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Grant Agreement No.: 773715

Project acronym: RESOLVD

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D2.5 – Functional laboratory tests of the prototype

Organization name of lead contractor for this deliverable: UPC	
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Primary Authors	UPC: M. Llonch-Masachs ; F. Girbau-Llistuella ; F. Díaz-González ; A. Sumper ; M. Aragüés-Peñalba
Contributors	-
Version	Version 2.0

Dissemination Level		
PU	Public	X
CO	Confidential, only for members of the consortium (including the Commission Services)	

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Deliverable reviews

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Version 2.0	Reception Date	13th of February 2020
	Revision Date	14th of February 2020
	Reviewers	Joaquim Meléndez (UdG)

Contributions of partners

Partner	Contribution
UPC	Main responsible for the development of the whole Power Electronics Device.

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Acronyms and abbreviations

DAB	Double Active Bridge converter
HLUC	High Level Use Case
ILEM	Intelligent Local Energy Manager
PCS	Power Conversion System
PED	Power Electronics Device
PWM	Pulse Width Modulation
SCADA	Supervisory Control And Data Acquisition
SOC	State of Charge

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Executive Summary

This report summarizes the work done in regard of the testing of the Power Electronics Device (PED), which is the main object for the Work Package 2 (WP2) of the RESOLVD project. This last deliverable of the WP reports the performance of the PED under various laboratory tests. The aim of these tests is to validate the performance of the PED so it can be integrated in the pilot of the project, in the frame of the work to be done in the WP5.

The tests address the functionality of the various power electronic modules of the PED. These include the front end inverters (AC-DC power electronic modules) and the Double Active Bridge, (DAB converters), each one integrating a battery pack (the lithium-ion and lead-acid ones).

In particular, 15 tests are carried out, classified in two main categories:

- **Tests related to the PED's hardware components.** Under this category, the included tests refer to the validation of inner functions and processes in the PED so it can work in stable a secure manner from an electrical perspective.
    - **T01.** Input filter pre-charge. This test refers to the start-up process of the DAB while connected to a battery at one of its ends.
    - **T02.** Hardware validation (at maximum power). This test refers to the electrical and thermal stability of a DAB converter while exchanging its rated power connected to a battery.
    - **T03.** Active DC-Link pre-charge. This test refers to the correctness of the process of charging the DC-link of the front-end power inverters of the PED, using energy from the connected batteries.
    - **T04.** Battery voltage control validation. This test refers to the validation of the control loops programmed in the DAB converters to control the voltage of a battery while this is being charged.
    - **T05.** Droop control validation. This test refers to the validation of the effectiveness of the control algorithm managing the power exchanged by each DAB converter while operated simultaneously.
    - **T06.** DC-Link bus pre-charge. This test refers to the correctness of the process of charging the DC-link of the front-end power inverters of the PED, using energy from the main grid.
    - **T07.** Active rectifier mode validation. This test refers to the correctness of the controller in charge of maintaining constant the voltage of the DC-link of the front-end power inverters of the PED.
    - **T08.** Inverter mode validation This test refers to the correctness of the controller included in the front-end inverters of the PED, in charge of regulating the magnitude of the currents exchanged at the grid side.

- **Tests related to the PED's service provision**. Under this category, the included tests refer to the validation of the provision of services by the PED at its connection point. For this tests, the PED is operated under three control modes: Grid Mode, Island Mode and Recovery Mode. The reader is referred to Section 4 for the description of each operating mode.

  PED under Grid Mode
    - **T09.** Follow active and reactive power setpoints.
    - **T10.** Current balancing. This refers to the service of balancing the current flowing through each of the three phases of the grid and from the connection point of the PED.
    - **T11.** Reactive compensation. This refers to the service of compensating reactive power flows at the grid connection point of the PED.
    - **T12.** Harmonic mitigation. This refers to the mitigation of current harmonics at the grid connection point of the PED.

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PED under Island Mode

- **T13.** Check grid forming functionality according to voltage and frequency setpoints. This refers to the service of acting as a voltage source, so forming a grid, in case there is a mains failure.

PED under Recovery Mode

- **T14.** Check the functionality of the PED for charging lead-acid battery.
- **T15.** Check the functionality of the PED for discharging lead-acid battery. Battery capacity nameplate validation.

Each of the tests are reported in a structured manner in Section 3. In particular, for each test, the following information is provided: 1. Name of the test; 2. Objective definition; 3. Related Use Case / KPI, when applicable; 4. Brief description of the test. Description of different scenarios, if needed; 5. Input and output data; 6. Graphical results; 7. Discussion.

Also, easing the integration tasks envisaged in the WP5, this report emphasizes in the operation modes and control logics drawing the software managing locally the PED, i.e. the Intelligent Local Energy Manager (ILEM). The ILEM, as the interface between the PED and the control system in charge (e.g. SCADA), manages exogenous control setpoints sent by the grid operator and translates them into control actions to be performed in a coherent manner by the different components of the PED. Its function is, thus, crucial for a stable operation of the PED and, as such, its logics are revised in this deliverable.

The main conclusions of this deliverable are:

- The PED hardware electrical stability and functionalities are successfully tested on a laboratory environment. The power electronic modules shown stable performance while operating at maximum power, also while in transient states such as pre-charging the DC-link at the start up process. The different controllers embedded into the PED for battery voltage management and DC-link droop control have been validated.
- The PED capabilities in regard of the provision of services at its connection point to the main grid are successfully tested. In particular, the following functionalities are checked: the capability of following active and reactive power set-points; the provision of grid current balancing, reactive power compensation and current harmonics mitigation; the capability of grid forming as well.
- The lead-acid battery pack performance and energy storage capacity has been checked. The energy storage capacity while discharged applying a constant current phase (0.2C) followed by a constant voltage phase to extract all available energy from the pack, is 15.1 kWh. The process takes 5.3 h. The battery pack, while also charged under the constant current – constant voltage charge method (and the constant current phase is at 0.15C rate), consumes 19.2 kWh, in a 6.7 h process. Thus, the energy efficiency of the pack results around 78.4%. The information provided by these tests are essential for the proper management of the battery while integrated in the pilot of the project.

1. Introduction

This report summarizes the work done in regard of the testing of the Power Electronics Device (PED), which is the main object for the Work Package 2 (WP2) of the RESOLVD project. This last deliverable of the WP reports the performance of the PED under various laboratory tests. The aim of these tests is to validate the performance of the PED so it can be integrated in the pilot of the project, in the frame of the work to be done in the WP5.

The tests address the functionality of the various power electronic modules of the PED. These include the front end inverters (AC-DC power electronic modules) and the Double Active Bridge converters (DC-DC converters), each one integrating a battery pack (the lithium-ion and lead-acid ones).

Also, easing the integration tasks envisaged in the WP5, this report emphasizes in the operation modes and control logics drawing the software managing locally the PED, i.e. the Intelligent Local Energy Manager (ILEM). The ILEM, as the interface between the PED and the control system in charge (e.g. SCADA), manages exogenous control set-points sent by the grid operator and translates them into control actions to be performed in a coherent manner by the different components of the PED. Its function is, thus, crucial for a stable operation of the PED and, as such, its logics are revised in this deliverable.

The whole performance of the ILEM will be tested once the PED is integrated in the pilot of the project, so it needs communication with the rest of the actors of the RESOLVD solution (i.e. distributor SCADA and the management cloud platform managing the whole network). The tests included in this deliverable, as commented above, are related to the functionalities of the PED triggered by a exogenous control action that will be sent by other actors of the RESOLVD solution once integrated in the pilot.

Following contents succinctly states the objectives of the report and its structure.

1.1. Objectives

The main objective of the report is

- to summarize the works done in regard of the testing of the functionalities of the PED in a laboratory environment.

The specific objectives are

- to evaluate the performance of the front-end inverters of the PED while providing services related to the grid power quality improvement, i.e. reactive power management, current harmonics compensation and phase load balancing;
- to evaluate the performance of the double active bridge (DAB) converters while charging and discharging the batteries embedded into the PED;
- to evaluate the performance of the control algorithm coordinating the two DABs of the PED while charging and discharging the two battery types at the same time;
- to validate the nameplate capacity of the lead-acid battery pack (the capacity of the lithium-ion pack was already reported in deliverable 2.3).

1.2. Report structure

Section 2 lists all performed tests and links them with the case studies defined for the RESOLVD project in the frame of WP1. Section 3 reports the assumptions, basis and input data for each of the tests and plots the obtained results. Finally, section 4 emphasizes the main conclusions of the work.

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2. General description of functional tests for the PED

Table 1 summarizes the High Level Use Cases (HLUC) for the RESOLVD project involving the PED. From these use cases, it can be derived that the PED is required to exchange active and reactive power at the point it is connected to the grid. It should also provide services related to grid power quality improvement (e.g. current harmonics compensation and load balancing). So at the end, different functionalities of the PED are exploited. Some of them refer to the management of the batteries (along with the associated dc-dc power converters) and some to the capabilities of front-end grid inverters.

Table 1 Summary of the High Level Use Cases (HLUC) for the RESOLVD project involving the PED.

