

EXPLOITING AUTOMATED DEMAND RESPONSE, GENERATION AND STORAGE CAPABILITIES FOR HIERARCHICAL FREQUENCY CONTROL IN ISLANDED MULTI-MICROGRIDS

Nuno José Gil
INESC Porto & ESTG Leiria
Portugal
ngil@estg.ipleiria.pt

J. A. Peças Lopes
INESC Porto
Portugal
jpl@inescporto.pt

Abstract – This paper presents a hierarchical approach to deal with the problem of frequency control in a medium voltage network comprising several microgrids and distributed generation sources operated in islanded mode. The role of automated load control and the possible contribution of local storage devices and grid-connected electrical or hybrid vehicles with onboard storage systems are some of the main developments assessed in this paper.

The hierarchical approach described here proves to be capable of dealing with large numbers of distributed microsources when performing tasks related to coordinated frequency control.

Keywords: Distributed generation, microgrid, frequency control, hierarchical control, demand control, vehicle-to-grid.

1 INTRODUCTION

Standard Distributed Generation (DG) units have been in use in distribution networks for quite a while. Currently there is a new trend that is leading to the installation of large numbers of micro-generation units in LV distribution grids. This large number of generation devices can hardly be considered manageable from a technical or commercial point of view unless new control architectures are adopted. In order to bring manageability to the system, the aggregation, in several levels, of groups of these small units operating in the same network, is the solution. Such approach will also open the possibility of obtaining contributions from micro-generation to participate in ancillary services provision.

Under this approach a new concept is being considered – the microgrid. A microgrid consists of a set of LV feeders on which several microsources, storage devices and controllable loads are connected (Figure 1). A microgrid also includes a local communication system and a hierarchical control structure which is headed by

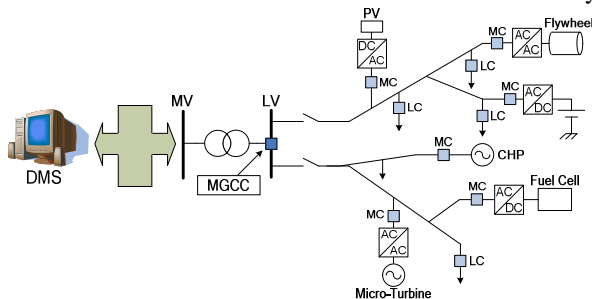


Figure 1: Microgrid concept. The MV network would include several of these LV microgrids.

the MGCC – MicroGrid Central Controller.

The enlargement of the control concept to a large number of microgrids leads to the multi-microgrid concept, a higher level structure formed at the MV level, consisting of several LV microgrids and DG units connected on adjacent MV feeders (Figure 2). The possibility of having a large number of controllable microgrids, DG units and MV loads under Demand Side Management (DSM) control requires the use of a hierarchical control scheme, headed by the CAMC (Central Autonomous Management Controller), which receives measurement data from the RTU (Remote Terminal Unit) and enables an efficient control and management of this kind of system. These concepts are being developed under the EU financed More-MicroGrids Project.

The implementation of controlled Load-Shedding programs (also known as Demand Response, Load Curtailment, Dispatchable DSM, etc.) was always thought

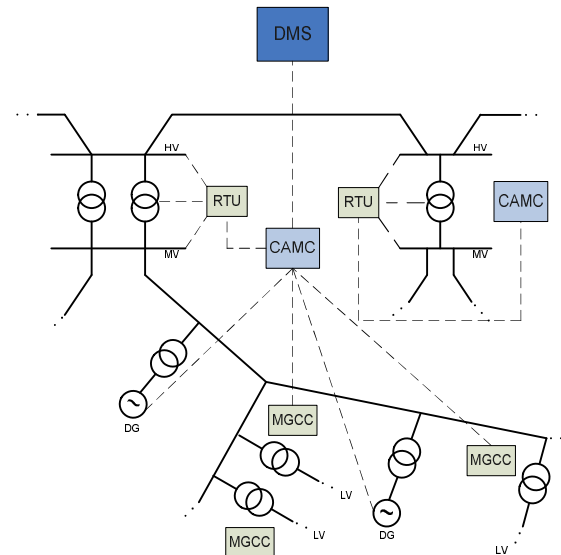


Figure 2: Relationships between the control system and the microgrids and DG units in a multi-microgrid MV network.

