



INESC TEC is devoted to science and technology, development and independent consulting, with a vast international experience.

INESC TEC

Smart Grid and Electric Vehicle Lab

The area of power and energy is an example of the capacity at INESC TEC to conduct multi-disciplinary projects and guarantee high quality in a professional stand.

The smart grid is the concept that guides the development of network technology and operation in the coming years – and the integration of electric vehicles, likely to happen in a large scale in the future, demands that smart solutions be idealized, developed and tested.

The expertise of INESC TEC in these areas is supported by an advanced laboratory facility wholly specified by the INESC TEC team.

September 2013



INESCTEC
TECNOLOGIA E CIÊNCIA
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INESCTEC smart grid and electric vehicle lab

document describing the main features of the Smart Grid
and Electric Vehicle Laboratory, developed by

INESC Technology and Science, Associate Laboratory

with identification of the main architecture, functions and
organization

INESC TEC USE version 1.0 September 2013

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INESC TEC smart grid and electric vehicle laboratory

I. WHAT IS INESC TEC

INESC Technology and Science (or **INESC TEC**) is an Associate Laboratory recognised as Excellent by the Ministry of Education and Science in Portugal. This is the highest level of recognition awarded for Science and Technology in Portugal.

INESC TEC is coordinated by the Institute for Systems and Computer Engineering of Porto (INESC Porto), a private and independent non-profit association, a Public Interest Institution with over 25 years of experience in fundamental and applied science and cooperation with industry. INESC Porto is also recognised as a Technological Infrastructure by the Ministry of the Economy in Portugal. INESC Porto's associates include the University of Porto (Faculties of Engineering, Sciences and Economy) INESC (based in Lisbon) and the Polytechnic Institute of Porto (namely the Higher Education Institute of Engineering in Porto). The Universities of Minho and UTAD are also privileged partners.

As illustrated in the figure below, identifying the areas of specialisation organized in four clusters, INESC TEC incorporates 12 Units in total and brings together close to 600 collaborators and 200 PhD holders. INESC TEC manages an annual budget of around 15 million Euros and its main source of income and projects comes from contracts with companies, followed by European and national projects from programmes offered by the European Union or the Portuguese government.

As an institute that works as an interface between universities and industry, **INESC TEC** develops activities that begin with the generation of knowledge and conclude with technology transfer and valorisation. The institute's structure follows the metaphor for a production chain of knowledge-value and extends the action of conducting fundamental science and developing prototypes, carrying it through to the launching of spin-off companies and the provision of advanced international consultancy services.

In order to do this, the institute combines the creative capacity and concrete knowledge of its academic researchers with a strongly professional approach to the problems and projects it is involved in, thanks to its body of permanent specialists.

As a result of its reputation as an independent, impartial and trustworthy institution, **INESC TEC** has provided international consultancy services in four different continents: Europe, North America, South America, (particularly in Brazil) and Africa.

INESC TEC also participates in training and advanced training programmes, particularly for doctoral students, in partnership with prestigious universities, such as MIT Carnegie Mellon and the University of Texas at Austin.

INESC TEC's activity covers multiple areas and can be applied in various markets, for example, Telecommunications, Health, Industry, Services and Public Administration.

The following sections present a succinct summary of the activities and experience of **INESC TEC** in the specific topic of **wind power modeling and solutions**.

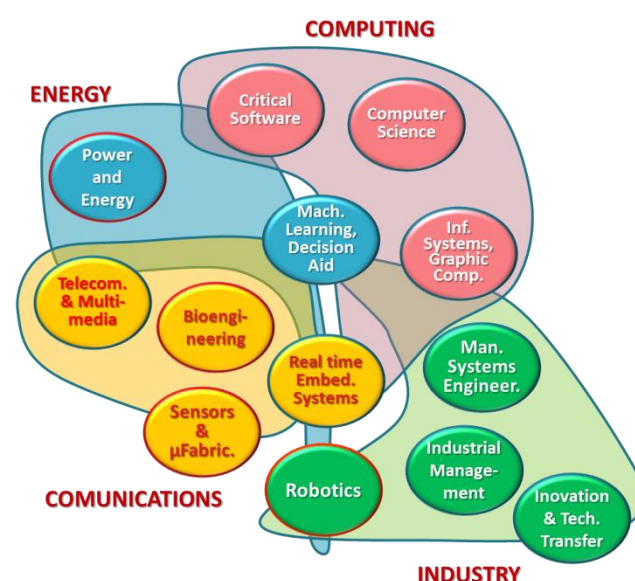


Figure 1. INESC TEC R&D Units and four clusters: Computing, Energy, Communications and Industry.

II. THE POWER SYSTEMS UNIT

The **Power Systems Unit (USE)** is **INESC TEC's** main actor in the area of electrical energy. The Unit employs close to 70 collaborators, including 16 PhD holders. It is internationally recognised for its expertise in problems relating to the integration of wind power and renewable energy in general in power systems. USE is also recognised in the areas of distributed generation and smart grids, areas traditionally associated with planning and operating power systems and designing and developing software for dispatch and control centres.

This high level of expertise has allowed specialists at **USE** to take on key roles in important European Union projects as part of the successive framework programmes that led to notable scientific and technical advances with considerable impact on industry. Furthermore, this recognition of the Unit's capabilities has led to contracts for development and consultancy with companies manufacturing equipment, generation, transmission and distribution companies, regulators, government agencies and investors. These activities have been developed in Europe, South America (particularly Brazil), the United States of America and Africa (particularly in Portuguese-speaking African countries).

INESC TEC's enhanced competencies in this area not only come from its high level of professionalism in its work but also from its globally recognised elevated level of science. **INESC TEC's** collaborators include various specialists that are IEEE Fellows and its teams regularly publish works in the most highly regarded international scientific publications. These specialists have contributed to various different areas, helping to advance knowledge and techniques with ideas, methods and algorithms which have later been adopted by industry.

The areas in which the Unit has advanced expertise and both works in and offers consultancy in are:

- Network and control centre management
- Forecasting power generation and characterising consumption
- Isolated systems
- Integrating renewable energy into large-scale systems

- Markets and regulation
- Microgrids, smart grids and electric vehicles
- Security and reliability

The Unit is also involved in advanced training for companies in the electricity sector through the EES-UETP European consortium. **INESC TEC** has run ELAB - the Luso-Afro-Brazilian Meeting for Energy, since 1991 which has brought together administrators, directors and technicians from all of the companies in the electricity sector in Portugal and Portuguese-speaking Africa as well as important companies and organisations in Brazil.

USE has fundamental calculating and simulation computational equipment and develops technical activities at its Smart Grids and Electric Vehicle laboratories.

USE's activity has resulted in the incubation of a spin-off company, PreWind, with participation from INESC Porto. This company provides wind power forecasting services for energy system generators and operators.

III. OTHER INESC TEC UNITS

Other R&D Units from **INESC TEC** contribute with knowledge and expertise to produce solutions to the wind power generation and integration problems.

The most important contributions come from UTM, the Telecommunications and Multimedia Unit, from USIG, the Information Systems and Graphic Computing Unit and from LIAAD, the Laboratory of Artificial Intelligence and Decision Aid.

These Units together with the Power Systems Unit contribute to the robust high-level capacity of **INESC TEC** to provide valuable service as well as integrated solutions to companies, regulators and government authorities. At the same time, **INESC TEC** remains a driver of innovative approaches, benefiting from scientific achievement and technical progress that characterize its action as an institution of excellence.

The following sections contain an abridged description of the Smart Grid and Electric Vehicle Laboratory at INESC TEC, one of the most advanced facilities in Europe in this area.

IV. INTRODUCTION TO THE SMART GRID CONCEPT

The vision of smart grids recommends a shift in the paradigm related to exploring distribution grids, following the large-scale integration of distributed generation, and in particular of micro-generation using active and integrated management on all exploration levels. In this context, the concepts of Microgrid (MG) and Multi-Microgrid (MMG) – developed respectively as part of European projects MICROGRIDS and MOREMICROGRIDS, where INESC TEC participated actively – play a fundamental role. This happens because these concepts assure a large-scale integration of micro-generation in Low Voltage (LV) distribution grids and a distributed generation in Medium Voltage (MV) grids, by providing an active and integrated control using storage systems and controllable charges.

If there is a local storage capacity, it is possible to explore these grids autonomously by integrating suitable control solutions, supported by communication solutions and by a progressive integration of distributed intelligence in the distribution grids. From this perspective, the integration of Electric Vehicles (EV) in the distribution grids is part of the solution as it provides added storage capacity, thus promoting the use of MG and MMG in emergency mode, operating in an isolated grid, thus contributing to improving quality of service. Furthermore, the added storage capacity can contribute locally to increase the integration of micro-generation, and globally to an increased integration of renewable sources in the electric power system with intermittency features, as is the case of solar and wind power.

In this context, the large-scale integration of EVs and micro-generation units, using renewable sources of energy, will have to be explored always seeking to avoid reinforcing grid infrastructures by adopting active control and management strategies for the existing resources. In that sense, the new operational vision of the distribution grid necessarily requires an intelligent management for the battery charging of the EVs and simultaneously their integration in the grid operation. This way it is possible to explore the added storage capacity to

supply system services.

The Laboratory of Micro-generation and Electric Vehicles was designed to support the development and testing of solutions and pre-industrial prototypes, promoting an active and intelligent management of electric grids in scenarios where there is a progressive integration of micro-generation units and EVs. The laboratory constitutes a physical space that integrates equipment and systems to assure that the distribution grid operates properly, both in normal and emergency modes. Simultaneously, the laboratory integrates EV battery charging strategies also involving the concept of Vehicle to Grid (V2G).

V. SMART GRIDS AND ELECTRIC VEHICLES LAB

In order to support the work related to the functional and technical specification of solutions and to the integration of micro-generation and EVs in a smart distribution grid, it is necessary to conduct a proof of concept and experimental validation. This way, the necessary conditions are created that make it possible to consolidate concepts, establishing solid connections, especially with industry, so that in the future it is possible to develop innovative solutions in this technological domain. The Laboratory of Micro-generation and Electric Vehicles integrates pre-prototyping processes for physical devices and/or software and equipment modules related to micro-generation and EVs. This physical space makes it possible to test, individually and in an integrated way, the concepts, decision process algorithms and communication protocols that will allow the distribution grid to operate in normal and emergency modes, as well as the concepts/procedures associated with the different charging/discharging of the EV batteries. Therefore, the main strategic goals of the laboratory are:

- Conducting postgraduate research in the domain of the integration of small micro-generation units in LV grids, involving the concept of microgrid and the associated control/operation functionalities.
- Developing postgraduate research in the domain of EV integration in the electric power distribution grid, and the respective connection equipment and control.

