From Knowledge Generation To Science-based Innovation

INESCTEC
TECHNOLOGY & SCIENCE
ASSOCIATE LABORATORY

COORDINATED BY
INESCPORTO
PORTUGAL

Aalborg 2015 Symposium on Microgrids

A Test Bed in a Laboratory Environment to Validate Islanding and Black Start Solutions for Microgrids

Clara Gouveia (cstg@inescporto.pt)
Carlos Moreira (cmoreira@inescporto.pt)
João Peças Lopes (jpl@fe.up.pt)
Centre for Power and Energy Systems - INESC TEC

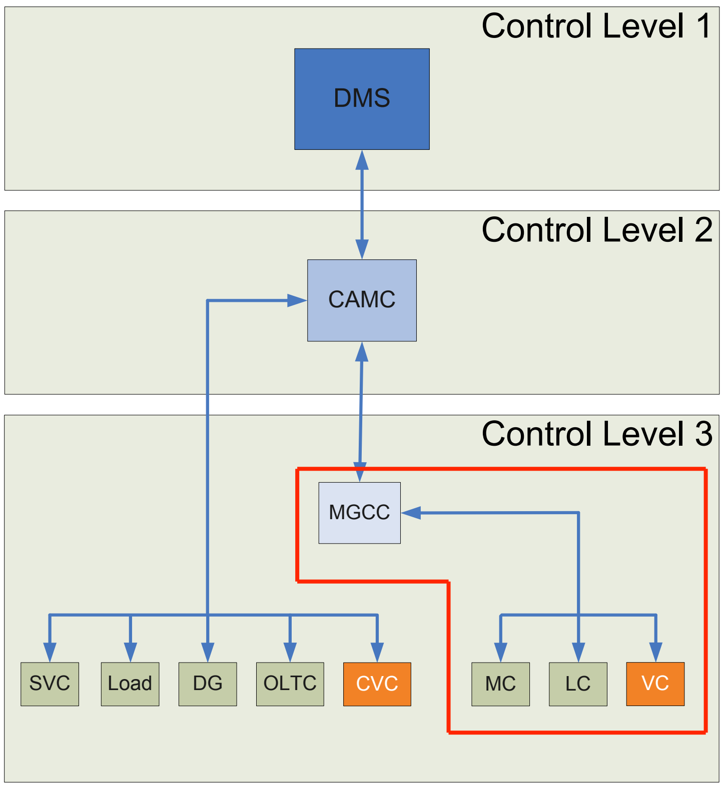
Research and Technological Development | Technology Transfer and Valorisation | Advanced Training | Consulting
Pre-incubation of Technology-based Companies

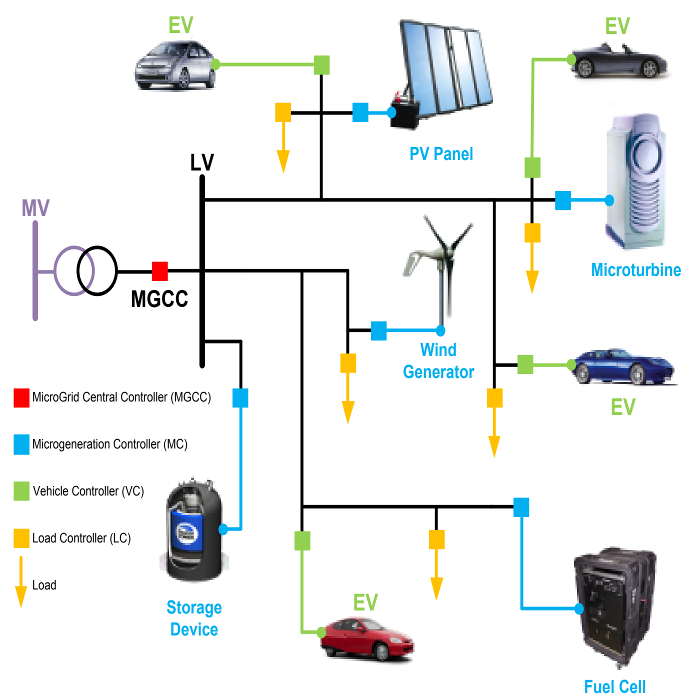
Outline

1. MG as smart distribution cell
2. Validation of MG operation concepts
3. Smart Grids and EVs Laboratory
   a) Main Objectives
   b) Infrastructures
   c) Control Functionalities
   d) Experimental Tests
   e) Conclusions
   f) Future Work

1.MG as smart distribution cell

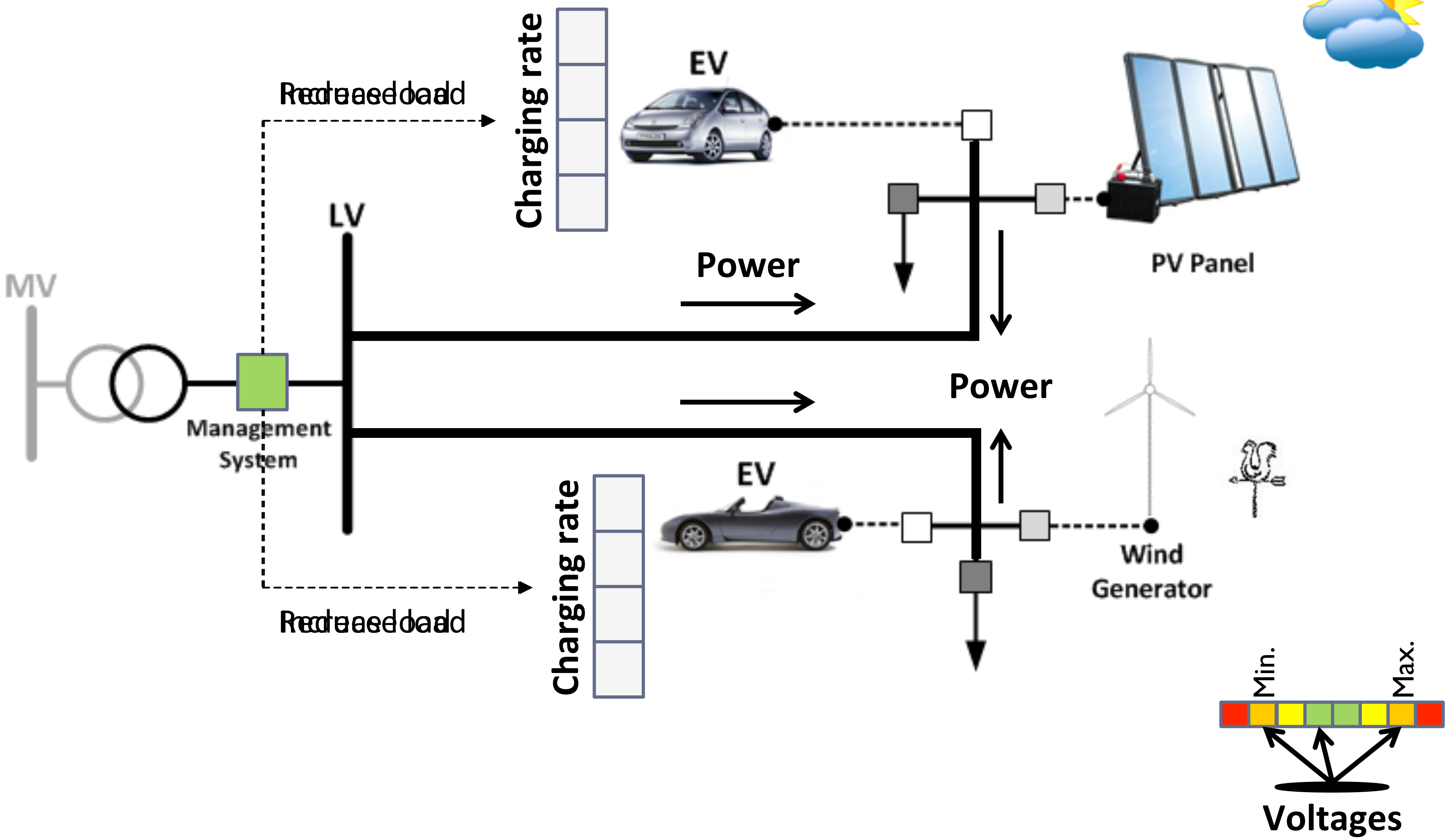
- The MG is a <u>flexible</u>, <u>active</u> and <u>controllable</u> LV system, incorporating: Microgeneration, Storage devices, Electric vehicles





1.MG as smart distribution cell

- Technical challenges – Integrated management of EV and RES



1.MG as smart distribution cell

The MG can be regarded as the cell of future Smart Grids:

- Enhance the observability and controllability of power distribution systems.
- Actively integrate electric vehicles and loads in the operation of the system.
- Increase the connection capacities for different distributed generation technologies.
- Promote the coordinated management of microgeneration, storage, electric vehicles and load, in order reduce system losses and improve power quality.
- Provide self-healing capabilities to the distribution network, due to its ability of operating autonomously from the main grid and perform local service restoration strategies.

1.MG as smart distribution cell – Emergency Operation

INESCTEC

MG faces severe challenges during islanding operation to maintain stability and quality of supply:

Inexistence of synchronous generation units -
the system is inertialess.

- Adoption of **local control strategies** compatible with the MG resources and power electronic devices:
  - Ensure voltage and frequency references.
  - Provide voltage regulation.
  - Provide frequency regulation, namely:
    - Primary frequency regulation
    - Secondary frequency regulation.
    - Load Control

