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Hierarchical Frequency Control in Multi-MicroGrids: The Participation of Electric Vehicles

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SUMMARY

The operation and planning of Low Voltage (LV) and Medium Voltage (MV) distribution networks have been changing over the last decade. Due to the presence of Distributed Generation (DG) and microgeneration, an active role has been attributed to these networks in grid operation. For this accomplishment, different conceptual approaches were developed. In [1], a hierarchical control structure was defined, considering that DG units, onload tap changer transformers, static var compensators and loads can be controlled by a hierarchically higher entity, the Central Autonomous Management Unit (CAMC). The CAMC is also responsible for the management of specific LV networks, the MicroGrids (MG), which in turn have autonomy to manage their loads and microgeneration units through an entity called MicroGrid Central Controller (MGCC). A MV grid with these characteristics plus some storage devices would then be called a Multi-MicroGrid (MMG), being, among other functionalities, able to operate isolated from the upstream network.

The recent appearance of a new type of load to the system, the Electric Vehicle (EV), expected to be largely integrated in the electricity grids in the upcoming years, has a great potential for adding controllability to the MMG. In this paper, an EV control droop (see [2]) will be introduced to improve the MMG performance when EVs operate as active elements. EV controllers are then able to receive setpoints from the CAMC and also actively update the droop settings in order to deal with different events that may occur on the MMG, for instance when moving from interconnected to islanded mode of operation.

The performance of the MMG with controllable EV will be compared with a MMG without the participation of EV. Additionally, multiple philosophies for setting the droops will be tested, considering that EV may inject power into the grid as storage devices or just act as controllable loads. Simulation results were obtained exploiting a dynamic simulation platform developed using the EUROSTAG and MATLAB environments.

KEYWORDS

Distributed Generation, Frequency Control, Multi-Microgrid, Electric Vehicles.

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1. INTRODUCTION

The increased presence of DG on distribution networks has lead to the development of new concepts able to deal with the management of the increased system complexity. The MMG concept exists at the MV level and consists, at its simplest form, in several MicroGrids and DG units connected on adjacent MV feeders. The MicroGrid aggregates several microsources, storage devices and controllable loads connected on the same LV feeder. All of this is interconnected through a local communication system and a hierarchical control structure managed at the MG level by a MGCC and at the MMG level by the CAMC [1].

The hierarchic control capabilities of this structure can be used to operate the MMG in islanded mode, in case any emergency occurs. This ability takes advantage of all the controllable elements inside the MMG. The fastest devices are of the highest importance to maintain the stability of the system in islanded mode and during the transition to this mode of operation. Storage elements, such as flywheels, are usually included in this group. However, other kinds of storage devices can be used, such as dedicated batteries or the batteries of EVs currently connected to the grid for charging purposes.

This work builds upon the hierarchical control structure defined in [1], now considering the inclusion of EVs as part of the set of controllable elements. Therefore, it was assumed that EVs can receive operation setpoint commands from devices higher in the control hierarchy. EVs can also be enabled to make use of their own autonomous control capabilities.

The MMG canonical control levels do not become substantially modified by the inclusion of the EVs in the system (Figure 1).

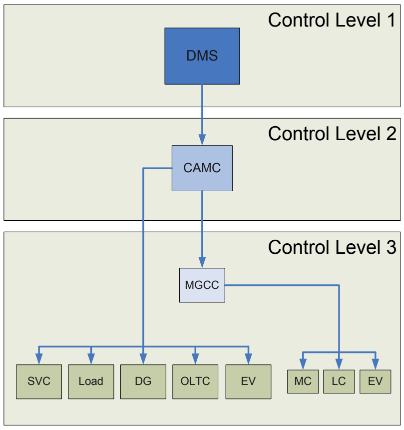


Figure 1: Hierarchical control scheme, including EVs (adapted from [1]).

