Electric Vehicles in Isolated Power Systems: Conceptual Framework and Contributions to Improve the Grid Resilience

J. A. Peças Lopes*, P. M. Rocha Almeida*, F. J. Soares* and C. L. Moreira*

** Instituto de Engenharia de Sistemas e Computadores do Porto (INESC Porto) and Faculdade de Engenharia da Universidade do Porto (FEUP), Portugal (e-mails: jpl@fe.up.pt, pedro.almeida@fe.up.pt, fsoares@inescporto.pt and cmoreira@inescporto.pt).*

Abstract: This paper presents a conceptual framework to enable a successful integration of Electric Vehicles (EV) into isolated power systems. The developed framework includes the management and control actions that might be implemented over EV in order to improve the system's resilience. Several dynamic stability simulations were performed, using a small isolated grid as a test system, in order to demonstrate the possible contributions EV may provide to fast power/frequency control, either as a highly flexible and controllable load and/or as an energy storage device.

Keywords: Aggregator, Automatic generation control, Electric vehicle, Frequency control, Islanded operation, Vehicle-to-grid.

1. INTRODUCTION

Today's world faces big environmental and social problems. Therefore, there are countless frontlines that need many researcher communities' attention. The instability of the crude oil markets is degrading the economy of importing countries and their inhabitants' quality of life. At the same time, environmental awareness is pushing modern world towards a future without the use of fossil fuels. Therefore, policy makers' decisions are increasingly contemplating sustainable alternatives to the conventional paradigm. Plug-in Electric Vehicles (EV) with advanced control techniques and renewable energies are two of such alternatives.

In islanded systems a mix of intermittent renewable generation and EV penetration with uncontrolled charging schemes may lead to a decrease of the robustness of operation, unless advanced control procedures are adopted. For instance, a large penetration of wind generation in an island, apart from the environmental benefits, contributes for the increase of the local energy autonomy, but it may also bring some disadvantages for power systems operation, as it may require increasing the reserve levels due to the intermittent characteristics of the primary energy source.

If managed properly, EV may be the solution for the problems described above, given that they will have a storage capability that can be used to help managing the network in some emergency conditions.

When parked and plugged-in, EV will either absorb energy and store it or provide electricity to the grid when, for instance, frequency changes. The latter is the distinctive feature of the Vehicle-to-Grid (V2G) concept allowing the provision of several ancillary services like reserves delivery (Kempton and Tomic, 2005). In this new paradigm, EV can be considered as the key support to boost the renewable energies usage, allowing at the same time to improve the overall performance of the electricity networks either functioning interconnected or in islanded mode.

The purpose of this work was to develop a holistic framework containing all the players involved in this new mobility paradigm, as well as the grid operational management and control strategies that should be implemented to allow a successful large scale integration of EV into isolated power systems. The proposed framework covers all the grid technical operation issues and the services potentially negotiated at the electricity markets when EV are present in the system.

Several simulations were performed in a small island's grid, under the referred control and management framework, aiming to access the EV impact on the system's dynamic behaviour when they participate in the primary frequency control. The analysis carried out focused on the EV effects on the system´s dynamic behaviour when different inverter control types are used (uncontrolled charging mode, controllable charging mode and EV performing V2G), when different control settings are used in order to parameterize EV response and when different shares of EV are willing to participate in the primary frequency control.

2. GRID CONTROL ARCHITECTURE

The technical management of an electric power system having a large scale deployment of EV will require the adoption of a hierarchical management concept where EV will be managed as clusters of distributed storage devices.

From the Distribution System Operator (DSO) standpoint, the energy consumption or the energy stored in an individual EV is too small to impact the grid in any significant manner. Thus, it makes sense to create an aggregator figure whose main functionality is the grouping of EV, according to their owners' willingness, so that together they represent a load/storage device with the adequate size to exploit economic issues in the electricity market (Guille and Gross, 2009). In this sense, the aggregator will act as an intermediary between EV owners and the electricity market. It will acquire electric energy from the market at lower prices and provide it to EV owners while, at the same time, it combines all the storage capacity available from the EV in the aggregation and uses it to offer several services in the market, like peak power, load shifting, reserves or even electric energy (Fig. 1).