Use case	Comments
HLUC01: Prevention on congestion and over/under voltage issues through local storage utilization and grid reconfiguration.	In this UC, the PED would exchange power during few hours (e.g. peak consumption hours) continuously with the grid for line congestion mitigation.
HLUC02: Voltage control through local reactive power injection.	In this UC, the PED might be required to exchange reactive power with the grid. This means that no battery is needed in this case.
HLUC03: Improving power quality and reducing losses through power electronics.	In this UC, the PED will compensate current harmonics and phase unbalances at its point of connection. As for the HLUC02, no battery is needed to do so.
HLUC04: Local storage utilization to reduce power losses.	In this UC, the idea is to manage energy storages optimally so as to reduce power flows within the grid, this way reducing involved distribution power losses. An example of application could be to store locally excess PV during central hours of the day, when demand is not high enough, and then use it when needed.
HLUC05: Self-healing after a fault.	In this UC, the PED would be required to act following an exogenous command to ensure the continuity of supply to customers nearby.
HLUC06: Power management in intentional and controlled-island mode.	For the PED, manage an intentional island means to ensure the security of supply for the customers connected to it. So in other words it performs the balancing between generation and demand thus exchanging the required power at all time. Addressing the mismatch between typical consumption and PV generation profiles, the PED would be required to exchange power continuously with the grid during several/few hours.
HLUC07: Detection and interruption of unintentional uncontrolled island mode.	In this UC the PED would be required to eventually exchange power with the grid just during a short time. Thus, requirements for the PED derived from this UC are not as stringent as for other UCs.

The analysis of the use cases suggests a list of tests for the PED. These tests are grouped in two categories: tests related to PED's hardware components and tests related to the PED's service provision. A list of the tests envisaged under each category is offered in the following.

Tests related to the PED's hardware components

- T01. Input filter pre-charge
- T02. Hardware validation (at maximum power)
- T03. Active DC-Link pre-charge
- T04. Battery voltage control validation
- T05. Droop control validation
- T06. DC-Link bus pre-charge
- T07. Active rectifier mode validation

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- T08. Inverter mode validation

Tests related to the PED's service provision

- PED under Grid Mode (see Section 4 for the description of this operation mode)
    - T09. Follow active and reactive power setpoints.
    - T10. Current balancing
    - T11. Reactive compensation
    - T12. Harmonic mitigation
- PED under Island Mode (see Section 4 for the description of this operation mode)
    - T13. Check grid forming functionality according to voltage and frequency setpoints.
- PED under Recovery Mode (see Section 4 for the description of this operation mode)
    - T14. Check the functionality of the PED for charging lead-acid battery.
    - T15. Check the functionality of the PED for discharging lead-acid battery. Battery capacity nameplate validation.

Each of the tests are reported in a structured manner in Section 3. In particular, for each test, the following information is provided:

1. Name of the test.
2. Objective definition.
3. Related Use Case / KPI, when applicable.
4. Brief description of the test. Description of different scenarios, if needed.
5. Input and output data.
6. Graphical results.
7. Discussion.

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3. Tests report

This section reports the results for each of the tests listed in Section 2. Tests related to hardware components are included in section 3.1. Tests related to the provision of services are included in section 3.2.

3.1. Test related to PED hardware components

This section reports the results for tests T01 to T08. These tests refer to the electrical stability of power electronic modules, including front end inverters and DABs.

PED hardware. Power electronic modules validation. DABs.

T01. Input filter pre-charge

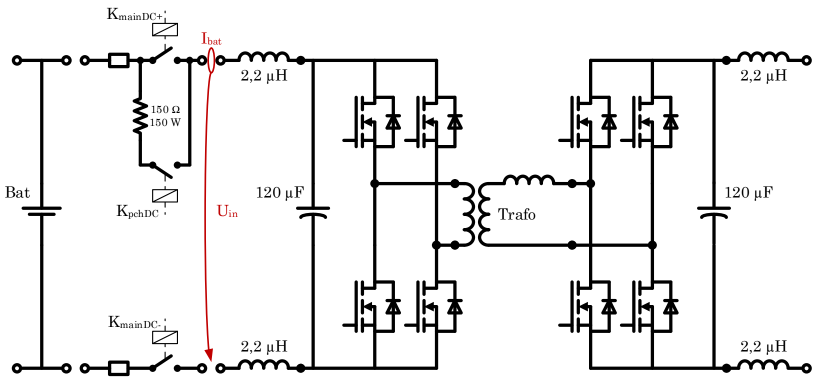
Objective definition

The aim of this test is to validate the stable behaviour of the DAB converter while in the transient state characterized by the connection process of a battery to one of its DC ports. Once the battery is connected the dc-link of the DAB converter is pre-charged by the battery. The dynamic behaviour of this process is checked in this test. In a synthetic phrase, the objective of the test is to validate the input filter pre-charge transition.

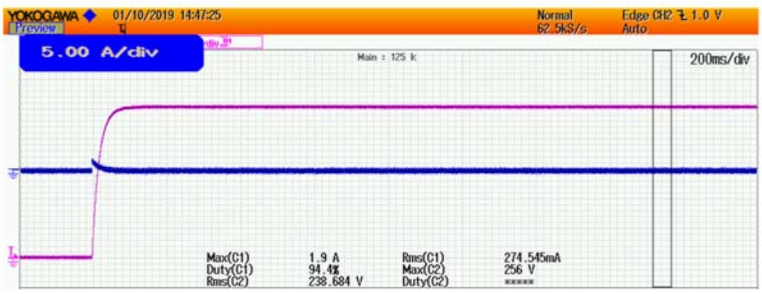
Test description

The test is done following the DAB pre-charge operation. First, contactors $K_{mainDC-}$ and K_{pchDC} (as shown in the figure below) are closed. Then, after 2 seconds, contactor $K_{mainDC+}$ is closed and K_{pchDC} is opened.

Test configuration



Results



Legend: I_{bat} – blue – 5 A/div ; U_{in} – magenta – 50 V/div

Conclusions

The input filter pre-charged is verified with a limited inrush current of 2 A for a battery of 256 V. These numbers are within admissible levels for a proper operation of the DAB.

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PED hardware. Power electronic modules validation. DABs.

T02. Hardware validation (max power)

Objective definition

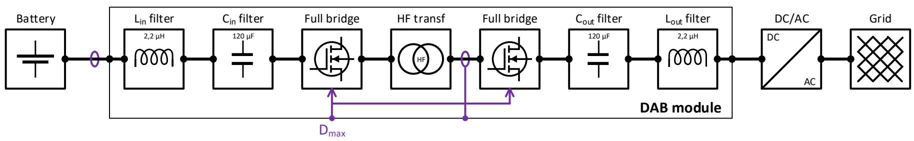
Validation of the hardware at maximum power.

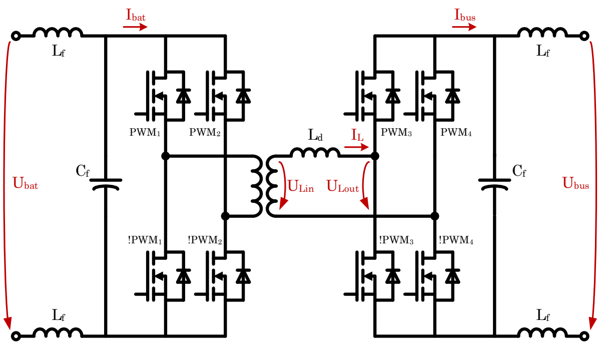
Test description

DAB converter is delivering its maximum power in open loop.

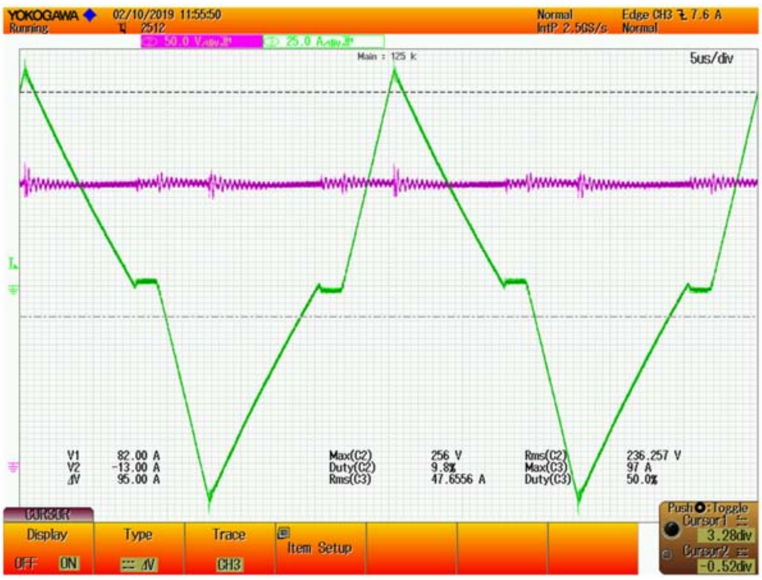
The battery is connected to one of the DC ports of the DAB converter (voltage U_{bat} in the figure below). At the other end, an external DC source controls the DC-link (voltage U_{bus} in the figure below) and drain the power given by the battery to the grid.