Low X/R ratio and short-circuit power
+
Unbalanced operation of LV network

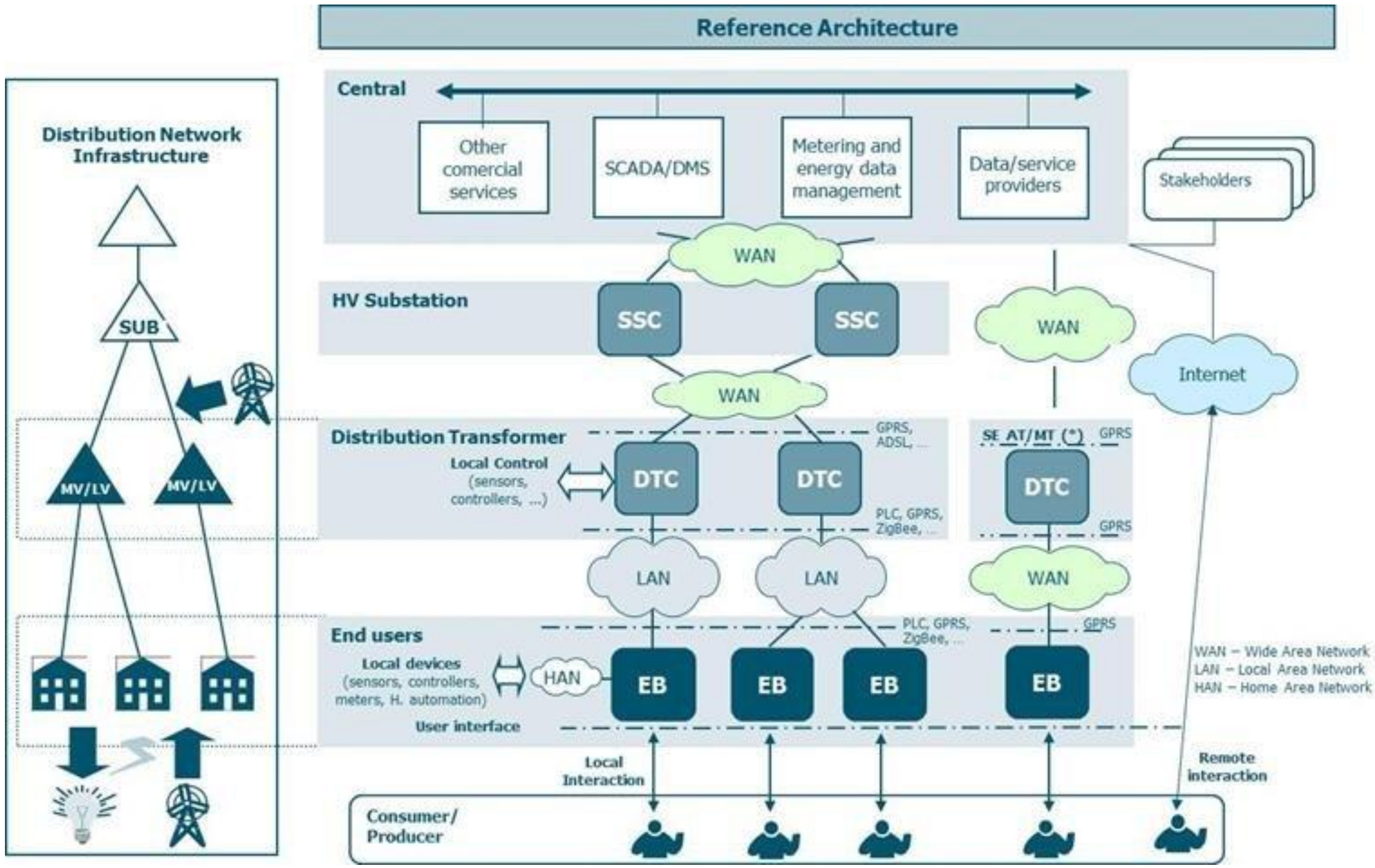
- Possible **degradation of power quality**, due to the increase of voltage unbalance.
- Voltage unbalance causes:
  - Decreases the life-time and efficiency of three-phase loads.
  - Increases the system losses.
  - Might compromise the MG synchronization with the MV network.

2.Validation of MG operation concepts

- Microgrid and More microgrid European projects
  - **Main goals and achievements**:
    - increase the penetration of RES and other micro-sources in order to contribute for the reduction of GHG emissions.
    - Development and demonstration of MicroGrids and Multi-Microgrids operation, control, protection, safety and telecommunication infrastructures.
    - To study the main issues regarding the operation of MicroGrids in parallel with the mains and in islanding conditions that may follow faults.
    - To identify the needs and develop the telecommunication infrastructures and communication protocols required.
- InovGrid Project
  - **Main goals and achievements**:
    - Definition of the reference model and specifications of smart metering infrastructure for the Portuguese utility - EDP Distribution.
    - Development of advanced functionalities such as coordinated voltage control, blackstart strategies using Distributed Generation, definition of new requirements for system protection and Medium voltage automatic reconfiguration capability.
    - Development of strategies to evaluate the potential costs and benefits of deploying the Multi-MicroGrid concept using multi-criteria decision aid methods.

2.Validation of MG operation concepts

- Inovgrid reference architecture – Smart Grid Portuguese Demonstrator



2.Validation of MG operation concepts

- Merge - Mobile Energy Resources in Grids of Electricity

  (FP7 funded project)

  - **Main goals and achievements**:
    - Development of a **management and control concept** that will facilitate the actual transition from conventional to EV.
    - **Identify potential smart control approaches** to allow the deployment of EV without major changes in the existing network and power system infrastructures.
    - To identify the most appropriate ways **to include EV into electricity markets through** the smart metering infrastructure.
    - To provide **quantitative results on the impact of integrating EV into the grid** of EU national power systems.
    - To provide **computational suite** able to identify and quantify the benefits that a progressive deployment of the MERGE concept will bring to the EU national power systems, taking into account several possible smart control approaches.

2.Validation of MG operation concepts

- REIVE – Smart Grids With Electric Vehicles

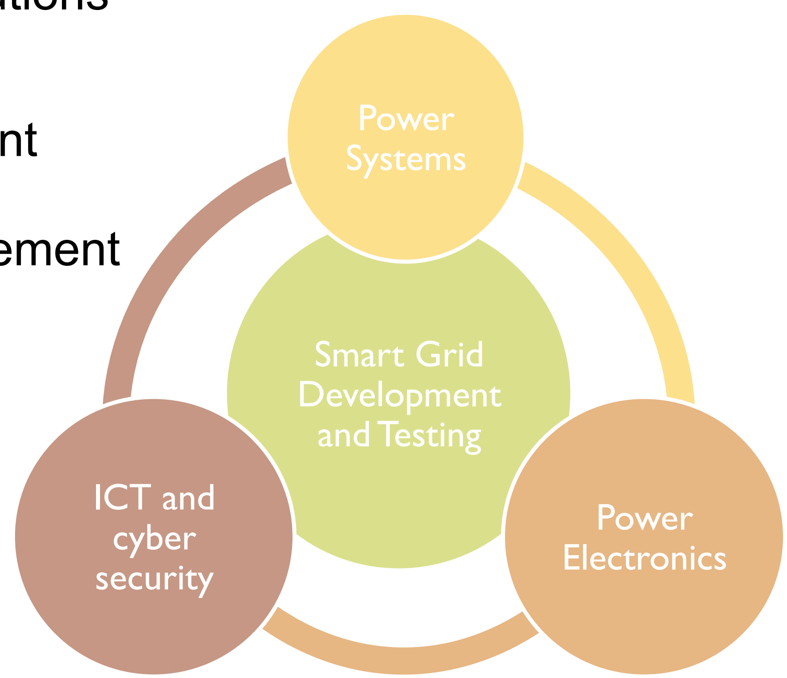
  (Portuguese funding – Innovation Fund from the Ministry of economics)

  - **Main goals and achievements**:
    - Study, **develop and test of technical solutions and pre-industrial prototype**s for the active and **intelligent management of electricity grids** with large scale integration of **microgeneration and electric vehicles**.
    - Develop a technical platform which:
      - is able to identify and quantify the benefits of a progressive deployment of EV and microgeneration technologies.
      - includes innovative control solutions for microgeneration and EV systems.
    - **Development of a laboratorial infrastructure – The MG and EV laboratory.**
    - Support industrial partners in order to deploy the technologies and products resulting from the concepts and prototypes developed.
    - To propose a regulatory framework capable of:
      - integrating EV users in a fair and non-discriminatory way,
      - deal with the additional investments in the network control and management structures in order to reliably accommodate a large number of EV.

3. Smart Grids and Electric Vehicles Laboratory

a) Main Objectives

- Development and testing of prototypes
- Development and testing of control devices and integrated management solutions
- Development of tests of communication solutions for smart metering infrastructures
- Testing EV batteries control and management
- Testing microgeneration control and management solutions
- Testing Active Demand Response and home area networks
- Developing and testing stationary storage and its control solutions for Smart Grids



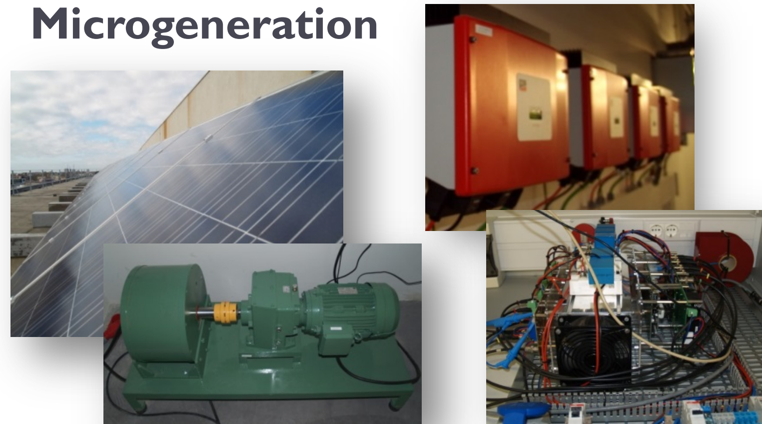
3. Smart Grids and Electric Vehicles Laboratory
b) Infrastructure

Storage

128 Lithium battery cells

25 kWh capacity Flooded Lead-Acid (FLA) and Sunny Islands inverters

Microgeneration



3kW wind micro-turbine and 15 kWp PV panels

Advanced metering and communication infrastructure

Electric Mobility

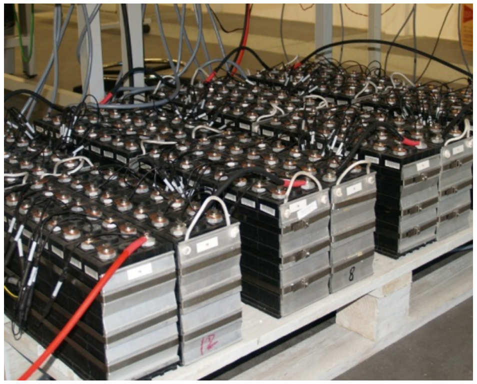
INESCTEC

Electric infrastructure:

- Renewable based microgeneration
- Storage
- Resistive load bank – 54 kW
- LV cables emulators (50 A and 100 A)
- Plug-in electric vehicles – Renault *Fluenze ZE and twizy*
- Microgeneration and EV power electronic interfaces
- Electric panel, command and measuring equipment

15 kWp photovoltaic panels

25 kWh capacity Flooded Lead-Acid (FLA)



128 Lithium battery cells

3 kW wind micro-turbine

3. Smart Grids and Electric Vehicles Laboratory
b) Infrastructure

Commercial DC/AC microgeneration inverters

The two 25 kW FLA battery bank are connected to two three-phase groups of grid forming inverters – SMA Sunny Island inverters, enabling:

- Testing MG islanding operation.
- The inverters provide the voltage and frequency reference to the isolated system, based on P-f and Q-V droops.

The PV and wind turbine emulator can be coupled to the network through:

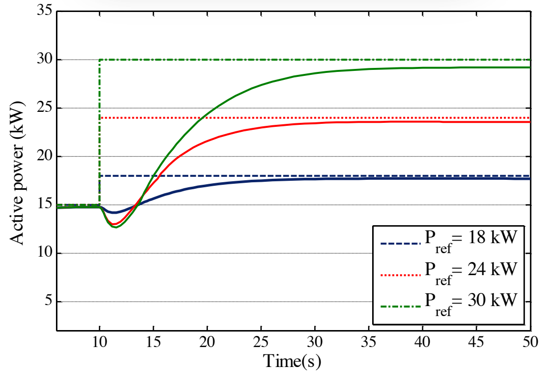
- Three DC/AC SMA Sunny Boy Inverters with 1.7 kW nominal power.
- DC /AC SMA Windy Boy Inverter with 1.7 kW nominal power.

The main objective is to explore the microgeneration commercial solutions and study potential limitations.