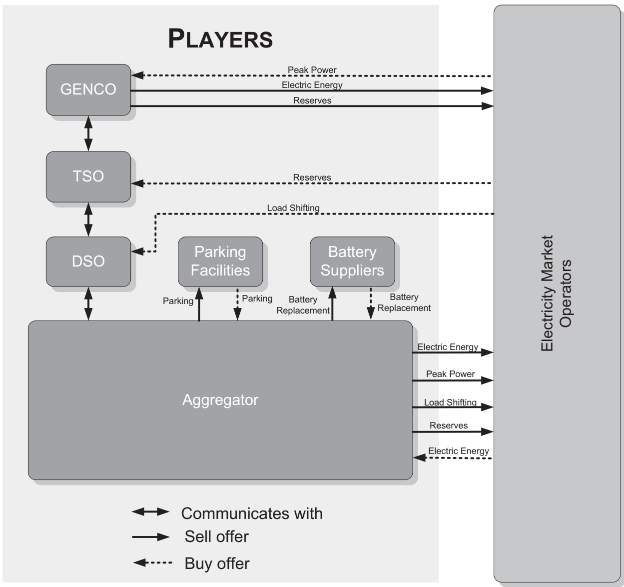

Fig. 1. Technical management and market framework for EV integration into electric power systems.

Peak power is a service to be acquired from the market by the Generation Companies (GENCO) that will allow them to avoid the use of expensive peak generators during high demand periods.

The load shifting is a service that DSO can purchase from the market in order to gain extra flexibility in the grid operation and management tasks, giving it the possibility of partially control the energy demand along the day (Lopes et al., 2009b). The load shifting service will then involve a careful management of the charging periods and of the power consumed by EV. To accomplish successfully such a complex task it is required to know at each moment the State of Charge (SOC) of each battery in the aggregation. This way, EV aggregation can act as a very effective resource by helping the network operator to operate the grid in a smooth way, enabling congestion prevention and voltage control, eventually postponing expenditures in grid reinforcements. Additionally, in electric systems characterized by a large integration of intermittent Renewable Energy Sources (RES), where a renewable generation surplus might exist, the load shifting service can also be used to make EV charge their batteries in the periods where that extra energy is available, avoiding to waste it.

In isolated grids EV battery charging/discharging rates need to be locally controlled through a simple approach like a frequency droop sensitive mode, as described in detail in the next section. From a dynamic stability perspective, EV aggregation can also be used for primary frequency control given that a proper management of EV power demand/supply helps to maintain around the clock the equilibrium between the total energy supply/demand. Nevertheless, different operating conditions may lead to special needs of the parameterization of the droops by the system operator. Having the forecasts for the load, generation and renewable production the DSO communicates to the aggregator how it wants the EV to behave when frequency deviations occur. After receiving this information, the aggregator will send set-points for each EV in order to adjust their droops according to the DSO requirements.

Regarding secondary frequency control, some modifications need to be introduced in conventional Automatic Generation Control (AGC) systems in order to make possible the regulation of EV power output in response to changes in system frequency and in the tie-lines interchanges scheduling - Pif_i in Fig. 2 (in this case for interconnected systems). These control functionalities to be provided by EV are intended to keep the scheduled system frequency and established interchange with other areas within predefined limits. The AGC system monitors and controls the power generation with the objectives of minimizing the Area Control Error (ACE), minimizing the operation costs, maintaining generation at fixed (base load) values and ramping generation according to a schedule specified by the operator. Like in the primary frequency control, the aggregators within the AGC domain will act as intermediates between AGC and EV, as it is shown in Fig. 2.