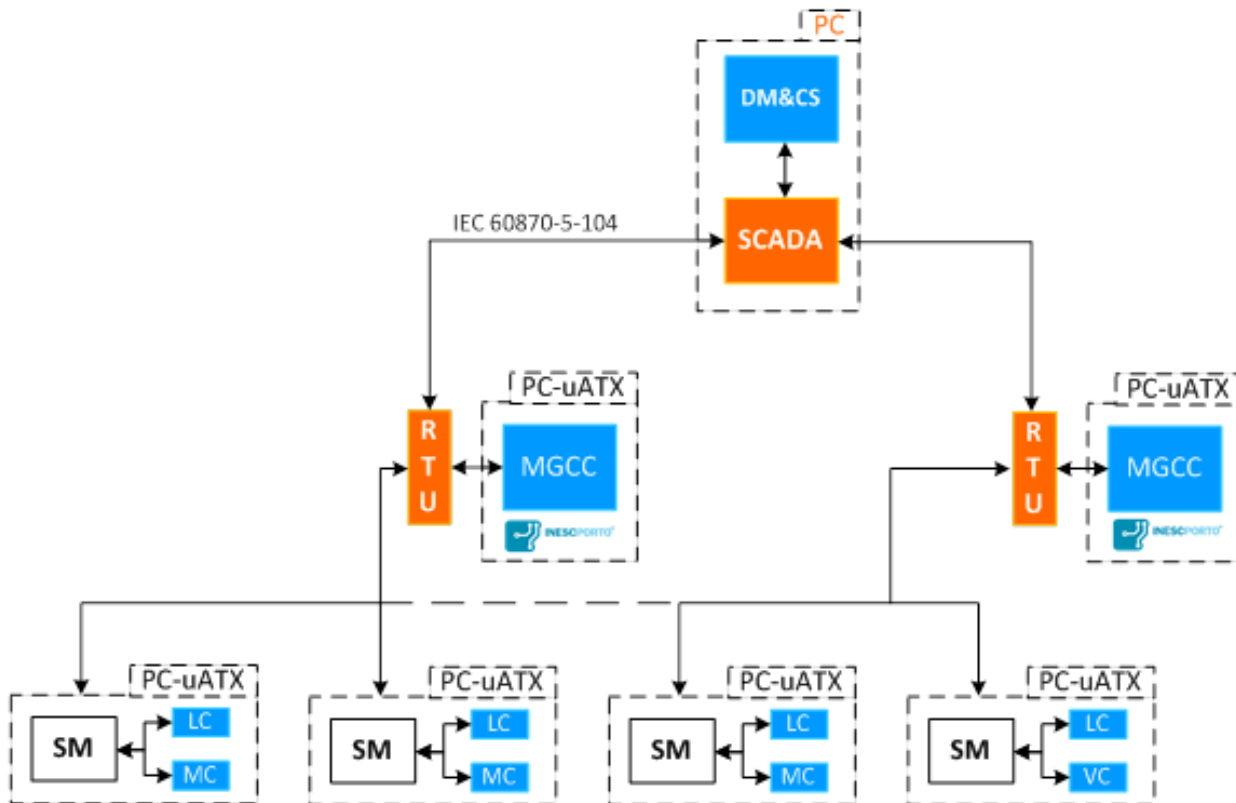


Figure 1. Diagram of the laboratory of smart grids and electric vehicles

- Consolidating the skills that support the transition from the current paradigm of power grids, aiming for a more decentralised operation paradigm with increasing levels of micro-generation and EV integration.
- Developing pre-prototypes for micro-generation systems and/or controllers and EVs that will make it possible to validate strategies/procedures that can be identified and validated in a simulation environment.
- Supporting national and international standardisation activities, by promoting an active participation in several international bodies such as the DERLab.
- Providing services to electric power suppliers in order to implement and consolidate the concept of microgrid.
- Providing services to micro-generation equipment manufacturing companies (such as converters, protection, control as well as communication systems).

- Transferring technology to the national industry, using the knowledge generated by developing pre-prototypes.

A. Implementing the laboratory

Taking into consideration the expansion requirements for the laboratory and its future evolution, the level of interaction/control with the equipment installed were organised according to the scheme (Figure 1).

This is a system that in a way brings to the laboratory a decentralised/hierarchical control structure that is intended for the concept of microgrid, with a special emphasis on the possibility of creating the conditions for connecting new devices, which ultimately would be similar to a plug-and-play system.

Generally speaking, the underlying idea for this functional organisation, at the level of control/interaction capacity with other devices, is that it is possible for them to share communication

protocols and/or interfaces which are proprietary or differentiated. The aim is to make it possible to use a backbone based on an Ethernet infrastructure and an open protocol for communication with local equipment.

The communication system will be managed by a central node that combines a SCADA system (responsible for monitoring and controlling the infrastructure) and a management and control software that will guarantee some of the functionalities typically found in DMS systems (node corresponding to the DM&CS – Distribution Management and Control System). At an intermediate level, it is possible to find MicroGrid Central Controller (MGCC) nodes that will contain software to control the operation of microgrids. The nodes in the lowest level represent Smart Meters (SM), which contain local control software modules, namely Micro-generation Controllers (MC), Load Controllers (LC) and Vehicle Controllers (VC). These will be responsible for respectively controlling the micro-generation systems, the controllable charges and the EVs.

The same SCADA system guarantees that there is communication between the different elements of the architecture. Between the central element, where the SCADA module is installed, and the Remote Terminal Units (RTU), the communications are based on the IEC 60870-5-104 standard. The communications between the RTU and the SM will be assured by a standard protocol to be developed by INESC TEC.

The different elements that will be implemented in PC platforms will make it possible to develop software solutions and modules for control inside the laboratory, assuring at the same time that there is enough flexibility in terms of hardware. Only this way will it be possible to test different technology and solutions.

The communication infrastructure makes sure that the controllers of the different hierarchical control levels communicate effectively, namely the MGCC and the local controllers (MC and LC and VC) which, in this context, represent the communication nodes.

Because the communication architecture used in

the laboratory aims at emulating several application scenarios in different concept demonstrations, it must have the same expansion, reconfiguration and modularity capacities.

These two last features will make it possible for each node to represent an entity in the power grid or a set of entities (for instance, a combination of local controllers).

Each node is implemented using a computer (PC) equipped with a set of communication standards that provide all the necessary input and output to implement the functionalities inherent to each node.

The communication channel used is wired (over Ethernet). This choice makes it possible to go from a channel virtually without noise or interference where the environment can be totally controlled. This way it will be possible to emulate different types of communication (with or without cable) and different technologies.

The channel will be modelled using an application that will manage buffers for messages exchanges between the nodes. The flow of information exchanged between the different communication nodes depends on the requirements of the functions to be executed by the controllers associated with the communication nodes.

This way, it is necessary to present predefined functionalities and communication restrictions associated with each node.

- Form the point of view of the electrical organisation of the laboratory's power system, the different equipment (charges, micro-generation units, EVs, prototypes) is connected to a highly configurable electric box, whose single-line SCADA diagram is represented in Figure 2.
- This is a single-line diagram of a set of buses (3 three-phase buses arranged longitudinally), which can be used to test different configurations in the laboratory, according to contact systems with remote control capacity via SCADA system.

Considering the entire architecture of the solution to integrate the different equipment installed in the

laboratory, as well as the support electric box, below is a summarised list of the main equipment available (see Figures 3 to 8):

1. An emulator of a 3 kW wind microgenerator, set up by a permanent magnet generator similar to those used in several types of horizontal axis micro turbines, which is activated by an induction engine controlled by a variable speed drive.
2. Photovoltaic solar panels (6 strings - 3x2 kWp + 3x3 kWp).
3. Two resistive loads with a 27 kW maximum unit power (capacity to operate in single-phase or three-phase scheme).
4. Low voltage 100 A and 50 A cable simulators with configurable resistance in two steps.
5. Accumulator batteries
 - o Lead-acid (64 units, 6V per cell, 400 Ah@20h)
 - o Ion-lithium: 128 cells (3,2 V and 40 Ah per cell), charger and a BMS management system.
6. Inverters for micro-generation units: SMA Sunny Boy (SB 1700 - 3 units, SB 3000 – 3 units), Windy Boy (WB 3000 - 1 unit).
7. Inverters for batteries (SMA Sunny Island SI5040, 6 configuration units for 2 three-phase banks).
8. Inverter prototypes for solar and micro wind power systems developed at INESC TEC.
9. A prototype of a bidirectional charger for EVs developed at INESC TEC.
10. A device to measure and register class A electrical magnitudes (Fluke 1760 TR analyser).
11. A device to measure and register electrical magnitudes installed to implement the set of buses (Janitza UMG96 e UMG103)
12. A plug-in electric vehicle and the respective charger (Home Charger by EFACEC).
13. Fast prototyping system for electronic power converters – dSPACE DS1103