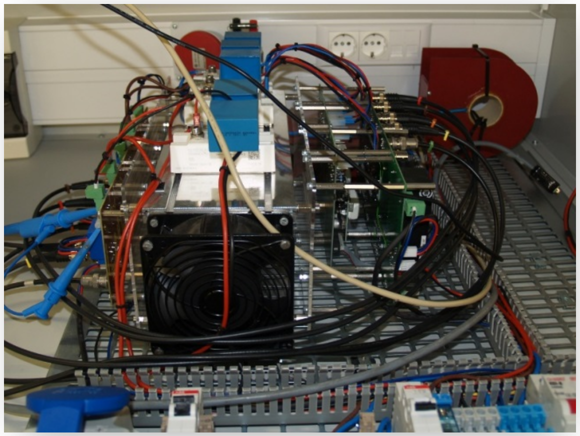
3. Smart Grids and Electric Vehicles Laboratory
b) Infrastructure

Controllable microgeneration emulator - 4 quadrant AC/DC/AC inverter

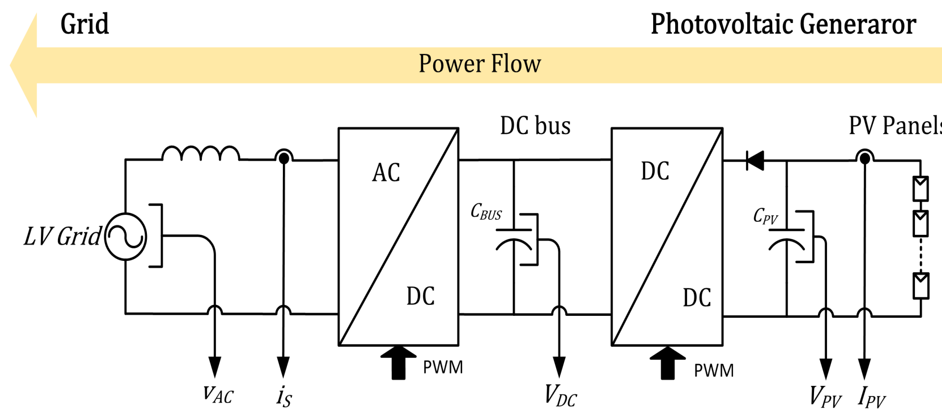
- The laboratory is equipped with a 20 kW three-phase AC/DC/AC custom-made four-quadrant inverter.
- The inverter power is controlled in order to emulate the response of controllable power sources such as Single-Shaft Microturbines or Fuel Cells.
- Enable the development and test of new frequency and voltage control strategies, in order to provide grid support during emergency conditions:
  - Microgrid islanded operation.
  - Microgrid restoration procedure.

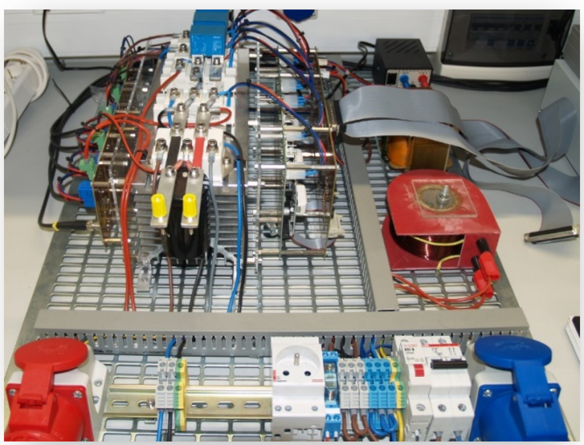


DC/AC microgeneration prototypes

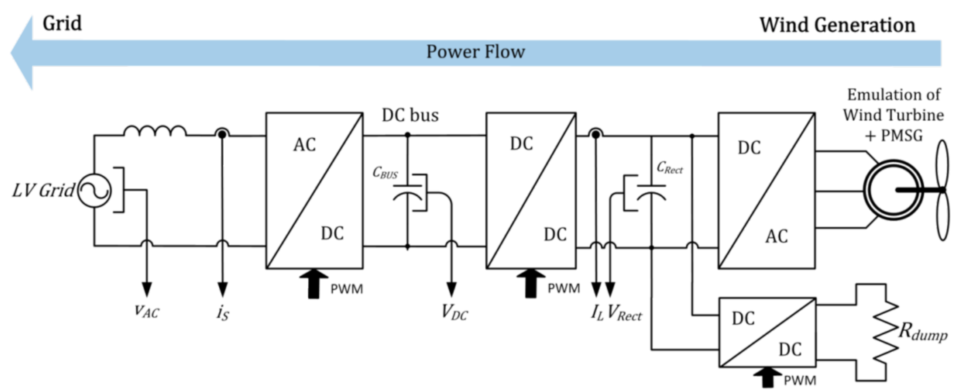


Solar DC/AC inverter prototype





Wind DC/AC inverter prototype



DC/AC microgeneration prototypes

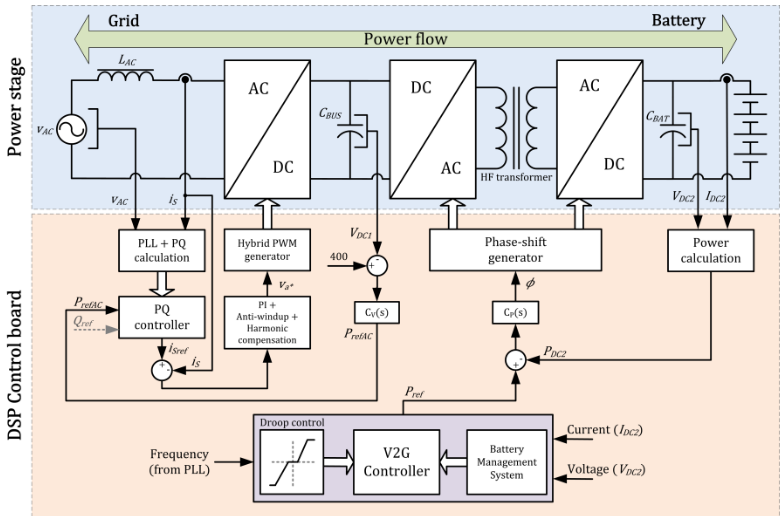
Main functionalities:

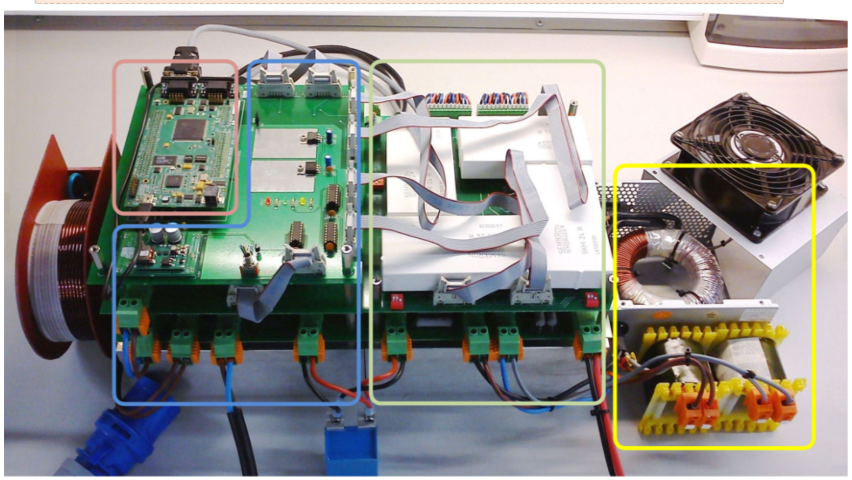
- Single-phase DC/AC inverters.
- Solar inverter with MPPT power adjustment.
- Active power control for voltage grid support.
- Bi-directional communication with the MGCC.
- Possibility of remote control.

Experimental Objectives:

- Development and Test of new voltage control strategies, in order to provide grid support.
- Integration of the new prototypes with the smart grid control and management architecture.

Bidirectional EV charger prototype



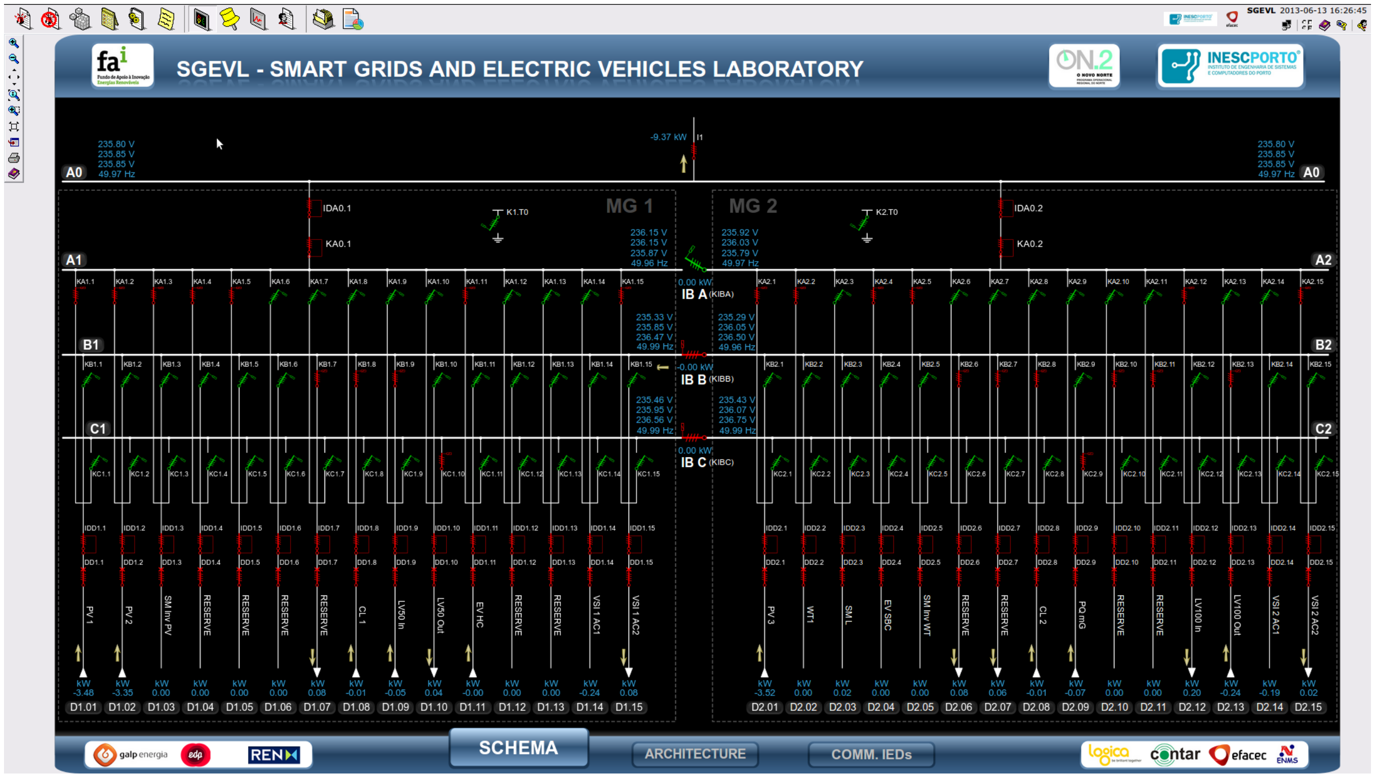


DSP Control Board | Full-Bridge Inverter | Dual Active Bridge | HF Transformer

- A 3.6 kW single-phase bi-directional DC/AC inverter prototype is connected to the lithium battery bank.
- The charging rate can be controlled in order to provide grid supporting functionalities.
- Smart charging and V2G capabilities.
- Bi-directional communication with the MGCC.
- Possibility of remote control.

