

# Coordinated Management of Distributed Energy Resources in Electrical Distribution Systems

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**Abstract**—Current electrical distribution systems are facing significant challenges due to the widespread deployment of Distributed Energy Resources (DER), particularly the integration of variable Renewable Energy Sources (RES). This requires a change in the paradigm of distribution grids from a purely passive perspective into fully active networks within the smart grid vision. This new paradigm involves new control and management architectures as well as advanced planning methods and operational tools for distribution systems exploiting a smart metering infrastructure. This infrastructure will enable leveraging data from smart meters and short-term forecasts of load demand and RES in order to manage the distribution system in a more efficient and cost-effective way, thus enabling large scale integration of RES. Future tests to be carried out in a new, state of the art laboratory environment will bring additional added-value to the validation of the proposed concepts and tools.

**Index Terms**—Smart Grid, Distributed Energy Resources, Renewable Energy Sources, Ancillary Services, Voltage Control.

## I. INTRODUCTION

The expected increase in the integration of DER at the several voltage levels of distribution networks brings additional difficulties for power system operation and planning [1]. In fact, large-scale connection and management of DER (including flexible generation, demand and storage devices) in the distribution network poses a challenge to the Distribution System Operator (DSO) in order to make the transition from passive to active, integrated networks [1], [2]. Several technical issues arise such as the voltage rise effect [3] and overloads in lines or transformers, which pose problems to the DSO that, without proper management, can lead to an increase in the cost of connection for Distributed Generation (DG) due to network reinforcement requirements.

Active distribution network management is considered as a key factor to achieve cost-effective solutions following DG integration in distribution grids at both the planning and operation stages of the distribution system, which constitutes a huge step beyond the current “fit-and-forget” approach.

Consequently, advanced monitoring, control and management functionalities must be developed in order to support the operation of distribution networks. The implementation of these new algorithms should be done in accordance with new visions for future distribution systems by exploiting hierarchical and decentralized control architectures. Also in order to foster the growth of DG, especially renewable-based sources with variable power generation characteristics, it is necessary to develop new advanced monitoring, control and management solutions under the smart grid paradigm.

According to the SmartGrids European Technology Platform [4], a smart grid is an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to deliver efficiently sustainable, economic and secure electricity supplies. The smart grid concept involves a revolution in power system planning and operation at various levels by adopting intelligent and decentralized control infrastructures that will allow managing all DER connected to it in an efficient way [4].

Therefore, active management of distribution networks will enable the DSO to maximize the use of existing circuits by taking full advantage of DER (generator dispatch, control of transformer taps, voltage regulators, reactive power management and system reconfiguration) in an integrated and coordinated way. This active approach to system operation can reduce the negative impact of DG on the network, thus minimizing requirements for grid reinforcements [5].

The main idea behind the control strategy presented in this paper is that it is possible to develop efficient solutions for managing distribution networks that will enable large scale integration of variable RES without jeopardizing operating conditions. These solutions must rely on advanced control and management algorithms to be integrated as software modules to be installed in distribution network control centers.

Some of these concepts will be developed also within the framework of EU project SuSTAINABLE that has recently started [6].

## II. DISTRIBUTION SYSTEM CONTROL ARCHITECTURE

### A. Proposed Control and Management Structure

In order to fully realize the smart grid vision, new management and control architectures must be defined that are able to address the distribution system as a whole. The main focus for the development of this architecture is to allow large scale integration of DER while improving the flexibility and reliability of the system.

The approach proposed in this paper aims at covering the whole distribution system and it defines different control layers corresponding to the main voltage levels from the HV grid down to the LV consumers, which correspond to a control and management hierarchy. The resulting framework assumes that a high-level coordination between these several hierarchical levels (central management, control level and local / field level) must be ensured at all times. The control and management architecture proposed here is represented in Figure 1.