of as useful in this kind of scenario. Loads that can be managed at the microgrid level are, for instance, normal customers (rewarded with special tariffs for allowing having their consumption partially curtailed if needed) or even electrical vehicles while charging their batteries. This concept is investigated in this paper taking into account the expected limitations that derive from the fact that the hierarchical control system isn't capable of

near instantaneous reaction, due mainly to speed limitations of the communication systems.

With the market introduction of vehicles containing storage systems, it is expected in the future that large numbers of these devices may be plugged into wall sockets. This may be particularly true for plug-in hybrid types, which typically would need to remain connected for large periods of time in order to be available when needed. This kind of storage resource, if properly harnessed and probably subject to incentives, could be used to fulfill the task of purpose built distributed storage systems. The proposed hierarchical control system could be quite helpful in coordinating the response of large numbers of these unorthodox storage devices, while keeping in mind the slower response that an extensive communication system may impose.

The inclusion of these new concepts into this paper aims to provide a view of the way how distribution grids can be operated in the future under a full SmartGrid concept.

Therefore, in this paper it will be described how an intermediate managing control structure – the CAMC, which controls the downstream agents depending from a MV bus of a HV/MV distribution substation – can be used to accomplish some management tasks in this kind of multi-microgrid system, namely frequency control in case of MV network islanding and also load-following in islanded operation.

To test this concept, a dynamic simulation platform built around Eurostag and MATLAB software packages was developed and is used in this work, proving its flexibility and adequacy, namely regarding simulation times.

2 HIERARCHICAL CONTROL

2.1 Introduction

The hierarchical control system can be represented by the block diagram in Figure 3. Only Control Levels 2 and 3 are implemented, as this work deals with a single autonomous multi-microgrid (a single MV network) without any intervention from the Distribution Management System (DMS) that is dealing with several MV networks.

The commands needed to balance generation and load are originated in the CAMC. These commands are sent to MGCCs, to independent DG units and also to controllable MV loads. MGCCs act as an interface between the CAMC and the internal active components of the microgrids, so that the CAMC doesn't need to have the details of each microgrid's constitution.

The CAMC will respond to power system frequency changes in a way similar to the one implemented in regular Automatic Generation Control (AGC) functionalities [1]. A PI controller is used to derive the requested global power change needed to restore system frequency. Then, an economical allocation algorithm will allocate contributions for this power change among all the power generation units, controllable MV loads and MGCCs under CAMC control but only if they are will-

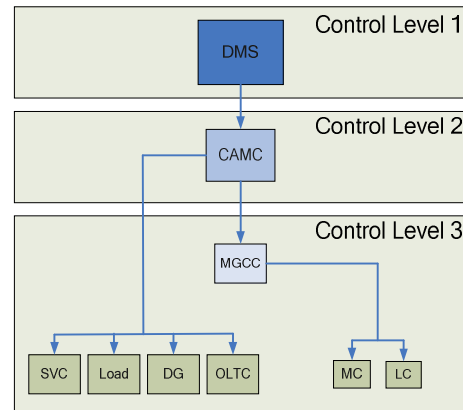


Figure 3: Hierarchical control scheme. The implementation considered here only focuses on control levels 2 and 3.

ing, at that point in time, to participate in frequency regulation.

Each of the MGCCs will also allocate the necessary power changes among its subordinate controllable loads and micro-generation units, through the Load Controllers (LC) and Microsource Controllers (MC). Some of these microsources do not usually have regulation capabilities (e.g., PV or wind generation, due to limitations in primary resource availability) and will not normally be asked to change power generation.