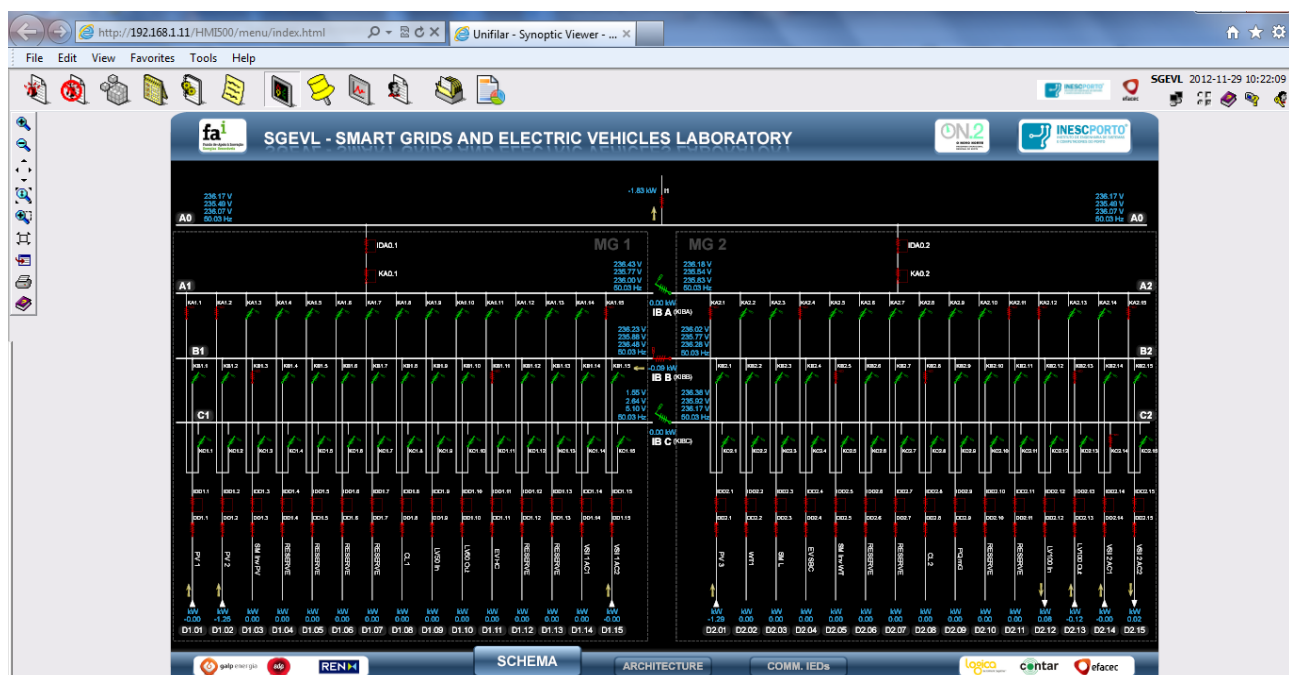


Figure 2. Diagram of the single-line set of buses implemented on SCADA level



Figure 3. Functional architecture of the laboratory

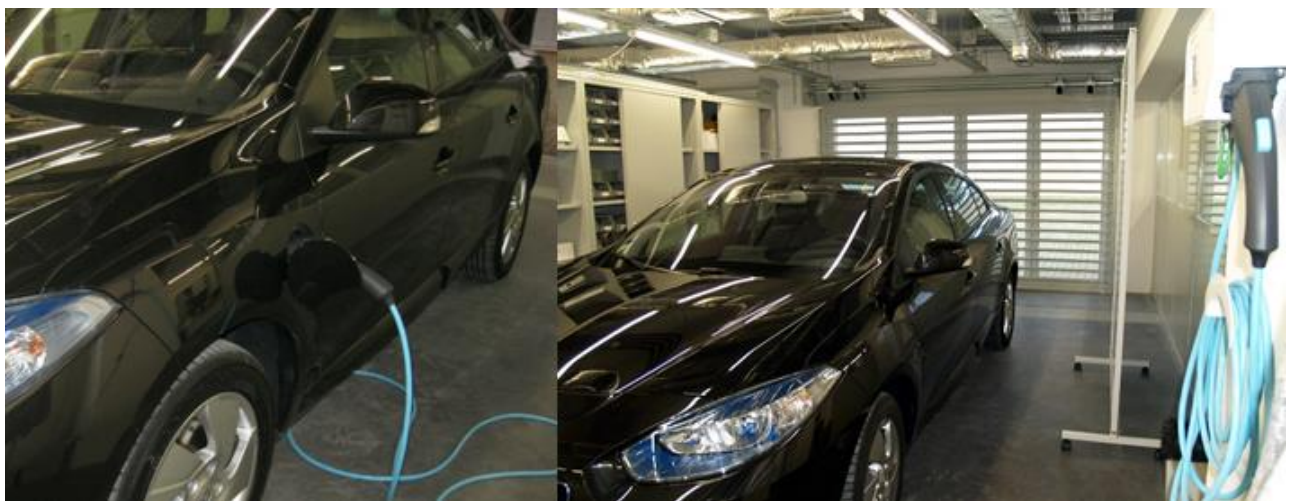


Figure 4. Plug-in electric vehicle and the respective charger (Home Charger by EFACEC)



Figure 5. SMA Sunny Island inverters and the respective lead-acid batteries



Figure 6. Emulator of the wind turbine (top left corner), solar panels (right) and SMA Sunny Boy inverters (bottom)



Figure 7: Electric panel in the laboratory



Figure 8. Resistive loads and low voltage cable simulators

B. Architecture of the Communication System

The solution provided currently at the laboratory is based on the advanced interfaces of the main nodes managing the low voltage distribution grid: the Energy Box (EB) at consumer level, and the MicroGrid Central Controller (MGCC) at distribution transformer substation level. The EB is a key element in electric power systems, taking into consideration the load management and micro-generation unit needs, as well as the smart charging mechanisms of Electric Vehicles (EV). Similarly, the MGCC is a system that, among other functionalities, materialises the management and control needs at the level of the low voltage distribution grid. This entity combines the information and supports decision processes, which come from the need for specific decision processes. This way, it was necessary to implement an advanced measurement acquisition system, called Data Acquisition Server (DAS), which guarantees that the information is distributed consistently and in real time to different entities.

The communication modules (interfaces and protocols) developed are integrated in several prototypes, thus making it possible for them to interact with themselves and with different commercial equipment. These are also integrated in other systems that provide information control and storage functions. To guarantee that different communication technologies are studied, a module called Medium Behaviour Controller (MBC) was developed as part of the smart grids, which makes it possible to emulate the different features of the communication system over Ethernet.

In order to adequately monitor and manage the process of smart battery charging of the EVs, it was necessary to develop and implement an eCAN – RS-232 communication interface. The solution is supported by the Spectrum Digital TMS320F28335 board, illustrated in Figure 9. The board is programmed using Matlab Simulink.

Several messages exchanged with the prototypes were implemented:

- Between the Main Control Unit and the Control Hardware of the Charger:



Figure 9. Control Board TMS320F28335

- Current charging power
 - Grid voltage
 - Current SOC
 - Final SOC
 - Charging strategy and parameters to control connection Time
 - Charging strategy and control parameters
- Between the Control hardware of the Charger and the BMS:
 - Current state of the battery load
 - Charging mode (Constant Current/Constant Voltage)
 - Battery Load Restrictions
 - Orders to charge, supply electricity to the grid and unload

Energy Box

One of the prototypes developed for the laboratory is based on an advanced version of an Energy Box (EB). This node is responsible for locally managing different devices associated with an electric power installation (domestic installation) and it is capable of collecting measurements and monitoring information, as well as sending configuration and control actions from the prototype of the EV smart charger and from the prototypes of micro-generation units, as presented in Figure 10.

The EB plays a fundamental role because it makes sure that there is an interaction with the system operator. This way, the EB prototype was given the capacity to respond to control and configuration requests from the distribution system operator, which will be sent by the hierarchically superior node, which is the MGCC.

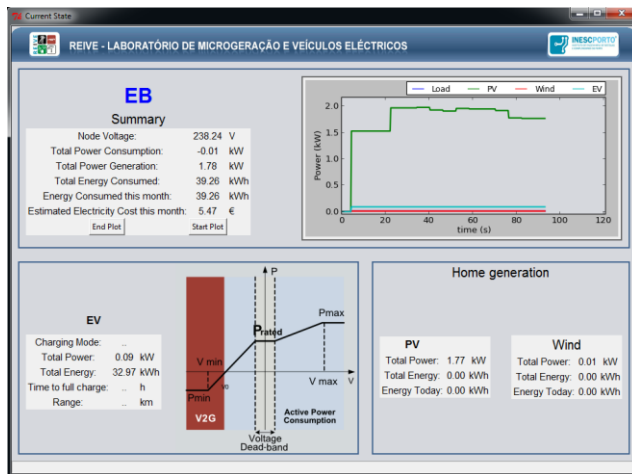


Figure 10. Configuration of the devices controlling the EB

The different devices that can be managed by the EB in the laboratory include the prototypes of the micro wind and solar generator, and the smart charger, with configurable control, and well as the EV (Renault Fluence ZE) that is connected to a commercial charger without configurable control. The EB has the capacity to configure the different prototypes, using the respective local controllers, according to the preferences/profiles of the different clients defined locally or through the remote parameters coming from the MGCC via the TCP/IP.

The prototype of the EB makes sure that there is a remote standardisation from the MGCC, thus making it possible for the EB to provide support services to the grid (voltage and frequency support). More specifically for micro-generation, the possibility of actively participating in frequency regulation was also considered. After all configuration parameters are received from the MGCC, the EB re-sends them to the different prototypes using an IP communication network through the UDP, which can be confirmed at the level of application. The EB is also capable of sending service quality parameters to the MGCC node (for instance, maximum and minimum voltages, factor generating imbalances between inverse and zero-sequence voltage).

The prototype of the EB incorporates additional functionalities comparatively to the commercial charger associated with the VE, and contains functionalities which are usually found in more advanced versions. It is capable of collecting

information from the vehicle, namely information on the battery charge, and deciding on the best operation strategy according to the local configuration. Even though the action of the commercial charger is only on/off, it is possible to decide on when is the best time to charge the EV according to some of the preferences defined in the EB, which may include charging the EV if there is a surplus of renewable generation.

A graphical interface (GUI) was created to display the different variables associated with local measurements (voltage, power and energy). In the laboratory, these variables are being acquired by the Data Acquisition Server (DAS). As the information is received by the DAS, the EB can equally register the total amounts of energy produced and used, thus making it possible to make an energy balance and to estimate the costs according to the tariff. Figure 11 shows an interface running in the machine that plays the role of an EB. This machine also sends to the MGCC the quality parameters calculated locally using the measurements received from the DAS in TCP/IP.

The interface registers the power in real time, presented in the form of a chart, as well as the load consumption, generation from renewable sources and the consumption or the penetration of power through the smart charger.

A specific field was created in the graphical interface for the generation coming from solar and wind prototypes. This field calculates the daily global energy and power. A specific section was also created for the smart charger which shows the charging mode (uncontrolled, controlled or V2G), power and energy meters, full time load estimation and autonomy expected for the set of batteries. This section contains a chart that illustrates the operation point of the charger in the P-V droop curve.

Another interface module, presented in Figure 11, makes it possible to configure the parameters associated with the functionalities of the charging station. Here, it is possible to define the charging mode, the time available for charging, the targeted battery status, the vehicle's model and whether it can be controlled from the MGCC.

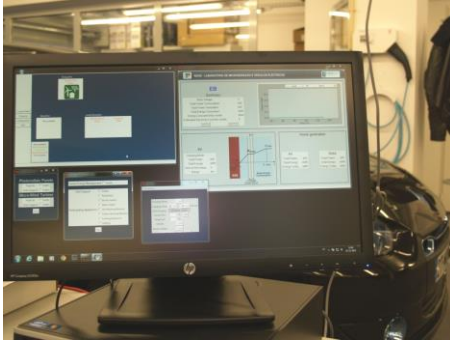


Figure 11. Interface of the domestic EB

MicroGrid Central Controller (MGCC)

The prototype corresponding to the Microgrid Central Controller (MGCC) was implemented in a machine and is responsible for managing different EBs. The MGCC is capable of collecting measurements and sending configuration and control actions and is equally responsible for local supervision and control corresponding to the Transformer Station.

The MGCC is not only capable of remotely configuring the control parameters of the different devices associated with the EB nodes that are available to operate in the system, but also assuring that the distribution system operator receives quality parameters from the EB. In particular, it is important to clarify that the MGCC makes it possible to remotely activate and parameterise the participation of the micro-generation units and the EV smart charger in certain services to support the distribution system operator:

- When the system operates normally, the MGCC remotely activates and parameterises the P-V droop, not only in the prototypes allocated to the micro-generation units, but also in the prototype of the EV smart charger, in accordance with the model presented in Figure 12 and in Figure 13.
- Depending on the grid's operating conditions, the operator can preventively activate the power control droop according to the frequency deviations. This situation is useful in operating conditions where a microgrid is isolated, and so controlling the frequency is key. The operation mode of the EV charger prototype is described in Figure 14.