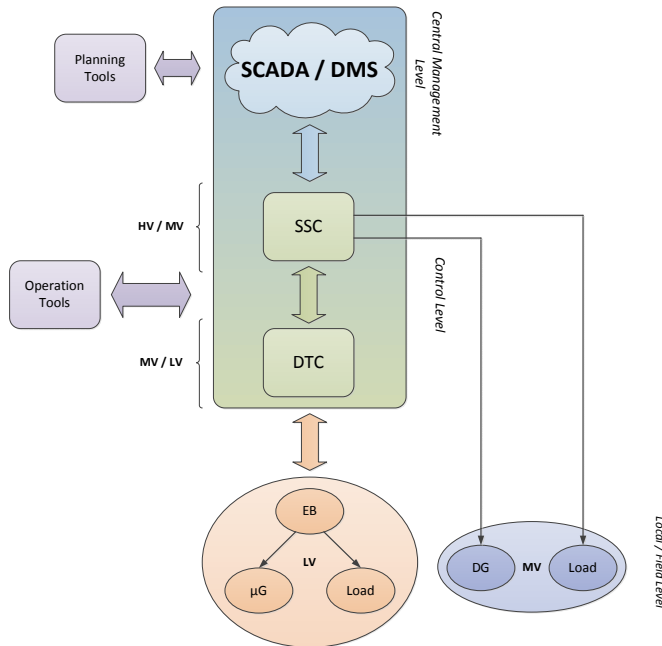


Figure 1. Proposed Control Architecture for Smart Grids

In this architecture, the MV grid will be managed by a Smart Substation Controller (SSC) housed at the HV/MV distribution substation level that will include local intelligence and several operational functionalities. Regarding the LV grid, it will be controlled by a Distribution Transformer Controller (DTC) located at the MV/LV substation level that will be responsible for managing the several DER (namely small controllable loads, under active DSM, and microgeneration –  $\mu$ G – units) at the LV level. At the LV level, advanced smart meters (named Energy Box – EB) associated to consumers and microgeneration sources will be used as interfaces not only to monitor but also to control these local resources. It must be stressed that the reference architecture for smart grids proposed in this research is based on the hierarchical architecture already implemented in the InovGrid test site in Évora (named InovCity) [7], [8].

The main focus of the development will be at the control level of MV and LV distribution grids where specific control functionalities must be developed in order to enable large scale integration of DER at the distribution level. The control and management of DG units connected to the MV will be performed at the HV/MV substation level, where the SSC will accommodate advanced functionalities and computational capabilities that will allow sending optimal set-points to DG units and other controllable network devices. This will allow integrating large amounts of DG without violating technical restrictions or compromising the robustness of operation. On the LV network, since microgeneration can introduce operational problems, these units must be managed using local control solutions, together with algorithms that will run at the DTC. Furthermore, active demand control must be included to ensure energy balance and ancillary services support to the network operator. Storage units at the LV and MV levels and other type of controllable loads, such as electrical vehicles (EV), must also be managed in real-time in order to mitigate negative impacts on the system.

In summary, the architecture defined here consists of 4 different levels with an integrated management and control strategy as follows:

- SCADA (Supervisory Control and Data Acquisition) / Distribution Management System (DMS) functionalities;
- HV/MV primary substation (SSC);
- MV/LV secondary substation (DTC);
- Microgeneration and active demand side (smart meters, inverter and home automation systems).

### B. Cost and Benefit Assessment

In order to be able to fully exploit the benefits from large scale integration of DER, especially RES due to environmental concerns, it is necessary to adopt new control strategies at the distribution system level. In that sense, the proposed architecture for smart grids can be regarded as a way to facilitate the integration of higher levels of DER (including DG units at the several voltage levels) in distribution networks.

Therefore, the costs of installing the proposed control solution as well as the benefits obtained from the advanced control functionalities to be implemented should be evaluated in order to correctly evaluate the interest of the proposed solution for each specific case.

Regarding communications, it is assumed that the communication infrastructure required to implement the proposed control architecture exploits the same Automatic Meter Reading (AMR) infrastructure adopted for remote advanced metering (usually referred to as smart metering) such as the one used in InovCity in Portugal [8]. It must be stressed that this infrastructure is supposed to be designed to support communication needs for control purposes, namely in terms of availability, reliability, interoperability and quality of service. This means that communications should not represent a substantial extra cost in the project.

The costs regarding the deployment of the several controllers mentioned in the previous section (including installation and operation cost) must also be assessed. The deployment cost includes mainly: a) the cost of the DTC and b) the cost of the advanced smart meter for either the microgeneration or the load (including flexible conventional load and EV) to be installed at the customer's premises.

Based on the experience gained in the InovGrid project and the work developed in [9], the cost for installing a DTC should be covered by the DSO. Indicative values for the several devices are as follows: 100 € for each advanced smart meter at the customer's site and 500 € for each DTC. Regarding operational costs, it comprises maintenance costs as well as fuel costs for non-renewable microgeneration sources such as microturbines used in Combined Heat and Power (CHP) applications, when they exist.

