limitation is reached. Ramp response measurements are reported in detail to confirm test validation:

- The ramp up of the first change measured at PCC is 2MW/min (33.34kW/s).
- The ramp up of the second change measured at PCC is 2MW/min (33.18kW/s).
- The ramp down of the third change measured at PCC is -2MW/min (-33.22kW/s).
- The ramp down of the fourth change measured at PCC is -2MW/min (-33.40kW/s).
- The ramp down of the fifth change measured at PCC is -2MW/min (-33.31kW/s).
- The ramp down of the sixth change measured at PCC is -2MW/min (-33.44kW/s).

- The ramp up of the seventh change measured at PCC is 2MW/min (33.33kW/s).
- The ramp up of the eighth change measured at PCC is 2.02MW/min (33.70kW/s).

PGM-4

In this test, signals measured at PCC are presented in Figure 88 to have a full view of the responses and the test conditions.

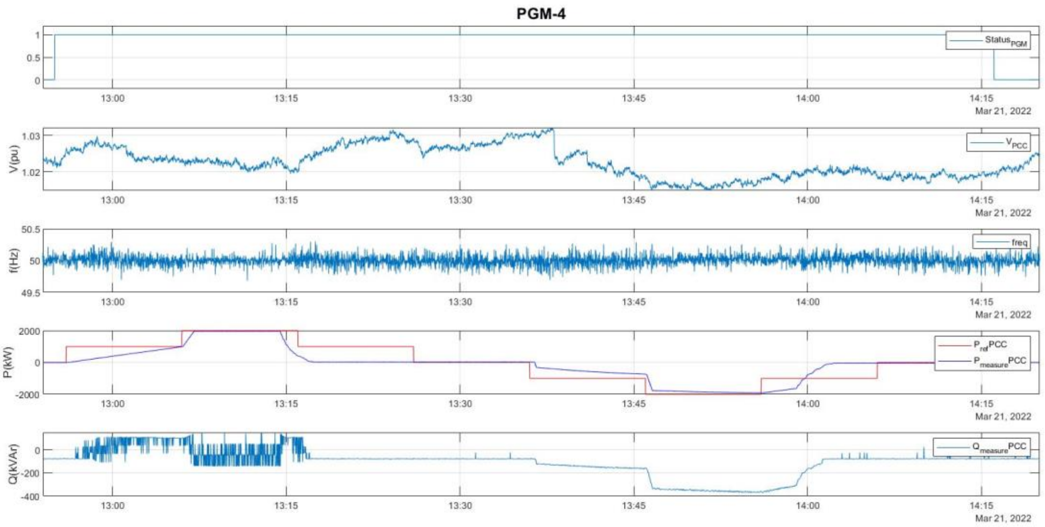

Figure 88: PGM-4 signals measured at PCC

In Figure 89 active power response at PCC and active power reference (without precomputed ramp) and global SOC are plotted.

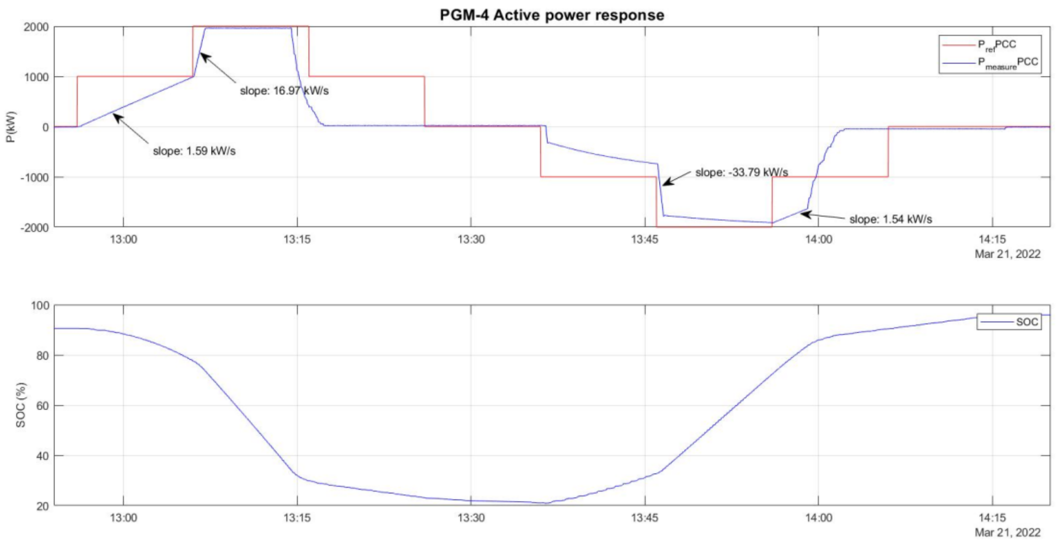

Figure 89: PGM-4 active power at PCC and SOC

As illustrated in Figure 89, the MCFS P response fulfil with the programmed setpoint until the SOC limitation is reached. A step-by-step analysis is described indicating the ramp achievement and so the acceptance criteria at each required time frame:

- The ramp up of the first change measured at PCC is 0.01MW/min (1.59kW/s).
- The ramp up of the second change measured at PCC is 1.02MW/min (16.97kW/s).
- The ramp down of the third change is not achieved due to SOC level.
- The ramp down of the fourth change is not achieved due to SOC level.
- The ramp down of the fifth change is not achieved due to SOC level.
- The ramp down of the sixth change measured at PCC is -2.02MW/min (-33.79kW/s).
- The ramp up of the seventh change measured at PCC is 0.01MW/min (1.54kW/s), until the SOC upper limit is reached.
- The ramp up of the eighth change is not achieved due to SOC level.

4.5.7. Program management (PGM-5, PGM-6)

This functionality enables the TSO to set a charge/discharge program that will be followed by the MCFS. This profile is specified in terms of charge/discharge power, starting time-point and duration time.

4.5.7.1. Test conditions definition

Purpose

The main goal of this test is to verify that the system executes the program with variations of active power setpoint when PGM_Status signal from MC is activated.

Pre-test conditions

Pre-test conditions and parameters for the test:

- Table 3Program management activated (PGM_Status = 1).
- SPT_P_Setpoint(1)= 0 MW
- Level-1 functionalities disabled
- Level-2 functionalities disabled
- Level-3 functionalities disabled except PGM
- F_PPC = 50 Hz
- V_PPC = 1 p.u.
- Lp= 0%
- Le = 0%
- Eta = 0 MWh
- PGM_RampUp = 2 MW/min
- PGM_RampDown = 2 MW/min
- PGM_Ti = 60 min

Methodology

The devices that take part along PGM-5 and PGM-6 tests are HFD, lead-acid battery and lithium-ion from ATENEA microgrid.

The main action performed is to track the active power setpoint for each program according to Table 50, where:

- SPT_P_Setpoint(2)= 2 MW

	SOCinicial [%]	PGM_P_setpoint [MW]
PGM-5	0	SPT_P_Setpoint(2)
PGM-6	100	-SPT_P_Setpoint(2)

Table 50 P setpoints and parameters for PGM-5 and PGM-6

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its active power response to completely charge/discharge the battery system in 15 minutes.

4.5.7.2. Test results

<u>**PGM-5:**</u>

Following the methodology and pre-test conditions for PGM-5, signals measured at PCC are shown in Figure 90 under the MC operation of the MCFS.

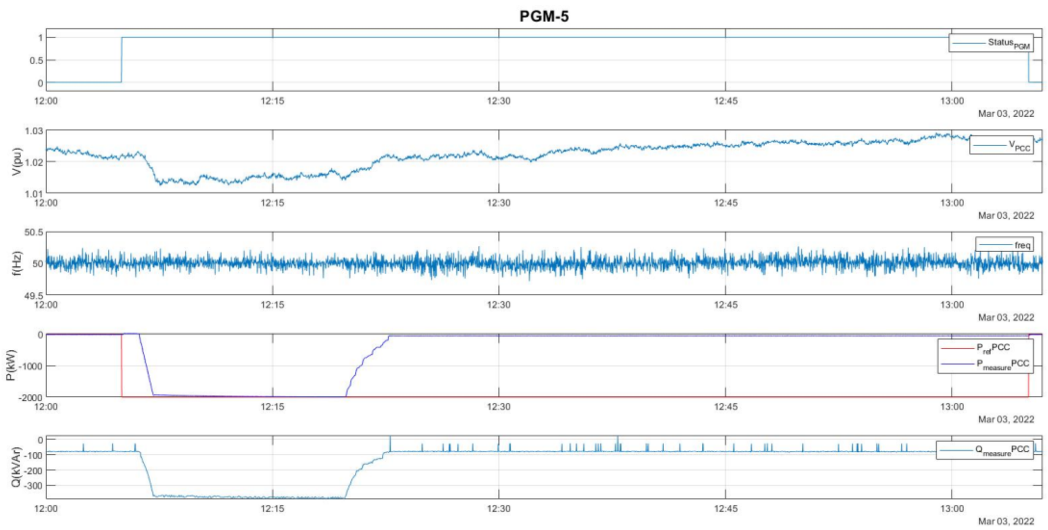

Figure 90: PGM-5 signals measured at PCC

PGM-5 active power response at PCC and global SOC are presented in Figure 91.

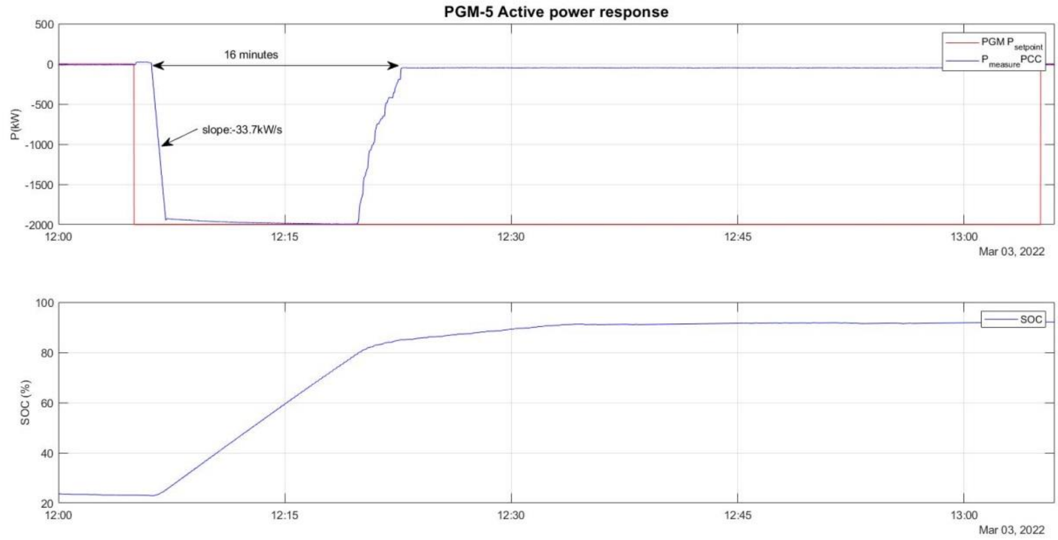

Figure 91: PGM-5 active power at PCC and SOC

The MCFS active power response acts until the state of charge of the battery changes from totally discharged to fully charged in 16 minutes. In this test the ramp down measured at PCC is 2.02MW/min (-33.7kW/s) accomplishing the requirements but in one minute in excess due to SOC control limitations, to prevent the state of heath of the hybrid storage system.

PGM-6:

The signals measured at PCC in this PGM-6 test are shown in Figure 92.

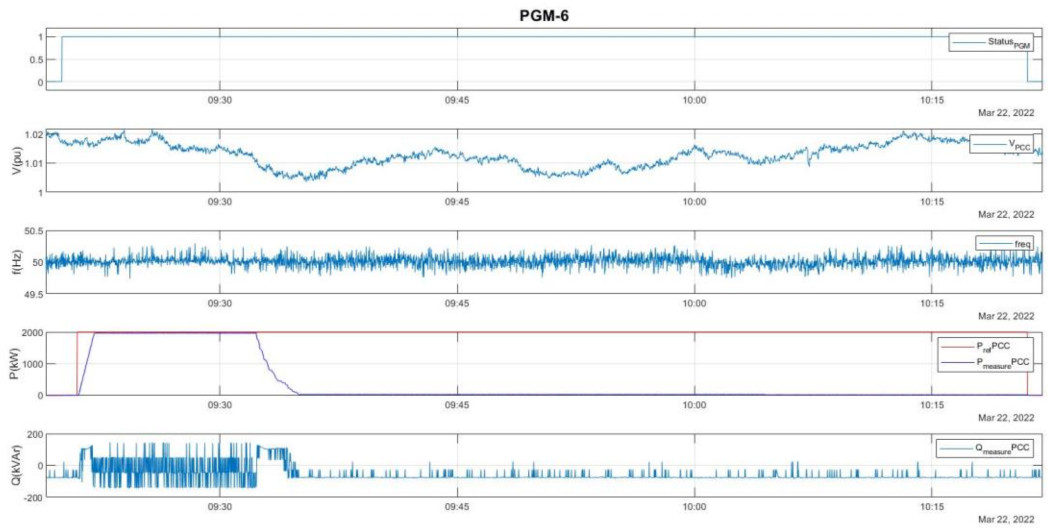

Figure 92: PGM-6 signals measured at PCC

PGM-6 active power response at PCC and global SOC are presented in Figure 93.

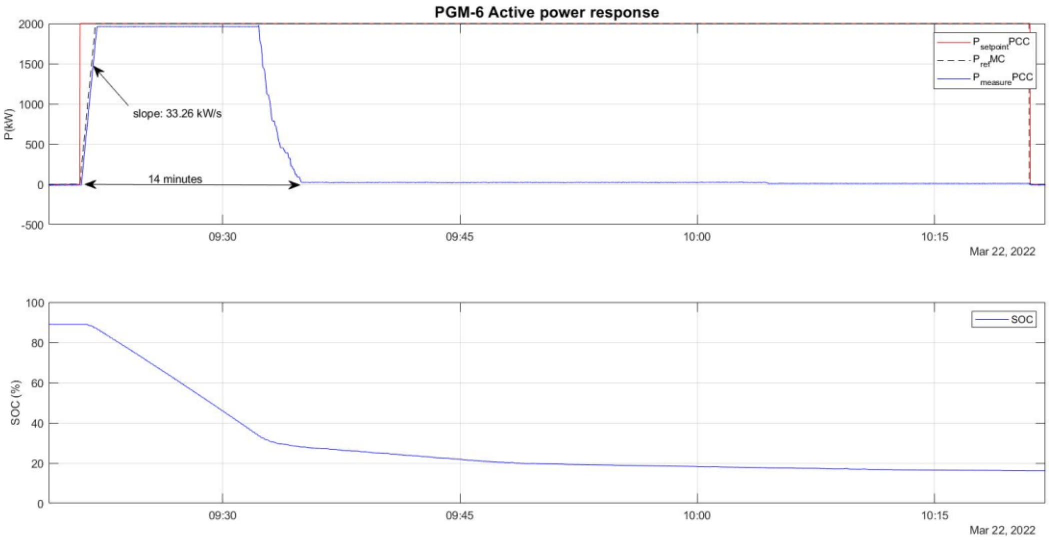

Figure 93: PGM-6 active power at PCC and SOC

The MCFS active power response acts until the state of charge of the battery changes from totally charged to totally discharged in 14 minutes. In this test, the ramp down measured at PCC is 2MW/min (33.26kW/s), accomplishing the requirements and preventing the state of heath of the hybrid storage system.

4.5.8. Congestion Management (CMT-1)

This functionality is designed to ensure that renewable energy production does not exceed a defined power limit in the node of interest. The MCFS will use its storage capacity to compensate the RES generation, charging or discharging active power so as to ensure the desired power at the reference bus.

4.5.8.1. Test conditions definition

Purpose

The main goal of this test is to verify that the system does not react to variations of renewable generation CMT_Status is deactivated.

Pre-test conditions

Pre-test conditions and parameters for the test:

- Table 3Congestion Management deactivated (CMT_Status = 0).
- Level-1 functionalities disabled
- Level-2 functionalities disabled
- Level-3 functionalities disabled except CMT
- F_PPC = 50 Hz
- V_PPC = 1 p.u.
- Lp= 0%
- Le = 0%
- Eta = 0 MWh

- SOCinicial = 100%
- CMT_NodeRenLimit (Lrn) = 1MW
- PV = 1MW

Methodology

The devices that take part along CMT-1 test are HFD, lead-acid battery and lithium-ion from ATENEA microgrid.

The main action performed is to track the active power PV generation and power limit in the node for different control parameters according to Table 51.

	PV	Lrn mode	Lrn	DischargeMode	DischargeProgram
CMT-1	1MW	0	0.5MW	0	0

Table 51 P setpoints and times for CMT-1

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its active power response to maintain the power limit in the node.

4.5.8.2. Test results

In Figure 94 CMT-1 signals measured at PCC are shown.

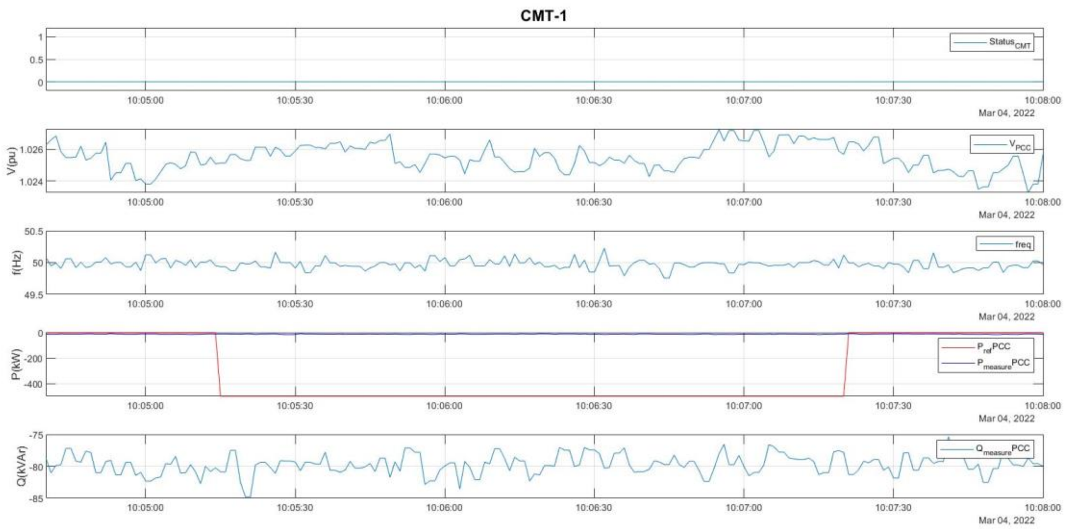

Figure 94: CMT-1 signals measured at PCC

PV active power, active power limit, active power response at PCC and its reference, as well as SOC, are presented in Figure 95.

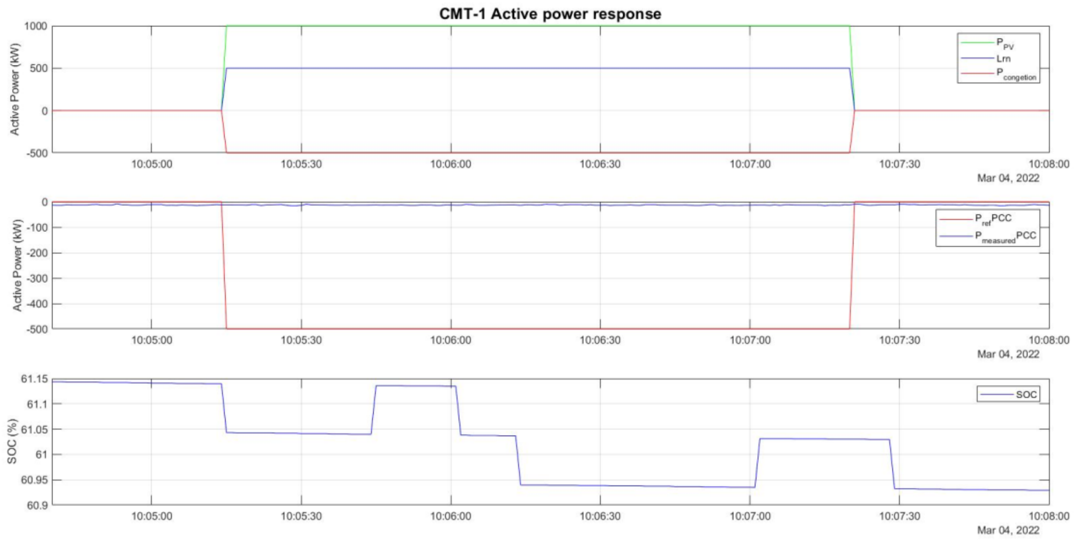

Figure 95: CMT-1 active power at PCC and SOC

Since CMT status is deactivated, the MCFS do not vary its active power response. As consequence, CMT-1 perfectly passes acceptance criteria.

4.5.9. Congestion Management (CMT-2)

This functionality is designed to ensure that renewable energy production does not exceed a defined power limit in the node of interest. The MCFS will use its storage capacity to compensate the RES generation, charging or discharging active power so as to ensure the desired power at the reference bus.

4.5.9.1. Test conditions definition

Purpose

The main goal of this test is to verify that the system reacts to variations of renewable generation to maintain the limit in the node.

Pre-test conditions

Pre-test conditions and parameters for the test:

- Table 3Congestion Management deactivated (CMT_Status = 1).
- Level-1 functionalities disabled
- Level-2 functionalities disabled
- Level-3 functionalities disabled except CMT
- F_PPC = 50 Hz
- V_PPC = 1 p.u.
- Lp= 0%
- Le = 0%
- Eta = 0 MWh
- SOCinicial = 0% optional other, SOCfinal=SOCinicial
- CMT_NodeRenLimit (Lrn) = 1MW
- PV = 1MW

Methodology

The devices that take part along CMT-2 test are HFD, lead-acid battery and lithium-ion from ATENEA microgrid.

The main action performed is to track the active power PV generation and power limit in the node for different control parameters according to Table 52.

	PV	Lrn mode	Lrn	Discharge Mode	Discharge Program	Minutes apart between changes
CMT-2	[1.5,0.5]MW	0	1MW	0	0	10

Table 52 P setpoints and parameters for CMT-2

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its active power response to maintain the power limit in the node.

4.5.9.2. Test results

CMT-2 signals measured at PCC are shown in Figure 96.

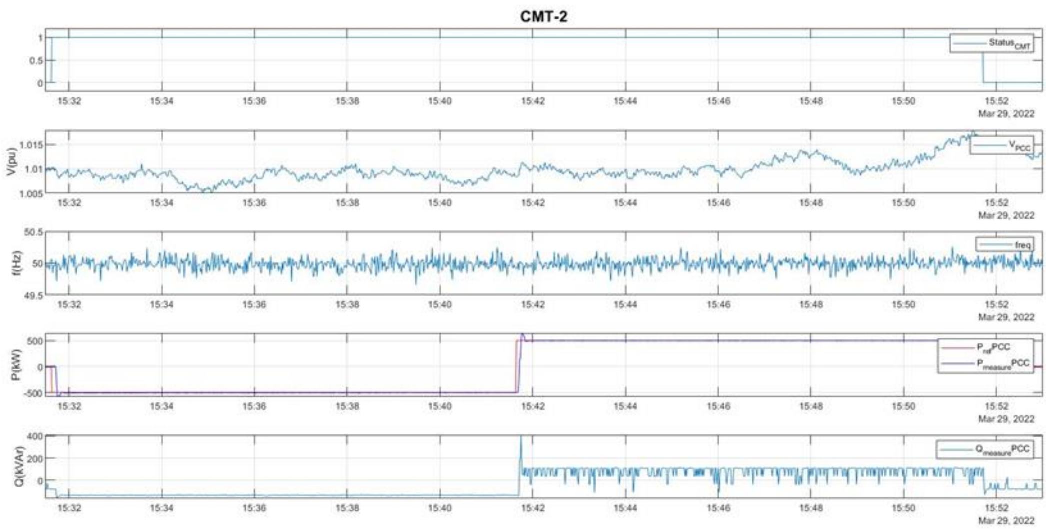

Figure 96: CMT-2 signals measured at PCC

In Figure 97, PV active power, active power limit, active power response at PCC and SOC are presented.

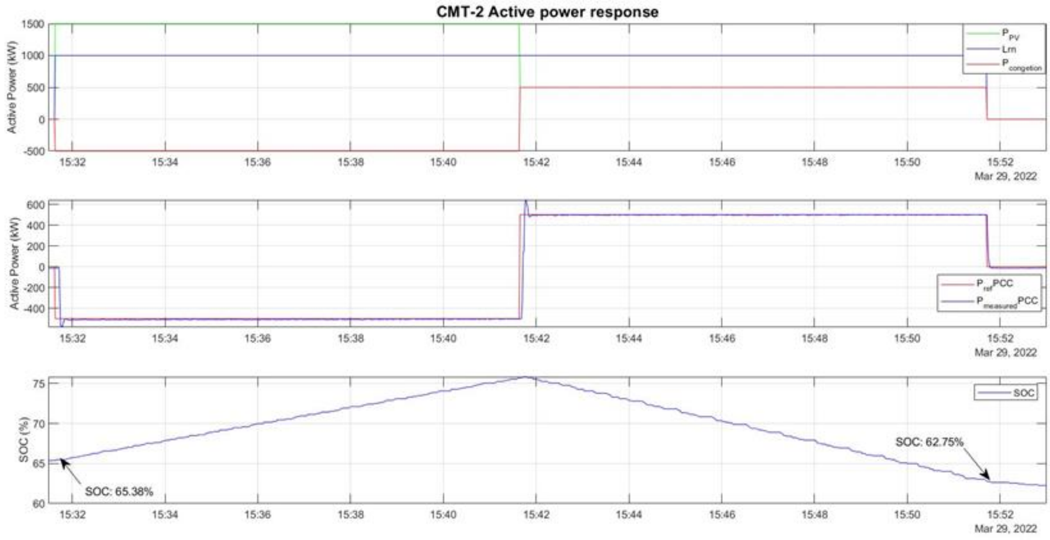

Figure 97: CMT-2 active power at PCC and SOC

The active power setpoint at PCC is the result of the difference between the active power limit established for the node and the PV generation. Therefore, the active power setpoint to fulfil with the active power limitation in the node is plotted with the active power measurement at PCC in Figure 97.

The active power response follows the setpoint, but the SOC level both at the beginning and at the end of the test are not equal. There is a small difference of 2.6% between them that may be caused by the different cycle efficiency (hysteresis) and constant active power losses in the system.

4.5.10. Congestion Management (CMT-3)

This functionality is designed to ensure that renewable energy production does not exceed a defined power limit in the node of interest. The MCFS will use its storage capacity to compensate the RES generation, charging or discharging active power so as to ensure the desired power at the reference bus.

4.5.10.1. Test conditions definition

Purpose

The main goal of this test is to verify that the system reacts to variations of renewable generation to maintain the limit in the node.

Pre-test conditions

Pre-test conditions and parameters for the test:

- Table 3Congestion Management deactivated (CMT_Status = 1).
- Level-1 functionalities disabled
- Level-2 functionalities disabled
- Level-3 functionalities disabled except CMT
- F_PPC = 50 Hz

- V_PPC = 1 p.u.
- Lp= 0%
- Le = 0%
- Eta = 0 MWh
- SOCinicial = 55 %
- CMT_NodeRenLimit (Lrn) = 1MW
- PV = 1MW

Methodology

The devices that take part along CMT-3 test are HFD, lead-acid battery and lithium-ion from ATENEA microgrid.

The main action performed is to track the active power PV generation and power limit in the node for different control parameters according to Table 53.

	PV	Lrn mode	Lrn	Discharge Mode	Discharge Program	Minutes apart between changes
CMT-3	[1.5,0.9]MW	0	1MW	1	[60;90] mins	10

Table 53 P setpoints and parameters for CMT-3

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its active power response to maintain the power limit in the node.

4.5.10.2. Test results

The CMT-3 is classified as a 3rd level functionality, which is controlled by the MC. Following the methodology, the signals measured at PCC during 90 minutes with a sampling rate of 1 second are shown in Figure 98.

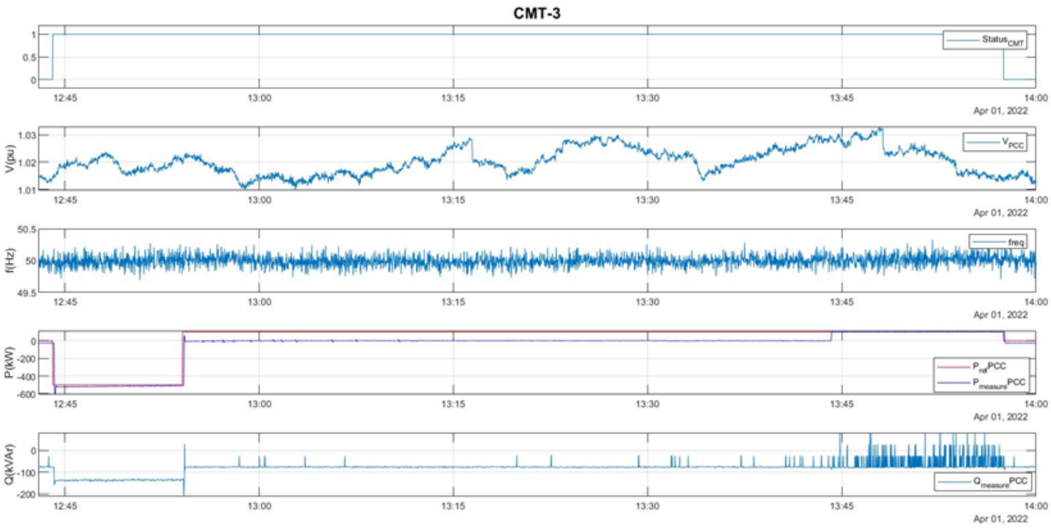

Figure 98: CMT-3 signals measured at PCC

In Figure 99, active power response at PCC according to power limitations and SOC are presented.

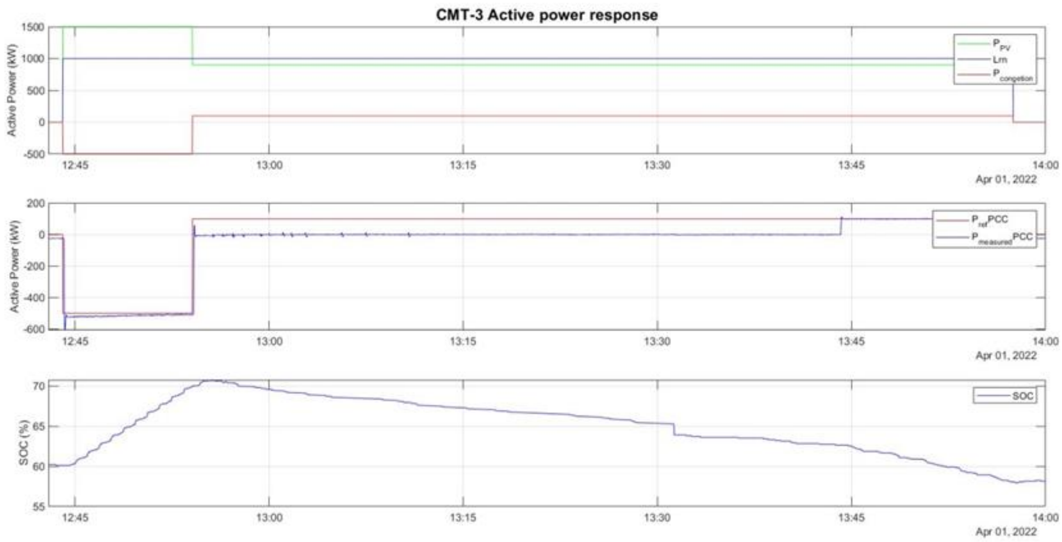

Figure 99: CMT-3 active power at PCC and SOC

The active power setpoint at PCC is the result of the difference between the active power limit established for the node, which changes dynamically, and the PV generation. However, only when the discharge mode is activated, the discharge is allowed. Therefore, the active power setpoint to fulfil with the active power limitation in the node is plotted with the active power measurement at PCC in Figure 99.

In this test, as the active power response follow the setpoint and at the same time the MC sets the control according to the prevention of the health status of the storage, this test passes the acceptance criteria.

4.5.11. Congestion Management (CMT-4)

This functionality is designed to ensure that renewable energy production does not exceed a defined power limit in the node of interest. The MCFS will use its storage capacity to compensate the RES generation, charging or discharging active power so as to ensure the desired power at the reference bus.

4.5.11.1. Test conditions definition

Purpose

The main goal of this test is to verify that the system reacts to variations of renewable generation to maintain the limit in the node.

Pre-test conditions

Pre-test conditions and parameters for the test:

- Table 3Congestion Management deactivated (CMT_Status = 1).
- Level-1 functionalities disabled
- Level-2 functionalities disabled
- Level-3 functionalities disabled except CMT
- F_PPC = 50 Hz
- V_PPC = 1 p.u.
- Lp= 0%
- Le = 0%
- Eta = 0 MWh
- SOCinicial = 55%
- CMT_NodeRenLimit (Lrn) = 1MW
- PV = 1MW

Methodology

The devices that take part along CMT-4 test are HFD, lead-acid battery and lithium-ion from ATENEA microgrid.

The main action performed is to track the active power PV generation and power limit in the node for different control parameters according to Table 54.

	PV	Lrn mode	Lrn	Discharge Mode	Discharge Program	Minutes apart between changes
CMT-2	[1.0,0.5]MW	0	[2.2,0.5]MW	0	0	10

Table 54 P setpoints and parameters for CMT-4

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its active power response to maintain the power limit in the node.

4.5.11.2. Test results

The same procedures as the CMT test are followed as for CMT-4 but considering specific values from Table 54. Signals measured at PCC in this test are shown in Figure 100.

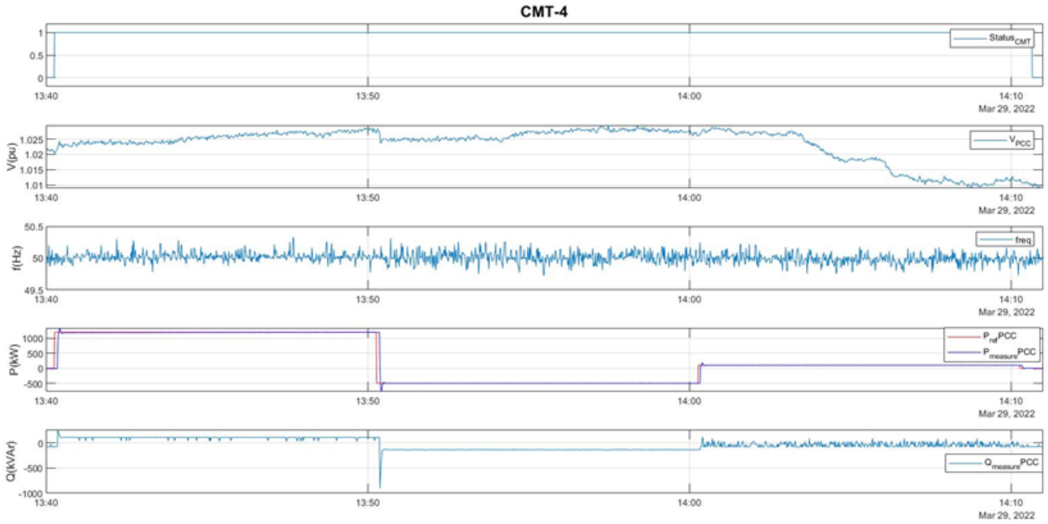

Figure 100: CMT-4 signals measured at PCC

In CMT-4 the active power setpoint at PCC is the result of the difference between active power limit changing in the node and the PV generation. In Figure 101, active power response at PCC and SOC are presented.

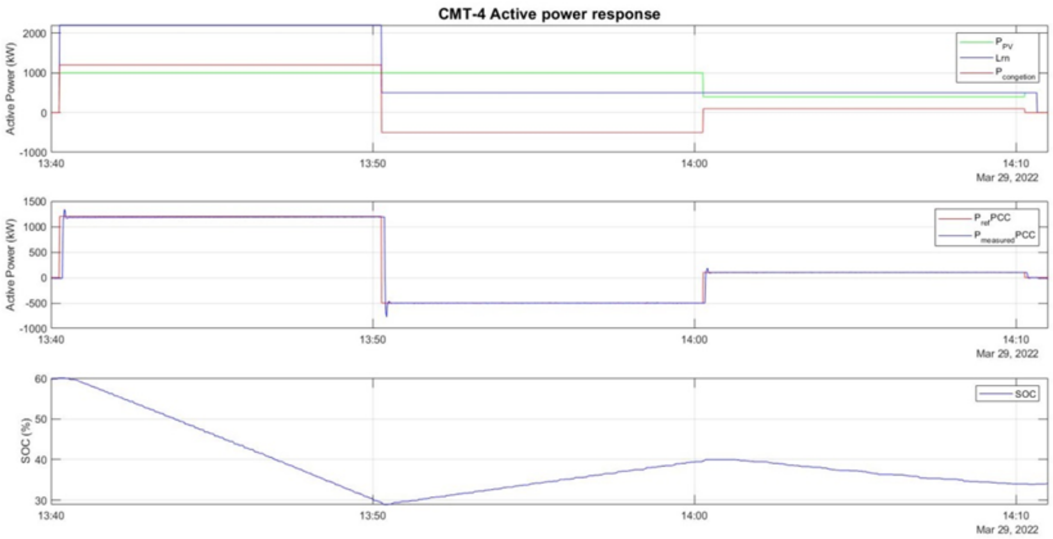

Figure 101: CMT-4 active power at PCC and SOC

The active power setpoint to fulfil with the active power limitation in the node is plotted with the active power measurement at PCC in Figure 101, in which it can be observed that the active power response follows the setpoint adequately. Accordingly, these results validate the test agreeing with the defined acceptance criteria.

4.5.12. Congestion Management (CMT-5)

This functionality is designed to ensure that renewable energy production does not exceed a defined power limit in the node of interest. The MCFS will use its storage capacity to compensate the RES generation, charging or discharging active power so as to ensure the desired power at the reference bus.

4.5.12.1. Test conditions definition

Purpose

The main goal of this test is to verify that the system reacts to variations of renewable generation to maintain the limit in the node.

Pre-test conditions

Pre-test conditions and parameters for the test:

- Table 3Congestion Management deactivated (CMT_Status = 1).
- Level-1 functionalities disabled
- Level-2 functionalities disabled
- Level-3 functionalities disabled except CMT
- F_PPC = 50 Hz
- V_PPC = 1 p.u.
- Lp= 0%
- Le = 0%
- Eta = 0 MWh
- SOCinicial = 55%
- CMT_NodeRenLimit (Lrn) = 1MW
- PV = 1MW

Methodology

The devices that take part along CMT-5 test are HFD, lead-acid battery and lithium-ion from ATENEA microgrid.

The main action performed is to track the active power PV generation and power limit in the node for different control parameters according to Table 55.

	PV	Lrn mode	Lrn	Discharge Mode	Discharge Program	Minutes apart between changes
CMT-5	2.1 MW	0	[1.2,2.2]MW	1	[20;80] mins	10

Table 55 P setpoints and parameters for CMT-5

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its active power response to maintain the power limit in the node.

4.5.12.2. Test results

The CMT-5 is classified as a 3rd level functionality, which is controlled by the MC. Following the methodology, the signals measured at PCC during 100 minutes with a sampling rate of 1 second are shown in Figure 102.

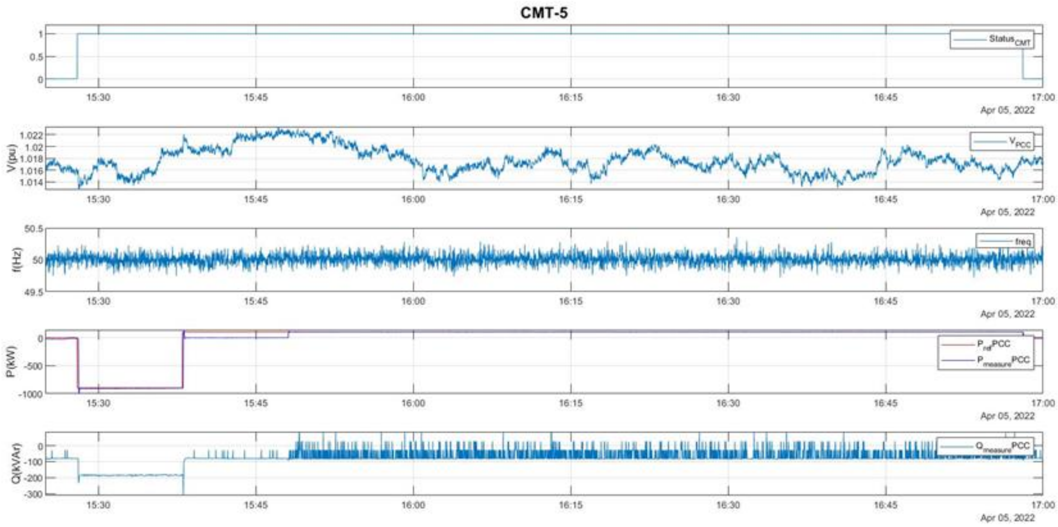

Figure 102: CMT-5 signals measured at PCC

In Figure 103, active power response at PCC and SOC are presented.

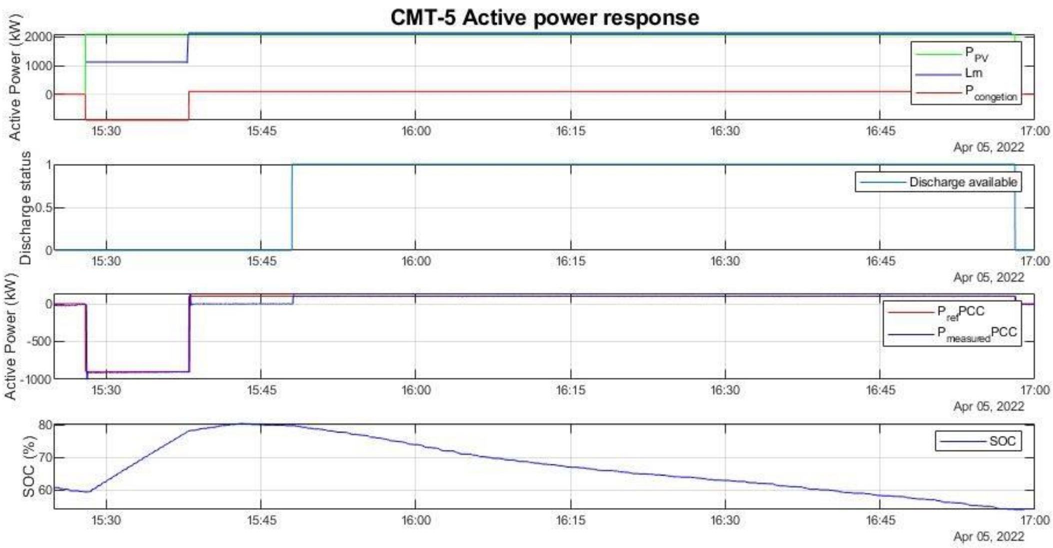

Figure 103: CMT-5 active power at PCC and SOC

In CMT-5, the active power setpoint at PCC is the result of the difference between the active power limit established for the node and the PV generation. Therefore, the active power setpoint to fulfil with the active power limitation in the node is plotted with the active power measurement at PCC, as can be seen in the Figure 103. When the discharging mode is activated, the discharge of the battery is allowed with an active power setpoint equal to the difference between limit and PV generation as it occurs in this test.

The active power response follows the setpoint and the discharging only happens when it is allowed, despite the fact that, due to the setpoint, it could be done before. Therefore, this test passes the acceptance criteria.

4.5.13. Summary for level-3 functionalities tests

The test conditions are verified and thus acceptance criteria for 3rd level functionalities tests results are summarized in

Table 1.

	Test condition	Acceptance
SPT-1	Follow P-set-point when corresponds	✓
SPT-2	Follow P-set-point according to SPT_tr variable	✓
SPT-3	Follow P-set-point according to defined ramps	✓
SPT-4	Follow P-set-point	✓
PGM-1	Don´t follow P-set-point	✓
PGM-2	Follow P-set-point	✓
PGM-3	Follow P-set-point according to defined duration	✓
PGM-4	Follow P-set-point according to defined ramps	✓
PGM-5	Follow P-set-point, full charge	✓
PGM-6	Follow P-set-point, full discharge	✓
CMT-1	Don´t follow P-set-point	✓
CMT-2	Follow P-set-point	✓
CMT-3	Follow P-set-point and discharge program	✓
CMT-4	Follow P-set-point	✓
CMT-5	Follow P-set-point and discharge program	✓

Table 56: Acceptance criteria for 3rd level tests

4.6. Combined Functionalities

Combined functionalities are different combinations of the previously presented functionalities to highlight the priority and effective coordination of services to provide the grid requirements. In this section, the results obtained from the tests performed to validate the combined functionalities are presented.

4.6.1. Power-frequency Regulation and Program Management (PFR-PGM-1 PFR-PGM-2 PFR-PGM-3)

The combination of these two functionalities enables the TSO to set a charge/discharge program at the same time that the power-frequency control is enabled. In case of unexpected frequency changes, the system may inject or absorb active power in response, taking into account that frequency regulation must be prioritised.

4.6.1.1. Test conditions definition

Purpose

The main goal of this test is to verify that the system reacts to both functionalities at the same time.

Pre-test conditions

Pre-test conditions and parameters for the test:

- Table 3P-f regulation activates (PFR_Status = 1)
- Program management activated (PGM_Status = 1).
- Level-1 functionalities disabled except PFR
- Level-2 functionalities disabled except PFR
- Level-3 functionalities disabled except PGM
- F_PPC = 50 Hz
- V_PPC = 1 p.u.
- SOCinicial = 50%
- PGM_P_Setpoint= 2 MW
- PFR_PmaxRange = [-Lp ; Lp]
- PFR_DeadBand = [-0,050 Hz ; +0,050 Hz]
- PFR_Droop= 4%
- Reserve parameters in Table 57

	Lp	Le	Eta
PFR-PGM-1	20%	15%	0 MW
PFR-PGM-2	20%	2%	0 MW
PFR-PGM-3	20%	15%	0.1MWh

Table 57 Power and energy reserves for PFR-PGM

Methodology

The devices that take part along PFR-PGM tests are HFD, redox-flow battery, lead-acid battery and lithium-ion from ATENEA microgrid.

The main action performed is to track the active power PV generation and power limit in the node for different control parameters according to Table 58.

	PFR-PGM-1		PFR-PGM-2		PFR-PGM-3	
Time[min]	f	| df/dt |	f	| df/dt |	f	| df/dt |
0	50 Hz	-	50 Hz	-	50 Hz	-
2	49.8 Hz	<= 0,5 Hz/s	49.8 Hz	<= 0,5 Hz/s	49 Hz	<= 0,5 Hz/s
3	50 Hz	<= 0,5 Hz/s	50 Hz	<= 0,5 Hz/s	50 Hz	<= 0,5 Hz/s
6	49.8 Hz	<= 0,5 Hz/s	49.8 Hz	<= 0,5 Hz/s	49 Hz	<= 0,5 Hz/s
7	50 Hz	<= 0,5 Hz/s	50 Hz	<= 0,5 Hz/s	50 Hz	<= 0,5 Hz/s
10	50.2 Hz	<= 0,5 Hz/s	50.2 Hz	<= 0,5 Hz/s	51 Hz	<= 0,5 Hz/s
11	50 Hz	<= 0,5 Hz/s	50 Hz	<= 0,5 Hz/s	50 Hz	<= 0,5 Hz/s
14	50.2 Hz	<= 0,5 Hz/s	50.2 Hz	<= 0,5 Hz/s	51 Hz	<= 0,5 Hz/s
15	50 Hz	<= 0,5 Hz/s	50 Hz	<= 0,5 Hz/s	50 Hz	<= 0,5 Hz/s

Table 58 f_PCC frequency profiles for PFR-PGM

Track the active power setpoint for each program according to the next table.

	PGM_P_setpoint [MW]	SPT_RampUp [MW/min]	SPT_RampDown [MW/min]	PGM_Ti [min]

PFR-PGM-1-2-3	[PGM_Pmax (100-Lp)/2,0,- PGM_Pmax (100-Lp), 0]	2	2	5

Table 59 P setpoint and times for PFR-PGM

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its active power response to the program times and frequency variations.

4.6.1.2. Test results

PFR-PGM-1:

The combined functionalities are PFR-n, which is classified as a 2nd level functionality, and PGM, which is classified as a 3rd level functionality, are controlled simultaneously by the MC. Following the methodology, the signals measured at PCC during 80 minutes with a sampling rate of 1 second are shown in Figure 104.

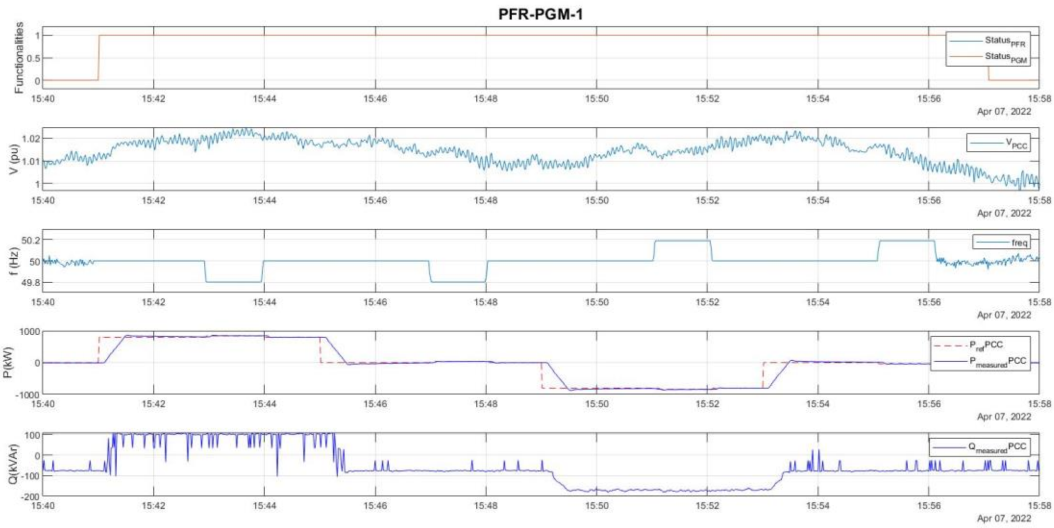

Figure 104: PFR-PGM-1 signals measured at PCC

In Figure 105, frequency and active power response at PCC are presented for PFR-PGM-1.

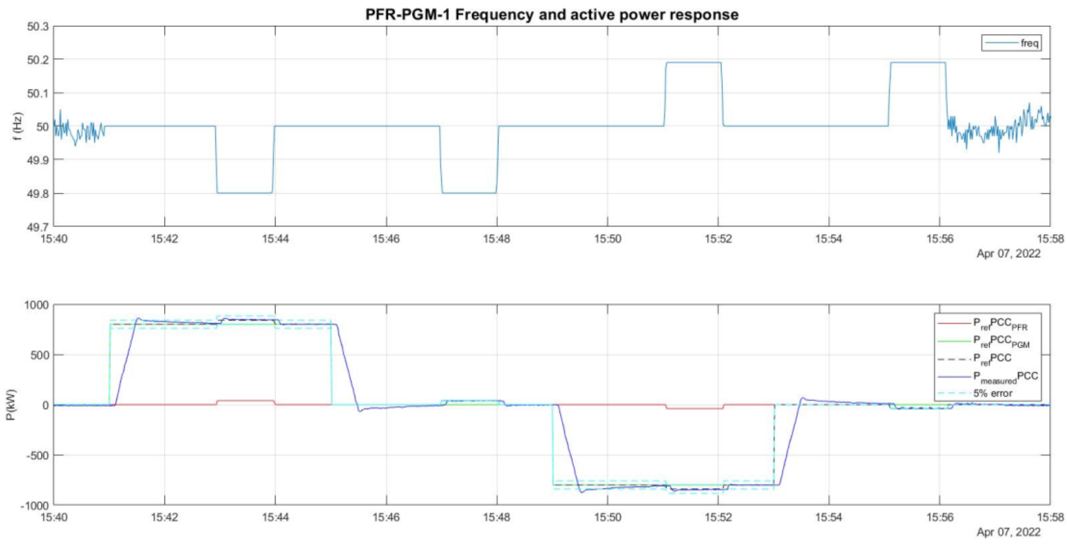

Figure 105: PFR-PGM-1 frequency and active power at PCC

The active power setpoint is followed according to the PGM active power profile. When the frequency experiences any variation, the active power response changes accordingly.

Therefore, this test passes the acceptance criteria.

PFR-PGM-2:

The combined functionalities are PFR-n, which is classified as a 2nd level functionality, and PGM, which is classified as a 3rd level functionality, are controlled simultaneously by the MC. Following the methodology, the signals measured at PCC during 80 minutes with a sampling rate of 1 second are shown in Figure 106.