It should be noted that the CAMC will only act if strictly needed and will not try to globally change setpoints in order to achieve a near optimum point of operation of the system. This justifies the choice of using power setpoint variations and not absolute power setpoints in order to make it possible to have a higher order control system, either automatic or manual, that would independently adjust microsource or DG output to setpoints other than the system optimal ones. One example of this “control system” could be the microsource individual owners who would adjust microturbines, for instance, according to their heating needs.

2.2 Load-Shedding Specifics

The approach to load-shedding is, in this context, fairly different from the one used in conventional systems, as the controllable loads will be under hierarchical control system supervision which isn't capable (mainly due to communication system limitations) to act in near instantaneous time-frames. Therefore, in these circumstances, load-shedding is not expected to reduce the amplitude of frequency excursions in the few seconds following a disturbance. It should be seen more as a kind of secondary reserve – rather than an emergency resource – helping the frequency return to the rated value faster or without depending so much on the availability of renewable resources or other generation systems.

In order to make the control algorithm as generic as possible so that its future evolution and software maintenance was not impaired, loads are regarded simply as negative generation, with few exceptions. In this way, a seamless integration of all kinds of controllable elements is achieved, as they share a substantial part of the prop-

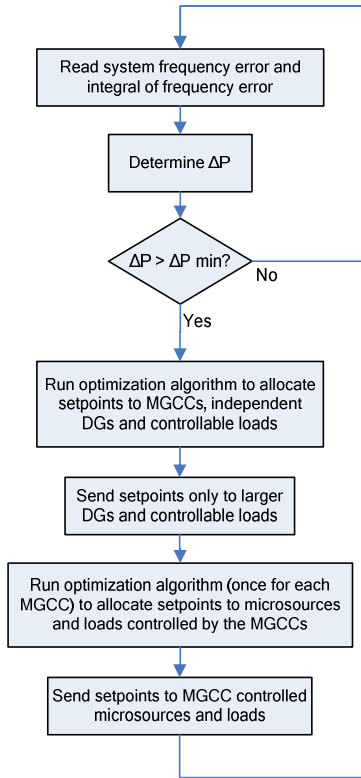


Figure 4: Implementation flowchart. This procedure runs once each period T_s .

erties relevant to the control (e.g., associated costs, limits on power variations, etc.).

The main difference that distinguishes between microsources and controllable loads resides on the fact that it is not feasible to keep loads disconnected indefinitely, so it is mandatory to reconnect them after the system frequency recovers. This is accomplished through the use of a control loop that runs on a larger time-scale, reconnecting loads after the system is running on a near steady-state condition for a predefined period of time.

Starting from the assumption that the system, after some time running stable and near the rated frequency, is capable of supporting the connection of some more loads, the control systems starts to reconnect the most expensive ones first. This is done step by step, always ensuring that there is enough available reserve on the multi-microgrid in order not to unnecessarily compromise the system's stability. Before each reconnection, the control system waits for the frequency to stabilize once again.

2.3 Control Details

System's frequency is continuously monitored by the CAMC (Figure 4). Every time interval T_s (sample time), if triggered by significant changes in frequency, the CAMC will send control setpoints to every MGCC, other DGs and controllable loads. This sample time T_s cannot be very small, mainly because of the constraints imposed by the communication system on which this control system depends.

Therefore, the frequency error and the frequency error integral will be used to determine the additional

power ΔP (1) to be requested to the available contributors under CAMC control: MGCCs, DGs and controllable loads.

$$\Delta P = \left(K_p + K_I \frac{1}{s} \right) \times (f_{rated} - f) \quad (1)$$

Where:

K_p predefined proportional gain;

K_I predefined integral gain;

f_{rated} nominal frequency value;

f actual frequency value.

It should be noted that this additional power can have negative values if the frequency rises over its rated value. In this way the CAMC can also respond to other disturbances, such as load loss while in islanded mode, commanding the distributed generation to reduce power output (including micro-generation curtailment, if necessary), eventually reconnecting some loads still disconnected at the moment or even restarting the charging procedure of grid connected hybrid vehicles.

Limits have to be enforced on the value of ΔP . Its value cannot be larger than the available reserve and, if ΔP is negative, its absolute value cannot be lower than the total generation available for curtailment.

