Using Vehicle-to-Grid to Maximize the Integration of Intermittent Renewable Energy Resources in Islanded Electric Grids

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***Abstract*—This paper presents the results of a dynamic behaviour analysis study developed with the objective of quantifying the amount of wind power that can be safely integrated in an isolated electricity grid where Electric Vehicles (EVs) are present. The assessment was performed considering two distinct situations: a) when EVs are only in charging mode and b) when EVs participate in primary frequency control. The test system, a small island, contains, in addition to wind generation, a small amount of solar PV plants and four conventional diesel generators. Only wind power influence in system's frequency was assessed since, from a dynamic perspective, this is the renewable resource whose high intermittency level might be more harmful for the electric system operation. Sudden wind variations were simulated and, for both situations, a) and b), the amount of Intermittent Renewable Energy Sources was maximized, keeping always the grid frequency within the limits defined by the power quality standards.**

***Index Terms*—Electric vehicles, frequency control, intermittent power sources, islanded operation, vehicle-to-grid.**

I. Introduction

ELECTRIC power systems are about to face a new challenge: the integration of electric vehicles in the grid. At the same time renewable energies need to increase their penetration in the generation mix to contribute for the decrease in CO_2 emissions. In islanded systems a mix of intermittent renewable generation and electric vehicles penetration with dumb charging schemes may lead to a decrease of the robustness of operation, unless advanced control procedures are adopted For instance, large penetration of wind generation in island systems, 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 to increase reserve levels due to the intermittent characteristics of the primary energy source.

As it is obvious, the same amount of intermittent renewable energy sources (IRES) connected in different networks will provoke different impacts, given the singular characteristics of each grid. Regarding frequency, it is expected a very stable profile for a large interconnected system, unless considerable amounts of IRES exists within and the renewables power resources suffer large variations. On the other hand the frequency of a small islanded system is very sensitive to load and generation variations, which constrains the amount of IRES that can be safely integrate in it. In the future it is expectable that distribution networks with a considerable amount of IRES may develop the capability of being operated in islanded manner. This will be the case of distribution grids when composed by a set of interconnected microgrids, which in case of fault will have the capability to operate autonomously in an islanded mode [1]. So an interconnected power system, under certain conditions, might turn into a group of isolated grids with a large amount of intermittent generation, requiring an increase in storage capacity to keep robustness of operation for those conditions.

If managed properly, Electric Vehicles (EVs) 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, EVs 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 [2]. In this new paradigm, EVs can be considered as the key support to boost the IRES usage, allowing at the same time to improve the overall performance of the electricity networks either functioning interconnected or in islanded mode.

In this paper a comparative study is performed to quantify the amount of wind power that can be integrated in an isolated electricity grid in two distinct situations: a) when EVs are only in a dumb charging mode and b) when EVs participate in primary frequency control. In addition to wind generation, the test system used for this purpose includes also a small solar PV plant and four conventional diesel generators. Only wind power influence in system's frequency is being assessed since, from a dynamic behaviour perspective, this is the power source whose high intermittency level might create more difficulties to electric system operation.

Dynamic simulations are performed for a feasible EVs integration scenario, taking into account the results obtained in the study described in [3]. Sudden wind power variations are simulated and, for both situations, a) and b), the amount of IRES is to be maximized, trying to

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keep grid frequency always within the limits defined by power quality standards [4].

II. Methodology

The methodology developed to evaluate the potential increase in wind generation for an isolated system, where EVs are present, is as follows:

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

2) EVs penetration was then characterized and the model for EVs 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 EVs are only in charge mode only and when they participate in primary frequency control.

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).

A. Scenarios characterization

The number of EVs integrated into the grid under study was determined taking into account the results described in [3]. In the referred paper, a smart management strategy for EVs charging was compared with a dumb charging approach.

The dumb charging approach assumes that EVs' owners are completely free to connect and charge their vehicles whenever they want, behaving in this way as simple loads. The smart charging strategy envisions an active management system, where there is a hierarchical control structure that continuously monitors all the elements connected to the grid and its state, exploiting the concepts used for the management of microgrids and multi-microgrids [1], [5]. This is mainly a steady state control approach that shifts battery charging for valley hours.

The smart charging approach was the strategy chosen to be employed in this study, to define the number of vehicles that are plugged-in and, among these, the ones that are really charging. It is important to refer that, being the EVs charging managed by a higher level entity, some of them might be connected to the grid but not charging due to grid's technical constraints. Some of the connected EVs might even be fully charged at the time considered for the simulation.