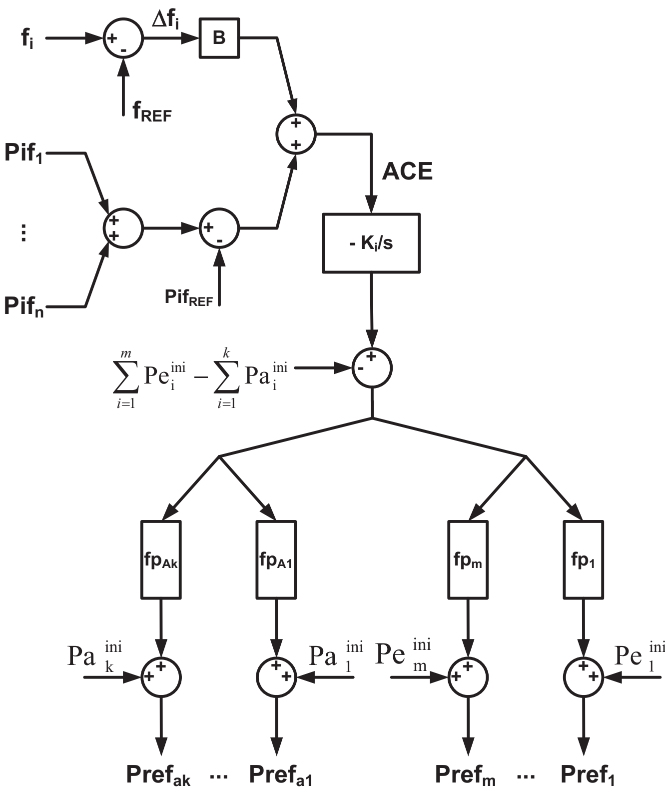

Fig. 2. AGC operation in the presence of EV aggregators.

In Fig. 2, f_i is the control area i measured frequency, f_{REF} the frequency nominal value, B the frequency bias, K_i the integral control gain, fp_i the generator i participation factor, $Pref_i$ the new active power output of the machine i, fp_{Ai} the aggregator i participation factor, $Pref_{Ai}$ the new active power output of the EV under the control of aggregator i, Pe_i^{ini} the active power output of generator i before the intervention of the AGC and Pa_i^{ini} the active power output of the EV under the control of aggregator i before the intervention of the AGC.

As it is obvious, the communications between all the entities, including EV, is crucial to make this new paradigm possible. The amount of data to be exchanged between all the entities involved is considerable, making the communication not so simple to be implemented. However, with the progressive developments that the smart metering technologies are facing, the communications problem might be solved in a fairly easy and inexpensive way. The smart metering solutions currently used for household consumers seem to be a very effective and adequate way to provide the communication infrastructures that will enable the control of such complex electricity services system.

3. ELECTRIC VEHICLES MODELLING

To enable all the envisioned EV modes of operation previously referred, a proper electronic interface control should be adopted, different from a simple diode bridge usually adopted for these purposes. In fact, the possible EV operation modes previously described require the adoption of advanced power electronic interfaces to make its interconnection to the distribution grid. For example, if a V2G operation mode is envisaged, it is necessary to consider the installation of a bidirectional power electronic interface on-board EV.

Being the system frequency an instantaneous indication of the power balance in the network, it must therefore be used to adapt the active power charging/discharging of the EV batteries. A frequency control droop loop, (Engler, 2005), is then adopted to adjust the active power set-point of an EV inverter interface, as described in Fig. 3. In this way a smart EV grid interface, capable of responding locally to frequency changes, is adopted instead of a dumb battery charging solution.

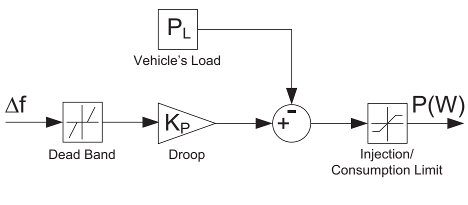

Fig. 3. Control loop for EV active power set-point.

To this conventional control method a dead band, where EV do not respond to frequency deviations, should be added to guarantee longevity of the batteries and thus a beneficial synergy between parties, the grid operator and the EV owners. This dead band as well as the slopes of the droops should be defined according to the composition of the system as well as the EV owners' willingness to help with system frequency regulation.

As EV batteries, under a V2G concept, can either absorb or inject active power, a saturation block with upper and lower limits must be added. A block providing the steady-state set-point of active power must also be included, working as an offset to the droop. This block represents EV normal consumption status, defined by the aggregation agent.