3. Smart Grids and Electric Vehicles Laboratory
b) Infrastructure

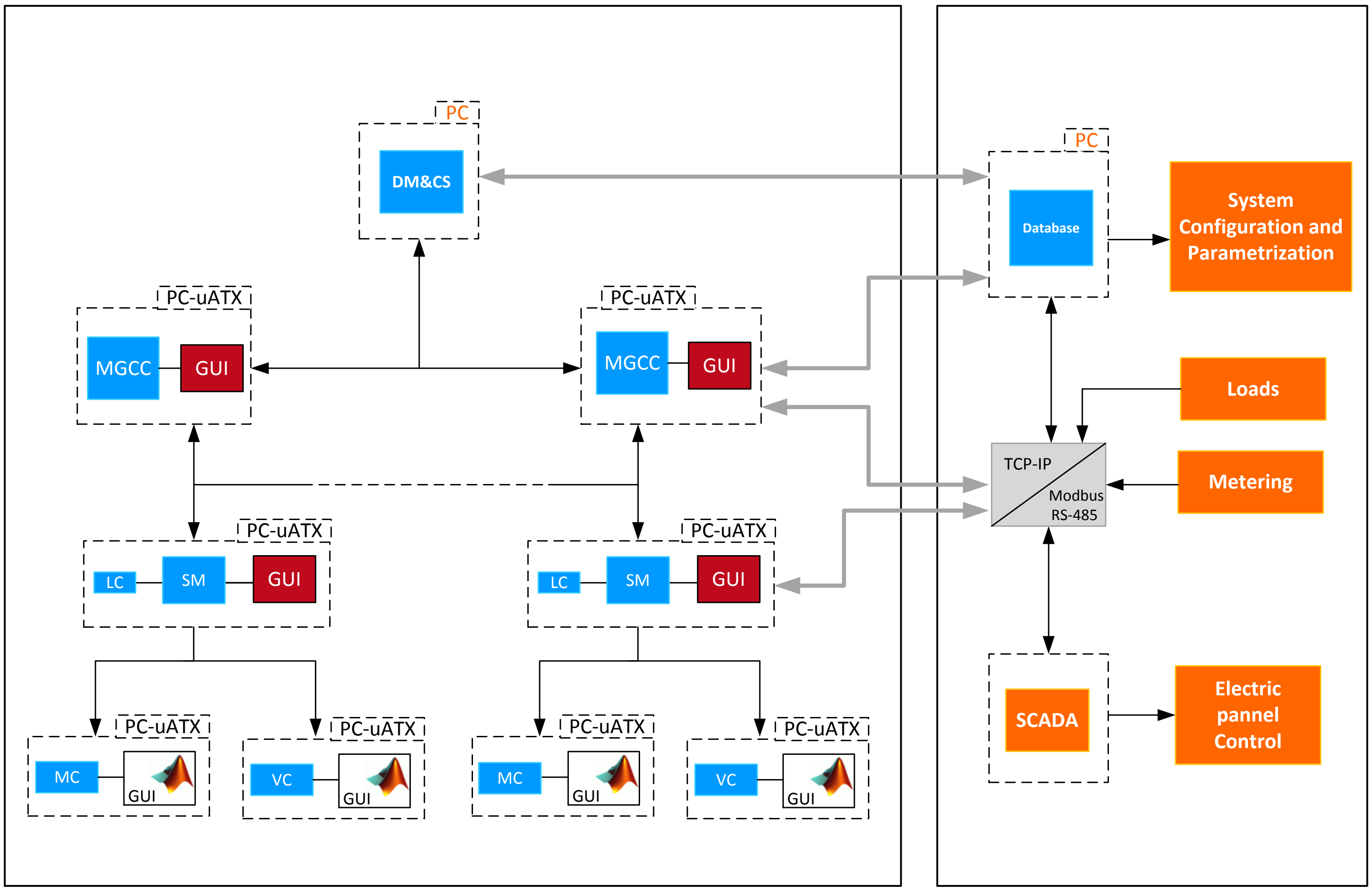
Electric panel - Command and data acquisition infrastructure



- Six 400 V busbars and thirty feeders commanded through contactors.
- Busbars interconnecting switches.
- Feeders equipped with a metering equipment.
- SCADA system to support the laboratory operation and monitoring.

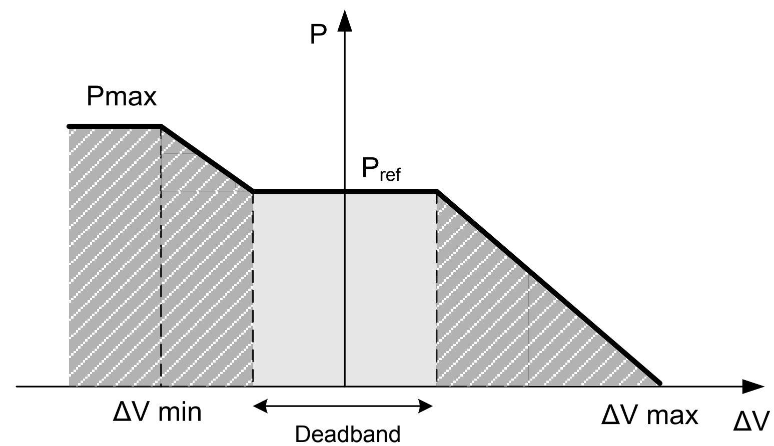
3. Smart Grids and Electric Vehicles Laboratory
b) Infrastructure

MG control and communication architecture



Microgeneration grid supporting functionalities

- Microgeneration prototypes are locally controlled through active power – voltage droop:
  - Provide voltage support to the LV network due to low X/R ratio.
  - Avoids microgeneration overvoltage tripping.



Control Rule:

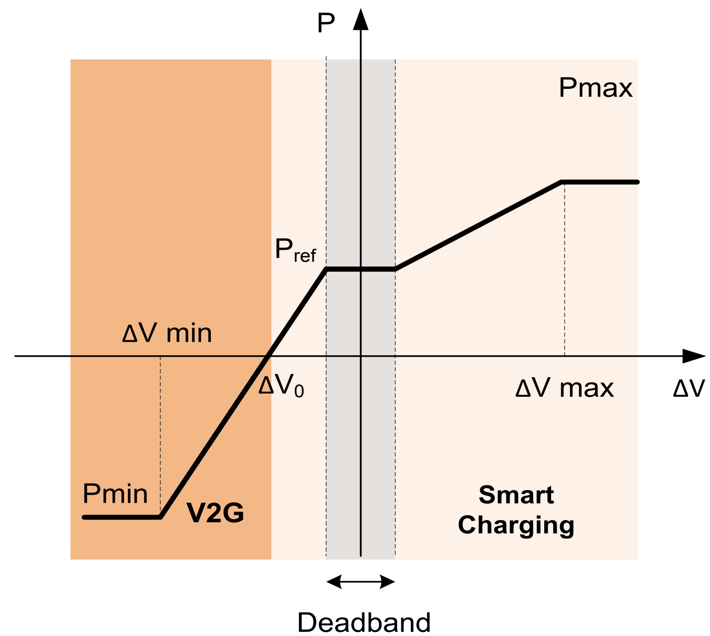
- Voltage **within** pre-defined limits → The unit **maintains** its reference power
- Voltage **rises** above the dead-band → Automatic **reduction** of the injected power
- Voltage **drops** below the dead-band → Automatic **increase** of power (limited to the maximum power that can be extracted from the primary source)

3. Smart Grids and Electric Vehicles Laboratory

c) Control Functionalities

EV grid supporting functionalities

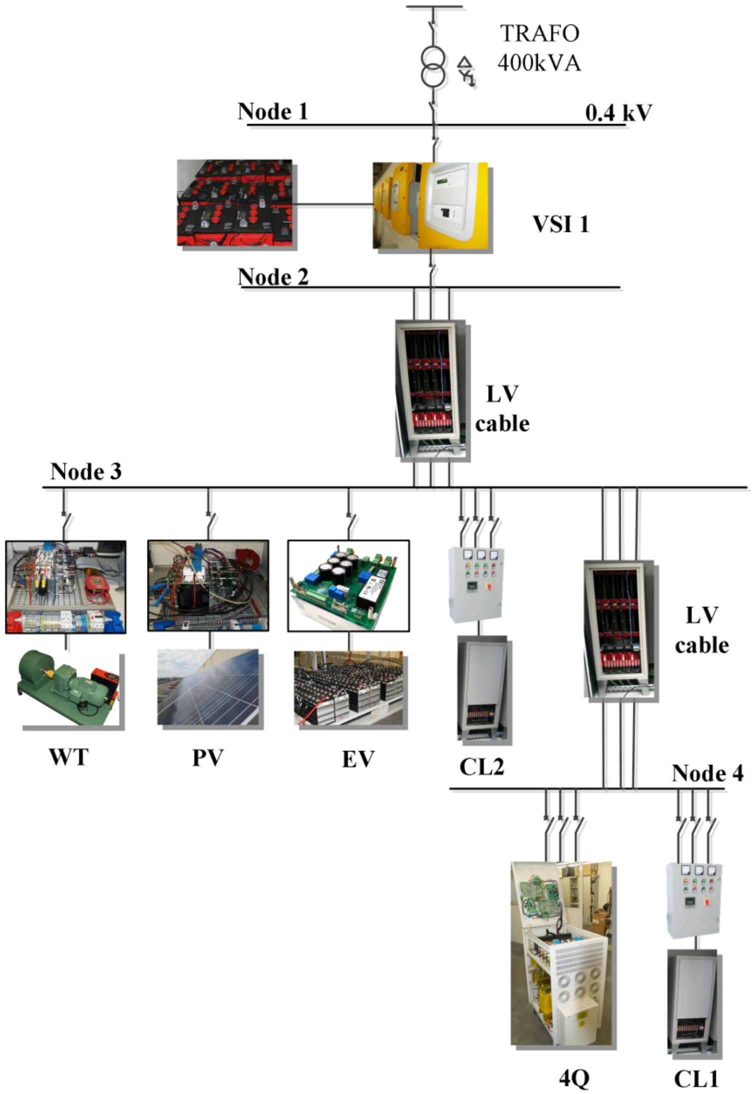
- The EV bidirectional charger prototype is locally controlled in terms of active power:
  - Provide **voltage support** to the LV network due to low X/R ratio.
  - Participate in the MG **frequency regulation** in emergency conditions.



Control Rule:

- Voltage/ Frequency **within** dead-band → The EV maintains its reference charging power
- Voltage / Frequency **rises** above the dead-band → Automatic increase of the EV charging power
- Voltage / Frequency **drops** below the dead-band → Autonomous decrease of the EV charging power or even power injection to the grid – V2G.