Test configuration





Results



Legend: U_{bat} – magenta – 50 V/div ; I_L – green – 25 A/div

Conclusions

This test shows the current shape at the output of the high-frequency transformer (green line) and the voltage at the battery terminals (magenta line). The battery considered for this test is the lead-acid one. This battery has a lower voltage (around 240 V) compared to the lithium-ion pack (around 400 V). This

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PED hardware. Power electronic modules validation. DABs.

T02. Hardware validation (max power)

makes it as the preferable battery to test the behaviour of the DAB at maximum power, because it implies the application of higher current. As shown in the graphical results, the current at the terminals of the high frequency transformer (current $\mathrm{I_L}$) presents a triangular shape with a peak value around 100 A. The power provided by the battery is

$$\mathrm{P = U_{bat} \cdot I_{bat} = U_{bat} \cdot I_L \cdot r_t = 236 \cdot 47.6 \cdot 2.25 = 25\ kW},$$

being $\mathrm{r_t}$ the transformation ratio of the high frequency transformer. The developed power is as expected, 25 kW, and the converter shown an stable electrical and thermal operation.

PED hardware. Power electronic modules validation. DABs.

T03. Active DC-Link pre-charge

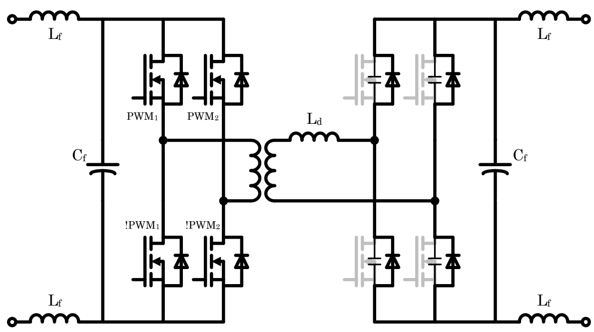
Objective definition

Validation of DC-Link pre-charge, always done by the DAB converter with the higher voltage ($\mathrm{U_{bat} \cdot r_t}$).

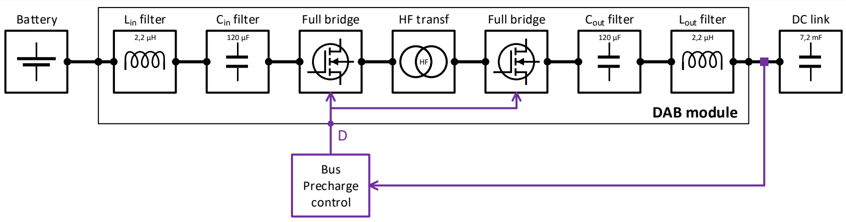
Test description

DAB converter pre-charges the DC-link up to 770 V using the first full bridge (battery side) synthetizing an increasing square voltage waveform (shifting the PWM signals). The second one only acts as a rectifier through its diodes.

Theoretically, the maximum output voltage should be the battery voltage multiplied by the transformer ratio (about 520 V). However, the semiconductor parasite capacitors of the second full bridge allow an increase of the DC-link voltage. These are charged when diode current is zero, adding this extra energy stored when the AC current direction changes.



Test configuration



Results

The DC-link is pre-charged up to 770 V in about 15 s.

Conclusions

Although it is slower than when it is done from the AC side, this strategy can be used when the inverter cannot manage the DC-link, under Island and Grid modes.

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PED hardware. Power electronic modules validation. DABs.
T04. Battery voltage control validation

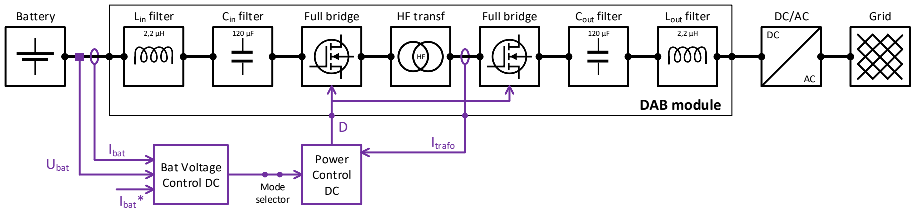
Objective definition

Validation of the battery charge and discharge at constant current, limiting the current (at constant voltage) when the battery is close to fully charge or discharge (maximum and minimum voltage respectively).

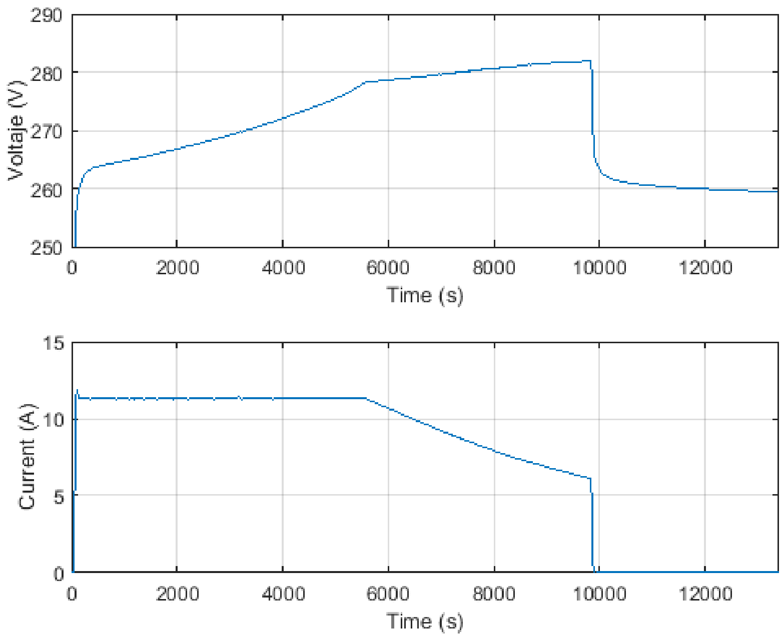
Test description

To conduct this test, an external AC/DC source keeps energised the DC-Link as the inverter would do. Then, the battery control manages the current up to a fixed value. Therefore, when the battery is near to the charge or discharge limits, the control algorithm saturates the current and keeps the voltage constant.

Test configuration



Results



Charge

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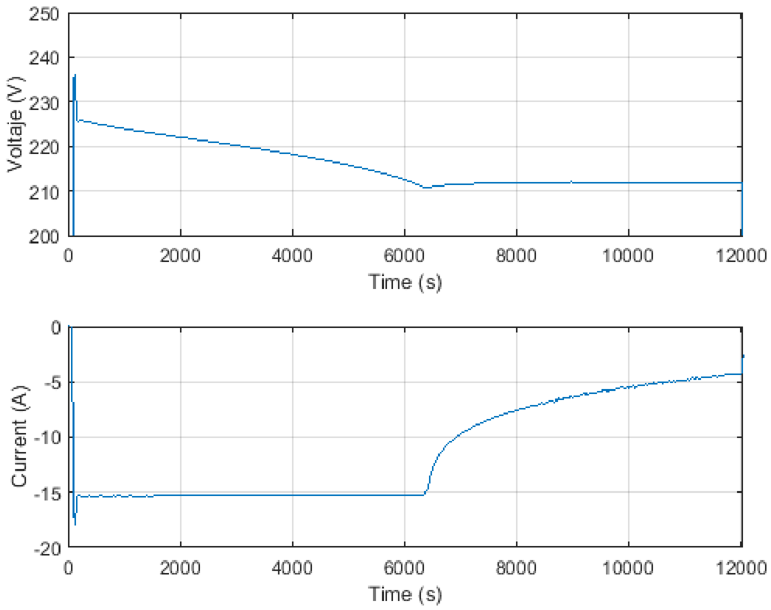
PED hardware. Power electronic modules validation. DABs.
T04. Battery voltage control validation



Discharge

Conclusions

The battery voltage control is able to manage the battery charge and discharge. It limits the voltage and decreases the current when the SOC is close to the limits, fully charged or discharged.

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PED hardware. Power electronic modules validation. DABs.
T05. Droop control validation – Primary, Secondary & Tertiary

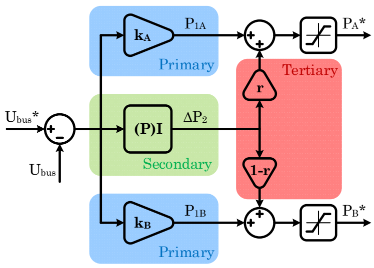
Objective definition

Validate the primary, secondary and tertiary modes of the droop control algorithm. The primary mode determines the power setpoints sharing under a suddenly load change, it means defining which battery reacts faster. The secondary mode modifies the power setpoints to restore the DC-link voltage. The tertiary mode defines the battery power sharing when the DC-link voltage is restored.

