Abstract— The interest in the MicroGrid (MG) concept has been increasing recently due to its capability of operating autonomously and to provide the necessary control and management mechanisms for the massive integration of plugged-in Electric Vehicles (EV) and microgeneration units. When operating in islanded mode, the MG relies on local energy storage to ensure the balance between generation and loads. Also, when isolated from the main grid the MG is more sensitive to power quality issues such as voltage unbalance, caused by the connection of single-phase loads and sources. In order to improve the MG emergency operation conditions, the EV should be envisaged as an active and flexible element of the grid, providing to the MG additional distributed load or storage capacity under the vehicle-to-grid (V2G) concept. This paper presents an evaluation of the potential benefits of adopting innovative EV charging control strategies in order to increase the MG resilience during emergency operation. The MG power quality in terms of voltage unbalance is also addressed and the feasibility of adopting voltage balancing strategies is demonstrated.

Keywords- Electrical Vehicles, Energy Storage, Islanding Operation, MicroGrid, Vehicle-to-grid.

I. INTRODUCTION

The development of a competitive power sector associated with environmental and security of supply issues have led to a new vision of future electricity networks – the Smart Grid concept – where both consumers and generation units play key active roles regarding operation and management requirements of the overall system. Under this new paradigm, the MicroSources (MS) and the Electrical Vehicles (EV) connected to Low Voltage (LV) distribution networks can be actively managed exploiting the Microgrid (MG) structure [1-2]. The MG is a highly flexible, active and controllable LV cell, composed of different renewable and low carbon energy sources, having the ability of operating interconnected with the upstream Medium Voltage (MV) network or autonomously in case of emergency conditions. These features contribute to the increase of system security and reduce its vulnerability to external attacks, resulting either from natural disasters or deliberated actions [3-4].

The MG hierarchical management and control structure provides the pathway for the massive deployment of EV and MS. However, the need of mitigating technical impacts resulting from EV and MS connection to LV grids requires the development of novel control and management functionalities under the MG operation concept [1-2]. When properly managed, the EV can be regarded as a very flexible load or storage device: when parked and connected to the LV network through proper interfaces, EV will controllably absorb energy and store it in their batteries, being also able to deliver it back to the grid - the Vehicle to Grid (V2G) concept. The ability of EV regarding the provision of energy storage capacity provides to System Operators additional resources to improve the operational conditions of distribution systems under emergency conditions. In fact, the MG storage capability is essential to ensure the success of the MG islanding procedure, during which the system experiences severe voltage and frequency variations due to the unbalance between local generation and load.

The adoption of innovative control strategies, taking advantage of the EV flexibility, acting both as a controllable load or storage device, potentially improves the MG frequency regulation and increases the safe integration of MS in islanded mode [1]. The additional storage capacity provided by EV has the potential to enhance MG resilience, avoiding large frequency excursions resulting from loads or MS power variations.

The LV distribution systems are usually operated under unbalanced conditions, mainly due to the uneven connection of single-phase loads and MS to the three-phases of the system. Voltage unbalance is a major drawback regarding the operation of three-phase loads (such as motor loads) decreasing its efficiency and lifetime and may compromise the MG synchronization with the MV network. When operating in islanded mode, the MG is more sensitive to this problem, which could be further accentuated by the connection of single-phase EV charging interfaces [2]. Therefore, active voltage compensation strategies are required in order to eliminate the unwanted negative and zero sequence voltages components, mainly during MG islanded operation.

The main goal of this paper is to demonstrate the benefits provided by EV active participation on the MG frequency regulation in emergency conditions (namely in islanding operating mode). The paper also identifies the benefits of EV participation regarding the MG load following capability, on the resulting improvements in the MG resilience and impact on the main storage capacity. The need of adopting voltage balancing mechanisms in specific power electronic interfaces is also analyzed in this paper.