Regarding benefit assessment, several technical and economic benefits may be obtained, namely: reduction in active power losses, reduction on greenhouse gas emissions due to active losses reduction and to the displacement of central thermal generation units by RES, deferral of investment in network assets and improved quality of service (regarding both continuity of supply and voltage quality) [10], [11].

Finally, a cost / benefit analysis must be performed taking into account the benefits and drawbacks of large-scale DER integration in order to identify fair cost sharing mechanisms between the customers and the DSO.

### III. ADVANCED CONTROL FUNCTIONALITIES FOR SMART GRIDS

Presently, large-scale integration of DER in electrical distribution systems, particularly renewable-based DG, is limited due to the potential negative effects that these resources may have on grid operation. The resulting impacts are mostly related to violation of technical constraints regarding bus voltage limits and line/transformer thermal limits.

In order to overcome these drawbacks it is necessary to ensure a coordinated control and management approach exploiting the flexibility of DER, including controllable loads, DG sources and storage devices. In fact, the last decades have seen the emergence of DMS, which enable monitoring and control of distribution networks and include several functionalities related to protection schemes and control based on estimation of the power/current injections regularly updated by the information provided by communicating meters [12].

This approach enables the development of fully active distribution networks, where several DER can be controlled in order to efficiently manage the system as a whole. Since distribution systems are complex systems that include a larger number of components, decision-making processes tend to address these problems by resorting to the definition of control areas that cover a limited physical space. In particular, hierarchical control in distribution system has received most attention in recent years.

This paradigm has been developed within the framework of the MICROGRIDS [13] and MORE MICROGRIDS [14] projects to make use of the controls offered by local flexible generation, demand and storage devices in order to improve power quality, and energy losses. Several advanced functionalities related to this have already been addressed in several papers available in the technical scientific literature [15], [16].

Therefore, a set of advanced functionalities must be developed to enable maximizing the integration of RES in distribution networks. These new functionalities exploit a predictive control / management approach, aiming at checking the viability of network operation for some hours ahead, which requires short term forecasting of load and generation at the bus level. Such an approach requires the following functionalities:

- Advanced local forecasting tools to predict renewable generation and load consumption;
- Advanced local distribution grid monitoring / state estimation, exploiting also information obtained from the smart metering infrastructure deployed on the grid;
- Advanced coordinated voltage control exploiting controllable generation, flexible loads, storage devices and conventional On Load Tap Changing (OLTC) transformers and capacitor banks;

Furthermore, this vision may be extended by developing advanced DMS functionalities that will exploit a close interaction with Transmission System Operator (TSO), such as:

- Coordinated deployment of capabilities of DG units, distributed storage and active demand response to provide ancillary services to the TSO side (such as voltage control, branch overload relief and secondary frequency control);
- Coordination between the TSO and DSO grid actions to implement advanced functionalities.

#### A. Advanced Local Forecasting

Advanced forecasting tools must be developed in order to obtain reliable load predictions at the MV level for a time frame up to 3 hours ahead. These tools should focus not only on accurate estimating of load, but also on identifying the behavior and characteristics of this load, especially by identifying the volume of controllable and non-controllable load.

In this case, it is assumed that data is available from the DTC that will have aggregated LV network data (based on data pre-processing) and MV loads that will have dedicated smart meters.

Moreover, new advanced forecasting tools to make predictions of generation for DG units (based on wind power and solar photovoltaic – PV) at the MV level must also be developed for a time frame up to 3 hours. These tools should rely on measured data for local and regional PV and wind

generation, that can be complemented with external data related to weather and environmental variables (for instance temperature, wind speed and direction, radiation level and cloud covering).

The outputs of these modules will feed other control and management algorithms at the MV level such as advanced coordinated voltage control.

*B. Advanced Local Distribution Grid Monitoring / State Estimation*

Distribution state estimation must also be revised in order to ensure sufficient robustness that is able to overcome lack of data or poor quality data collected from smart meters or RTUs located in the grid by exploiting historical information.

Identifying the current network topology is essential in order to be able to achieve efficient control of the MV distribution system. This includes using status information of switching devices, real-time measurements, pseudo measurements (forecasted or historical load data) as well as available information from smart meters. In this case, synchronized information from the AMR infrastructure, Smart Global Positioning Systems (GPS) and synchronized Phasor Measurement Units (PMU) devices can also be used.