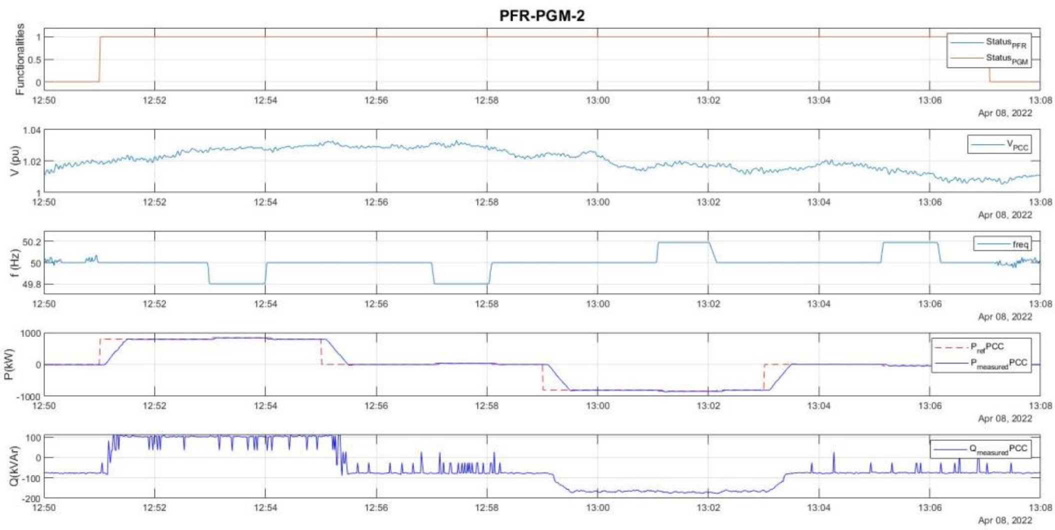

Figure 106: PFR-PGM-2 signals measured at PCC

Frequency and active power response at PCC are show in Figure 107.

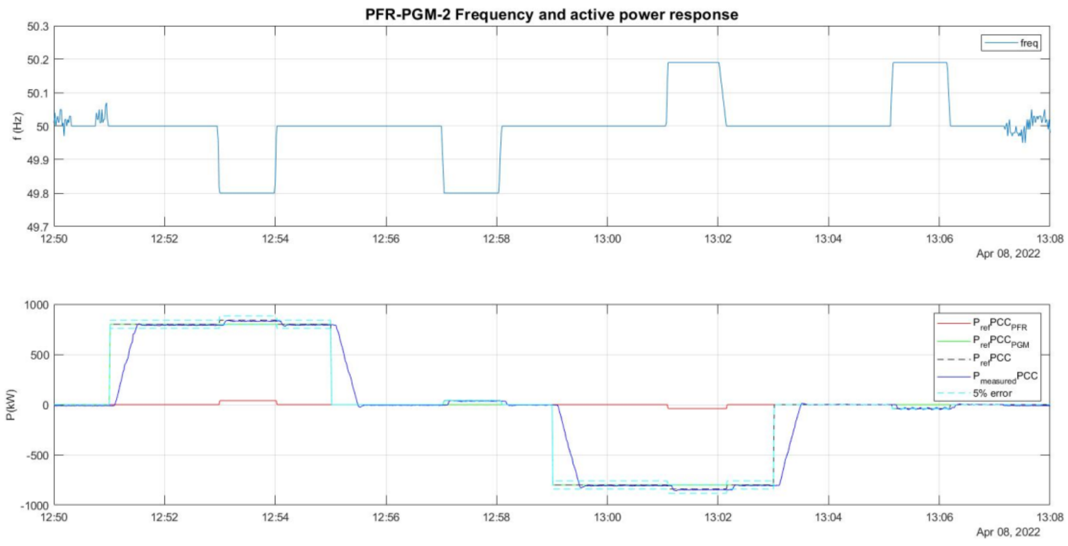

Figure 107: PFR-PGM-2 frequency and active power at PCC

The active power setpoint is followed according to PGM defined active power profile and, when the frequency experiences any variation, the active power response changes accordingly.

In this test, one objective was to observe the performance of the system when not enough energy was reserved for 2nd level functionalities. However, the reserved energy was enough for this test and the limitation cannot be seen. In spite of that, this test passes the acceptance criteria.

PFR-PGM-3:

The combined functionalities are PFR-p, which is classified as a 1st level functionality, and PGM, which is classified as a 3rd level functionality, are controlled simultaneously by the MC. Following the methodology, the signals measured at PCC during 80 minutes with a sampling rate of 1 second are shown in Figure 108

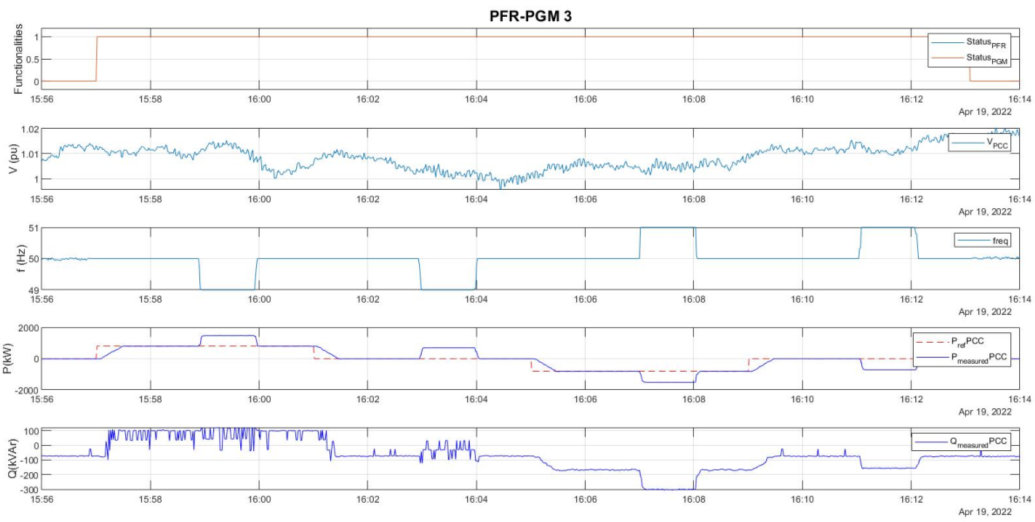

Figure 108: PFR-PGM-3 signals measured at PCC

Frequency and active power response at PCC are show in Figure 109.

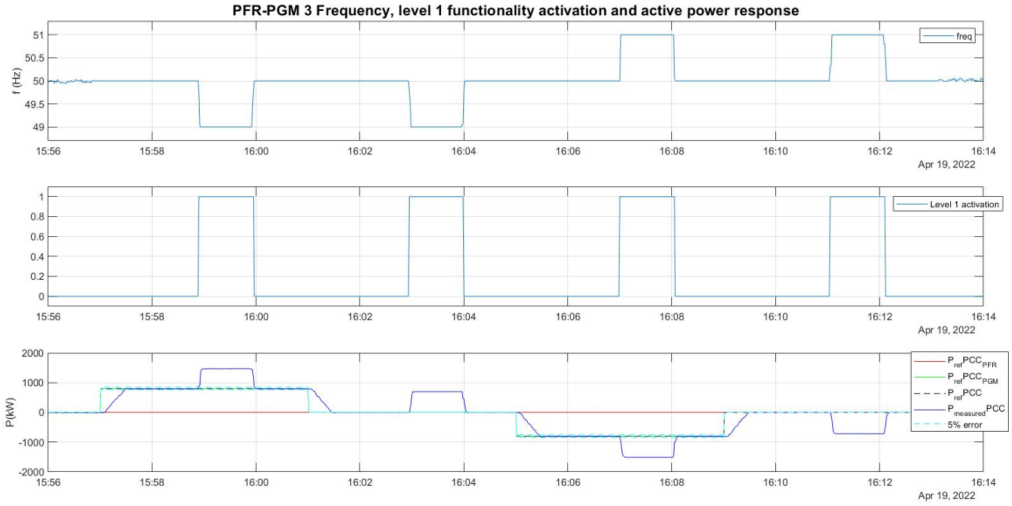

Figure 109: PFR-PGM-3 frequency and active power at PCC

Since PFR-p functionality response is more critical than PGM, when the frequency varies in a way that the HFD must react to solve the frequency deviation, the HFD activates a flag that communicates to the MC that it is solving an urgent event. Then, the MC, in order to avoid adding more distortion to the grid, maintains the last setpoint before the activation of the flag until the situation returns to a less critical status.

The HFD, due to the frequency variation along this test, provides +700kW when the frequency decrease to 49Hz and –700kW when the frequency changes from 50Hz to 51Hz. These power values and the power setpoints by PGM can be observed at PCC. Given that, the PGM profile is defined as changes from 0kW to 500kW and –500kW, when the frequency response is activated, the measures at PCC change from 0kW to 500kW, to 1200kW for a frequency value of 49Hz, and from 0kW to –500kW and –1200kW when the frequency is 51Hz.

The performance of this test is accepted.

<u>Summary for PFR-PGM tests</u>

The test conditions are verified and thus acceptance criteria for PFR-PGM tests results are summarized in Table 60.

Test condition		Acceptance
PFR-PGM-1	Follow P-set-point and to frequency deviation (continuous)	✓
PFR-PGM-2	Follow P-set-point and to frequency deviation (continuous)	✓
PFR-PGM-3	Follow P-set-point and to frequency deviation (perturbed regime)	✓

Table 60: Acceptance criteria for PFR-PGM tests

4.6.2. Power-frequency Regulation and Congestion Management (PFR-CMT-1 PFR-CMT-2 PFR-CMT-3)

The combination of these two functionalities enables the TSO to limit the active power in a certain node and reduce the effect of variability of renewable energy generation. At the same time, in case of unexpected frequency changes, the system may inject or absorb active power in response, taking into account that frequency regulation must be prioritised.

4.6.2.1. Test conditions definition

Purpose

The main goal of this test is to verify that the system reacts to both functionalities at the same time.

Pre-test conditions

Pre-test conditions and parameters for the test:

- Table 3P-f regulation activates (PFR_Status = 1)
- Program management activated (PGM_Status = 1).
- Level-1 functionalities disabled except PFR
- Level-2 functionalities disabled except PFR
- Level-3 functionalities disabled except CMT
- F_PPC = 50 Hz
- V_PPC = 1 p.u.
- SOCinicial = 50%
- PFR_PmaxRange = [-Lp ; Lp]
- PFR_DeadBand = [-0,050 Hz ; +0,050 Hz]
- PFR_Droop= 4%
- CMT_NodeRenLimit = changes
- CMT_StatDynMode =1
- CMT_DischargeMode=0

	Lp	Le	Eta
PFR-CMT-1	20%	15%	0MW
PFR- CMT-2	20%	1%	0MW
PFR- CMT 3	20%	15%	0.1 MWh

Table 61: Power and energy reserves for PFR-CMT

Methodology

The devices that take part along PFR-CMT tests are HFD, redox-flow battery, lead-acid battery and lithium-ion from ATENEA microgrid.

Frequency disturbance in the grid and times:

	PFR-CMT-1		PFR- CMT -2		PFR- CMT -3	
Time[min]	f	| df/dt |	f	| df/dt |	f	| df/dt |
0	50 Hz	-	50 Hz	-	50 Hz	-
3	50.2 Hz	<= 0,5 Hz/s	50.2 Hz	<= 0,5 Hz/s	51 Hz	<= 0,5 Hz/s
4	50 Hz	<= 0,5 Hz/s	50 Hz	<= 0,5 Hz/s	50 Hz	<= 0,5 Hz/s
7	49.8 Hz	<= 0,5 Hz/s	49.8 Hz	<= 0,5 Hz/s	49 Hz	<= 0,5 Hz/s
8	50 Hz	<= 0,5 Hz/s	50 Hz	<= 0,5 Hz/s	50 Hz	<= 0,5 Hz/s

Table 62: f_PCC frequency profiles for PFR-CMT

Track the active power PV generation and power limit in the node for different control parameters.

	PV	Lrn mode	Lrn	Discharge Mode	Discharge Program	Minutes apart between changes
PFR-CMT-1-2-3	1 MW	1	[1.5,0.5]MW	0	0	[1,4,5]

Table 63: P setpoint for PFR-CMT

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its active power response according to the limit in the node and frequency variations.

4.6.2.2. Test results

PFR-CMT-1:

The combined functionalities are PFR-n, classified as 2nd level, and CMT, classified as 3rd level, are controlled simultaneously by the MC. Following the methodology, the signals measured at PCC during 10 minutes with a sampling rate of 1 second are shown in Figure 110.

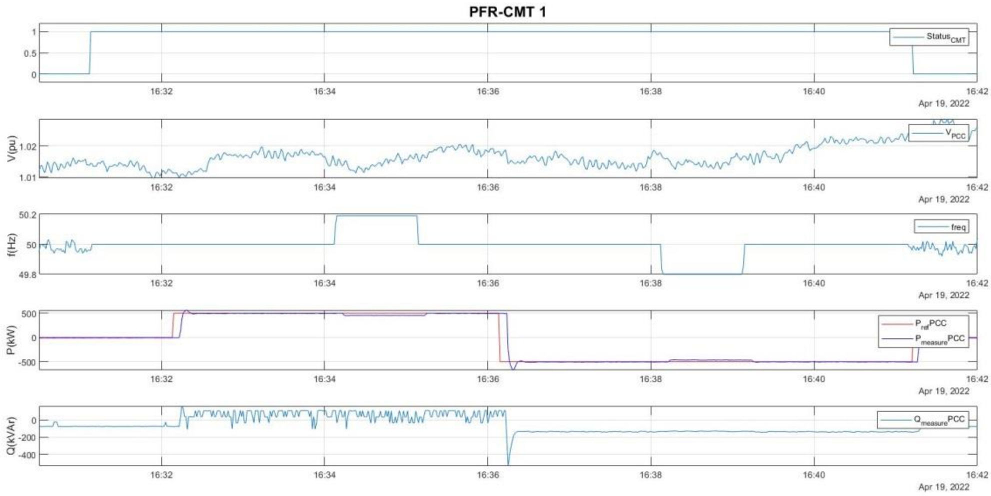

Figure 110: PFR-CMT-1 signals measured at PCC

In Figure 111, frequency, active power response at PCC according to power limitations and SOC are presented.

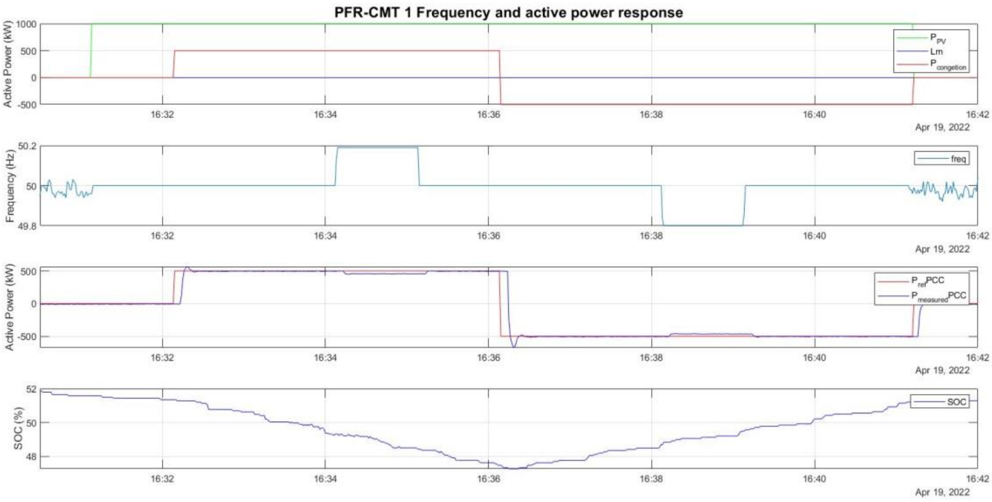

Figure 111: PFR-CMT-1 frequency and active power at PCC

The active power setpoint at PCC is the result of the difference between active power limit established for the node and the PV generation. The active power setpoint to fulfil with the CMT active power limitation in the node is plotted with the active power measurement at PCC that also represent the active power response due to frequency variations (see Figure 111.

In this test, the active power response follows the CMT setpoint in normal frequency moments. When the frequency experiences a deviation, the active power at PCC changes until the frequency is restored.

Therefore, this test passes the acceptance criteria.

PFR-CMT-2:

The combined functionalities are PFR-n, which is classified as a 2nd level functionality, and CMT, which is classified as a 3rd level functionality, are controlled simultaneously by the MC. Following the methodology, the signals measured at PCC during 10 minutes with a sampling rate of 1 second are shown in Figure 112.

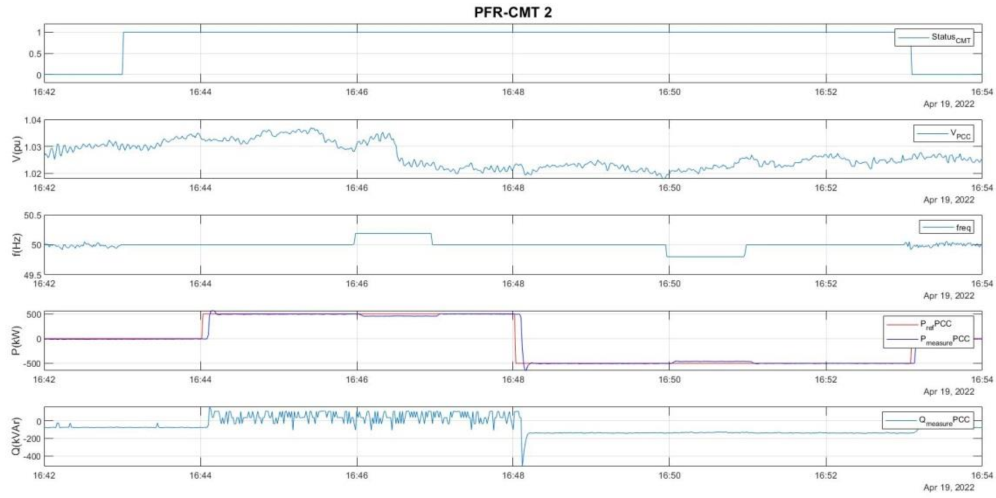

Figure 112: PFR-CMT-2 signals measured at PCC

In Figure 113, frequency, active power response at PCC according to power limitations and SOC are presented.

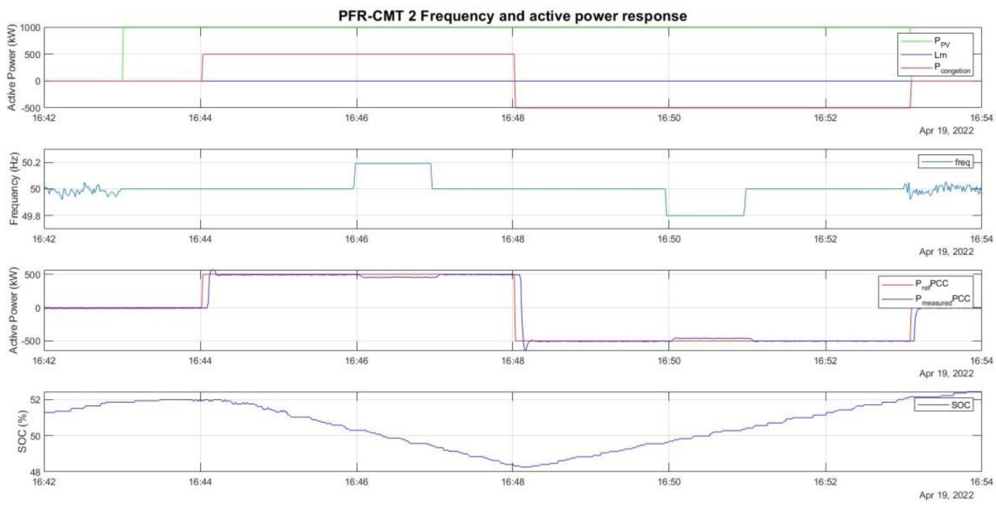

Figure 113: PFR-CMT-2 frequency and active power at PCC

The active power setpoint at PCC is the result of the difference between active power limit established for the node and the PV generation. The active power setpoint to fulfil with the CMT active power limitation in the node is plotted along with the active power measurement at PCC that also represent the active power response due to frequency variations (see Figure 113.

In this test, the active power response follows the CMT setpoint in normal frequency moments. When the frequency experiences a deviation, the active power at PCC changes until the frequency is restored.

In this test, one objective was to observe the performance of the system when not enough energy was reserved for 2nd level functionalities. However, the reserved energy was enough for this test and the limitation cannot be seen. Despite that, this test passes the acceptance criteria.

PFR-CMT-3:

The combined functionalities are PFR-p, which is classified as a 1st level functionality, and CMT, which is classified as 3rd level functionality, are controlled simultaneously by the MC. Following the methodology, the signals measured at PCC during 10 minutes with a sampling rate of 1 second are shown in Figure 114

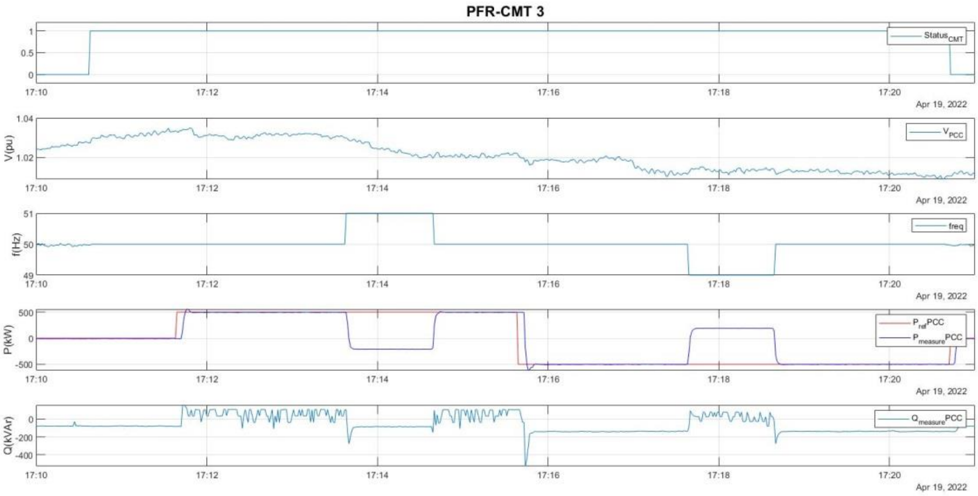

Figure 114: PFR-CMT-3 signals measured at PCC

In Figure 115, frequency, active power response at PCC according to power limitations and SOC are presented.

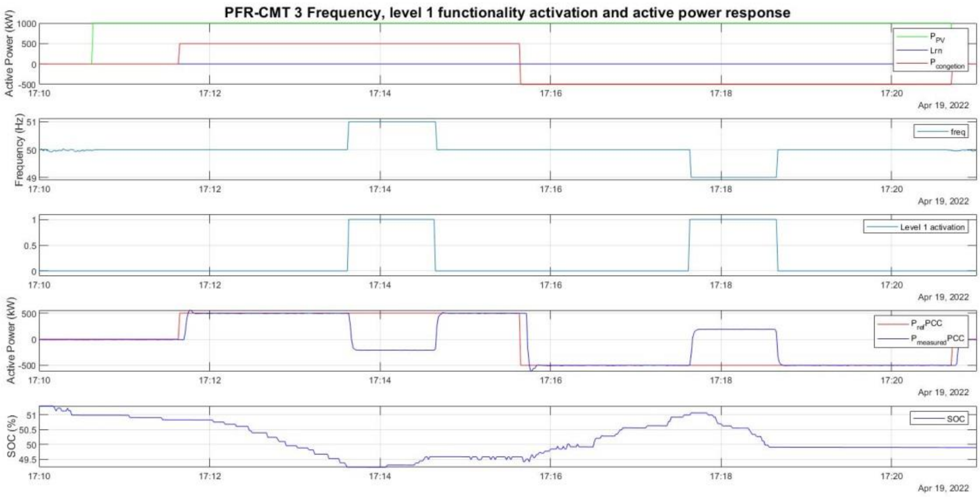

Figure 115: PFR-CMT-3 frequency and active power at PCC

The active power setpoint at PCC is the result of the difference between active power limit established for the node and the PV generation. The active power setpoint to fulfil with the CMT active power limitation in the node is plotted with the active power measurement at PCC that also represent the active power response due to frequency variations (see Figure 115.

In this test, the active power response follows the CMT setpoint in normal frequency moments. When the frequency experiences a deviation, the active power at PCC changes until the frequency is restored. Since PFR-p functionality response is more critical than PGM, when the frequency varies in a way that the HFD must react to solve the frequency deviation; the HFD activates a flag that communicates to the MC that it is solving an urgent event. Then, the MC, in order to avoid adding more distortion to the grid, maintains the last setpoint before the activation of the flag until the situation returns to a less critical status.

The HFD, due to the frequency variation along this test, provides +700kW when the frequency decrease to 49Hz and –700kW when the frequency changes from 50Hz to 51Hz. These power values and the power setpoints by PGM can be observed at PCC. Given that the PGM profile is defined as changes from 0kW to 500kW and –500kW, when the frequency response is activated, the measures at PCC change from 500kW, to -200kW for a frequency value of 49Hz, and from –500kW and 200kW when the frequency is 51Hz.

The performance of this test is accepted.

Summary for PFR-CMT tests

The test conditions are verified and thus acceptance criteria for PFR-CMT tests results are summarized in Table 64.

	Test condition	Acceptance
PFR-CMT-1	Follow P-set-point and to frequency deviation (continuous)	✓
PFR-CMT-2	Follow P-set-point and to frequency deviation (continuous)	✓
PFR-CMT-3	Follow P-set-point and to frequency deviation (perturbed regime)	✓

Table 64: Acceptance criteria for PFR-CMT tests

4.6.3. Power-frequency Regulation and Voltage Control based on Reactive Power Setpoint (PFR-VCQ)

The combination of these two functionalities enables the TSO to set a reactive power reference to control reactive power at PCC. At the same time that, in case of unexpected frequency changes, the system may inject or absorb active power in response, taking into account that frequency regulation must be prioritised.

4.6.3.1. Test conditions definition

Purpose

The main goal of this test is to verify that the system reacts to both functionalities at the same time.

Pre-test conditions

Pre-test conditions and parameters for the test:

- Table 3P-f regulation activated (PFR_Status = 1)
- V control based on Q setpoints activated (VCQ_Status = 1).
- Level-1 functionalities disabled
- Level-2 functionalities disabled except PFR and VCQ
- Level-3 functionalities disabled
- F_PPC = 50 Hz
- V_PPC = 1 p.u.
- SOCinicial = 50%
- Lp = 100%
- Le = 100%
- Eta = 0 MWh
- PFR_PmaxRange = [-Lp ; Lp]
- PFR_DeadBand = [-0,050 Hz ; +0,050 Hz]
- PFR_Droop= 4%
- VCQ_Q_LimMAX = Q_MCFS (capacitive)
- VCQ_Q_LimMIN = -Q_MCFS (inductive)
- VCQ_VMAX = 1,05 pu
- VCQ_VMIN = 0,95 pu
- VCQ_RAMP = 2 MVAr/min

Methodology

The devices that take part along PFR-VCQ tests are HFD and redox-flow battery from ATENEA microgrid.

Frequency disturbance in the grid and times:

PFR-VCQ		
Time[min]	f	| df/dt |
0	50 Hz	-
3	50.2 Hz	<= 0,5 Hz/s
4	50 Hz	<= 0,5 Hz/s
7	49.8 Hz	<= 0,5 Hz/s
8	50 Hz	<= 0,5 Hz/s

Table 65: f_PCC frequency profiles for PFR-VCQ

The control will be validated for different reactive setpoints, both capacitive and inductive, with and without ramp in the setpoint, according to the next table.

Time [min]	VCQ_Qconsigna	VCQ_RAMP	VCQ_RAMP_Status
0	+Q_MCFS/2 (inductive)	2 MVAr/min	0
5	-Q_MCFS/2 (capacitive)	2 MVAr/min	1

Table 66 Q Control Parameters profile for PFR-VCQ

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its active power response according to frequency variations and its Q according to setpoints.

4.6.3.2. Test results

The combined functionalities are PFR-n and VCQ, which are classified as 2nd level functionalities, are controlled simultaneously by the MC. Following the methodology, the signals measured at PCC during 10 minutes with a sampling rate of 1 second are shown in Figure 116.

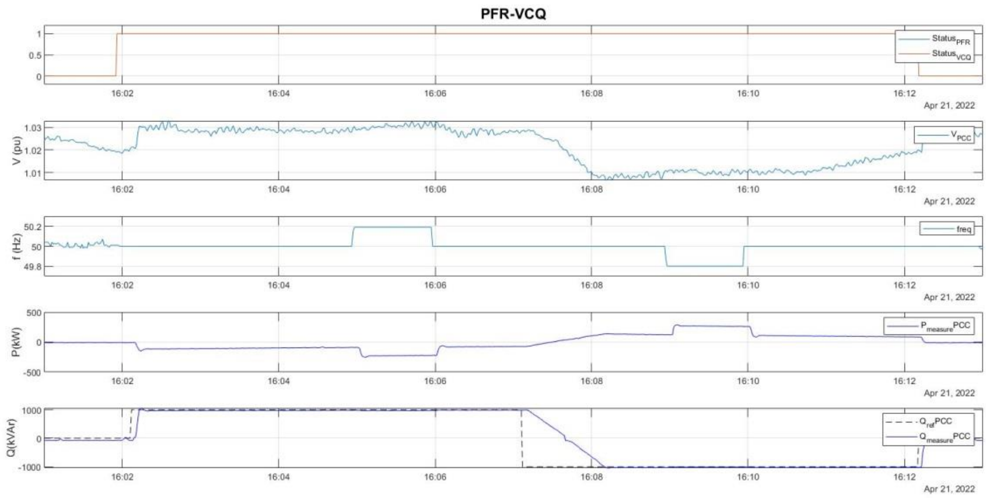

Figure 116: PFR-VCQ signals measured at PCC

The reactive power setpoint is followed according to VCQ defined power profile. Also, the different active power setpoints, as result of frequency deviations, are achieved. It is important to highlight the reactive power has less priority than the active power.

Regarding the reactive power response, its performance is correct and according to setpoint and Q ramp status.

Regarding the active power at PCC, when any frequency deviation occurs, the functionality PFR-n acts and a new active power setpoint is reached to solve the frequency deviation. However, when there is no frequency deviation, the active power measured is not controlled and, due to the effect of VCQ setpoints, the active power at PCC experiences some small changes.

Therefore, this test passes the acceptance criteria.

Summary for PFR-VCQ test

The test conditions are verified and thus acceptance criteria for PFR-VCQ test results are summarized in Table 67.

Test condition		Acceptance
PFR-VCQ	Follow Q-set-point and responds to frequency deviation (continuous)	✓

Table 67: Acceptance criteria for PFR-VCQ test

4.6.4. Voltage Control based on Reactive Power Setpoint and Program Management (VCQ-PGM)

The combination of these two functionalities enables the TSO to set a charge/discharge program along with a reactive power reference to control reactive power at PCC.

4.6.4.1. Test conditions definition

Purpose

The main goal of this test is to verify that the system reacts to both functionalities at the same time.

Pre-test conditions

Pre-test conditions and parameters for the test:

- Table 3Program management activated (PGM_Status = 1)
- V control based on Q setpoints activated (VCQ_Status = 1).
- Level-1 functionalities disabled
- Level-2 functionalities disabled except VCQ
- Level-3 functionalities disabled except PGM
- F_PPC = 50 Hz
- V_PPC = 1 p.u.
- SOCinicial = 50%
- Lp = 0%
- Le = 0%
- Eta = 0 MWh
- VCQ_Q_LimMAX = Qn_HFD (capacitive)
- VCQ_Q_LimMIN = -Qn_HFD (inductive)
- VCQ_VMAX = 1,05 pu
- VCQ_VMIN = 0,95 pu
- VCQ_RAMP = 2 MVAr/min
- PGM_RampUp = 2 MW/min
- PGM_RampDowni = -2 MW/min
- PGM_Ti=10
- SPT_P_Setpoint(1)= 1 MW
- SPT_P_Setpoint(2)= -2 MW

Methodology

The devices that take part along VCQ-PGM tests are HFD, lead-acid battery and lithium-ion from ATENEA microgrid.

The main action performed is to track the active power setpoint for each program according to Table 68.

	PGM_P_setpoint [MW]	SPT_RampUp [MW/min]	SPT_RampDown [MW/min]	PGM_Ti [min]
VCQ-PGM	[SPT_P_Setpoint(1), 0, SPT_P_Setpoint(2), 0]	2	2	10

Table 68 active power setpoint and times for VCQ-PGM

The control will be validated for different reactive power setpoints, both capacitive and inductive, with and without ramp in the setpoint, according to Table 69.

Time [min]	VCQ_Qconsigna	VCQ_RAMP	VCQ_RAMP_Status
5	-Q_MCFS /2 (inductive)	2 MVAr/min	0
15	+Q_MCFS /2 (capacitive)	2 MVAr/min	1

Table 69 Control parameters profile for VCQ-PGM

Signals to be measured

- V_PCC
- f_PCC
- P_HFD
- Q_HFD

Acceptance criteria

The MCFS must vary its active and reactive power according to setpoints.

4.6.4.2. Test results

The combined functionalities are VCQ, which is classified as a 2nd level functionality, and PGM, which is classified as a 3rd level functionality, are controlled simultaneously by the MC. Following the methodology, the signals measured at PCC during 70 minutes with a sampling rate of 1 second are shown in Figure 117.

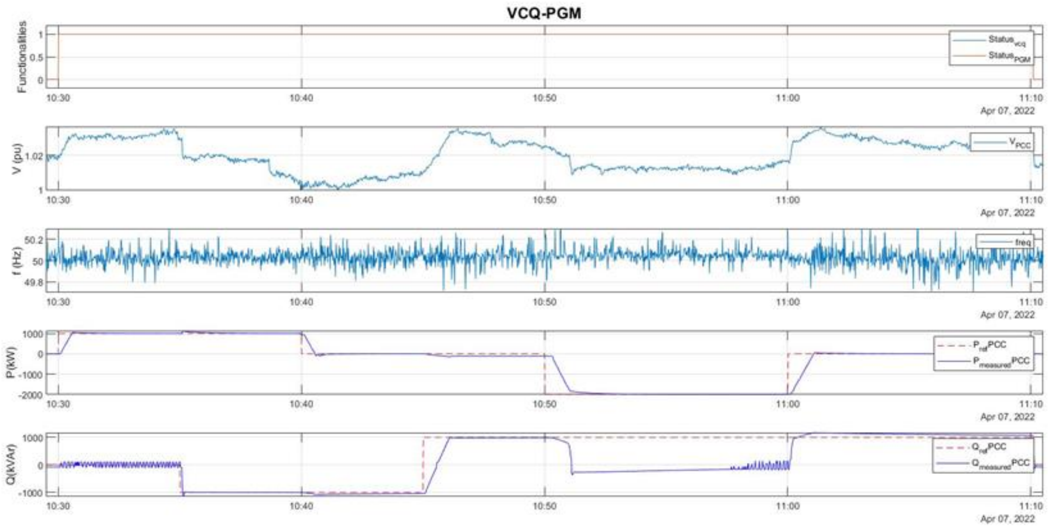

Figure 117: VCQ-PGM signals measured at PCC

In Figure 118, active power and reactive power response at PCC are presented for VCQ-PGM.

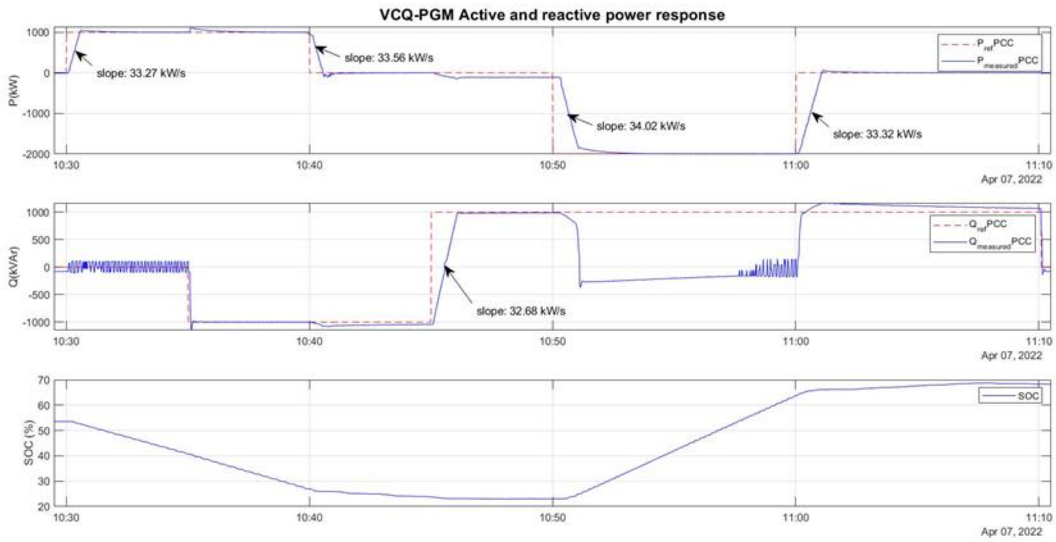

Figure 118: VCQ-PGM active and reactive power at PCC

The active power setpoint is followed according to PGM active power profile. Also, the reactive power setpoint is perfectly followed according to VCQ profile.

It is important to remark that two limitations are experienced along the test. The first one is related to the priority order. In this case the reactive power has less priority than the active power. Subsequently, when both setpoints are established to be supplied at the same time, reactive power is not achieved. The second limitation is the one related with SOC limits, which has been commented in previous tests.

Another point to highlight is the ability of the MCFS to replicate the magnitude of the measured ramp that follows each setpoint. In active power the measured values are:

- The ramp up of the first change measured at PCC is 2.00MW/min (33.27kW/s).
- The ramp down of the second change measured at PCC is -2.01MW/min (-33.56kW/s).
- The ramp down of the third change measured at PCC is -2.04MW/min (-34.02kW/s).
- The ramp up of the fourth change measured at PCC is 2.00MW/min (33.32kW/s).

In reactive power the measured values are:

- The ramp up of the first change measured at PCC is 1.96MW/min (32.68kW/s).

Therefore, this test passes the acceptance criteria.

Summary for VCQ-PGM test

The test conditions are verified and thus acceptance criteria for VCQ-PGM test results are summarized in Table 70.

Test condition		Acceptance
VCQ-PGM	Follow P-set-point and responds to frequency deviation (continuous)	✓

Table 70. Acceptance criteria for VCQ-PGM test

4.6.5. Inertia emulation control and Power-frequency Regulation. Perturbed regime (INE-PFRp)

The combination of these two functionalities enables the TSO to set an increase of active power as a function of frequency derivative, while it also considers the rapid variations of the power exchanged with the grid, measuring frequency at the PCC.

4.6.5.1. Test conditions definition

The device must vary its active power as a function of the frequency derivative and frequency variation, as fast as possible, and as a function of the inertia emulation (INE) and Power-frequency regulation (PFR).

The disturbance tested is an underfrequency event, where the frequency will drop from 50Hz to 49Hz with a derivative of 1 Hz/s. The parameters implemented for each functionality are as follows:

- INE_H = 4 s
- INE_DeadBand = +/- 0,5 Hz/s
- INE_df/dt limit = 0 Hz/s
- INE_t = 200 ms
- PFR_PmaxRange = [-100 % ; +100 %]
- PFR_DeadBand = [-0,050 Hz ; +0,050 Hz]
- PFR_Droop = 4 %
- P_HFD_pretest = 0.3 * Pn

The contributions of each functionality are calculated as follow;

- For the inertia emulation, as described in Section 4.2.1, the formula governing the power increase versus frequency derivatives is:

$$\Delta P = 2 \cdot \overline{H} \cdot \frac{\partial f}{\partial t} = 2 \cdot 4[s] \cdot \frac{2800[kW]}{50[Hz]} \cdot 1 \left[\frac{Hz}{s}\right] = \mathbf{448}\ \boldsymbol{kW}$$

- For the PFR-p, as described in Section 4.2.3, the equation governing the power droop in response to frequency variations for PF regulation for a 4% droop is as follows:

$$|\Delta P| = \frac{|\Delta f|}{f_n} \cdot \frac{P_{max}}{0.04} = \frac{0.95^{(*)}}{50} \cdot \frac{2500\ [kW]}{0.04} = \mathbf{1187.5}\ \boldsymbol{kW}$$

$*: \Delta f = f_n - (f_{disturb} - f_{DeadBand}) = 0.95\ Hz$

The ideal combined operation shall consist of a first actuation of the inertia emulation, which shall bring the theoretical value in a time period lower than 200ms, enough time to iterate a correct measurement of the frequency derivative. Thereafter, the level 2 frequency response should bring the reference power to its theoretical value according to the implemented droop.

4.6.5.2. Test results

The results obtained from this combined test are shown in the following graphs.

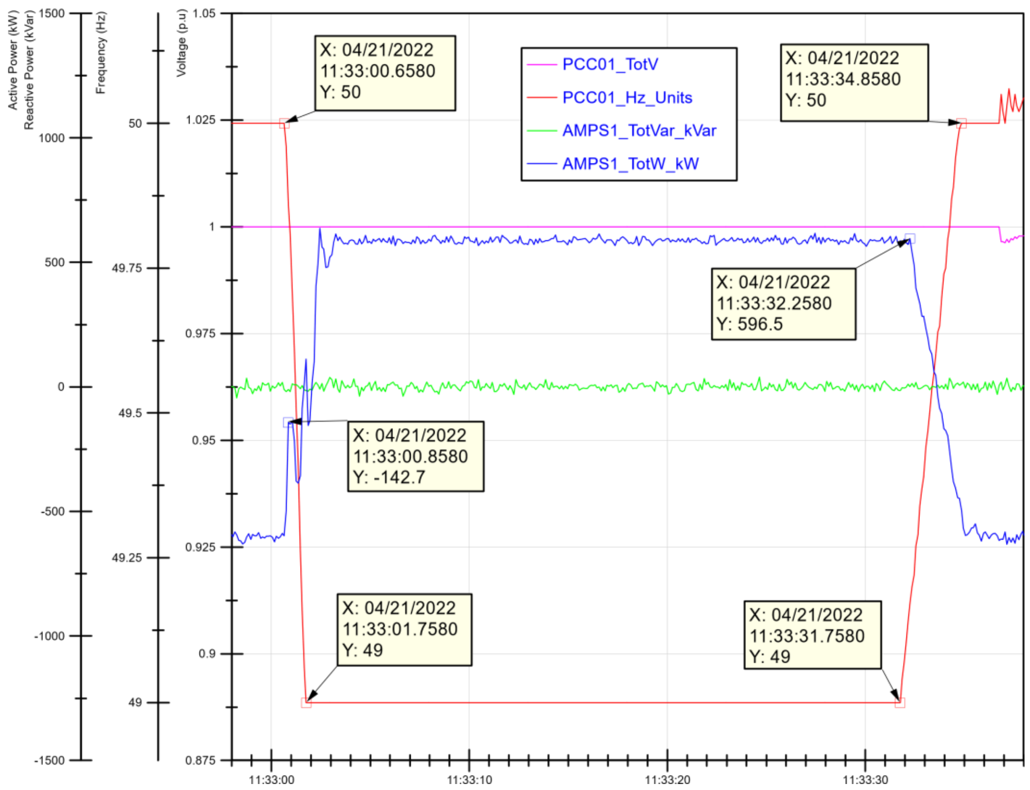

Figure 119. Results for INE-PFRp combined functionality

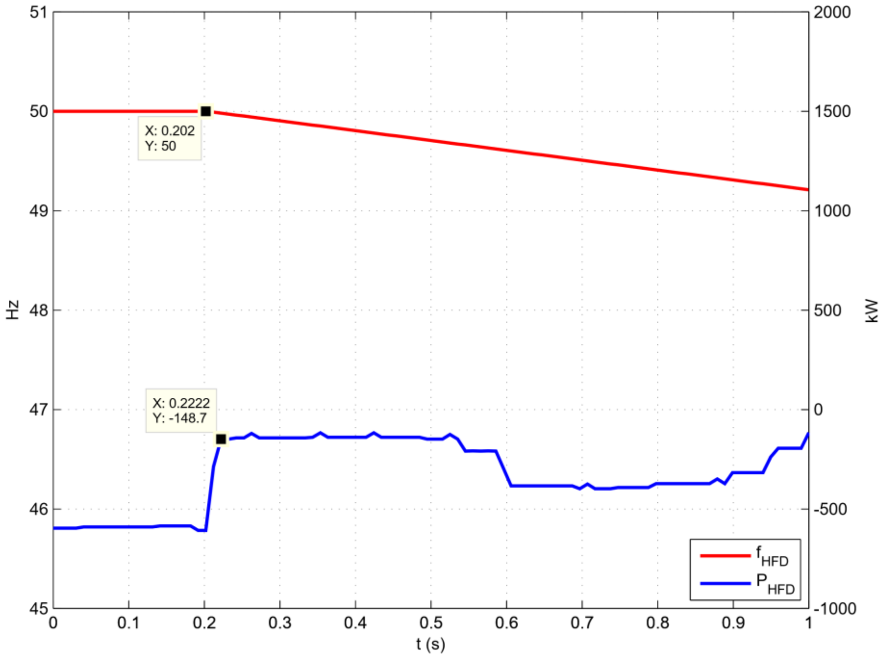

Figure 120. Frequency and Active Power in INE-PFRp results

The test values have been represented using the two data acquisition systems, the PPC (slow, values at 100ms) and the one stored in the DSP (fast, values in this case at 10 ms). Thus, it is possible to check values in the permanent for the entire duration of the test and to verify the initial response times.

Considering that pre-test power setpoint is -600 kW, it is observed that the INE control has:

- An initial response corresponding to the inertia emulation of 451.3 kW.
- With respect to the expected value, there is a deviation of 0.74 %.
- In terms of response time, it can be seen that the calculation of the derivative is fast enough to obtain an inertial response in 20ms and
- Deviation is very small, which means
- a very satisfactory result.

The power-frequency control achieves:

- A power increase of 1196.5 kW in the steady state,
- resulting in a deviation of 0.76 %.

In the transient regime, an oscillation in the initial ramp can be observed, which is caused by the coexistence of the two functionalities at the same time. The inertia response must be fed back to the plant PI and a tuning process is necessary, which still needs to be debugged.

However, it can be seen that this does not affect the deviations with respect to the theoretical value, nor does it greatly affect the response time, with room for future analysis of improvement.

4.6.6. Fast Frequency Response and Power-frequency Regulation. Nominal regime (FFR-PFR)

The combination of these two functionalities enables the TSO to set active power as a function of frequency variations, while it also responds to the rapid variations of the power exchanged with the grid, measuring frequency at the PCC. This combination combines a level-1 functionality (FFR) and level-2 functionality (PFR), which operate at the perturbed regime and normal operation, respectively.

4.6.6.1. Test conditions definition

The device must vary its active power as a function of the frequency variation as a function of the frequency response control levels: Fast one, level 1-FFR, and steady state, level 2-PFR.

The disturbance tested is an underfrequency event in which the frequency will drop from 50Hz to 49Hz with a derivative of 2 Hz/s. The parameters implemented for each functionality are as follows:

- FFR_PmaxRange = [-100 % ; +100 %]
- FFR_DeadBand = [-0,050 Hz ; +0,050 Hz]
- FFR_Droop = 4 %
- PFR_PmaxRange = [-100 % ; +100 %]
- PFR_DeadBand = [-0,050 Hz ; +0,050 Hz]
- PFR_Droop = 4 %

Both functionalities are governed by the same characteristic curve and configured with the same droop. The response time has the same ramp rate for both functionalities. So, the combined response of both is essentially the same, only differing in the PI dynamic of the plant.

The equation controlling the power increase in response to frequency variations for PF regulation for a 4% droop will be as follows for both functionalities:

$$|\Delta P| = \frac{|\Delta f|}{f_n} \cdot \frac{P_{max}}{0.04} = \frac{0.95}{50} \cdot \frac{2500\ [kW]}{0.04} = \mathbf{1187.5\ kW}$$

The frequency derivative is higher in this case. Since there is no inertia emulation and the frequency response performs only against varying values, the final reference value is the same as in the previous case.

4.6.6.2. Test results

The results obtained from this combined test are shown in the following graphs:

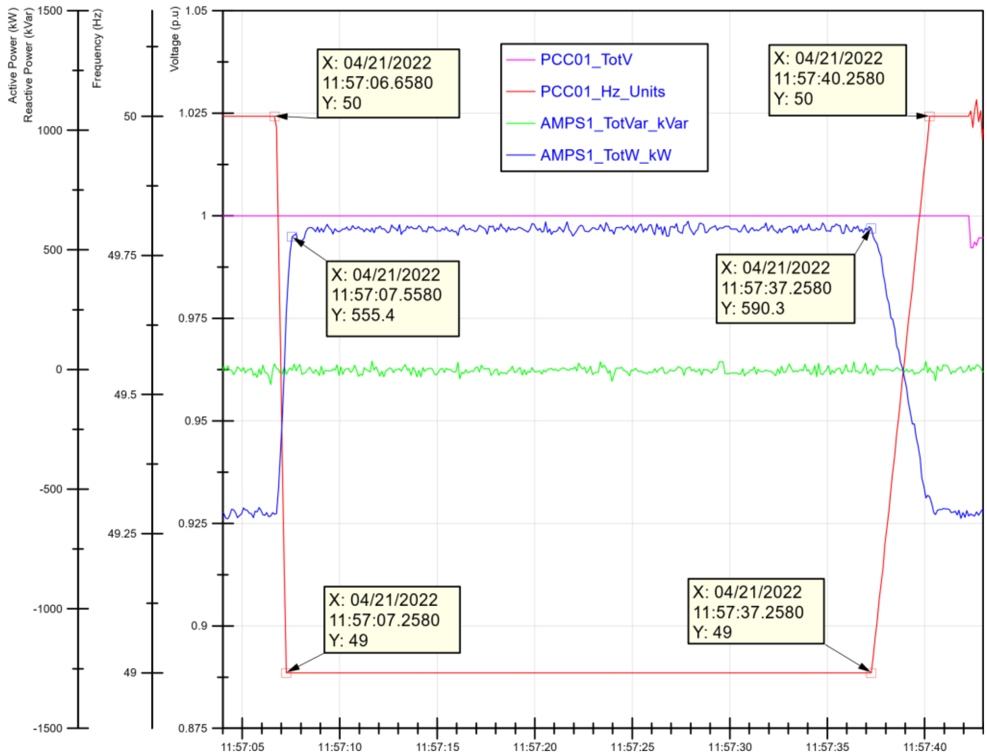

Figure 121. Results for FFR and PFR combined functionality

The calculation of the response time for a droop is key in combined functionalities tests. Considering that the reference is set by the frequency variation, when variation reaches -0.5 Hz, the response must rise to 50% of the final value. Therefore, the time from reaching 49.5 Hz until the 50% value (593.75 kW in this case) can be taken as the response time for Fast Frequency Response.

In order to check this time, Figure 122 is gathered, corresponding to the same test captured with the DSP with 5ms sampling.

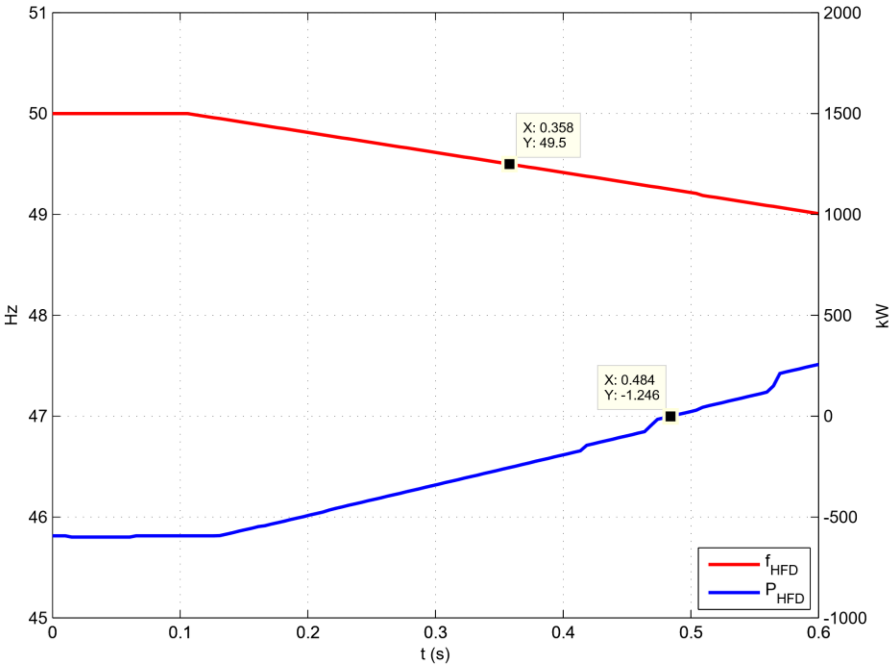

Figure 122. Frequency and Active Power in INE-PFR results

Given that the pre-test power reference is -600 kW, the steady state response of the combined action of the PFs functionalities is 1190.3 kW, resulting in a deviation of 0.24 %.

Checking Figure 122, it can be obtained that the FFR response time for this test is 126 ms. Therefore, the deviation and response time values fully meet the requirements.

4.6.7. Inertia emulation control, Power-frequency Regulation. Nominal regime and Voltage Control based on Voltage Setpoint (INE-PFRp-VCV)

The combination of these three functionalities enables the TSO the capability of simultaneously setting active and reactive power setpoints. Active power, as previously explained, is set as a function of frequency variations, operating at the disturbed operating regime and normal operation regime. The reactive power is set as a function of the voltage measurement and the defined control parameters.

4.6.7.1. Test conditions definition

The device must vary its active power as a function of the frequency variation as a function of the different control levels. In case of a severe perturbation, the level 1 active power control (INE) must respond. In the steady state, the level 2 power-frequency response must take control of the active power provision. In addition, the HFD will have level-2 reactive control capabilities based on a voltage setpoint. Thus, in the event of disturbances in the voltage values, the equipment will respond with reactive current injection/absorption in order to keep voltage level at the assigned reference.

The disturbance to be tested consists of a loss of active and reactive currents in the grid, leading to a drop in frequency and voltage values. Specifically, the grid will see its frequency decrease to 49 Hz with a rate of 1 Hz/s, while the voltage will experience an abrupt dip up to 0.9 p.u. in the voltage (~1ms).