This paper enhances the MMG simulation platform, described in [1], focused on control levels 2 and 3, leaving out the DMS (Distribution Management System). Thus, only the behaviour and control of a single MV network spanning from one HV/MV substation will be under analysis. As stated in [1], the CAMC will be the main source for all the production change commands. These commands are derived from the power system's frequency, in a way similar to the one implemented in regular Automatic Generation Control (AGC) functionalities. The power generation change requested to the production system in case of frequency variation is derived from the system frequency through a simple PI controller as follows.

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

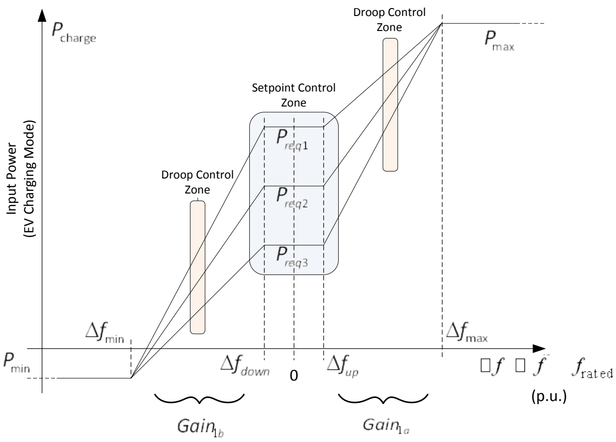
Afterwards, an economical allocation algorithm distributes this power change among the DG units and MGCCs under CAMC control which are willing, at that point in time, to participate in frequency regulation. Each MGCC then allocates the generation request among its subordinate microgeneration units. This economical allocation algorithm requires the unitary costs of each power production device. This algorithm could, in fact, be replaced by any kind of optimization/allocation algorithm according with some specific purpose.

With the inclusion of sheddable or controllable loads, the whole hierarchical control system requires few adaptations. For instance, it is necessary to specify a cost for each unit load disconnection [3]. In a

similar way, the inclusion of EV units in the hierarchical control system also requires the specification of costs which are no less than the customer remuneration for allowing the manipulation of the charging rates of EVs in the benefit of the dynamic behaviour of the MV grid.
The next sections will present the adopted model for EVs, results from two case studies and the main conclusions of this work.

2. EV MODEL DESCRIPTION

The development of the EV model has taken into account its required behaviour and target simulation software (EUROSTAG v4.3) and can be used to represent either a single EV or a cluster of EVs in a single location (e.g.: a parking lot). It was modelled as a simple power injector using the block available in the EUROSTAG library. However, it was programmed to respond to frequency deviations and to receive setpoints, allowing it to behave as a load or to inject power to the grid.
In summary, the adopted EV model, which enhances the model presented in [2], is capable of: (i) being configured to inject power into the grid, following a Vehicle to Grid (V2G) behaviour, (ii) receiving setpoints from a structure higher in the control hierarchy, (iii) responding autonomously to frequency deviations (autonomous frequency control), (iii) subjecting the autonomous response to a dead-zone to avoid continuous operation of the control system, and (iv) adjusting proportional gains (hence, the droops) of the frequency control system according to the current operating points and operational limits of the EV charger/inverter.
All operation points related to these project specifications can be identified in Figure 2, where three different charging setpoints are shown simultaneously. The gains that should be used for control in the over- and under-frequency zones of operation are shown in Figure 2 as well. Such dynamic adjustment allows for a maximum control range regardless of the setpoint currently chosen. If $P_{\min}$ is negative the EV is allowed to inject power into the grid. Hence, V2G behaviour can be enabled by setting $P_{\min} < 0$.
The EUROSTAG implementation details are available in [4].



$$Gain_{1a} = \frac{P_{\max} - P_{req1}}{\Delta f_{\max} - \Delta f_{up}}$$

$$Gain_{1b} = \frac{P_{req1} - P_{\min}}{\Delta f_{down} - \Delta f_{\min}}$$

Figure 2: EV setpoint and droop control.