Fig. 4 shows schematically the droop configuration that can be implemented for the EV grid interface control strategy. For frequency deviations larger than the defined dead band, the EV battery will respond according to one of the given slopes. If frequency suffers a negative deviation then the battery will inject power into the grid. On the contrary, if there is a positive deviation then the battery absorbs power from the grid.

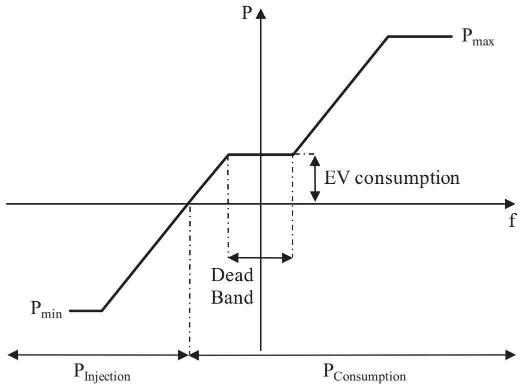

Fig. 4. Droop control for EV.

4. DYNAMIC SIMULATION OF AN ISOLATED SYSTEM

Concerning an isolated system, the research described in (Lopes et al., 2009a) evaluated the benefits of using V2G to maximize the integration of intermittent renewable energy resources in an island. The island analysed has an electrical load ranging from 1770 kW at the valley hours to 4200 kW at the peak hour and a generation system with 4 diesel units (performing primary and secondary frequency regulation as well as voltage control), 2 wind turbines and a mild photovoltaic (PV) penetration. The objective of this study was to demonstrate the technical feasibility of integrating an extra wind turbine without jeopardizing the system dynamic behaviour. The vehicle fleet was composed by 2150 vehicles, corresponding in average to 1 vehicle per household, being 15% of them EV. Full description of the case study can be found in (Lopes et al., 2009a).

The methodology developed to evaluate this potential increase in wind generation, with the presence of EV, was as follows:

1) The isolated system was characterized, in terms of available generation and load and these components modelled and assumed to be connected to a single bus system.

2) EV penetration was then characterized and the model for EV connections, featuring V2G, developed. This model was afterwards included in the single bus system.

3) A sudden decrease on wind power generation was simulated and its impact on the system's frequency was evaluated for two different situations: when EV are in charge mode only and when they participate in primary frequency control. The period chosen to perform that study referred to a valley hour (5 a.m.), where wind power represented a considerable share in the electricity being generated. Such period was selected once it represents a worst case scenario for frequency deviation issues. Due to the system's high dependency on the wind power production, if a sudden decrease in wind speed occurs, system frequency might drop to levels that may jeopardize EN 50.160 standards.

4) The amount of wind power generation (by increasing the wind power installed capacity) was increased and the feasibility of this new situation was assessed by repeating step 3).

In (Lopes et al., 2009a) a fixed droop (0.1 Hz dead zone and P_{rated} MW/Hz droop) and a V2G approach for all studied scenarios were considered. However, different operating conditions may lead to special needs of the parameterization of the droops by the system operator or the adherence of the EV owners might be to different inverter control types.

First, the different inverter control types were tested: uncontrolled charging mode, controllable charging mode and EV performing V2G. This way it is possible to understand their effects on the system operation. Second, the effects of the droop control variables were tested in order to understand how the system could adapt those parameters under several stress situations. More specifically, when subject to large disturbance proneness the system operator could ask the aggregator to adjust the EV droop control in a more demanding manner. Conversely, in a situation where large disturbances are not likely to occur, the inverter control could be relaxed in order to spare EV batteries life. Third, if EV owners' adherence to primary frequency control provision varies, then to achieve similar results the control droops will have to be modified. This stage of the research shows how several adherence levels should be handled in terms of system operation in order to get a constant grid resilience level.

All the studies performed consider that EV are consuming 200kW when the sudden wind speed variation described in (Lopes et al., 2009a) occurs.

4.1 Different Control Types

Fig. 5 to Fig. 8 depict the system response to the shortfall on wind considering three different control types:

1) Uncontrolled charging mode: EV do not participate in primary frequency control.

2) Controllable charging mode: EV participate in primary frequency control by reducing their load ($P_{min} = 0$ in Fig. 4).