Furthermore, in order to ensure accurate results and estimated uncertainty, it is necessary to identify the minimum number and location of additional voltage and current sensors in the distribution network.

*C. Advanced Coordinated Voltage Control*

In order to maximize the integration of renewable energies in distribution networks, advanced operation strategies need to be developed and implemented at the HV/MV substation level that are able to control voltage magnitudes and real power injections. At a first stage, advanced control schemes must be designed for distribution devices (e.g. OLTC transformers, capacitor banks, and storage devices) in order to support the voltage profiles within the network in a coordinated way, taking also into account local voltage control capabilities. The coordination of these devices with power electronic interfaces of installed DG units is also essential in order to avoid overvoltages during low load periods and ensure that voltage constraints are not violated, thus avoiding the disconnection of DG. Secondly, new tools must be developed for supporting distribution system operation based on an integrated operational management of distributed flexibility (i.e. controllable demand, generation and energy storage).

Therefore, the development of an optimization tool to obtain solutions for a multi-temporal Optimum Power Flow (OPF) was proposed and is now under development, by exploiting the information from the forecasting tools, mentioned previously, and using state estimation results, in order to define set-points for OLTC transformers, capacitor banks, batteries and other storage devices, as well as controllable demand and controllable DG units. Technical constraints of the MV network linked to physical components limits must be taken into account. Also, several objective functions can be considered such as minimization of total active power losses (Figure 2. ), minimization of the number

of on load tap changes in the HV/MV transformers (Figure 3. ), minimization of spilled renewable energy (Figure 4. ) and maximization of the available flexible power that may be used for ancillary services.

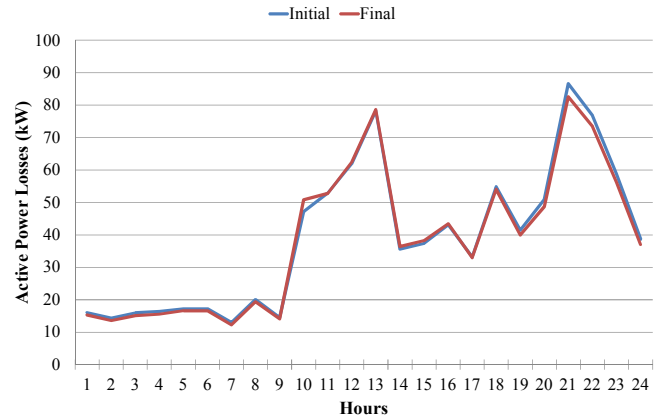


Figure 2. Active Power Losses

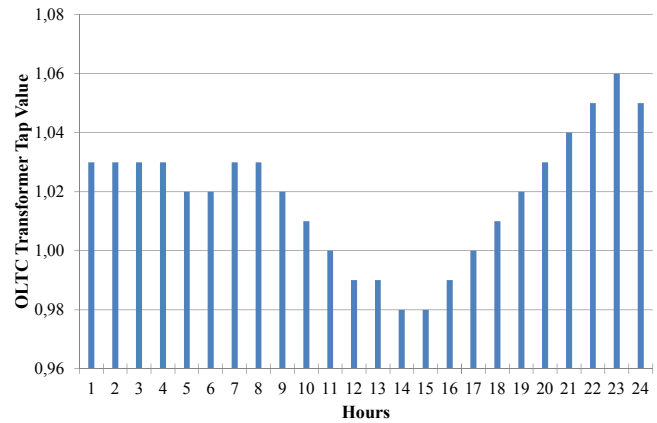


Figure 3. OLTC Transformer Settings

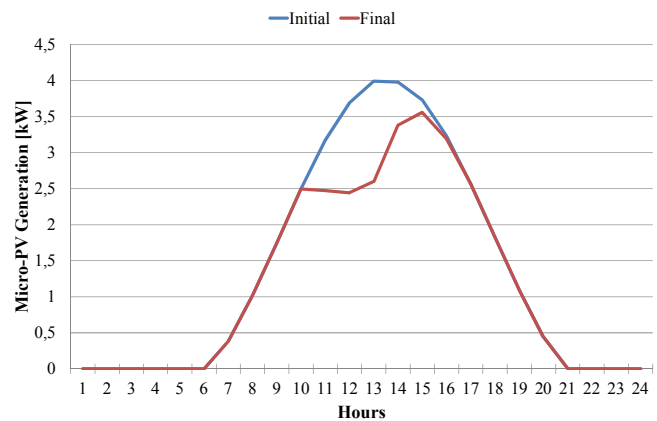


Figure 4. Renewable Generation Spillage

In particular, large-scale integration of variable RES in LV networks may cause voltage problems in scenarios with excess local generation and low demand, given the fact that these grids usually have a very low X/R ratio. In extreme cases, this

may even result in the reversal of the power flows in distribution lines to force excess generation through the MV/LV transformer. Therefore, in these cases, it may be necessary to spill some of this generation (as suggested in Figure 4. for a PV generator) in order not to compromise the operation of the distribution system [15].