The parameters implemented for each functionality are as follows:

- INE_H = 4 s
- INE_DeadBand = +/- 0,5 Hz/s
- INE_df/dt limit = 0 Hz/s
- INE_t = 200 ms
- PFR_PmaxRange = [- 100 % ; + 100 %]
- PFR_DeadBand = [- 0,030 Hz ; + 0,030 Hz]
- PFR_Droop = 4 %
- VCV_Vconsigna = 1,00 pu
- VCV_Kv = 2
- VCV_DeadBand = [- 0,025 pu ; + 0,025 pu]
- VCV_Lim_Q1 = 0 pu
- VCV_Lim_V1 = 0.95 pu
- VCV_Lim_Q2 = - 1 pu
- VCV_Lim_V2 = 0.98 pu
- VCV_Lim_Q3 = 1 pu
- VCV_Lim_V3 =1.03 pu
- VCV_Lim_Q4 = 0 pu
- VCV_Lim_V4 = 1,05 pu
- VCV_Q_LimMAX = Qn_HFD (capacitive)
- VCV_Q_LimMIN = - Qn_HFD (inductive)

Since the simulated disturbance is analogous to the Section 4.6.6, the active power contributions of the INE and PFR functionalities are identical to that case:

$$\Delta P_{INE} = \mathbf{448\ kW}\ ;\ \Delta P_{PFR} = \mathbf{1187.5\ kW}$$

For the calculation of the reactive power required, we use the equation already seen in section 4.3.2. In the case of this test, the parameters would be:

$$\frac{\Delta Q}{Q_n} = K_v \cdot \frac{\Delta V}{V_n} \rightarrow \Delta Q = 2 \cdot \frac{2000\ [kVAr] \cdot 0.1\ [p.u.]}{1[p.u.]} = \mathbf{400\ kVAr}$$

The same disturbance is tested with reactive control disabled. The objective of those test is to check if the FFR or PFR controls are affected by the VCV one.

4.6.7.2. Test results

The results obtained from this combined test are shown in the following graphs:

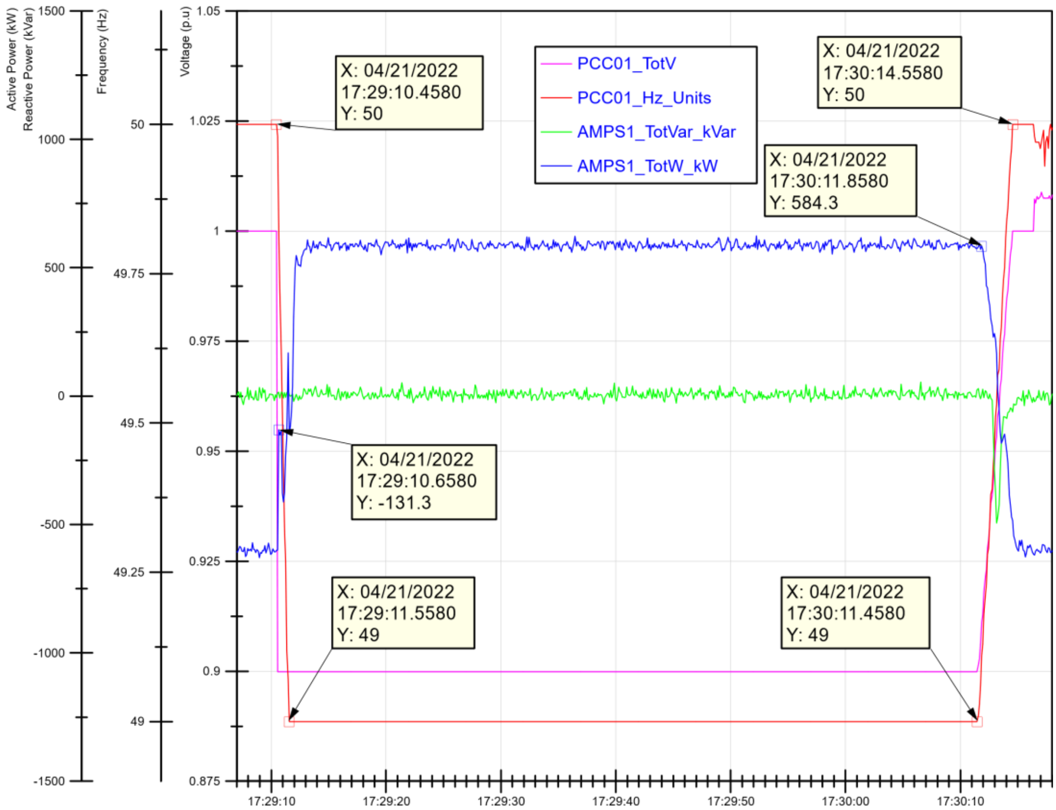

Figure 123. Results for FFR & PFR & VCV combined functionality with reactive control disabled

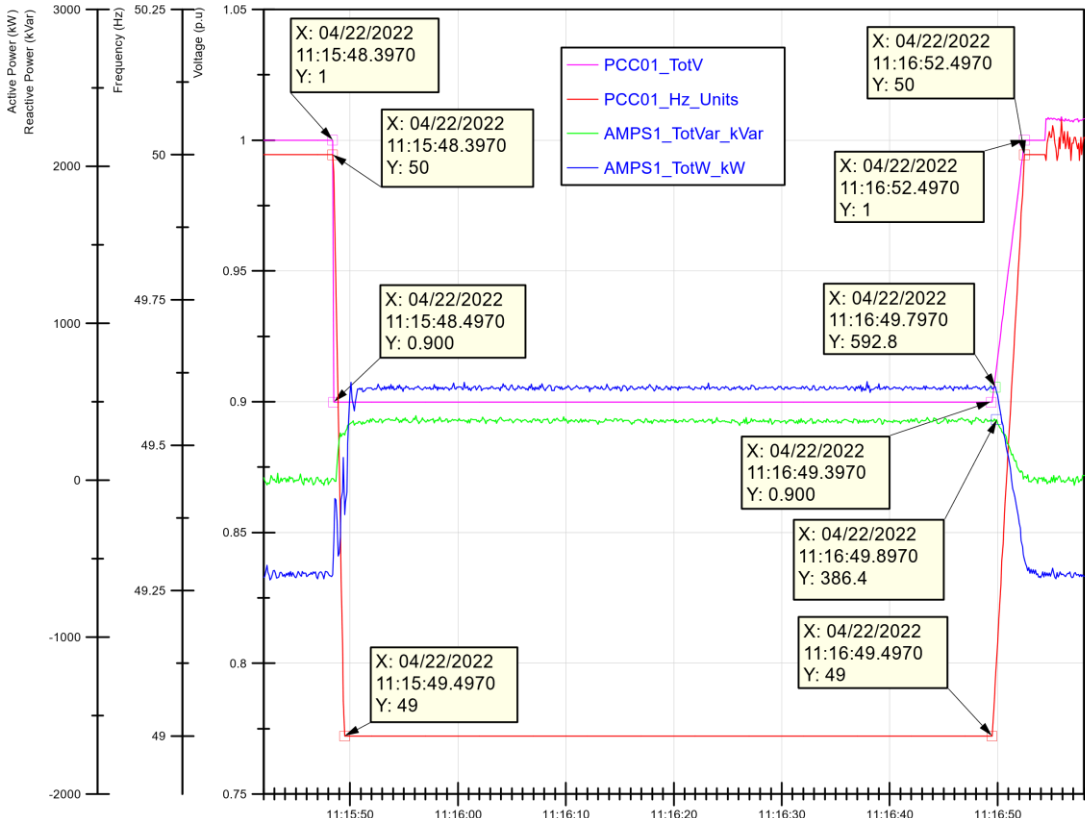

Figure 124. Results for FFR & PFR & VCV with reactive control connected

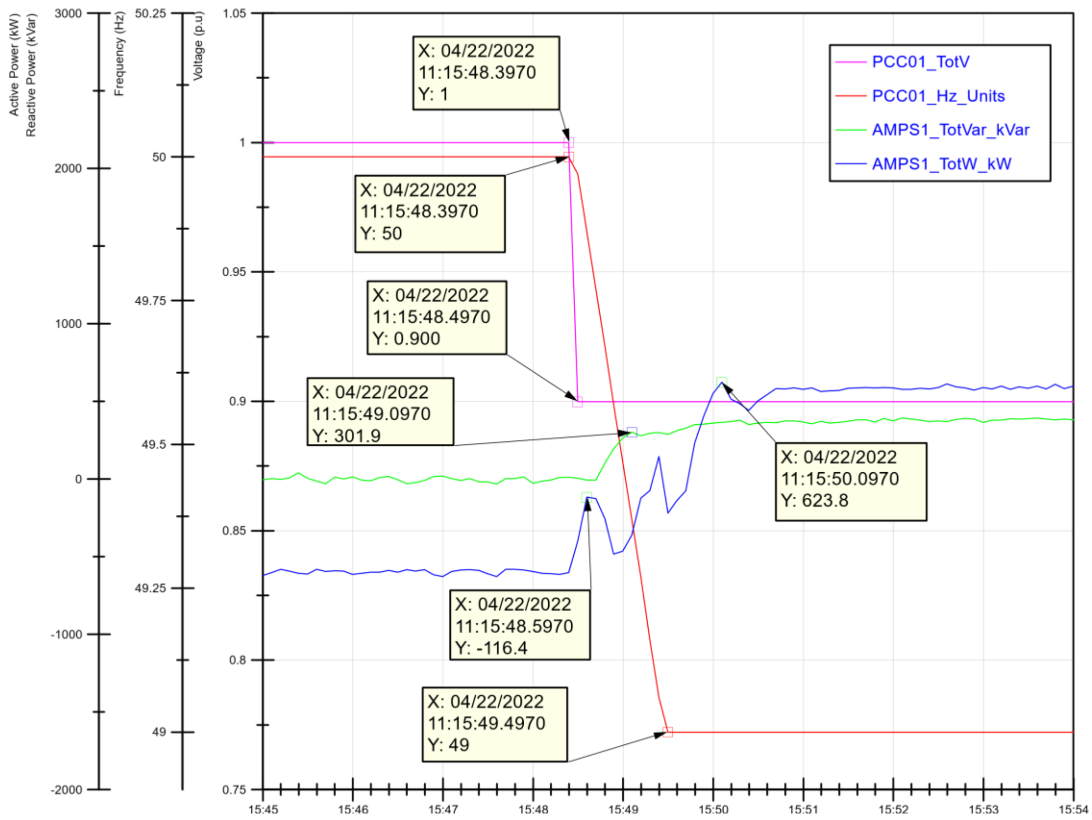

Figure 125. Zoom on initial FFR & PFR & VCV test with reactive control connected

Figure 123 shows the results with the reactive control disabled:

- The response time of the inertia emulation obtained is a maximum of 200ms (it should be noted that it was measured with a sampling rate of 100ms).
- The deviation is 4.62 %. In the steady state, at the end of the test, a deviation of 0.27 % is observed.

The results with the reactive control activated are shown in Figure 124:

- In this case, the response time of the inertia emulation is not affected by the reactive control.
- Its deviation is 7.94 %, and in the steady state it is 0.45 %.
- Regarding reactive control, the response time for 75% of the reference is 500ms, and its deviation in the steady state is 3.4%.

In general terms, no serious conflicts are observed between active and reactive control functionalities. However, overall performance can be optimized, especially with regards to initial response of the INE-PFR implementation.

5. Simulation description and results

The objective of this WP, as a part of the OSMOSE project, is to bring a useful tool in order to provide the flexibility so that European power systems can handle a high share of renewables. In particular, the demonstrator developed in this WP is intended to provide a solution to instability issues and RES integration in the isolated power system formed by the islands of Lanzarote and Fuerteventura (Spain). Since the demonstrator had to be set up in CENER facilities, simulations become useful to predict the impact of such technologies in an isolated power system. In this context, different simulation models have been developed in this work package. So as to evaluate them, it is needed to test the different functionalities that have been modelled. The simulations performed to this purpose have to be executed on a simulator that enables to recreate the conditions and characteristics of the physical demonstrator. Lately, a simulator of the Lanzarote-Fuerteventura power system was used to analyse the impact of the HFD.

5.1. Simulation method

The different functionalities implemented in the MCFS work in different time frames, which influences the simulation environment to be used. Furthermore, each specific device requires its own models, which obliges to have a platform to enable communication between models from different environments and co-simulation. In this section, the main points of the simulation method used to test the models are described.

5.2. Models

Three main models are needed to perform these simulations. A grid model is needed as a base for transient stability and power flow simulations, a specific is needed to evaluate the performance of the HFD and, finally, a MC model is needed to test its performance. These models are described next.

5.2.1. Grid model

A grid model has been created based on the electrical description of CENER inner grid provided by CENER. Detailed data about each electrical circuit involved, including lines and transformers, and about characteristics of the PCC has been used to build the grid model. Nonetheless, given the particular characteristics of the experimental method used in this study, the simulator needed to allow to “reproduce” the signals the models had to respond to. For this reason, the grid model has been designed so as to comply with the requirements of the simulation platform (PSS-E) for this kind of simulations.

In Figure 126, the single-line schematic of grid model, based on the MCFS demonstrator is shown. A “play-back” generator model has been used to “reproduce” voltage and frequency time series so a set of contingencies may be recreated. This generator model imposes the voltage and frequency conditions at its bus, so it cannot be paired with an infinite generator. For this reason, the circuits linking ATENEA substation with the outer grid have been substituted by the “play-back” generator model. This model has been connected to a 20-kV bus to which the output line of the HFD and the 20/0’4kV transformer that feeds the ATENEA microgrid are connected. The PCC, which is used as the reference bus for the different controls, is bus 30 (CT-HFD).

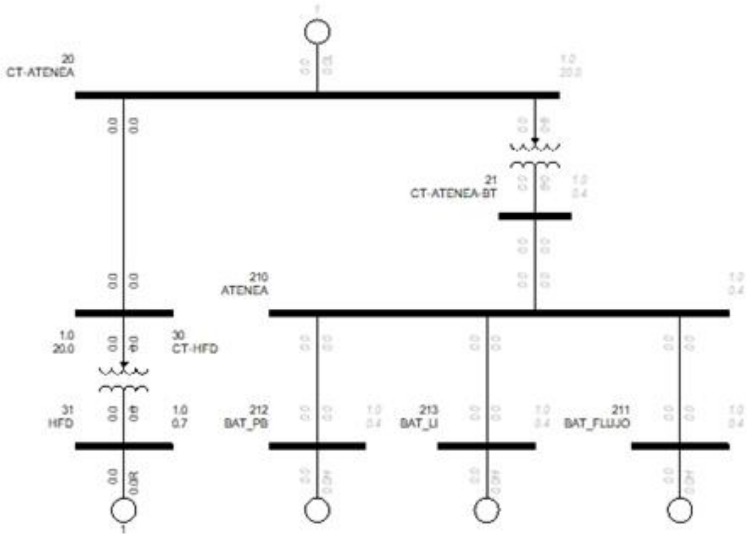

Figure 126: single-line schematic of the grid simulator.

Alternatively, a grid simulator of the Lanzarote-Fuerteventura power system has been used to evaluate the impact of the HFD in this isolated power system. The Lanzarote-Fuerteventura power systems is formed by two power systems linked by a submarine cable. Each island has its own power station, located at Punta Grande (Lanzarote) and Las Salinas (Fuerteventura). This grid simulator has been provided by REE.

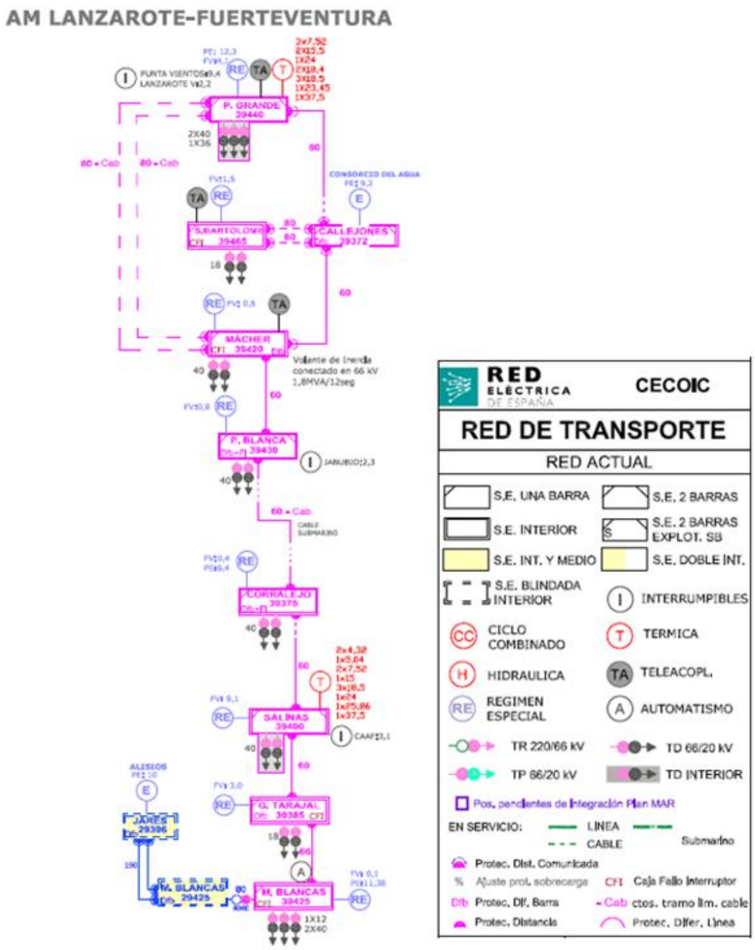

Figure 127: single-line schematic of the Lanzarote-Fuerteventura power system.

5.2.2. HFD model

The HFD model is composed of two complementary models developed for PSS-E. One of them is a generator model and the other is a plant control model. This models, as well as their configuration information has been provided by the HFD manufacturer (GPTech). The model configuration has been modified so as to enable or disable the corresponding functionalities in each simulation. This has been also modified to obtain the desired response of the controllers. The HFD model has been validated throughout this project.

5.2.3. MC model

The MC model has been developed using Simulink and consists of a single model comprising a plant control module and an energy management/optimisation module. This model, its documentation and its configuration has been provided by CENER. The model utilises the input data to calculate the consign values with which the HFD, and the rest of flexibility devices, are fed. The input data is obtained from simulations based on the aforementioned grid and HFD models using PSS-E. Apart from this data, the MC model is provided with a data file so as to configure each control algorithm for each simulation. The MC model is executed iteratively based on this configuration file until the pre-defined number of iterations is met to so the output data can be stored. The output of the MC model at each simulation step conditions the behaviour of the HFD in the next grid simulation.

5.3. Simulation environments

As mentioned before, the HFD and MC models have been developed utilising two distinct simulation environments, which are based on different programming languages. On the one hand, the HFD model has been developed using the Power Systems Simulator for Engineers (PSS-E) software. This is a renowned power systems simulation software capable of performing a wide variety of analysis; namely power flow or short circuit calculations, transient simulations, or reliability tests. PSS-E comprises a Python library that enables to execute the instructions needed to automate any of its tools.

On the other hand, the MC model has been developed using Matlab/Simulink. Simulink is a visual programming environment based on Matlab programming environment. Matlab is a numerical computing system that includes an integrated development environment and its own programming language (M). Taking advantage of the so called “engines”, it is possible to call Matlab functions written in other languages, such as C, Fortran or Python.

5.4. Simulation platform

The variety of simulation environments used to develop the different models needed to perform the simulations has become a major challenge during this task. To tackle this challenge, a co-simulation platform has been developed to enable the simultaneous simulation of both the HFD and MC models and the communication between them. Apart from the difficulties related to the integration of two models implemented in different simulation environments, we have faced compatibility issues that led us to design de simulation platform as a distributed platform with synchronisation mechanisms. This co-simulation platform, developed in Python, is referred to as PyCoSim.

The compatibility issues that were found are related to the architecture of the software system used. Given that both PSS-E and Matlab/Simulink may be automated via Python code, this could have been the common point from which co-simulation and data exchange could have been set. Nonetheless, the version of the PSS-E software used in this project was not compatible with such applications, while Matlab/Simulink versions that included the Python engine were 64-bits applications. Therefore, the challenge was not only to communicate two models embedded in different simulation environments, but to execute them simultaneously and in different processes.

The communication mechanism used, within the distributed execution scheme, was the synchronisation mechanism, instead of orchestration. Under this mechanism, each process has its own intelligence to know when it has to wait for the other process(es), when it should be self-executed or when it has to provide the other process with data so they can be executed. This is made via sentinel files, in which each process may write and read so their execution is synchronised.

The development of this platform is based on the knowledge gained in the development of PySelf, another simulation platform implemented in the first stages of this project. From this experience we understood the importance of automation to handle the great number of simulations needed. Especially when different kinds of simulations need to be performed. For this reason, PyCoSim enables not only to coordinate the data exchange between PSS-E and Matlab/Simulink and to coordinate time management so as to enable co-simulation.

PyCoSim also enables to automate the management and visualisation of the results, providing output files and plots that merge information from both processes. Nevertheless, we should note that PyCoSim is not able to perform transient simulations due to the limitations of PSS-E to handle exogenous events generated by the MC in each simulation step.

The transient simulations related to level-1 and level-2 functionalities have been performed taking advantage of PySelf, which also enabled to automate the management of the results and the generation of plots. Level-3 functionalities have been tested using PyCoSim. These tests use PSS-E to perform the power flow calculations needed to update the grid state so the MC can make decisions.

5.5. Simulation results

As already mentioned, several simulations have been performed in this study to evaluate both the models and the grid simulator. In this section, the results obtained from these tests are presented.

5.5.1. Level-1 functionalities

Level-1 functionalities are intended to ensure the stability of the power system. Since the actions performed under these functionalities need to be as fast as possible, they are implemented in the HFD itself. These functionalities have been tested through transient simulations whose results are presented next.

Fast Frequency Response (FFR)

So as to test the FFR functionality, an over-frequency test has been carried out. A data series has been provided to the “play-back” generator model to emulate a frequency deviation near 51.5 Hz (1.03 p.u.). Three different configurations have been tested, configuring the FFR droop to 1%, 4% and 12%. These configurations are referred to as RMAX, RINT and RMIN, respectively. In this test, functionalities related to both frequency control (RPF) and voltage control (VCV) are disabled. In Figure 128 and Figure 129, the frequency profile and the active power response of the HFD are shown.

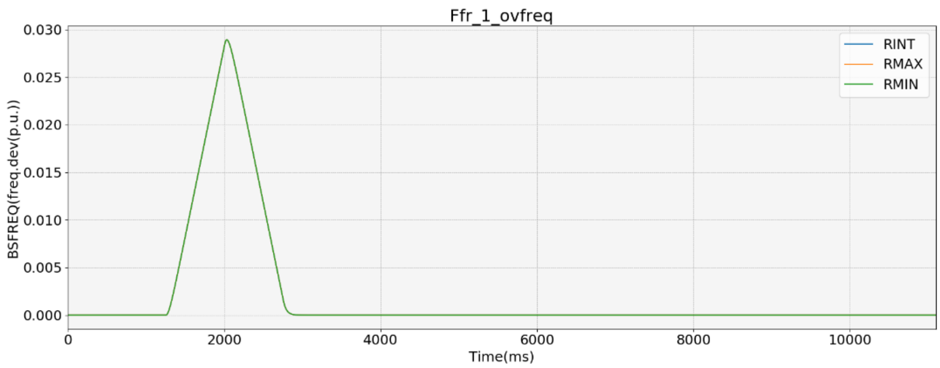

Figure 128: simulation of FFR, over-frequency test. Frequency deviation.

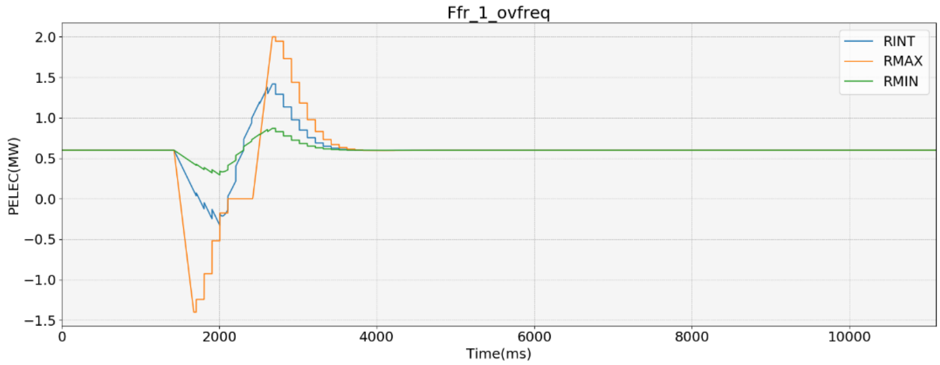

Figure 129: simulation of FFR, over-frequency test. Active power at the evacuation line.

An under-frequency test has also been carried out. A data series has been provided to the "play-back" generator model to emulate a frequency deviation near 48 Hz (0.96 p.u.). Three different configurations have been analysed, configuring the FFR droop to 1%, 4% and 12%. These configurations are referred to as RMAX, RINT and RMIN, respectively. In this test, functionalities related to both frequency control (RPF) and voltage control (VCV) are disabled. In Figure 130 and Figure 131, the frequency profile and the active power response of the HFD can be found.

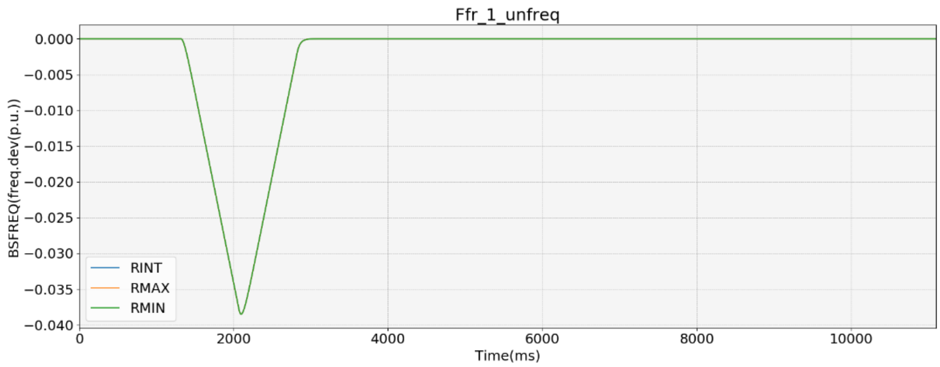

Figure 130: simulation of FFR, under-frequency test. Frequency deviation.

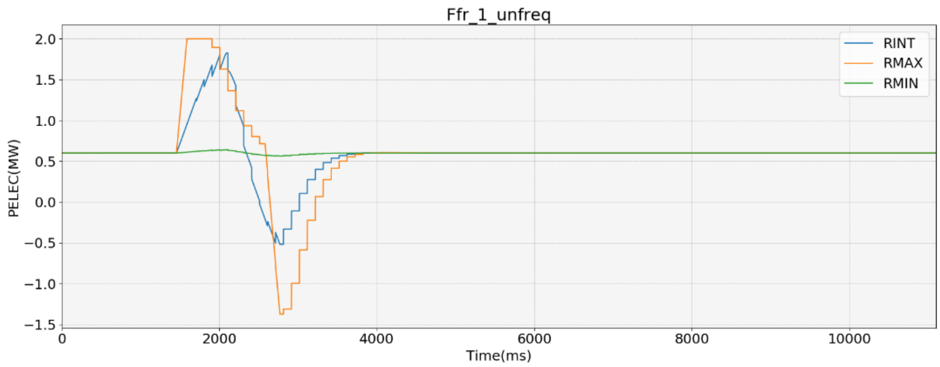

Figure 131: simulation of FFR, under-frequency test. Active power at the evacuation line.

This test has shown that the HFD model is able to respond to frequency deviations as a function of the droop value both for over and under-frequency disturbances. The model initial response is almost immediate, but its active power injection and its rate of change depends on the droop configuration. It can be seen that the RMAX configuration provides the maximum amount of power and that the RINT response gets close to that value as expected. However, in RINT and RMIN configurations, the frequency deviation begins to decrease before the power output reaches its maximum.

Fast Reactive Current (FRC)

In order to evaluate the FRC functionality, a simulation has been performed emulating a three-phase short circuit. A data series has been provided to the “play-back” generator model to emulate a voltage dip reaching 0.05 p.u.. Three different configurations of the FRC slop (K) have been tested; namely 6, 5 and 3.5. These configurations are referred to as RMAX, RINT and RMIN, respectively. In this test, functionalities related to both frequency control (RPF and FFR) and voltage control at normal operation (VCV) are disabled. In Figure 132 and Figure 133, the voltage profile and the reactive power output of the HFD can be found.

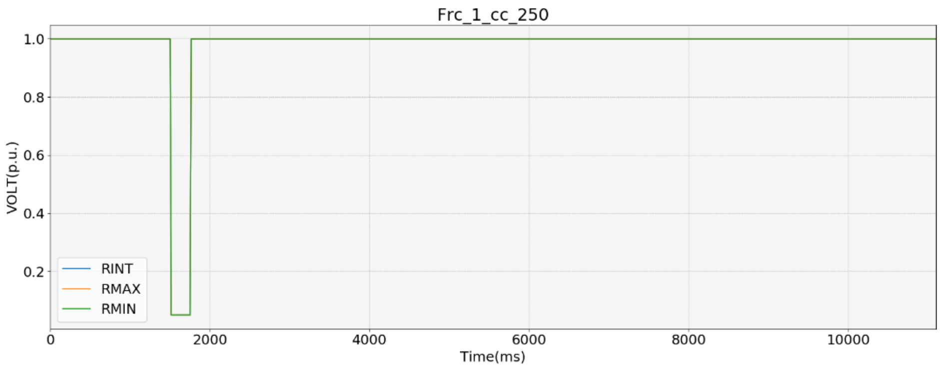

Figure 132: simulation of FRC, short circuit test. Voltage.

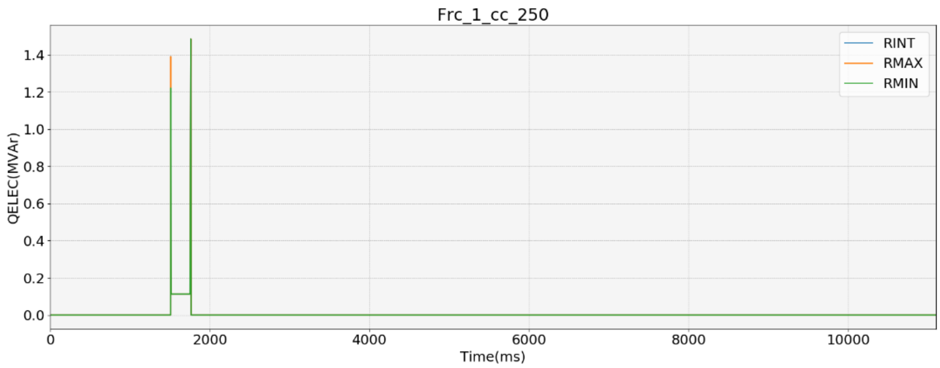

Figure 133: simulation of FRC, short circuit test. Reactive power at the evacuation line.

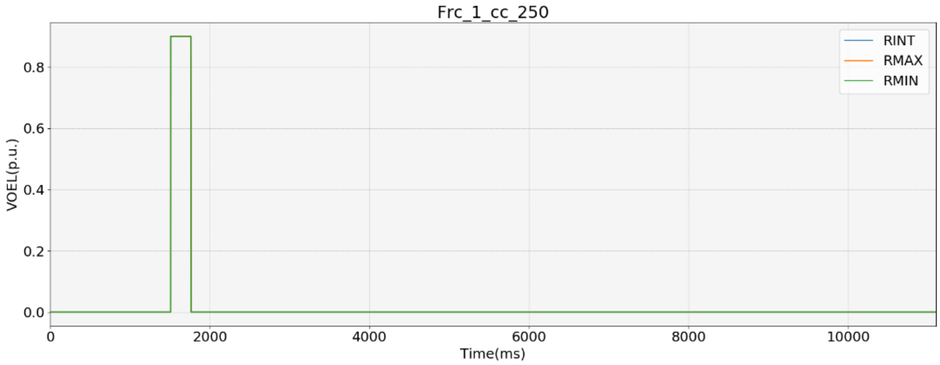

Figure 134: simulation of FRC, short circuit test. Reactive power reference (per unit).

This test shows how the FRC functionality provides fast reactive power response to severe voltage disturbances. When the voltage falls under 0.85 p.u. the HFD reactive power output provides instant reactive power. However, the reactive power output is curtailed, maybe due to the ramp limit (see Figure 133). In Figure 134, the reactive power reference provided by the FRC can be observed. This reference is set to the maximum (0.9 p.u.) for all configurations since, for all of them, the voltage falls below their point of maximum output.

An over-voltage simulation has also been performed using a data series to recreate a voltage increase up to 1.3 p.u.. Three different configurations of the FRC slop (K) have been tested; namely 6, 5 and 3.5. These configurations are referred to as RMAX, RINT and RMIN, respectively. In this test, functionalities related to both frequency control (RPF and FFR) and voltage control at normal operation (VCV) are disabled. In Figure 135 and Figure 136, the voltage profile and the reactive power output of the HFD are shown.

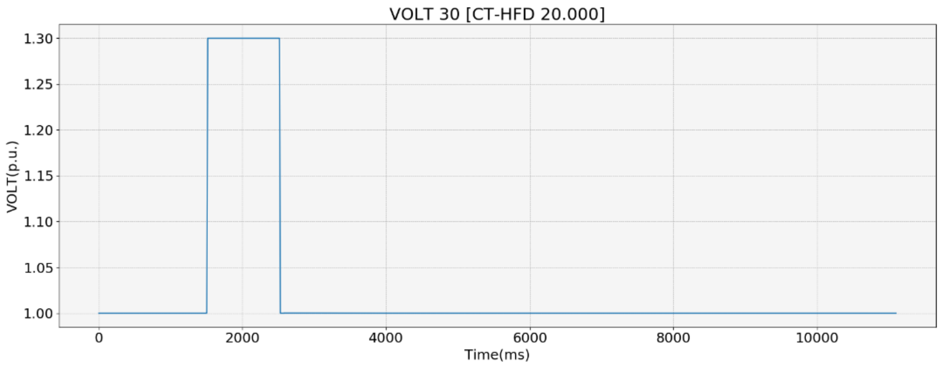

Figure 135: simulation of FRC, over-voltage test. Voltage.

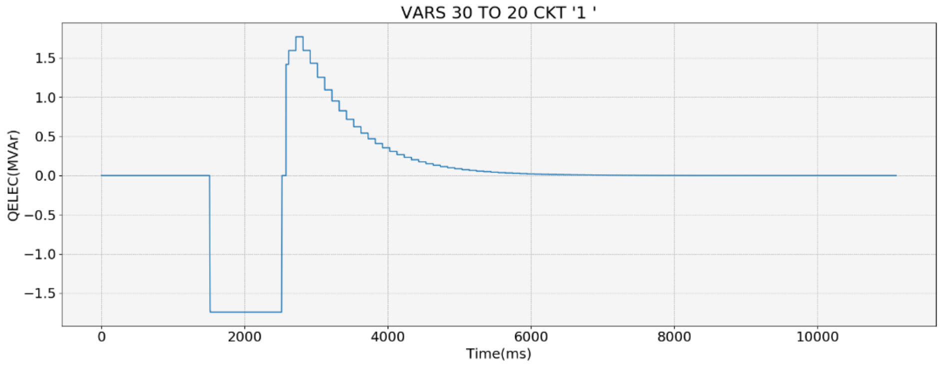

Figure 136: simulation of FRC, over-voltage test. Reactive power at the evacuation line.

In the over-voltage test it is found that the FRC provides maximum inductive reactive power almost instantly. Nonetheless, after the disturbance has ended, the reactive power output varies. This may be due to the reactive power control, which is enabled when the voltage control for normal operation is disabled. While the FRC is enabled, the VCQ has no control on the output. However, due to the fast recovery of the reactive power output, and once the FRC is disabled, the VCQ takes control of the output and imposes the remaining part of its dynamic response.

Power-frequency Response, perturbed regime (PFR-p)

So as to test the functionality intended to provide power-frequency response in perturbed operation state, an over-frequency test has been carried out. A data series has been provided to the "play-back" generator model to emulate a frequency deviation near 51.5 Hz (1.03 p.u.). Three different configurations have been tested, configuring the PFR-p droop to 1%, 4% and 12%. These configurations are referred to as RMAX, RINT and RMIN, respectively. In this test, functionalities related to both frequency control (FFR) and voltage control (VCV) are disabled. In Figure 137 and Figure 138, the frequency profile and the active power response of the HFD are shown.

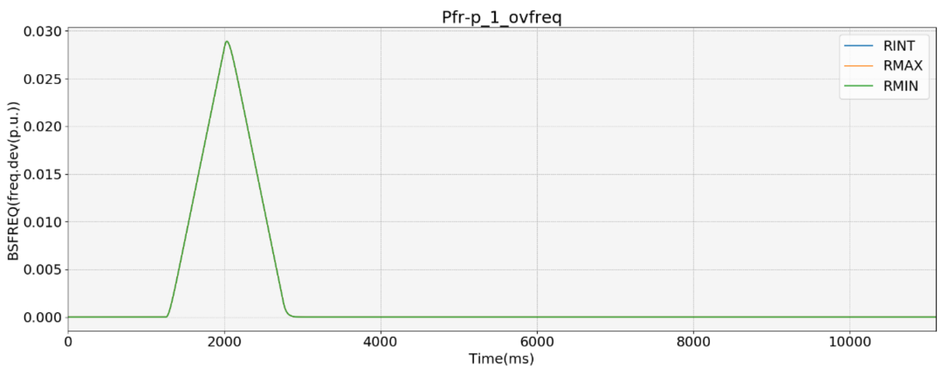

Figure 137: simulation of PFR-p, over-frequency test. Frequency deviation.

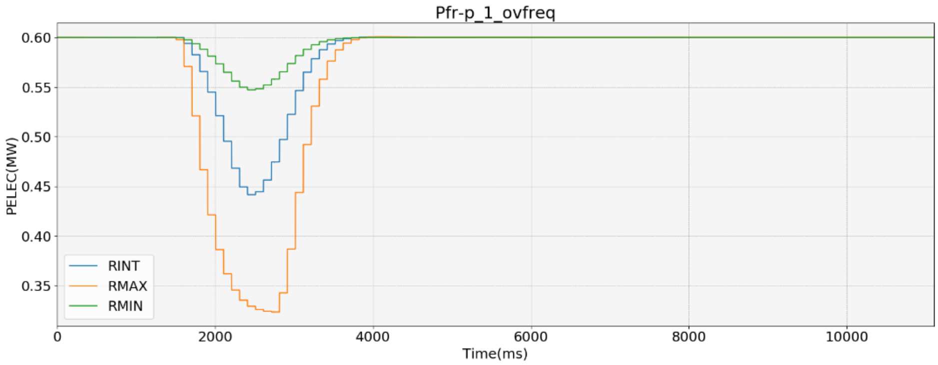

Figure 138: simulation of PFR-p, over-frequency test. Active power at the evacuation line.

An under-frequency tests has also been carried out using three different configurations of the PFR-p droop: namely, 1%, 4% and 12%. These configurations are referred to as RMAX, RINT and RMIN, respectively. In this test, functionalities related to both frequency control (FFR) and voltage control (VCV) are disabled. In Figure 139 and Figure 140, the frequency profile and the active power response of the HFD are shown.

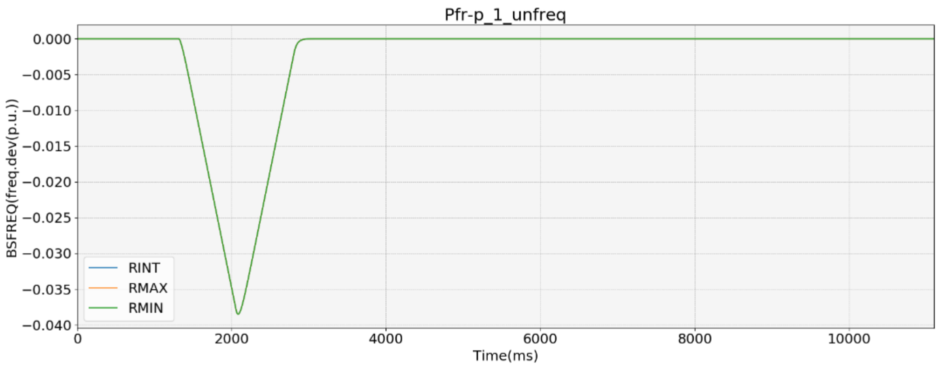

Figure 139: simulation of PFR-p, under-frequency test. Frequency deviation.

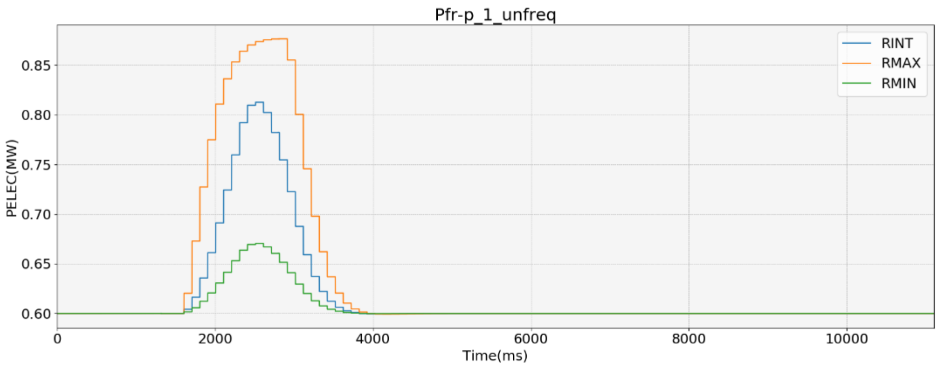

Figure 140: simulation of PFR-p, under-frequency test. Active power at the evacuation line.

The results obtained from these simulations demonstrate that the HFD model is able to perform fast frequency regulation using the power-frequency response functionality. This response is dependent on the droop configuration, but it is also influenced by the PI controller configuration (which has not been varied in these tests). It can be seen that the maximum response is reached only when the RMAX configuration is used. For RINT and RMIN, the frequency perturbation starts to decrease before the maximum respond is reached. Since, in this test, the output is limited to 0.46 p.u., it can be seen that the response matches the expected value.

5.5.2. Level-2 functionalities

Level-2 functionalities are intended to perform voltage and frequency control once the stability of the power system is ensured. They are implemented both in the HFD itself and in the MC for the sake of redundancy. However, only level-2 functionalities implemented in the HFD will be tested here. These functionalities have been tested through transient simulations whose results are presented next.

Power-frequency Response, normal operation regime (PFR-n)

An over-frequency test has been carried out to test the functionality intended to provide power-frequency response in normal operation state. A data series has been provided to the “play-back” generator model to emulate a frequency deviation near 50.25 Hz (1.005 p.u.). The PFR-p droop has been set to 4% and the deadband has been set to +/-0.05 Hz. In this test, functionalities related to both frequency control (FFR) and voltage control (VCV) are disabled. In Figure 141 and Figure 142, the frequency profile and the active power response of the HFD are shown.

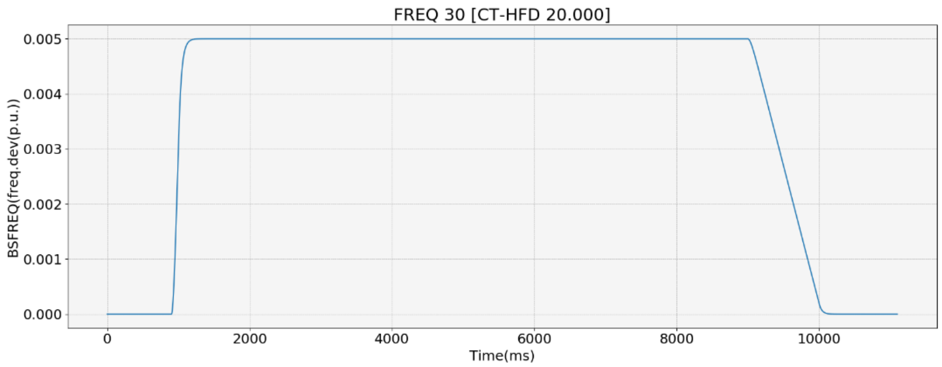

Figure 141: simulation of PFR-n, over-frequency test. Frequency deviation.

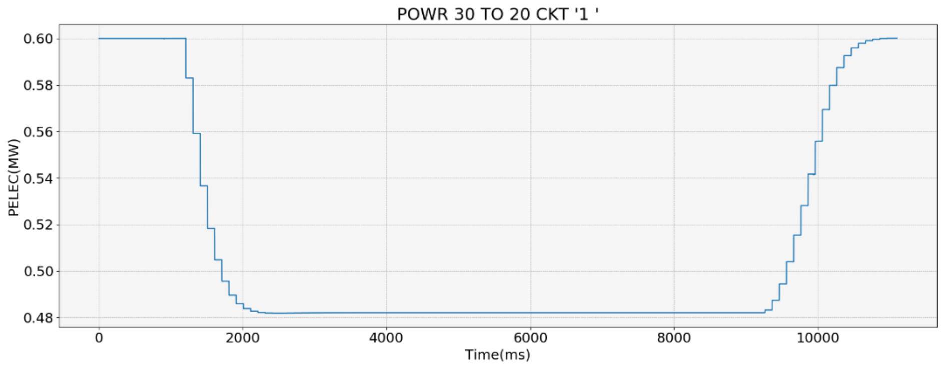

Figure 142: simulation of PFR-n, over-frequency test. Active power at the evacuation line.

An under-frequency test has also been carried out, in which a data series emulating a frequency deviation near 49.75 Hz (0.995 p.u.) has been used. The PFR-p droop has been set to 4% and the deadband has been set to +/-0.05 Hz. In this test, functionalities related to both frequency control (FFR) and voltage control (VCV) are disabled. In Figure 143 and Figure 144, the frequency profile and the active power response of the HFD are shown.

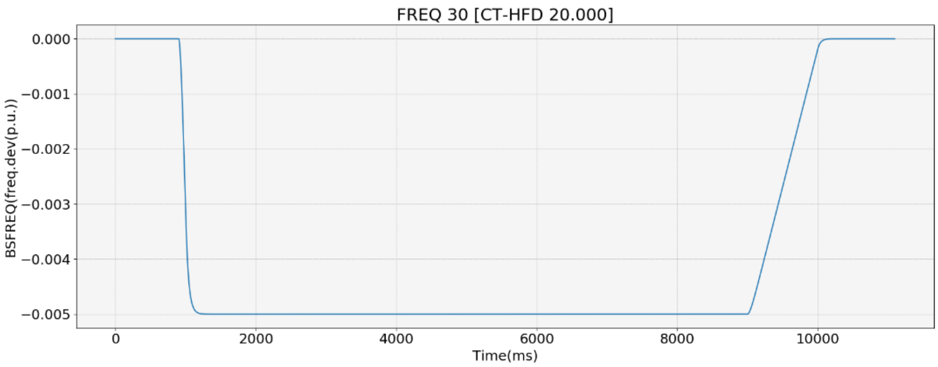

Figure 143: simulation of PFR-n, under-frequency test. Frequency deviation.

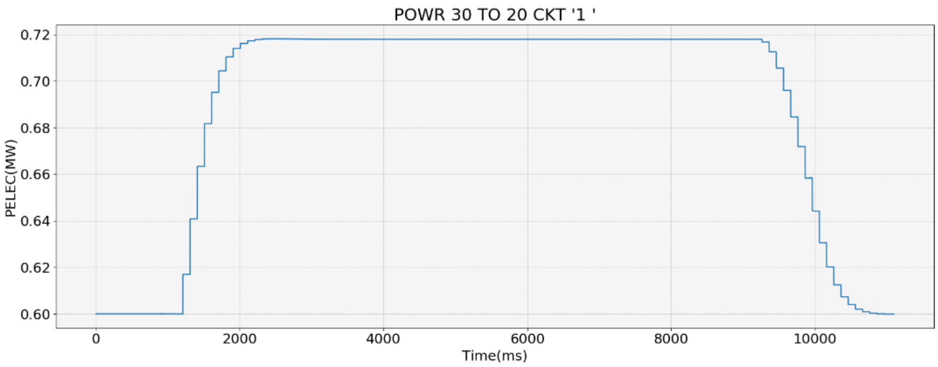

Figure 144: simulation of PFR-p, under-frequency test. Active power at the evacuation line.

The PFR control is based on a droop control, which determines the final active power output, which in turn is ensured by a PI controller. The PI controller determines the response speed of this functionality. The configuration of the PI controller has not been varied in this study. This configuration provides a response time of 0.8s and a settling time of 0.9s.

Voltage control based on voltage setpoint (VCV)

In order to evaluate the VCV functionality, a simulation has been carried out using a “flat” voltage profile to analyse the response of the control to a consign change. In the first test, the voltage reference has been set to 1.1 p.u. when the simulation time reaches 1s. Three different configurations of the VCV slop (K) have been tested; namely 75, 2 and 0.8. These configurations are referred to as RMAX, RINT and RMIN, respectively. In this test, functionalities related to both frequency control (RPF and FFR) and fast reactive current response (FRC) are disabled. In Figure 145 and Figure 146, the voltage profile and the reactive power output of the HFD are represented.

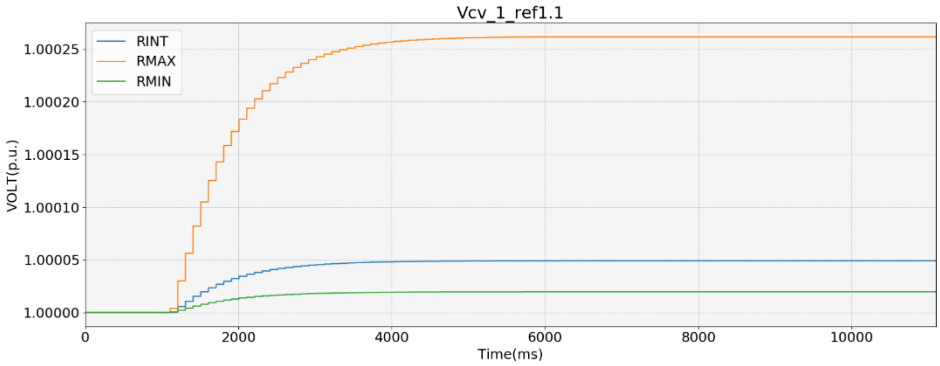

Figure 145: simulation of VCV, voltage reference change to 1.1 p.u.. Voltage.

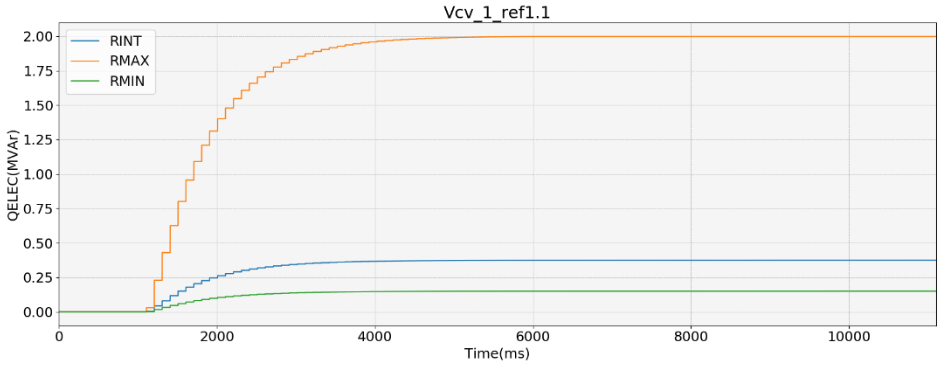

Figure 146: simulation of VCV, voltage reference change to 1.1 p.u.. Reactive power at the evacuation line.

In the second test, the voltage reference has been set to 0.9 p.u.. The same three different configurations of the VCV slop (K) have been tested. In Figure 147 and Figure 148, the voltage profile and the reactive power output of the HFD can be found.

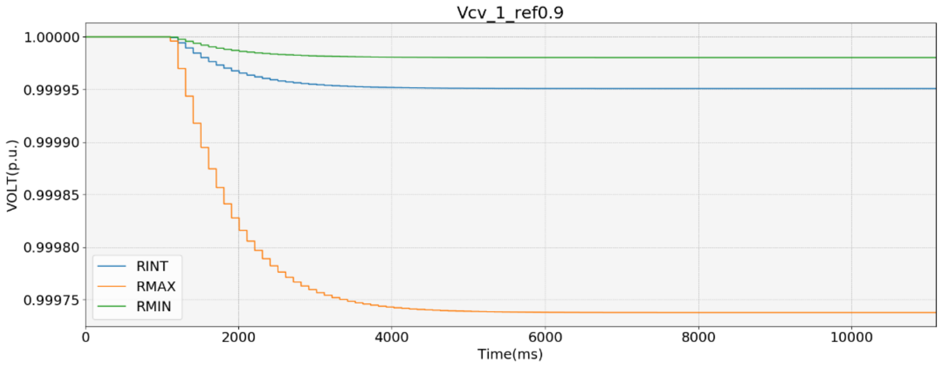

Figure 147: simulation of VCV, voltage reference change to 0.9 p.u.. Voltage.

