Electric Vehicles Charging Management and Control Strategies

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***Abstract*—This paper presents a holistic framework for electric vehicles integration in electric power systems together with their charging management and control methodologies that allow minimizing the negative impacts in the grid of the charging process and maximize the benefits that charging controllability may bring to their owners, energy retailers and system operators. The performance of these management and control methods will be assessed through steady state computational simulations and then validated in a microgrid laboratory environment.**

Keywords—Communications; Electric Vehicles; Management and Control Strategies; Microgrids; Smart Grid Laboratory.

I. Introduction

The global warming is one of the environmental reasons leveraging the large scale adoption of Electric Vehicles (EV). According to the OECD, the transportation sector accounts for more than 50% of the world's oil consumption and is responsible for *ca.* 20% of the world's CO_2 emissions, being naturally one of the principal targets of countries' policies to mitigate the climate change problematic.

While the integration of moderate quantities of EV into the electric power system does not provoke any considerable impacts, their broad adoption would most likely create technical problems in what concerns the grid operation and management. To overcome them, two paths can be followed: reinforce the existing infrastructures and plan new networks in such way that they can fully handle the EV integration; or develop and implement enhanced charging management strategies capable of controlling EV charging according to the grids' capabilities. While the former is a rather expensive solution that will require high investments in network infrastructures, the latter yields more benefits from the grid perspective once it provides elasticity to the EV loads.

Given this context, and considering the expected growth in EV integration levels, detailed studies about the impacts of integrating EV in power systems should be performed to evaluate the best approaches to follow in the future. These studies will require the development of comprehensive and standardized EV models and simulation tools that can be used in a wide variety of scenarios, including different EV types and power systems with distinct characteristics.

This paper addresses this topic by presenting a holistic EV integration framework and EV management and control methodologies. The effectiveness of these methodologies was assessed through steady state computational simulations and validated in a microgrid laboratory.

II. Electric Vehicle Integration Architecture

The technical management of an electric power system, having a large scale deployment of EV will require, for their battery charging, a combination of a centralized hierarchical management and control structure with a local control located at the EV grid interface based on the microgrid concept [1] [2]. The simple use of a smart device interfacing the EV with the grid does not solve all the problems arising from EV integration in distribution networks. These interfaces can be rather effective when dealing with the occurrence of voltage drops that may be caused by EV charging, by locally decreasing charging rates through a voltage droop control approach. However, this local solution fails to address issues that require a higher control level, such as managing branches' congestion levels or enabling EV to participate in the electricity markets. For these cases, coordinated control is required and a hierarchical management and control structure responsible for the entire grid operation, including EV management, must be available. Therefore, the efficient operation of such a system depends on the combination and coordination of local and centralized control modes. The latter control approach relies on the creation of an adequate communications infrastructure [3] capable of handling all the information that needs to be exchanged between EV and the central control entities organized in a hierarchical structure.

A. Normal System Operation

When operating the grid in normal conditions, EV will be managed and controlled by a new (central) entity – the aggregator – whose main functionality will be grouping EV, according to the willingness of their owners, to exploit business opportunities in the electricity markets [4]. If EV would enter this market individually their visibility would be small and rather unreliable due to their stochastic behaviour. Nonetheless, if an aggregating entity exists, with the purpose of grouping EV to enter in the market negotiations, then the provided services would be more significant and the confidence on its availability much more accurate. It is important to stress that the aggregator should always take into account the drivers requests, which will provide information about power demand and connection period via the smart meters (SM). In the same regional area, several aggregators might co-exist and compete to gather as much clients as possible. This competition will be beneficial for the EV owners, who will be able to choose as aggregator the company that better fits their needs. Given the complexity of the information that an aggregator needs to collect and process, a hierarchical management structure, independent from the DSO, is suggested in this document (Fig. 1).