In this context, voltage support may be regarded as an ancillary service that can be assured by different providers through specific bilateral contracts or under a market framework [17].

The integration of distributed storage devices, either stationary (batteries) or mobile (EVs) will be addressed in future work to be carried out.

#### IV. PROOF OF CONCEPT IN LABORATORY

In line with the specification of new management and control architectures for the distribution system (Figure 1. ), it is necessary to create realistic and adequate conditions for experimental validation and proof of concept. Therefore, INESC Porto developed an LV distribution microgrid laboratory, with several controllable microgeneration units and loads, as well as with the corresponding control interfaces and communication infrastructure that supports the integrated operation of all components. This laboratorial infrastructure is the physical space that allows process integration and pre-prototyping activities of physical devices and / or software modules, either for microgeneration units, grid control interfaces and communication devices. Being an integrated infrastructure, it allows testing individually and in grid integration conditions the concepts, algorithms and decision-making processes, as well as communication protocols, which allow the operation and control of distribution network in different operating conditions. The architecture of the laboratorial infrastructure incorporates the decentralized structure / hierarchy of control proposed for the operation and control of the distribution grid, as represented in Figure 5.

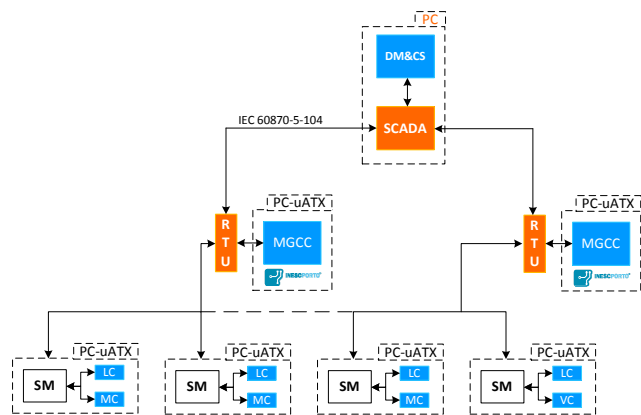


Figure 5. General Architecture of the Smart Grids Laboratory

The microgrid laboratory management and control structure was implemented considering three management and control layers, namely: the Distribution Management and Control System (DM&CS), which coordinates the operation of the distribution network; the Microgrid Central Controller (MGCC, functionally equivalent to the DTC), which ensures

the management and control of the microgrid and the lower control layer, constituted by the Smart Meters (SM, functionally equivalent to the EB) associated to the microgrid local controllers, namely: Microsource Controller (MC), Load Controller (LC) and the electric Vehicle Controller (VC).

Currently, INESC Porto's laboratorial infrastructure integrates the following equipment:

- An electric panel with six 400V busbars interconnected by switches and with thirty outputs connected to the different laboratorial equipment. All the feeders are commanded through contactors.
- A control and signal acquisition panel responsible for the laboratory automation. The system integrates a small SCADA system.
- A 3 kW wind micro-turbine emulator.
- 6 kWp of PV panels.
- 54 kW resistive load bank.
- LV cables emulators (100 A and 50 A).
- Two Flooded Lead Acid battery banks with 25 kWh capacity (for 1 h) and 128 Lithium battery cells (3.2 V, 40 Ah) for the EV charging prototype.
- Two three-phase groups of SMA Sunny Island inverters.
- Two SMA Sunny Boys and a Windy Boy, which can be coupled to the PV strings and to the wind micro-turbine emulator.
- Two single-phase DC/AC bi-directional inverter prototypes for testing vehicle-to-grid (V2G) concepts and for microgeneration applications.
- An AC/DC/AC 3-phase inverter with controllable active power output.