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II. MICROGRID ARCHITECTURE WITH EV

The management and control of a MG is usually conducted by a hierarchical system as represented in Fig. 1, which integrates several decentralized control functions. The management and control system is organized in two main layers: the Microgrid Central Controller (MGCC) and the local controllers for the MS (MC), loads (LC) and for the EV (Vehicle Controller – VC). The MGCC is installed at the MV/LV substation and concentrates the high level decision making for the technical and economic management of the MG. In normal interconnected mode the MGCC performs MS dispatch, voltage coordination, security assessment and load and micro-generation forecasting, transmitting the resulting set-points to the local controllers (MC, LC and VC) [1-2].

In emergency mode, the local controllers will provide primary frequency and voltage regulation, while the MGCC will perform a secondary control to ensure that the MG voltage and frequency return to their nominal values [3]. Local primary frequency control schemes ensure the MG stability and reduce the communication requirements between the MGCC and the local controllers.

![Figure 1. MG Architecture with EV][1]

III. MG REGULATION SYSTEMS FOR EMERGENCY OPERATION

The successful MG islanded operation relies in the combination of primary and secondary frequency and voltage control strategies coordinated with the main storage device response, EV connected to the grid, controllable MS response and load shedding schemes. These regulation strategies are implemented by controlling the inverters connected to the MG elements. The two most common inverters control strategies are PQ inverter control and Voltage Source Inverter (VSI) control [3-4].

In the MG, only the main storage unit inverter is operated as a VSI, since the MS usually lack the necessary storage capacity. The VSI emulates the behavior of the synchronous machines, providing primary frequency regulation by adjusting its power output to the values of the angular frequency through P-ω droop and measured voltage through Q-V droops. The other MS inverters are controlled with a PQ strategy, being the set-points of P and Q provided either by the MGCC or by other forms of local intelligence.

The primary regulation strategies can be complemented by the implementation of load shedding schemes, in order to avoid large frequency excursions that can compromise MG transient stability in the moments subsequent to islanding. The load shedding mechanism can be implemented as an emergency functionality in the LC, where it is possible to parameterize a set of steps corresponding to different load shedding levels as a function of the MG frequency deviation.

Primary frequency control does not ensure the restoration of frequency to its nominal value. In order to promote adequate secondary control aiming to restore frequency to the nominal value after a disturbance, two main strategies can be followed: local secondary control, by using a PI controller at each controllable MS, or centralized secondary control mastered by specific algorithms to be embedded in the MGCC software modules. In this paper, a simple approach is used, based on a local secondary control strategy. In both cases, target values for active power outputs of the primary energy sources are defined based on the frequency deviation error.

The adoption of innovative regulation EV regulation schemes can contribute to reduce the main storage solicitation and smooth the MG transition to islanding operation. The strategies to be identified should take advantage of the distributed storage capacity and high controllability offered by the EV connected to the LV network [1-2]. The EV control strategy adopted in this paper is based on the P-ω droop control strategy and is represented in Fig. 2. According to [1], the EV will change its power output based on the MG frequency, contributing to balance the MG generation and load. For frequencies around 50 Hz the EV charges its battery at its nominal power. A dead-band is considered to avoid frequent solicitation of the EV batteries resulting from small frequency deviations. When the frequency drops below the dead-band minimum, the EV reduces its power consumption and if the frequency drops further below the zero-crossing frequency (f0), the EV starts to inject power into the grid, becoming a V2G. When the MG frequency increases to values superior to the dead-band maximum, the VE can also increase its power consumption.

![Figure 2. EV Frequency-Droop characteristic][2]
The parameters of the frequency-droop characteristic will depend on the EV charger characteristics and on the willingness of EV owners to participate in such services. These parameters may differ from grid to grid and can be changed by the MGCC, in order to coordinate the EV participation with the other MG frequency regulation mechanisms (load shedding schemes and availability of energy storage devices).