3. Smart Grids and Electric Vehicles Laboratory
d) Experimental tests



Test system configuration:

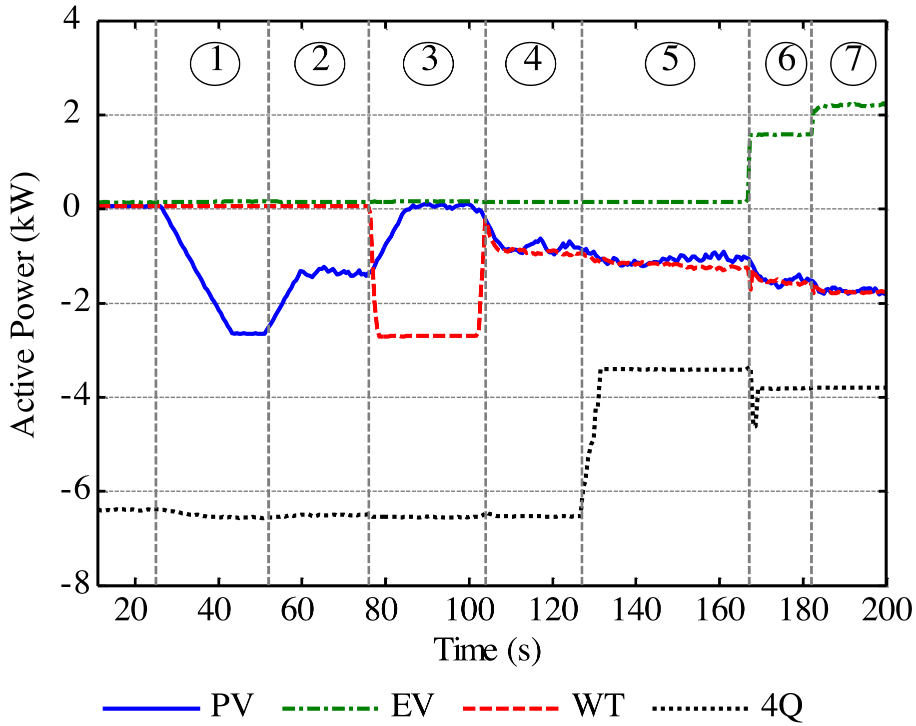
- Two PV strings connected to a DC/AC solar power converter prototype.
- The wind-turbine emulator.
- EV charger prototype.
- 52 kW resistive bank.
- MG node is interconnected to the main grid through a 100A LV cable emulator, which has a 0.6 Ω resistance.
- 20 kW four quadrant AC/DC/AC inverter

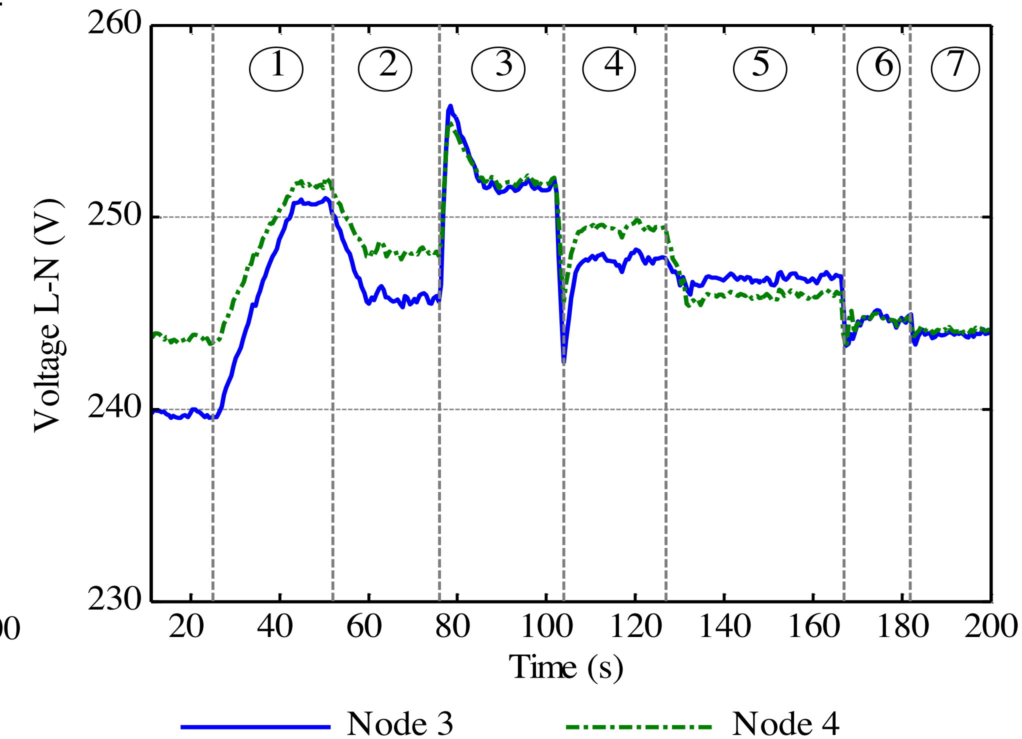
Experimental tests:

- **Interconnected mode of operation**
  – Test voltage regulation strategies.

d) Experimental tests

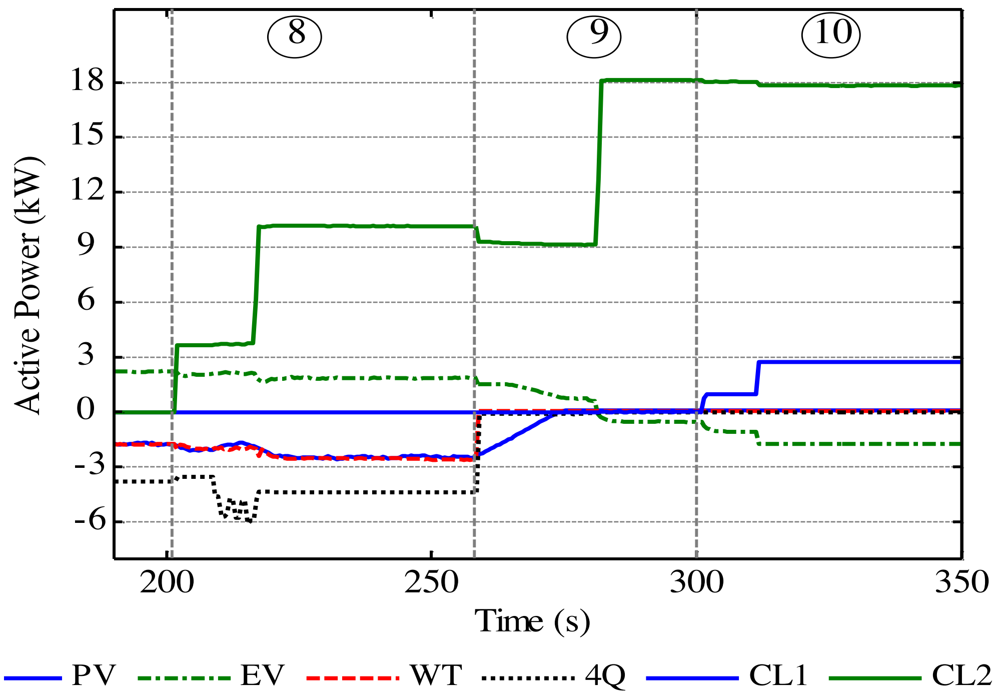
Interconnected Mode of Operation

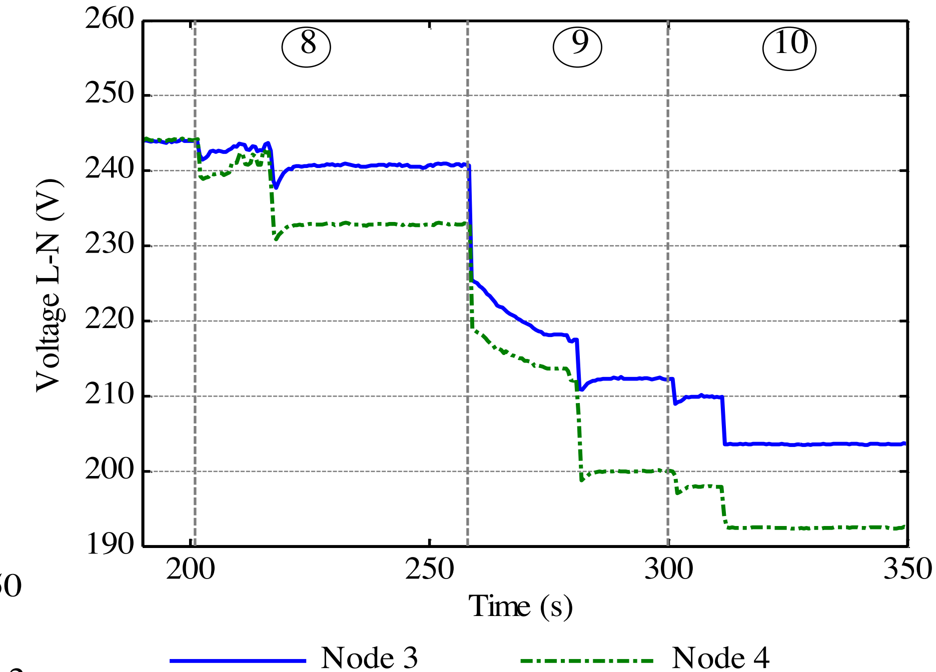




- High integration of μG at off-peak hours may cause overvoltage problems (1-5).
- Adopting droop based strategies enables local active power control in order to reduce voltage in problematic nodes (2,4-5).
- Coordination between μG and EV is achieved through droop strategies also avoiding wasting RE (6,7).

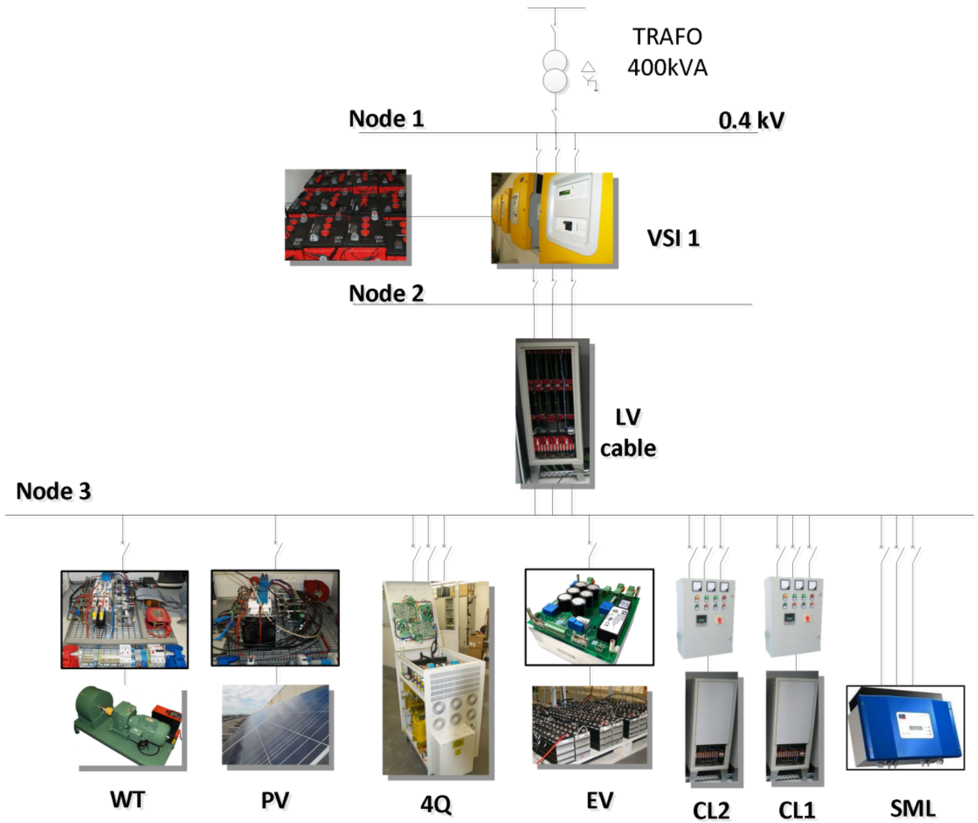
Interconnected Mode of Operation





- EV may also contribute to avoid undervoltage problems through P-V droop strategy (9,10)
- For larger voltage disturbances the EV storage capacity can also contribute to ensure adequate voltage levels (10).