The period chosen to perform this study refers to a valley hour (5 a.m.), where wind power represents 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 risky levels. The wind profile considered to assess the dynamic behaviour of the islanded system is presented in Fig. 1. As one can observe, in just 1 s, the wind speed suffers a change of 37%, falling from 9.5 to 6 m/s.

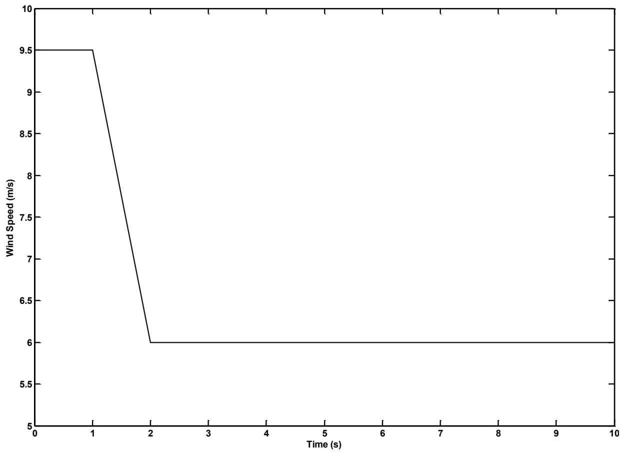

Fig. 1. Wind speed profile.

It was assumed a total number of 2150 vehicles on the island and, from these, 323 (15%) were assumed to be electric.

The EVs fleet considered includes plug-in hybrid vehicles and two types of full electric vehicles, each one of them with a different rated power charging: 1.5 kW for the hybrid, 3 kW for the medium sized EV and 6 kW for the large sized EV [6], [7]. The medium sized EV (EV1) and the large sized EV (EV2) intend to represent cars with different driving ranges developed by automotive manufacturers to face different customers' needs. The share of hybrid EVs was considered to be 40%, whereas the remaining 60% was equally split by EV1 and EV2. This distribution was chosen since it is almost certain that plug-in hybrid vehicles will start to be sold far before full electric vehicles.

The total load resulting from the EVs battery charging, at 5 a.m. and when the aforementioned smart charging strategy is considered, is of 402 kW (19% of the total), being the remaining conventional load of 1770 kW. It was assumed for the purpose of this study that the total instantaneous power that is available from EVs' batteries, connected to the grid at 5 a.m., either for injection or consumption is approximately 851 kW. This means that all the vehicles are in an intermediate state of charge.

Concerning generation capacity, the island contains 4 diesel generators (two with 1500 kW capacity and the other with 1800 kW), 100 kW of dispersed solar PV plants (which will not be taken into account in the studies performed since they are related to night period scenarios) and 2 wind turbines (with 660 kW each).

Two scenarios were defined, being the only difference between them the amount of wind power produced. In the first one, the wind power represents 41% of the total generation, with 900 kW, being the remaining power, 1272 kW, assured by the diesel generators. In the second scenario, a third wind turbine of 660 kW was assumed to be installed in the island. Thus, the share of the wind power was increased to 1272 kW, representing, in this case, 59% of the total generation. The wind power was limited to this value, given that both diesel generators had to be kept running at their minimum technical limits: 450 kW (30% of the full capacity).

Table I shows the electric system's characterization, in terms of load and generation, for both scenarios (at 5 a.m.).

TABLE I
SCENARIOS DESCRIPTION

	Scenario 1	Scenario 2
$P_{Total\ load}$ (kW)	2172	2172
P_{load} (kW)	1770	1770
$P_{EV\ load}$ (kW)	402	402
$P_{EV\ available}$ (kW)	851	851
P_{wind} (kW)	900	1272
P_{sync1} (kW)	636	450
P_{sync2} (kW)	636	450

B. Grid modelling

As it was mentioned before, the system under study represents a small isolated grid. The local network is presented in Fig. 2.