If the absolute value of the required power variation ΔP is larger than a predefined threshold (related to a deadband), the control system will proceed to determine how to optimally distribute the power requests through the available sources. Unitary generation costs for each of the sources (MGCCs and other DGs) are used for this purpose. The optimization is based on standard linear optimization techniques:

$$\begin{aligned} \min_x z &= c^T x \\ \text{subject to} \quad \sum x &= \Delta P \\ x &\geq b_1 \\ x &\leq b_2 \end{aligned} \quad (2)$$

Where the vectors represent:

c generation cost and load curtailment prices;

x generation or load setpoint variations;

b_1 smallest variations allowed (lower bounds);

b_2 largest variations allowed (upper bounds).

The set of restrictions (2) can also define which generators/loads participate in frequency regulation. This can be done by setting to zero the i^{th} elements of both b_1 and b_2 corresponding to units that cannot be adjusted.

Because loads are considered as negative generation, the corresponding coefficients (elements in vector c of prices) are negative.

In order to avoid globally changing setpoints (e.g., decreasing production from expensive microsources and replacing them with less expensive ones), it is necessary to adjust the lower and upper bounds in (2) according to the ΔP value:

$$\begin{cases} \Delta P > 0 \Rightarrow b_1 = 0 \\ \Delta P < 0 \Rightarrow b_2 = 0 \end{cases} \quad (3)$$

The enforcement of these conditions (3) assures that no microsource will decrease its production so that another can increase it (i.e., there will not be any unsolicited power transfers between microsources).

This optimization is performed each period T_s and will originate a vector representing the power generation changes to be requested to microgrids (MGCCs), independent DG units (e.g., CHP) and loads (MV load-shedding operations).

Each MGCC will now use the power change requested by the CAMC to establish the main restriction of a new optimization procedure (identical to the one used before by the CAMC) which will determine the power changes to be requested to microsources and controllable loads under MGCC control.

3 VEHICLE-TO-GRID CONTRIBUTION

3.1 Concept Description

The concept of vehicle-to-grid (V2G) consists in a very large scale use of plug-in hybrid vehicles that are connected to the LV grid. This kind of hybrid vehicle is supposed to remain connected to the mains when not in use (typically at night) so that it is fully charged when needed, and is meant to run mainly from batteries. Typical current standard hybrid vehicles have low power electrical drive units and small batteries with a storage capacity of only around 1-2 kWh. Future plug-in hybrid vehicles would need larger batteries and more powerful drive systems which would make V2G applications more convenient [7]. Assuming that a power converter is adapted to the vehicle so that power could be delivered to the grid, one could expect that several kW might be injected for relatively large periods of time, if needed [7]. In this research, it was assumed that the interface inverters of such devices are of the Voltage Source Inverter (VSI) type, which allows power control based on frequency droop [6]. A cluster of several of these vehicles together with other storage devices (flywheels and batteries) could, if integrated in the control system of a microgrid, efficiently establish a storage reserve that would be of great help to the islanded operation of the network at the microgrid and multi-microgrid levels.

3.2 Contribution Possibilities

Storage devices can help in two possible ways: a) they can act autonomously, with their output power P_{VSI} responding to system frequency changes providing energy used to balance initially the system using a proportional control element as described by (4) or b) they can receive setpoints controlled from a central location, in a hierarchical way.

$$P_{VSI} = K_p \times (f_{rated} - f) \quad (4)$$

These two control methods are not mutually exclusive: while an autonomous response will undoubtedly improve the system's response to the initial frequency deviations following a disturbance, the hierarchical system can take over after that initial response and real-

locate each source and storage element contributions according to some predefined criteria. This two-step approach can be justified by the intrinsically slow nature of the hierarchical control scheme, which suggests that grid connected storage devices under hierarchical control should be regarded as secondary reserve while, in order to be able to limit initial frequency excursions, storage devices must be capable of acting autonomously if necessary. However, these actions are only possible while enough energy is stored in the storage devices. From the simulation point of view, the implementation of such control capability required a step by step evaluation of the energy injected into the grid and a comparison with the available nominal storage values in each existing storage or cluster of storage devices.