The configuration of the electric panel is very flexible, allowing the arrangement of different microgrid configurations. The SMA Sunny Islands allow testing microgrid operation when interconnected to the main grid or islanded. In case there is a grid failure, the Sunny Island DC/AC inverter defines the frequency and voltage magnitude reference, supplying the loads through the battery banks. This will allow testing the robustness of the developed prototypes and the validation of the microgrid emergency control strategies. The SMA Sunny Boy and Windy Boy will allow comparing the commercial solutions for coupling the microgeneration with the AC network with the developed AC/DC inverter prototypes, regarding the effectiveness of the additional control strategies developed. On the other hand, the AC/DC/AC inverter will also allow emulating controllable microgeneration technologies such as single-shaft microturbines or solid oxide fuel cells.

The laboratory supervision and automation is carried out through a SCADA system. This system is responsible for the electrical network configuration, protection and metering infrastructure supporting the laboratory operation. A

communication network is deployed consisting of an Ethernet infrastructure used to interconnect the different elements of the control structure. This network interacts with the SCADA system and provides a clean and independent data exchange medium over which is possible to ensure connectivity and emulate communication related performance parameters such as delays, losses, jitter, and other quality of service indicators associated to real-world communication solutions.

### A. Voltage Control in the LV Distribution Grid

As previously explained, the voltage rise effect in LV distribution grids is related to the low X/R ratio in this type of grids, as well as with the reduced simultaneity between load and renewable generation profiles such as solar PV. Under certain conditions, significantly high voltage profiles in LV distribution grids may lead to overvoltage tripping of microgeneration, thus limiting the possibility of increasing the amount of RES that can be integrated in the system without affecting power quality. In order to overcome this situation, it is necessary to develop efficient control mechanisms at the microgeneration power electronic interfaces for conditioning the power that is injected into the LV grid.

The possibility of conditioning the power injected by power electronic converters used in microgeneration units in an LV distribution grid is organized in a hierarchical structure, as represented in Figure 6. In the local control level (MC and power electronic converter of a microgeneration unit), the injected power is governed by a droop control functionality relating the node voltage deviations with active power injections. The higher hierarchical control level (the DTC or MGCC), as a supervision and control unit responsible for the operation and management of the LV grid, has the responsibility of periodically defining the most adequate parameters of the droop function operating at each microgeneration unit.

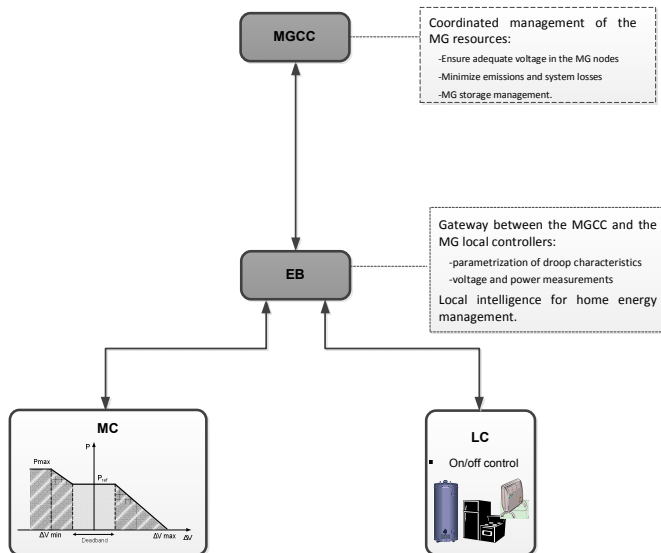


Figure 6. General Overview of the LV Grid Control

The general idea behind this local control rule is as follows: there is a voltage dead-band within which the operator defines the maximum power that can be injected in

the grid (which, in principle, corresponds to the maximum power that can be extracted from a micro wind generator or from a PV panel). If the voltage rises, the local control autonomously starts reducing the injected power. Conversely, if the voltage drops and if the injected power is lower than the maximum power that can be extracted from the primary source, the controllers allows for a power increase.

In order to implement the desired control functionalities within the laboratory infrastructure, several additional developments were required. First of all, commercially available power electronic interfaces for microgeneration units do not allow the implementation of the desired control functionalities. Therefore, power electronic interfaces for PV panels and micro wind turbines were developed. In PV panels, modifications in injected power are provided through the modification introduced in the maximum power point tracking algorithm, thus temporally degrading the operating conditions of the panel [18]. For micro wind turbines, the solution for locally absorbing the power that cannot be injected in the grid was achieved through the connection of a dump load for the dissipation of the excess of power [19].