3. RESULTS

The results shown here were obtained using the aforementioned simulation platform developed with MATLAB and EUROSTAG. The latter is used to simulate the physical world (the electrical network), while the former is the one responsible for the simulation of the higher level (hierarchical) control system, difficult to implement resorting only to EUROSTAG programming elements [1,3]. The detailed models implemented in EUROSTAG include those of EVs and also of other power sources, such as microturbines, wind generators, fuel cells, storage devices coupled with power inverters, asynchronous generators and conventional synchronous generators.
The following case studies were developed:

- Test Case 1: EVs behave as controllable loads while their batteries are charging. Charging rate can be modified in some of the EVs through setpoints sent by CAMC/MGCC. All of the EVs have the autonomous frequency control capability enabled.

- Test Case 2: A significant number of EVs can behave as storage devices while connected to the grid. As in Test Case 1, charging rate can be modified in some of the EVs through setpoints sent by CAMC/MGCC (long term power injection is not allowed). All of the EVs have the autonomous frequency control capability enabled (with bi-directional mode: load-shedding and power injection).

Both of the case studies will use the same base test network, described in the following section.

3.1 Test Network

The test network is shown in Figure 3 (see [3] for a more thorough description). This network was built to behave as a Multi-MicroGrid with 13 microgrids.

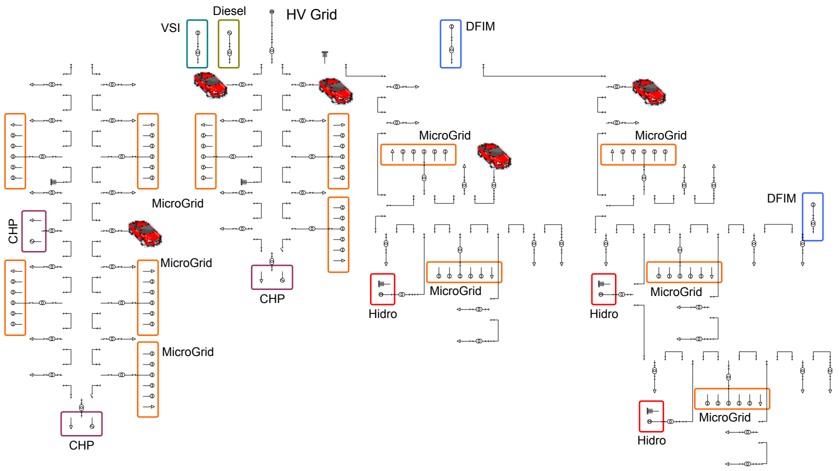


Figure 3: Test network.

The network is connected to the upstream HV grid through a single interconnection. In the following case studies, the transition to islanded operation will be the main analysis subject. The representation of EV penetration has been simplified and was assumed to be 10% of the load in each node [4]. The initial power output of some sources was increased when compared to the adopted base system in order to cope with the 10% load increase from EV origin.

Starting from a steady-state point of operation, the following system disturbances will be analyzed:

- Emergency transition to islanded operation (worst-case scenario – a loss of about 4 MW of imported power) – starting at a simulation time of 20 s;
- Load-following operation (ramp load increase of approximately 1.5 MW during 10 seconds) – starting at a simulation time of 100 s.

3.2 Case Study 1

In this first, more conservative scenario, all the EVs have the autonomous proportional frequency control in an active state. However, since it is considered to be the option most agreed upon, the EVs were not allowed inject power into the grid, behaving therefore as frequency dependent controllable loads. The EVs can also receive setpoints for their power consumption from a management unit which is higher in the hierarchy (the CAMC or a MGCC). This capability is only enabled for a selected number of EVs in order to better visualize the EV effect on the secondary frequency regulation. EV model parameters are presented in [4].

Figure 4 (left) shows that the frequency stabilization was achieved at the rated value after the described disturbances. This result highlights that the islanding process and the islanded operation can be successfully accomplished for this test network using the Multi-MicroGrid control schemes.