4 POWER SYSTEM MODELING

Eurostag 4.2 was chosen as the main power system modeling platform. However, Eurostag is unable, on its own, to provide enough flexibility to allow for the implementation of complex control algorithms. Because of this limitation, the hierarchical control algorithm was implemented in MATLAB which calls Eurostag for simulation runs which last for the time defined as the CAMC sample time. At the end of each run, the frequency value and the integral of the frequency error are extracted from Eurostag data files and used to determine the new setpoint values. Additionally, the estimated communication system delay times are also calculated and the Eurostag data files are then modified, in order to enable setpoint modification and load variations on the next dynamic simulation run.

Some of the dynamic models of the power system components came directly from Eurostag's library but most of them where not available in the version of Eurostag used and had to be implemented in this platform. This was the case of the Double Fed Induction Machine Wind Generator (DFIM), storage elements with VSI, the GAST Microturbine and the SOFC Fuel Cell (the two last generators are used inside each microgrid).

The DFIM model is based on the approach described in [2-3] but includes additional modules for pitch and de-load control which could enable it to participate in primary frequency regulation [5].

The fuel cell and microturbine models are based on [4] with a few small adaptations.

A small diesel generator was also considered, required only to enable the network to have some frequency regulation capability, namely when the hierarchical control is disabled.

As already mentioned, the VSI model assumes the presence of some type of storage element coupled to it. As most of the user models in Eurostag, it is modeled as a power injector and is programmed to emulate the behavior of a synchronous machine, e.g., injecting active power when system frequency transitorily drops [6]. The VSIs can also be controlled by two different and complementary systems, as mentioned before, so they are equipped with a standard proportional controller and

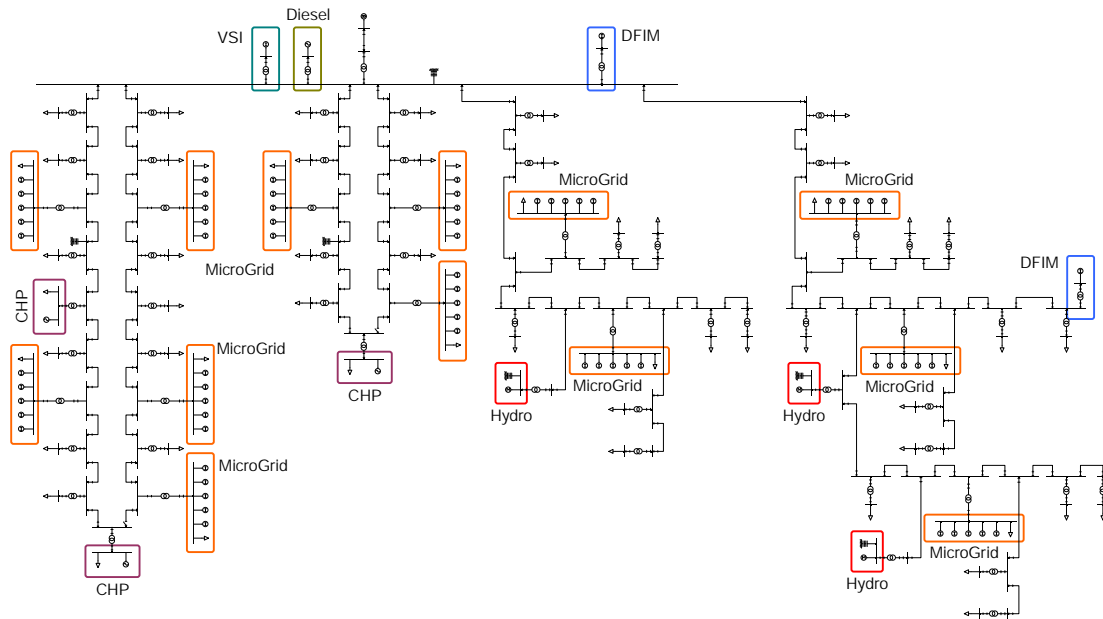


Figure 5: The complete test network.

also respond to setpoints received from the control system.