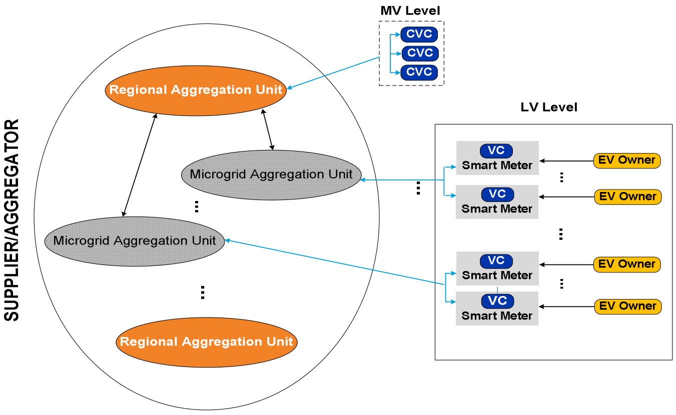

Fig. 1 Aggregators' hierarchical management structure

Since each aggregator develops its activities along a large geographical area, e.g. a country, it will be composed by two different types of entities: the Regional Aggregation Unit (RAU) and the Microgrid Aggregation Unit (MGAU). The RAU is considered to be at the High Voltage (HV)/MV substation level, with possibly 20000 customers, communicating with several downstream MGAU which, by their turn, will be at the MV/LV substation level, with around 400 customers each. The RAU and the MGAU were created in order to decrease communications and computational burden that a real implementation of the concept would require. This will provide the aggregator pre-processed information regarding groups of EV located in the LV and MV grids. Each EV must have a specific interface unit – the Vehicle Controller (VC) – to enable bidirectional communications between the EV and the upstream aggregator. The VC will be located in the smart meter to which EV will be connected and the smart metering communication infrastructure should be used to support this architecture. In addition to the VC there is a new type of element, the Cluster of Vehicles Controller (CVC), designed to control the charging of large parking lots (e.g. shopping centres), and fed directly from the MV network. Individual controllers of EV under a CVC management do not need an active VC communicating with upstream hierarchical controllers. For normal operation, the VC will interact with the MGAU and the CVC directly with the RAU.

B. *Abnormal System Operation or Emergency Mode*

When grid normal technical operation is compromised, market management can be overridden by the DSO, through the technical operation control hierarchy, described in Fig. 2. For these abnormal or emergency conditions, it makes sense to adopt the MG and MMG [5] concepts. In fact, the MG and MMG already contemplate the existence of a hierarchical monitoring and management solution, including a suitable communications infrastructure, capable of managing the presence of EV, either individually connected at the LV level or as a cluster (e.g., fleet charging station or fast charging station) connected at the MV level. Within a LV MG, a MicroGrid Central Controller (MGCC) may control EV batteries through the VC. As depicted in Fig. 2, within a MMG environment, the elements of the MV grid, including MG and CVC, can be technically managed by a control entity, named Central Autonomous Management Controller (CAMC), to be installed in the HV/MV substation. All CAMCs will be under the supervision of a single Distribution Management System (DMS), which is directly controlled by the DSO. It is important to stress that, in abnormal system operation conditions or in emergency modes, all technical management and control tasks are a responsibility of the DSO, being performed by a main control entity, the DMS, and by the other distributed entities, CAMC and MGCC.

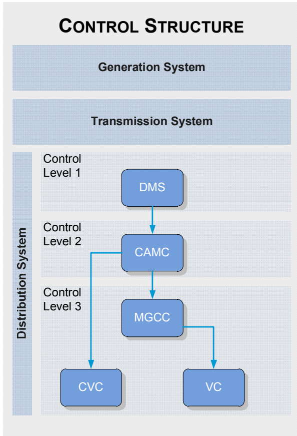

Fig. 2 Hierarchical control scheme for a multi-micro-grid with EV

III. STEADY STATE SIMULATIONS

The large deployment of EV is very likely to provoke changes in the power demand patterns, causing changes in the grids' voltage profiles, branches' congestion levels and energy losses, namely at the distribution level, where the EV will connect for charging purposes. Thus, it is important for DSO to develop new approaches to evaluate the impacts provoked by EV in distribution networks. Hence, an approach was developed in this work, which assumes that the load inherent to EV charging will appear in the grid nodes proportionally to the residential power installed in each node. Additionally, the approach presented also allows evaluating the maximum number of EV that can be safely integrated in a given network when three charging strategies are implemented: dumb charging, multiple tariff and smart charging [4]

The methodology proposed is essentially focused on determining the locations and time periods during which EV will plug-in to charge, when the three charging strategies referred are adopted. The EV battery charging was assumed to be performed always at a constant power rate of 3 kW. Additionally, it was considered that the EV batteries State-of-Charge (SOC) in the moment of plug-in is unknown. For this reason, an average charging time of 4 h was assumed for all the EV. Assuming an energy consumption of 0.2 kWh/km, the daily energy absorbed (12 kWh) would be enough for travelling ca. 60 km without needing to recharge.