As the system frequency deviates from the rated value, the frequency control coordination is triggered and the conveyance of setpoints is initiated. As examples, the control setpoints for the CHP and Hydro units are illustrated in Figure 5 as well as the setpoints and generation response for one of the MicroGrids.The Hydro unit was commanded to change its control setpoint before the CHP unit. Such result is obtained since we assumed the Hydro unit cost is inferior to the CHP or MicroGrid costs.

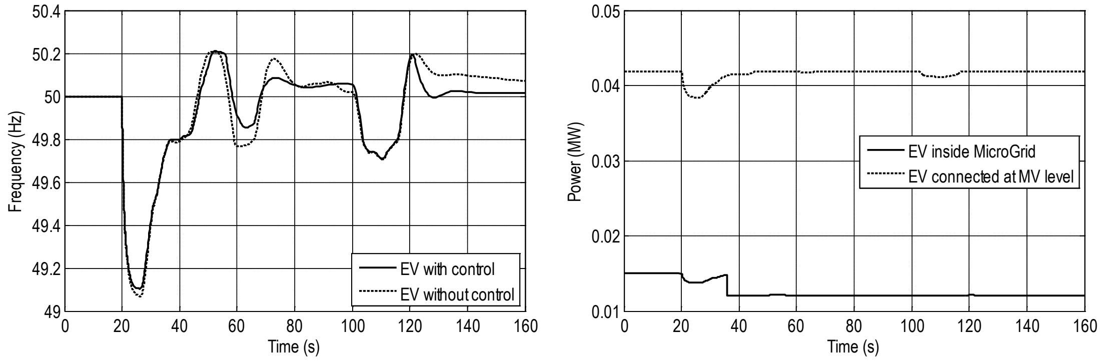


Figure 4: Frequency (left) and EVs (right) responses during islanding and islanded operation (load following).

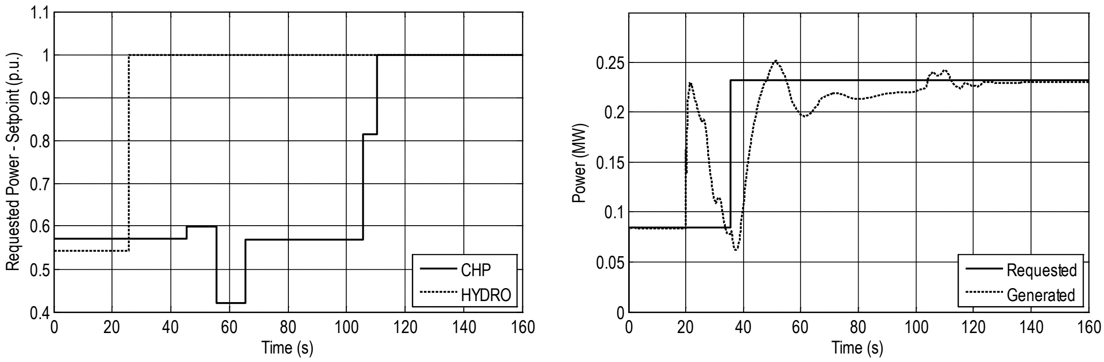


Figure 5: Control setpoints for the CHP and Hydro units (left); setpoints and generated power in a MicroGrid (right).

The generation sources within the MicroGrid respond to the MGCC setpoint commands in a similar way. However, in the right picture of Figure 5 it is possible to see that the MicroGrid starts contributing to minimize the effects of the frequency drop even before receiving any sepoint. This happens because the MicroGrid contains two kinds of storage elements: a dedicated flywheel and also a small EV group. Since the flywheel seems to mask the effect of the EV presence, the EVs contributions are shown on their own in Figure 4 (right). The EVs at the MV level can represent, for instance, a larger battery charging station or a cluster of EVs in a shopping centre parking garage. It is also noticeable the influence of the higher level, hierarchic, frequency control on the power input of the MicroGrid connected EV when it receives a setpoint change command just after their initial droop based response. Thus, the combined effects of these two independent types of control systems (contribution to primary and to secondary frequency control) are shown superimposed on each other.