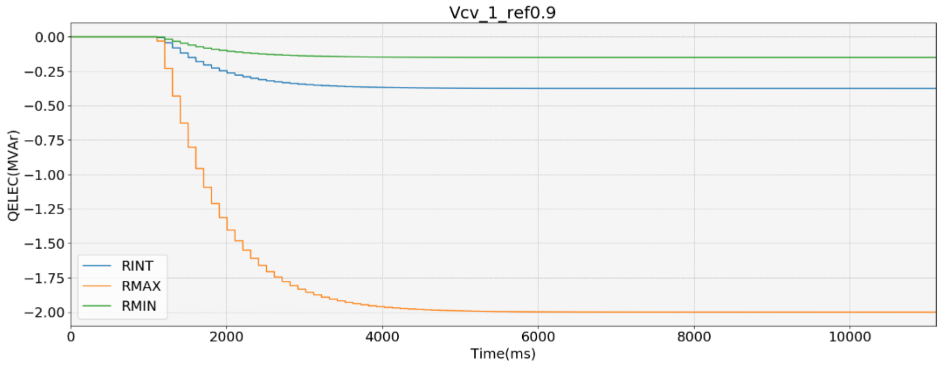

Figure 148: simulation of VCV, voltage reference change to 0.9 p.u.. Reactive power at the evacuation line.

The VCV control is based Q/V curve similar to a droop control. Therefore, the reactive power output is dependent on the voltage reference value and the slope of the Q/V curve. It can be seen that, in the RMAX configuration, the reactive power output reaches the rated value. In the RINT and RMIN configurations, the output coincides with the expected value. The reactive power reference is ensured by a PI controller, which determines the response speed of this functionality. The configuration of the PI controller has not been varied in this study. This configuration provides a response time of 1.8s and a settling time of 2.3s.

Voltage control based on reactive power setpoint (VCQ)

The HFD may collaborate in voltage control by executing the reactive power management actions ordered by the MC. So as to evaluate the VCQ functionality, a simulation has been carried out using a “flat” voltage profile to analyse the response of the control to a consign change.

Three tests have been carried out, in each of them the reactive power reference has been set to 1, 0.5 and -1 p.u. respectively. In this test, functionalities related to both frequency control (RPF and FFR) and voltage control at normal operation (VCV) are disabled. In Figure, Figure 150 and Figure 151, the reactive power output of the HFD is represented for each of the aforementioned test.

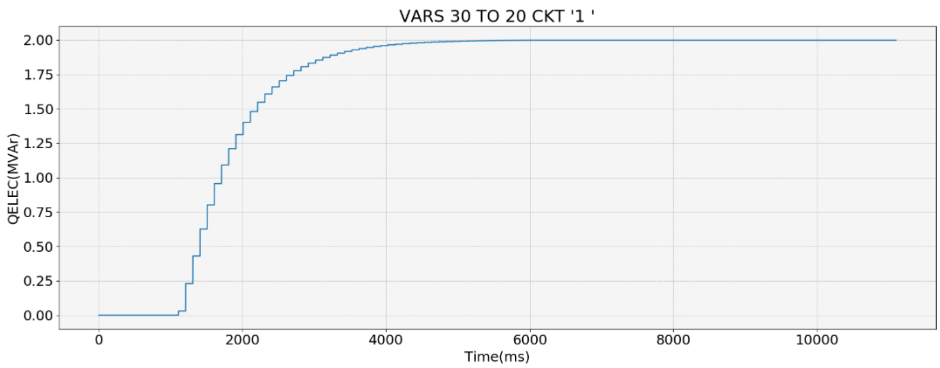

Figure 149: simulation of VCQ, reactive power reference change to 1 p.u. (2 MVAr). Reactive power at the evacuation line.

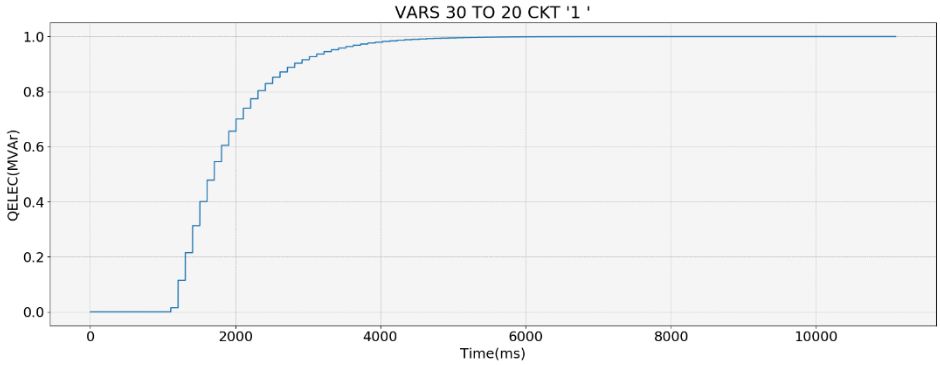

Figure 150: simulation of VCQ, reactive power reference change to 0.5 p.u. (1 MVAr). Reactive power at the evacuation line.

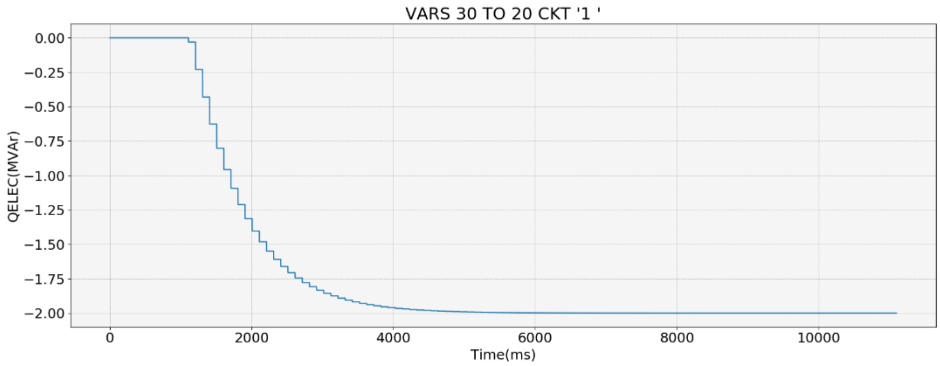

Figure 151: simulation of VCQ, reactive power reference change to -1 p.u. (-2 MVAr). Reactive power at the evacuation line.

These tests have demonstrated that the HFD model adequately responds to changes in its reactive power reference. The reactive power control and the voltage control share the same PI controller, which determines the response speed of this functionality. The configuration of the PI controller has not been varied in this study. This configuration provides a response time of 1.8s and a settling time of 2.3s.

5.5.3. Level-3 functionalities

Level-3 functionalities are intended to provide power systems management optimisation tools. These tools enable TSOs to perform management strategies that are superimposed on level-1 and level-2 functionalities. In this section, the results of the evaluation of the level-3 functionalities implanted in the MC model are presented.

Setpoint Tracking (SPT)

Two tests have been carried out to evaluate the SPT functionality. In each of them, a different data series has been used to provide the MC with different active power reference values. In the first test, this profile interacts with the minimum time to update the active power reference. In Figure 152, the active power references for the SPT functionality, the active power reference imposed by the MC to the HFD and its active power output may be seen.

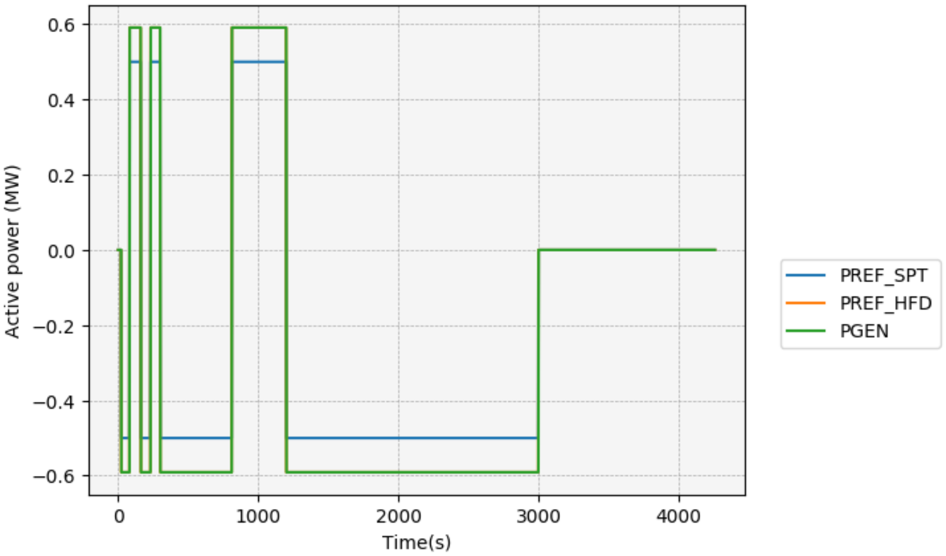

Figure 152: simulation of SPT, active power reference change (0, 0.5, -0.5 MW) and time to update power reference (1, 5, 10 minutes). Active power references and active power output.

In the second test, the active power profile interacts with the active power ramp limit. In Figure 153, the active power references for the SPT functionality, the active power reference imposed by the MC to the HFD and its active power output are presented.

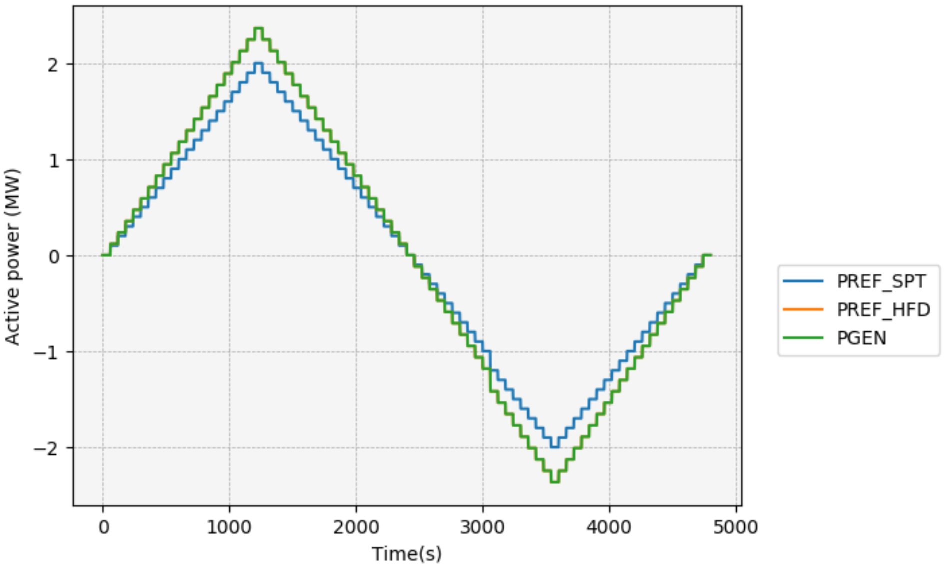

Figure 153: simulation of SPT, active power reference change as a ramp (0, 2, -2 MW). Active power references and active power output.

From these tests, it is observed that the generated power coincides with the active power reference imposed to the HFD. However, this reference is scaled up from the active power reference set for the SPT functionality. Furthermore, it is found that the series of reference values coincide with the minimum time to update and that the ramp limit does not affect this test.

Program Management (PGM)

So as to evaluate the PGM functionality of the MC model, two tests have been. In each of them, a different data series has been used to provide the MC with different active power reference values. In these tests, the same discharge profile interacts with the active power ramp limit. In Figure 154 the ramp limit is fixed at 2 MW, and the active power references for the PGM functionality, the active power reference imposed by the MC to the HFD and its active power output may be seen.

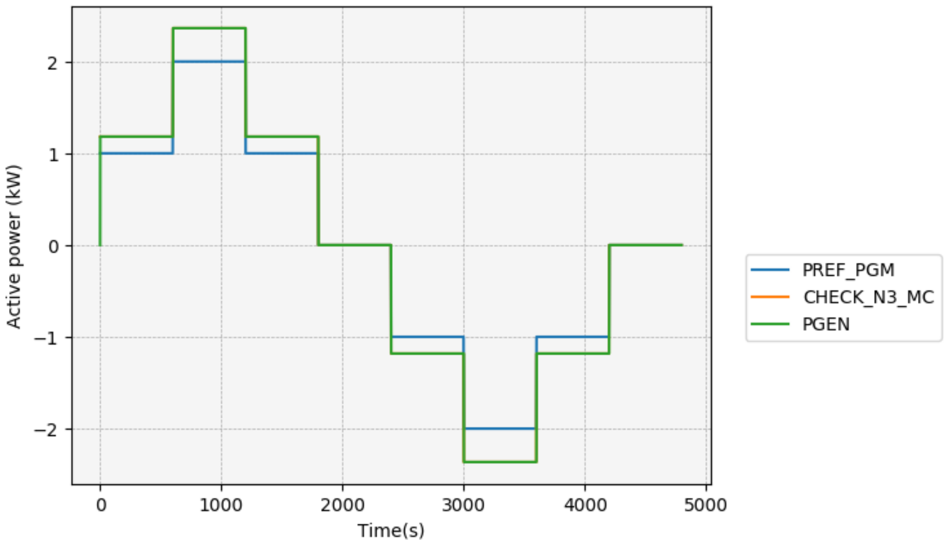

Figure 154: simulation of PGM, active power reference change (0, 1, 2, -1, -2 MW) and ramp limit (2 MW). Active power references and active power output.

In Figure 155 the ramp limit changes from 0.1 to 2 MW, and the active power references for the PGM functionality, the active power reference imposed by the MC to the HFD and its active power output may be seen.

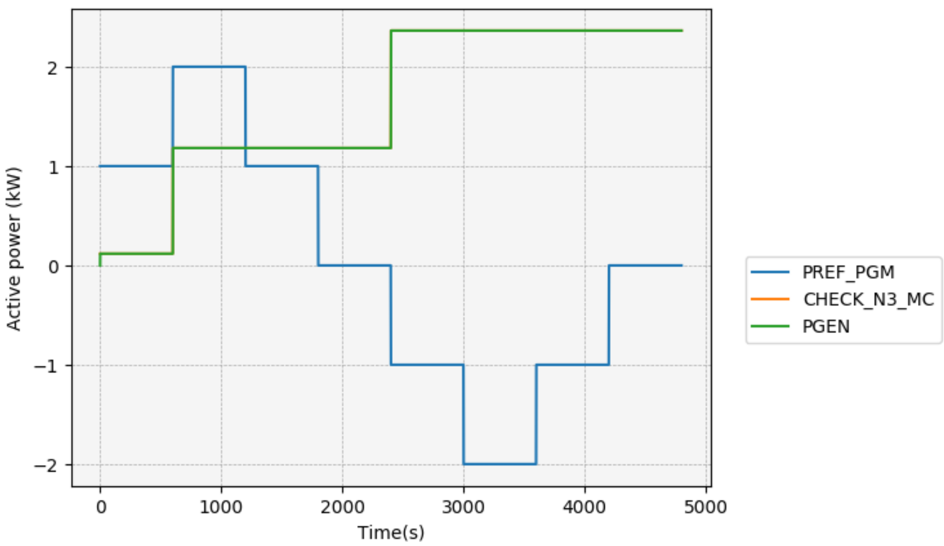

Figure 155: simulation of PGM, active power reference change (0, 1, 2, -1, -2 MW) and ramp limit (0.1, 1, 2 MW). Active power references and active power output.

These tests demonstrate the influence of the ramp limit in this functionality. In Figure 154 it may be observed that, when this limit is greater than the programmed setpoint, it has no influence on the final active power reference sent to the HFD. Contrarily, in Figure 155 it is found that, when the ramp limit interferes with the programmed setpoint, the final active power reference coincides with the ramp limit.

Congestion Management (CMT)

Two tests have been carried out to evaluate the congestion management functionality. In each of them, two different data series have been used to provide the MC with a renewable generation profile and a renewable power limit profile. The CMT control is expected to manage the active output of the HFD so that the total amount of power in the controlled bus does not exceed the renewable power limit. In the first test, this limit is fixed at 0 MW during the whole simulation. In Figure 156, the renewable generation profile, the renewable power limit, the active power reference imposed by the MC to the HFD and its active power output are plotted.

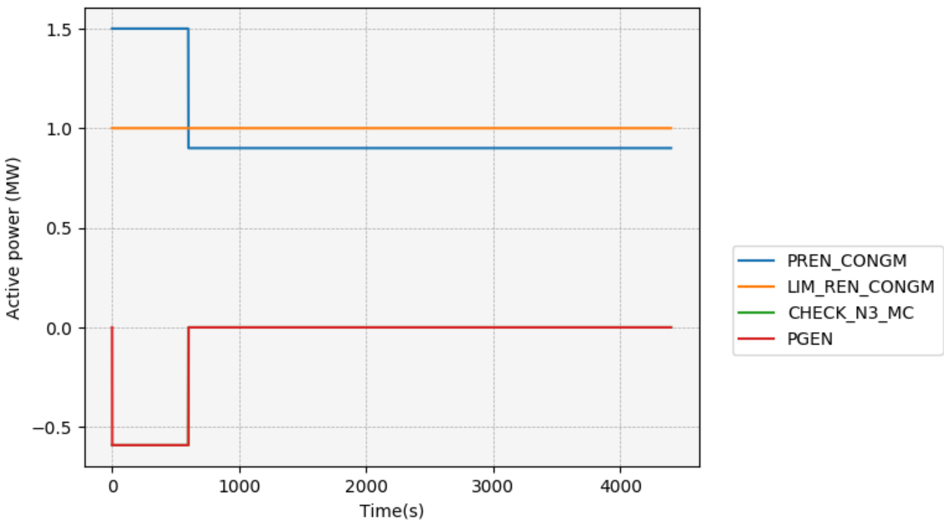

Figure 156: simulation of CMT, renewable power change (1, 0.4, 0.5 MW) renewable power limit (0 MW). Renewable power output, renewable power limit, active power references and active power output.

In the second test, this limit is fixed at 1 MW during the whole simulation. In Figure 157, the renewable generation profile, the renewable power limit, the active power reference imposed by the MC to the HFD and its active power output are plotted.

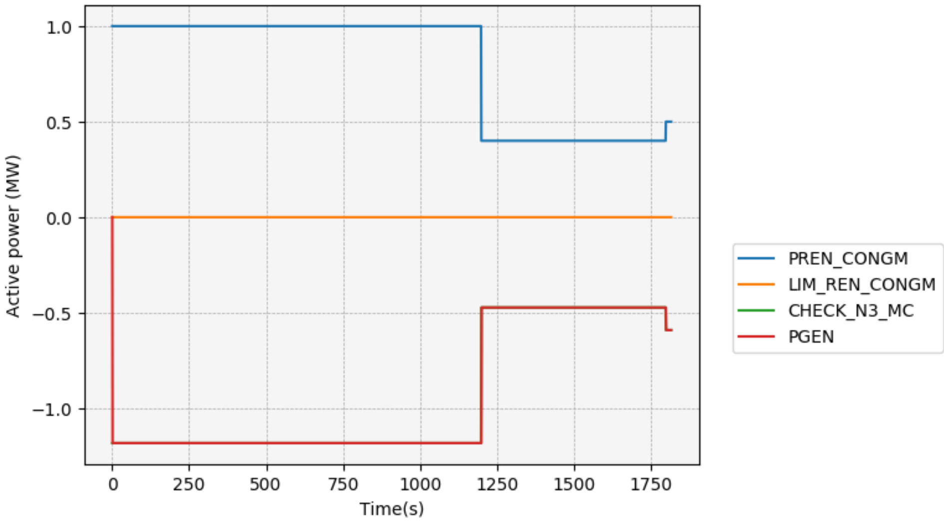

Figure 157: simulation of CMT, renewable power change (1.5, 0.9 MW) renewable power limit (1 MW). Renewable power output, renewable power limit, active power references and active power output.

These tests have demonstrated that the MC model, in cooperation with the HFD model, is able to ensure a given amount of generated power at a given bus. The system has managed to adjust the output of the HFD to adapt the renewable generation profile. However, once more it is found that the HFD is scaled up from the expected value.

5.5.4. Simulations in an isolated power system

So as to test the performance of the HFD in an isolated power system, simulations have been carried out using a grid simulator of the power system formed by the islands of Lanzarote and Fuerteventura. For these simulations, the HFD model has been configured according to the characteristics of the device that would be installed in Gran Tarajal (Fuerteventura). For instance, active and reactive rated power have been set to 13 MW and 25 MVAr respectively.

Disconnection of three generators

In this section, the impact of the HFD in terms of power system stability, under a contingency caused by the disconnection of three generation units, is analysed. This contingency leads to a sensible decrease both in voltage and frequency. In this test, the FFR and the VCV contingencies have been combined and the peak demand scenario has been used.

In Figure 158, the frequency deviation caused by this contingency, both with and without the HFD, can be found. In Figure 159, the active power output through the evacuation line is plotted.

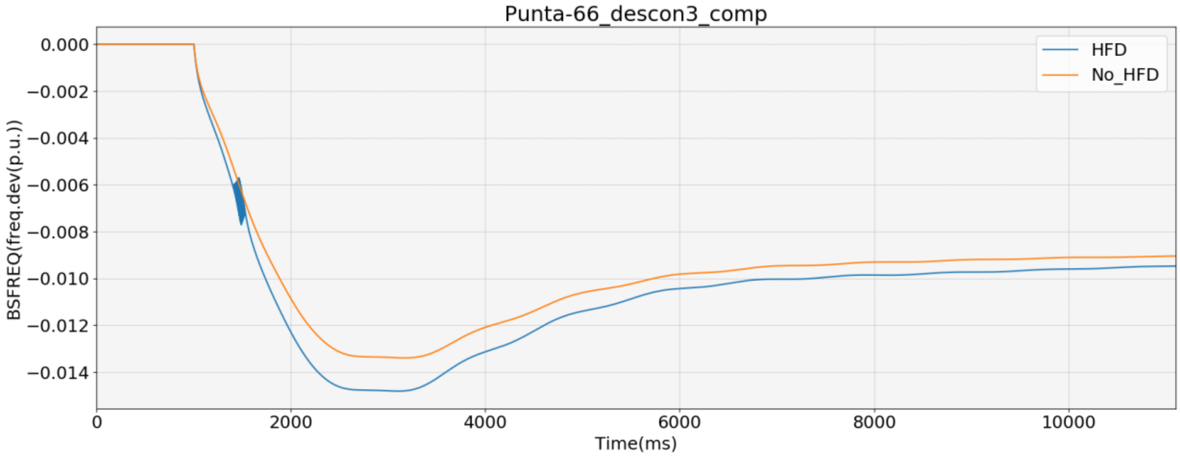

Figure 158: disconnection of three generators (LZ-FTV, peak scenario). Frequency deviation at the PCC.

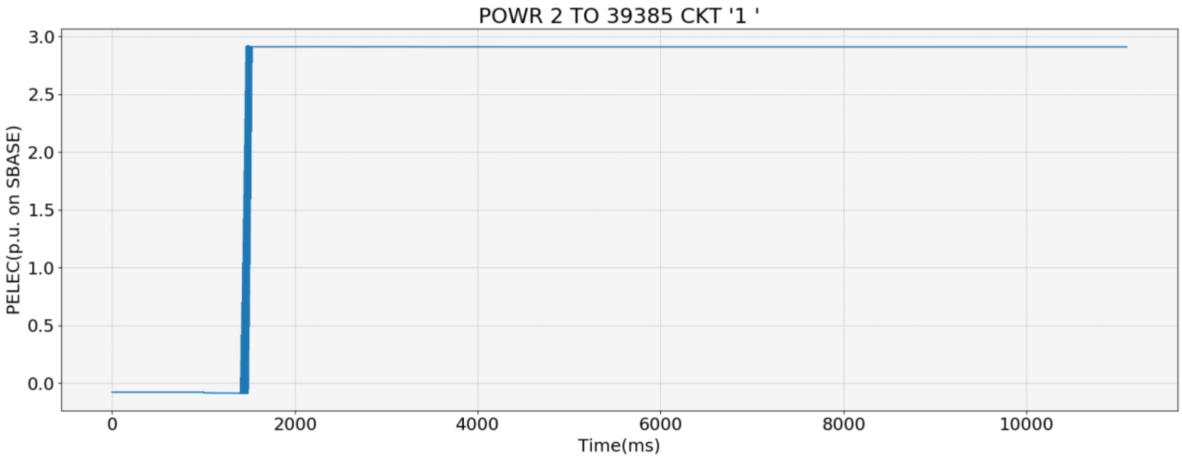

Figure 159: disconnection of three generators (LZ-FTV, peak scenario). Active power in the evacuation line.

In this tests, the active power controllers are configured so that 3 MW are enabled for FFR response and 10 MW are reserved for RPF response. It can be seen that the model respects this restriction. Furthermore, the injection of 3 MW is able to reduce the frequency deviation from 49.3 Hz (0,985 p.u.) to 49.35 Hz (0.987 p.u.).

In Figure 160, the perturbation caused by the contingency on the voltage at the PCC can be seen. The voltage at the PCC is shown for both the case of the power system with and without the HFD. In Figure 161, the reactive power output through the evacuation line is plotted.

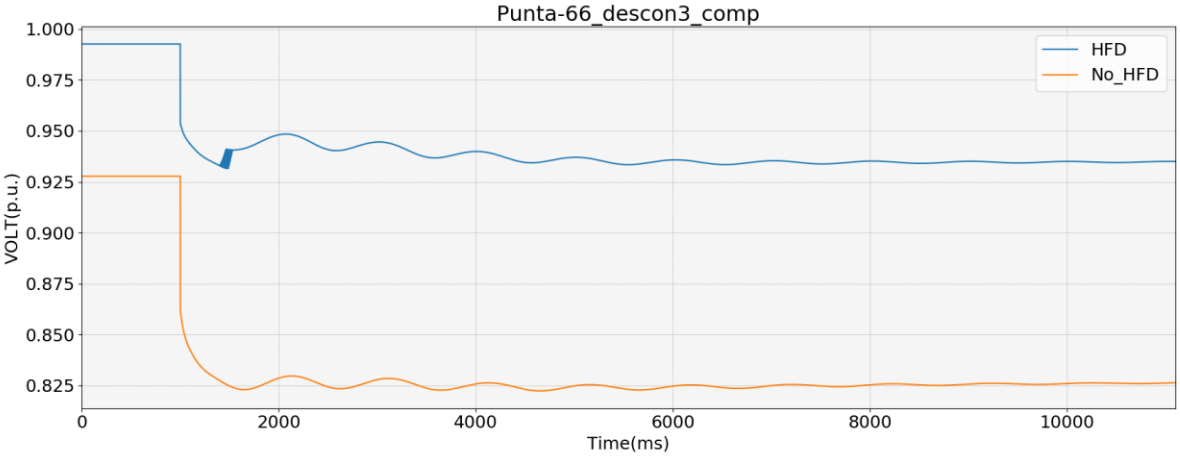

Figure 160: disconnection of three generators (LZ-FTV, peak scenario). Voltage at the PCC.

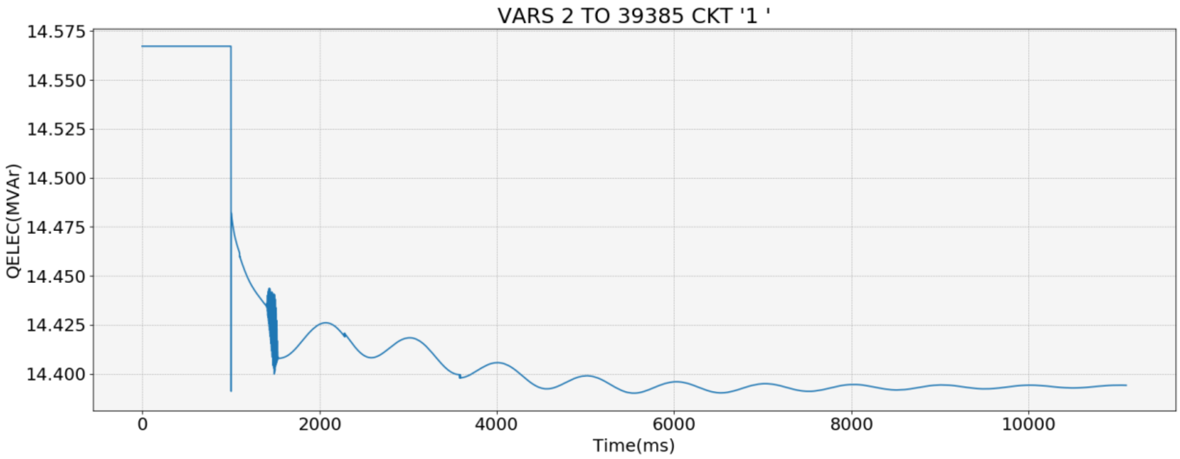

Figure 161: disconnection of three generators (LZ-FTV, peak scenario). Reactive power in the evacuation line.

Focusing on the behaviour of voltage, it can be observed that, without the HFD, the initial voltage level is near to the security limit (0.9 p.u.). After the contingency, this limit is overpassed and voltage reaches 0.825 p.u.. The HFD is able to set the voltage near unity before the contingency occurs, but it is also able to maintain the voltage at an acceptable level after the disconnection of the generation units.

3-phase fault at PCC

In this section, the impact of the HFD in the power system stability when a three-phase fault occurs at the PCC is analysed. This contingency lead to a sever voltage dip. In this test, the FRC functionality is analysed. The peak demand scenario has been used in this test.

In Figure 162, the perturbation caused by the short circuit on the voltage at the PCC can be seen. The voltage at the PCC is shown for both the case of the power system with and without the HFD. In Figure 163, the reactive power output through the evacuation line is plotted.

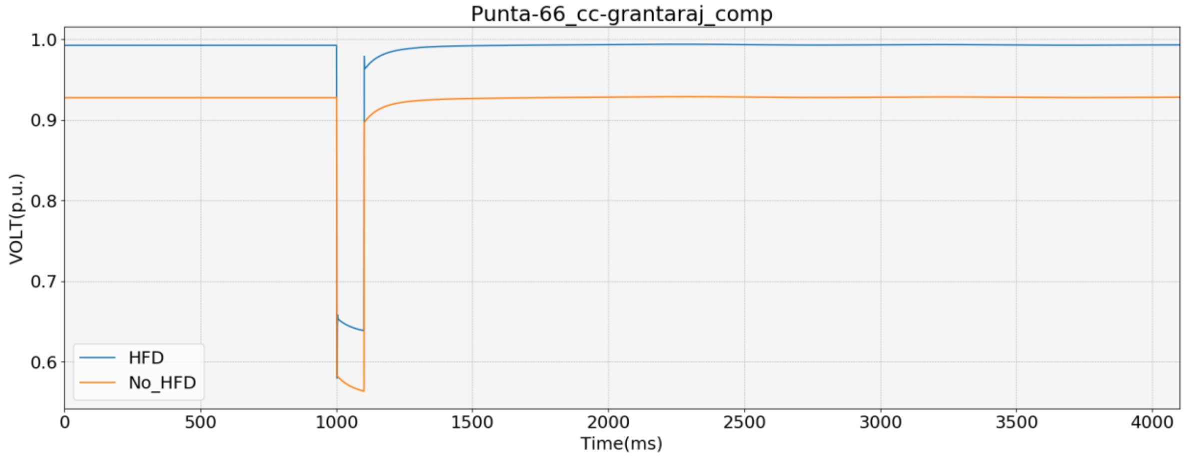

Figure 162: 3-phase fault at the PCC (LZ-FTV, peak scenario). Voltage at the PCC.

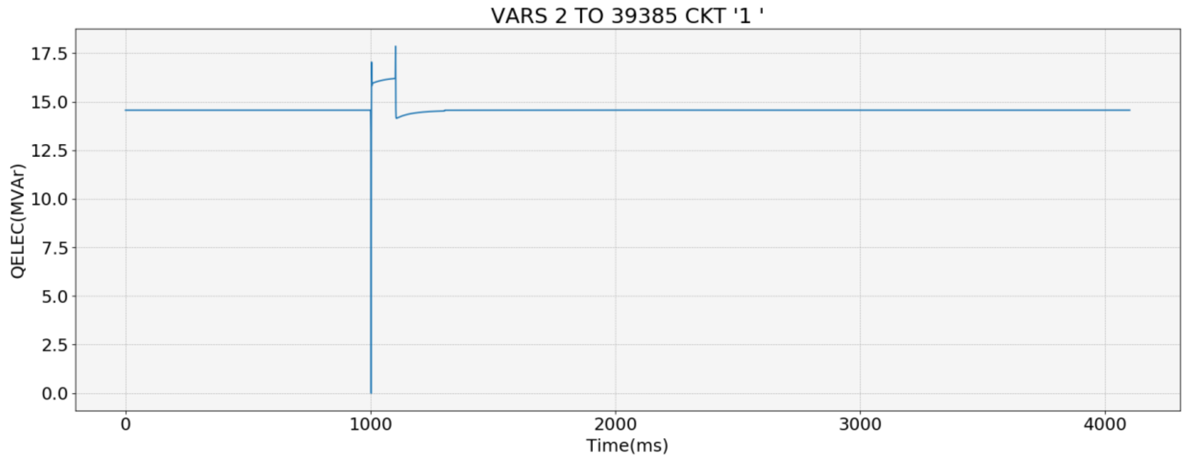

Figure 163: 3-phase fault at the PCC (LZ-FTV, peak scenario). Reactive power in the evacuation line.

As in the previous test, there is a major difference in the initial voltage levels due to the voltage control of the HFD. During the fault, voltage falls drastically, but the performance of the device is able to reduce the voltage fall sensibly. It should be noted that, given the characteristics of the model, once the voltage ride-through mode is activated, the HFD model disconnects during a single simulation time-step. Then, the model returns to provide control according to its configuration.

6. Conclusions

Within the OSMOSE project, WP-4 faced the challenge of designing a Multi-component Flexibility system (MCFS) able to provide multiple grid services in order to enhance power systems stability and allow an increased RES integration. The final solution is composed of devices of different technologies managed by a Master Control.

On the one hand, a modular synchronous compensator (STATCOM) has been designed and implemented along with a new battery energy storage system. These have been coupled with a set of super-capacitors to form a hybrid flexibility device capable of providing multiple low-level grid services. On the other hand, a Master Control algorithm has been developed to provide the TSO with high-level functionalities so different operation strategies can be carried out. The MC comprises its own SCADA and communicates with the HFD and other flexibility devices to acquire data from them so as to deliver setpoints for the different controllers.

A demonstrator has been built so as to test the efficacy of the MCFS in real operating conditions. This deliverable shows the results obtained from the tests performed to evaluate the operation of the demonstrator. The tests were conducted under real operation of the demonstrator and allowed the validation of all the functionalities defined in the technical requirements.

The evaluation of the obtained results allowed us to get the following conclusions:

- Attending to the technical requirements, the new hybrid flexibility device has shown to be able to operate at the specified voltage and frequency conditions during the required times and to provide the required active and reactive power.
- In relation to low-level functionalities providing fast response to disturbances, the device has proven to be able to provide inertia emulation, power frequency regulation and trapezoidal response under disturbances. The device responded according to its requirements, in order to maintain the stability of the grid. Its capability of fast reactive current injection under disturbances was also successfully validated.
- In relation to low-level functionalities focused on grid management, the hybrid flexibility device has demonstrated its efficacy in providing voltage and power-frequency control once grid stability was achieved. The effectiveness of these functionalities has been proven both when the control is managed by the low-level local controllers at the HFD and when the Master Control is in charge of such controls.
- Attending to high-level functionalities, the capability of the Master Control to coordinate the different flexibility devices so grid services are provided in an efficient manner has been demonstrated. The Master Control has proved to be effective under different operator requirements; such as active power setpoint tracking, charge/discharge program following and congestion management. Additionally, the Master Control has demonstrated to consider the state of charge and state of health of the equipment to ensure an efficient operation.

- Priority and coordination criteria between different functionalities of the demonstrator were also evaluated. It has been proven that high-level functionalities can be combined with low-level functionalities to enable a strategic management while ensuring grid security. The results showed the capability of the MCFS to provide high-priority grid stability services and to comply with other functionalities simultaneously.

In addition to the real operation tests, simulation models have been developed and simulations have been carried out to provide insights about the performance of the HFD in an isolated power system. These simulations have shown how this technology could help to mitigate severe voltage and frequency issues that are common to these power systems.

In summary, the obtained results demonstrate the good performance of both the new hybrid flexibility device and the Master Control, as well as their capabilities to provide multiple and combined flexibility services to the grid. The efficacy of the hybridization, between the STATCOM and the storage devices (the battery system and the super-capacitors) and its capability to provide wide range of grid services have been demonstrated. The Master Control implementation has shown to allow an optimal coordination of different energy storage devices by generating the appropriated setpoints taking into account the devices status and degradation.

7. Annexes

In this section, additional data is presented to provide particular information which has not been included in the main part of this document for the sake of clarity.

7.1. Graph results

Graph results of the different test, and which have not been provided before, can be found in this section so the reader can access to all the data used to validate the different functionalities.

7.1.1. Graph results for VST-1 test

In the following figures, the results of VST-1 tests using voltage profiles from f (see Table 5. values for VST-1 test) are presented. In each figure, the voltage profile and the active and reactive power output are represented.

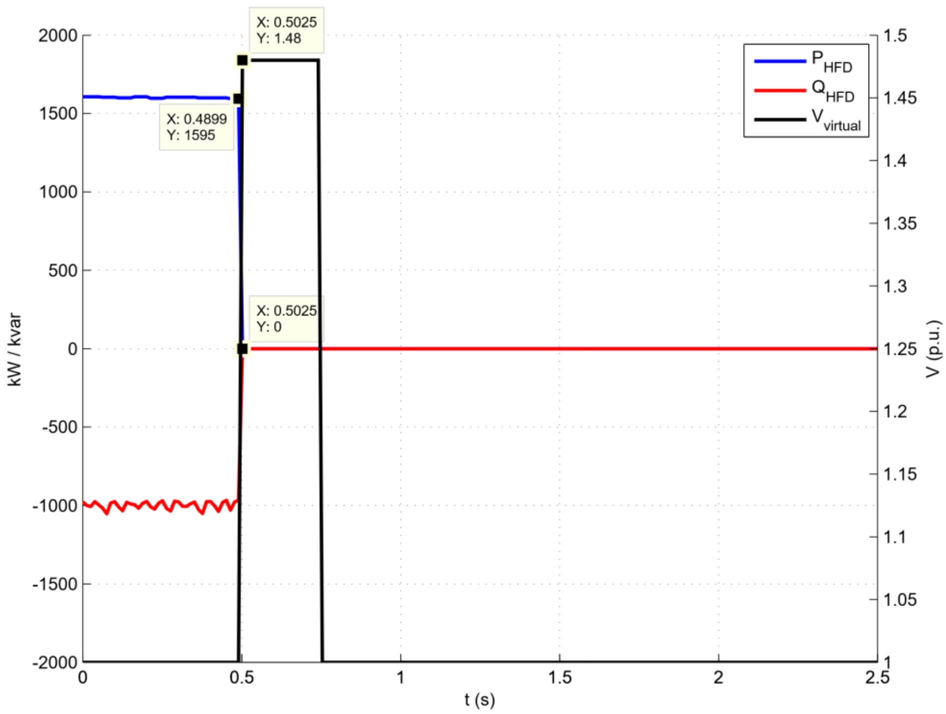

Figure 164: VST-1 (a) results

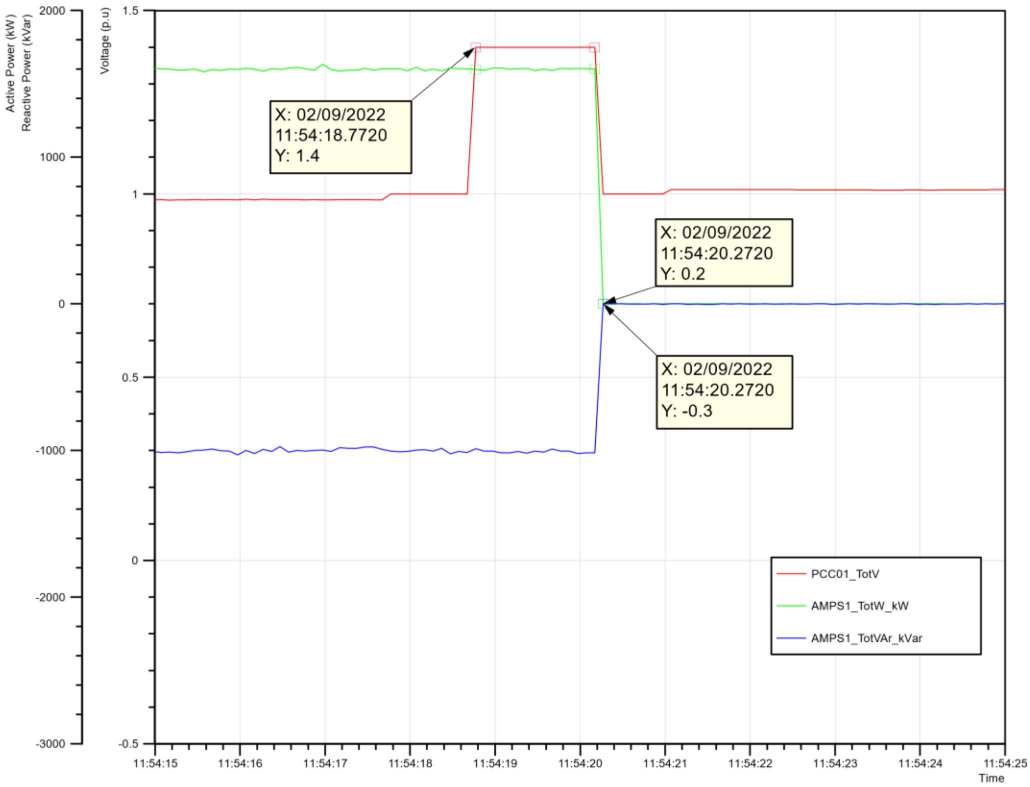

Figure 165: VST-1 (b) results

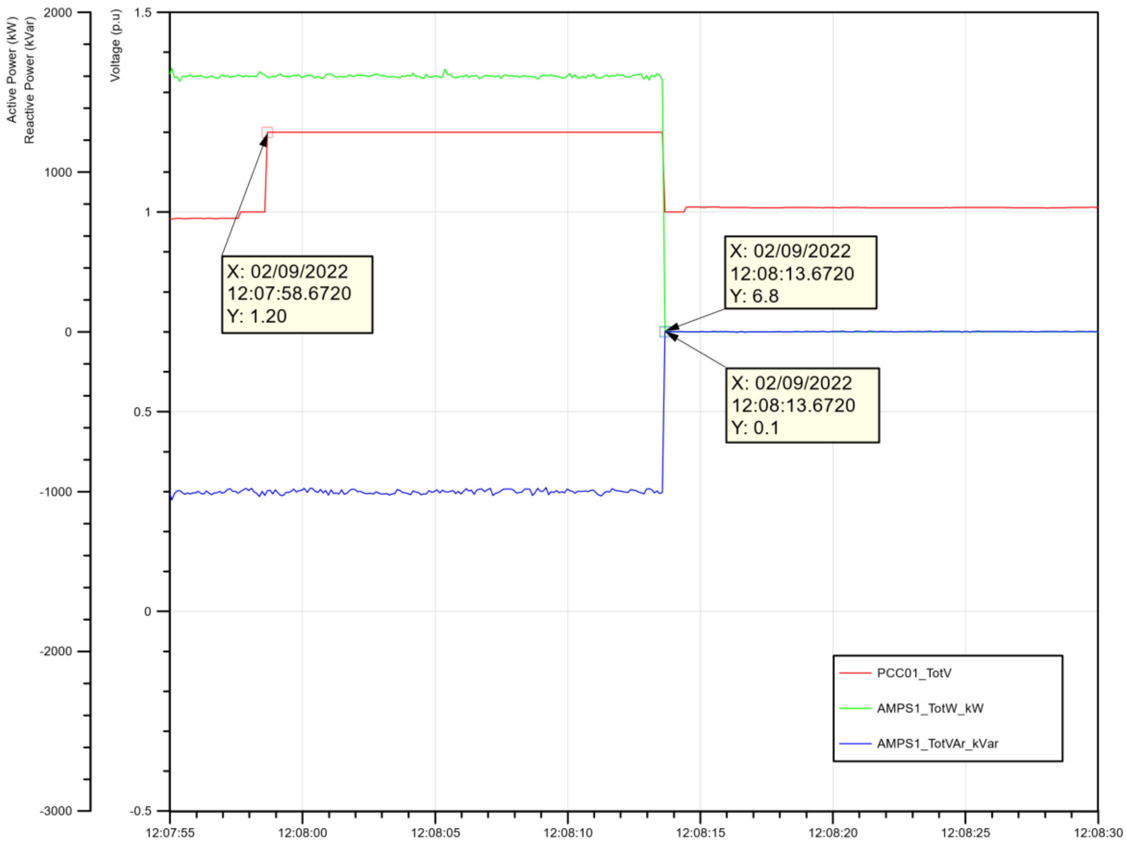

Figure 166: VST-1 (c) results

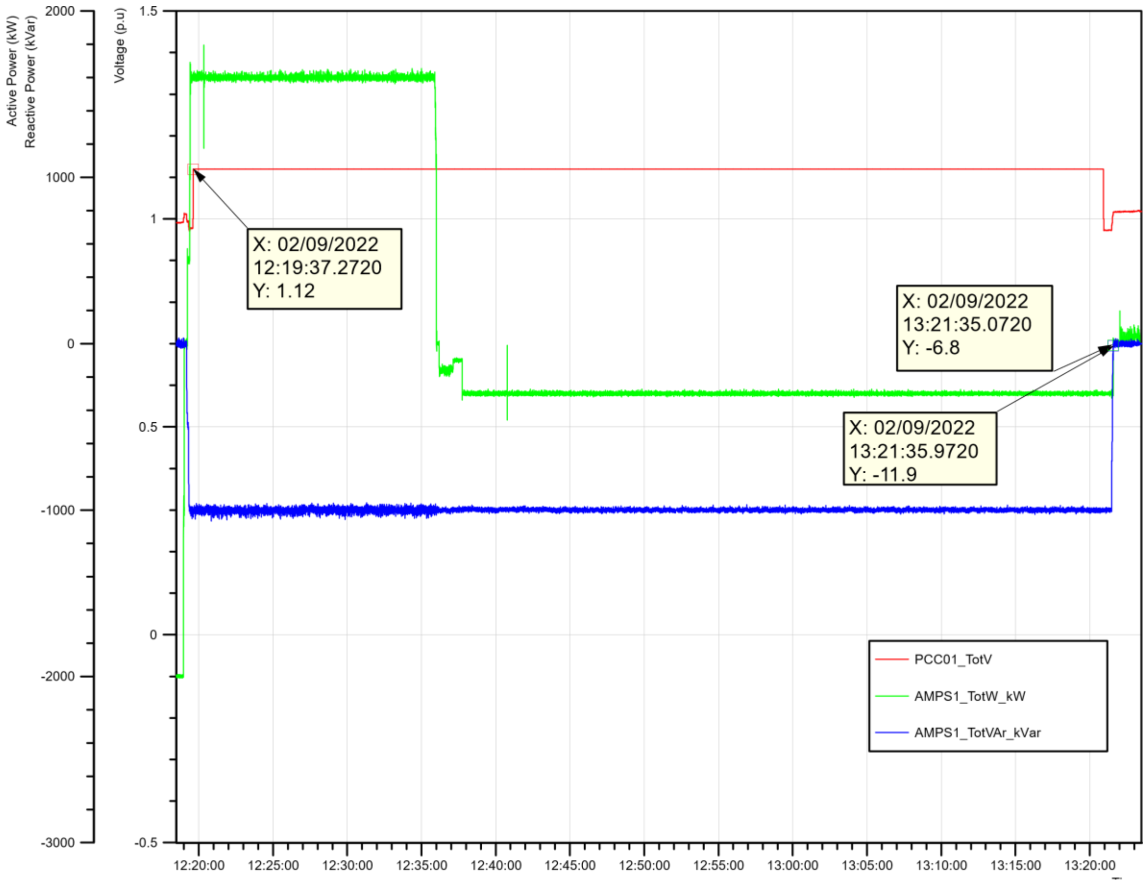

Figure 167: VST-1 (d) results

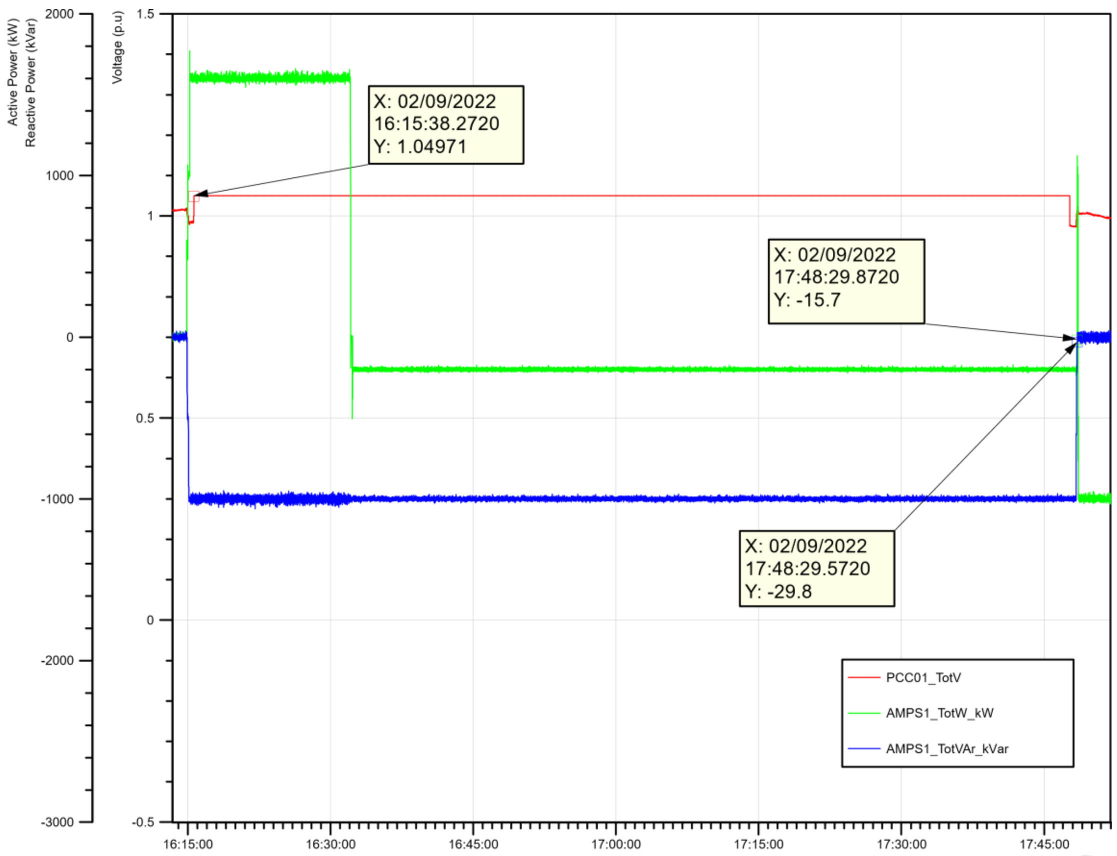

Figure 168: VST-1 (e-1) results

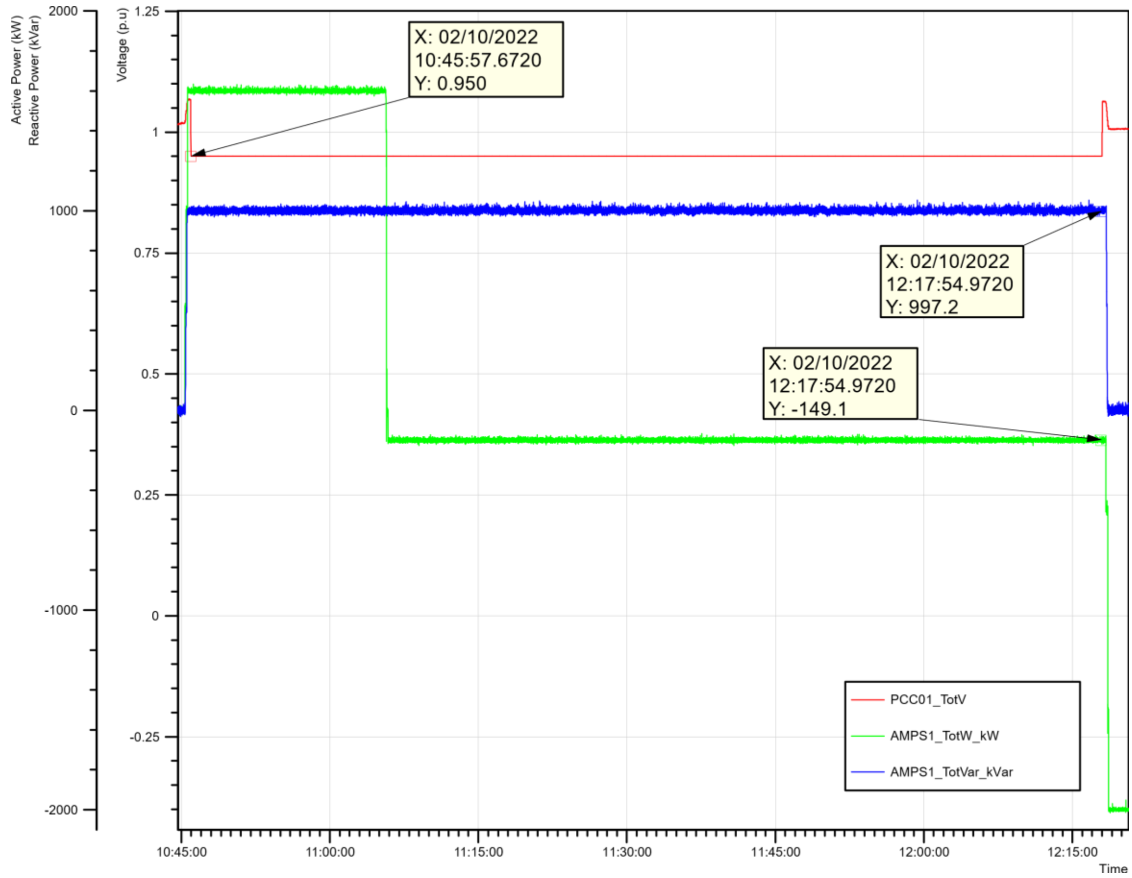

Figure 169: VST-1 (e-2) results

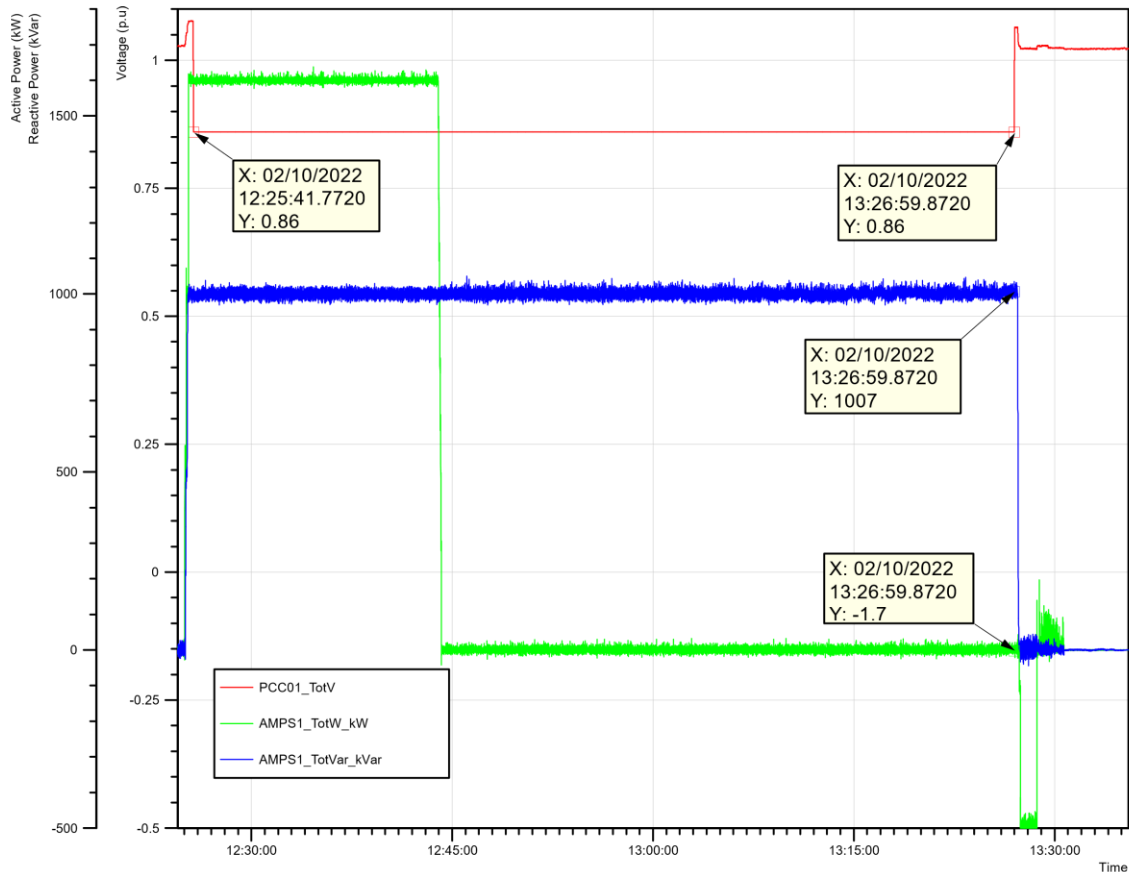

Figure 170: VST-1 (f) results

7.1.2. Graph Results for VST-2 test

In the following figures, the results of VST-2 tests using voltage profiles as per defined in Table 7 are presented. In the following figure, the voltage profile and the active and reactive power output are represented.