The first step of the methodology is to define the time period during which each EV will be connected to the grid. For that, it is assumed that EV only make two journeys per day and that they are plugged-in only in the time periods between the last journey of one day and the first journey of the next day. The two moments when EV make their daily journeys are drawn using the probability distribution presented in Fig. 3, being always assured a minimum period of connection of 4h.

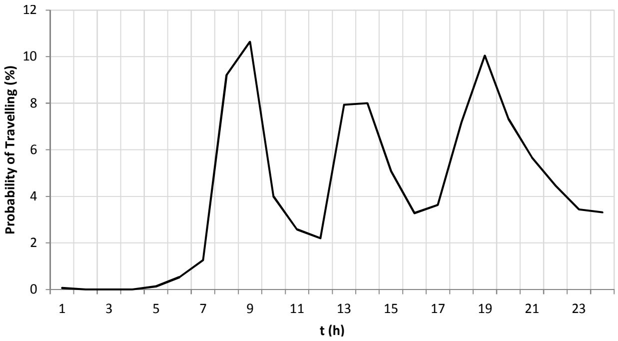

Fig. 3 Probability distribution used to define the EV daily journeys [6]

The second step of the approach is defining the periods during which EV will effectively charge. These periods will vary in accordance with the charging strategy under consideration, as mentioned in [1].

In this approach, the smart charging is formulated as an optimization problem, as shown below, being the main objective the minimization of the networks' peak load.

$$\min \left\lfloor \max_{t=1:24h}\left(\sum_{j=1}^{m} CL_t^j + \sum_{i=1}^{n}\left(EVC_t^i\right) \times 3\right)\right\rfloor \quad (1)$$

subject to:

$$\sum_{t=1}^{24} EVC_t^i = 4, \begin{cases} i \in [1,n] \\ t \in [1,24] \end{cases} \quad (2)$$

$$EVP_t^i \geq EVC_t^i, \begin{cases} k \in [1,n] \\ t \in [1,24] \end{cases} \quad (3)$$

where:

- $\lfloor \max\left(CL_t^j + \sum_{i=1}^{n}\left(EVC_t^i\right) \times 3\right)\rfloor$ – network's peak power, in kW;
- CL_t^j – conventional load in bus j, in kW, in time step t;
- EVC_t^i – used to define the periods t when EV i will charge; if $EVC_t^i = 1$, the EV i will charge in moment t, else if $EVC_t^i = 0$, the EV will not charge; the $n \times 24$ binary variables EVC_t^i are the decision variables of the optimization problem;
- t – is the time step index;
- i – is the EV index;
- n – number of EV in the network's geographical area;
- j – is the bus index;
- m – is the number of buses in the network;
- EVP_t^i – is used to define the periods t when EV i is parked and plugged-in to the grid;

The equality constraint presented in Equation (2) assures that all EV will charge exactly 4h, whereas the condition implemented in Equation (3) assures that EV will only charge when they are plugged-in. The constant 3 presented in Equation (1) is referred to the charging rate, in kW, assumed for all EV.

After determining the periods when EV will charge, the network buses where EV plug-in for charging are calculated taking into account the proportion of residential power installed in each node. Then, all EV are tagged with a bus number, indicating the bus where they plug-in for charging. Finally, the total load in the grid is calculated by adding the conventional load to the respective EV load.

The impacts provoked by the EV on a MV grid from a semi-urban area, used as test case, are evaluated using the methodology described. Firstly, the number of EV that can be safely integrated in the grid are evaluated considering all EV as dumb charging, multiple tariff and smart charging adherents. Then, three more simulations are performed to evaluate the effectiveness of the smart charging when compared with the dumb charging and with the multiple tariff, regarding the impacts in the grid operating conditions.

The maximum allowable EV integration in the grid is presented in Fig. 4. The percentages are relative to the total number of conventional vehicles in the geographical area covered by this network, which is ca. 12700 vehicles.