3. Smart Grids and Electric Vehicles Laboratory
d) Experimental tests



<u>Test system configuration</u>:

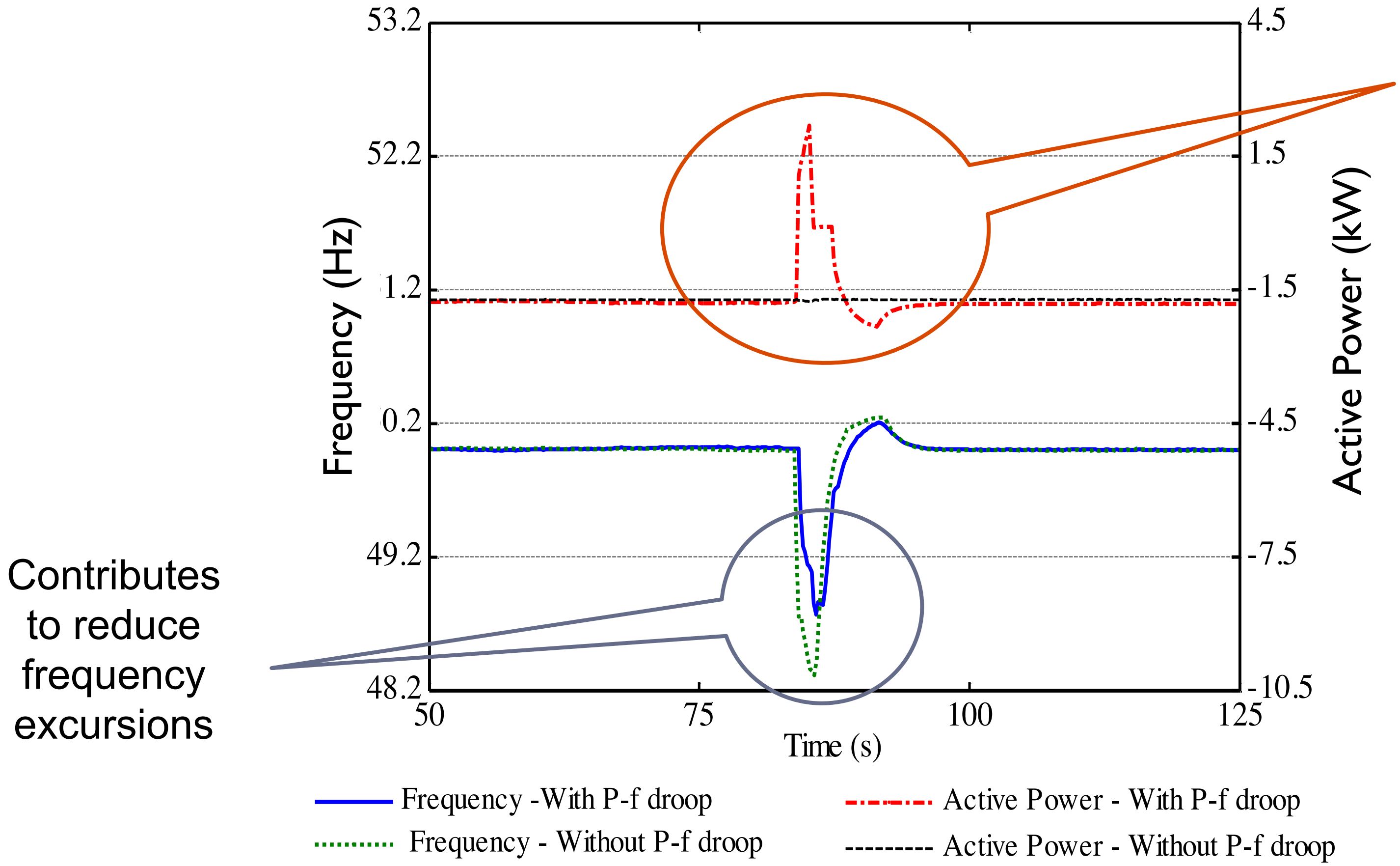
- Two PV strings connected to a DC/AC solar power converter prototype.
- The wind-turbine emulator.
- EV charger prototype.
- 52 kW resistive bank.
- MG node is interconnected to the main grid through a 100A LV cable emulator, which has a 0.6 Ω resistance.
- Four quadrant AC/DC/AC inverter

<u>Experimental tests</u>:

- **Islanded mode of operation** – Test frequency regulation strategies:
  - Primary frequency control
  - Secondary frequency control
  - Load Control

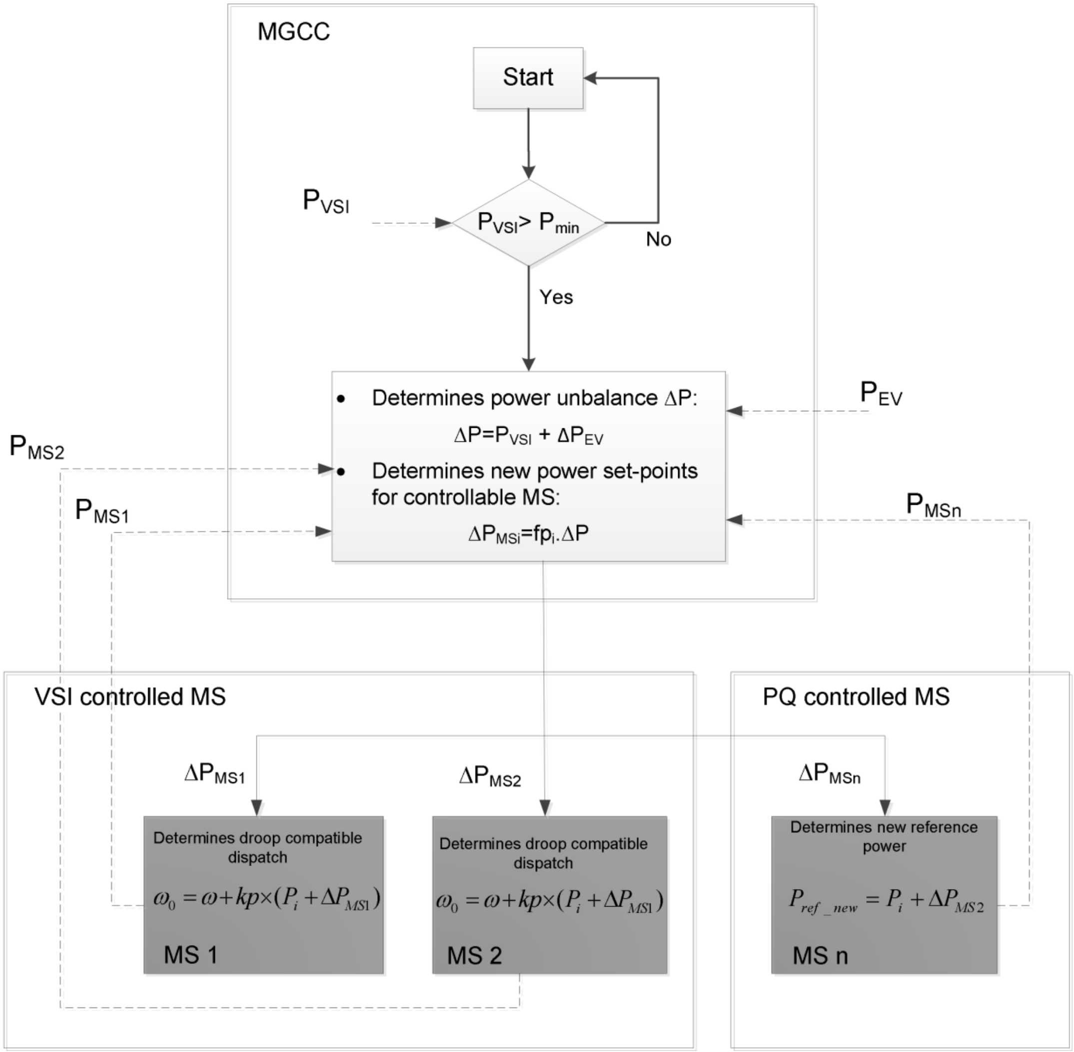
d) Experimental tests

Islanded Mode of Operation



MG frequency and EV active power response during MG islanding

Implementation of Central Secondary control strategy

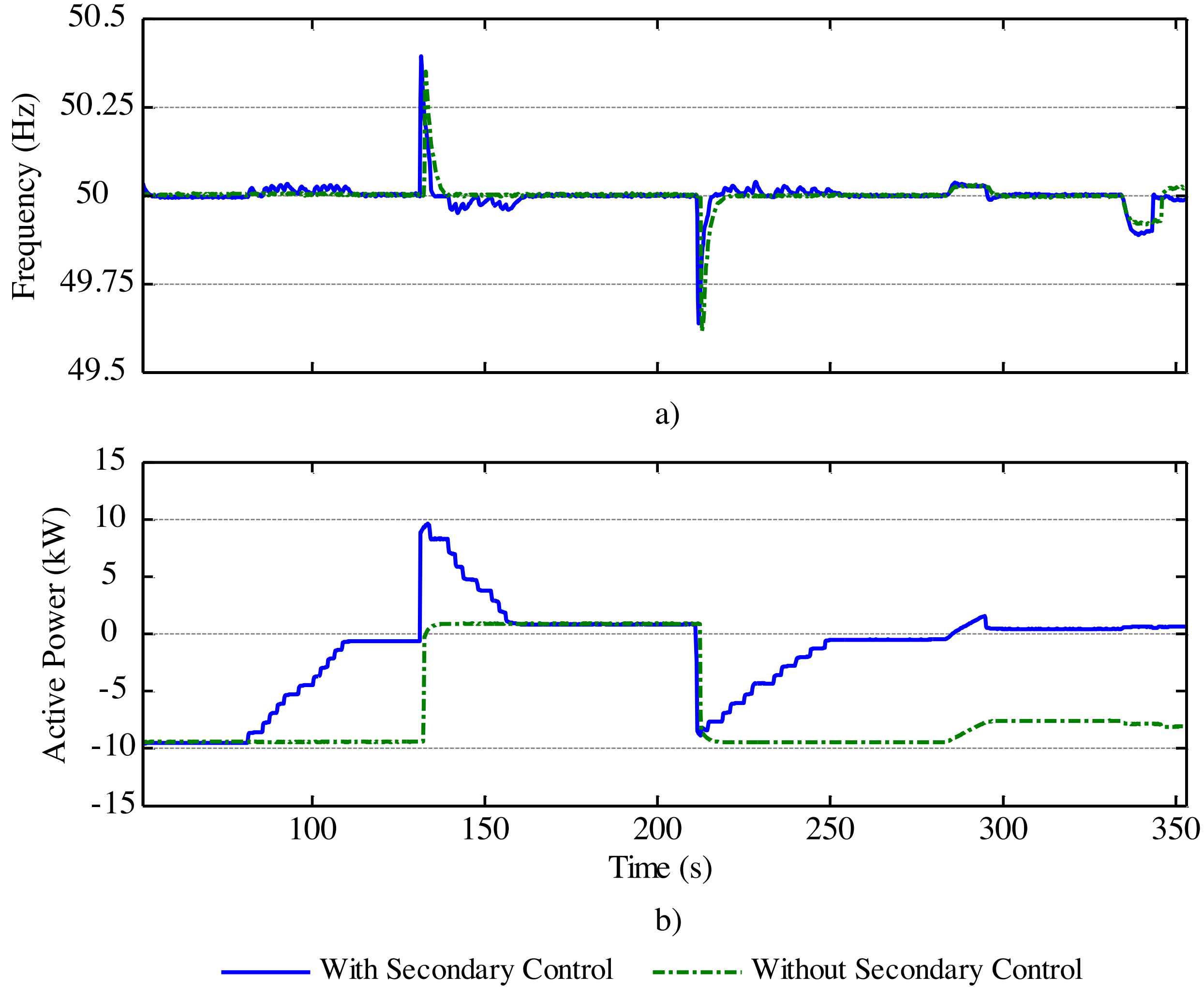


Power set-points determined based on reserve capacity (R)

$$\begin{cases} fp_i = \dfrac{R_i}{R} \\ \Delta P_{MS_i} = \Delta P \times fp_i \\ \sum_{i=1}^{n} \Delta PMS_i = \Delta P \end{cases}$$

- Runs at the MGCC
- Coordination PQ and VSI µG inverters.