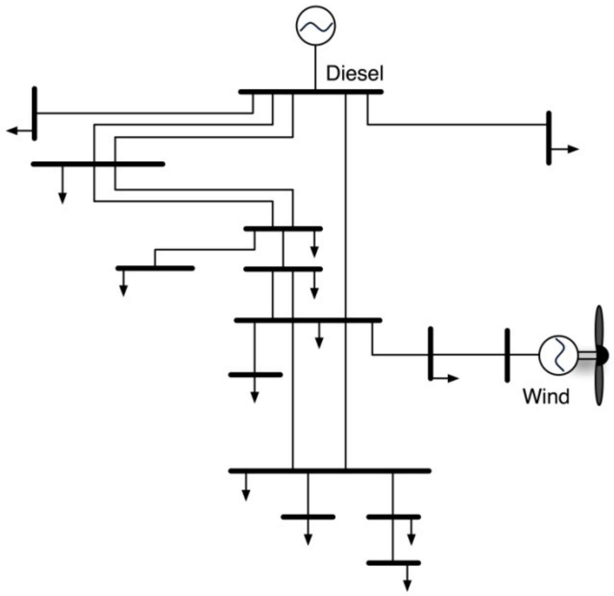

Fig. 2. Isolated system single-line diagram.

From this network a single bus model of the system was developed, assigning to each generation technology a well dynamic model. Transformers to connect the different network voltage levels were considered to make it possible to refer the machines parameters in their own bases.

For the conventional diesel generator, a common 4th order model was taken from the literature [8]. Frequency regulation is performed through conventional proportional and integral control loops. The wind generator was modelled as a simple induction wind generator as described in [8].

Using *MatLab/Simulink*, the previously described system was assembled following the general principles used for dynamic stability studies in conventional power systems, which consist on keeping the sources model in the time domain (solution of a set of differential equations) and to use a steady state frequency domain model to represent the electrical components and their links. The network components were represented as constant impedance elements, being the network currents computed through the network algebraic equation [10].

In the adopted model, the output of each power source is an electromotive force (emf) as it is the usual approach followed in conventional power systems dynamic studies. The electric network, composed in this case only by the transformers, is represented by its admittance matrix in the d-q reference frame, in which the fast transients associated to the network are neglected [11], [12].

C. EV modelling

To properly model EV grid interface it was necessary to define the control strategy to be adopted for these connections. The EV grid battery interface was modelled as a PQ inverter control strategy as described in [1]. In this strategy, the inverter is used to supply certain values of active and reactive power fixed by set-points.

This kind of control can be achieved using an inverter control scheme based on a current-controlled voltage source.

As described in [1], this method computes the instantaneous active and reactive components of the inverter current: the active component is in phase with the voltage and the reactive component with a 90 degrees (lagging) phase-shift, being both limited in the interval [-1, 1].

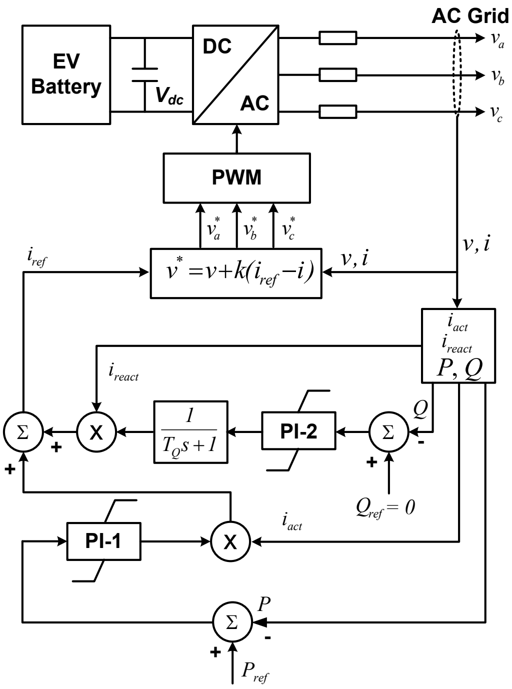

Fig. 3. PQ inverter control system [1].

The active component is used to control the DC link voltage and, consequently, the inverter active power output, in order to balance EV battery and inverter active power output. The reactive component controls the inverter reactive power output. Power variations in EV battery lead to a variation of the DC link voltage, which is corrected via both Proportional-Integral regulators (PI-1 and PI-2), by adjusting the active current output. In this work, this inverter will be operated with a unit power factor (Q_{ref} = 0 in Fig. 3).

The system frequency is an instantaneous indication of the power balance in the island network. Frequency is therefore used to adapt the active power charging /discharging of the EV batteries. A frequency control droop loop is then adopted to adjust the active power set-point of the PQ EV inverter interface (P_{ref} in Fig. 3), as described in Fig. 4. In this way a smart EV grid interface, capable of responding locally to frequency changes, is adopted instead of a dumb battery charging solution.