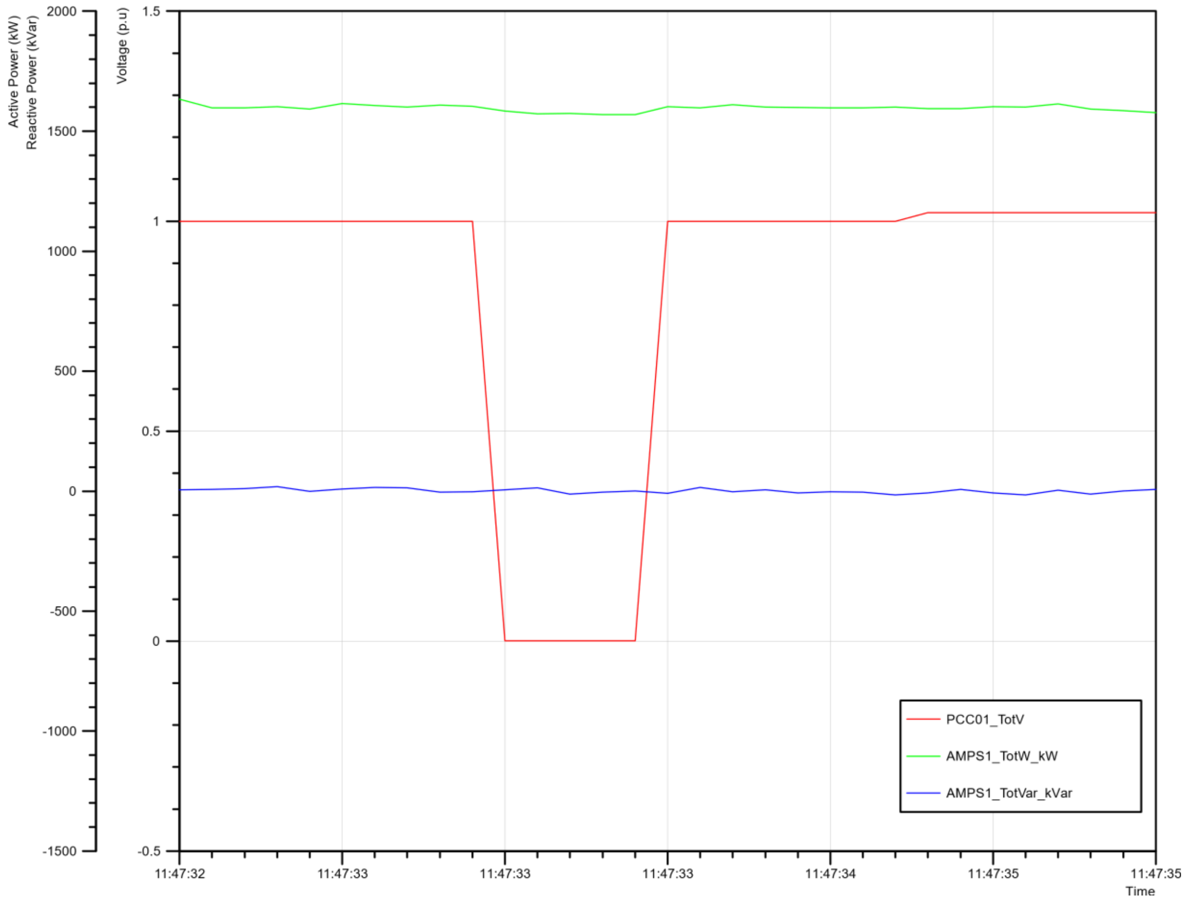

Figure 171: VST-2 (a)

The test for a three-phase fault at 0 p.u. is shown in Figure 171: VST-2 (a). The fact that the PPC only captures nominal voltage data at the PCC and with a sampling rate of 100ms makes it necessary to use the DSP acquisition software, which stores the data of the direct and inverse sequence virtual profiles and with a much higher resolution.

The remaining tests captured with the DSP are shown below. The positive and negative sequence of voltage are plotted in the following figures, as well as the HFD active power output. The minimum operating time limit of the device and its tripping limit are superimposed in the charts.

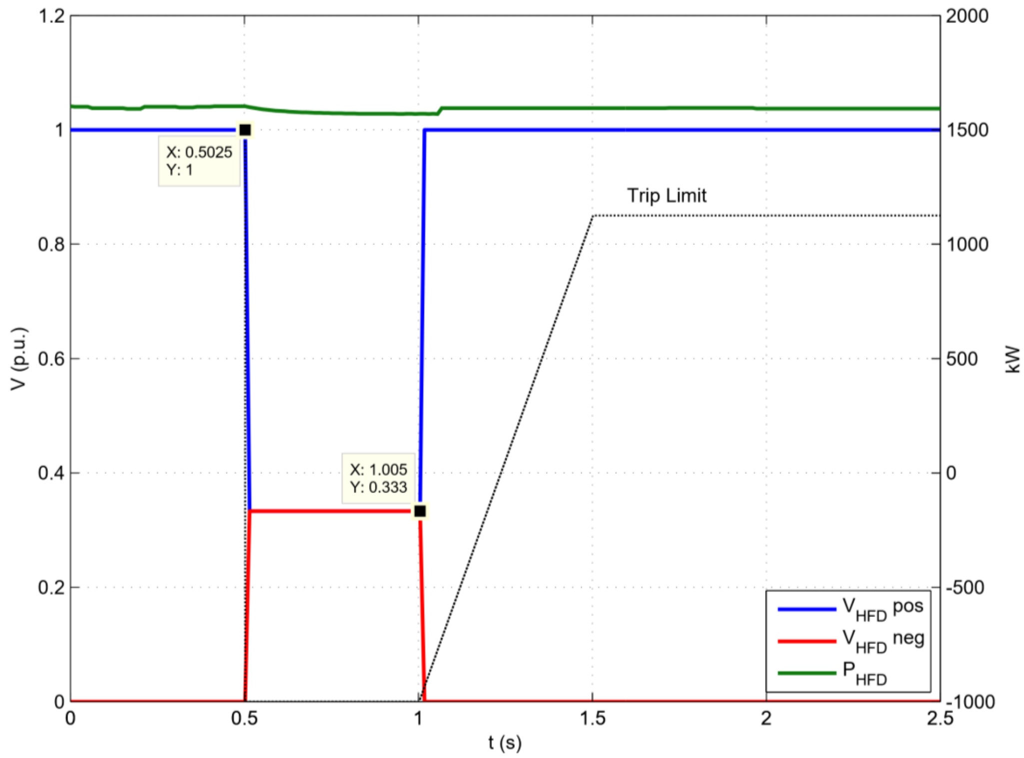

Figure 172: VST-2 (b)

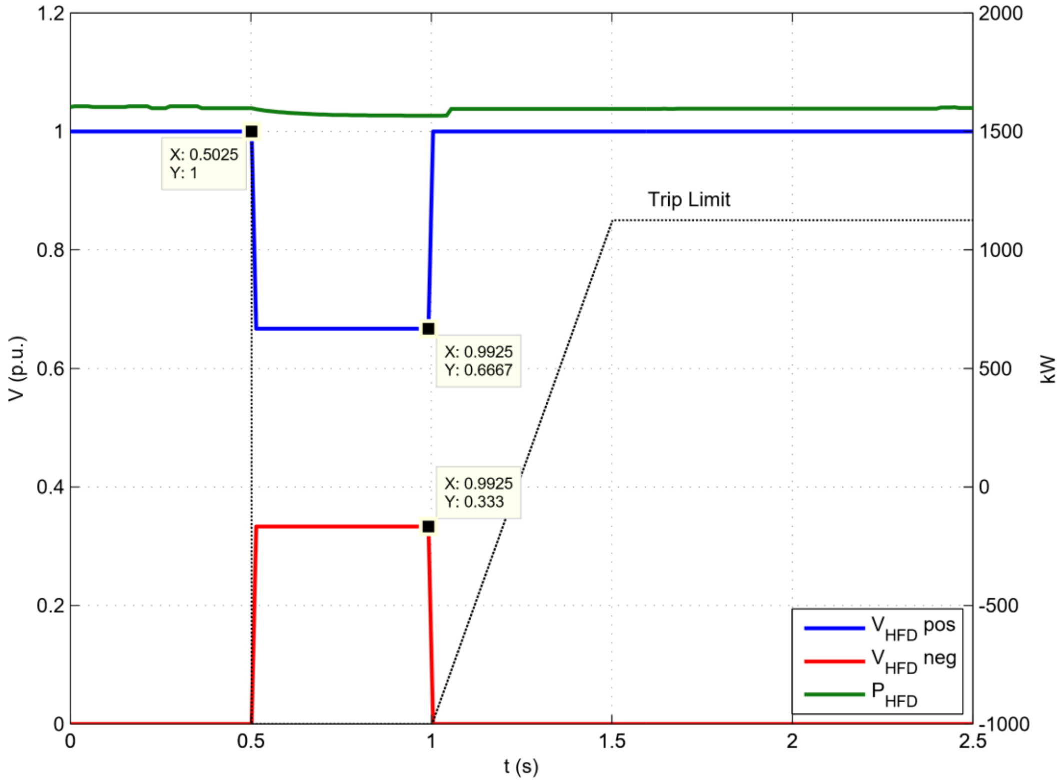

Figure 173: VST-2 (c)

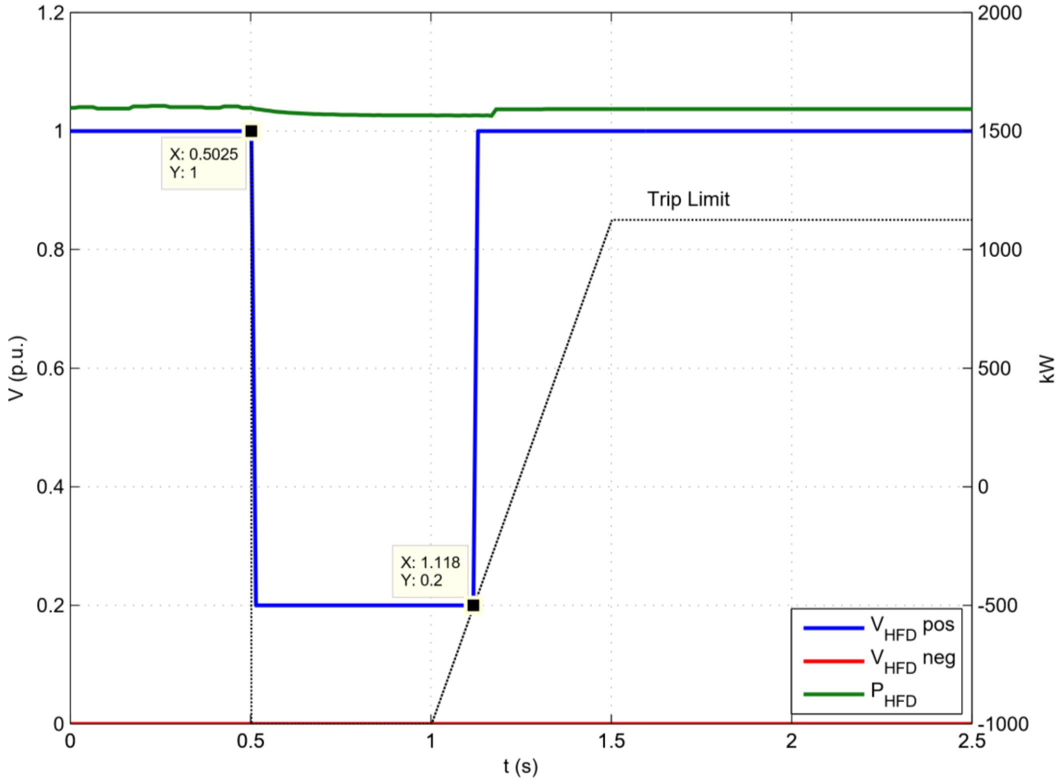

Figure 174:VST-2 (d)

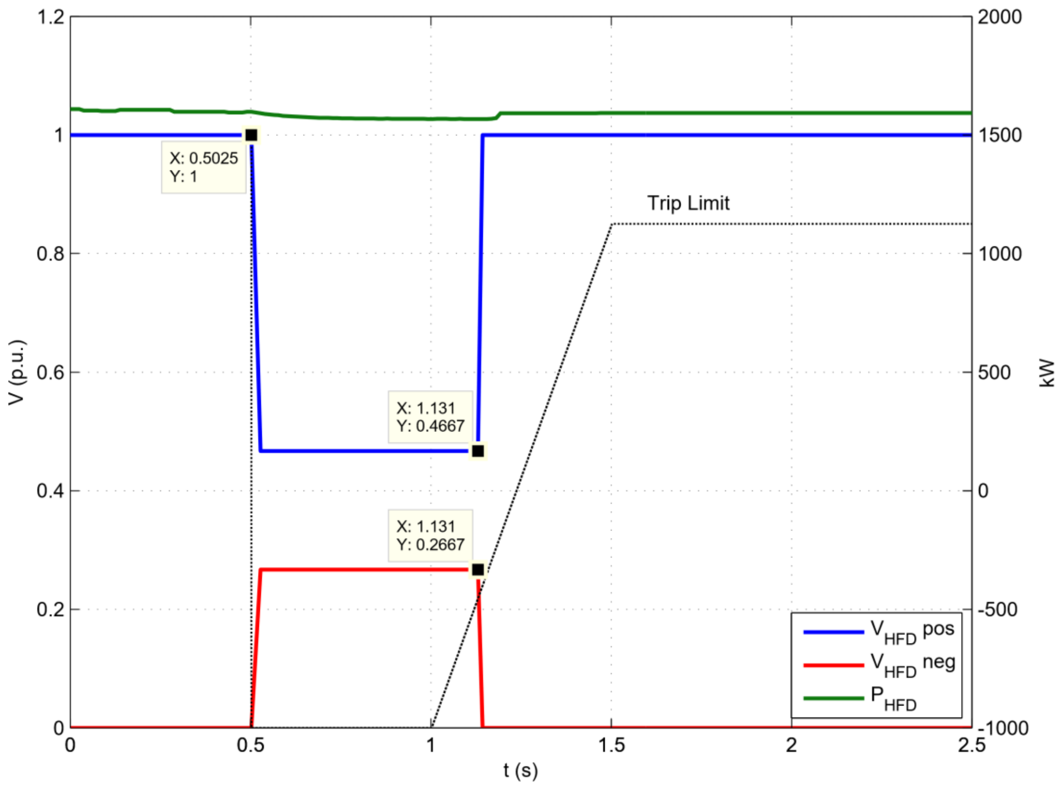

Figure 175: VST-2 (e)

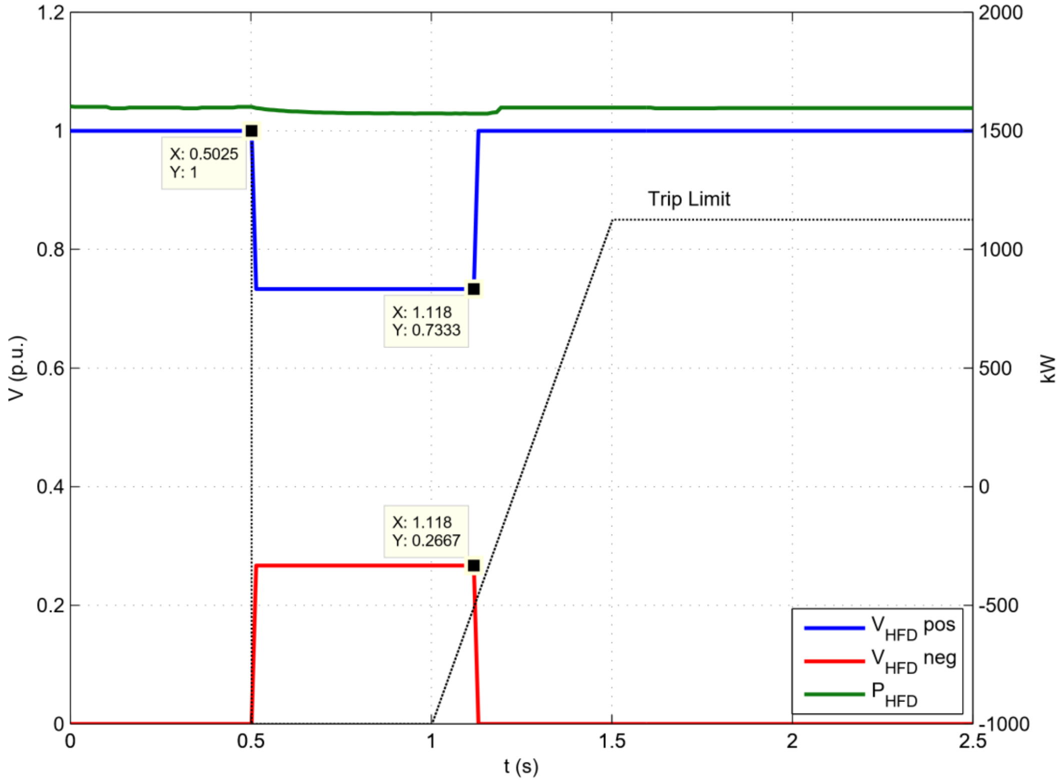

Figure 176: VST-2 (f)

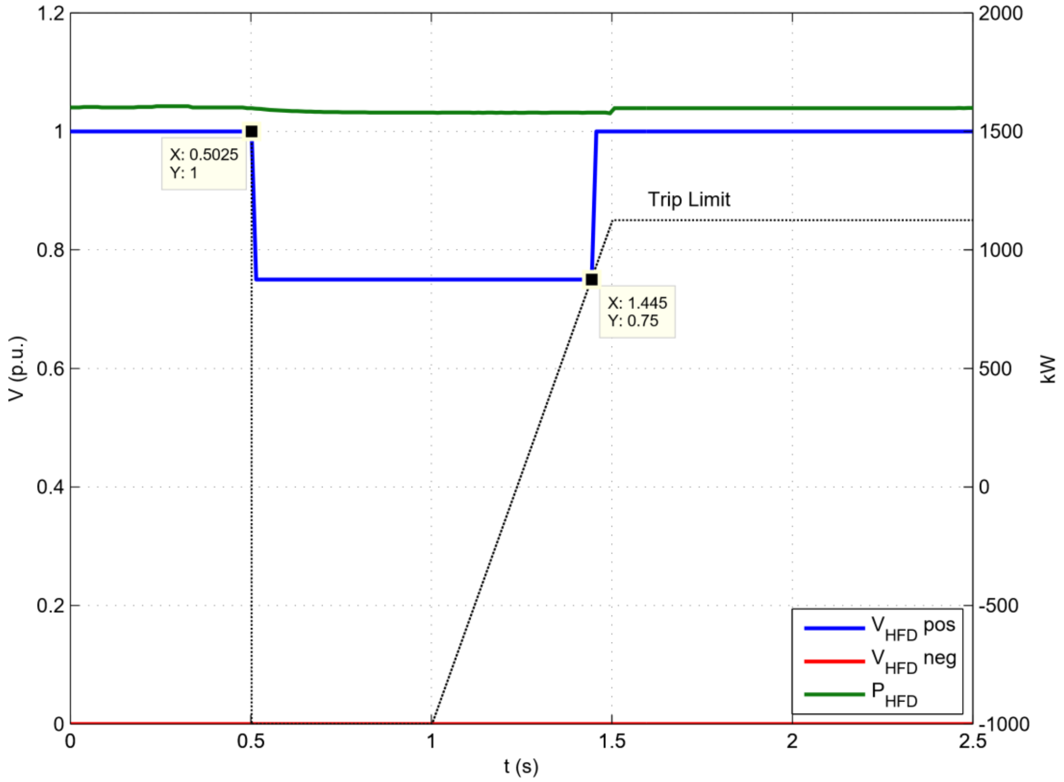

Figure 177: VST-2 (g)

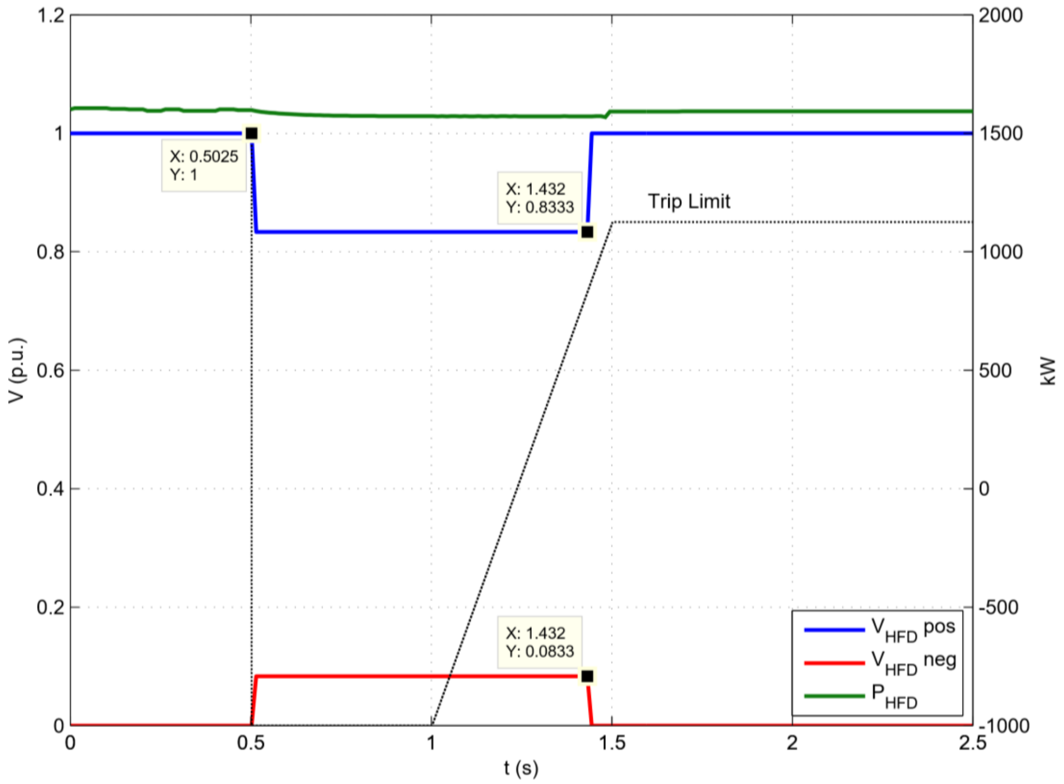

Figure 178: VST-2 (h)

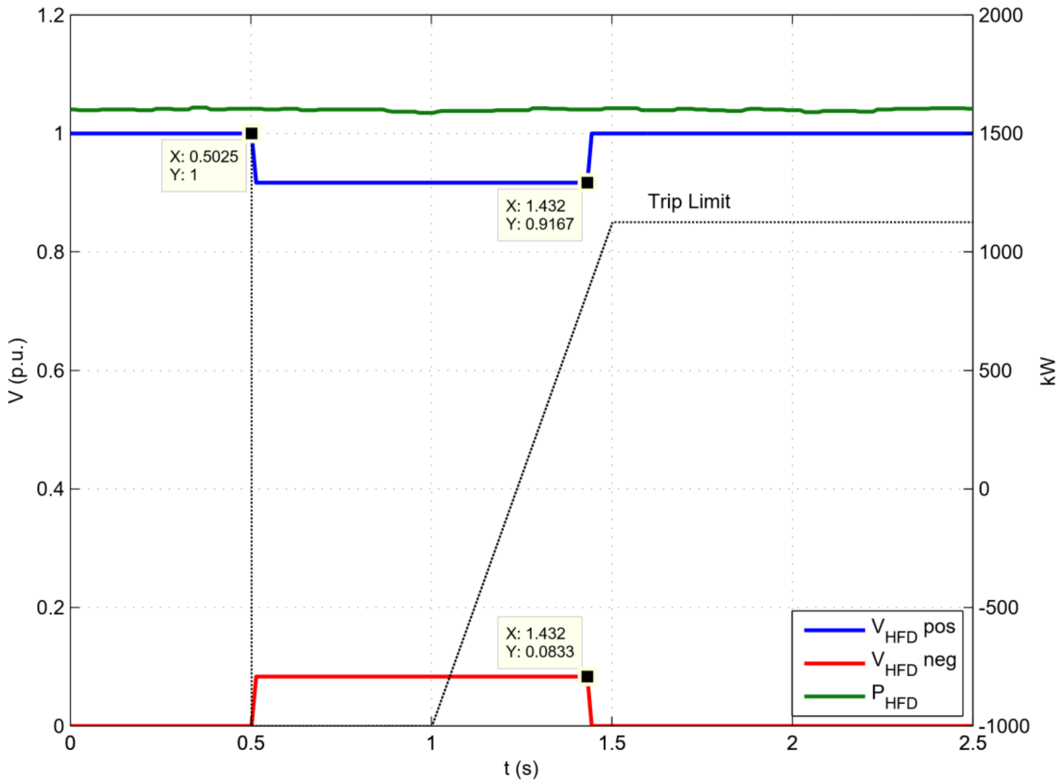

Figure 179: VST-2 (i)

7.1.3. Graph Results for FST-1 tests

In the following figures, the results of the FST-1 tests are presented. For each test, a frequency profile has been used according to Table 10. Values for FST-1 test. In the figures, frequency, voltage and total active and reactive power output of the HFD, all of them measured at the PCC, are represented.

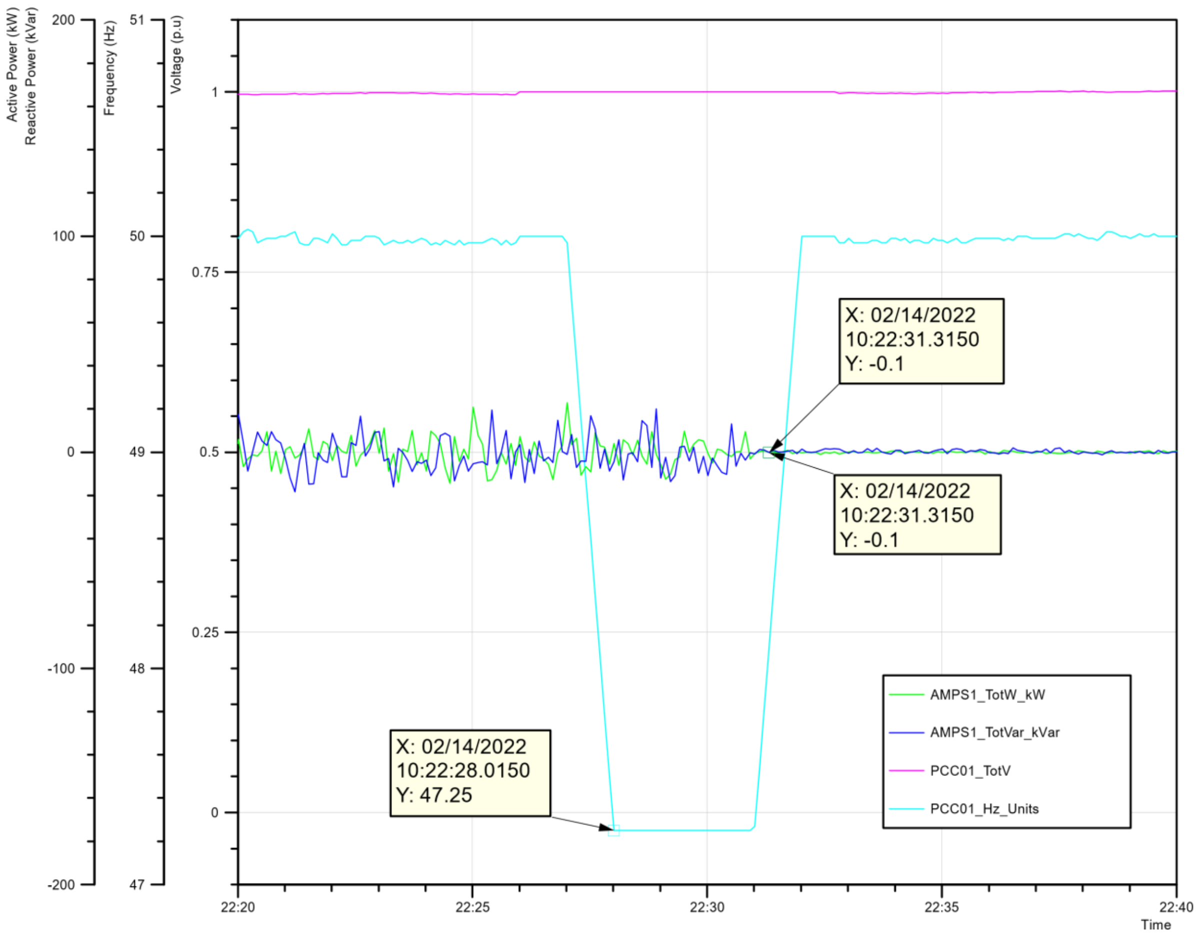

Figure 180: FST-1 (a)

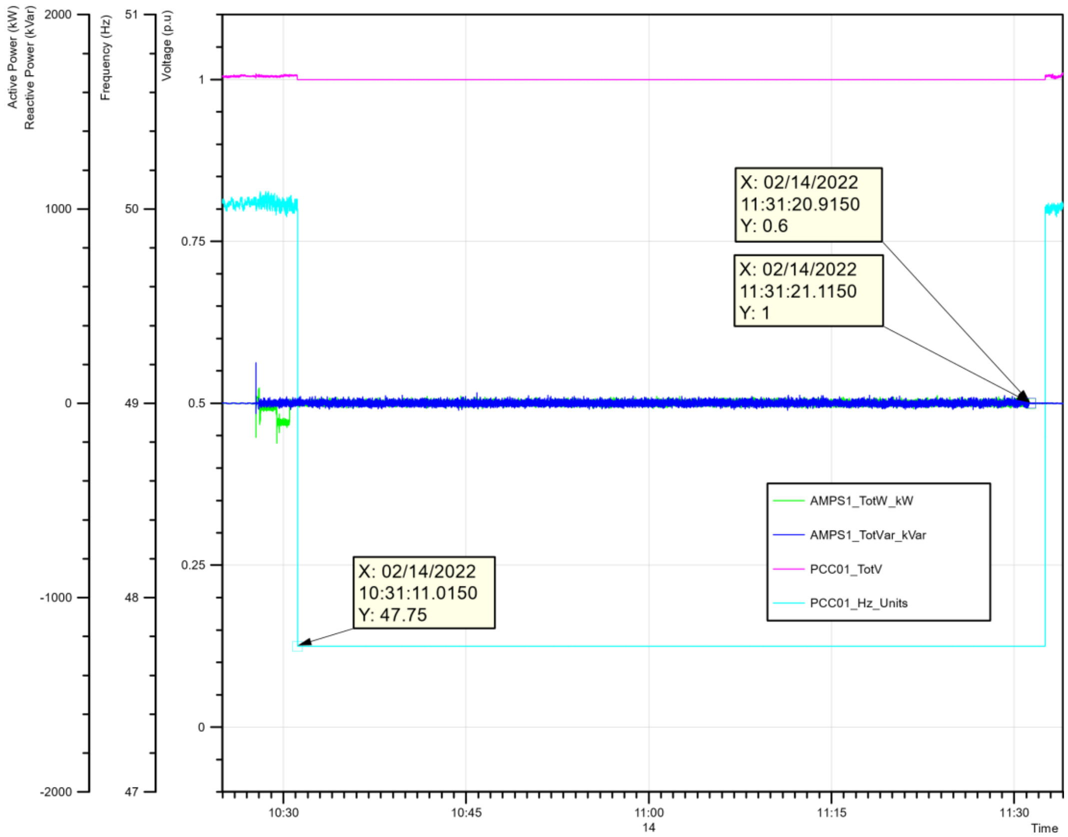

Figure 181: FST-1 (b)

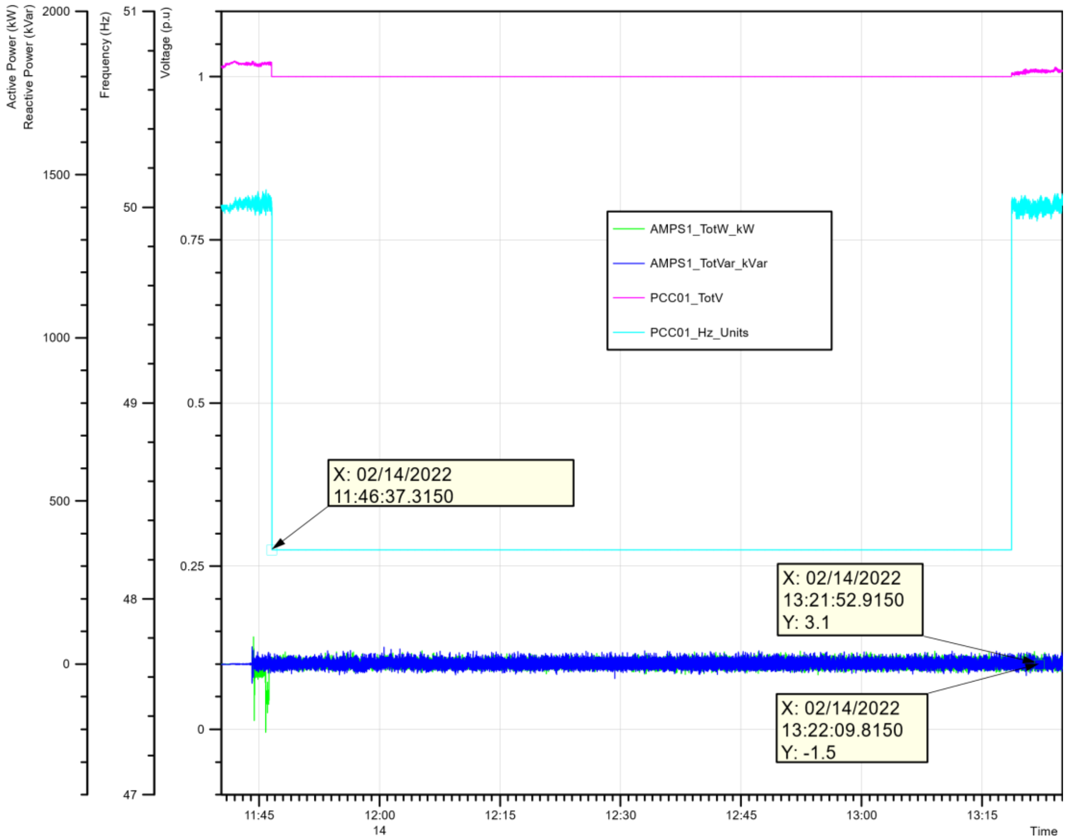

Figure 182: FST-1 (c-1)

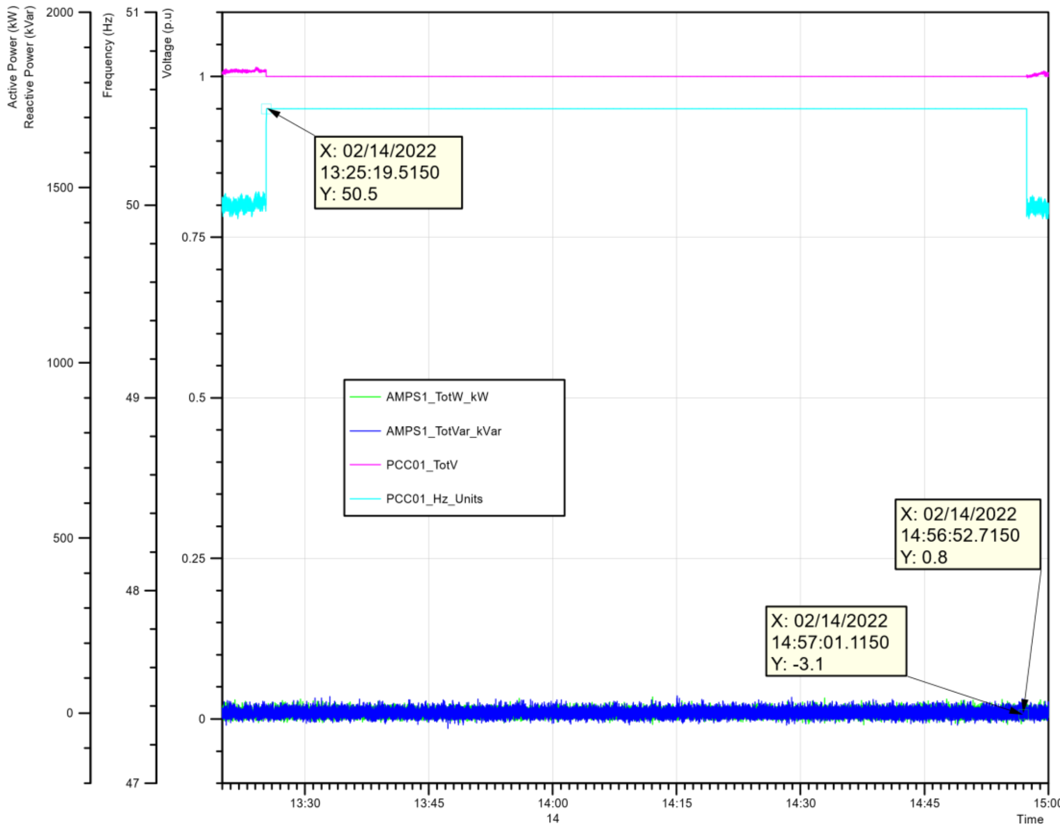

Figure 183: FST-1 (c-2)

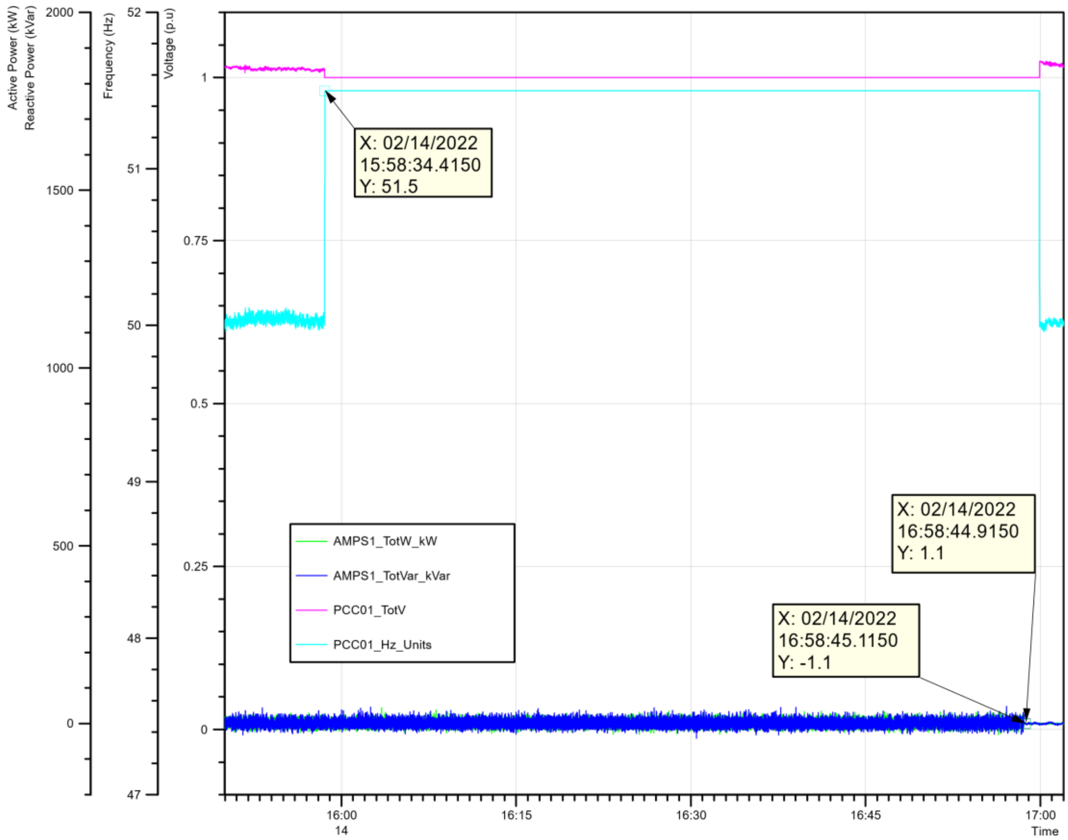

Figure 184: FST-1 (d)

7.1.4. Graph results for INE-0 & INE-1 tests

The results of the different test performed to validate the inertia emulation control are presented in this section. In the following figures, frequency and voltage data series are represented, as well as active and reactive power output.

The first figure corresponds to the first two tests, which are intended to evaluate the performance of the equipment when the inertia emulation is disabled (INE-0 (a) and INE-0 (b)). The profiles representing negative and positive frequency deviations (a and b), have been evaluated in a single test. Similarly, the response of the HFD to a frequency deviation whose frequency derivative does not reach the deadband of the control (INE-1(a)) is represented.

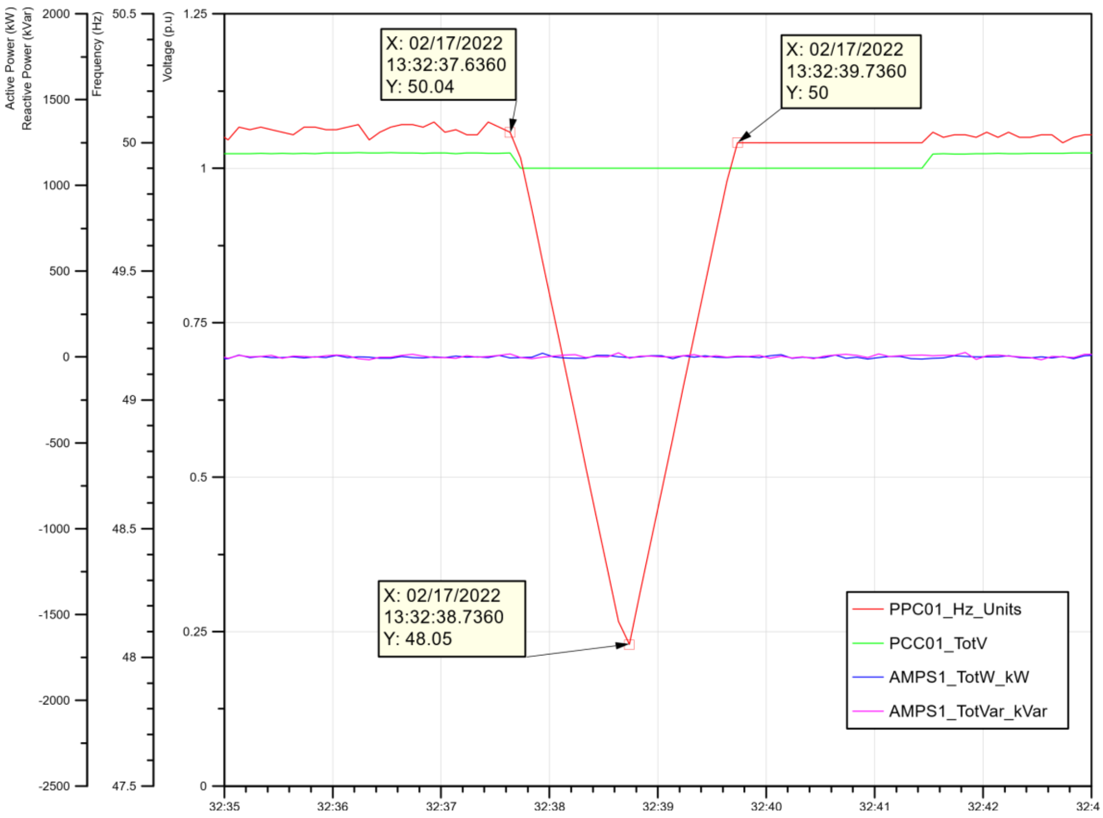

Figure 185: INE-0 (a,b)

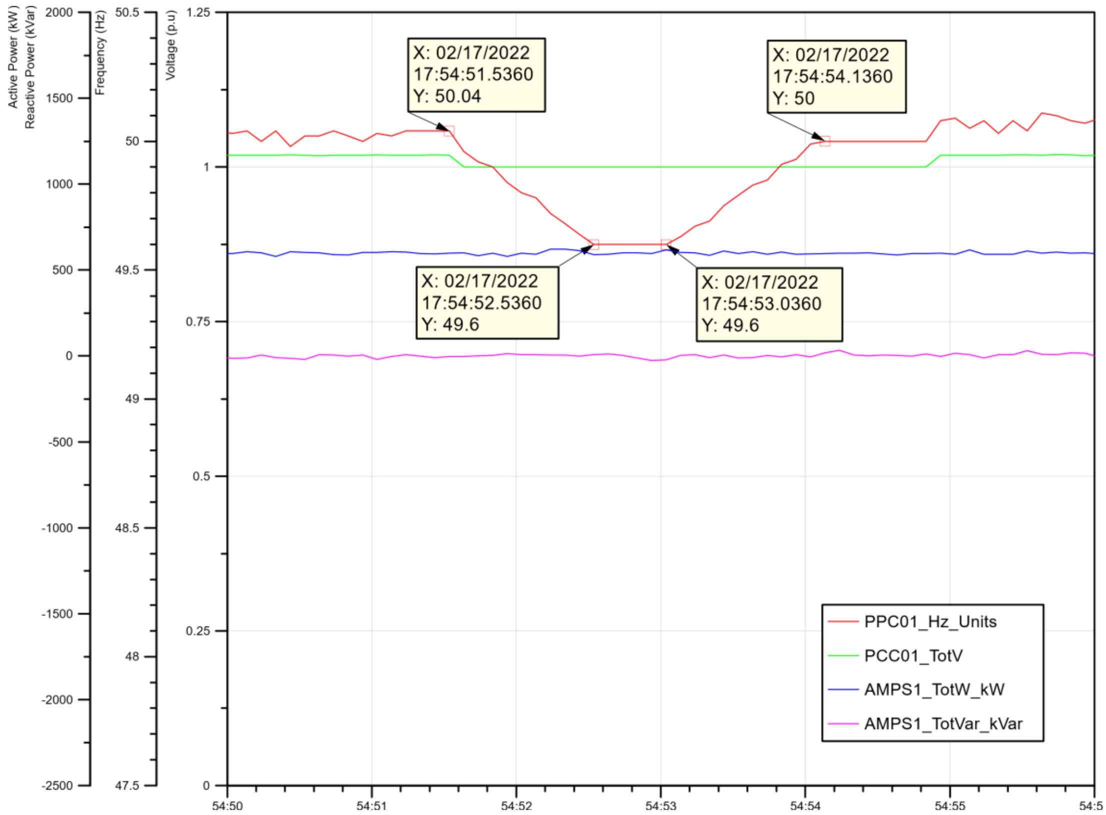

Figure 186: INE-1 (a,h)

The next figures show the results of the tests performed to validate the performance of the inertia emulation control (INE-1). Disturbances with different values of frequency derivative have been tested and different values of inertia have been set (profiles c to i) for these tests.