Islanded Mode of Operation – MG storage response to secondary frequency control



3. Smart Grids and Electric Vehicles Laboratory

d) Experimental tests

INESCTEC

Implementation of coordinated emergency load control

Characterize the MG operating state

The algorithm determines:

- MG storage capacity
- Microgeneration reserve capacity
- Imported/ Exported power

↓

Determine the severity of the disturbance

Power unbalance resulting from:

$$\Delta P_{shed} = R - P_{unbalance}$$

↓

Determine the amount of load to shed

In case the MG **does not have enough reserve capacity**, the algorithm **activates selective load shedding scheme**

↓

Evaluate the MG security during islanded operation

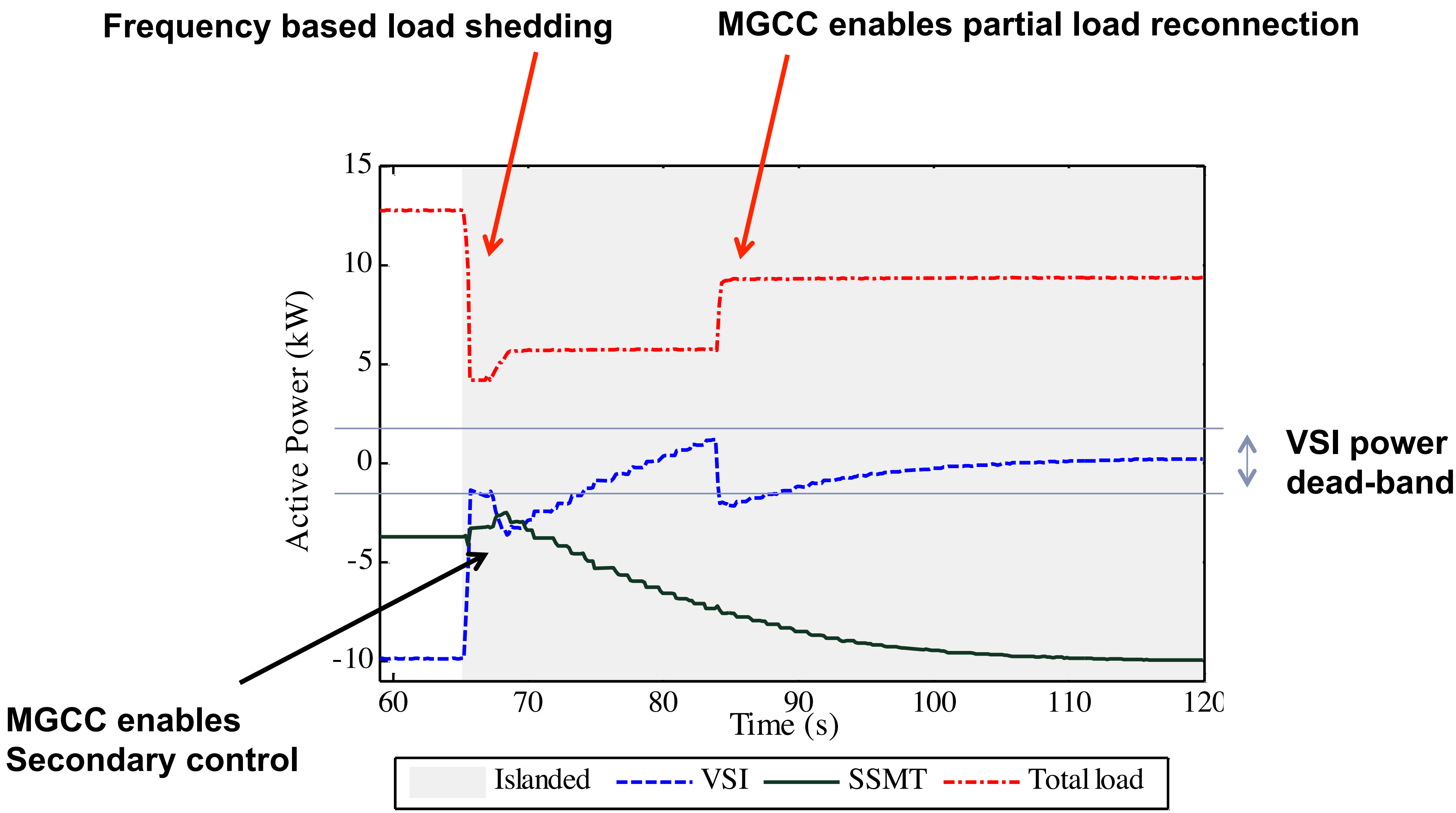
The algorithm evaluates:

- MG has enough **storage capacity** to support the disturbance.
- If **frequency** remains within admissible limits

→ **Temporary load shedding**

3. Smart Grids and Electric Vehicles Laboratory

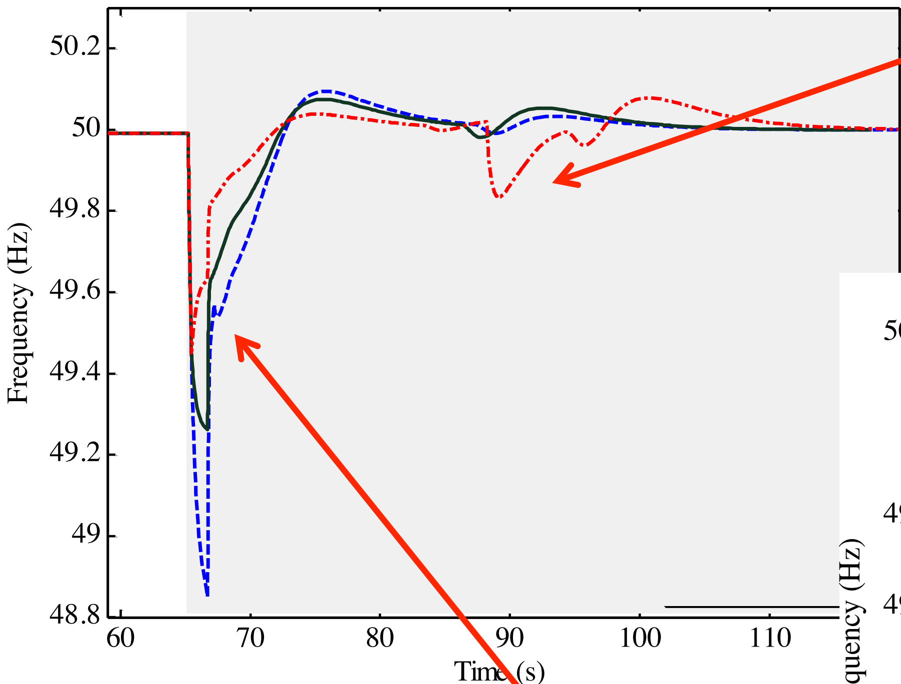
d) Experimental tests



3. Smart Grids and Electric Vehicles Laboratory

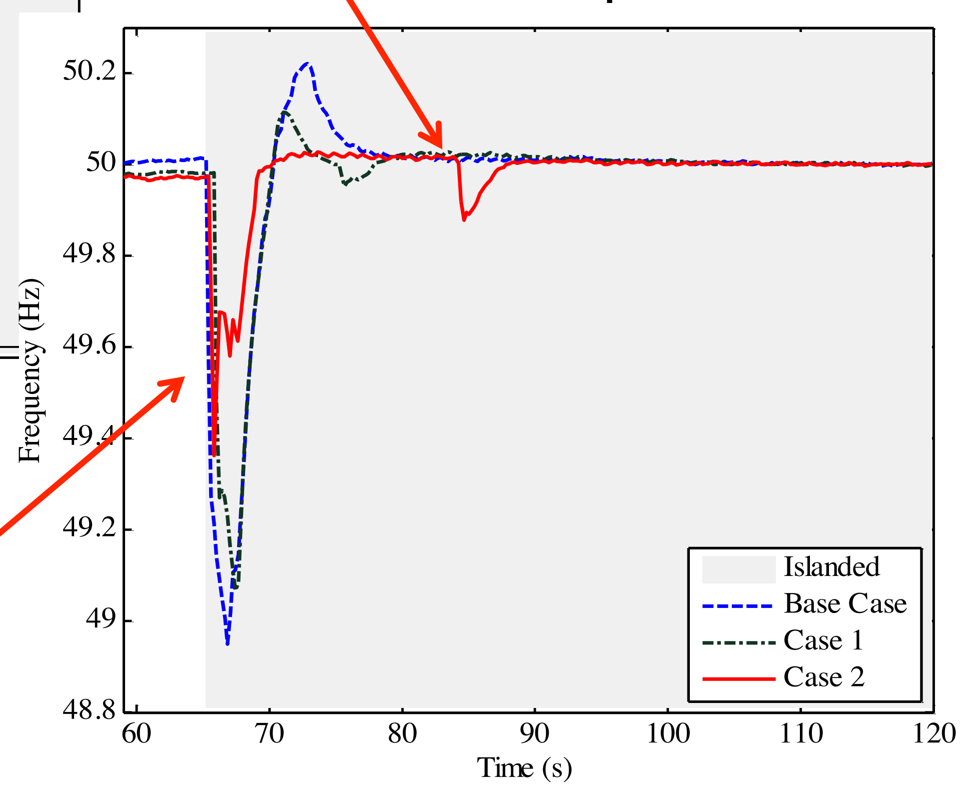
d) Experimental tests

MGCC enables partial load reconnection



Simulation results

Experimental Results



Frequency based load shedding

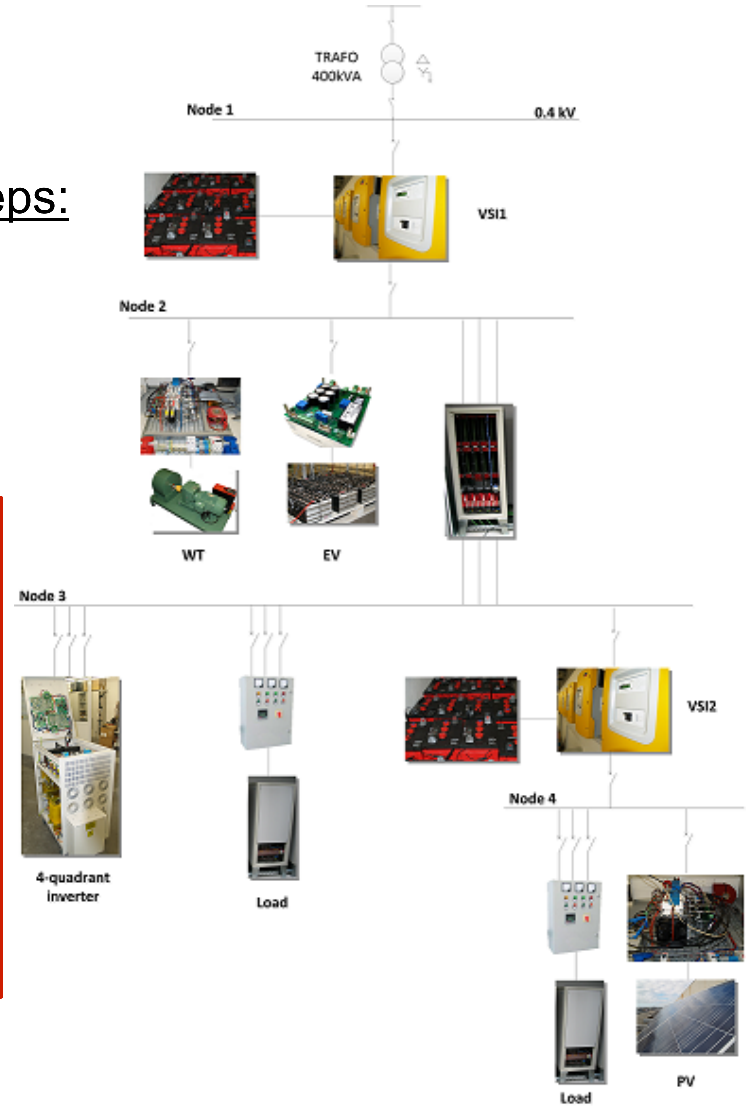
3. Smart Grids and Electric Vehicles Laboratory