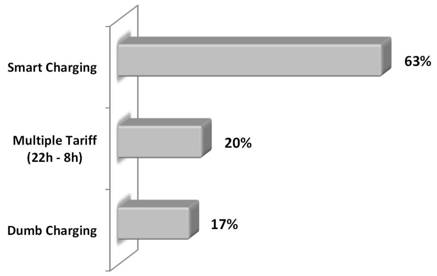

Fig. 4 Allowable EV integration in the MV grid from a semi-urban area

Fig. 5 shows the load diagrams changes for the charging strategies addressed, assuming an EV integration percentage of 63%. The worst bus voltage is presented in Fig. 6.

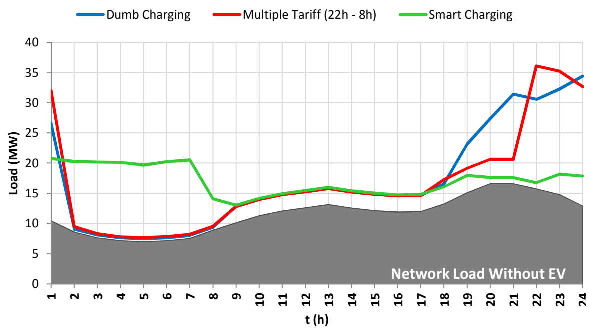

Fig. 5 Changes in the load diagram with an EV integration of 63%

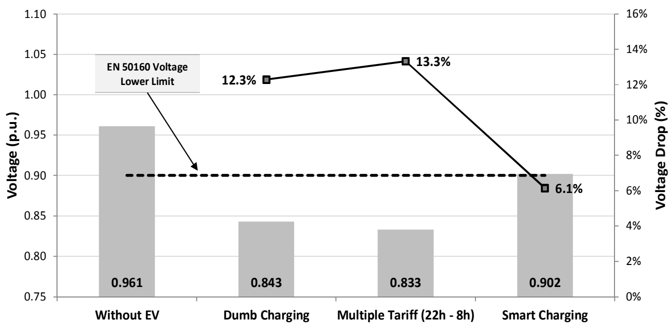

Fig. 6 Worst bus voltage

Fig. 7 show an overall overview of the lines loading for the scenarios studied, providing a clearer picture of the three charging methods impact in this matter.

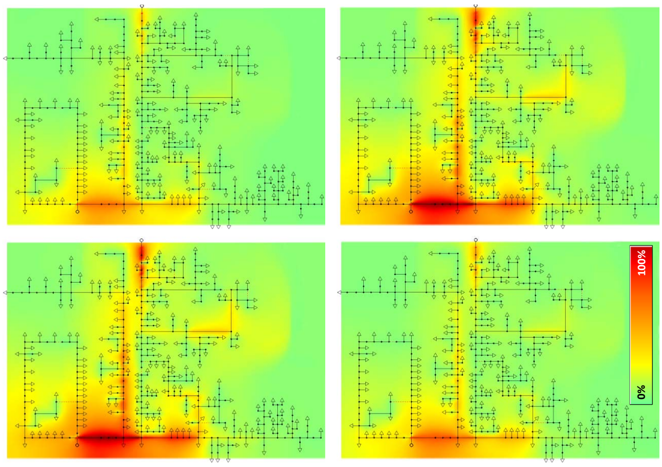

Fig. 7 Line loading in the peak hour without EV (upper left), dumb charging (upper right), multiple tariff (lower left) and smart charging (lower right)

Fig. 8 shows the absolute values of losses for the selected day (bars), on the left axis, and their value relative to the overall energy consumption (squares), on the right axis. As expected, the smart charging method is the one that provides better results since it optimizes the load distribution during the day, minimizing the occurrence of high peak loads where the consumption reaches very high values. The peak load periods are the most critical for the losses as they are proportional to the square of the current, which is very high in such conditions.

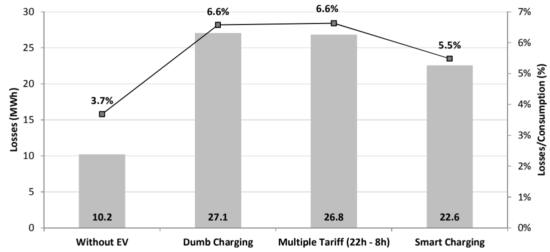

Fig. 8 Energy losses in all the scenarios studied (during the entire day)

IV. Experimental Validation of Electric Vehicles Management and Control Methods

This section presents the laboratory infrastructure where the performance of the developed control and management concepts were tested.