As the storage element is limited in capacity, the VSI can only inject power for a certain period of time before its reserves are depleted.

5 TEST SYSTEM

The adopted test network represents what could possibly be the typical structure of a MV grid containing multiple microgrids and several kinds of larger DG systems (Figure 5).

In this network one has assumed four zones, two rural and two urban (the loops in Figure 5, on the left), connected to a HV/MV substation. We can find in this system a relatively large number of microgrids, all connected to MV buses, and also some other typically DG oriented generation systems: a small diesel group, several CHP and hydro units, two doubly-fed induction machines (DFIM) corresponding to wind-generator systems and a storage element interfaced with the MV grid via a voltage source inverter (VSI). The approximate active power initially generated by each of these units, in the considered scenario, can be found in Table 1, along with the rated power of each of the units.

All the microgrids have a 150 kW / 50 kVAr equivalent controllable load and also the same mix of micro-

Source	Output Power (MW)	Rated Power (MW)
Diesel	1	1.1
VSI	0	1
DFIM 1 & 2	4 / 2	9
Hydro 1, 2 & 3	1.5 / 1.5 / 0.8	2.2 / 2.2 / 1.1
CHP 1, 2 & 4	1 / 1 / 0.5	2.1 / 2.1 / 1.1
Microgrids (13)	0.1	0.25 (+0.15 VSI)

Table 1: Test network initial active power generation.

sources: a small wind-generator, a fuel cell, a microturbine, a photo-voltaic generator and a storage element connected to the grid via a VSI (representing storage elements, including grid connected hybrid vehicles).

There are also some capacitor banks that are used for two purposes: to guarantee a better voltage profile throughout the network and, additionally, to provide sufficient reactive power to balance reactive generation and reactive load under islanded operation.

6 TEST CASE RESULTS

6.1 Test Case Setup

The test case analyzed shows a situation where the MV network containing the microgrids is importing approximately 5.3 MW of active power from the upstream HV network, in order to be able to supply a total load of 19.9 MW.

Starting from this point, in steady-state, the HV/MV branch is disconnected at $t = 10$ s and the multi-microgrid system will become islanded. In order to evaluate the load following capabilities of this control approach, it was assumed that at $t = 110$ s the load at several nodes begins to change at a rate of 4% per second for 10 s (for total increase of nearly 0.9 MW).

The sample time in use is $T_s = 5$ s. Lower values can accelerate the system's response but, even if technically possible to attain, they could also create some stresses on the control system. The most adequate value will ultimately depend on the communication system in use and on the mix of microsources and other DGs on the system.

6.2 Results

The first results, in Figure 6, show how the hierarchical control present in this multi-microgrid manages to recover the frequency to the rated value after the islanding occurred. Although the minimum frequency value

after the disturbance remains practically unaltered, in the moments that follow the system's behavior is much better.

The frequency recovery is due to the fact that the CAMC is sending setpoints to the microgrids and other DG units dispersed on the MV network. The Diesel group also plays a part but, as it is working near its maximum limit, the contribution is very modest. In Figure 7 the setpoints sent to one of the microgrids and to one of the DGs (a CHP unit) are shown, together with the corresponding output power. The order by which the microgrids or the DG units start to contribute is based on their cost as a direct consequence of the optimization method adopted. Therefore, in this case, it becomes clear that the microgrids are considered to be less expensive than the CHP unit. Figure 7 also shows how the

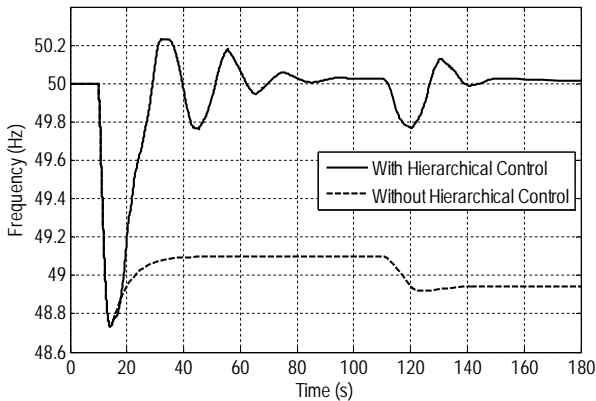


Figure 6: Frequency with and without hierarchical control.