d) Experimental tests

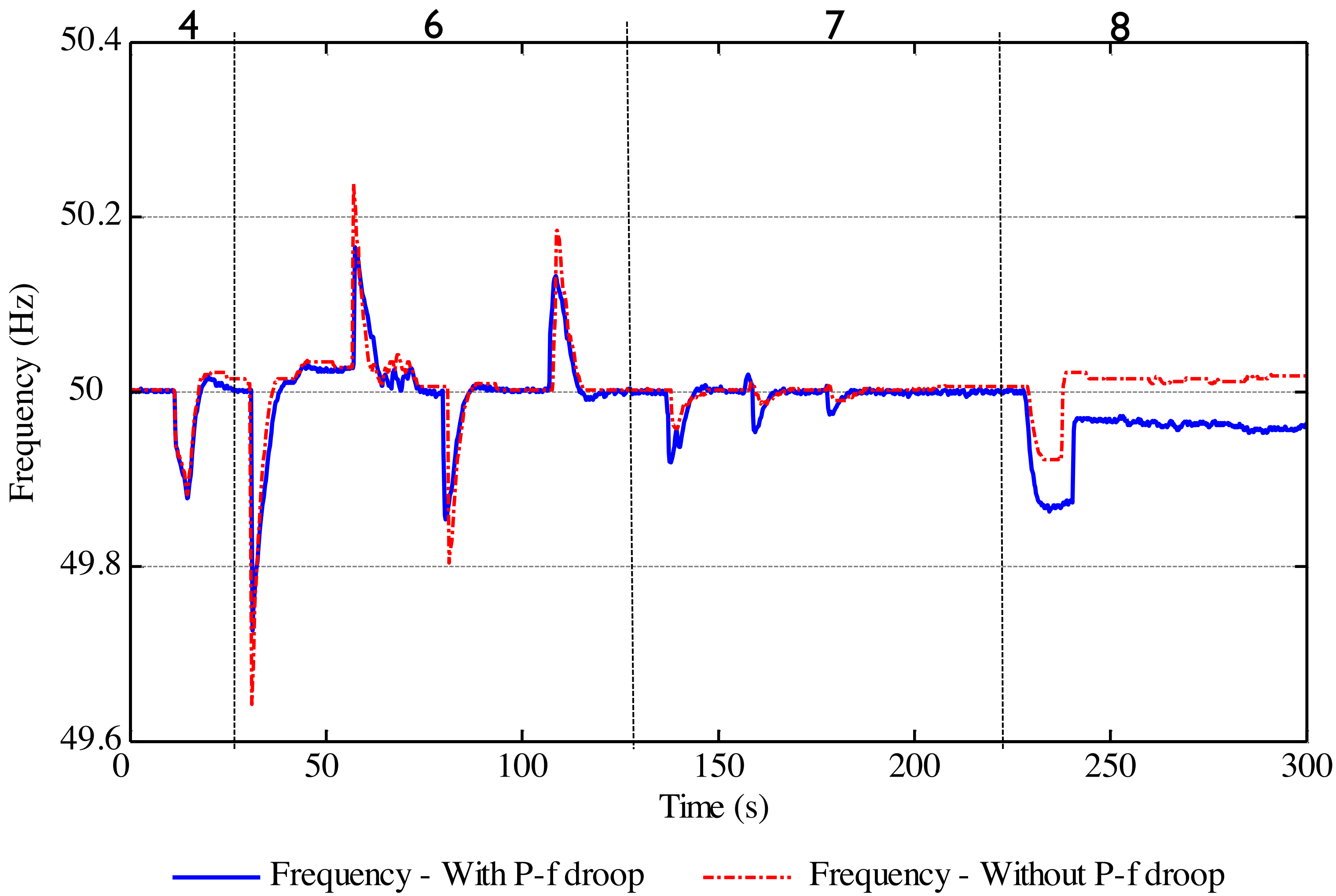
➢ <u>MG Blackstart</u>

The procedure is constituted by the following steps:

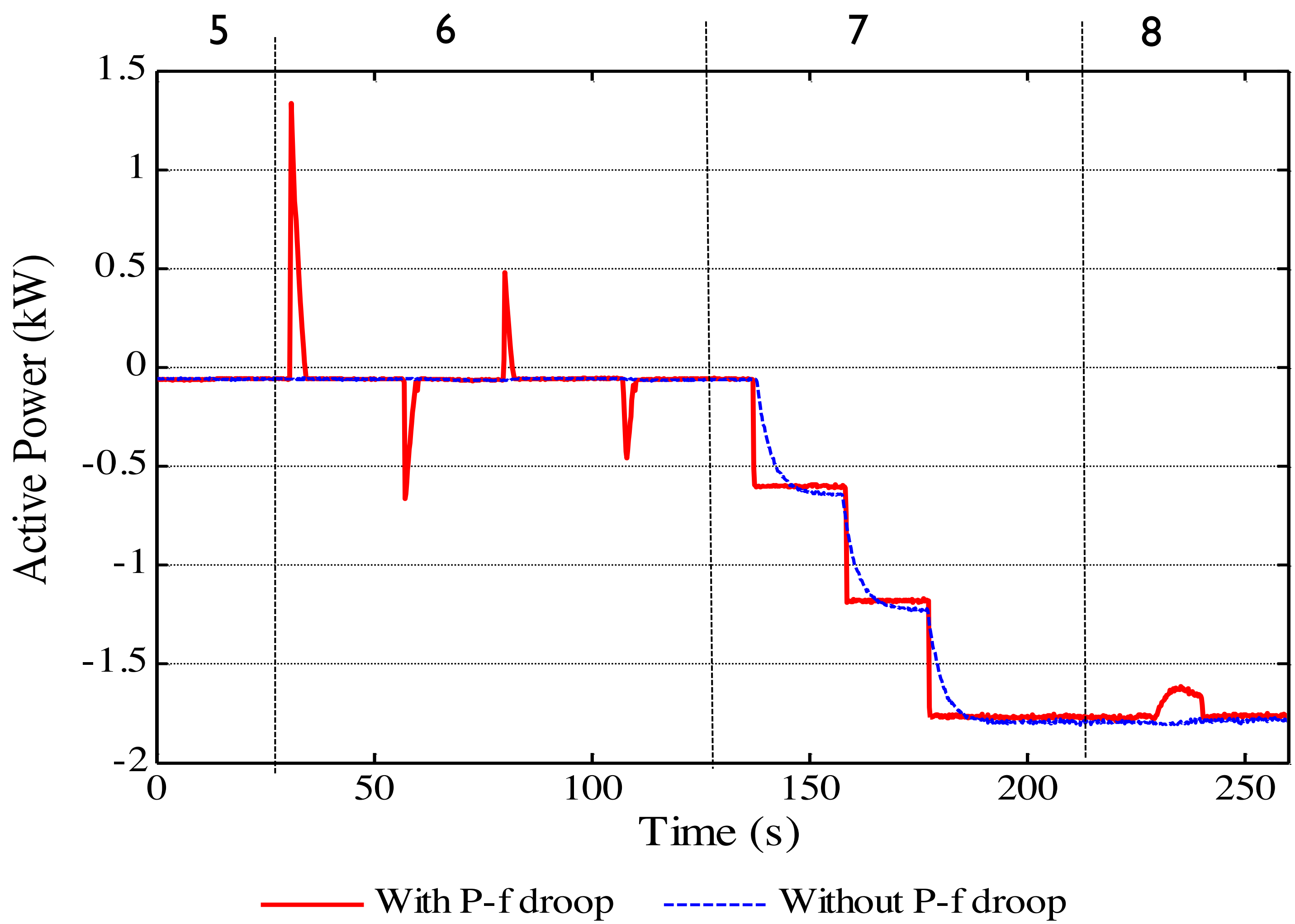
1. MG status determination
2. MG preparation
3. MG energization
4. Synchronization of the running MS to the MG
5. Connection of EV
6. Coordinated reconnection of loads and non-controllable MS
7. Enable EV charging
8. MG synchronization with the main grid



BlackStart Procedure – MG frequency



BlackStart Procedure – EV power response



e) Conclusions

- **MG voltage regulation capabilities**
  - P-V droop strategy is able to **maintain the voltage within admissible limits**, **avoiding overvoltage tripping** of the microgeneration units.
  - When having more than one microgeneration unit controlled with P-V droop, they are able to **share the voltage disturbance** without relying in complex communication infrastructures.
  - The **coordination of microgeneration and EV charging** increases the system efficiency, while maintaining voltage within admissible limits.
  - From the consumers perspective it will reduce its power consumption and **maximize the use of its microgeneration installed capacity**.
- **MG frequency regulation capability**
  - The participation of EV in the MG frequency regulation can **reduce the unbalance between the generation and load** within the islanded system.
  - This will enable a more **efficient management of the MG storage capacity**.

3. Smart Grids and Electric Vehicles Laboratory
e) Conclusions

- The industrial development of smart grid related products enhances the **importance of experimental demonstration facilities**.

- **The MG and EV laboratory plays a key role in the consolidation of innovative solutions for the development of smart grid**:

  - Development of **microgeneration and EV grid-coupling inverter prototypes** incorporating innovative control strategies.

  - **Local control strategies** provide to system operators **additional operation resources**, in order to deal with the **crescent integration of DER resources and EV**.

  - Local control strategies are also complemented by advanced **MG controllers** to be installed at the consumers premises – the **Energy Box** and at the MV/LV substations, the **MGCC**.

  - Higher control levels will be responsible for coordinating the devices installed in the field: Loads, EV, microgeneration and storage.

3. Smart Grids and Electric Vehicles Laboratory

f) Future Work

- Conceptualization of innovative SCADA / DMS systems for low-level grid control, based on Microgrid management and control functionalities.

- Development and testing of active demand side management solutions involving the definition of in house functionalities, ancillary services provision and remuneration schemes.

- Development and testing of Microgeneration, DG and EV control and management tools.

- Development of advanced forecasting tools for EV and PV based microgeneration.

- Developing and testing stationary storage and its control solutions for Smart Grids