IV. VOLTAGE BALANCING MECHANISMS

Voltage unbalance is one of the power quality problems affecting the MG particularly in islanded mode, requiring the implementation of additional compensation strategies. According to the European Standard EN50160, voltage unbalance can be measured by the voltage unbalance factor (VUF) determined by Eq. 1, where \( V_1 \), \( V_2 \) are respectively the positive and negative sequence voltage values. In this work the zero sequence voltage unbalance (VUF\(_{\text{zero}}\)) was also measured as indicated in Eq. 2, being \( V_0 \) the zero sequence voltage.

\[
\%\text{VUF} = \frac{V_1}{V} \times 100\% \quad (1)
\]

\[
\%\text{VUF}_{\text{zero}} = \frac{V_0}{V} \times 100\% \quad (2)
\]

According to the European Standard EN50160, in each bus the negative phase sequence component should be within 2% of the positive phase sequence, given a 10 minute average value [5]. The zero sequence voltage component has no significant impact on the MG loads. However, at the point of common coupling (PCC) it may compromise the synchronization of the islanded MG with the MV grid.

In order to provide adequate voltage compensation, the Voltage Source Inverter connected to the main storage is equipped with a voltage balancing mechanism, being the main building block represented in Fig. 3. The VSI balancing unit is able to provide three independent output reference voltages, regardless of the MG loading conditions. As explained in [6-7], the implementation of the controls in the stationary reference frame reduces the need of significant synchronous frame transformations. However, the use of proportional-integral resonant controllers is required to eliminate the unwanted negative and zero sequence components of output voltages. Frequency and magnitude of the desired output voltages are determined though P-\( \omega \) and Q-V droops, flowing adequate active and reactive power measurements at the output of the unit. Different sets of control parameters might be adopted for grid connected mode and islanded mode respectively.

V. MG SIMULATION SCENARIOS

For the development of the study presented in this paper, two typical LV networks were considered: an urban and a rural LV distribution networks. The urban LV network has a nominal voltage of 380 V and is composed by eight nodes with a total load of 177.8 kW, including three-phase and single-phase loads connected by 312m of the underground. The rural LV network is constituted by thirteen nodes and has a total load of 217.2 kW, including three-phase and single-phase loads, connected by 1135m of aerial line and 94m of underground line.

In order to build the MG simulation scenarios, a 150 kW storage unit was considered, to be placed at the MV/LV substation of both networks. The MS were distributed by the network nodes. In the urban scenario only three-phase power generating units were considered, namely single-shaft gas microturbines (SSMT). In the rural area network, a large amount of small single-phase renewable-based microgeneration units was considered, namely of Wind Turbines (WT) and Solar Photovoltaic panels (PV), operating with constant power outputs for the time frame of the simulations cases described in this paper. The main characteristics of the rural and urban MG are summarized in table I and II (the deferrable loads are those that are considered as candidates to be shed in case of severe frequency deviations following MG islanding).

| TABLE I. URBAN MG SCENARIO | Type of Connection | Total | Deferrable Loads |
|-----------------------------|--------------------|-------|-----------------|
| Load (kW)                   | 38.5               | 69.8  | 32.4            | 37.1  | 177.8 | 104.65 |
| MS (kW)                     | 150                | 0     | 0               | 0     | 90    | -      |
| E.V. (kW)                   | 0                  | 22.3  | 24.3            | 6.73  | 57.7  | -      |

| TABLE II. RURAL MG SCENARIO | Type of Connection | Total | Deferrable Loads |
|-----------------------------|--------------------|-------|-----------------|
| Load (kW)                   | 87.9               | 44.4  | 38.3            | 46.6  | 217.2 | 175.2  |
| MS (kW)                     | 90                 | 25.5  | 31.7            | 38.5  | 185.7 | -      |
| E.V. (kW)                   | 0                  | 21.9  | 19.6            | 17.6  | 59.8  | -      |

In this study the EV are assumed to be connected to the MG through single-phase chargers. This type of connection will correspond to slower charging modes, where vehicles need to be connected to the grid during long periods, offering higher control flexibility [1]. Different parameters were chosen for the EV control, reflecting the different willingness of EV owner’s on participating in the MG operation. The maximum and minimum power considered is the nominal EV chargers power, which varies between 3 and 10 kW (reflecting different ratings of EV and EV aggregations per MG node). At the nominal frequency the power absorbed was considered 75% of the
nominal power. Different EV frequency droop characteristics were obtain as a consequence of the EVs different charging rates. The EV frequency-droop parameters are presented in Table 3.