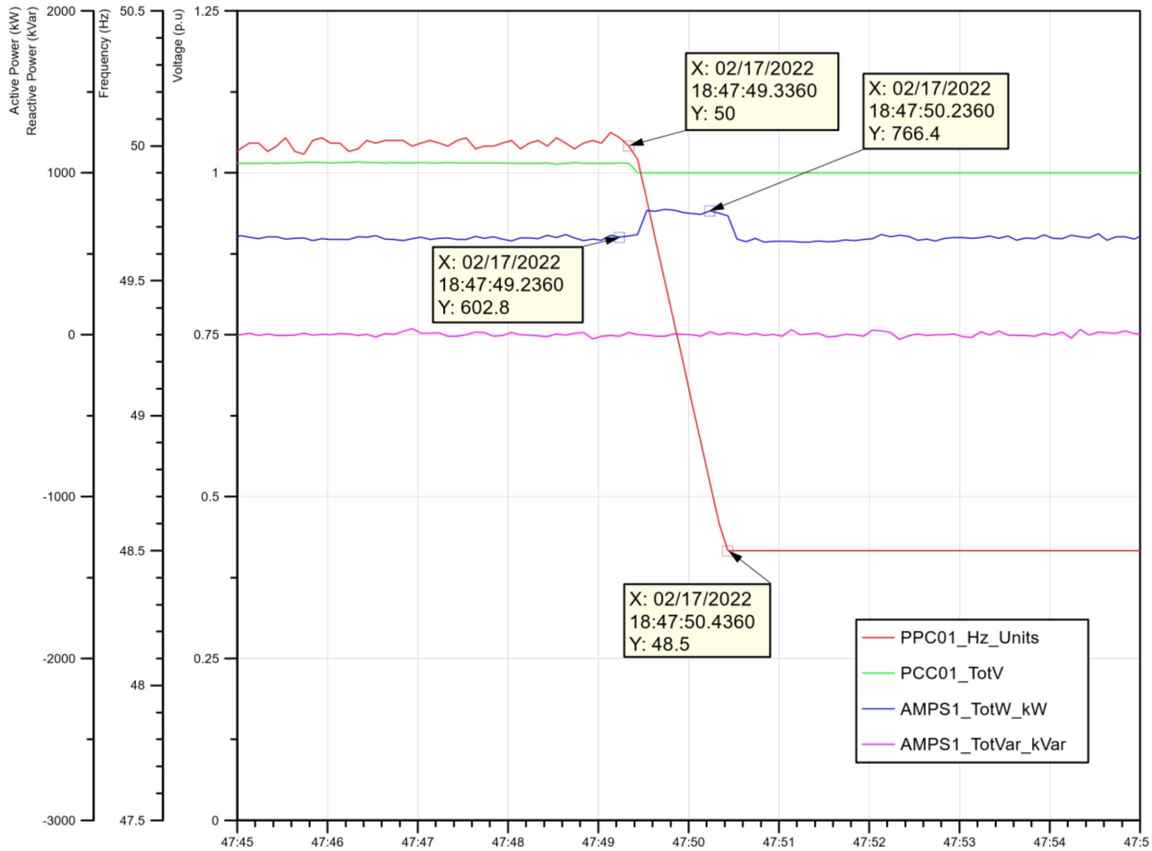

Figure 187: INE-1 (b)

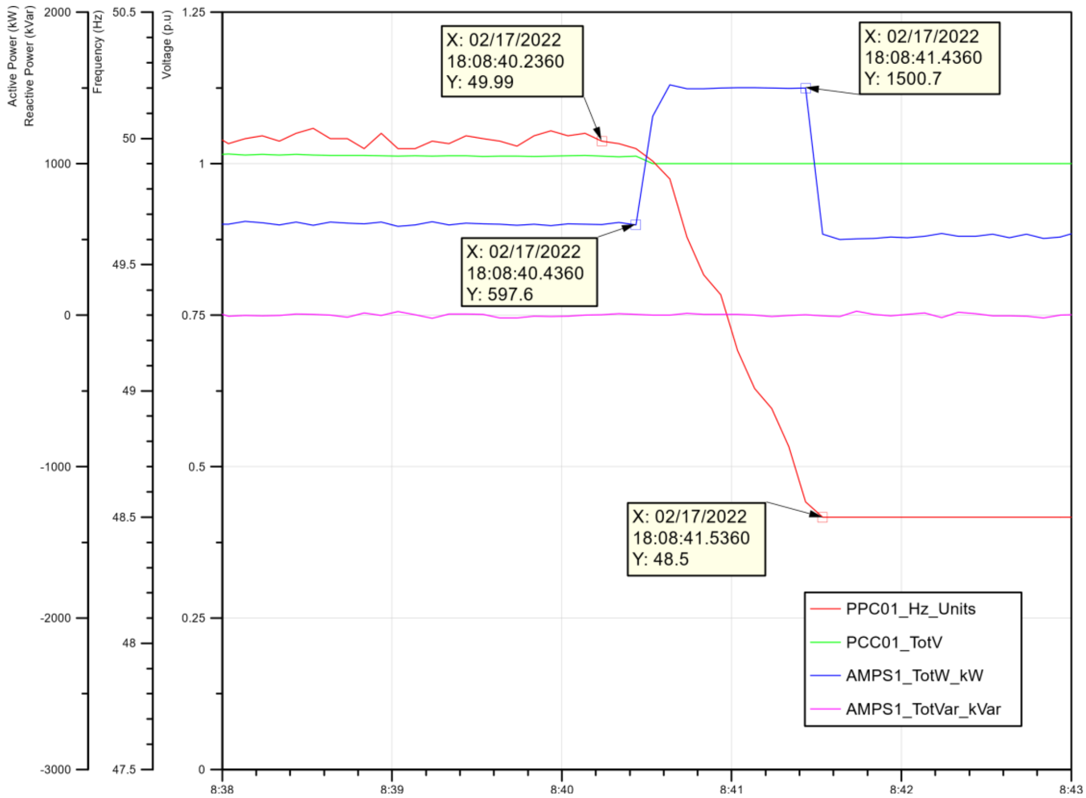

Figure 188: INE-1 (c)

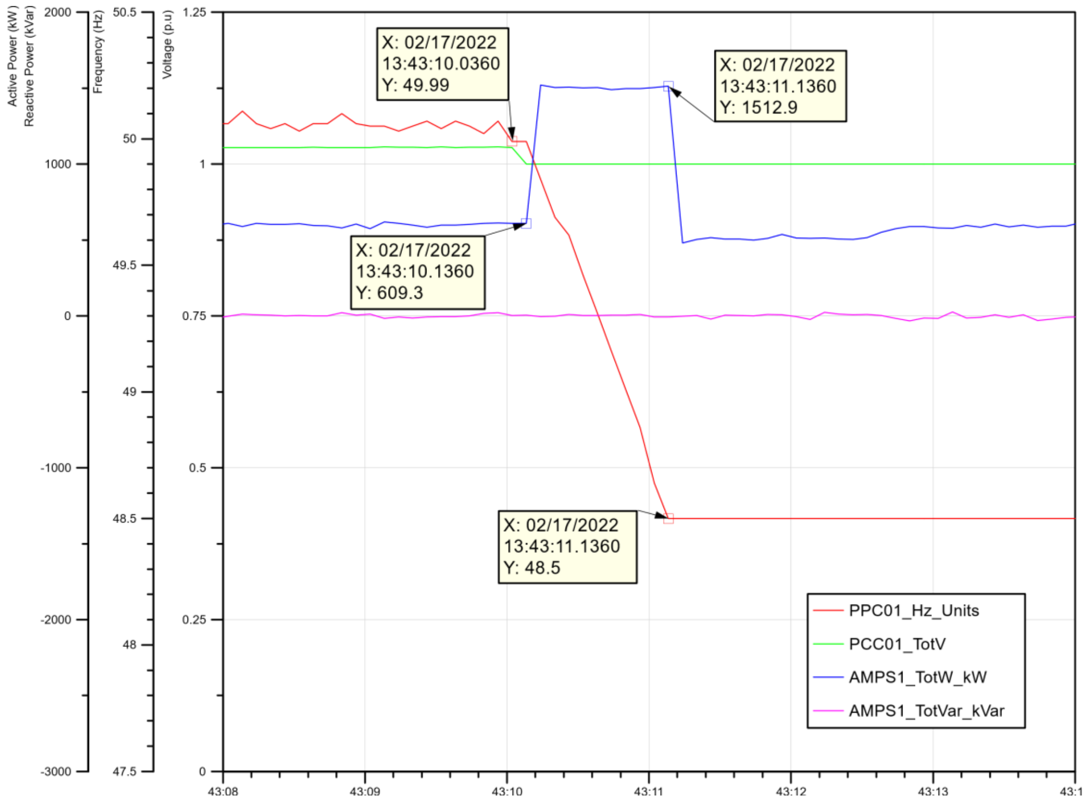

Figure 189: INE-1 (d)

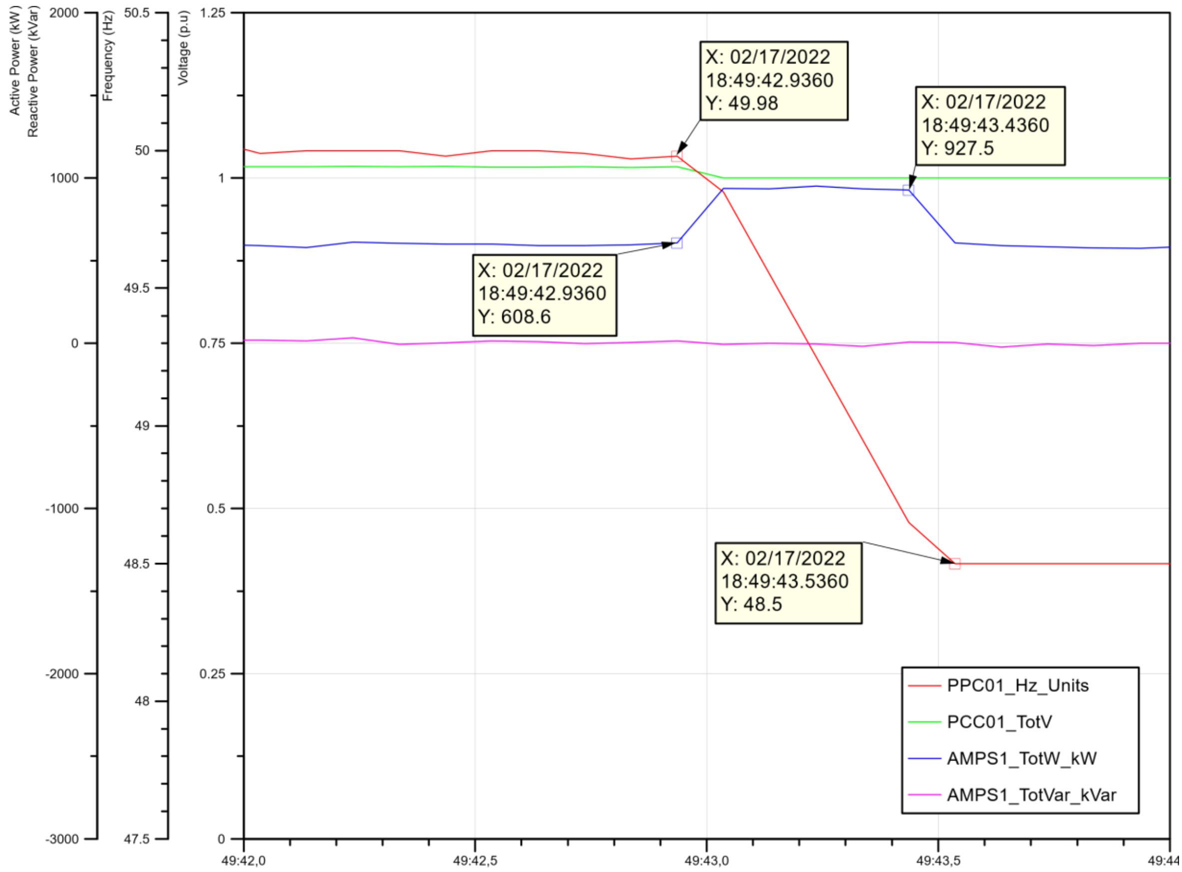

Figure 190: INE-1 (e)

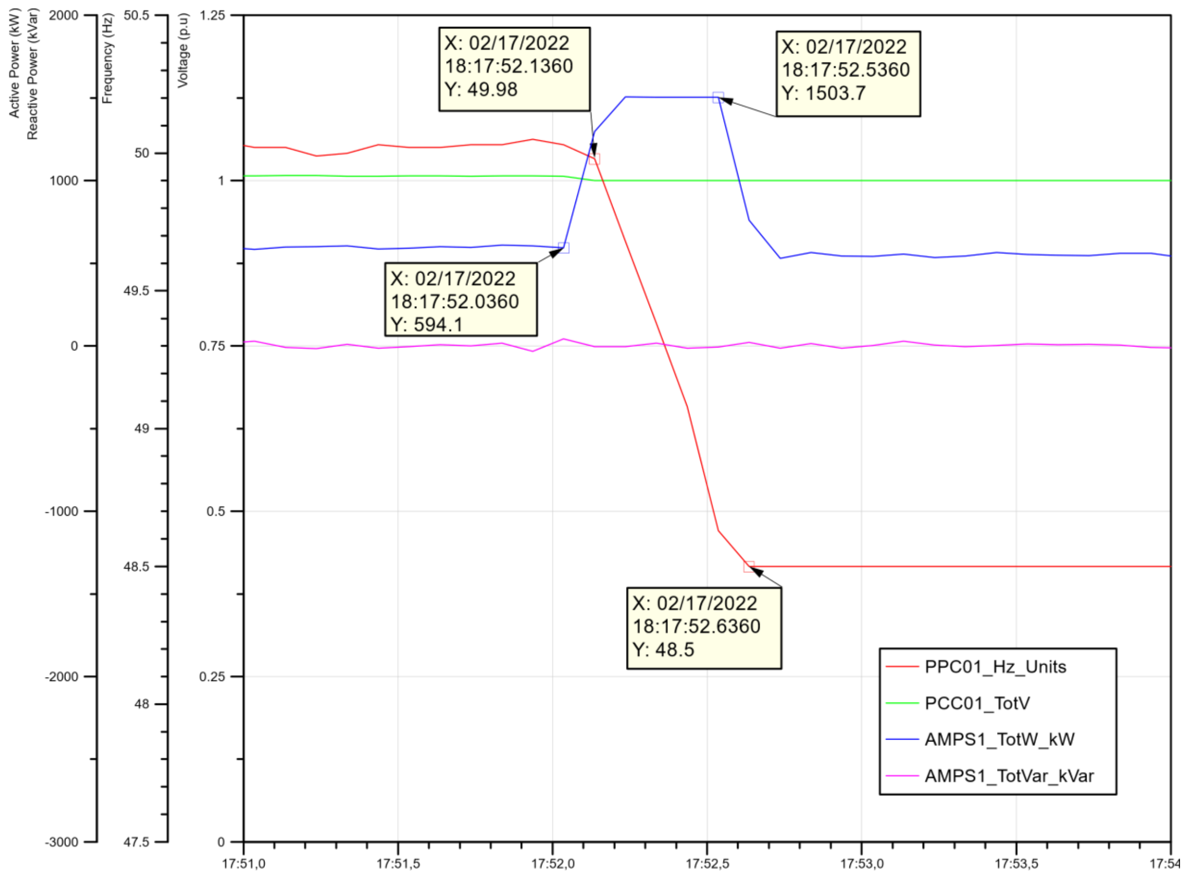

Figure 191: INE-1 (f)

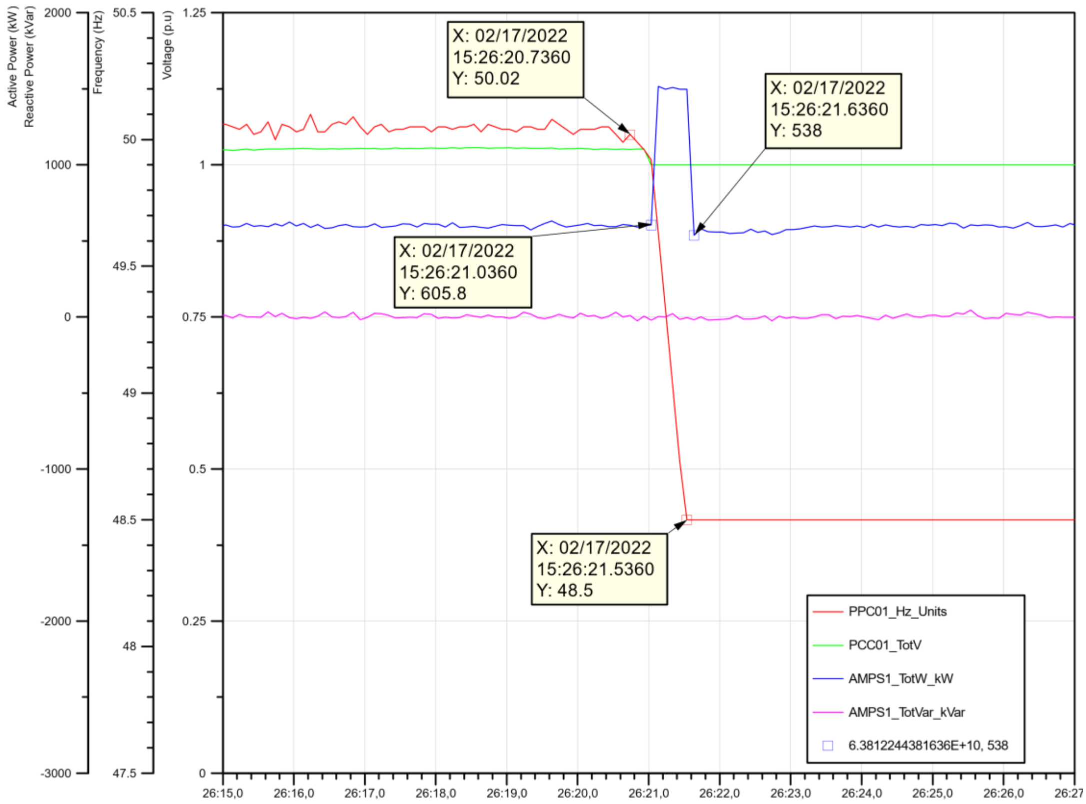

Figure 192: INE-1 (g)

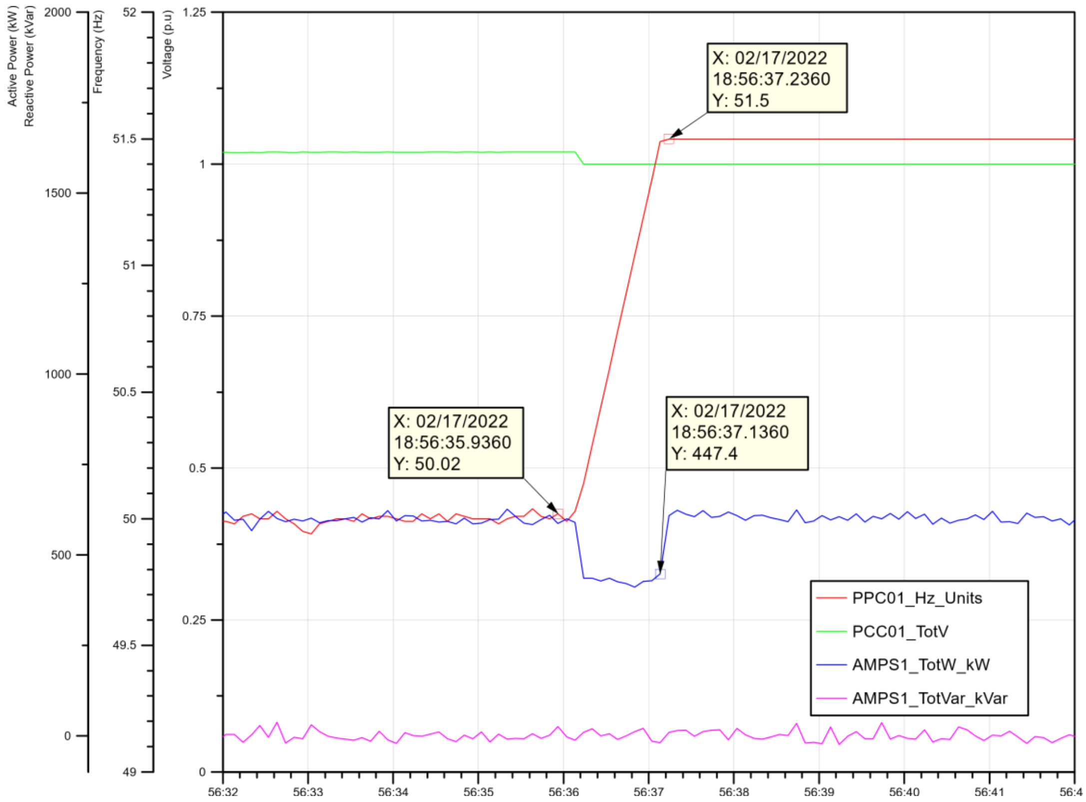

Figure 193: INE-1 (i)

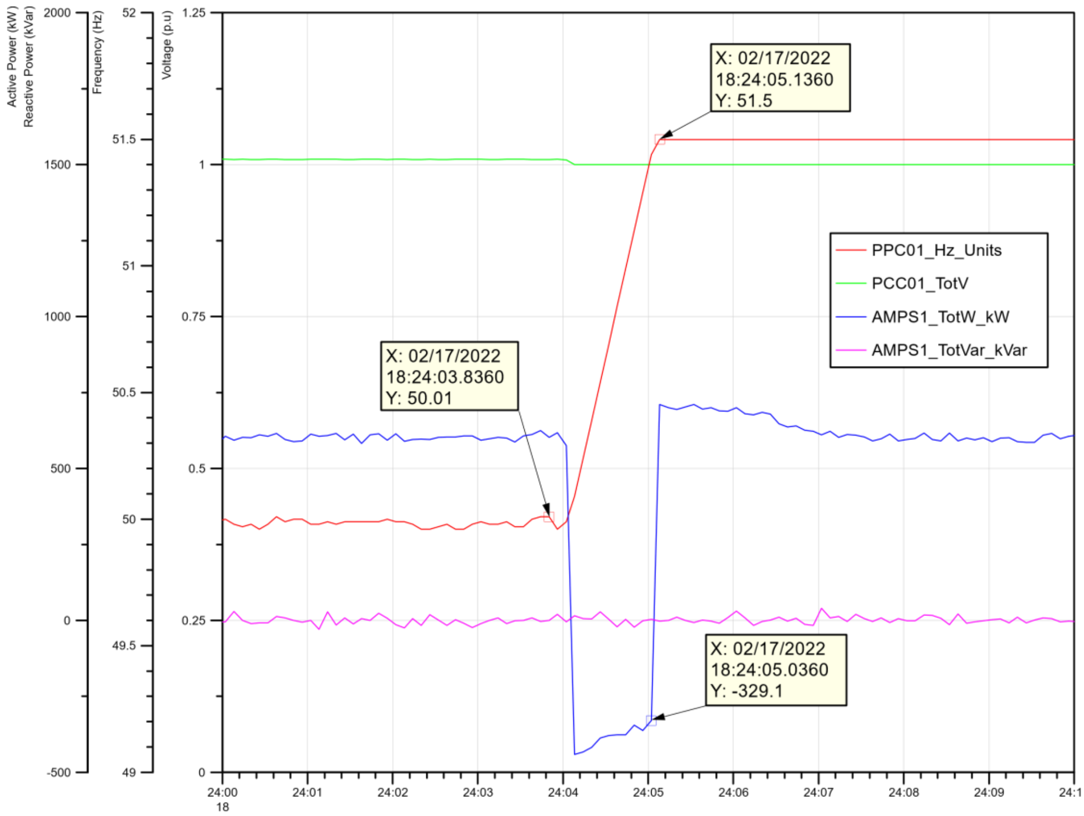

Figure 194: INE-1 (j)

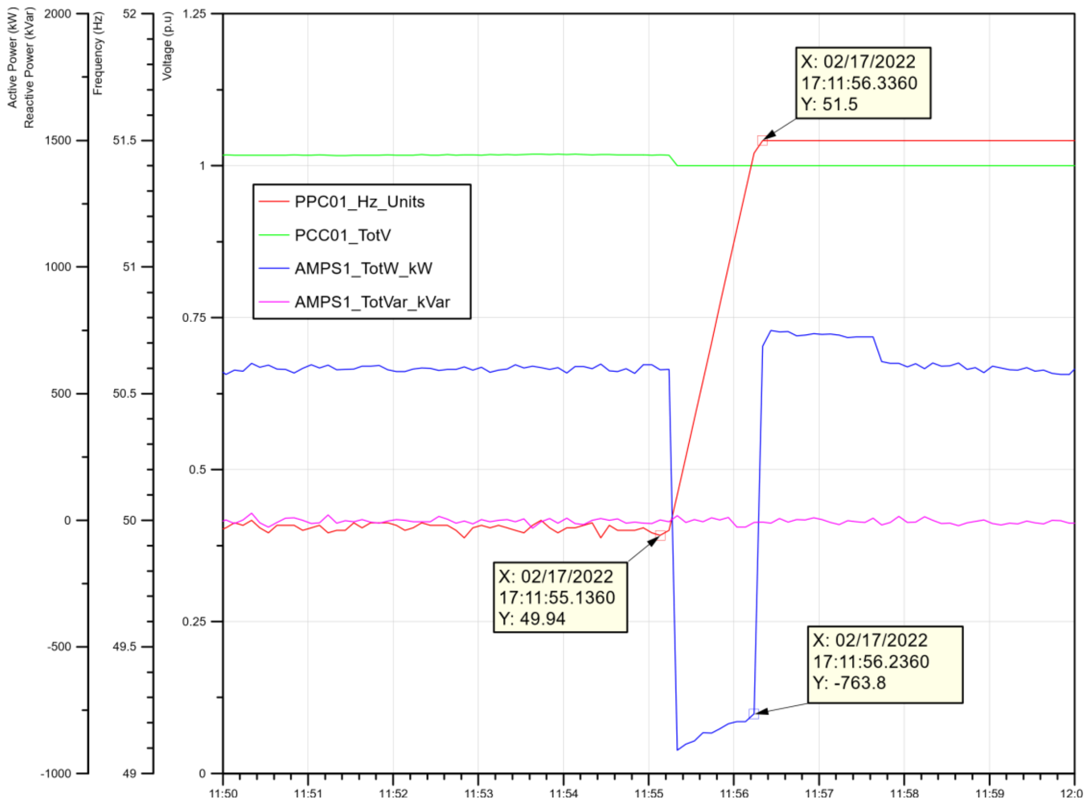

Figure 195: INE-1 (k)

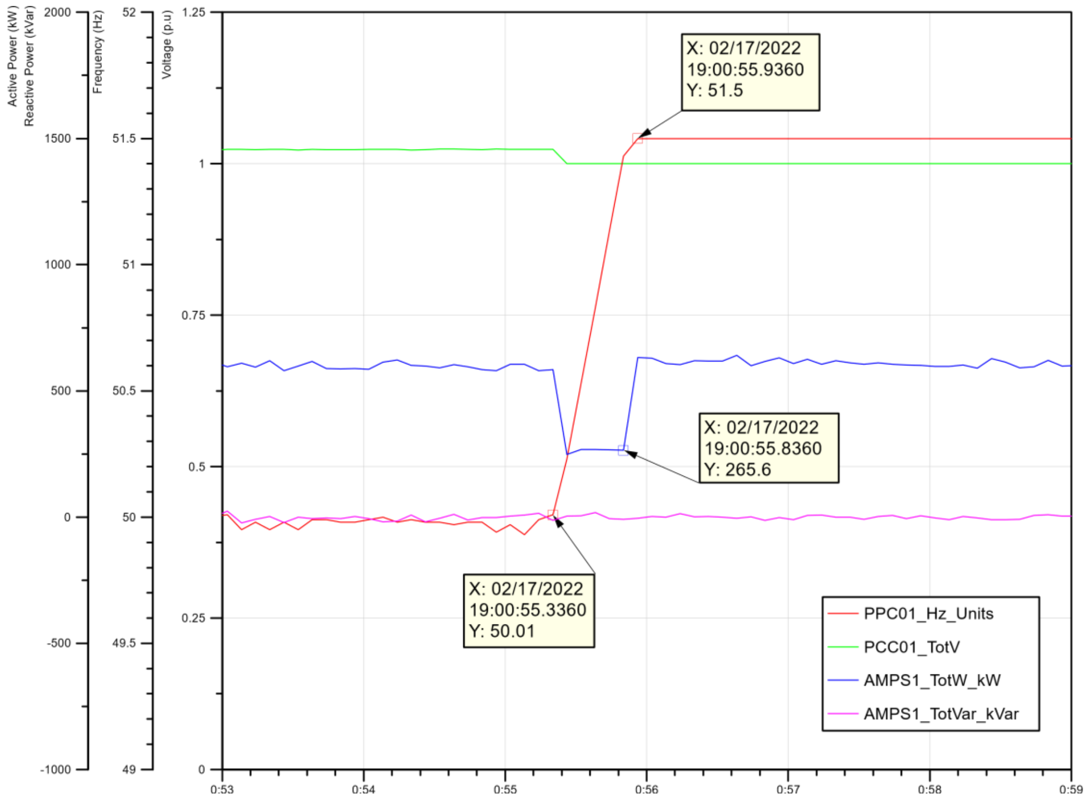

Figure 196: INE-1 (l)

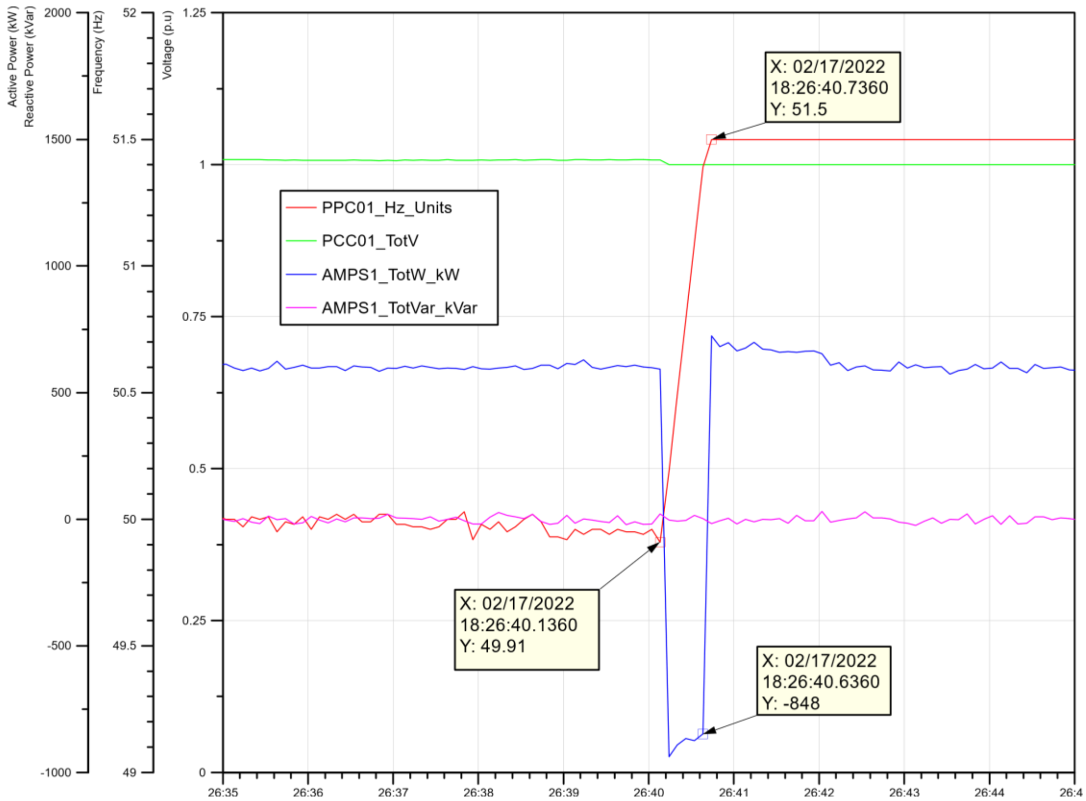

Figure 197: INE-1 (m)

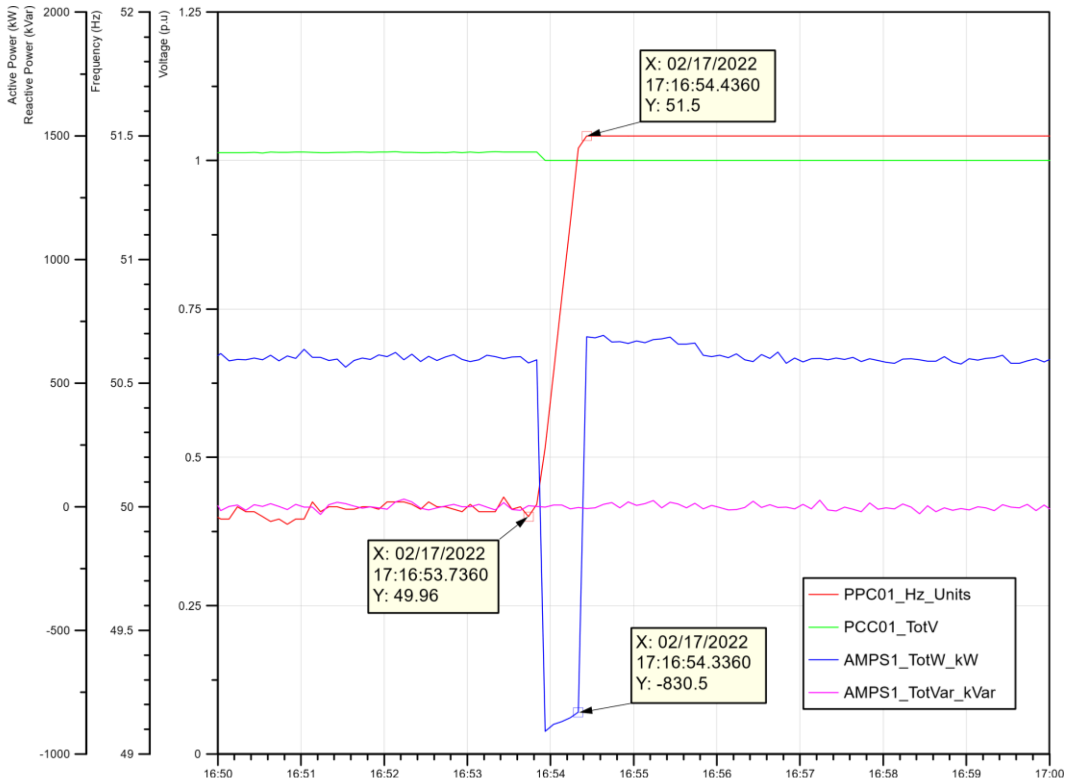

Figure 198: INE-1 (n)

7.1.5. Graph Results for FFR-0 & FFR-1 tests

The results of the different test performed to validate the Fast Frequency Response control are presented here. In the following figures, frequency and voltage data series are represented, as well as active and reactive power output.

The first figure corresponds to the first two tests (FFR-0(a) and FFR-0(b)), which are intended to evaluate the performance of the equipment when the FFR functionality is disabled. The profiles representing negative and positive frequency deviations (a and b), have been evaluated in a single test. The remaining figures in this section show the results of the tests performed to validate the performance of the FFR control (FFR-1). Disturbances with different values of frequency deviation have been recreated and different configurations of the controller have been set (profiles c to n) for these tests.

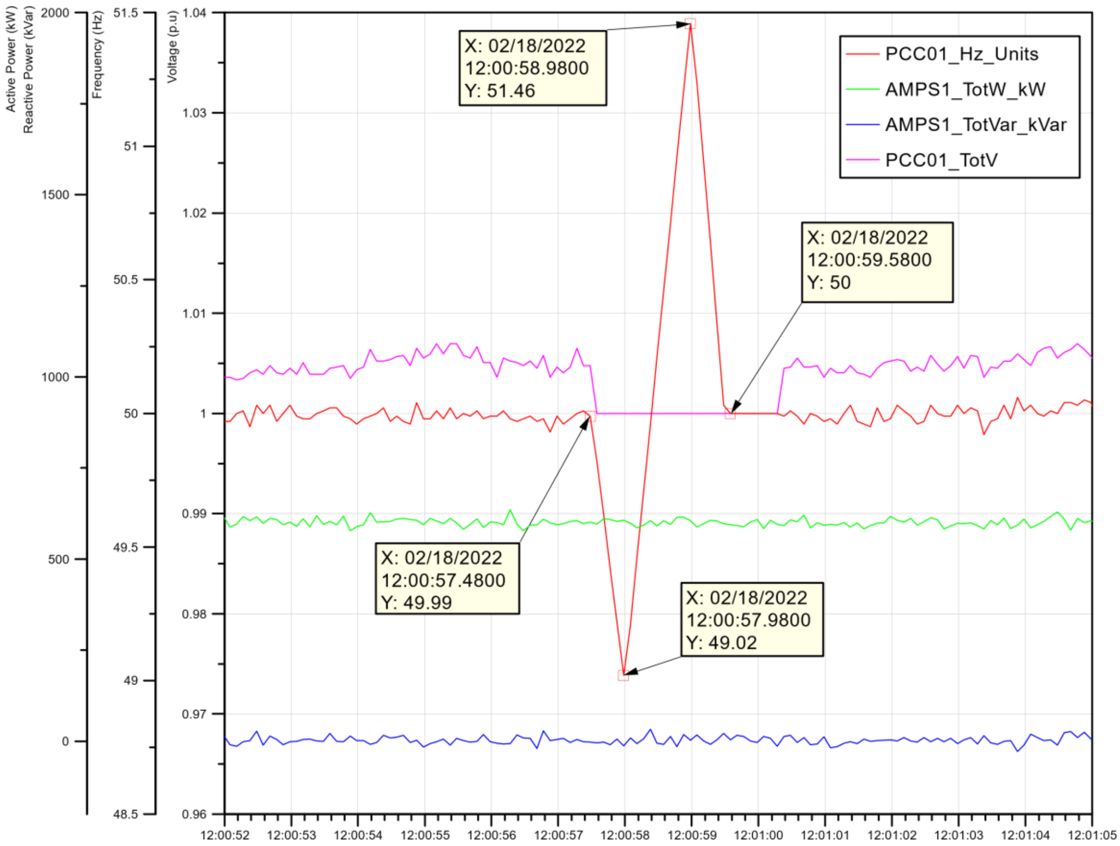

Figure 199: FFR-0 (a,b)

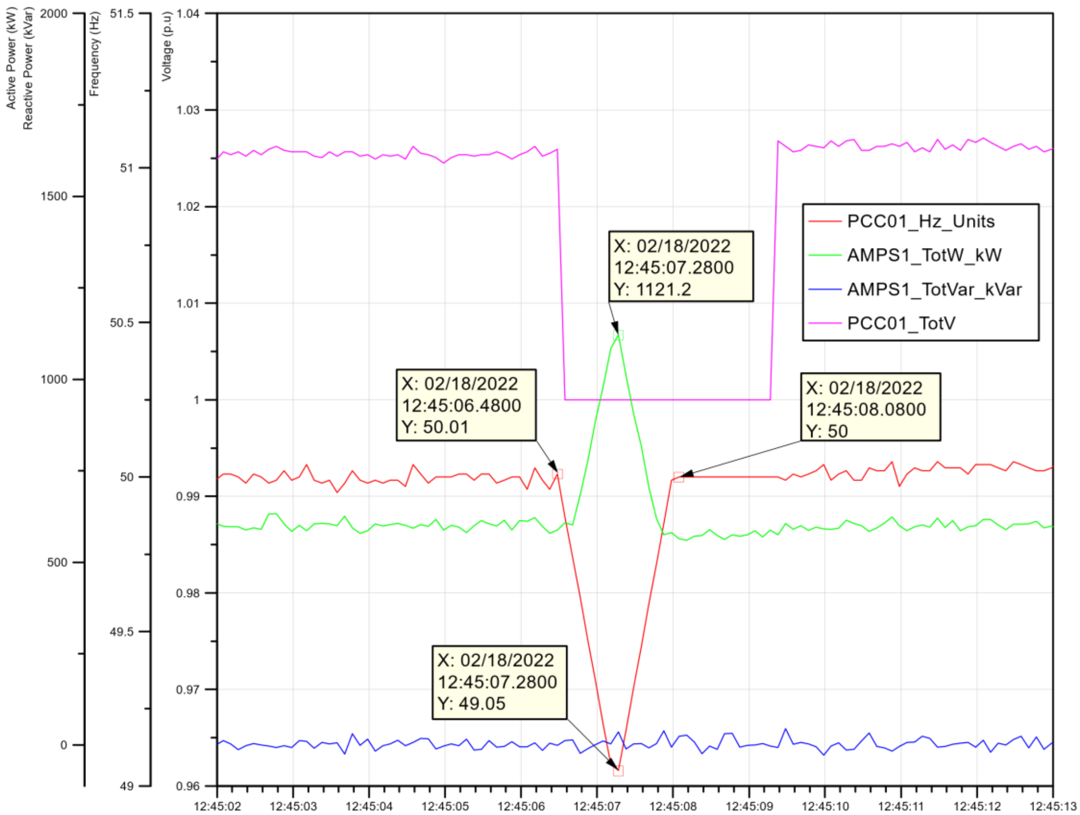

Figure 200: FFR-1 (a)

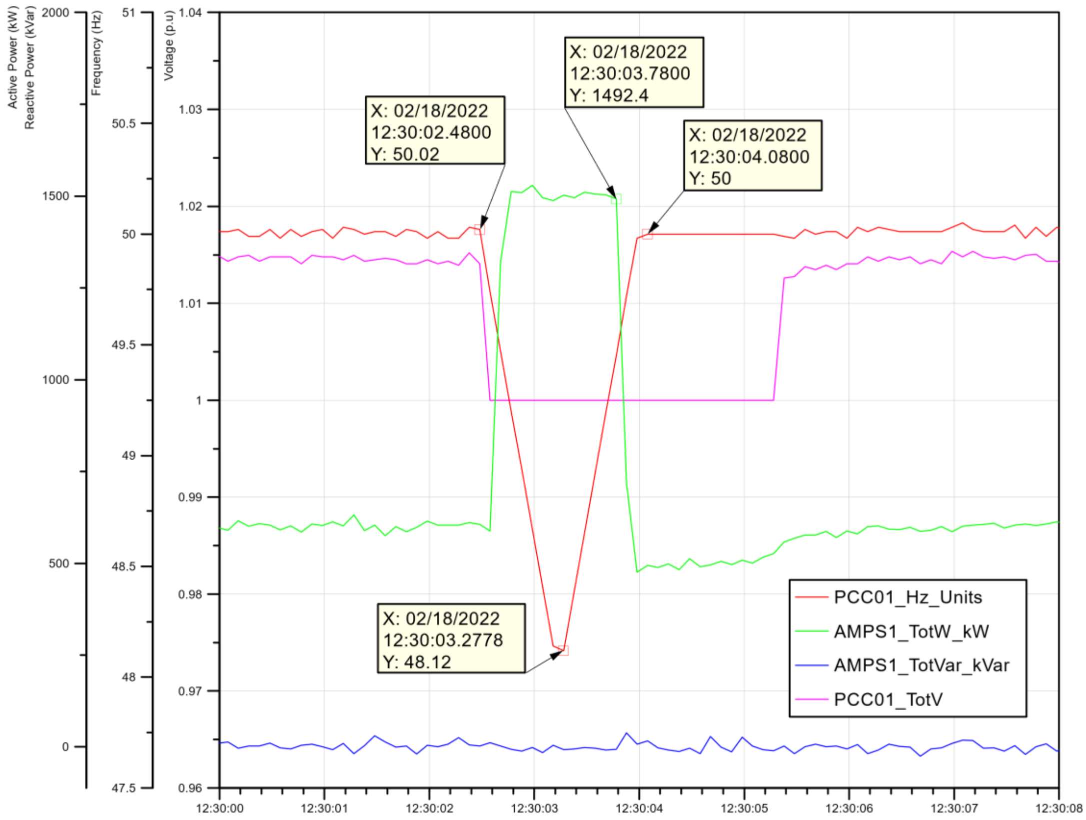

Figure 201: FFR-1 (b)

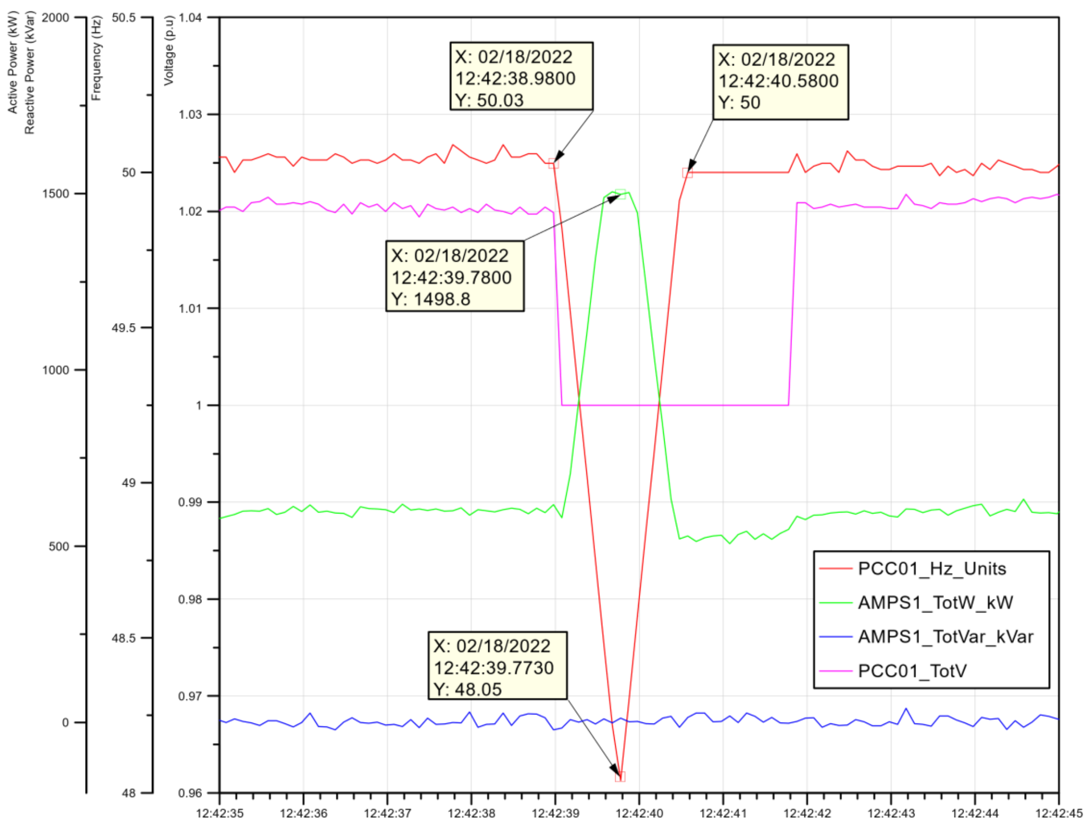

Figure 202: FFR-1 ©

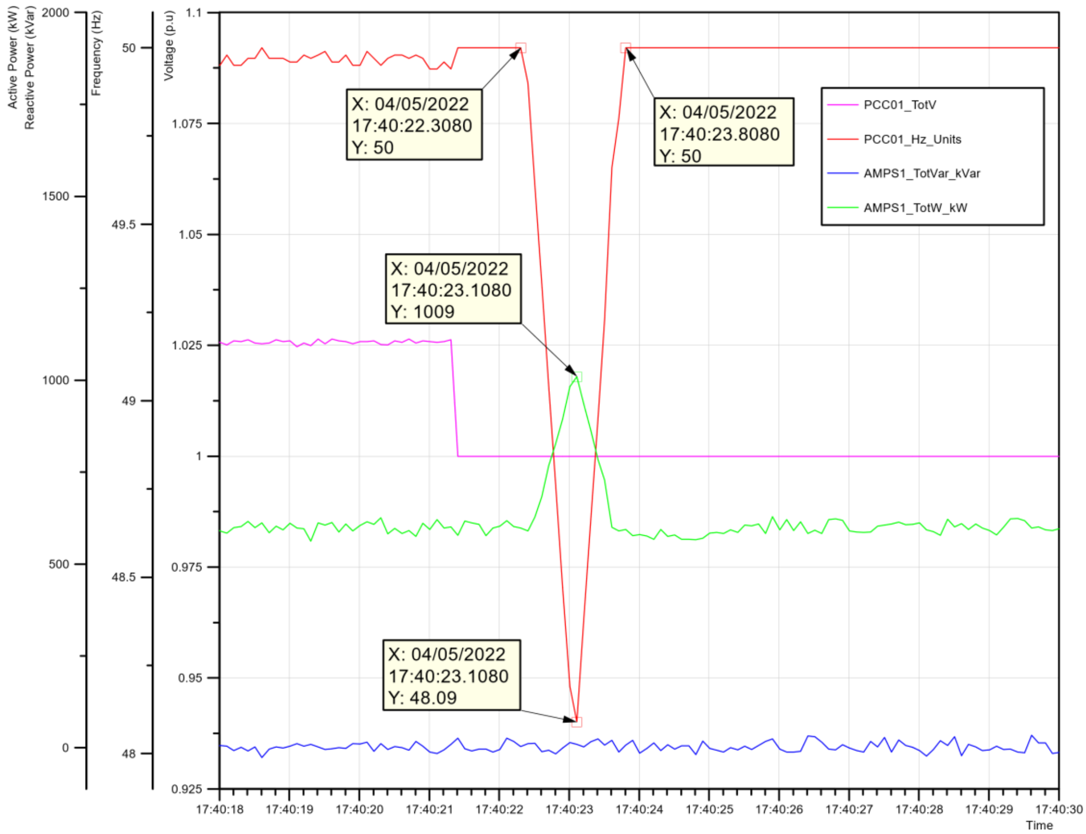

Figure 203: FFR-1 (d)

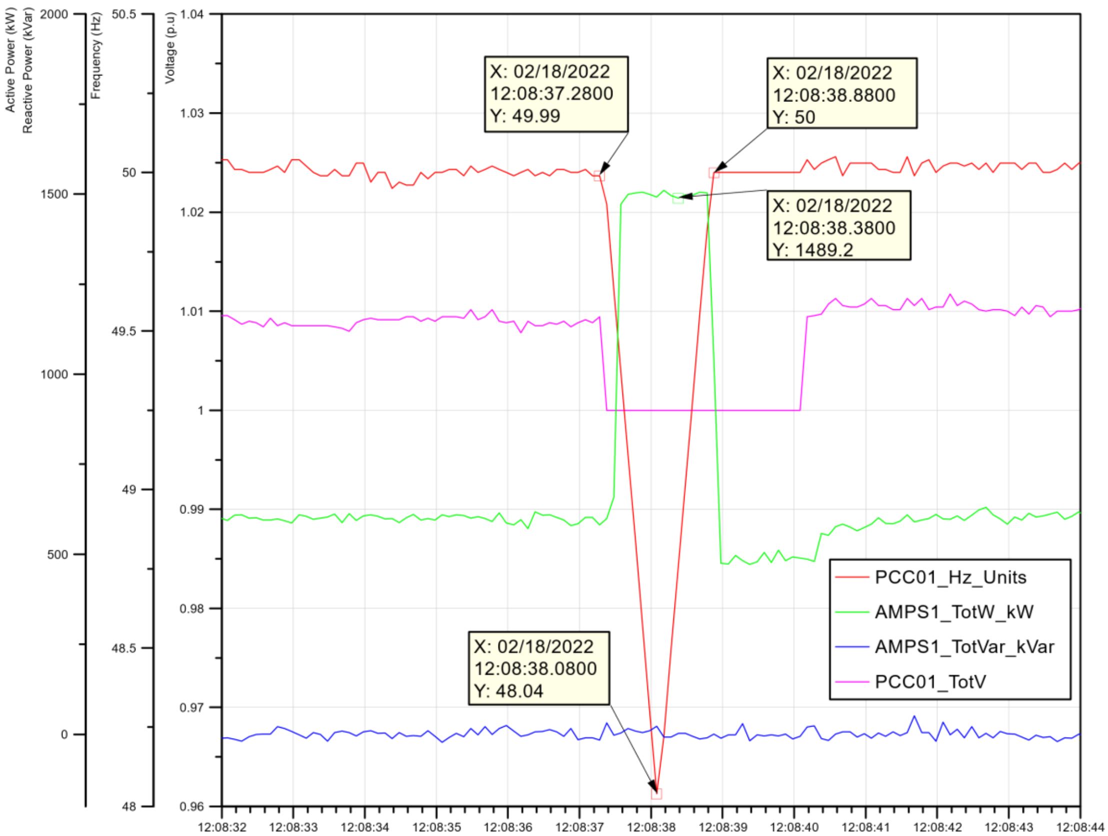

Figure 204: FFR-1 (e)

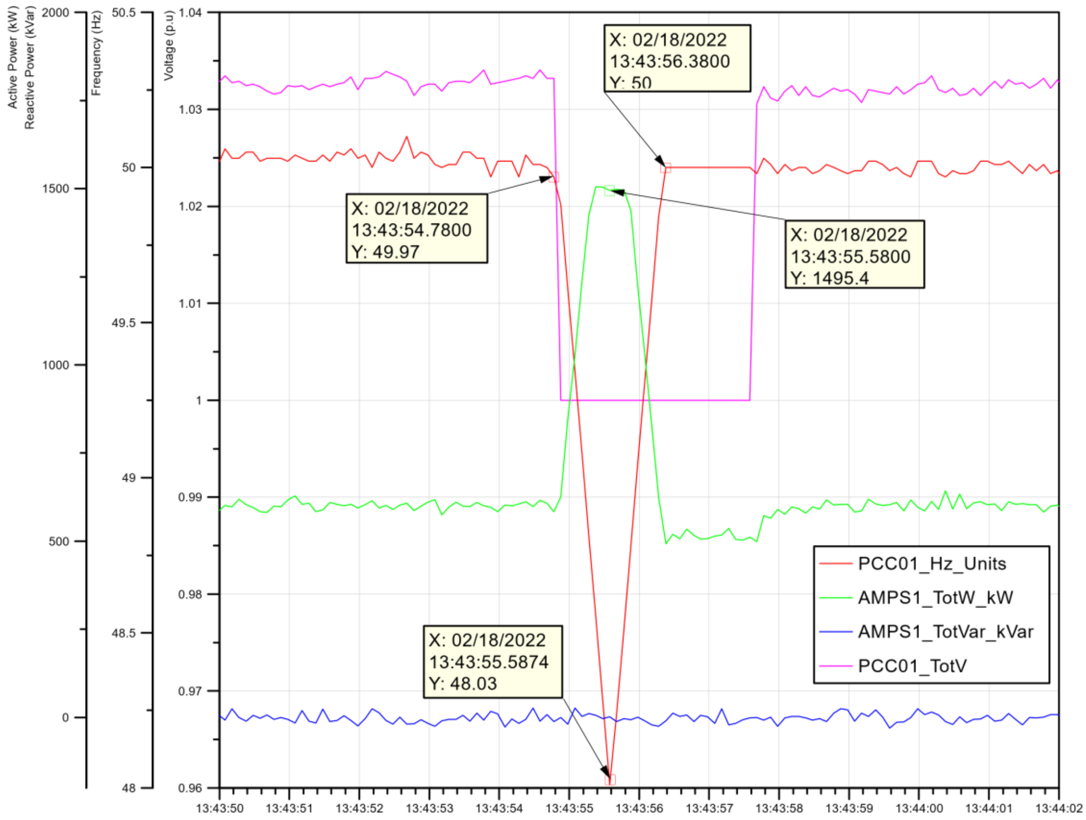

Figure 205: FFR-1 (f)