3) V2G mode: EV participate in primary frequency control either by reducing load or injecting power into the grid.

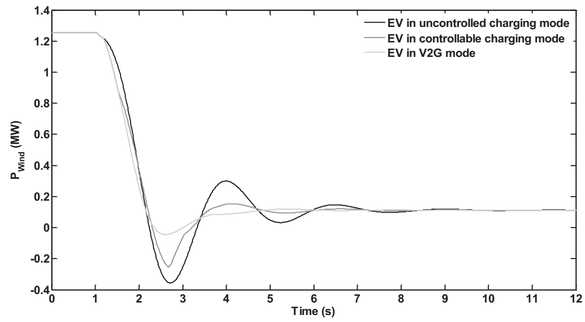

Fig. 5. Wind turbines active power for the three control types.

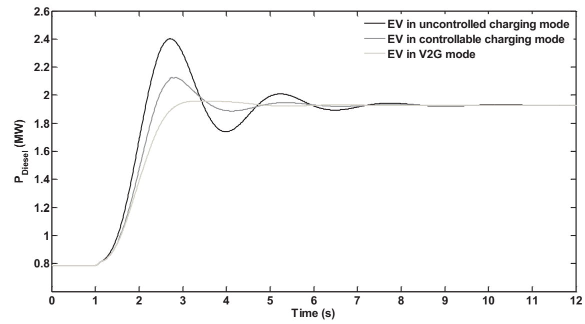

Fig. 6. Diesel units active power for the three control types.

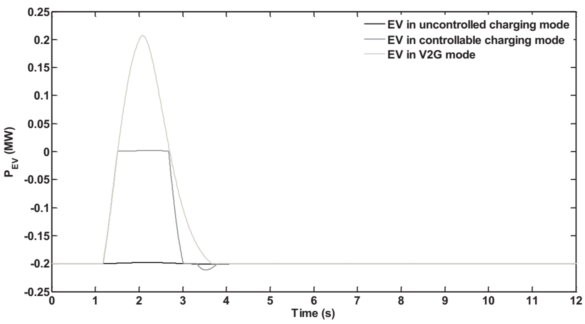

Fig. 7. EV active power for the three control types.

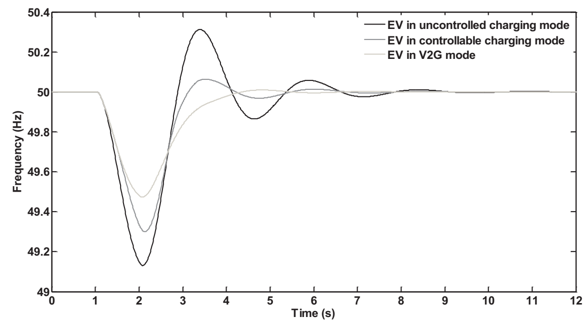

Fig. 8. System frequency for the three control types.

In the last 2 cases, and depending on the system operating conditions, a methodology for an adaptive definition of EV parameters could be developed based on machine learning techniques under a set of off-line studies. This would make EV more responsive in grid operating scenarios where the occurrence of certain disturbances can make the system more vulnerable.

The attained results show that when EV are operating in the controllable charging mode their reaction to frequency deviations is the same as in the V2G mode while EV are not requested to inject power into the grid. Nevertheless, the controllable charging mode prevents this and so the diesel units have to take over frequency control alone. The EV return then to their initial operating state faster than in the V2G mode. The effect visible for controllable charging mode on Fig. 7 (time interval: 3s to 4s) is due to the overshoot in the frequency response, resultant of the more demanding diesel reaction.

As it was expected the controllable charging mode reduces the frequency drop when compared with the uncontrolled charging mode, but is not as effective as the V2G mode. However, the result proves that a less demanding control for EV is also effective in a much more attractive framework for EV owners.

4.2 Effect of Tuning the Droop Control Variables

Fig. 9 to Fig. 12 show how the system reacts to different sets of inverter control parameters.