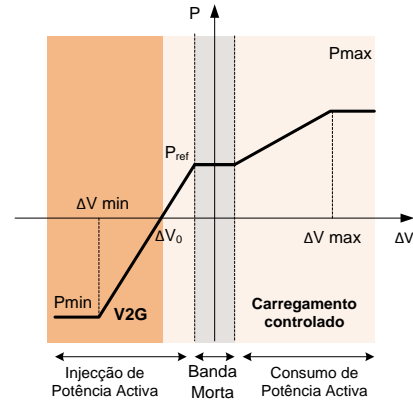


Figure 12. P-V droop for the EV smart charger

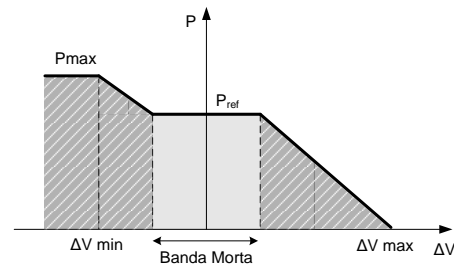


Figure 13. P-V droop for the micro-generation units

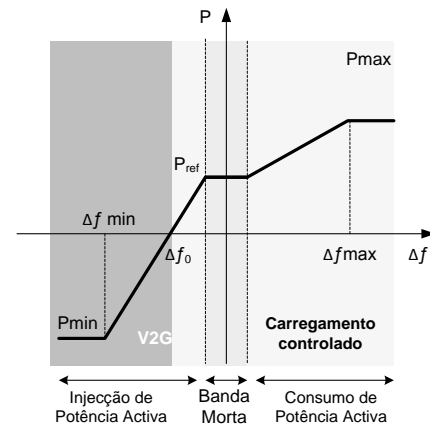


Figure 14. P-f droop for the EV smart charger prototype

Two graphical interfaces were implemented in Python, thus enabling the interaction with the MGCC prototype. In Figure 15 it is possible to see the interfaces running in the machine corresponding to the MGCC. The first interface is responsible for presenting the magnitudes in the form of a table and a chart. This interface shows not only the total global power associated with consumption and generation, but also differentiates total EV consumption, power generation from renewable sources and total generation. From the

operational point of view, real-time measurements for frequency, voltage and current are provided, as well as voltage quality indicators.

The second interface makes it possible to remotely configure the control parameters of the prototypes within the EB (Figure 16). The parameters can be introduced manually, saved locally in a file and afterwards uploaded and sent to the EB prototype. In this interface it is possible to select the communication network to be used from those available at the time, such as the laboratory's Ethernet network or the external wireless mesh network. The choice of network allows greater flexibility in terms of communication scenarios and technologies to be tested, and it is enhanced by using the MBC module.



Figure 15. Photo of the MGCC and the respective interfaces of the support modules

Data Acquisition Server (DAS)

The Data Acquisition Server (DAS) is a prototype that was developed in order to satisfy the need for collecting, from all prototypes and equipment installed in the laboratory, specific information related to measuring electric magnitudes that characterise their operation using different communication technologies.

The electric box installed in the laboratory contains 37 metering devices. These devices are electrically and successively connected to all outputs in the microgrids in the board.

This way, it is possible to collect in real time all kinds of measurements from every electrical output. Simultaneously, all metering devices equipment use a communication system that is common to the SCADA installed in the laboratory.

This system is characterised by RS-485 serial communication following the ModBus RTU protocol. The SCADA monitors all measurements from the 37 systems and decides on the automatisms installed in the board. The main message flows involving the DAS are identified in Figure 17. The RS-485 ModBus RTU communication system is a Master/Slave system that uses USB/RS-232 converters for RS-485, as presented in Figure 18.

REIVE - LABORATÓRIO DE MICROGERAÇÃO E VEÍCULOS ELÉTRICOS

Variable Microgeneration Voltage Grid Support

Wind P-V Droop configuration		Active Power Set-point - Psp			
Maximum Active Power - Pmax	2250				
Minimum Voltage - V-min	225	Voltage Dead-band Minimum- Vdb-min	230	Voltage Dead-band Maximum- Vdb-max	250
Enable P-V Droop	<input type="checkbox"/>	Enable Frequency Control	<input type="checkbox"/>	Checksum -6407	
Solar P-V Droop configuration		Active Power Set-point - Psp			
Maximum Active Power - Pmax	3000				
Minimum Voltage - V-min	225	Voltage Dead-band Minimum- Vdb-min	230	Voltage Dead-band Maximum- Vdb-max	250
Enable P-V Droop	<input type="checkbox"/>	Enable Frequency Control	<input type="checkbox"/>	Checksum -7157	

Electric Vehicle Voltage and Frequency Grid Support

EV P-V Droop configuration		Active Power Set-point - Psp		Maximum Active Power - Pmax		Enable Vehicle-to-Grid - V2G	
Minimum Active power - Pmin	0			3000			1
Minimum Voltage - V-min	215	Zero-Crossing Voltage - V0	225	Voltage Dead-band Minimum- Vdb-min	230	Voltage Dead-band Maximum- Vdb-max	245
Enable P-V Droop	<input type="checkbox"/>						
EV P-f Droop configuration		Active Power Set-point - Psp		Maximum Active Power - Pmax		Enable Vehicle-to-Grid - V2G	
Minimum Frequency - f-min	49.5			49.9			50.1
Zero-Crossing Frequency - f0	49.5	Frequency Dead-band Minimum- fdb-min	49.9	Nominal Frequency - fn	50.1	Frequency Dead-band Maximum- fdb-max	50.5
Enable P-f Droop	<input type="checkbox"/>					Checksum -1660	

Select IP | GUI Update | Save | Load | Send

Figure 16. Interface of the MGCC to manage the grid support services

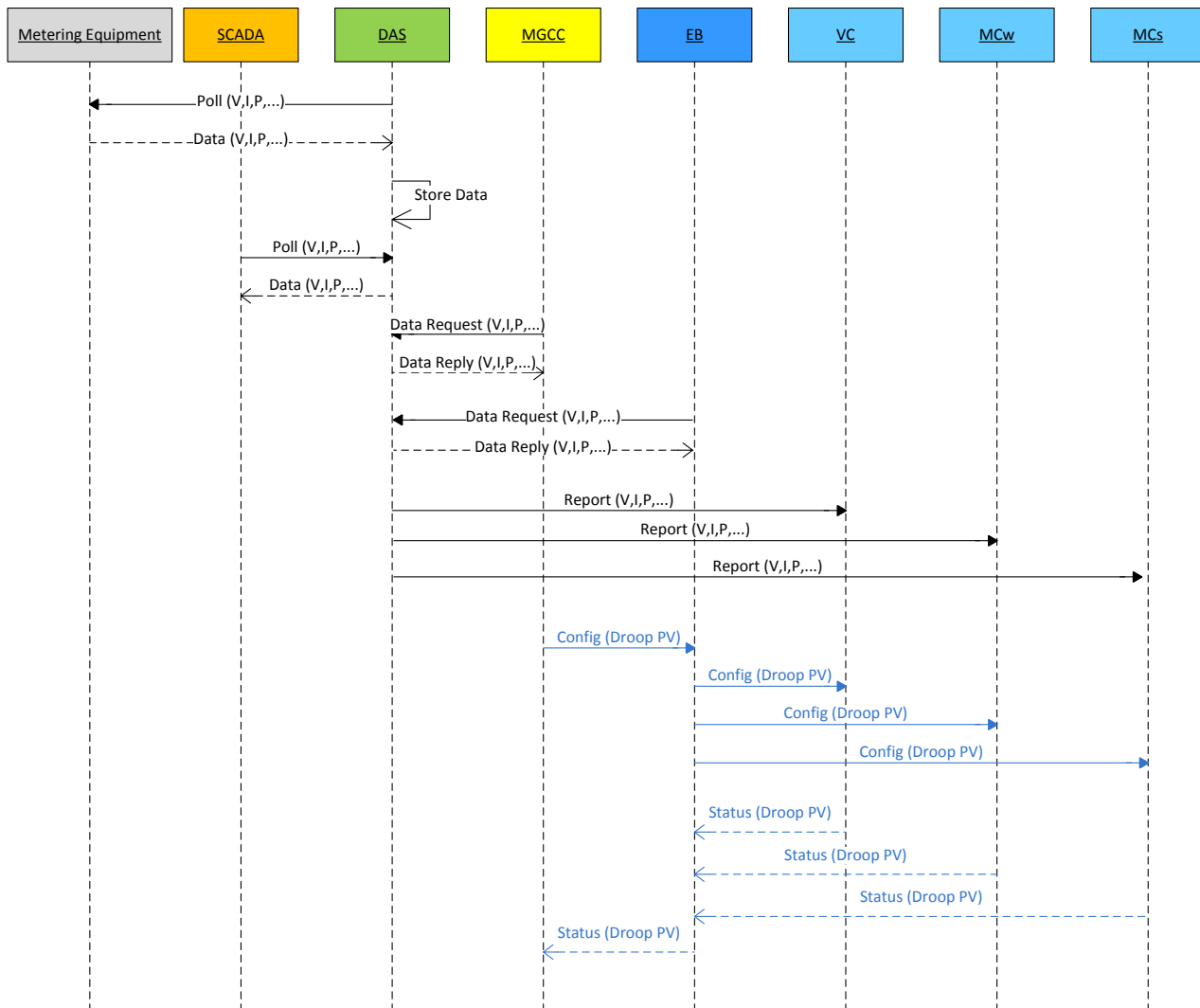


Figure 17. The MGCC and the respective support module interfaces

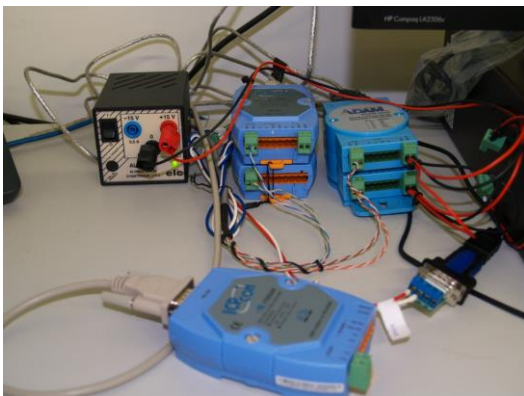


Figure 18. RS-232 converters or USB for RS-485

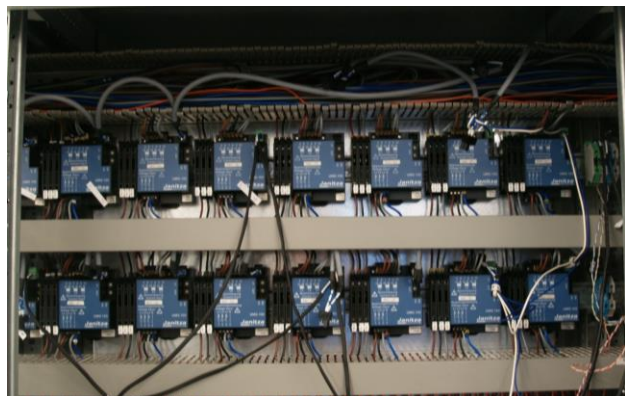


Figure 19. Metering stations installed in the Laboratory

This means that only a device can question the slaves at each instant. Inherently, that means that only a message can be exchanged at each instant in each bus.

In the machine that houses the DAS, a Master ModBus/RTU was firstly developed via RS-485 with enough flexibility to allow the user to configure the measurements to be read from any metering

equipment. In the ModBus protocol, it is possible for the Master to obtain answers, through a simple request, on more than one measurement. Therefore, instead of making n questions to obtain n answers, there are n questions for y answers, where $n \ll y$. This process was conducted cyclically in order to obtain measurements from all devices in

the lowest amount of time possible.