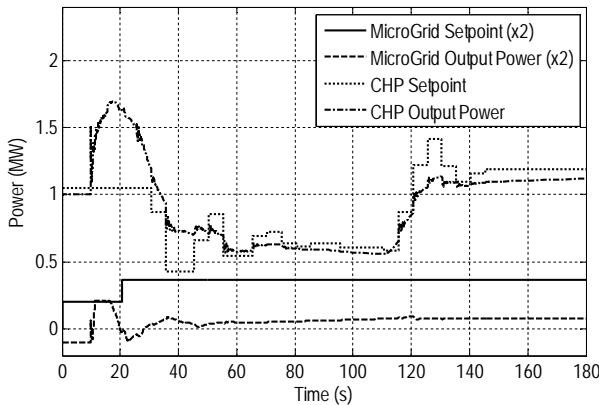


Figure 7: Example setpoint commands and output powers.

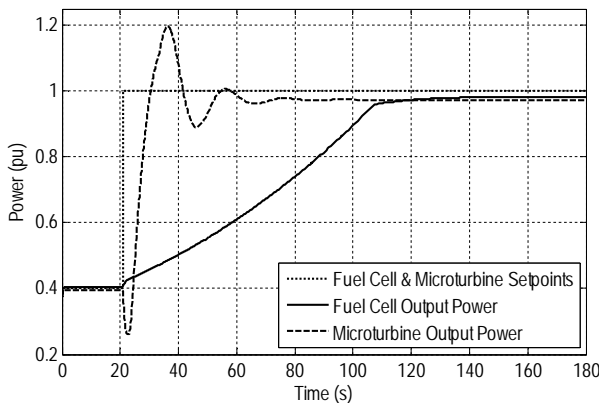


Figure 8: Example setpoint commands and output powers inside one of the microgrids.

algorithm is ready to cut generation in case the frequency rises above the rated value (generation curtailment).

The sources inside the microgrids are also subject to setpoint attribution according to a similar price dependent optimization algorithm. Figure 8 shows how the microgrid setpoint translates into individual setpoints for each of the microsources inside that same microgrid.

As previously mentioned, the hierarchical control algorithm is capable of acting on controllable loads, integrating them in the optimization process. The expected benefits include the increase in system response speed (Figure 9), while still complying with the optimization rules (in this case, economically sensible) adopted by the algorithm.

All the previous simulation results benefit from the usage of the storage elements as active and autonomous participants on frequency regulation. As mentioned before, this was accomplished through the use of proportional controllers and is considered essential to limit the initial frequency deviation following any disturbance, due to the very fast response of this kind of autonomous control. The next picture (Figure 10) clearly illustrates the importance this kind of fast control has when acting together with the proposed hierarchical control scheme. The autonomous proportional control on the storage elements significantly improves the minimum value of frequency after the main disturbance from 47.60 Hz to 48.75 Hz.

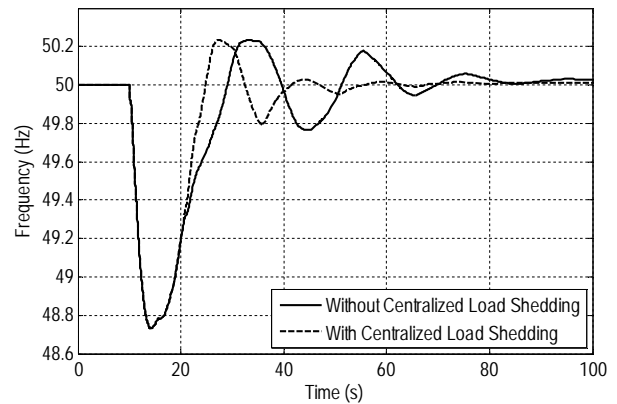


Figure 9: Comparing system response with and without centralized load-shedding.