Test description

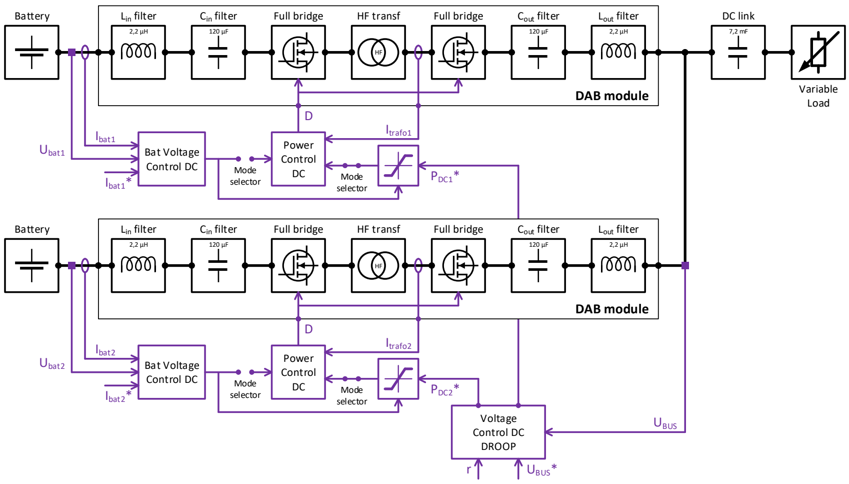
DAB converter is managing the DC-link voltage through the droop control algorithm. Then, it is observed how the power sharing ratio behave under a load perturbation, dynamically and in steady state.

Primary control: $k_A = 3 \cdot K_B$ *Secondary control: ts < 200 ms* *Tertiary control: r = 0.3*



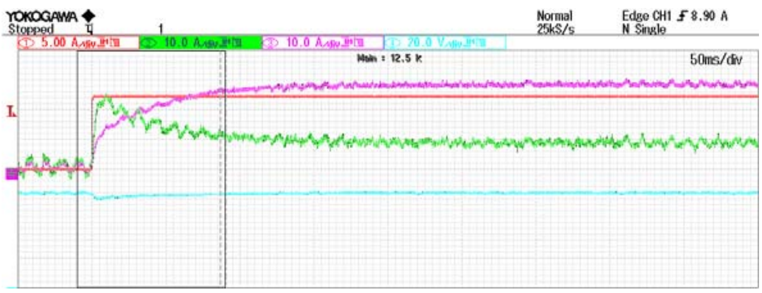
P_A* : Lithium power setpoint P_B* : Lead-acid power setpoint

Test configuration



Results

U_{bat_A}= 346 V U_{bat_B}= 241 V



U_{bus} – cyan – 20 V/div (700 V offset) I_{bus} – red – 5 A/div

I_{bat_A} – green – 10 A/div I_{bat_B} – magenta – 10 A/div

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PED hardware. Power electronic modules validation. DABs. **T05. Droop control validation – Primary, Secondary & Tertiary**
Conclusions
When a power perturbation modifies the DC-link voltage, primary control reacts immediately slowing down the voltage droop. Lithium battery primary droop factor is three times higher than the lead-acid one then, it reacts faster. Secondary control readjusts the DC-link voltage. And tertiary control shares the power need in terms of the defined ratio.

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PED hardware. Power electronic modules validation. Front-end inverter.

T06. DC-link pre-charge

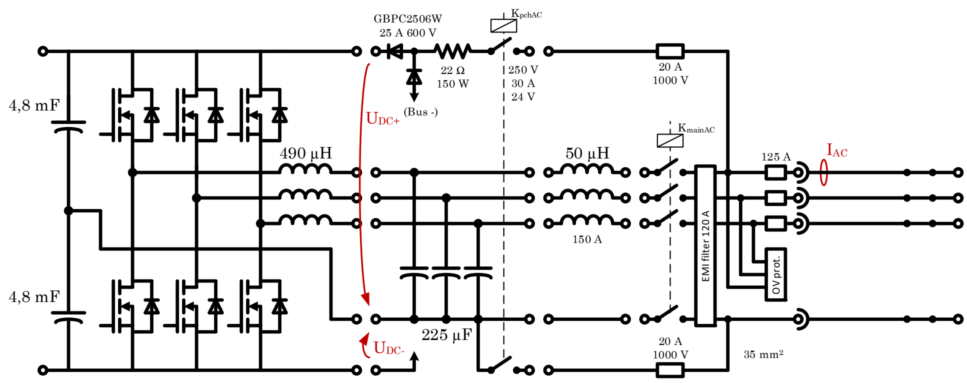
Objective definition

At the time of starting up the PED, the DC-link of the front-end inverters of the PED should be pre-charged. As a reminder, this DC-link interfaces the DC side of the front-end inverters of the PED with the DAB converters. Pre-charge means that a contactor should be activated somehow, closing the circuit between the grid and the DC link, thus a current will flow from the grid to the DC-link and the DC-link voltage will increase till reaching a certain magnitude, that is suitable to trigger other phases of the starting process of the PED. This test validates such DC-link pre-charge transition.

Test description

The test is done following the inverter pre-charge operation. First, contactor K_{pchAC} is closed. Then, when the DC link voltage reaches 620 V, contactor K_{mainAC} is closed and contactor K_{pchAC} is opened.

Test configuration



Results

When the pre-charge contactor relay is closed, the DC-link is connected to one of the phase of the external grid through a 22 Ω resistor and a monophasic rectifier. Then, the bus reaches 620 V in less than 5 s (the speed depends on the grid voltage level).

Conclusions

The DC-link pre-charge is validated.

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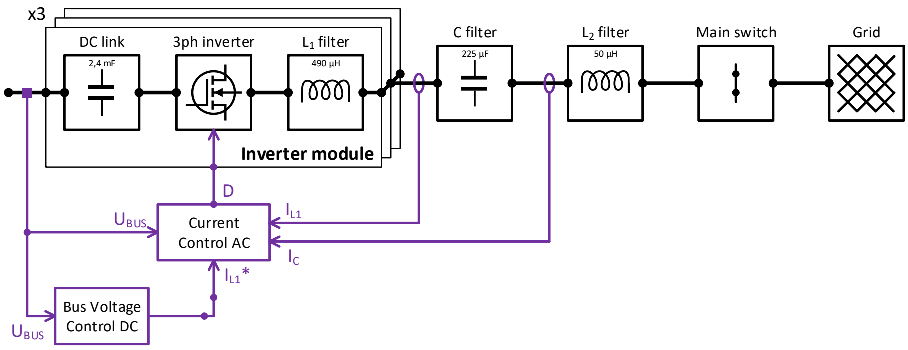
PED hardware. Power electronic modules validation. Inverter.
T07. Active rectifier mode validation
Objective definition
Validation of the inverter acting as an active rectifier, managing the DC-link voltage.
Test description
During this test, the inverter is focused on the DC side, managing the DC-link voltage at 800 V.
Test configuration

Results
The inverter is able to manage the DC-link voltage stable at 800 V.
Conclusions
The active rectifier mode is validated.

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PED hardware. Power electronic modules validation. Inverter.

T08. Inverter mode validation

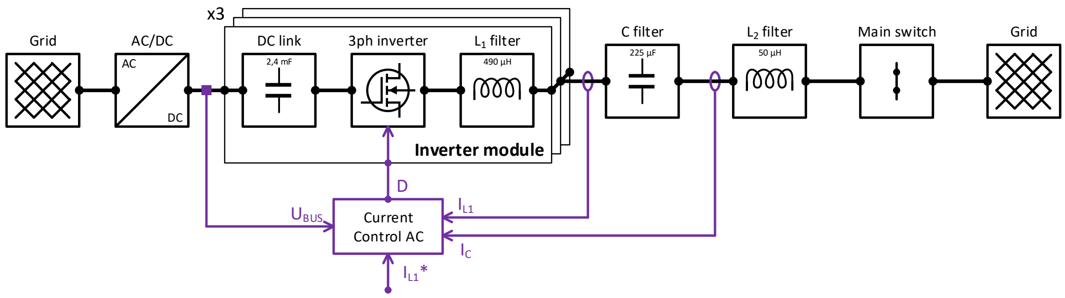
Objective definition

Validation of the inverter connected to the grid, delivering some amount of current.

Test description

During this test, the inverter is focused on the AC side, managing the AC current.

Test configuration



Results

The inverter is able to deliver currents to the grid, up to 36 A_{rms} per phase.

Conclusions

The inverter can manage currents up to 36 A_{rms} per phase per phase independently and control odd harmonics up to the 11^{th}.

3.2. Test related to the provision of services by the PED

This section reports the results for tests T09 to T15, all related to the provision of services by the PED at the electrical system it is connected to. For some tests (tests T09 to T12), the power electronic modules of the PED are switched to "Grid Mode" (see section 4). Under this control mode, the PED can be managed to follow active and reactive power setpoints and provide services related to the grid power quality improvement, i.e. current balancing, reactive power compensation and current harmonic mitigation. For test T13, the front end inverters of the PED are acting as a voltage source, so feeding an isolated grid. For tests T14 to T15, the PED is operating under the "Recovery Mode". This mode is useful to test the PED while in maintenance actuations, for instance. For more description on Grid Mode, Island Mode and Recovery Mode, the reader is referred to section 4.

Tests related to the provision of services of the PED

- PED under Grid Mode
  - T09. Follow active and reactive power setpoints.
  - T10. Current balancing.
  - T11. Reactive compensation.
  - T12. Harmonic mitigation.
- PED under Island Mode
  - T13. Check grid forming functionality according to voltage and frequency setpoints.
- PED under Recovery Mode
  - T14. Check the functionality of the PED for charging lead-acid battery.
  - T15. Check the functionality of the PED for discharging lead-acid battery. Battery capacity nameplate validation.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773715

PED hardware. Services validation. Grid Mode.