A. Infrastructure

The laboratory was created to be a flexible and scalable structure, to allow an individual and integrated testing of new concepts and control algorithms to be housed at different smart grid hierarchical levels, as well as different communication architectures, technologies and protocols. The laboratory electric and automation equipment includes: renewable based microgeneration (3 kW wind micro-turbine emulator and 6 kWp photovoltaic panels), storage (25 kWh capacity Flooded Lead-Acid (FLA) battery banks, 128 Lithium battery cells for the EV charging prototype), a 54 kW resistive load bank and a plug-in electric vehicle, which is charged by a single-phase commercial home charger. In order to implement the smart charging and V2G strategies, a bi-directional inverter prototype was also developed and connected to a lithium battery bank.

A communications infrastructure was implemented as an overlay to the existing SCADA system, allowing the implementation of a MG management and control structure. As represented in Fig. 9, the management and control structure was implemented considering three levels, namely: the DM&CS – Distribution Management and Control System, which coordinates the operation of the distribution network; the MGCC that ensures the management and control of the MG; and the lower control level constituted by SM, associated with MG local controllers, namely: Microsource Controller (MC), Load Controller (LC) and Vehicle Controller (VC). The SM acts as a gateway between the MGCC and the local controllers, having bi-directional communication capabilities. It is able to receive set-points from the MGCC and forward them downstream to local controllers and send metering data and other type of information upstream. The SM has also local management and processing capability, to integrate the owner's preferences regarding the participation on grid support services and remote management of load and generation.

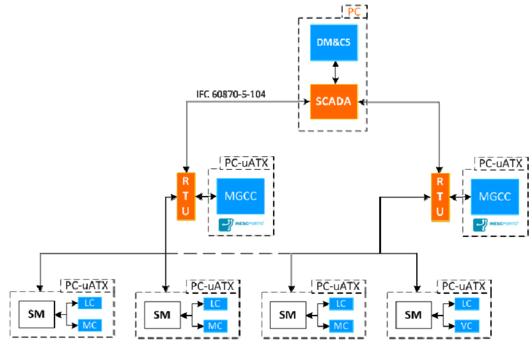

Fig. 9 Laboratory management and control architecture.

The MG high level management and control functionalities are housed in the MGCC. The information received from smart meters namely power generation, load, EV, responsive loads and power quality indicators are processed and aggregated according to the system operator needs. The information received is then used by local software modules, responsible for managing the MG technical operation, during normal and emergency conditions. An Ethernet infrastructure is used to interconnect the different elements of the control structure, thus providing a communication network between the different control levels, also providing an interaction with the SCADA system. This network it is also responsible for conveying the metered data from inverters, developed prototypes and the other laboratory equipment, through the use of specific protocol converters. A Medium Behaviour Controller (MBC) was developed to allow the emulation of different communication technologies. The Ethernet is used as a controllable communication medium where distributed MBCs are able to impose controlled and variable bandwidth values and define different profiles of data packets delays and losses.

B. Laboratory Tests

1) Interconnected Mode

The main objective of the MG test in interconnected mode is to evaluate the performance of the P-V droop control incorporated at the microgeneration units and at the EV power electronic converters (single-phase units) and its remote parameterization through the MGCC. The simulated scenario considers high penetration of renewable based generation in low load conditions. Fig. 10 provides an overview of the results obtained. At t=104 s, the micro-wind generator power production increased to 1.8 kW approximately. As shown in Fig. 11, the voltage in phase A of node 2 suffers a significant increase. At t=167 s, the PV panel starts to inject power into the grid, causing a voltage increase from 240 V to 247.2 V. As a result of the actual phase voltage, the MGCC remotely sends to the EB a command to enable the droop control functionality in the micro wind turbine emulator at t=230 s, making it possible a reduction on the active power injected by this unit, as well as the subsequent reduction in the phase voltage. At t=270 s, the droop control functionality in the PV panel power electronic interface was also activated. Both units have the same droop parameters they start injecting the same amount of active power and thus share the power reduction equally.