Besides collecting data, other client functionalities were implemented, namely the logs of the data and charts obtained in real time. Figure 20 shows a graphical interface and the respective modules to visualise the communication status, the generation of charts, the values collected and the logs created.

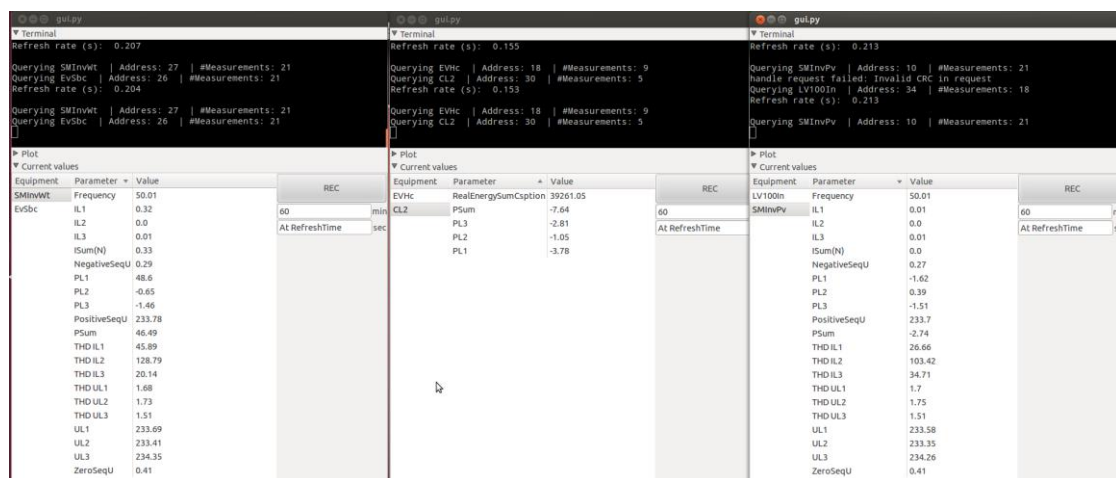


Figure 20. The different modules in the DAS

A module to represent the time evolution of several electric magnitudes was also developed, depicted in Figure 21.

Four modules were defined and implemented in the DAS:

- ModBus/RTU Master
- ModBus/RTU Server
- ModBus TCP/IP Server
- APC

Another module was created in the machine where the DAS is running, which is called SCADA Access Moderator (SCADA.AM).

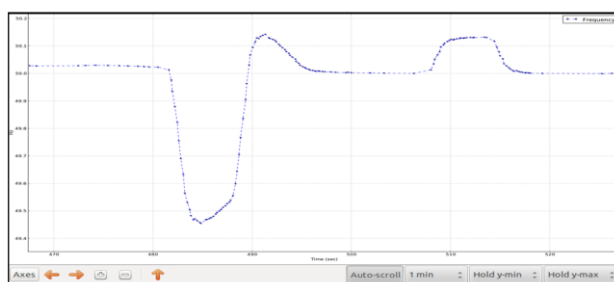


Figure 21. Frequency droop collected by the DAS

This module serves as an interface between the SCADA control and the remaining systems in the laboratory. This way, it is possible for the external modules to send orders to the SCADA, acting as a module that validates and filters the respective commands, thus promoting the safety of the devices. The logical architecture of the DAS and SCADA.AM modules is presented in Figure 22.

Figure 23 shows the modules and interfaces running in the machine corresponding to the DAS.

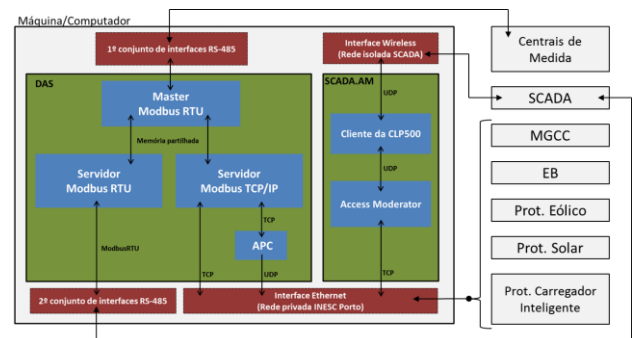


Figure 22. Logical architecture of the DAS and SCADA.AM modules



Figure 23. Different modules in the DAS

Medium Behaviour Controller (MBC)

A Medium Behaviour Controller (MBC) module was developed in order to make it possible to develop scenarios to test the effect/impact of communications in the operation of electric grids. This module makes it possible to configure bandwidth values, delays and packet losses to simulate the different behaviours of the communication technologies or the restrictions that they may suffer.

The main purpose of this module is controlling an Ethernet interface in order to simulate the features of other types of connections, such as Wi-Fi, 3G, or others. In their core, the different types of data connections differ essentially in the three parameters mentioned above: bandwidth, delays and loss rates.

The choice was to develop a Web interface that starts with a simple authentication form. After the users log on, there are presented with a list of the grid interfaces in the system. After an interface is

selected, the options to configure the interface are presented. Each interface has two modes:

- None: no type of emulation is applied, the interface functions normally;
- Statistical: the emulation is applied with the three parameters mentioned above. By selecting this option, three fields are provided to define the Bandwidth, Delay and Loss parameters.

Finally, the Apply button makes it possible to add the new configurations to the interface selected.

Runs as www-data (apache) Runs as root

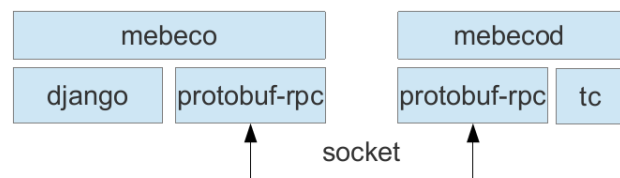


Figure 24. Logical architecture of the MBC module

The interface presented in Figure 25 contains three methods:

1. ListInterfaces: this method makes it possible for the Web application to obtain a list of grid interfaces in the system;
2. GetConfig: this method allows the Web application to obtain the current configuration of a grid interface. The configuration is defined by the mode (ConfigMode), which can be MODE_NONE or MODE_STATISTICAL, and by the three parameters of the statistical mode: bandwidth, delay and loss;
3. SetConfig: this method allows the Web application to change the current configuration of a grid interface.

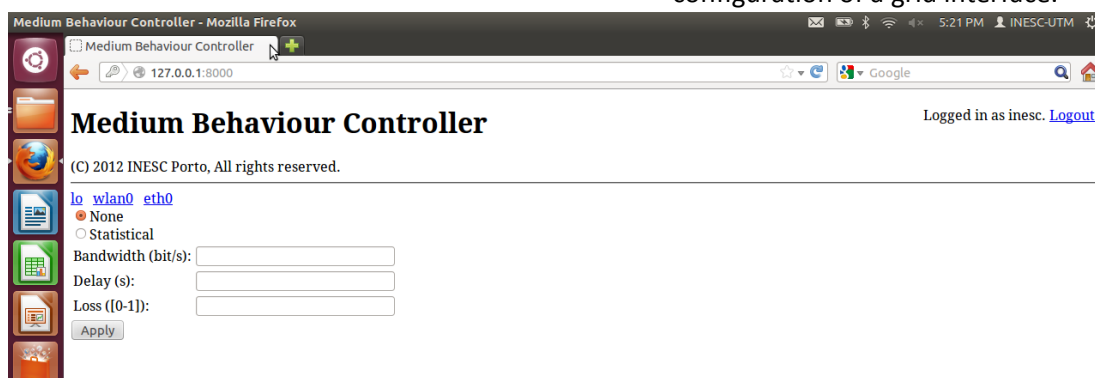


Figure 25. Interface of the MBC

Although the laboratory contains equipment at a short distance, it was considered important to add a wireless mesh network, namely to assess and study new application scenarios in the future. The wireless mesh network equipment – MAPs – installed in the laboratory is presented in Figure 26.



Figure 26. Wireless mesh network equipment in the Laboratory

Wireless mesh network

The network used is based on a solution developed at INESC TEC. This solution makes it possible to extend the infrastructure (wired network) by using a set of wireless MAPs. In these networks, there is one or more Master MAP connected to an infrastructural network, which can provide Internet access or not. The remaining MAPs (slaves) are directly connected to the Master MAP (single hop) or through other slaves (multi hop), thus making it possible to provide external access to the clients connected to each one of the MAPs.

The solution developed also makes it possible for the network to perform its own configuration, which means that the network is configured automatically when a new MAP is installed, and no other action is required from the user. The reconfiguring capacity is also possible as the network can dynamically adjust the topology when there is a temporary or definitive failure in a MAP or when the best path to the Master MAP is found (due to the variable quality of the wireless connections).

For the mesh network considered here, the MAPs

capable of operating in the order of 5 GHz were chosen, following the IEEE 802.11a standard. This standard was chosen instead of the most common one (IEEE 802.11b/g, in the order of 2.4 GHz) due to the high saturation in the between the 2.4 GHz, where over 100 different APs were found. Thus, using the 5 GHz allows the mesh network to be more isolated relatively to the other networks, minimising the interference caused by the systems already installed and improving performance.

C. Prototypes of the Electronic Power Converters

Generally speaking, the equipment available on the market operates without any type of interaction (or a very limited interaction) with the entities responsible for technically managing the distributions network. In some cases, this can harm the normal operation of the electric grid. Therefore, the pre-industrial prototypes developed make it possible to actively and intelligently manage the electric grid by accommodating in real time the state of the operating conditions of the electric grid. As a result, it is easier to develop new support services for the grid with the abovementioned micro-generation units.

The aim with the development of the prototypes was to create the conditions to test the advanced control functionalities to be integrated in the micro-generation and EV charging units. The goal is to maximise the integration of renewable energies and facilitate the progressive integration of EVs in the electric grid. In other words, these new control functionalities make it possible to respond to the new operational challenges brought about by the widespread use of EVs and micro-generation units.

The modularity concepts are at the foundation of the architecture for the three prototypes. Therefore, each prototype contains a set of modules (hardware and software) that share and manipulate information to operate properly. This methodological organisation made it possible to secure parts of the power circuits for each of the units developed. The specificities in each pre-prototype are more accentuated in the control layer. This type of organisation makes it possible to create an expandable system, which is desirable to develop the project and to promote the use of the experimental platforms in the future when

validating the advanced operating concepts of the power systems.

More specifically, the following classes of physical subsystems were designed and implemented for each prototype:

- Energy conversion chain;
- Electronic devices dedicated to operating power semiconductors and the respective electronic protection;
- Current and voltage transducers (CC and C.A.) and the respective signal conditioning chain;
- Communication devices and interface with the operator;
- Digital signal processor and associated circuits.

The pre-prototypes were materialised by implementing power circuits. More specifically, printed circuit boards were designed for the different signal and power circuits. The units' power circuits were assembled in order to create a pre-industrial unit. Other than these activities, and in order to guarantee that the different subsystems are operating in each prototype, a set of integration and testing activities were conducted in order to validate the operation.

After that, and in order to provide each prototype with its own control unit, hardware and software were designed, implemented and tested in order to transfer the control units to a control board based on the eZdsp TMS320F28335. Finally, each prototype was integrated in the laboratory of microgrids and electric vehicles in order to test and demonstrate the operation of the controllers that implement the microgrid's management and control systems with EV integration and micro-generation systems.