Additionally, and regarding the need of developing interfaces for LV grid managing and control purposes EB and DTC level interfaces were also developed. Figure 7. shows the smart meter graphic interface, concentrating lower level information regarding microgeneration, consumption and possibly EV connected to that node. The smart meter has bi-directional communication capabilities, being able to receive set-points from the MGCC and redirect them to the local controllers and at the same time sends measurements and other type of information upstream. The microgrid high level management and control functionalities are expected to reside in the MGCC. The information received from the smart meters will be aggregated according to the operator needs.

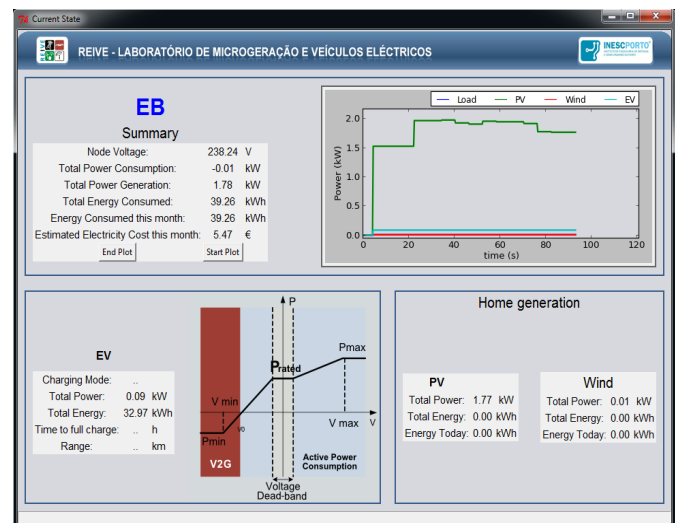


Figure 7. Energy Box Interface

As shown in Figure 8. , aggregated information may include real-time data acquired locally at the MV/LV substation and aggregated data from the smart meters, such as power generation, consumption level, EV, responsive loads

and power quality information. The information received is supposed to be used by local software modules, responsible for managing the MG technical operation.

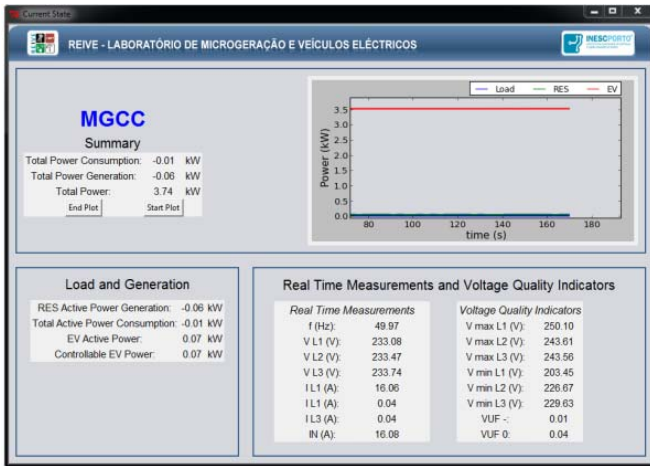


Figure 8. General DTC Interface

### B. Experimental Results

In order to test the effectiveness of the LV distribution grid voltage control strategy previously described, a simple experimental set-up was organized. It consists of the MV/LV distribution substation, a LV cable simulator and a LV node contained a controllable load, a PV panel and a micro wind turbine emulator, both of which are connected to the grid through power electronic converters incorporating the previously mention drop control strategy. The operation of the system is supported through the EB and DTC interfaces, as well as through an Ethernet based communication infrastructure. The overview of the test conditions can be observed in Figure 9.