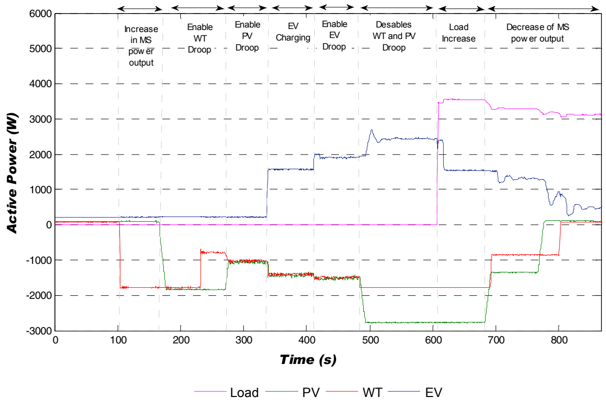

Fig. 10 Main results of the MG interconnected scenario - test 1.

At t=330 s, the EV charger prototype is connected to the MG and starts charging with a reference power of 1.5 kW. Since the MG load increased and the voltage decreased, the microgeneration units increased their power output.

In order to show the effectiveness of the MG control strategy, the EV P-V droop was activated at t=410 s and the microgeneration units voltage droop was disabled at t=480 s. As shown in Fig. 10 and Fig. 11, the microgeneration power output has increased, raising the MG voltage. As consequence the EV increases its power consumption to approximately 2.5 kW, maintaining the voltage at 242 V. At t=600 s a 3 kW load was connected and the voltage dropped below 235 V. Since this voltage is within the EV droop dead-band, the EV decreases the charging power to the reference value (1.5 kW). At t=680 s the power output from the microgeneration units started to decrease, simulating the end of the day. As a consequence the voltage dropped below 225 V, surpassing the voltage dead-band of the EV voltage droop control, which resulted in the reduction of its charging power.

2) Islanded Mode

In the beginning of the experiment the MG was connected to the main grid, importing approximately 12 kW from the upstream network. The EV prototype is charging and the microgeneration units were maintained disconnected in order to simulate the worst case scenario. One of the three-phase SMA Sunny Island group was synchronized with the main grid and it was charging the battery banks. Fig. 12 provides an overview of the MG state during the experiment, regarding load, generation, EV and the grid. The SMA Sunny Island is disconnected from the main grid at t=33 s to simulate an unplanned islanding event.

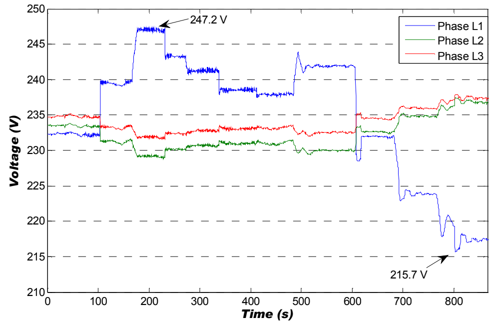

Fig. 11 Voltage at node 2 for the MG interconnected scenario-test 1.

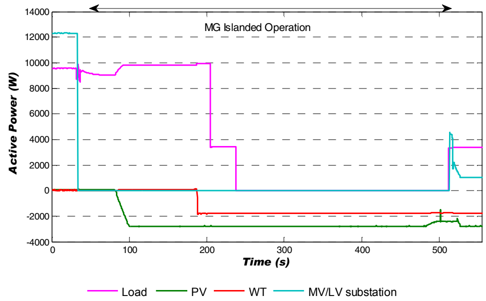

Fig. 12 Main results of the MG islanded scenario.

Fig. 13 compares the MG frequency response and the EV power output after the islanding. The MG frequency decreases bellow 48.6 Hz. Since the zero-crossing frequency of the EV droop characteristic dropped below 49.5 Hz, the EV inverted the power flow and started to inject power into the grid. The Sunny Island secondary control recovers the frequency to 50 Hz in about 3 s, and the EV returns to its reference charging power (1.5 kW).

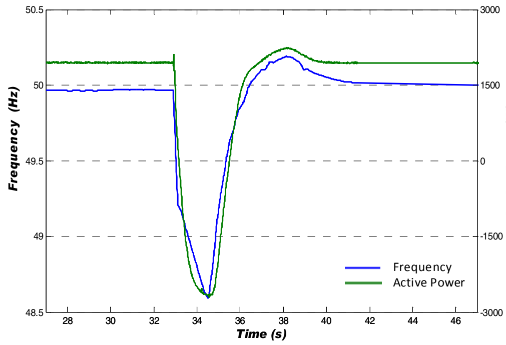

Fig. 13 MG frequency and EV active power during the islanding event.