The two MG scenarios were modeled in a Matlab/Simulink environment through the use of the SymPowerSystems toolbox and user-defined models [2-3]. The simulation platform was developed in order to analyze the dynamic behavior of the overall MG, together with the control strategies discussed in section IV. Detailed description of the dynamic models of MS, storage devices and EV chargers adopted can be found in [8].

| TABLE III. EV FREQUENCY- DROOP PARAMETERS |
|------------------------------------------|
| Frequency-Droop Parameters | Values |
| Nominal Frequency (Hz) | 50 |
| Zero-Crossing Frequency (Hz) | 49.5 |
| Maximum Frequency (Hz) | 51 |
| Minimum Frequency (Hz) | 49 |
| Frequency Dead-band (Hz) | 0.2 |

VI. RESULTS AND DISCUSSION

The results discussion presented in this section are organized according to the main evaluation objectives of the paper. Therefore, the first part of this section focus on the identification of the main advantages resulting from the adoption of EV f-droop characteristics regarding MG islanding operation, namely: load following capability and the impact on the main storage unit solicitation. The second part of the discussion is dedicated to the study of the benefits of using voltage balancing mechanisms for improving voltage quality.

A. MG Islanding with EV

In the beginning of the simulation both MG (rural and urban) are considered to be connected to the upstream MV grid. To study the benefits of the EV participation in frequency regulation three cases were considered: 1) a base case where the EV do not respond to frequency variations, being regarded as conventional loads; 2) a case where the EV chargers are controlled with a frequency-droop strategy with a zero-crossing frequency of 49.5 Hz and 3) a case where the EV chargers are controlled with a frequency-droop strategy with a zero-crossing frequency of 49.7 Hz.

After 10s, the MG is suddenly disconnected from the main grid and becomes isolated. In the moments subsequent to MG islanding, since the MG was importing a significant amount of power from the MV network, the system suffers a frequency drop, as represented in Fig. 4. In order to sustain the initial frequency drop, about 60% of the MG total load is gradually disconnected. The SSMT remain connected to the network and the secondary frequency control starts to respond immediately leading to the correction of the frequency deviation (the slow response of the SSMT leads to a significant time for frequency recovery).

In Fig. 4 it can also be observed that the EV participation significantly reduces the initial frequency deviation (around 0.09 Hz, being the EV just reducing the absorbed power from the grid). Regarding MG frequency behavior, it is possible to observe that in case 1 the frequency returns to the nominal value faster than in the base case. In fact, without the EV participation in the frequency regulation, only the main storage unit and the SSMT (which has a slower response) are responsible for the frequency control, thus being responsible for a slower frequency restoration times.

Fig. 5 presents the power absorbed/injected by the EV for case 3. Increasing the zero-crossing frequency to 49.7 Hz forced the EV to inject power into the grid, consequently reducing the initial frequency deviation and allowing a faster recovery of the MG frequency to its nominal value. The participation of EV occurs around the 10 seconds subsequent to the MG islanding and is able to reduce the solicitation of the main storage device.

![Figure 4. Urban MG frequency response after the islanding.](image)

The storage unit response is represented in Fig. 6 where it is possible to observe an important reduction of the total power injection by the VSI when EV are active elements in the MG control process. The main difference relies in the responses subsequent to the islanding, where the storage unit injects power to the grid to compensate the unbalance between load and generation. When the MG frequency reaches the nominal value (50 Hz) the power injected by the storage unit is zero.

![Figure 5. Power Absorbed/Injected by the urban MG EV.](image)

In the case considering the EV participation, the response of the SSMT for the secondary frequency regulation is more stable and the increase on the SSMT power output required is smaller. Fig. 7 and Fig. 8 present the power output of the
SSMT for the base case and for case 1 (with the participation of EV). When the frequency reaches 50 Hz the power output in both cases is the same since EV return to their pre-disturbance power consumption when the MG frequency becomes within a pre-specified dead-band. Therefore, after the final value of the MG load to be supplied is the same in both situations.