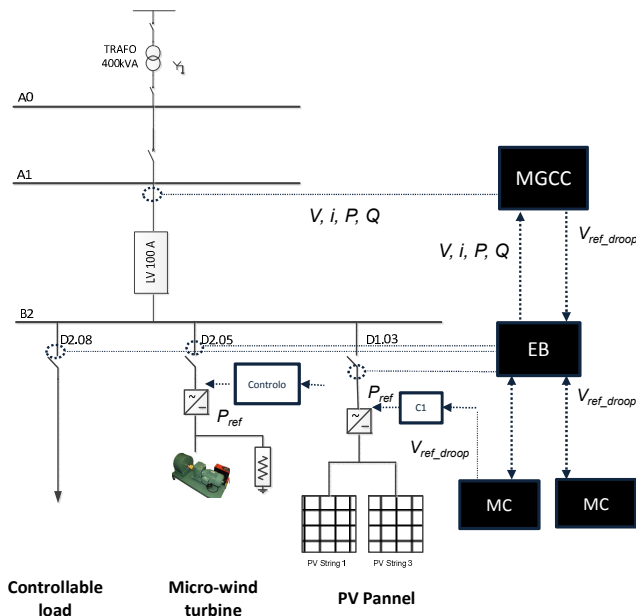


Figure 9. Overview of the Experimental Set-up

For the experimental set up presented in Figure 9., the B2 load was kept constant. The main objective of the experiment is to demonstrate the performance of the droop control incorporated at the microgeneration units power electronic converters (single-phase units) and its remote parameterization through the MGCC. Figure 10. provides an overview of the main results that were obtained.

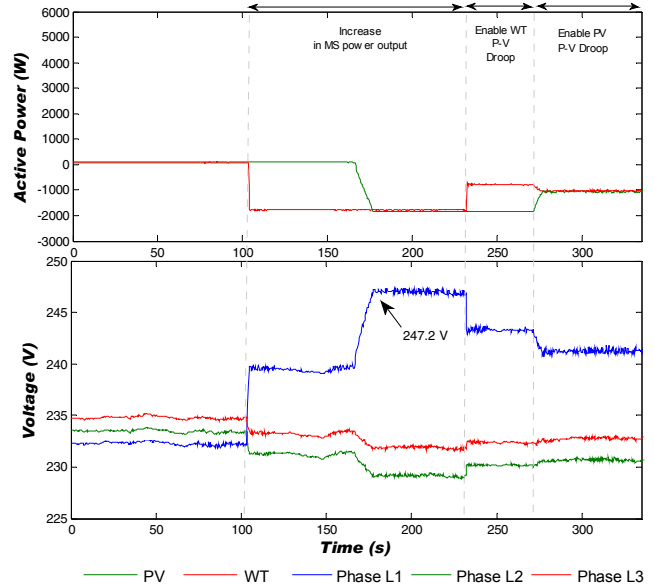


Figure 10. Main Results of the Experimental Procedure

The main steps of the experimental procedure consisted on:

- 1) At  $t = 104$  s, an increase in the active power production in the micro wind generator emulator was simulated. As a result, a significant increase in the phase a voltage occurred.
- 2) At  $t = 167$  s, an increase of the active power production in the PV panel was simulated. As a result, another significant increase in the phase a voltage was observed.
- 3) As a result of the actual phase a voltage, which is monitored by the MGCC through periodic information remotely sent by the EB, it was decided to activate the droop control functionality in the micro wind turbine emulator at  $t = 230$  s, which lead to a reduction in the active power injected by this unit, as well as a reduction in the phase voltage.
- 4) At  $t = 270$  s, the droop control functionality in the PV panel power electronic interface was also activated. Both units were generating the same amount of power and their droop control functionalities were parameterized equally. Therefore, it is possible to observe they share the active power reduction, being possible to observe a significant reduction in the corresponding voltage.

The obtained results from the experiment carried out clearly demonstrate the voltage control capabilities the decentralized control structures proposed for the distribution grid can provide. However, additional research is still required

in order to derive procedures able to automatically suggest adequate droop setting parameters to the operator, taking into account grid operating conditions.

## V. FINAL REMARKS

The progressive deployment of distributed RES especially the ones based on variable renewable technologies requires the development of a more flexible operation and management of the distribution system, namely exploiting different DER such distributed systems for active load management and storage devices.

Consequently, new operational tools for managing distribution networks at the several voltage levels systems are required in order to ensure a more efficient management of the whole distribution system within the smart grid paradigm. In this context, advanced coordinated voltage control emerges as a key functionality for supporting distribution network operation, involving a new set of functionalities for DMS.

Also, it must be stressed that modest DER integration does not require advanced and sophisticated control and management architectures, such as the one presented in this paper. However, large-scale DER penetration requires the deployment of the proposed concept as an efficient solution to deal with the increased complexity of the grid management. This will provide a better insight that can, and potentially lead to the development of specific regulatory framework that can include policies based on incentives for encouraging the adhesion of DER owners to these concepts.

Finally, testing and validation of these new advanced functionalities in a laboratory environment specially developed for this purpose is an added-value since it will enable evaluating the performance of the tools developed as well as the feasibility of the control and management architecture proposed in this paper.

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