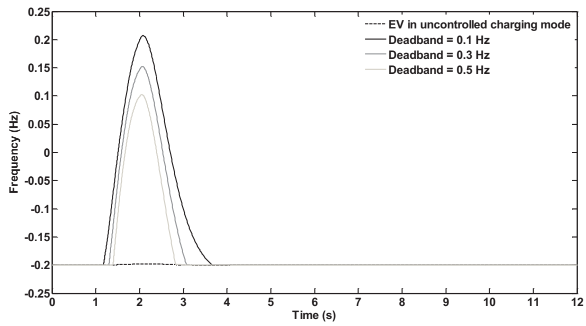

Fig. 9. EV active power for three possible dead bands.

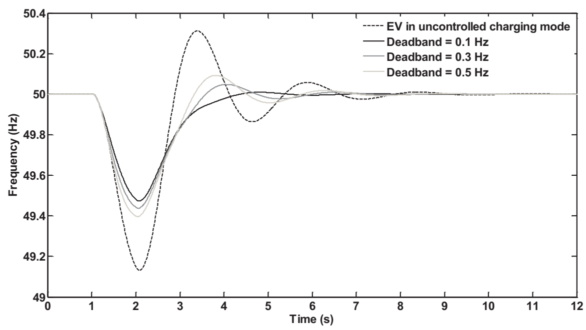

Fig. 10. System frequency for three possible dead bands.

In Fig. 9 it is observable that increasing dead bands result in larger delays in response to the same disturbance. While this delay occurs the diesel units are forced to react faster and so the contribution of EV is smaller for increased dead bands.

However, the frequency drop gain of all tested dead bands is very good compared to the uncontrolled charging mode results, Fig. 10. The dead band adjustment may then be an important parameter to enable the use of EV on the important service of primary frequency control while safeguarding the batteries lifetime.

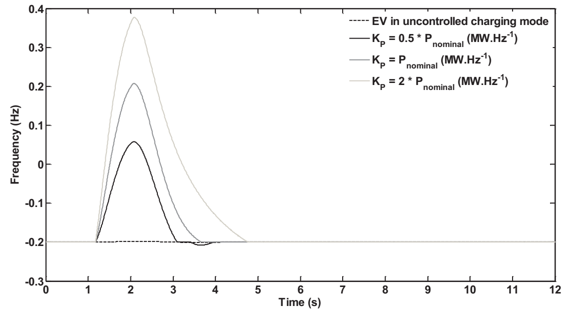

Fig. 11. EV active power for three droop values.

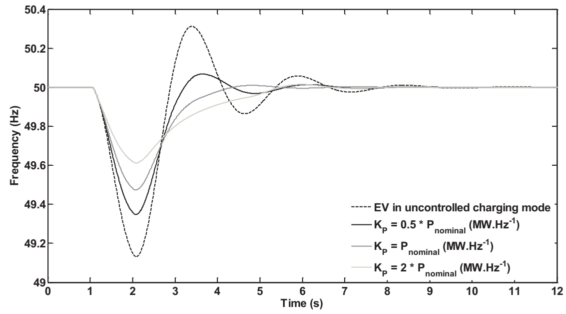

Fig. 12. System frequency for three droop values.

Fig. 11 depicts the EV active power for three droop values. It shows that changing the droop value carries large changes on the active power. Nevertheless, its effect on the frequency is not so great, as it can be seen in Fig. 12. The most important effect of the EV contribution for frequency control is the fact that their electrochemical batteries respond much faster than the diesel units. So, either by adjusting the droop or by changing the dead band, a solution that serves both the interests of the system operator and the EV owners can easily be attained.

4.3 Controlling Different Adherence Levels

Fig. 13 and Fig. 14 show how the system reacts to several levels of adherence of EV owners to V2G operation mode. In this case the droops were adjusted in each scenario to obtain, if possible, the same frequency deviation.

It is observable that it was possible to achieve the same frequency deviation and overall power variation for 100%, 75% and 50% V2G control mode adherence by the EV owners. To do so the droops were increased as adherence decreased. Considering a K_P droop in the 100% V2G scenario, $4/3.K_P$ and $2.K_P$ droop were required in the 75% and 50% V2G cases, respectively.