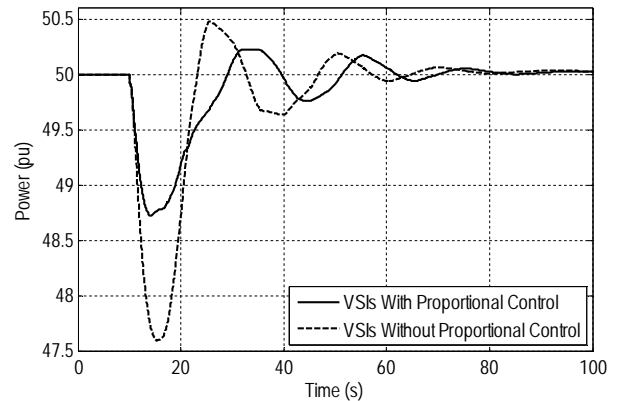


Figure 10: System response with and without autonomous proportional control in storage devices inside microgrids.

As mentioned before, storage elements (which include the vehicle-to-grid type) can also be centrally managed by being included in this global optimization approach. This control scheme is used in addition to the proportional control previously mentioned and is exploited only if the storage elements have enough energy reserves available. As these storage elements have a very fast response, it is expected that the possibility of increasing their output power will reduce the need to perform load-shedding actions. The results obtained corroborate this assertion showing that, when the storage elements inside the microgrids are centrally managed, no load-shedding occurs inside these microgrids. In fact, without centralized management, all the thirteen MGCCs requested load-shedding operations for several times after $t = 145$ s (totaling nearly 660 kW after $t = 180$ s), while with centralized management no load-shedding occurred.

7 CONCLUSIONS

The feasibility of the use of this kind of control system approach when used in large size distribution systems was demonstrated on a test system.

Tasks related with coordinated frequency control were successfully fulfilled, either after islanding or for load-following purposes. The setpoint modification commands sent to DG units, microgrids and controllable loads, enable the frequency to return to the rated value in a reasonable amount of time.

Centralized load-shedding, albeit not as fast as the conventional, independent approach, has shown to be of some help in this frequency recovery, while keeping the compliance to the economically sensible optimization rules used in this approach.

The presence of storage devices in the network, including those of the vehicle-to-grid type, proves essential to manage the initial frequency excursion following large disturbances. Also, the inclusion, in the hierarchical control system, of the storage devices power output setpoints, has also shown to be able to alleviate the burden on load-shedding.

The implemented simulation platform and algorithm are flexible and fast, being capable of dealing with relatively large networks and numbers of distributed devices with simulation times, in this case, approaching real-time, even on a modest laptop.

Hierarchical control is expected to provide a flexible, easier to implement and potentially cost effective way to efficiently control networks with multiple microgrids and high penetration levels of DG. However, this new control paradigm will require substantial changes to the standard practice for distribution networks management, namely regarding protection and automation systems which will need to be adjusted or developed to allow MV islanded operation.

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Nuno José Gil received the Electrical Engineering degree (five-year course) in 1997 from the University of Coimbra, Portugal, and the M.Sc. degree in 2003 from the University of Porto, Portugal, where he is presently pursuing the Ph.D. degree in Electrical Engineering. Currently, he is an Assistant Professor at the School of Technology and Management – Polytechnic Institute of Leiria, Portugal, and a Researcher in the Power Systems Unit of Instituto de Engenharia de Sistemas e Computadores do Porto (INESC Porto), Portugal.

J. A. Peças Lopes (M'80–SM'94) received the Electrical Engineering degree (five-year course), the Ph.D. degree in electrical engineering, and the Aggregation degree from the University of Porto, Porto, Portugal, in 1981, 1988, and 1996, respectively. He is an Associate Professor with aggregation in the Department of Electrical Engineering, Faculty of Engineering, University of Porto. In 1989, he joined the staff of Instituto de Engenharia de Sistemas e Computadores do Porto (INESC Porto) as a Senior Researcher, and he is presently Coordinator of the Power Systems Unit.