3.3 Case Study 2

This second scenario setup is identical to the first one except for the fact that some of the EVs are now allowed to also inject power in the grid if needed while the other act as standard, fixed loads. (The ones that can change their input/output power are those in the test network central urban and rural areas – the three branches closer to the HV link in the larger MV bus). The power modification needed is assessed through the value of the system frequency: for instance, low frequency values would require an increase in the power injection.

Because EVs other than these have the autonomous control disabled, the parameters were set so that the response would be firm enough. For instance, $P_{\min}$ is intentionally set very low even taking into consideration that the use of EVs in this very unconventional way is not consensual: increasing the number of charge/discharge cycles of EVs can eventually compromise their batteries' longevity and having a substantial power injection on off-peak hours can conduce to reverse power flows in some branches of the network, which is something seldom foreseen in network planning. However, operation at these extreme points should only occur for a few seconds at a time.

Like the previous scenario, the charging rate can be modified in a subset of the EVs through setpoints sent by CAMC/MGCC. However, it was considered that this could only be done regarding the charging rate and not allowed for setting any longer-term power injection to the grid.

Figure 6 shows the Frequency (left) and EV (right) responses for this case study. The frequency response to the disturbances is slightly improved regarding the previous scenario. However, it should be taken into account that the amount of EVs that are contributing to the limiting of the initial frequency excursion has been reduced by more than half.

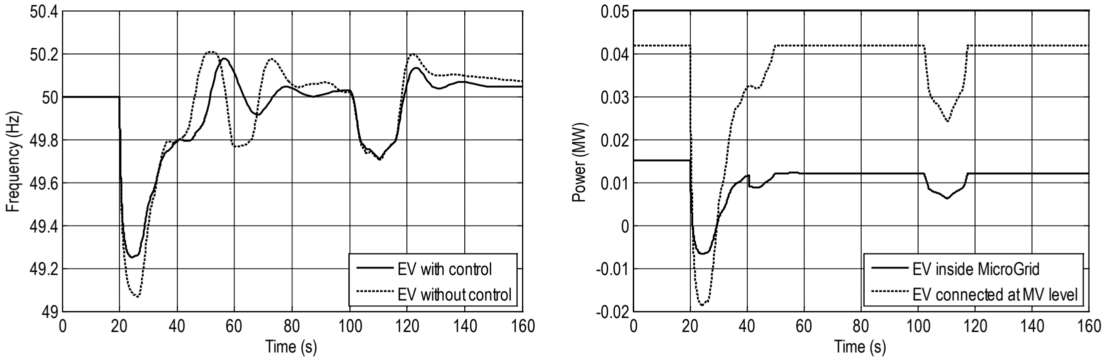


Figure 6: Frequency (left) and EV (right) responses during islanding and islanded operation (load following).

The EVs are now actively contributing to increase the amount of generated power on the isolated MMG. The negative power values indicate that the EVs are no longer behaving as loads and are now injecting power into the grid. As in the previous scenario, the combined effects of the two independent types of control systems can be verified in the picture.

4. CONCLUSIONS

The increasing future grid penetration of large numbers of EVs will undoubtedly lead to the existence of control systems capable of managing the additional load. The work here presented shows that it is feasible that these EVs can be managed in order to be used as a system resource, while behaving either as controllable loads or storage devices (V2G). The EVs are here integrated in a hierarchical control system structure with a Multi-MicroGrid and several MicroGrids.

The advantages of this kind of operation can be particularly noticed when the system is in stressful situations, namely while transitioning to (or operating in) islanded mode. The additional power reserve can be of great value, permitting the safe, albeit temporary, operation in islanded mode, while avoiding the shedding of important loads.

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