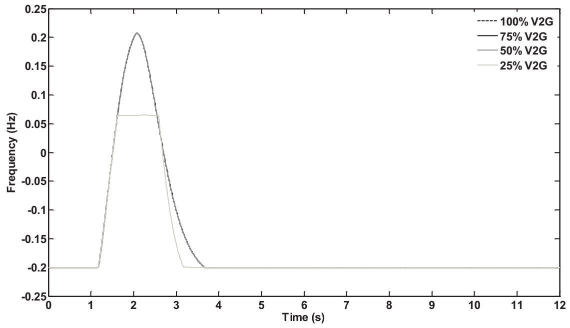

Fig. 13. EV active power for several adherence levels.

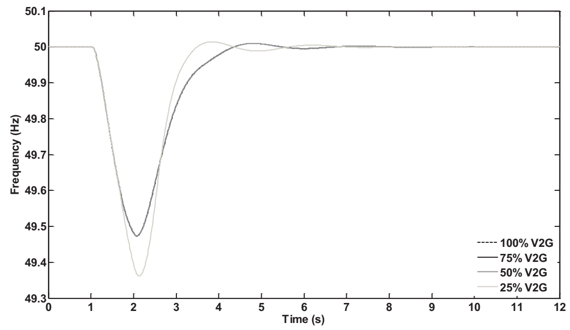

Fig. 14. System frequency for several adherence levels.

In the 25% V2G scenario a $4.K_P$ droop was used, but EV injection capacity was not enough to meet required level demanded by the disturbance.

The usage of these droops is however dependent of the inverter/battery capability of coping with these operation scenarios.

5. CONCLUSIONS

In this paper an innovative conceptual framework for large scale deployment of EV in isolated power systems was described. The proposed approach assumes that EV can be extremely flexible and highly controllable loads and can also act as a storage device able to inject power in the system (V2G operation mode). Such intrinsic EV characteristics can be exploited from the grid perspective as a set of system regulating services, helping in this way in the overall load/generation balance.

The framework suggested for the large scale integration of EV in electric power system is highly dependent on a new market player: the aggregator. This new entity will act as an intermediary between EV owners and the electricity market and will have the capability of providing a novel set of services both to EV owners and grid operators.

Regarding the provision of primary frequency control from EV, this research described results obtained with different control approaches for EV inverters, showing that the adoption of a controllable battery charging mode is quite effective in isolated grids. Periodic adjustments of the electronic grid interface control parameters (triggered by the operating conditions of the system) can easily be performed to achieve less demanding operation conditions for EV and to improve the system robustness of operation, namely regarding frequency deviations.

A massive deployment of EV will allow also a safe increase of the intermittent and variable RES installed power, like wind power and PV generation, namely in isolated power system, since EV batteries will be capable of providing fast frequency compensation capabilities to the system.

The dependency of the effectiveness of frequency control to the service adherence was also addressed in this research. As expected, the results concerning this issue lead to the conclusion that increasingly EV adherence rates to such service provision schemes result in a growing system's robustness level.

Appendix A. AKNOWLEDGEMENTS

This work was supported in part by Fundação para a Ciência e Tecnologia under Grants SFRH/BD/48491/2008 and SFRH/BD/47973/2008 and within the framework of the Project with the Reference MIT-Pt/SES-GI/0008/2008.

REFERENCES

ENGLER, A. 2005. Applicability of droops in low voltage grids. *International Journal of Distributed Energy Resources,* 1.

GUILLE, C. & GROSS, G. 2009. A conceptual framework for the vehicle-to-grid (V2G) implementation. *Energy Policy,* In Press, Corrected Proof.

KEMPTON, W. & TOMIC, J. 2005. Vehicle-to-grid power fundamentals: Calculating capacity and net revenue. *Journal of Power Sources,* 144**,** 268-279.

LOPES, J. A. P., ALMEIDA, P. M. R. & SOARES, F. J. 2009a. Using Vehicle-to-Grid to Maximize the Integration of Intermittent Renewable Energy Resources in Islanded Electric Grids. *International Conference on Clean Electrical Power.* Capri, Italy.

LOPES, J. A. P., SOARES, F. J. & ALMEIDA, P. M. R. 2009b. Identifying Management Procedures to Deal with Connection of Electric Vehicles in the Grid. *PowerTech'2009.* Bucharest, Romania.