T09. Active and Reactive power

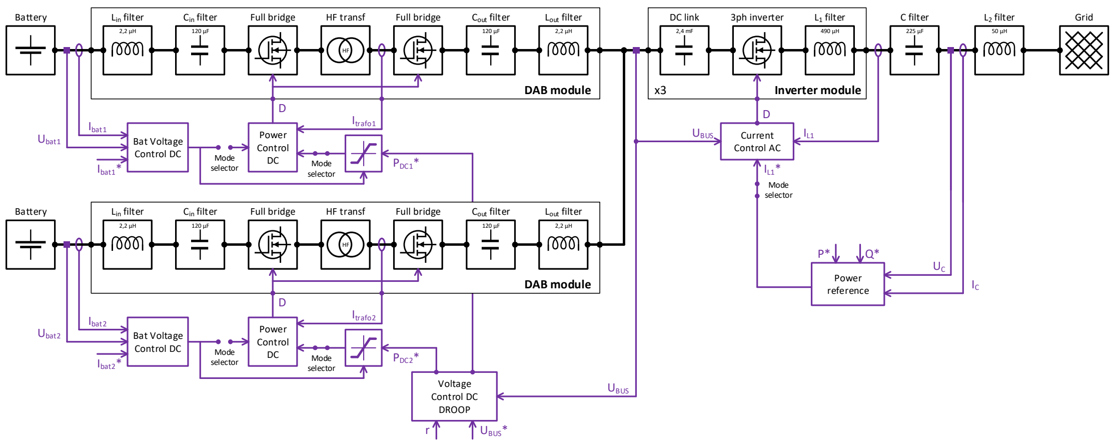
Objective definition

Validation of the Grid Mode, delivering active and reactive power to the grid.

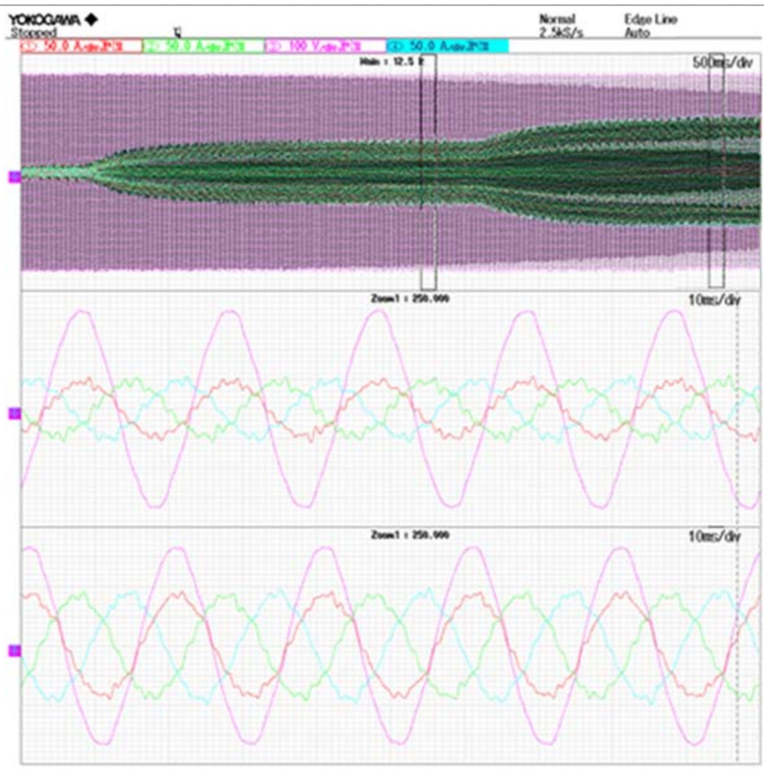
Test description

During this test, the PCS is fully integrated. Both batteries are managing the DC-link by means of each DAB converter. And the inverter delivers the active and reactive power setpoints.

Test configuration



Results



Active power

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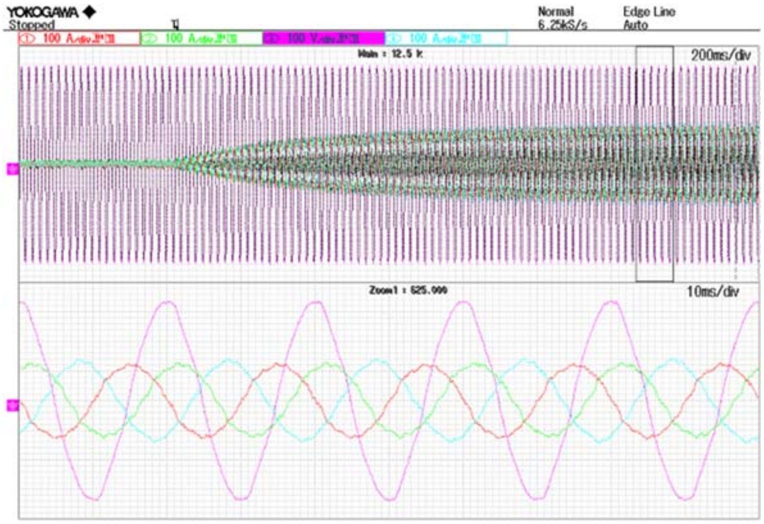
PED hardware. Services validation. Grid Mode.

T09. Active and Reactive power

Legend: U_{grid_R} – magenta – 100 V/div ; I_{grid_R} – red – 50 A/div ; I_{grid_S} – cyan – 50 A/div ; I_{grid_T} – green – 50 A/div



Reactive power

Legend: U_{grid_R} – magenta – 100 V/div ; I_{grid_R} – red – 50 A/div ; I_{grid_S} – cyan – 50 A/div ; I_{grid_T} – green – 50 A/div

Conclusions

The PCS is able to deliver active and reactive power up to 75 kVA, following a power setpoint change in about 1 s.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773715

PED hardware. Services validation. Grid Mode.

T10. Current balancing

Objective definition

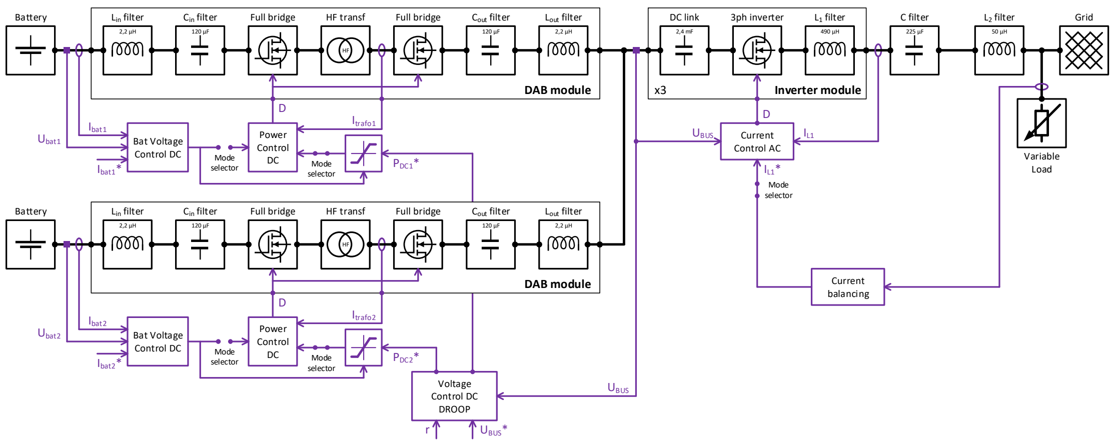
Validation of the power quality services under Grid Mode, balancing the current consumption of the load.

Test description

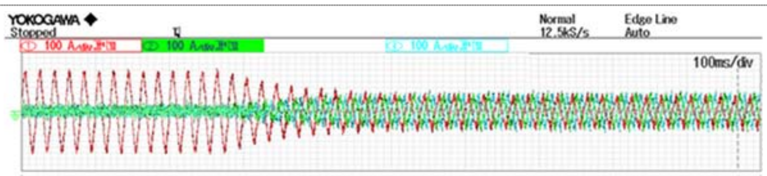
For this test, the PCS is fully integrated. Both batteries are managing the DC-link by means of each DAB converter. The inverter measures the load currents and compensate the load unbalanced consumption.

Test configuration

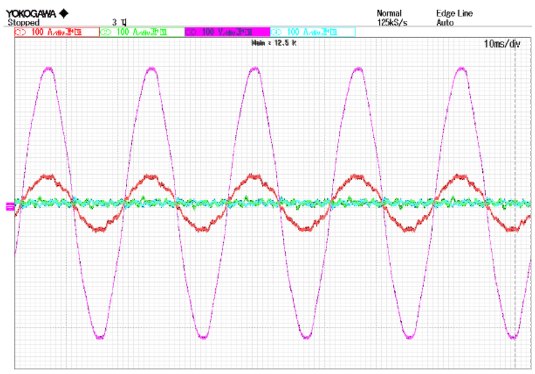
During the test, a monofasic loal load of 11 kW is connected to the R phase.