D. Laboratory Testing

INESC TEC's laboratory makes it possible to conduct tests that confirm the interest and the capacity to actively manage the distribution grid with strong integration of micro-generation units and EVs. Below are some examples of laboratory tests based on an electric configuration in the laboratory's set of buses, represented in Figure 27. From the electric point of view, the system contains a node to which the different micro-generation

interface prototypes and EV charging system are connected, as well as the loads and the commercial charging system for EVs, the Home Charger by EFACEC. This node is electrically connected to the laboratory's general bus (A0) using a low voltage channel emulator (LV 100 A). From the point of view of the system's supervision and control, interfaces were specifically developed for the Energy Box (Smart Meter), as well as for the MGCC.

Testing scenarios were considered in order to assess the integrated management mechanisms in the low voltage grid (microgrid – MG), incorporating the following scenarios:

- Scenario 1 –MG operating connected to the upstream grid and considering an off-peak scenario, with a high amount of energy being generated from renewable sources.
- Scenario 2 – MG operating connected to the upstream grid contemplating a scenario where load is high and no energy is produced from renewable sources.
- Scenario 3 –MG operating in isolated mode.

Taking into consideration the system presented in Figure 27, the test conducted for Scenario 1 includes the following steps, documented by the results in Figure 28:

1. For $t=104s$, increase generation in the wind micro-generation unit, reaching 2kW, thus increasing voltage in node 2.
2. For $t=167s$, increase solar micro-generation unit, reaching 2kW, thus causing an increase and additional voltage in node 2.
3. As a result of the voltage in node 2, in $t=23s$ the MGCC activates the strategy to control P-V voltage in wind micro-generation, which reduces the power injected into the grid and, consequently decreases the voltage.
4. For $t=271s$, the MGCC activates the strategy to control the P-V voltage in solar micro-generation. The two micro-generation units share the power that stops being injected into the grid.
5. For $t=338s$, the prototype of the EV bidirectional charger begins the charging process with a reference power of 1.5 kW.
6. For $t=411s$, the MGCC activates the strategy to control the P-V voltage in the EV, and it is

confirmed that there is a slight adjustment in the charging power. Simultaneously, the local P-V control mechanisms in the micro-generation unit are deactivated.

7. For $t=484s$, there is an increase in solar generation of about 3 kW and only the prototype of the EV bidirectional charger continues participating in the MG voltage control, thus simulating a situation where there is a high generation of power from uncontrolled renewable sources. This way, the voltage increase leads to an increase in the charging rate of the EV charger prototype.
8. For $t=606s$, there is a load increase in the grid, leading to a decrease in voltage. In this situation, the prototype of the EV charger adjusts the charging rate, reducing it so as to compensate for the significant decrease in the voltage.

9. For $t=688s$, the generation of the solar and wind micro-generation decreases gradually, thus leading to an additional decrease in voltage. In this case, the EV charger prototype continues to adjust the charging rate, reducing it in order to compensate for the voltage decrease found.

An example is presented in Figure 29 containing a graphical representation of the command and control of the micro wind turbine emulator. The display presents the power injected into the grid and the power dissipated locally in the dump-load.

Figure 30 shows the graphical representation of the EB, including the data found during the testing conditions in this scenario.

Figure 31 also provides a graphical representation of the MGCC in these same conditions.

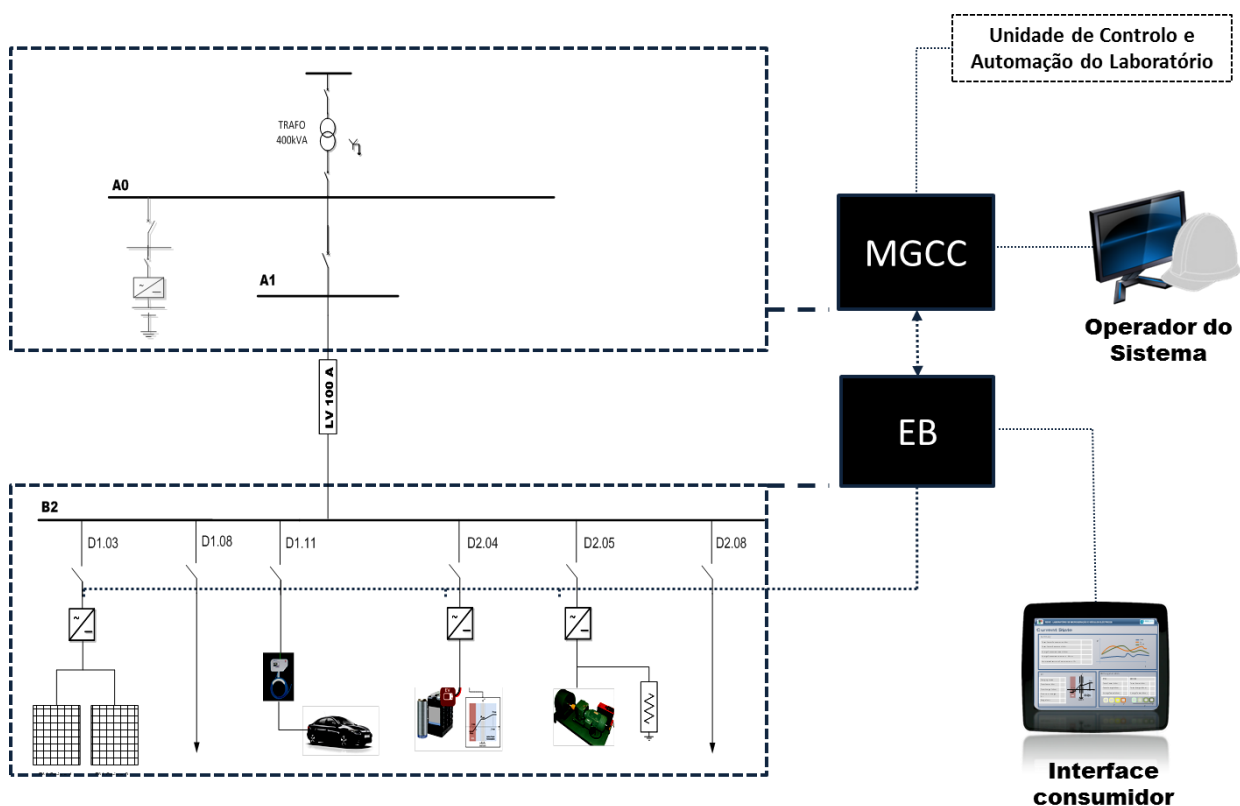


Figure 27: Diagram of the active control of the distribution grid for laboratory testing

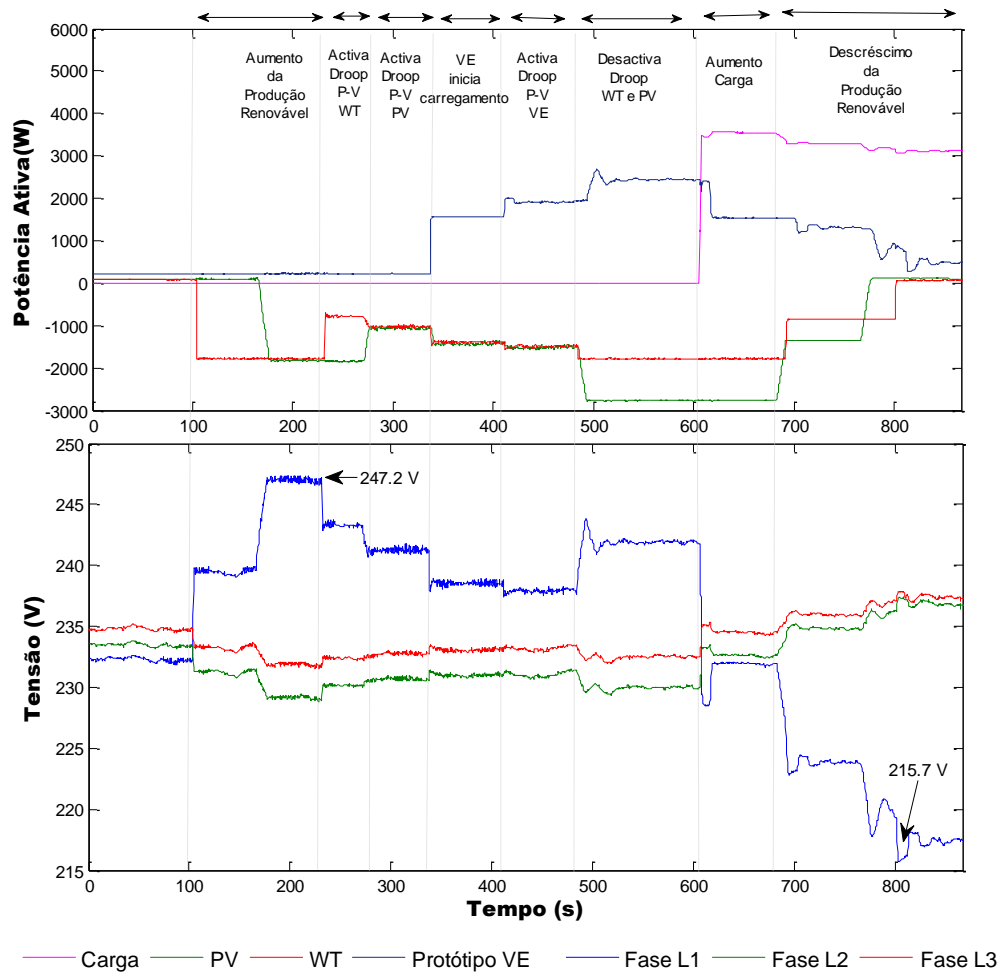


Figure 28: Results referring to scenario 1



Figure 29: Graphical representation of the micro wind turbine controller – Power injected into the grid and power dissipated in the dump-load