At t=100 s the microgeneration starts to inject power in the grid and the load starts to decrease at t=200 s. As the MG generation exceeds the load, the Sunny Island inverters start to charge the FLA battery bank. After some time, the batteries are full and the frequency starts to increase. As shown in Fig.14, for t=324 s the MG frequency surpassed the EV frequency dead-band (50.1 Hz). Thus, EV increased its charging power to its maximum (3 kW) due the operation of the frequency droop control. At t=500 s the inverters start the resynchronization process and the MG is reconnected at t=510 s.

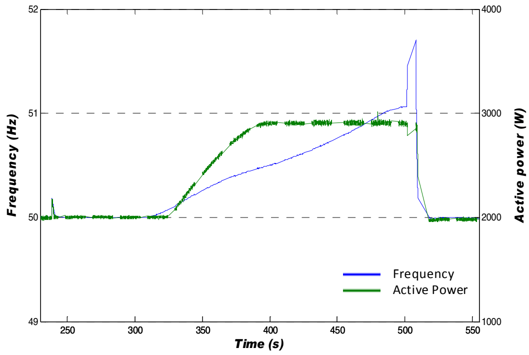

Fig. 14 MG frequency and EV active power response

3) Impact of communications

As mentioned the MG operation results from the combination of central and local control schemes and to ensure a robust control implementation it is important to account for the uncertainty introduced by the communications system. Using the MBC data exchange delays and losses were emulated to understand their impact in the MG operation.

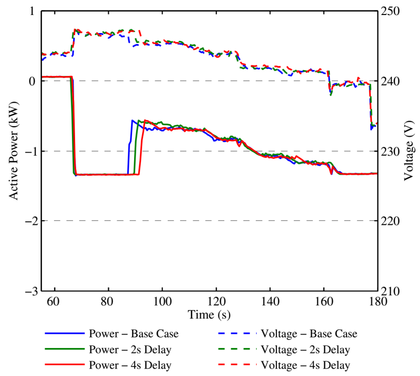

Fig. 15 PV active power and voltage response considering delays only

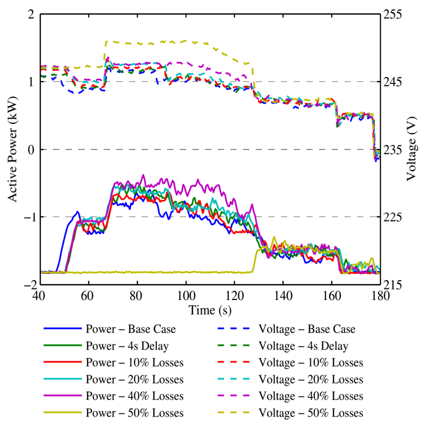

Fig. 16 PV active power and voltage response considering delays with losses

In a similar experiment, depicted in Fig. 15, where the connection of the PV inverter to the grid is triggered at t=65 s, and then followed by the activation of the local droop, around t=90 s. Average delays of 2 and 4 s in the communications between the MGCC and local controllers are considered in the activation of the droop control.

Additional experiments were conducted, considering the occurrence of losses in the exchanged data. In Fig. 16 it is possible to observe that communication-related failures can have a significant impact in terms of the MG operation.

V. Conclusions

This paper presented an integration framework for EV in electric power systems. This framework is capable of dealing with the several system operation conditions, providing EV the capability of being an active element within the grid, instead of a typical passive load. In this way, benefits for both system operators and EV owners are expected, by granting more resilience and controllability to power systems.

Concerning the methodology presented for steady state, it was shown that it is appropriate to make expeditious studies in distribution networks. Results showed that power systems can handle, up to a certain level, the penetration of EV without considerable changes in the grid if a dumb charging approach is used. Nevertheless, when the share of EV reaches a given value, it is necessary to reinforce the grid or implement advanced management and control strategies for EV charging.

Results obtained from the experimental tests proved that the EV management and control methods developed are also effective in real-world environments.

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