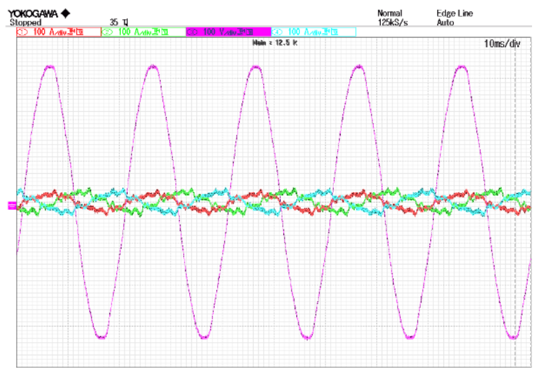
Results



After



Before



Legend: U_{grid_R} – magenta – 100 V/div ; I_{grid_R} – red – 100 A/div ; I_{grid_S} – cyan – 100 A/div ; I_{grid_T} – green – 100 A/div

Conclusions

The PCS is able to balance local unbalanced consumptions in about 200 ms.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773715

PED hardware. Services validation. Grid Mode.

T11. Reactive compensation

Objective definition

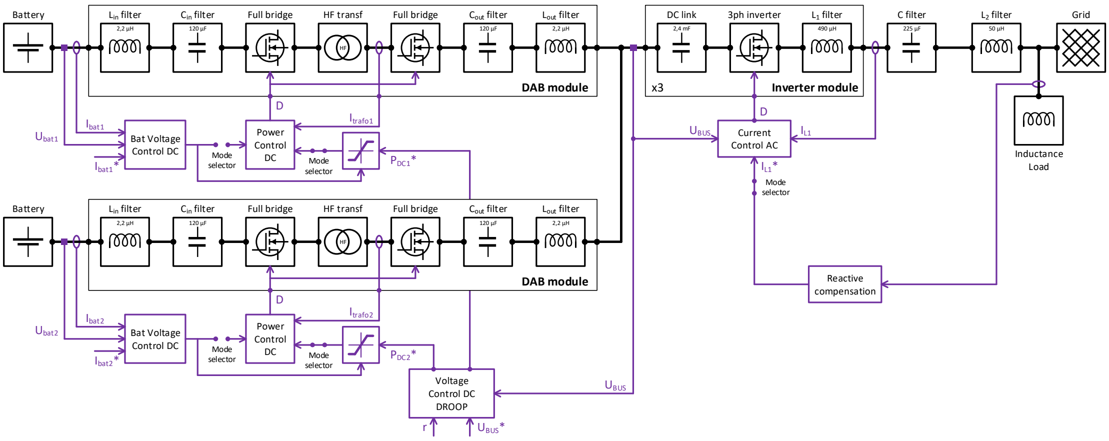
Validation of the power quality services under Grid Mode. Load reactive power compensation.

Test description

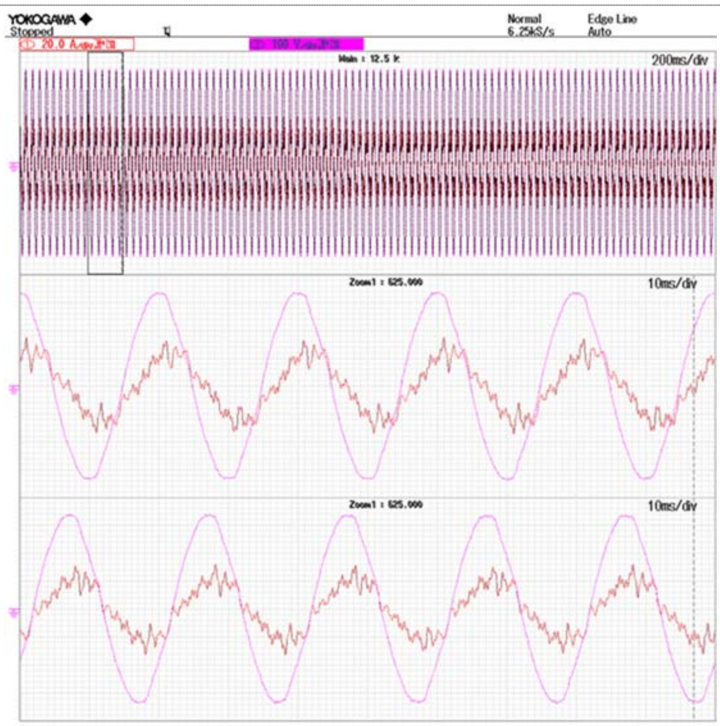
During this test, the PCS is fully integrated. Both batteries are managing the DC-link by means of each DAB converter. The inverter measures the local load currents and compensate the reactive consumption.

Test configuration

During the test there is connected a trifasic loal load of 13.5 kVA and a PF of 0.8



Results



Legend: U_{grid_R} – magenta – 100 V/div ; I_{grid_R} – red – 50 A/div

Conclusions

The PCS is able to significantly compensate the reactive consumptions of the local load.

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PED hardware. Services validation. Grid Mode.

T12. Harmonic mitigation

Objective definition

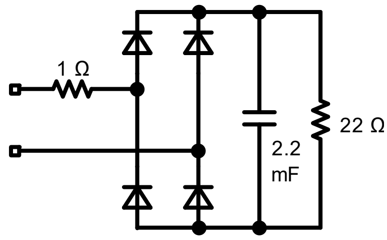
Validation of the power quality services under Grid Mode, compensating the harmonic consumption of the load.

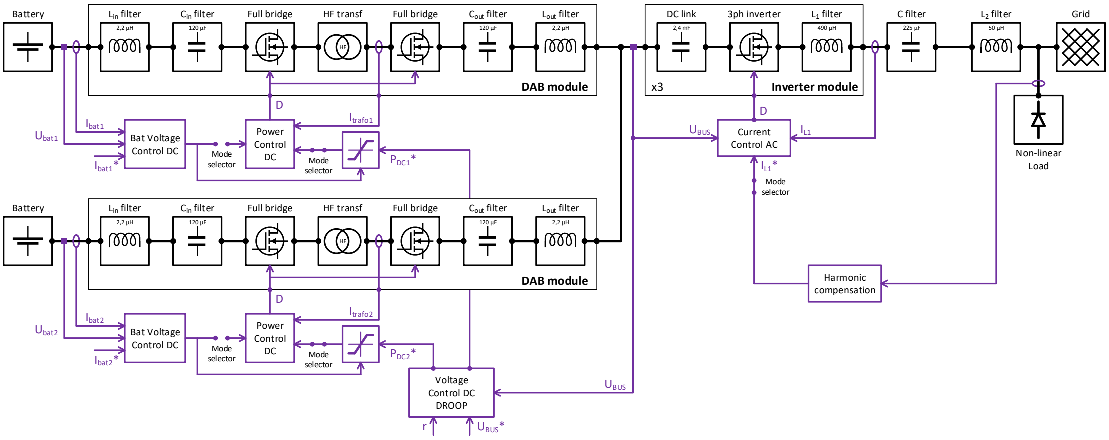
Test description

During this test, the PCS is fully integrated. Both batteries are managing the DC-link by means of each DAB converter. The inverter measures the local load currents and compensate the harmonic consumption of the grid.

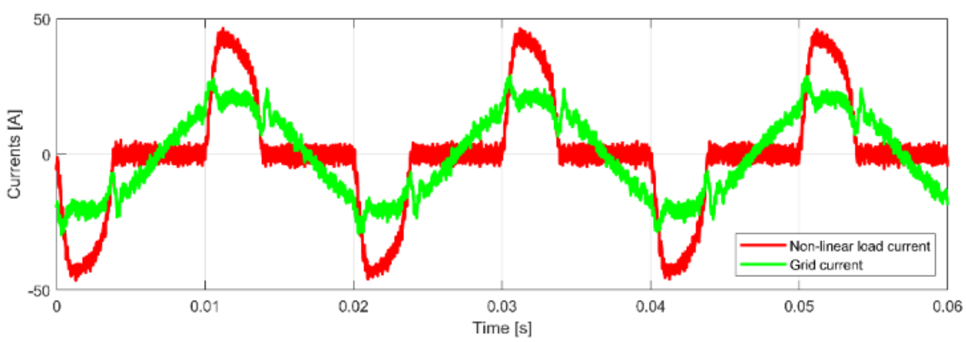
Test configuration

During the test there is connected the following momofasic non-linear load to one phase.





Results



Conclusions

Taking into account that the converter can manage odd harmonic currents up to the 11^{th}, the PCS is able to significantly mitigate the harmonic consumptions of the local load.

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PED hardware. Services validation. Island Mode.