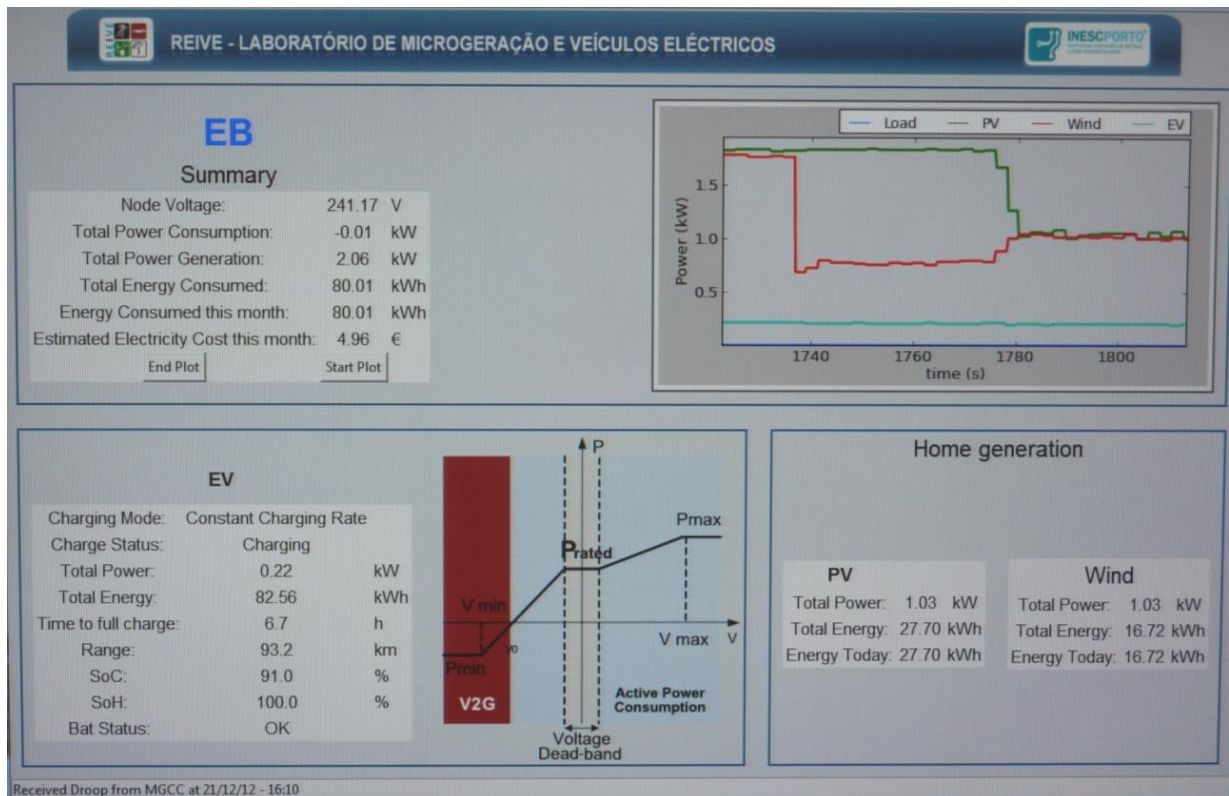


Figure 30: Graphical interface of the EB – results found during the conditions in scenario 1

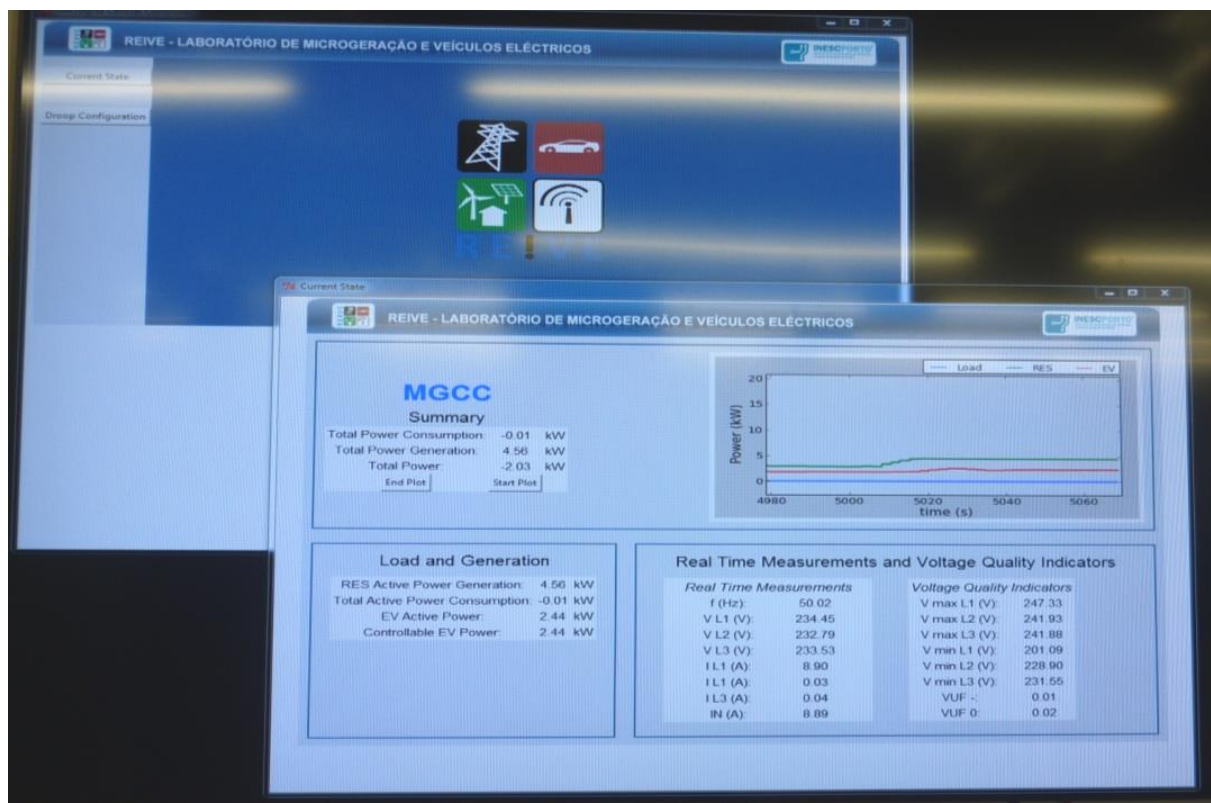


Figure 31: Graphical interface of the MGCC – results found during the conditions in scenario 1

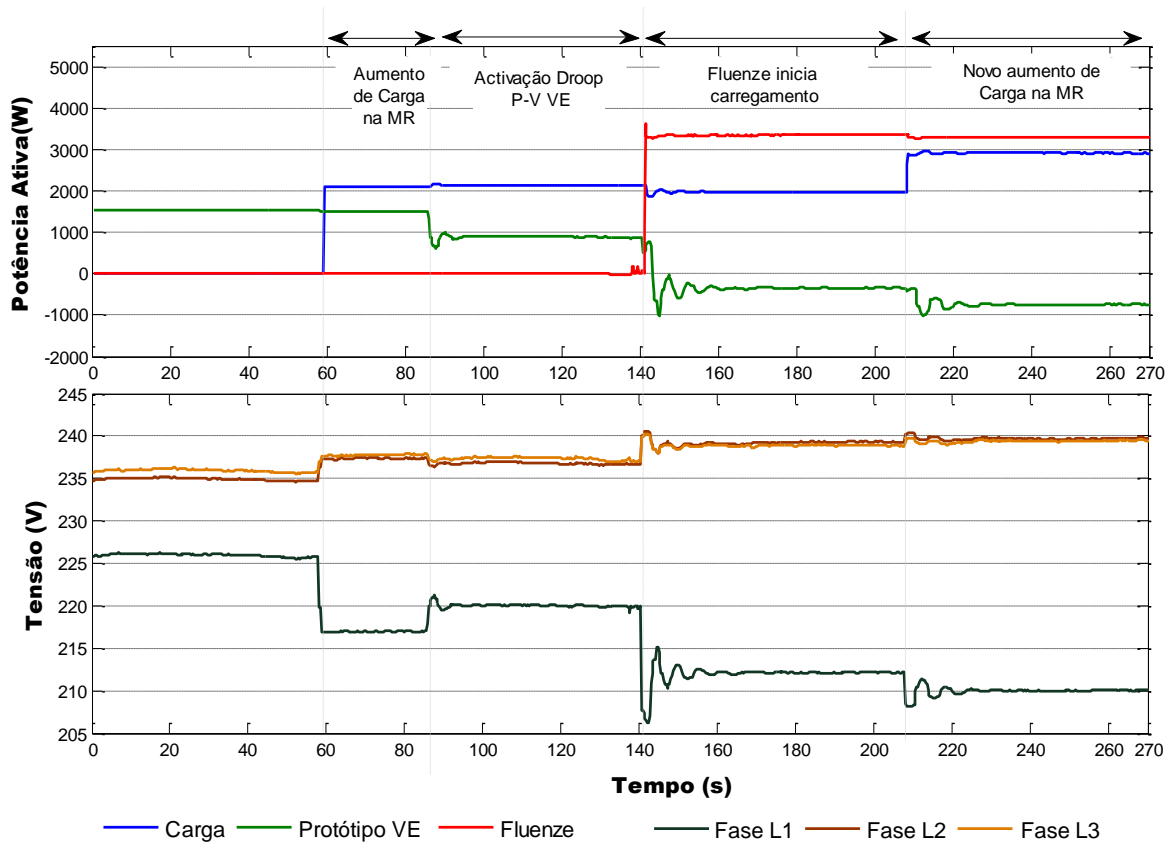


Figure 32: Results referring to scenario 2

Taking into consideration the system presented in Figure 27, the test conducted for Scenario 2 includes the steps presented below. The results are documented in Figure 32:

1. At the beginning of the test, the prototype of the EV bidirectional charger charges the batteries at a reference power of 1.5 kW. For $t=59s$ there is a load increase in node 2.
2. In $t=60s$, a load is introduced in node 2, leading to a decrease in voltage.
3. Because the voltage decreases, the MGCC activates the P-V strategy to control voltage in the EV charger prototype in $t=85s$. As a result, the charging rate of the prototype decreases.
4. For $t=141s$, the commercial charger (the Home Charger by EFACEC) starts charging the EV Fluenze, which corresponds to a load increase of 3.3 in node 2. Consequently, the prototype of the EV charger reduces the charging rate, thus responding to the voltage decrease. At this moment, the prototype goes into V2G mode and starts

injecting power into the grid due to the fact that voltage is low.

5. For $t=208s$, there is a new load increase in node 2. It is verified that when operating in V2G mode, the EV charger prototype injects more power into the grid to support the voltage decrease.

Taking into consideration the testing system presented in Figure 27, Scenario 3 contemplates the operation of the microgrid (MG) in isolated mode in order to demonstrate that the EV charger prototype developed has the capacity to actively control grid frequency under these conditions. For that, the EV charger prototype uses an active power local control strategy (droop) – frequency.

The SMA Sunny Island inverters, which are connected to the batteries, form a grid unit. These are responsible for regulating the frequency and the voltage during the operation in isolated mode. Complementarily, the aim is to validate if the EV charger prototype can participate in the process of regulating frequency in the isolated MG.

Taking into consideration the system presented in Figure 27, the test includes the steps presented below. The results are documented in Figure 33:

1. At the beginning of the test, the MG is connected to the MV grid, importing about 12.3 kW (curve corresponding to the Transformer substation in the following image). The prototype of the EV is connected to the MG and is charging the respective batteries with a reference power of about 2 kW. For $t=33s$, the MG is isolated, thus significantly reducing the frequency. Simultaneously, there is an autonomous reaction to the EV prototype, which goes into V2G mode in order to support the frequency in the grid.
2. For $t=83s$, there is an increase in solar micro-generation and at $t=187s$ there is an increase in wind micro-generation.
3. For $t=205s$, there is a decrease in load, which is disconnected at $t=240s$. From this moment on, all power coming from renewable sources is

absorbed by the Sunny Island inverters, which in their turn will charge their batteries.

4. From $t=330s$, it is found that batteries reach a near nominal load state, and therefore the Sunny Island inverters tend to increase the frequency in the grid so that this situation is interpreted as one requiring a decrease in generation. In this case, the system takes advantage of the situation so that the EV charger prototype can respond to the excessive rise in frequency by increasing the respective charging rate.
5. For $t=512s$, the charge is reconnected and the synchronisation with the upstream grid is terminated.