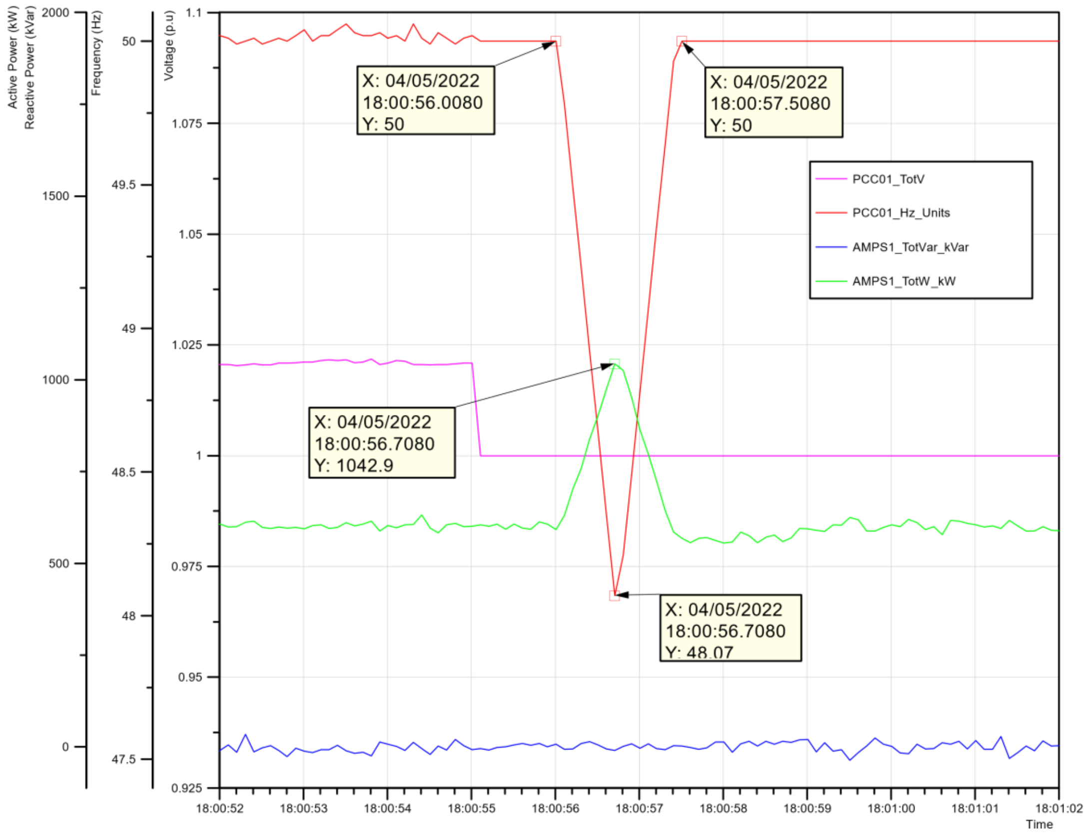

Figure 206: FFR-1 (g)

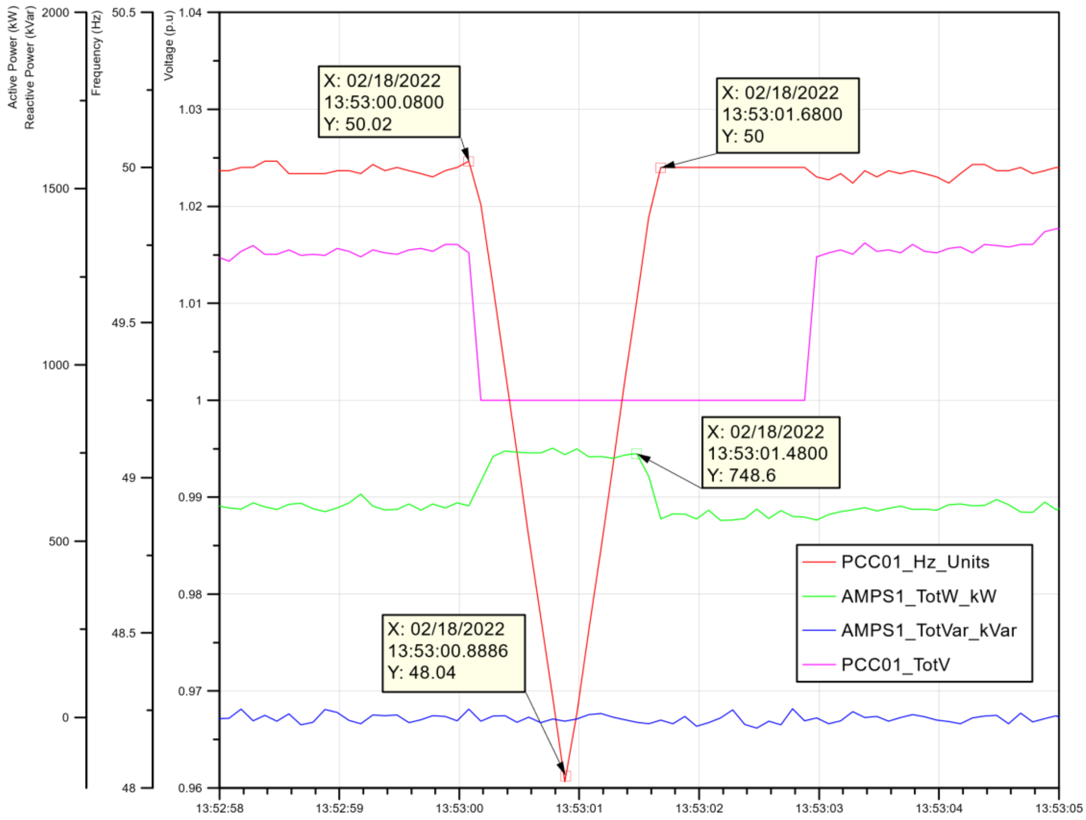

Figure 207: FFR-1 (h)

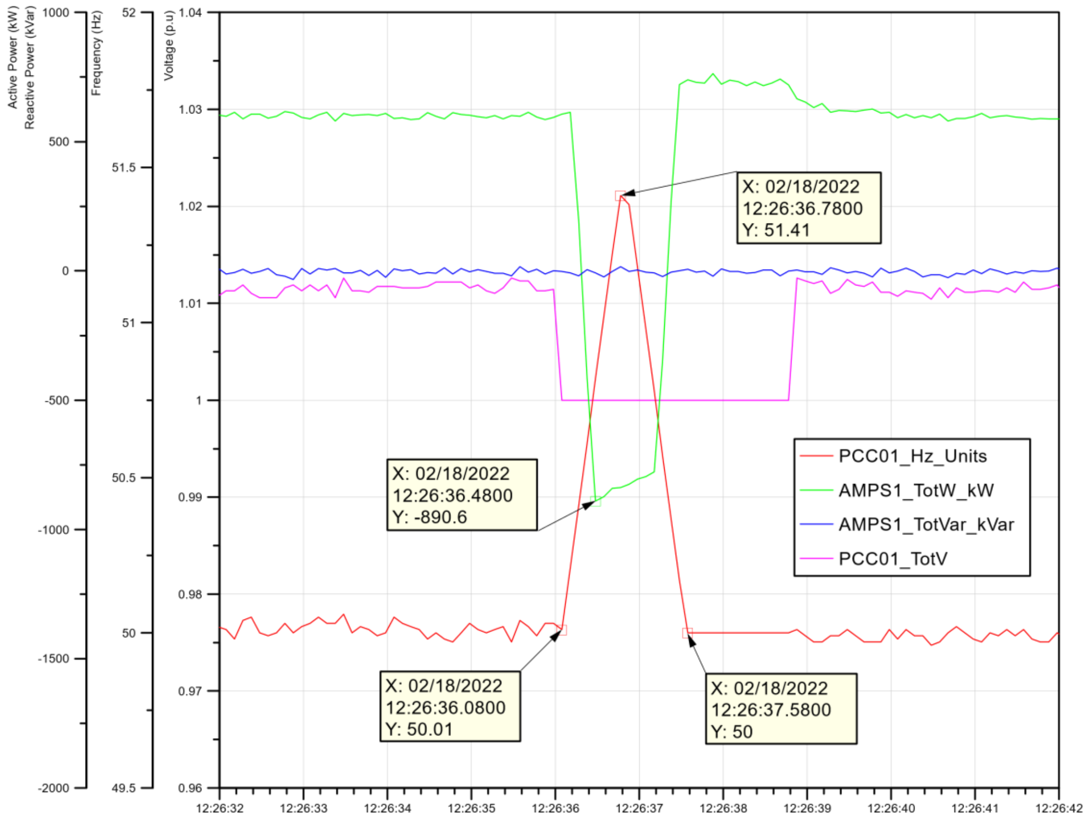

Figure 208: FFR-1 (i)

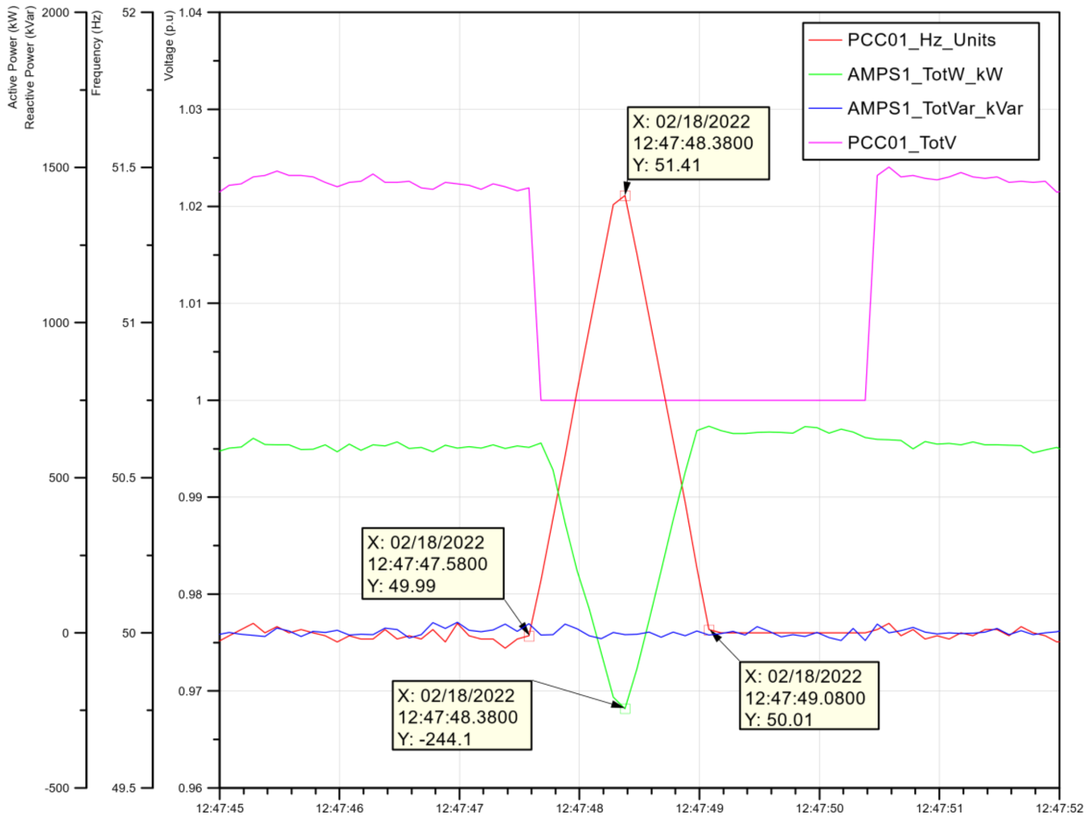

Figure 209: FFR-1 (j)

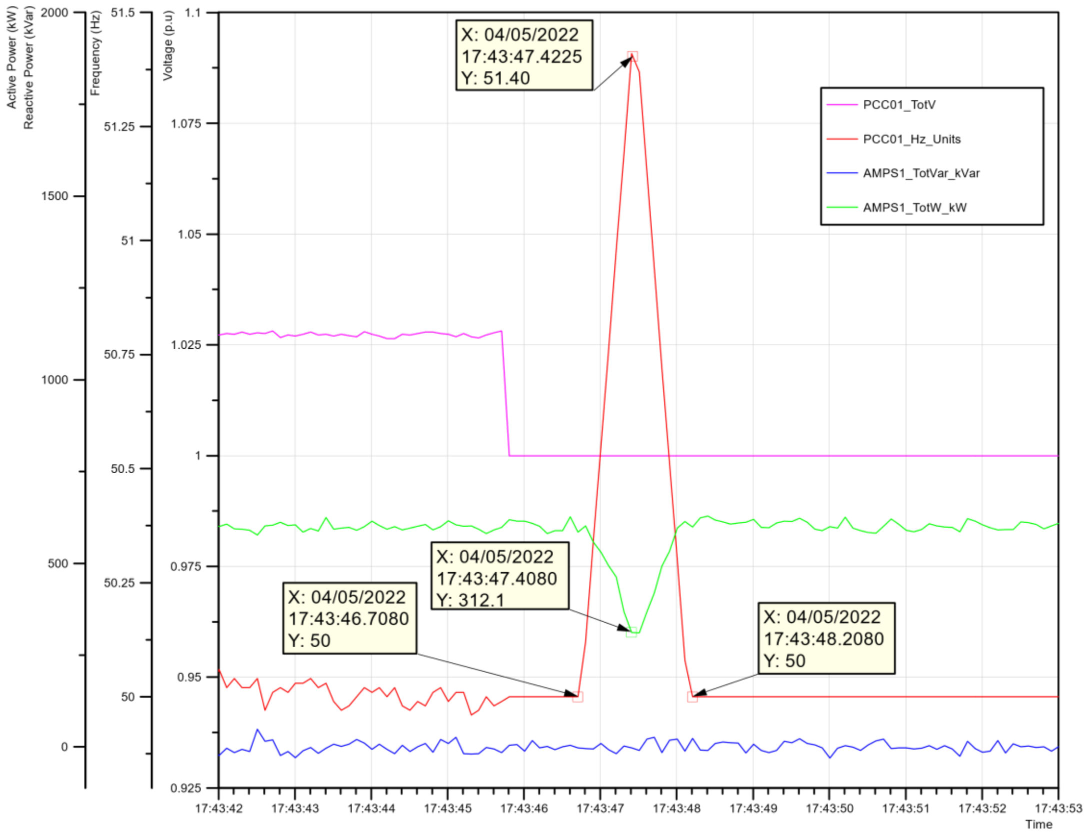

Figure 210: FFR-1 (k)

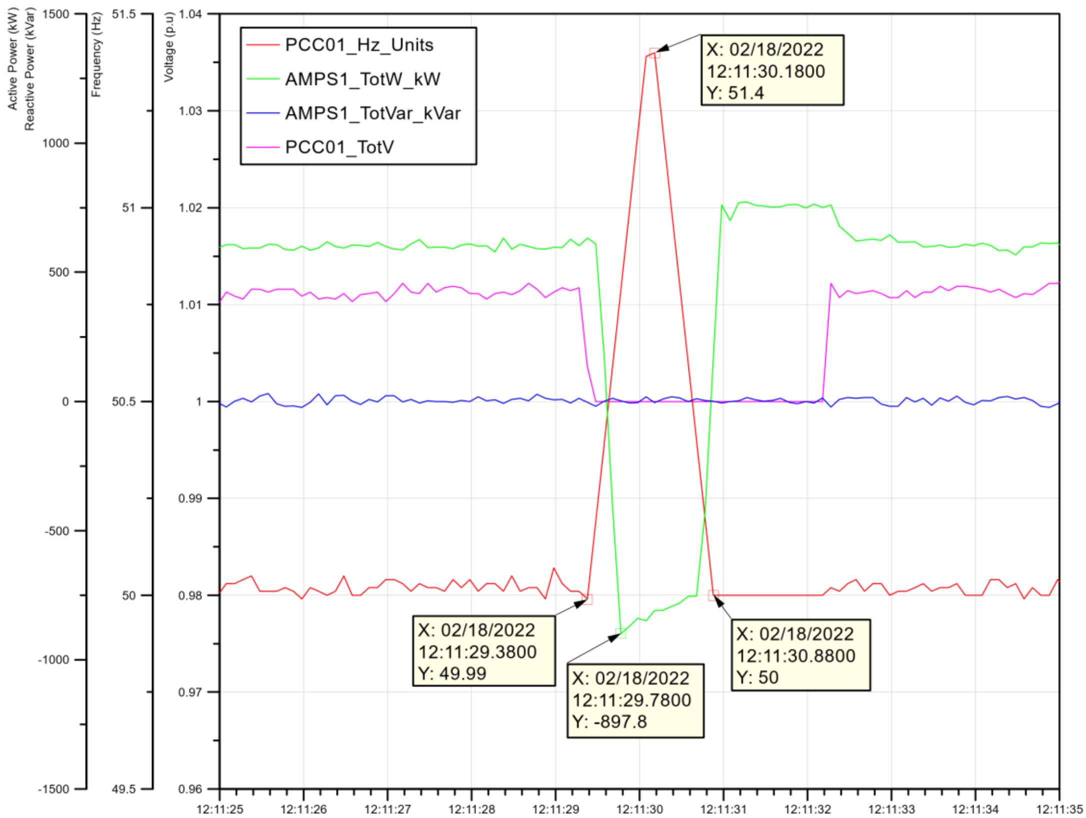

Figure 211: FFR-1 (l)

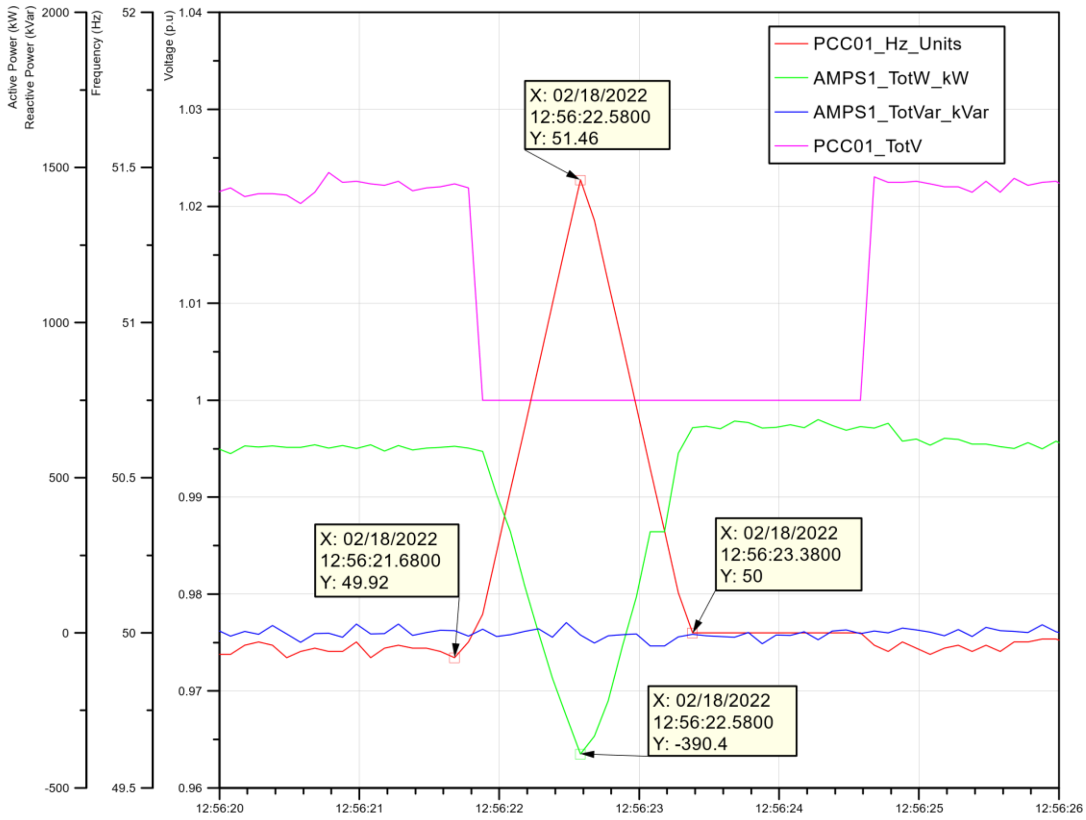

Figure 212: FFR-1 (m)

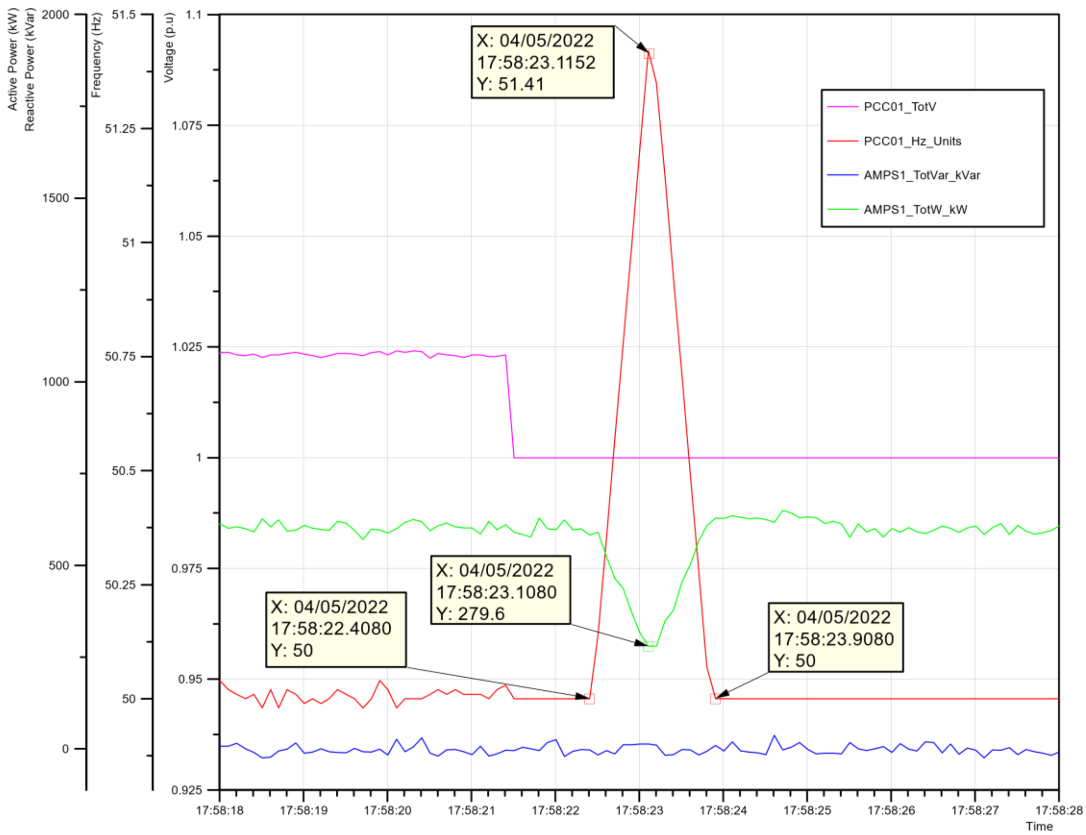

Figure 213: FFR-1 (n)

The disturbances consist of up and down ramps of 750ms. Therefore, ramps with up to 2.66 Hz/s would be contemplated, enough to check a fast response speed of the performance.

As explained in section 3.5, for FFR-0 and FFR-1 tests, DSP acquisition software was used.

7.1.6. Graph Results for PFR-p tests

The results of the different test performed to validate the power-frequency response in the perturbed regime are presented next. In the following figures, voltage, frequency, active power output and reactive power output are represented for the different frequency profiles and control configurations (tests from a to f).

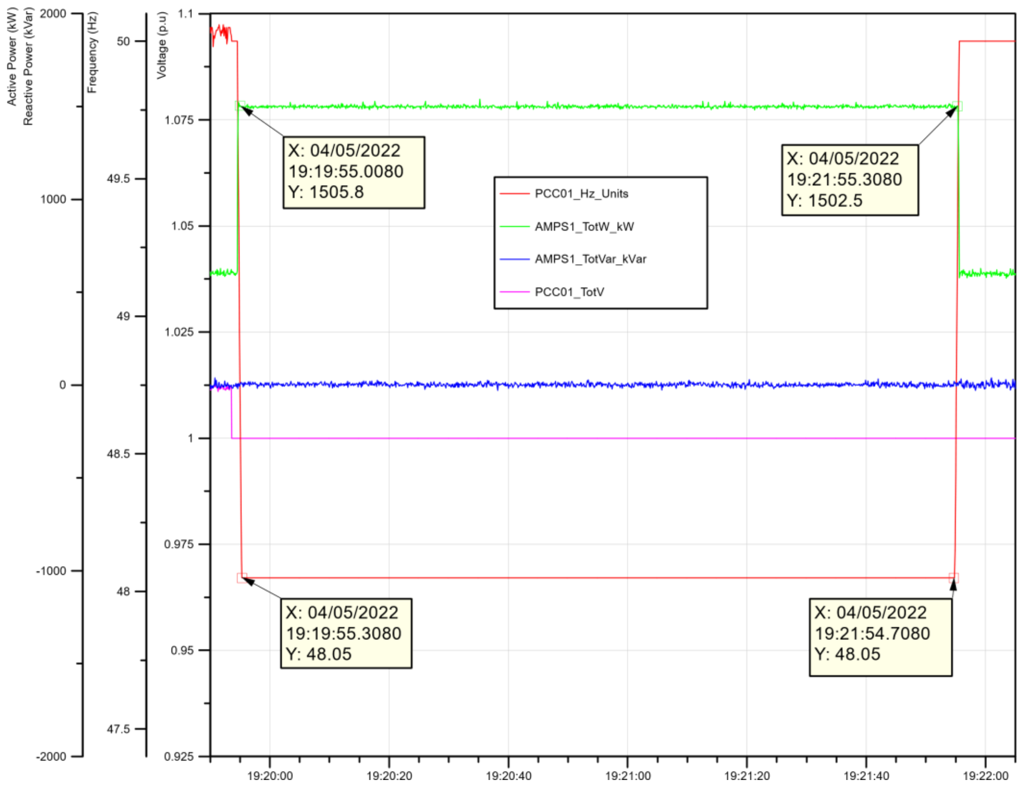

Figure 214: PFR-p (a)

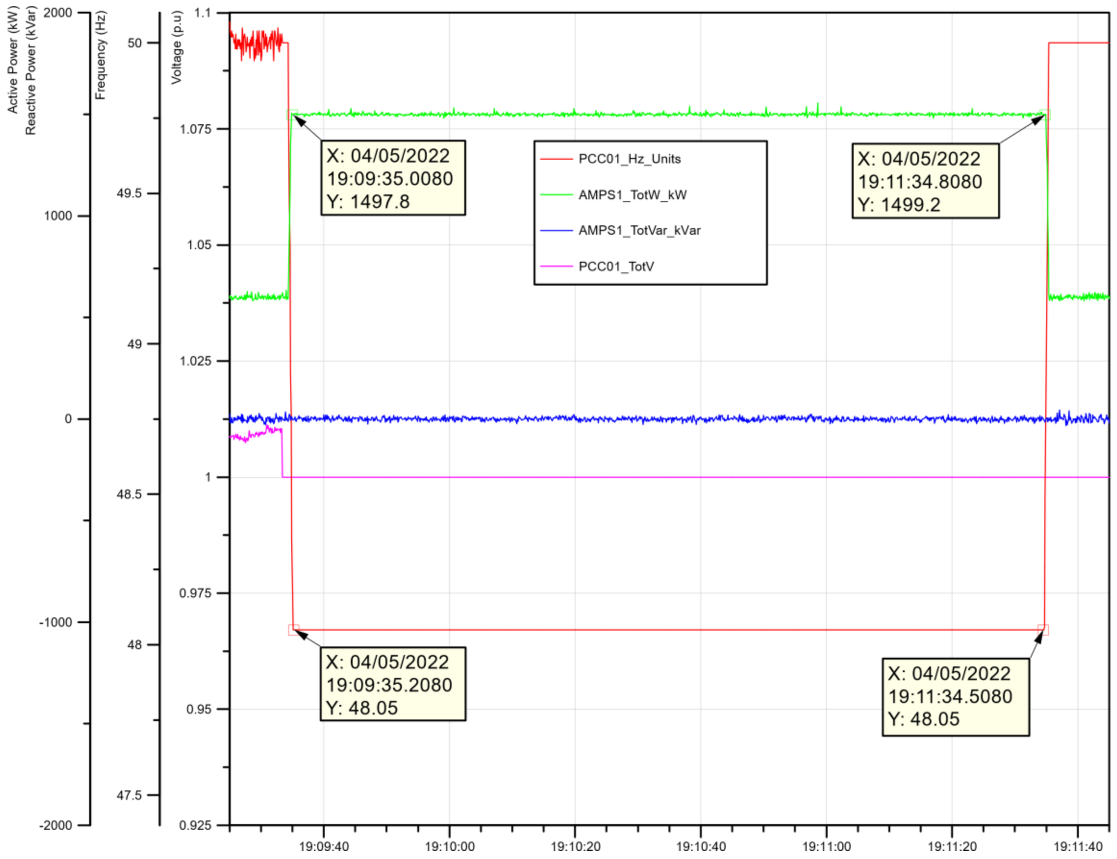

Figure 215: PFR-p (b)

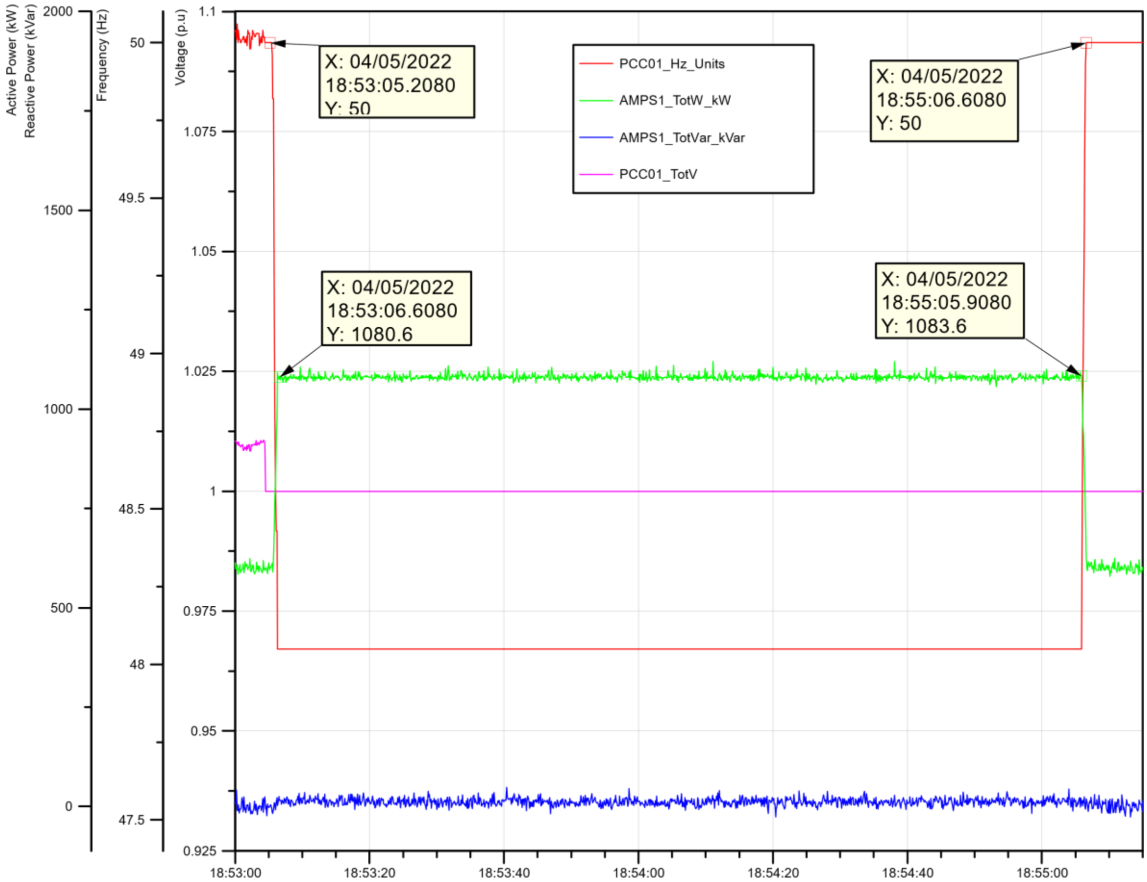

Figure 216: PFR-p (c)

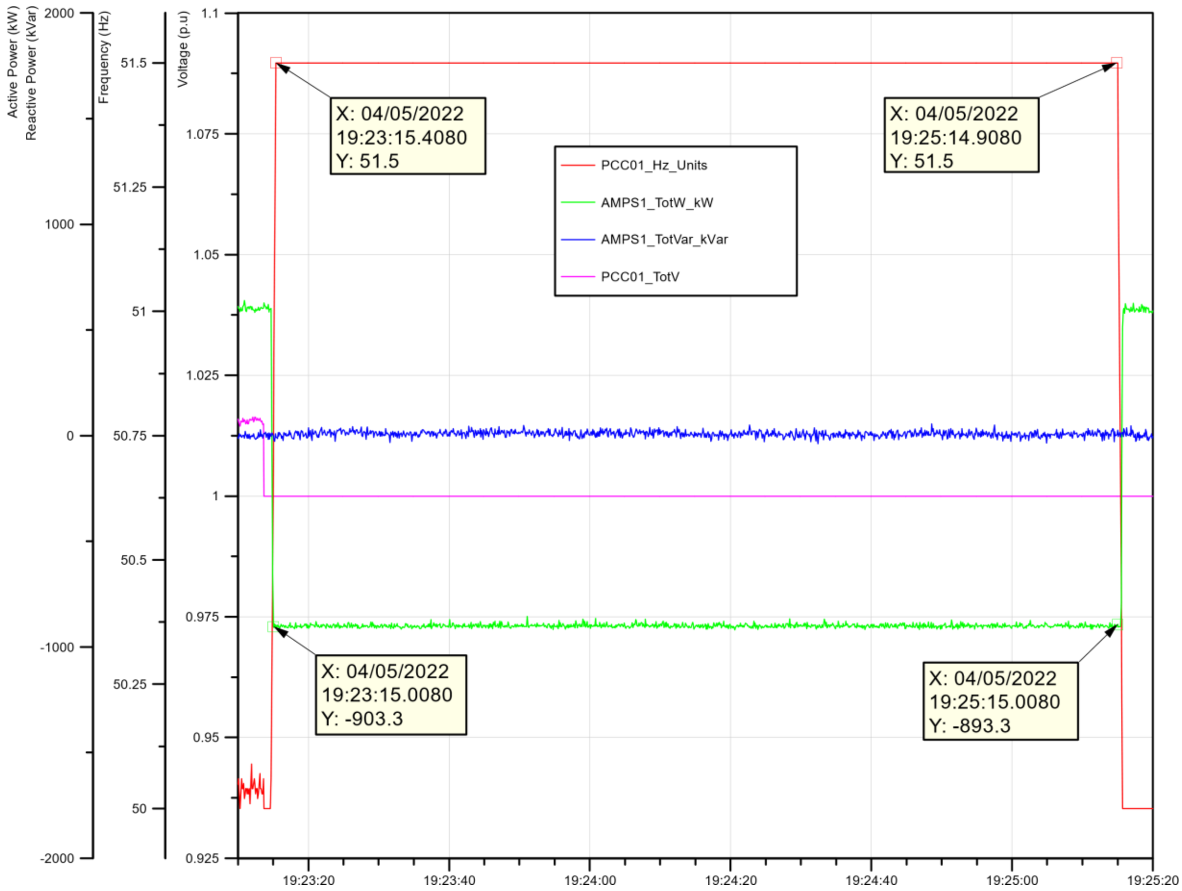

Figure 217: PFR-p (d)

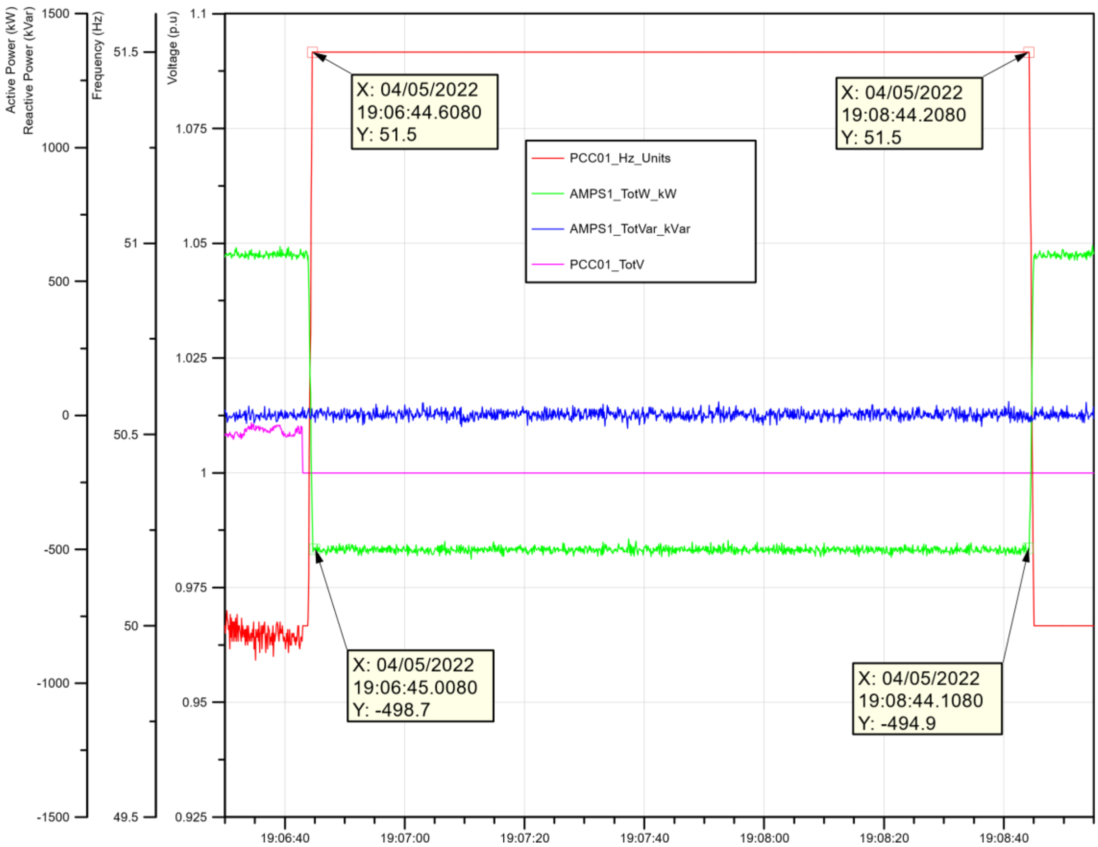

Figure 218: PFR-p (e)

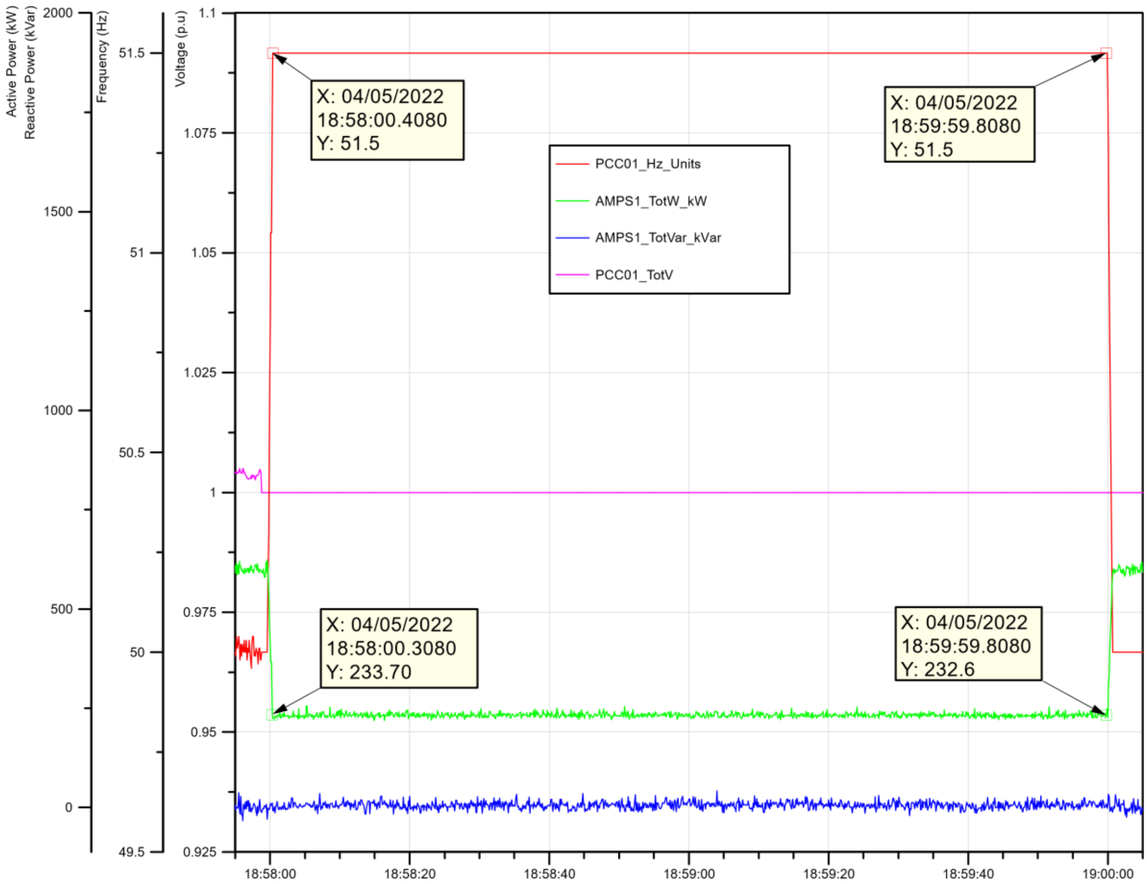

Figure 219: PFR-p (f)

7.1.7. Graph results for FRC tests

The results of the different test performed to validate the FRC functionality are presented next. In the following figures, the positive and negative sequence of the setpoint and output currents are plotted for the different frequency profiles and control configurations (tests from a to g). The voltage profile is also represented.

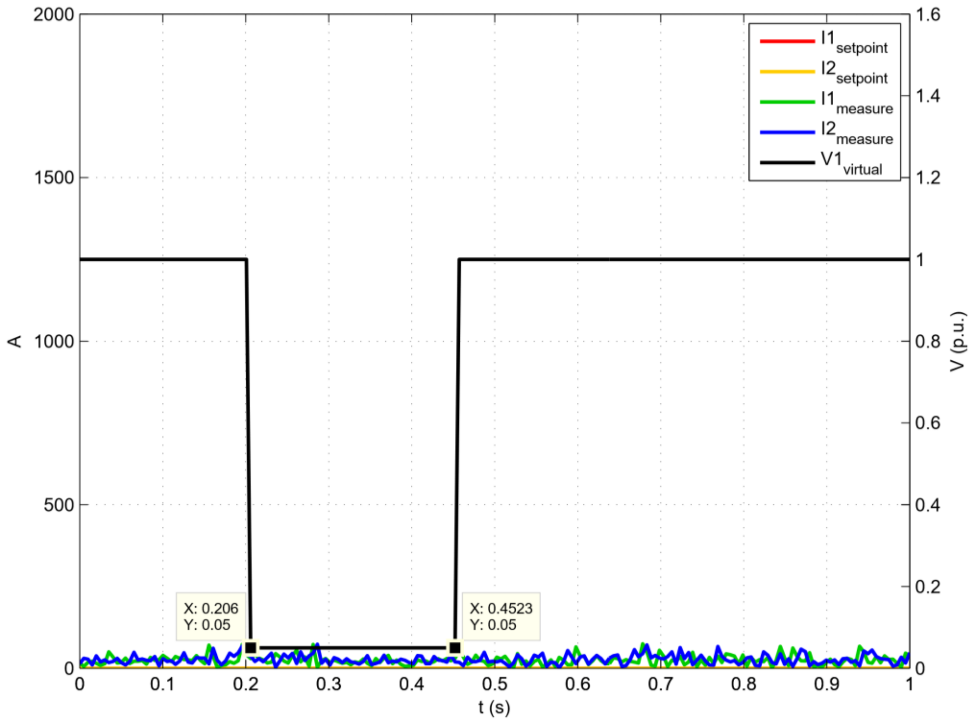

Figure 220: FRC-0 (a)

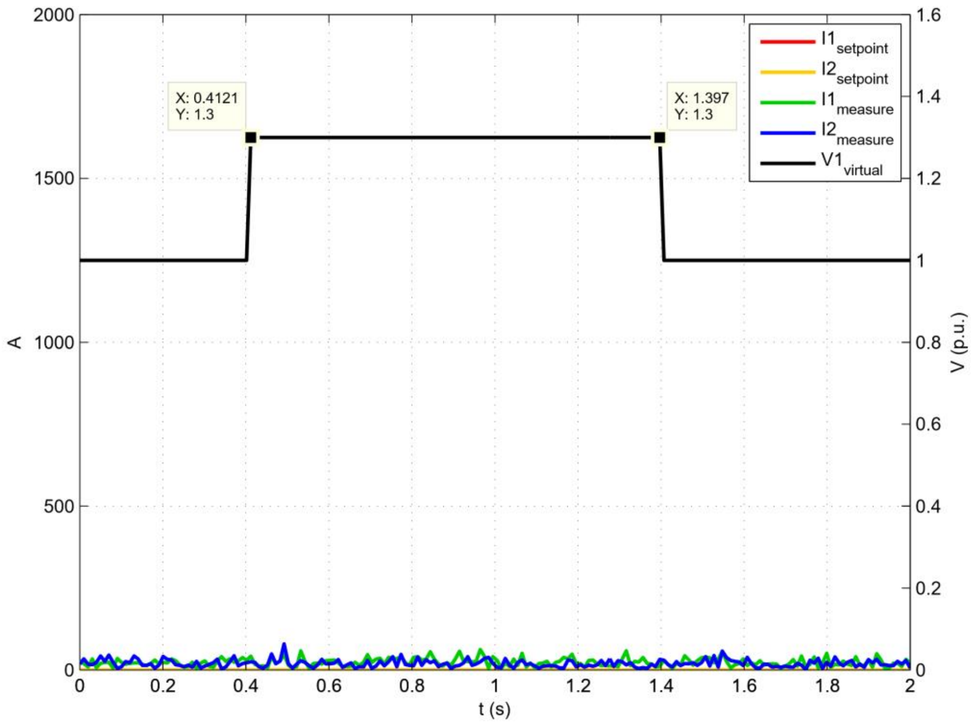

Figure 221: FRC-0 (b)

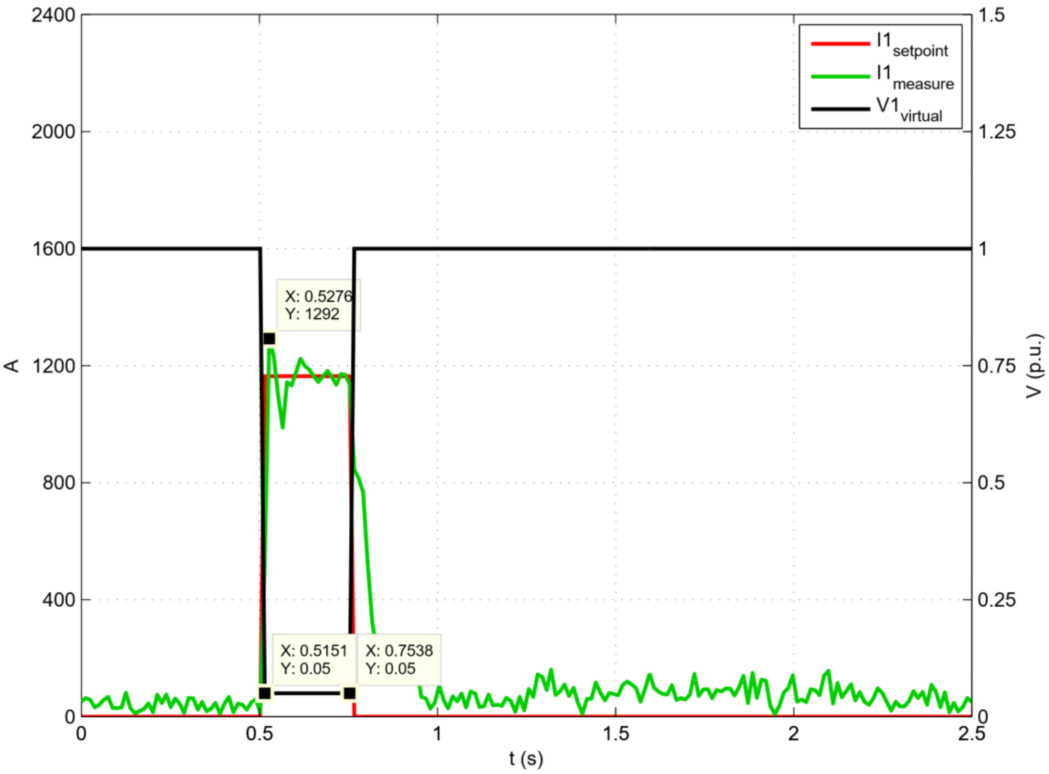

Figure 222: FRC-1 (a)

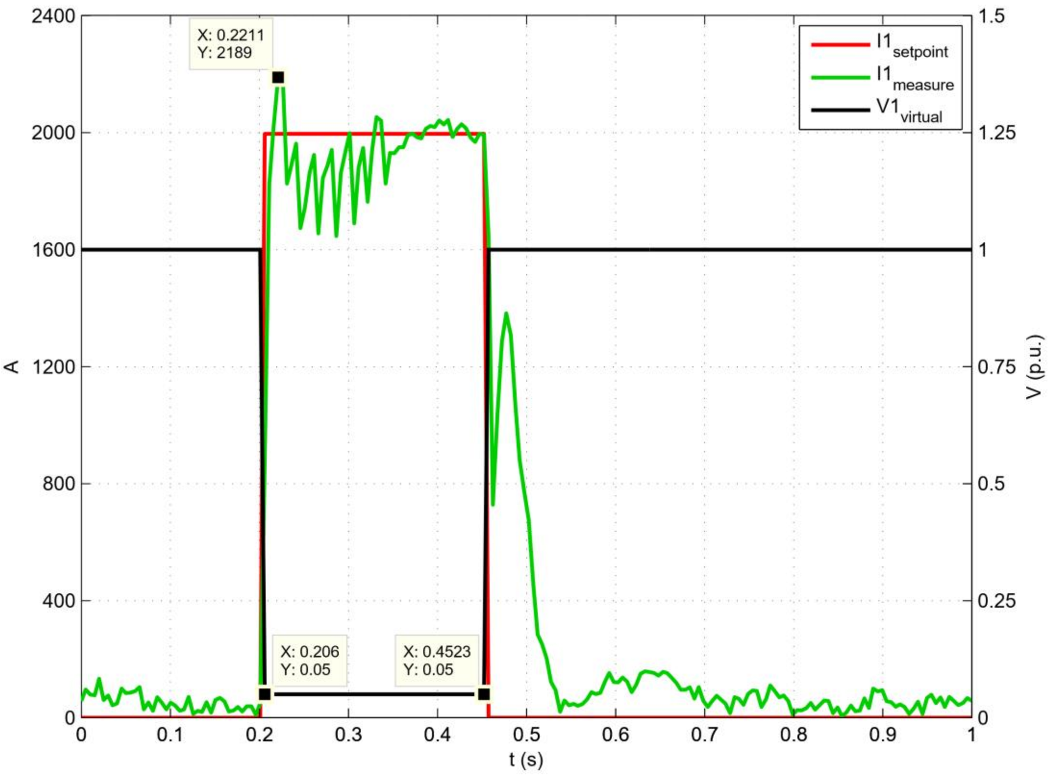

Figure 223: FRC-1 (b)

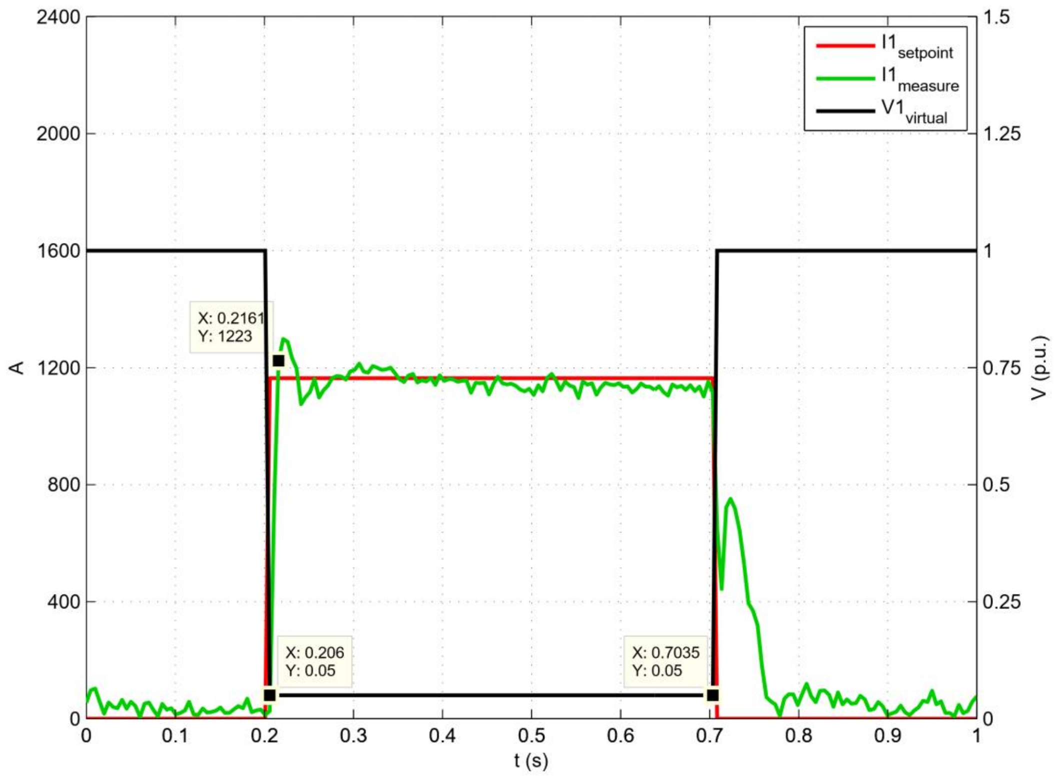

Figure 224: FRC-1 (c)