T13. Grid forming

Objective definition

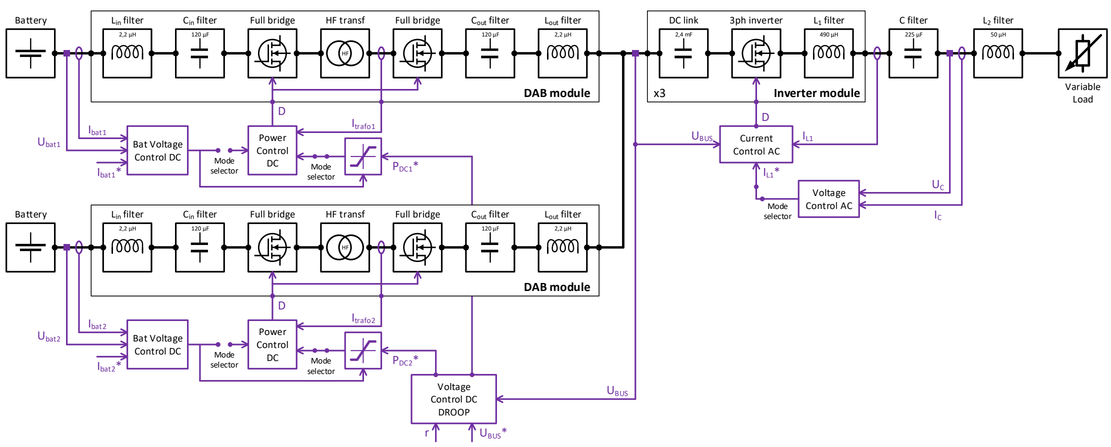
Validation of the grid forming under Island Mode.

Test description

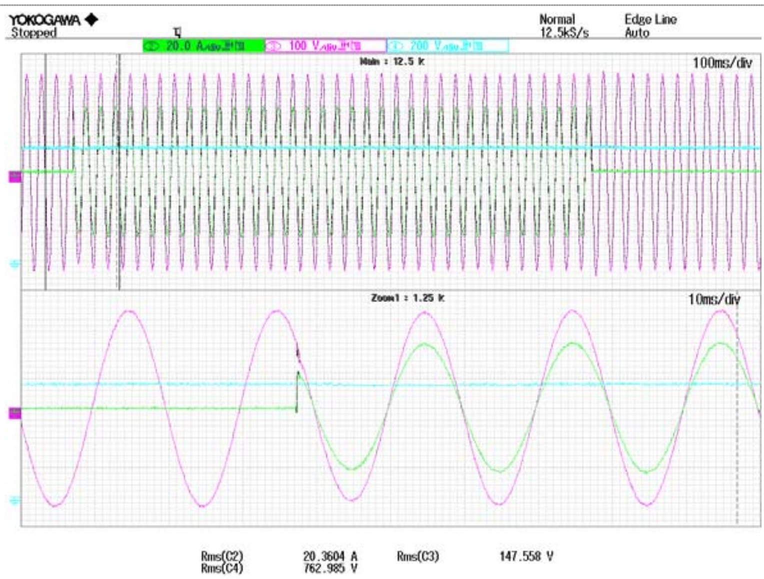
During this test, the PCS is fully integrated. Both batteries are managing the DC-link by means of each DAB converter. The inverter manage the output AC voltage and frequency.

Test configuration

During the test, a monofasic loal load of 7 kW is suddenty connected and disconnected to the R phase.



Results



Legend: U_{bus} – cyan – 200 V/div ; U_{grid_R} – magenta – 100 V/div ; I_{grid_R} – red – 50 A/div

Conclusions

The PCS is able to manage the AC voltage and frequency under unbalanced perturbations of the load.

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PED hardware. Services validation. Recovery Mode.

T16. Lead-acid battery charge

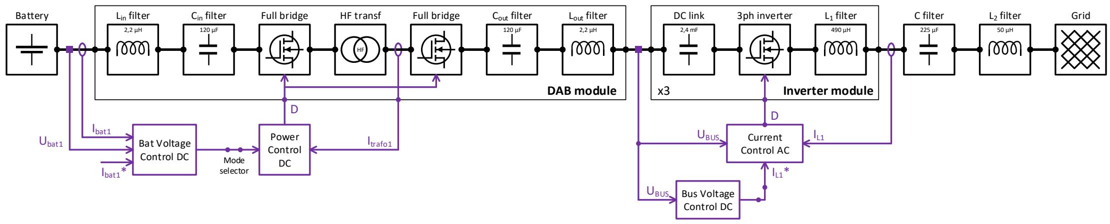
Objective definition

Validation of the battery charge process under Recovery Mode.

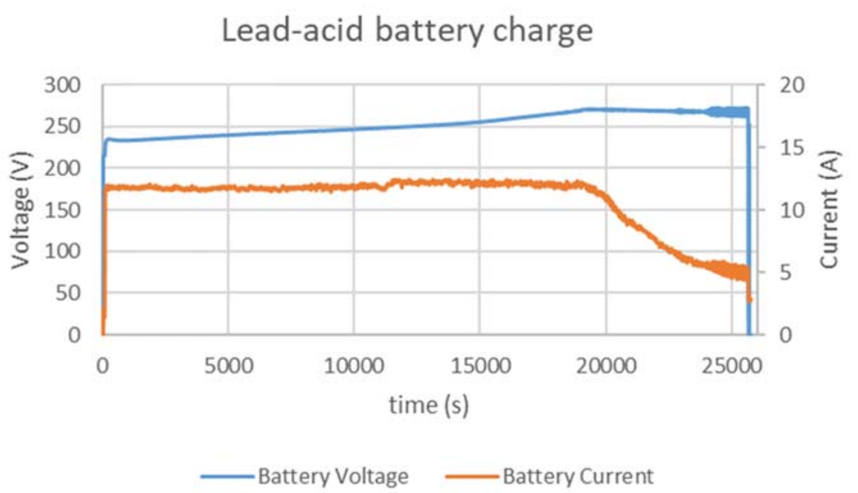
Test description

During this test, the PCS is fully integrated. The inverter is managing the DC-link and DAB converter deal with the charge process of the battery.

Test configuration



Results



Conclusions

The charge process of the lead acid battery pack has been correctly performed. The DAB converter correctly implements the two phases of the charge procedure for a battery pack, i.e. a first phase applying constant current, followed by a second phase in which the voltage of the battery pack is maintained constant.

The charge process ends at the point of reaching a minimum current, so a cut-off current, fixed around 3 A. The battery pack voltage at fully charged condition is 269 V. The phase at constant current was done at 11.5 A approximately. According to the nameplate of the battery, this corresponds to 0.15C rate.

The energy consumed by the battery in this process is around 19.2 kWh and time employed is 6.7 h.

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PED hardware. Services validation. Recovery Mode.

T17. Lead-acid battery discharge

Objective definition

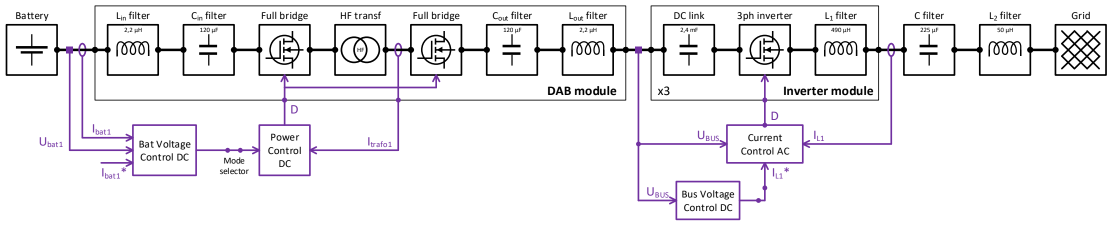
Validation of the battery discharging process under Recovery Mode.

Test description

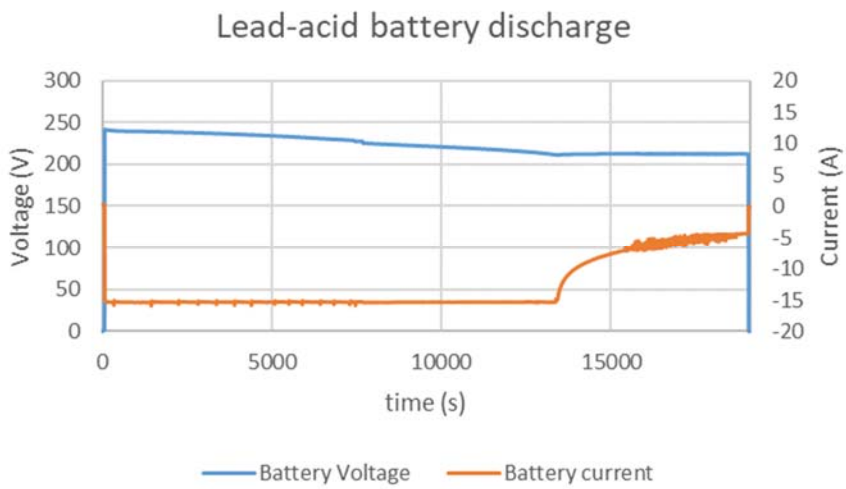
During this test, the PCS is fully integrated. The inverter is managing the DC-link and DAB converter deal with the discharging process of the battery.

Test configuration

This test is condcuted following a battery discharge at 0.2 C



Results



Conclusions

The discharge process of the lead acid battery pack has been correctly performed. The DAB converter correctly implements the two phases of the discharge procedure for a battery pack, i.e. a first phase applying constant current, followed by a second phase in which the voltage of the battery pack is maintained constant.

The charge process ends at the point of reaching a minimum current, so a cut-off current, fixed around 3 A. The battery pack voltage at fully discharged condition is 211 V. The phase at constant current was done at 15 A approximately. According to the nameplate of the battery pack, this corresponds to 0.2C rate.