An example of the graphical interface of the EV bidirectional charger controller is provided in Figure 34. In this image it is possible to visualise the transition corresponding to the moment when the MG becomes isolated (the frequency is represented in blue and the charging power is represented in red).

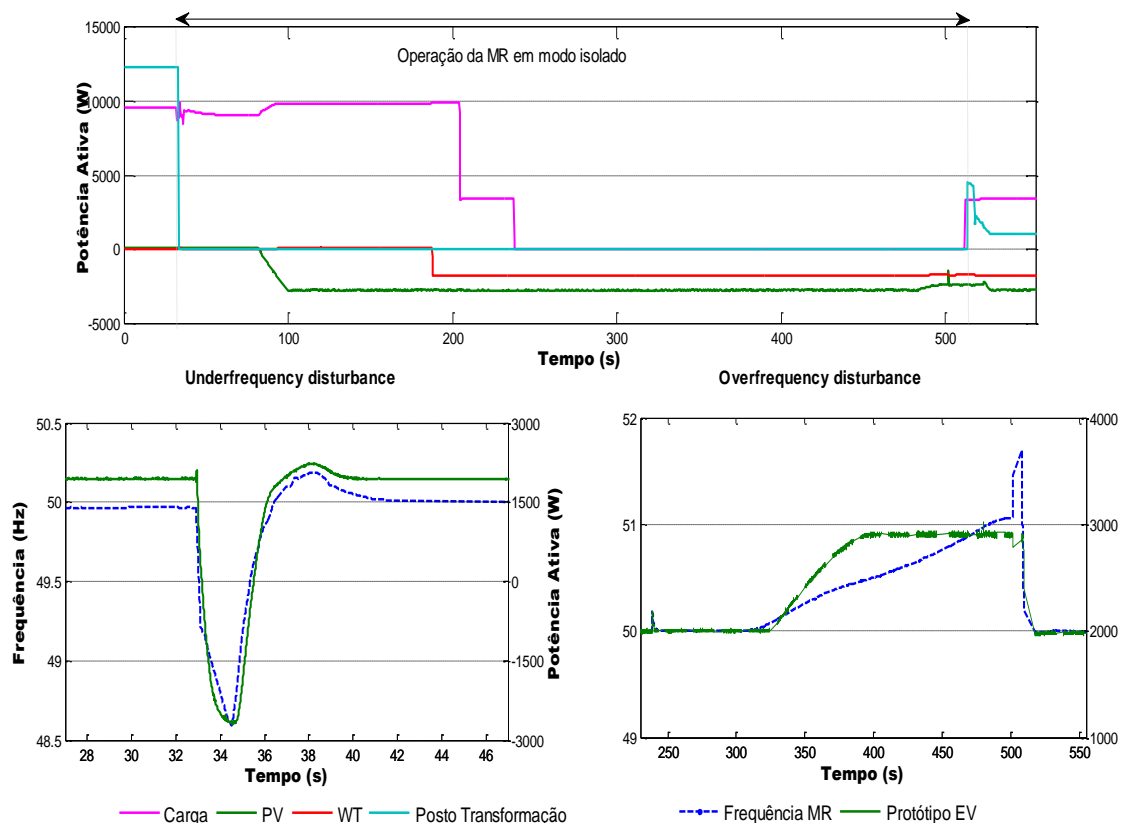


Figure 33: Results referring to scenario 3 – MG operating in isolated mode

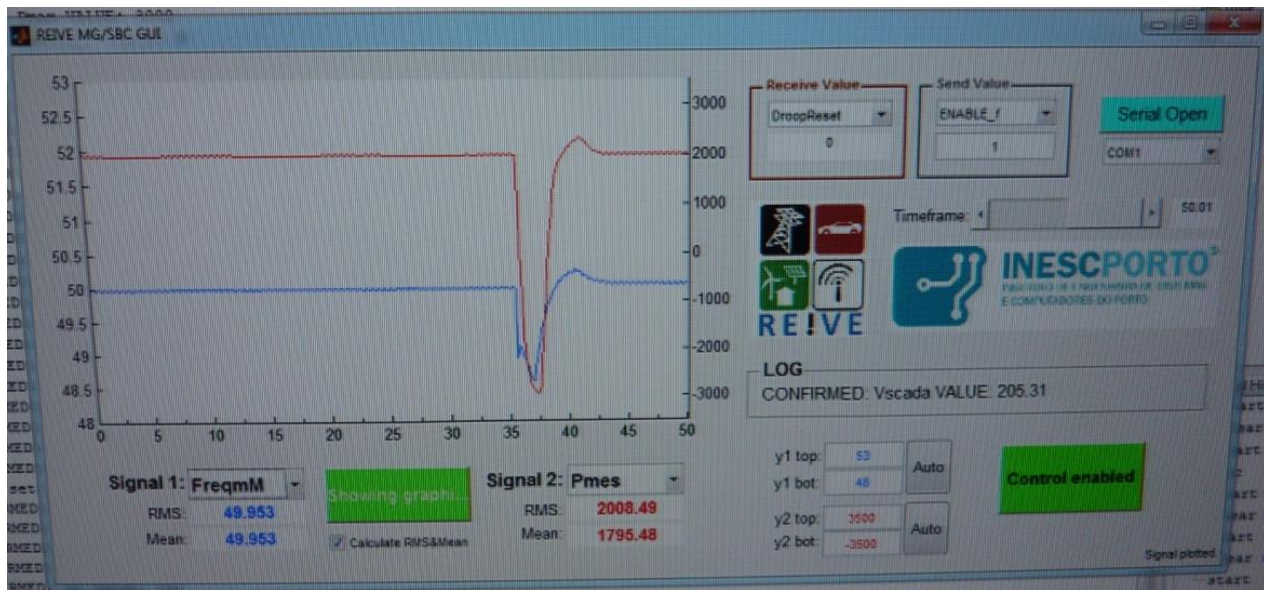


Figure 34: Graphical interface of the EV bidirectional charger prototype

E. KEY PERSONS IN THE AREA



and

At **INESC TEC**, a strong group of researchers are involved in the global problems of the large scale integration of renewable sources, control centers, distribution operation and design, micro-grids, smart grids and integration of electric vehicles.

This group is highly experienced. The work developed spans from fundamental research, applied research under contract, development and prototyping and their activities extend to the launching of spin-off companies. At the same time, advanced training at post-graduation level is continuously carried out.

Most of these researchers are also Professors at the Engineering School of the University of Porto (denoted FEUP). The main actors are

- Prof. João Peças Lopes
- Prof. Manuel Matos
- Prof. Vladimiro Miranda

- Dr. André Madureira
- Dr. André Monteiro
- Dr. Carlos Moreira
- Dr. Fernanda Resende
- Dr. Filipe Soares
- Prof. Hélder Leite
- Dr. Jean Sumaili
- Prof. João Gama
- Prof. José Nuno Fidalgo
- Prof. Jorge Pereira
- Eng. Luis Seca
- Prof. Maria Helena Vasconcelos
- Dr. Mauro Rosa
- Dr. Ricardo Bessa
- Prof. Tomé Saraiva

Together with these highly qualified persons at PhD level, a team of contracted researchers and developers as well as junior researchers and PhD students continuously develop work that may advance the human knowledge and provide technology transfer to utilities, regulators, companies and public administration.

VI. REFERENCES



The following companies and entities are given as reference to the professional and high quality of the work developed by **INESC TEC** in technical development or advanced consulting contracts in the area of power systems, namely including smart grids:

ABB – ABB Ltd, Switzerland

AMPLA – Ampla Energia e Serviços SA, Rio de Janeiro, Brazil

ANL – Argonne National Laboratory, Department of Energy (DoE), United States of America

APREN – Associação dos Produtores de Energias Renováveis, Portugal

BANDEIRANTE – Empresa Bandeirante de Energia, São Paulo, Brazil

COGEN – COGEN Portugal, Associação Portuguesa para a Eficiência Energética e Promoção da Cogeração, Portugal

COPPETEC – Fundação Coordenação de Projetos, Pesquisas e Estudos Tecnológicos, Universidade Federal do Rio de Janeiro, Brazil

DGGE – Direção Geral de Geologia e Energia, Portugal

EDA – Eletricidade dos Açores SA, Portugal

EDP Distribuição – EDP Distribuição de Energia SA, Portugal

EDP Energias de Portugal, S.A.

EDP Produção – EDP Gestão da Produção de Energia SA, Portugal

EEM – Empresa de Eletricidade da Madeira SA, Portugal

EES-UETP – Electric Energy Systems – University Enterprise Training Partnership (European Consortium), Spain

EFACEC – EFACEC Engenharia e Sistemas SA, Portugal

ELECTRA – ELECTRA SARL, Cape Verde

ELETROPAULO – AES Eletropaulo, São Paulo, Brazil

ENERCON – ENERCON GmbH, Germany

ERSE – Entidade Reguladora dos Serviços Energéticos, Portugal

ESB – Electricity Supply Board, Ireland

FCT – Foundation for Science and Technology, Portugal

HEO – Hungarian Energy Office, Hungary

IBERDROLA – IBERDROLA SA, Spain

JRC/IET – Joint Research Center, Institute for Energy and Transportation, European Commission, the Netherlands

MEI – Ministry of the Economy and Innovation, Portugal

ONS – Operador Nacional do Sistema Elétrico, Brazil

PPC – Public Power Corporation, Greece

RAVE – Rede Ferroviária de Alta Velocidade SA, Portugal

REE – Red Eléctrica de España SA, Spain

Regional Government for Madeira, Portugal

Regional Government for the Azores, Portugal

REN – Redes Energéticas Nacionais SA, Portugal

RTE – RTE Réseau de Transport d'Electricité SA, France

TBE – Transmissoras Brasileiras de Energia, Brazil

USAID – United States Agency for International Development, United States of America

USAID/REAP – United States Agency for International Development / Regulatory and Energy Assistance Project (to Bosnia-Herzegovina), United States of America

WS-Energia – WS Energia SA, Portugal

VII. A TEAM OF EXPERTS



INESC TEC's team of experts is composed of experienced researchers with a solid scientific track record and robust sediment of experience in developing solutions with technology transfer to industry and advanced consulting.

At the same time, advanced human resource training, including at PhD level, is led at INESC TEC together with the University of Porto in Portugal and MIT and CMU from the USA.

One of the team leaders (Prof. Vladimiro Miranda) is an IEEE Fellow and also recipient of the IEEE PES Renewable Energy Excellence Award 2013. Another of the team leaders (Prof. Peças Lopes) received the CIGRÉ Technical Committee Award for 2011 – Study Committee C6, Distribution Systems and Dispersed Generation. Both researchers are at the Board of Directors of INESC Porto, the coordinating entity of **INESC TEC**.

The Coordinator of the Power Systems Unit of **INESC TEC** is Prof. Manuel Matos, who is responsible for over 60 researchers with backgrounds as diverse as Electrical Engineering, Economy, Applied Mathematics, Physics, Applied Meteorology or Computer Science.

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