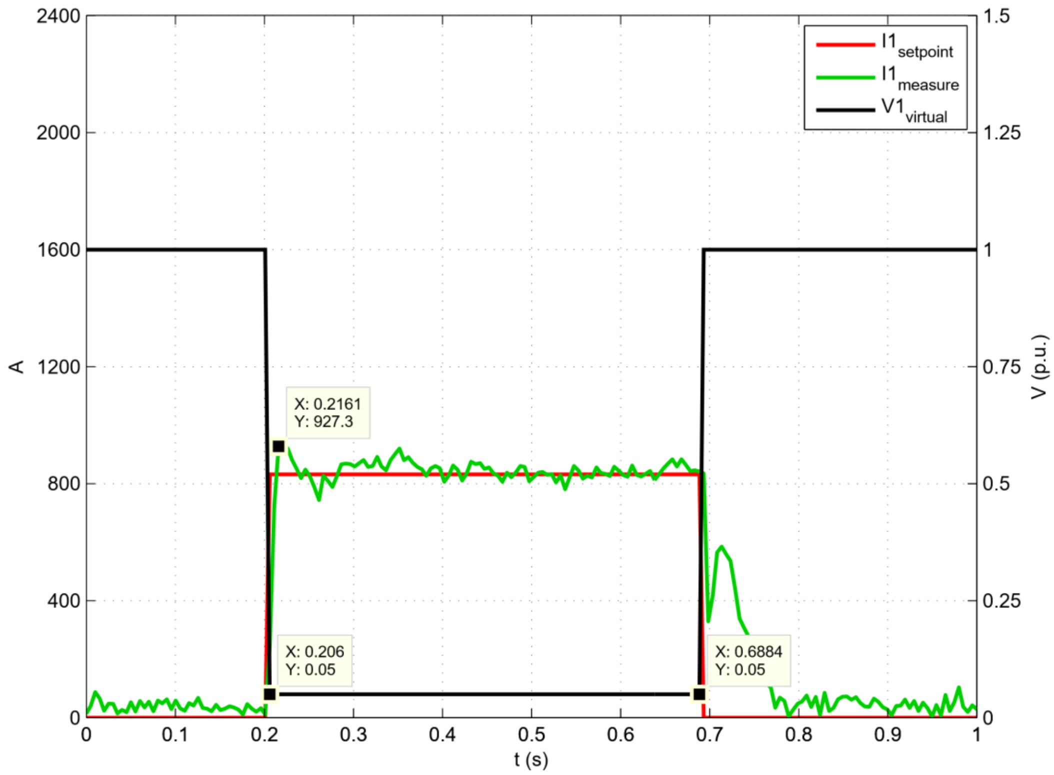

Figure 225: FRC-1 (d)

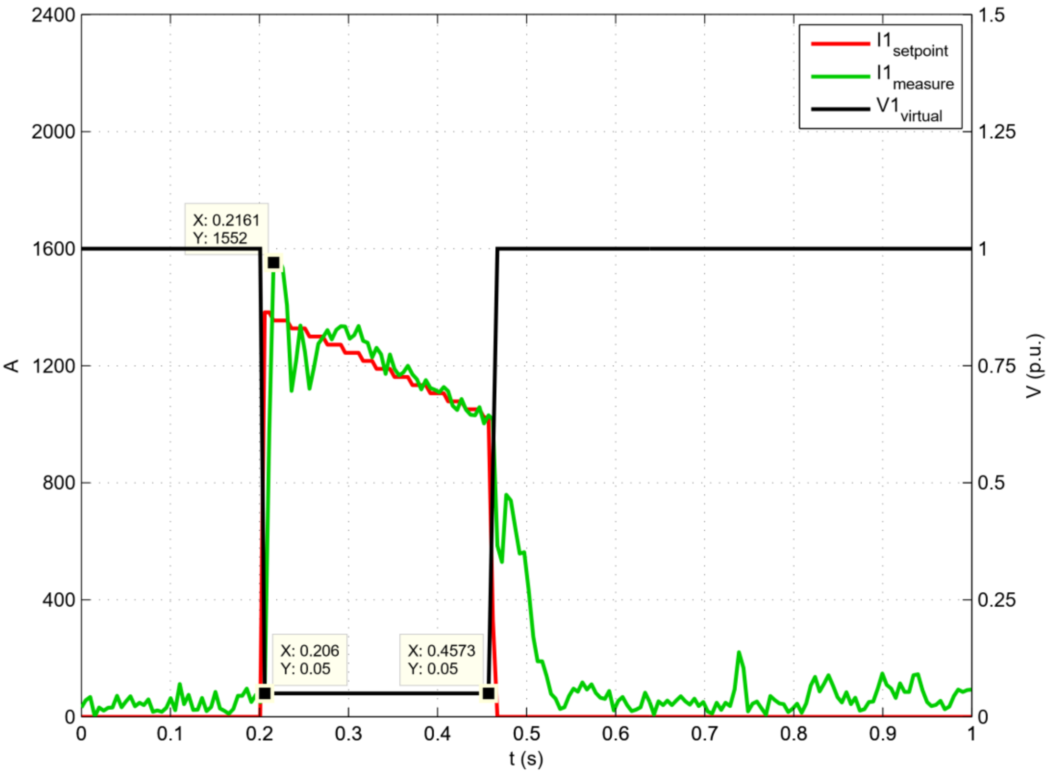

Figure 226: FRC-1 (e)

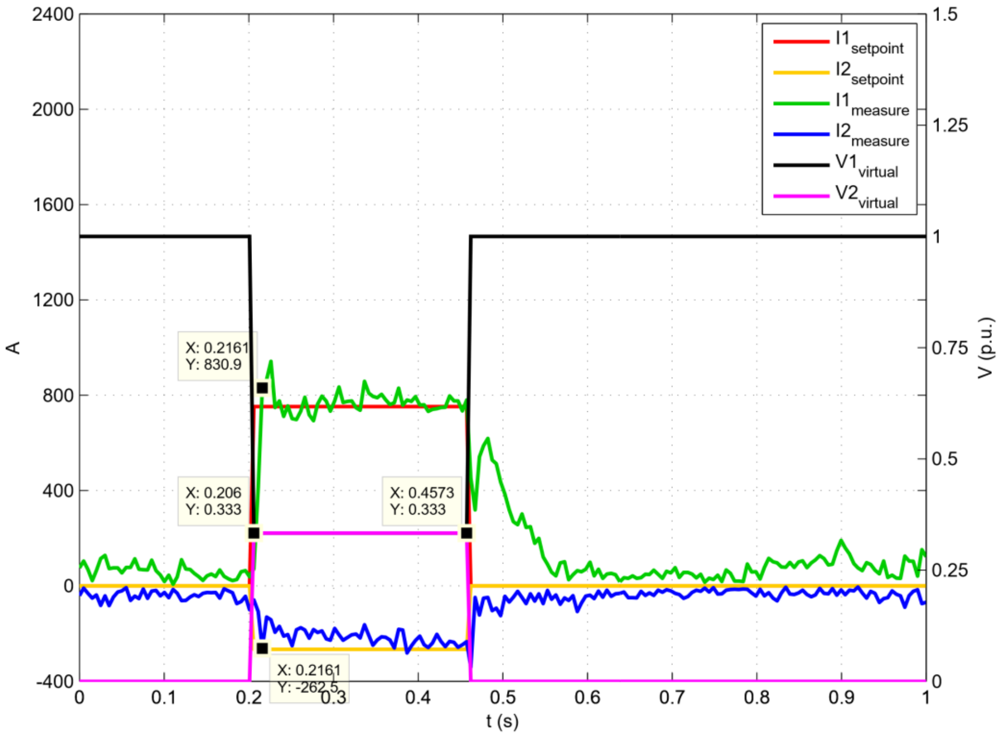

Figure 227: FRC-1 (f)

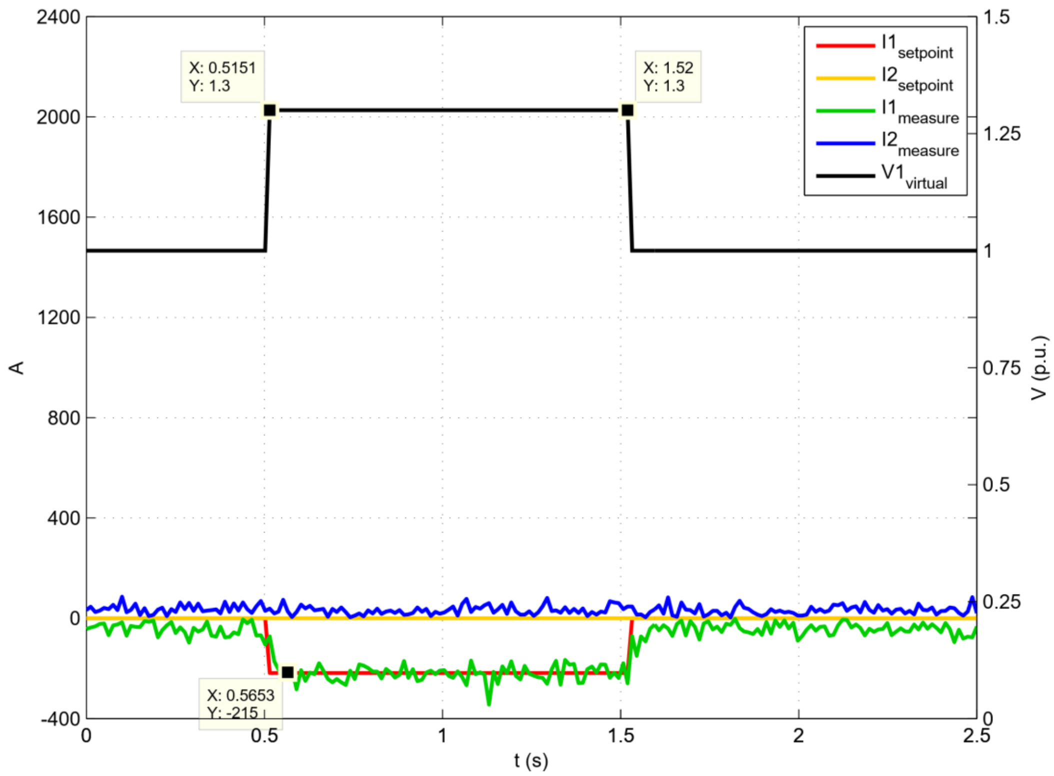

Figure 228: FRC-1 (g)

NOTE: Axis time values should be carefully checked. Due to the sampling rate of the acquisition, it may appear that the profiles do not match the defined duration.

7.1.8. Graph Results TRP tests

The results of the different test performed to validate the TRP functionality are presented next. In the following figures, voltage, frequency, active power output and reactive power output are represented for the different frequency deviations and control configurations (tests from a to e).

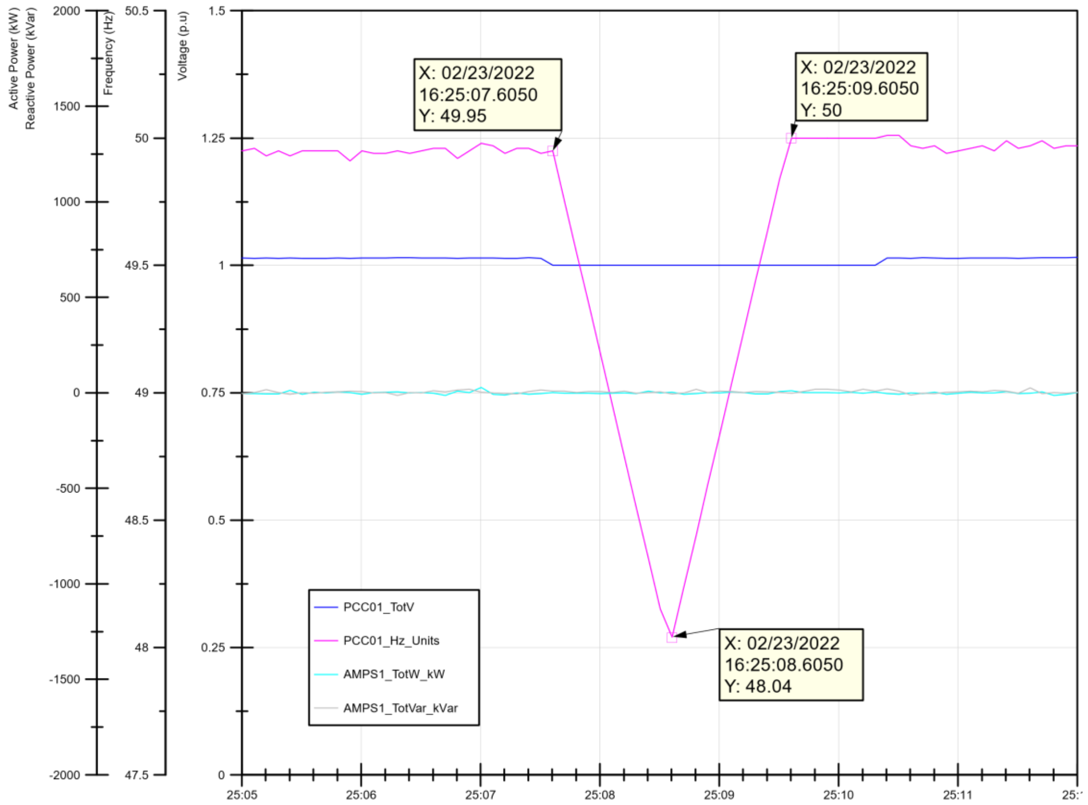

Figure 229: TRP (a)

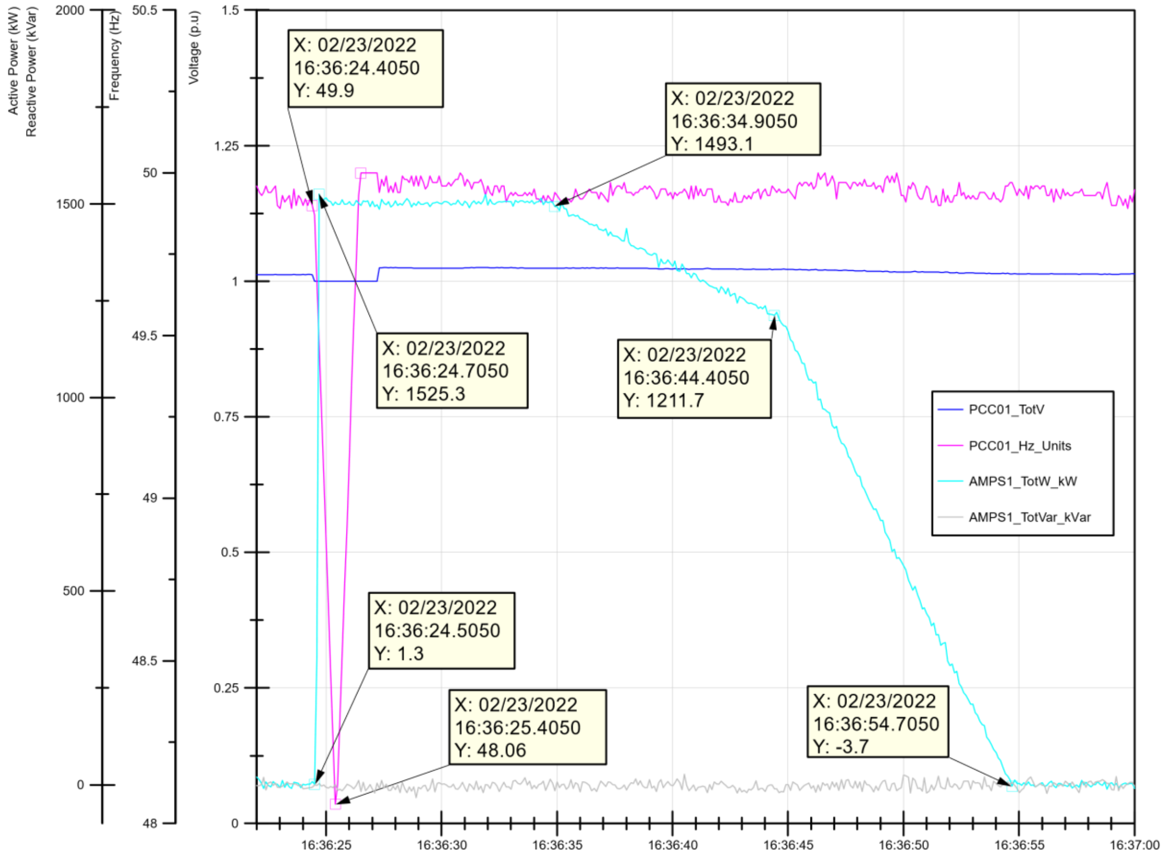

Figure 230: TRP (b)

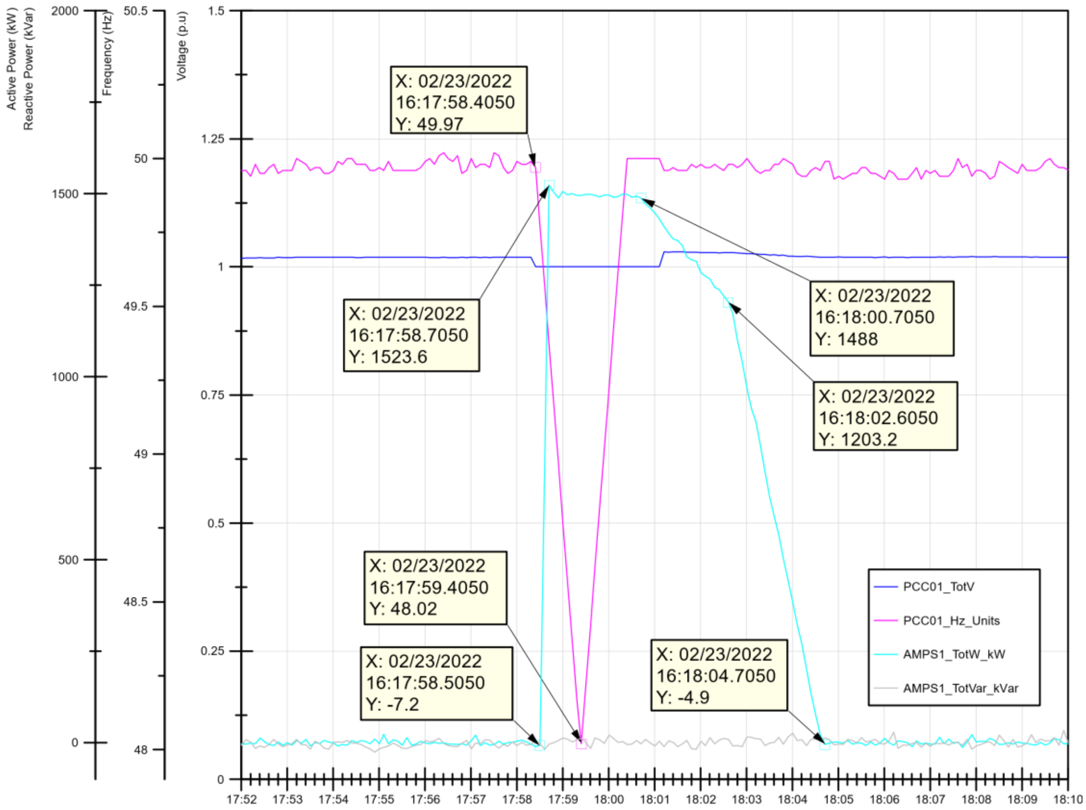

Figure 231: TRP (c)

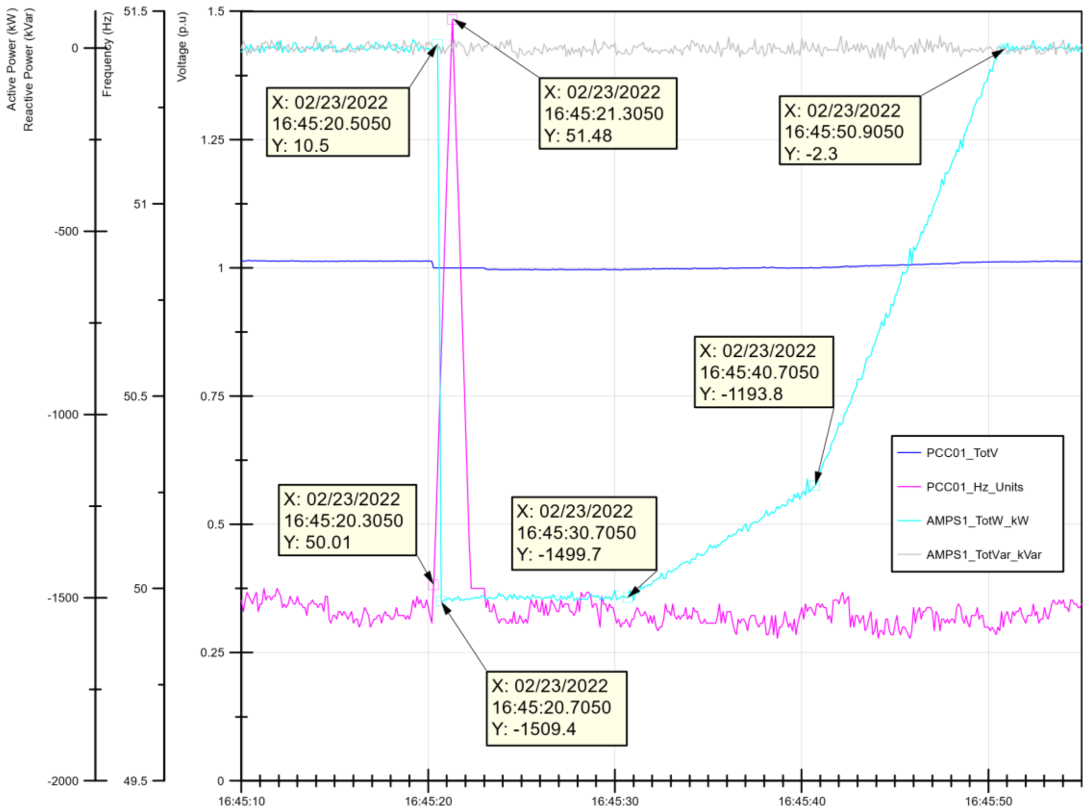

Figure 232: TRP (d)

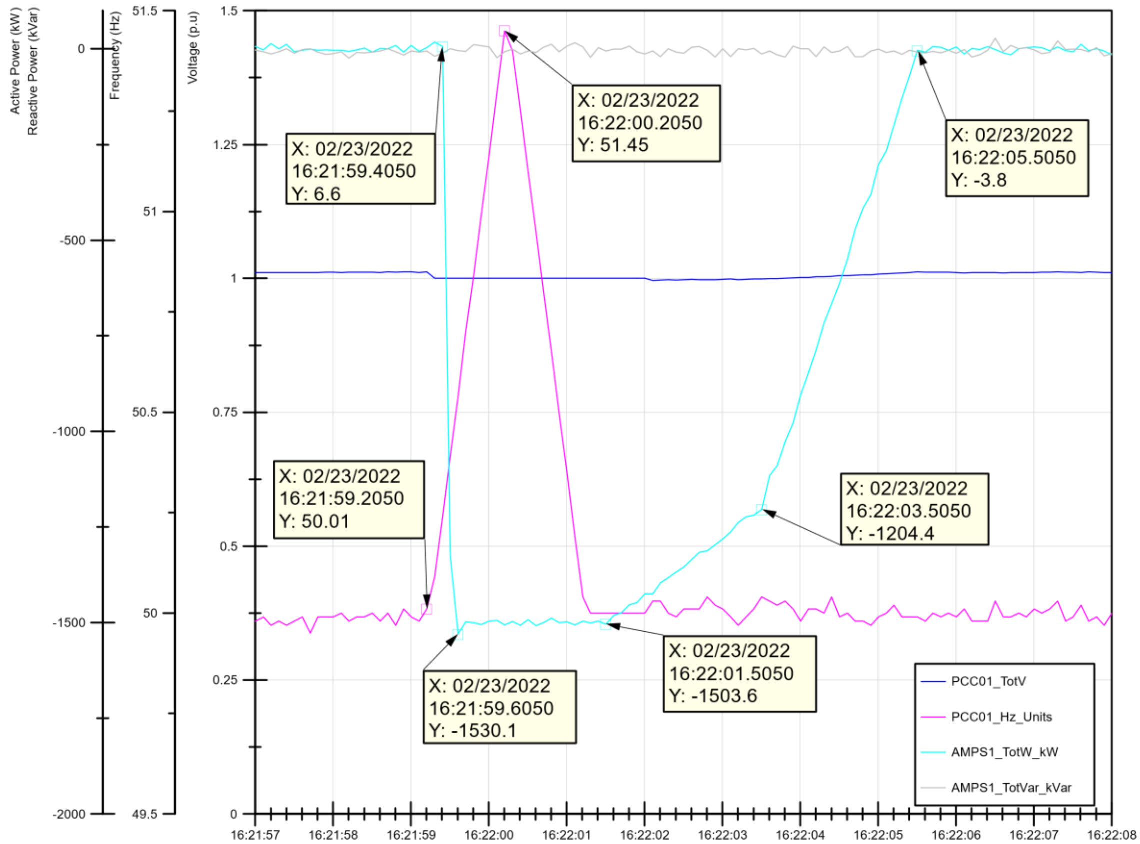

Figure 233: TRP (e)

7.1.9. Graph Results for VCV tests

The results of the different test performed to validate the VCV functionality are presented next. In the following figures, active and reactive power output, as well as the voltage setpoint profile and the output voltage, are represented for the different voltage setpoints and control configurations (tests from a to h).

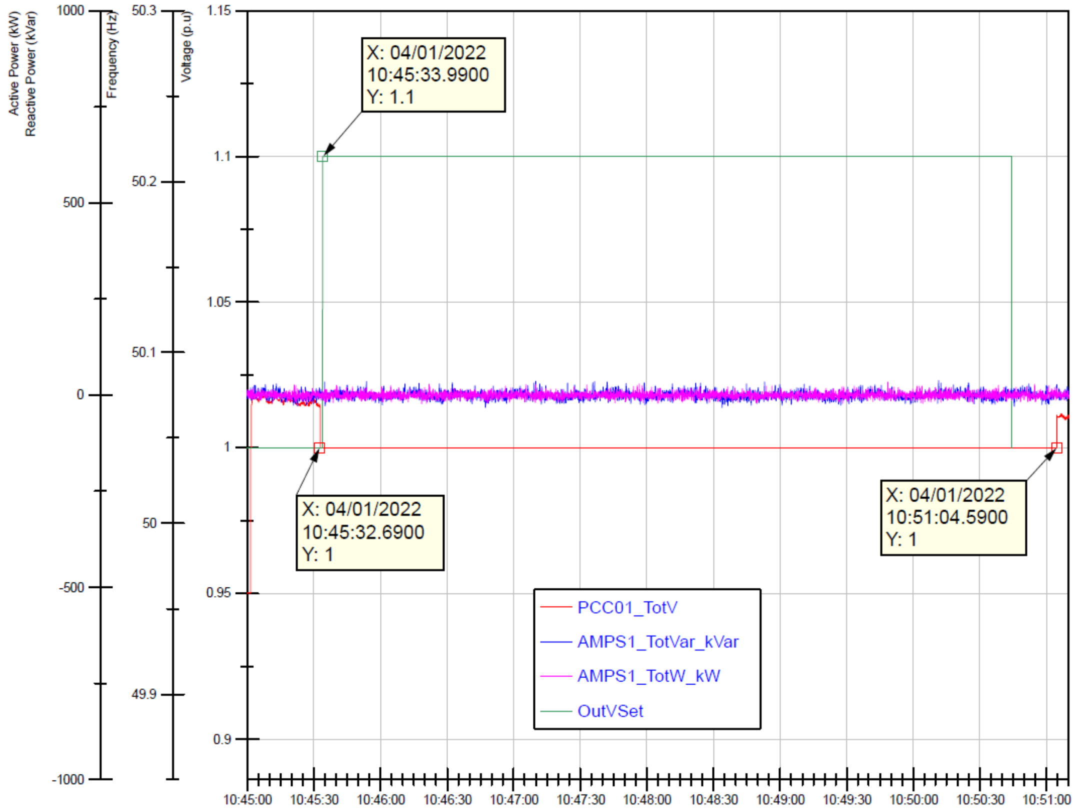

Figure 234. VCV (a)

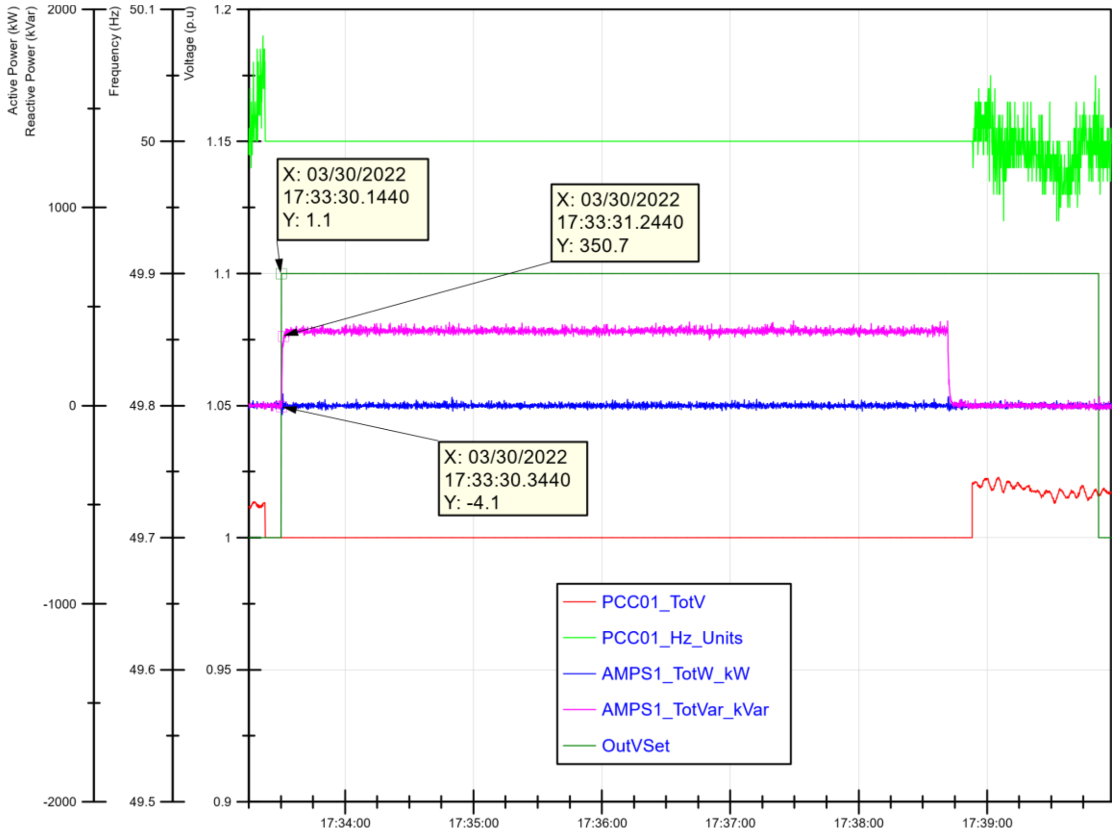

Figure 235. VCV (b)

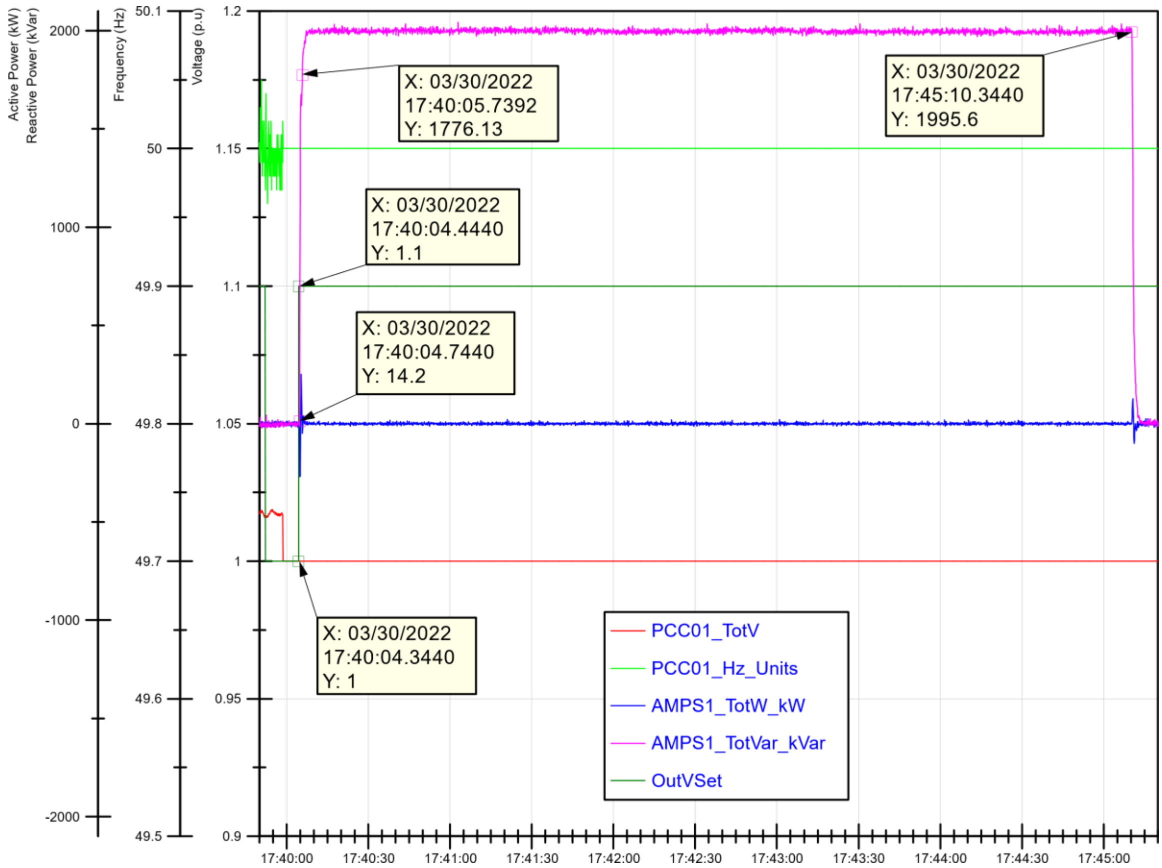

Figure 236. VCV (c)

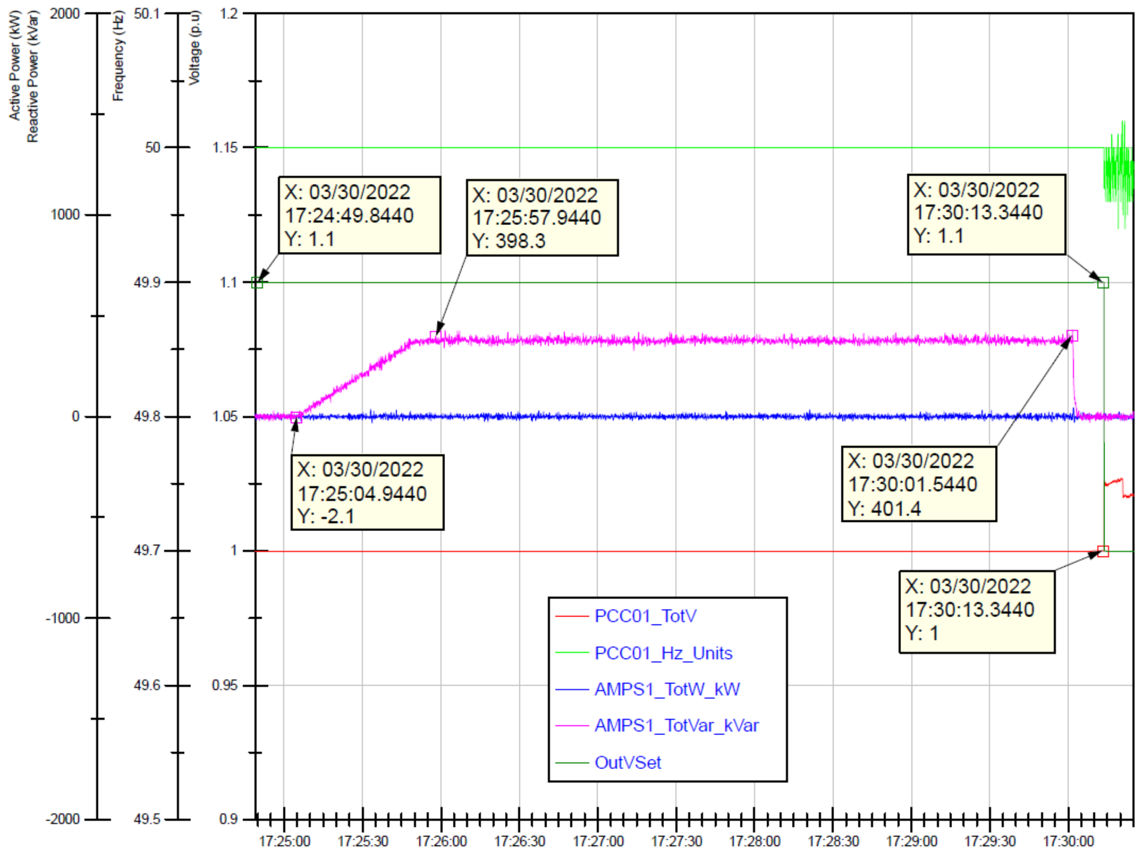

Figure 237. VCV (d)

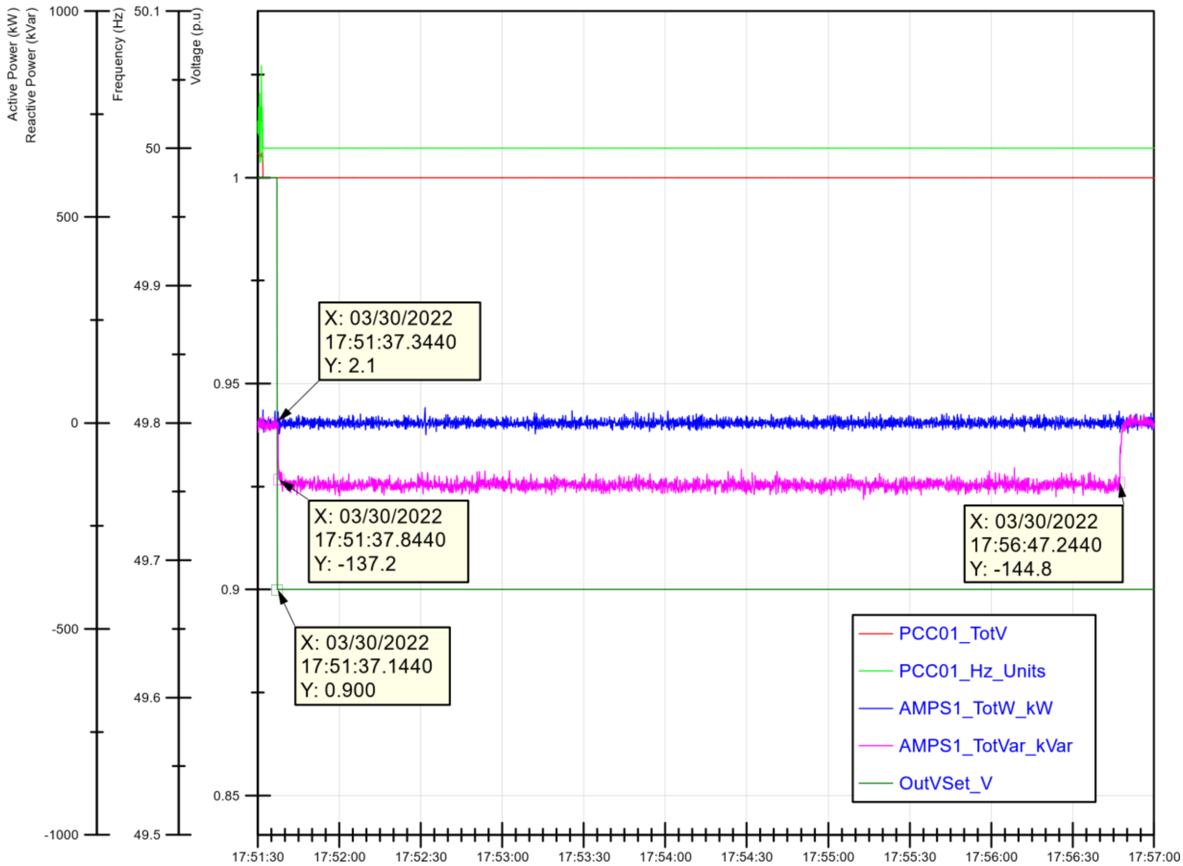

Figure 238. VCV (e)

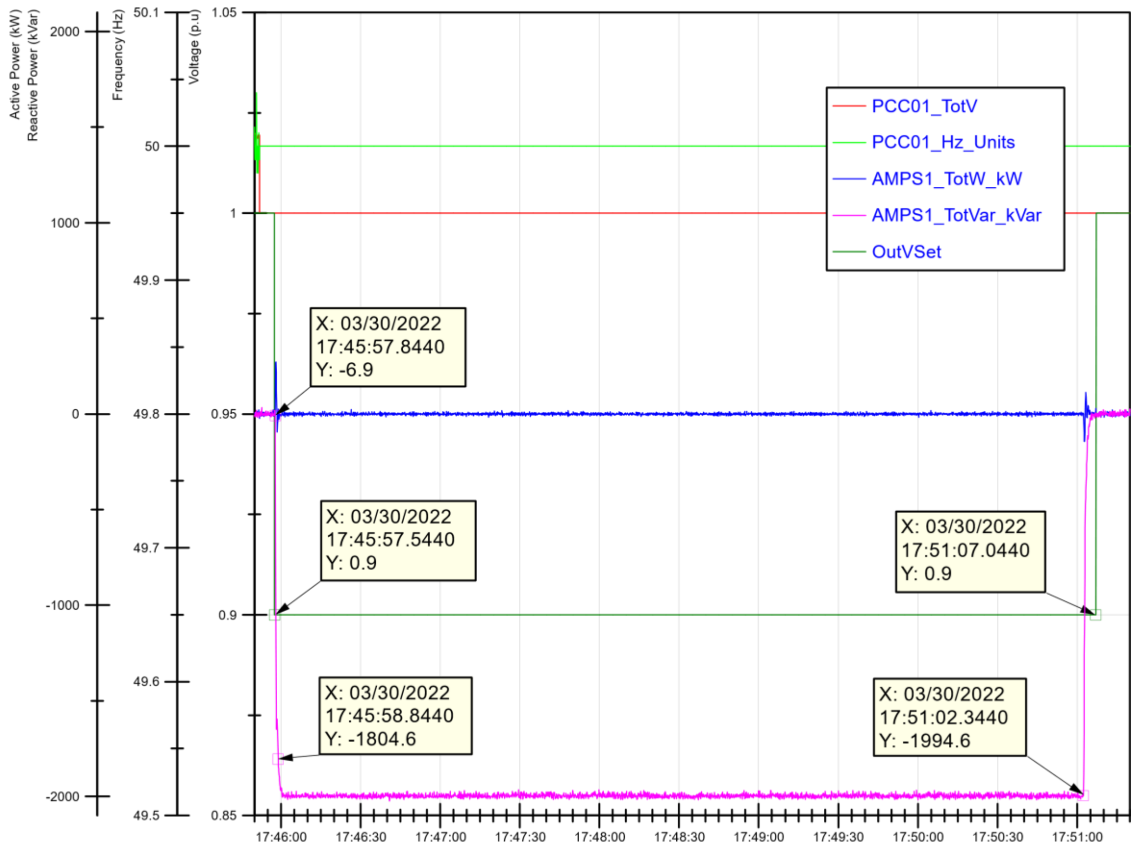

Figure 239. VCV (f)

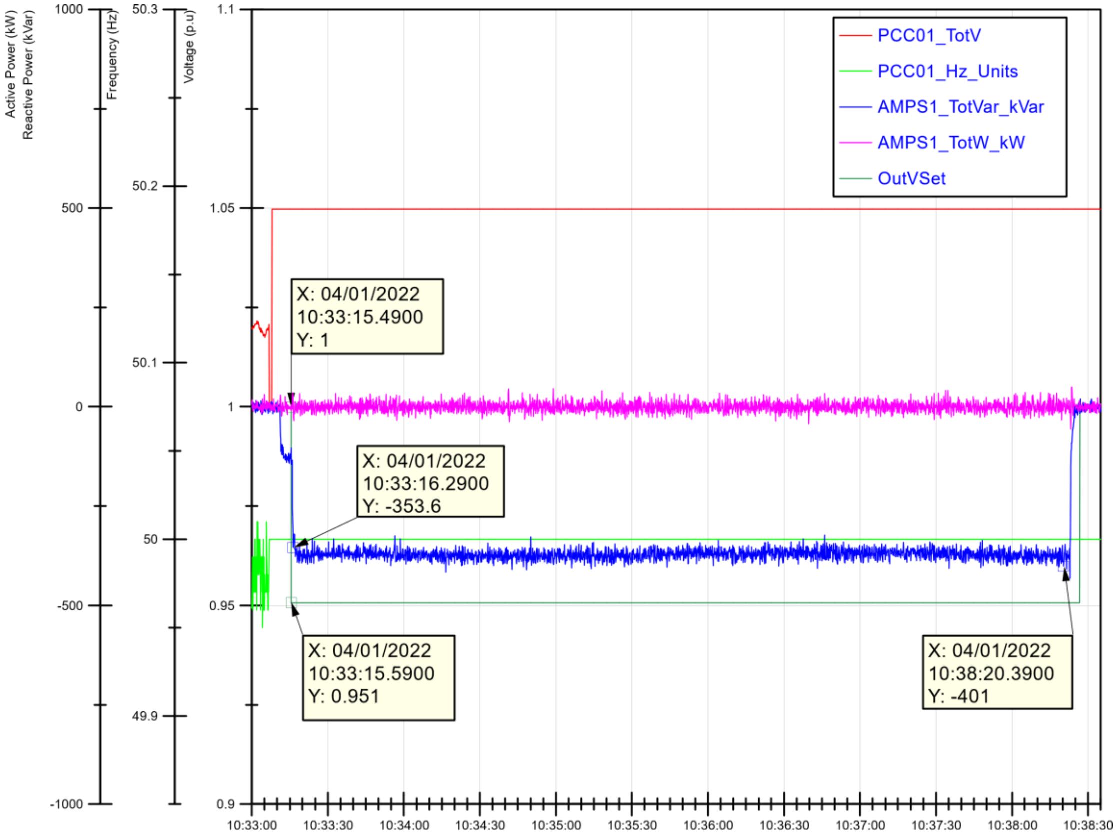

Figure 240. VCV (g)

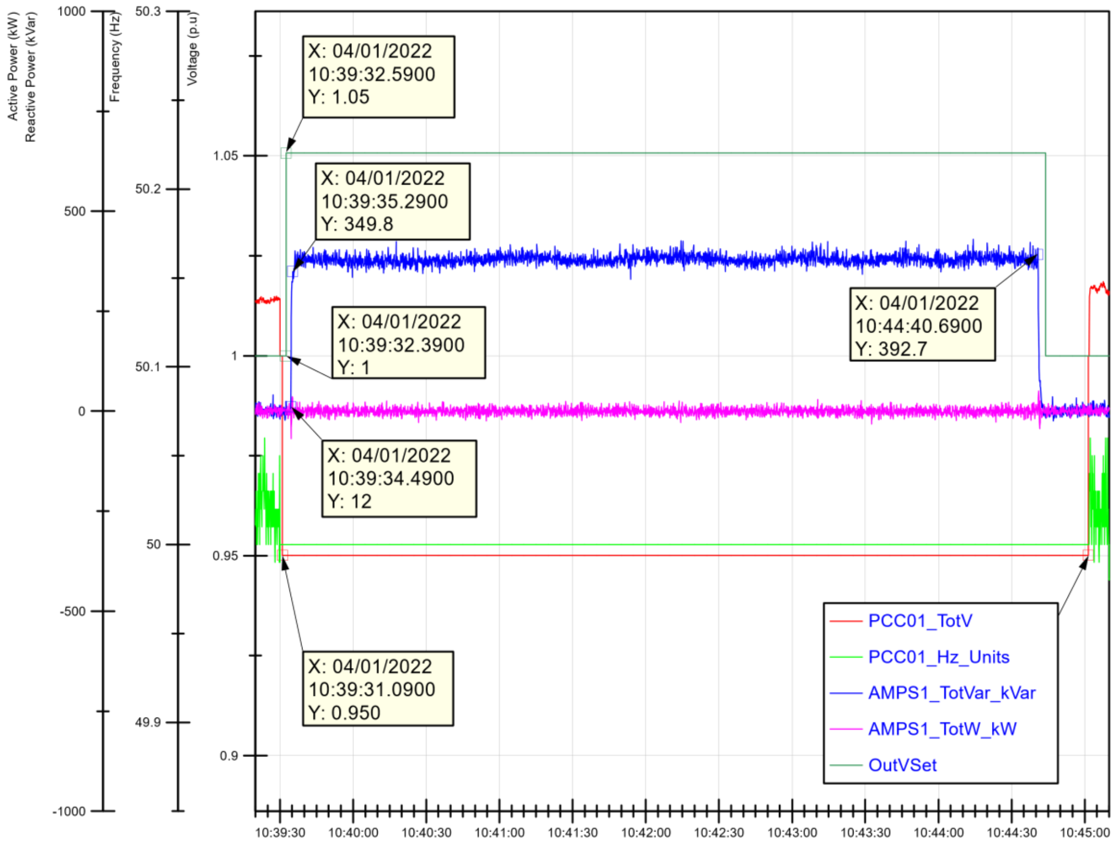

Figure 241. VCV (h)

7.2. Parameters and variables

In this section, the variables and parameters used to describe the pre-conditions of the tests are described.

VARIABLE/PARAMETER	DESCRIPTION
VCV_Vconsigna	Rated voltage at the point of interconnection for VCQ functionality
Vn	nominal V (rms) of the MCFS
VCV_Deadband	dead band (DV/Vnsa) for VCQ functionality
VCV_Kv	slope Kv for VCV
Pn	nominal P of the MCFS
VCV_RAMP_consigna	Voltage setpoint variation ramp per minute.
Qn	Nominal Q of the MCFS
VCV_Lim_Q1	Output Q limit as a function of V at the PCC. Point (Q1; V1). Basis: Qn
VCV_Lim_Q2	Output Q limit as a function of V at PCC. Point (Q2; V2). Base: Qn
VCV_Lim_Q3	Output Q limit as a function of V at PCC. Point (Q3; V3). Base: Qn.
VCV_Lim_Q4	Output Q limit as a function of V at PCC. Point (Q4; V4). Base: Qn.
VCV_Lim_V1	V at PCC associated to point (Q1; V1). Base: Vn.
VCV_Lim_V2	V at the PCC associated with point (Q2; V2). Base: Vn.
VCV_Lim_V3	V in the PCC associated with point (Q3; V3). Base: Vn.
VCV_Lim_V4	V in the PCC associated with point (Q4; V4). Base: Vn.
VCV_Q_LimMAX	Maximum capacitive Q limit for VCV functionality
VCV_Q_LimMIN	Maximum inductive Q limit for VCV functionality
VCQ_RAMP_consigna	Setpoint variation ramp of Q per minute
VCQ_Lim_Q1	Output Q limit as a function of V at PCC. Point (Q1; V1). Base: Qn
VCQ_Lim_Q2	Output Q limit as a function of V at PCC. Point (Q2; V2). Base: Qn.
VCQ_Lim_Q3	Output Q limit as a function of V at PCC. Point (Q3; V3). Base: Qn.
VCQ_Lim_Q4	Output Q limit as a function of V at PCC. Point (Q4; V4). Base: Qn.
VCQ_Lim_V1	V at PCC associated to point (Q1; V1). Base: Vn.
VCQ_Lim_V2	V at the PCC associated with point (Q2; V2). Base: Vn.
VCQ_Lim_V3	V in the PCC associated with point (Q3; V3). Base: Vn.
VCQ_Lim_V4	V in the PCC associated with point (Q4; V4). Base: Vn.
VCQ_Q_LimMAX	Maximum capacitive Q limit for VCQ functionality
VCQ_Q_LimMIN	Maximum inductive Q limit for VCQ functionality
f_MCFS	f nominal of the MCFS
PFR_Deadband	DB for P-f regulation PFR
PFR_PmaxRange	Range of P in relation to P-nominal of the P-f regulation PFR
PFR_insensibilityHz	Insensitivity to the frequency response of the PFR in Hz
PFR_Droop	Droop for PFR
Lp	Power allocation for 2nd level functionalities
Le	Energy allocation for 2nd level functionalities
Eta	Capacity allocation for 1st level functionalities
CMT_NodeRen_TR	Measure of renewable generation

CMT_StatDynMode CMT_NodeRenLimit	Maximum renewable allowed at the node. The value depends on the mode selected prior to entry and the value of the limit associated with that mode.
CMT_DischargeMode	Discharge configuration for CMT functionality: 0 free discharge; 1 according to program; initial default value 0
CMT_DischargeProgram	Configuration of the programmed unloading hours. One value for each of the 24 hours of the day. 1 indicates that it is possible to download at that time, 0 indicates that it is not.
PGM_Pi	Setpoint sent for PGM functionality
PGM_RampUpi	Ramp up for PGM functionality
PGM_RampDowni	Ramp down for PGM functionality
SPT_tr	Setpoint evaluation interval
SPT_P_Setpoint	Setpoint sent for SPT functionality
SPT_RampUp	Ramp up for SPT functionality
SPT_RampDown	Ramp down for SPT functionality
VCV_RAMP_consigna_Status	Signal for activation (1=ON) or deactivation (0=OFF) of the voltage ramp for VCV functionality
VCQ_Qconsigna	Reactive power setpoint for VCQ functionality
VCQ_RAMP_consigna_ON/OFF	Ramp activation signal (1=ON) or deactivation signal (0=OFF) of the Q ramp for VCQ functionality

Table 71. Description of variables and parameters for test conditions