The energy provided by the battery pack in this process is around 15.1 kWh and the time employed is 5.3 h. The energy provided by the battery pack while discharged at constant current is 13 kWh and the time employed is 3.7 h. The manufacturer specifies the capacity of the battery while discharged at constant current. According to this, and at 0.2C rate, the storage capacity of the pack should be around 15 kWh. The difference between the tested performance (13 kWh) and the expected one (15 kWh) can

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PED hardware. Services validation. Recovery Mode.
T17. Lead-acid battery discharge
be associated to some degradation of the batteries at the time of writing this report, so after being utilized them in the laboratory during the last months for development purposes. It is interesting to note that in the second phase of the discharge process (at constant voltage and reduced current), the battery pack just provides the difference between 15.1 kWh and 13 kWh, so around 2.1 kWh. This second phase takes the difference between 5.3 h and 3.7 h, so around 1.6 kWh. The reduced energy provided by the battery while in this second phase of the discharge process, so while reaching low state of charge (SoC) condition, is the reason why, in practice, the minimum admissible SoC is limited to a relatively high value. Finally, comparing the total energy consumed by the battery in the charge process and the total energy provided by it while in the discharge process, it can be concluded that the round trip efficiency of the process is around **78.4%**.

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4. Final notes on the Intelligent Local Energy Manager (ILEM)

The PED, as a system, is managed from exogenous signals and the local controller, so the link between the PED and the rest of the world is the ILEM software. Figure 1 plots the operation modes for the PED as programmed into the ILEM software. As can be noted, the final ILEM state machine proposes three operation modes: Scheduled mode (state X2), Non-Scheduled mode (state X1) and Local mode (state X4). This state machine slightly diverges from what was presented in previous deliverable (deliverable 2.3) for this WP2. This is because to ensure an optimal and easy integration in RESOLVD network environment (e.g. grid operator SCADA and cloud management platform).

Under the Scheduled mode, the PED is governed by the cloud management platform, that recurrently provides power schedules to be exchanged with the grid for the provision of various services. While in Scheduled mode, the PED is not acting as a grid forming converter, so it does not support an islanded grid.

Under the Non-Scheduled mode, the PED can act as a voltage or current source, so it can support an islanded grid or following active and reactive power setpoints sent by the grid operator SCADA and cloud management platform.

Finally, the Local mode is the one adopted for testing the different capabilities of the PED in the laboratory environment. This is an operation mode reserved for testing and configuring the PED. It may be useful for the final user of the PED while installed in the pilot of the project for maintenance actuations.

The transitions among states or operation modes are carried out through the grid operator SCADA. In Figure 1, it can be also noted the states from and to the user can switch. For instance, to get into state X2 (Scheduled mode), the user should previously act into state X1 and apply the SCADA "TurnOnScheduled" command. In addition, it can get to state X2 from state X4 and applying, again, the command SCADA "TurnOnScheduled".

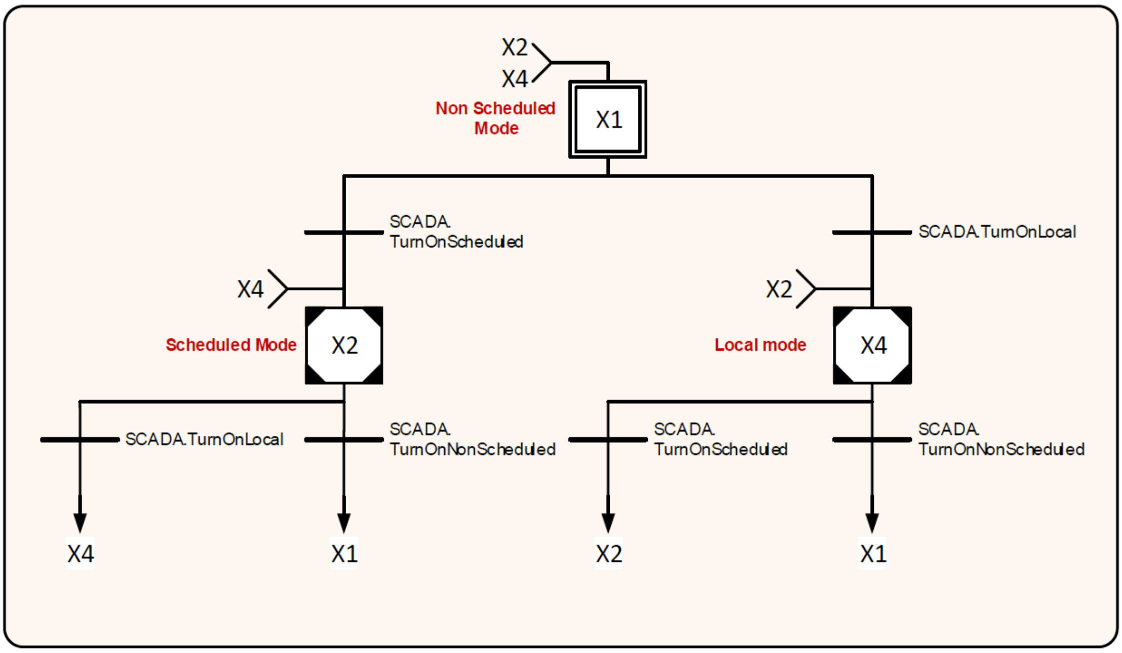

Figure 1 Operation modes for the PED as programmed into the ILEM software.

The performance of the ILEM while governing the PED, also its interaction with the SCADA and the cloud management platform, is to be fully tested in the frame of WP5, once the PED is in the pilot of the project.

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Each of the three operation modes of the ILEM is correlated to an operation mode of the power electronic modules of the PED, which are Grid Mode, Island Mode and Recovery Mode. This is explained in Figure 2.

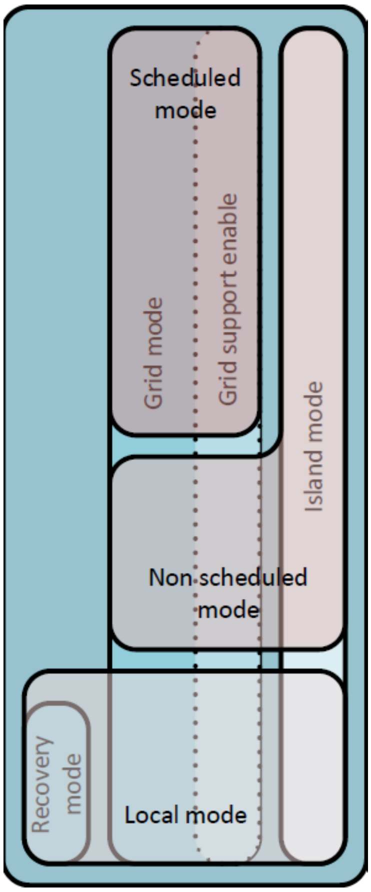

Figure 2 Operation modes for the PED as programmed into the ILEM software. Correspondence to the operation modes of the power electronic modules (Grid Mode, Island Mode and Recovery Mode).

As can be noted, while the ILEM is under the Scheduled mode (so it is receiving exogenous active and reactive power set points), the front end inverters of the PED are under the Grid Mode. This means, in practice, that the PED is acting as a current source, not as a voltage source. In other words, the duty of maintaining a constant voltage and frequency of the network is not for the PED, but for the main grid operator.

The front end inverters of the PED are also acting as a current source, but they also can act as a voltage source, when the ILEM is operating the PED under the Non Scheduled mode. This means that, in case of not receiving a table with the power schedules for the next 24 hours, but just manual setpoints from the grid operator, the PED can exchange active and reactive power (power electronics under the Grid Mode) or it can be commanded to form a grid itself (power electronics under the Island Mode).

Finally, when the ILEM is operating the PED under the Local Mode (for maintenance actuations, for instance), the power electronics of the PED can be configured either to Recovery Mode, Grid Mode or Island Mode, so all functionalities can be easily validated.

5. Conclusions

The main conclusions of this deliverable are summarized as follows:

- The PED hardware electrical stability and functionalities are successfully tested on a laboratory environment. The power electronic modules shown stable performance while operating at maximum power, also while in transient states such as pre-charging the dc-link at the start up process. The different controllers embedded into the PED for battery voltage management and DC-link droop control have been validated.
- The PED capabilities in regard of the provision of services at its connection point to the main grid are successfully tested. In particular, the following functionalities are checked: the capability of following active and reactive power setpoints; the provision of grid current balancing, reactive power compensation and current harmonics mitigation; the capability of grid forming as well.
- The lead-acid battery pack performance and energy storage capacity has been checked. The energy storage capacity while discharged applying a constant current phase (0.2C) followed by a constant voltage phase to extract all available energy from the pack, is 15.1 kWh. The process takes 5.3 h. The battery pack, while also charged under the constant current – constant voltage charge method (and the constant current phase is at 0.15C rate), consumes 19.2 kWh, in a 6.7 h process. Thus, the energy efficiency of the pack results around 78.4%. The information provided by these tests are essential for the proper management of the battery while integrated in the pilot of the project.

References

- Datasheet for Ultracell VRLA battery, model UCG75-12. URL: http://ultracell.co.uk/datasheets/UCG75-12.pdf. Accessed: 15.07.2019