B. Voltage Balancing Mechanisms

The MG simulation scenarios had considerable unbalances between the phases, due to a non-even distribution of single-phase loads and MS. However, as expected, the rural MG had higher voltage unbalance since it is constituted by long aerial lines with dispersed loads and has a considerable amount of single-phase MS. After the islanding there is 95.7 kW of single-phase power generation from the MS and 87.1 kW of both three-phase and single-phase loads. In this paper only the results obtained for the Rural MG are illustrated.

To study the importance of the voltage balancing unit, two cases were considered: a base case where the main storage unit is connected to the MG through a three-leg inverter with frequency and voltage droops; and a second case where the VSI is a four-leg inverter with a balancing unit. In both cases the EV participate in the MG frequency regulation. The benefits of the balancing unit will be quantified by the voltage unbalance factor (%VUF), described in section IV.

Fig. 9 and Fig. 10 present the %VUF at the VSI terminals with and without the balancing unit. Without the balancing unit both zero sequence and negative sequence voltage unbalance are superior to the limit of 2% imposed by the EN50160 standard. However, the implementation of the voltage balancing mechanism eliminates both voltage components at the VSI output. This reduction will avoid large currents that otherwise would occur when the MG was synchronized and reconnected to the upstream network.
The effectiveness of the balancing unit depends on its distance to the unbalanced load/source. Since the Rural MG is constituted by long aerial lines, the voltage balancing effects are smaller at the nodes electrically more distant from the VSI. Figures 11 and 12 present the voltage unbalance at the node electrically more distant from the VSI, for the base case without the balancing unit and for the case with the balancing unit, respectively.

In the base case, the voltage unbalance increases after the islanding, violating the acceptable limits. In fact, the single-phase MS such as PV and WT remain connected to the system regardless of the shed load, increasing the unbalance between the phases. When the balancing unit is considered the negative sequence voltage unbalance is reduced 1.468% \((V_2/V_1)\), being able to maintain the unbalance within the acceptable limits. However, the balancing unit has no effect on the zero sequence voltage components, which remains at 6.8% \((V_0/V_1)\), after the islanding. The results obtained reinforce the need of developing local voltage regulation mechanisms for unbalanced LV networks.

![Figure 11. Rural MG without the voltage balancing unit: VUF at the node electrically more distant from the VSI.](image1)

![Figure 12. Rural MG with the voltage balancing unit: VUF at the node electrically more distant from the VSI.](image2)

**VII. CONCLUSIONS**

This paper demonstrates the feasibility of the active integration of EV and MS in MG emergency control strategies. When analyzing the MG dynamic behavior after a disturbance in the MV grid, it was demonstrated that the EV participation in the frequency regulation led to a smoother MG transition from the interconnected mode to unplanned islanding. The results obtained from numerical simulation demonstrate that the adoption of such scheme reduces the initial frequency deviation and leads to a faster recovery of the MG frequency to the nominal value. The EV frequency-droop strategy is flexible enough to reflect the EV chargers characteristics, EV owner willingness to participate in the MG operation and to be coordinated with the other frequency and voltage regulation mechanisms. As a consequence of the immediate response of EV to the frequency deviation, it was demonstrated that the adopted EV frequency control strategy reduces the power solicitations to the MG main storage unit. However, the impact on the main storage state of charge will depend on the MG pre-fault load/generation conditions as well as on the number of EV connected to the network.

Regarding the MG voltage balancing mechanisms, the obtained results demonstrate the feasibility of the proposed approach for the cancelation of unwanted negative and zero sequence voltage components at the VSI terminals where was installed. It was also possible to observe that in other MG nodes a significantly reduction of voltage unbalance was obtained. However, the effectiveness of the balancing unit will depend on its distance to the unbalanced load or source, requiring the development and identification of additional voltage balancing strategies.

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