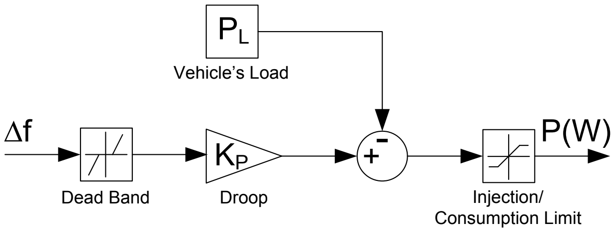

Fig. 4. Control loop for EVs active power set-point.

To this conventional control method a dead band, where EVs do not respond to frequency deviations, was added to guarantee longevity of the batteries and thus a beneficial synergy between parties, the grid operator and the EVs 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 EVs owners' willingness to help with system frequency regulation. After several tests for this case study, a 0.1 Hz dead zone was used and P_{rated} MW/Hz droop was defined.

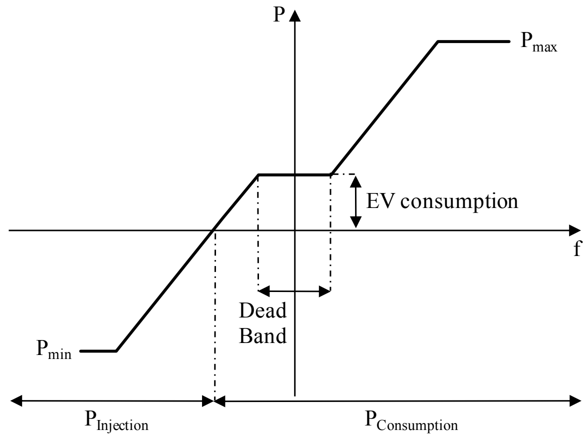

Fig. 5. Droop control for EVs.

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

Fig. 5 shows schematically the droop configuration 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.

III. Result Analysis

Dynamic simulations were performed for the chosen scenarios, taking into account the wind power disturbance described in Figure 1. Results that describe the dynamic behaviour of the system are shown in Fig. 6 to 9 for scenario 1 and Fig. 10 to 13 for scenario 2.

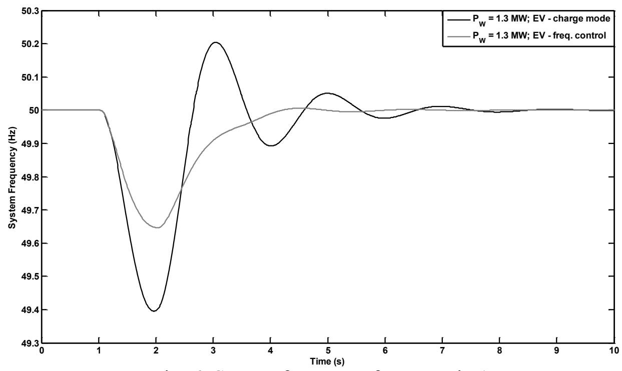

Fig. 6. System frequency for scenario 1.

Fig. 6 shows that during the valley hours, when there are only two diesel units online, the system frequency drops to 49.40 Hz following the considered disturbance In this case only the diesel units are responsible for frequency control. Nevertheless, if EVs participate in frequency control, not only will the frequency drop to a smaller value, 49.65 Hz, but also the pre-existing overshoot will cease to occur.

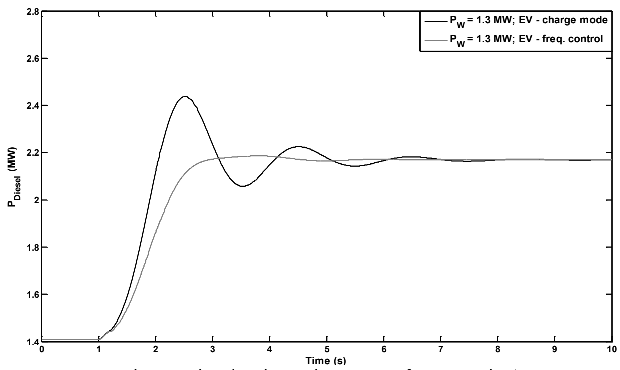

Fig. 7. Diesel units active power for scenario 1.

Fig. 7 to 9 depict the active power behaviour of the several generation units that compose the local generation portfolio at the time of the shortfall on wind generation. When the diesel units are the only load followers frequency oscillations take place due to the integral control loop that tries to swiftly push frequency to its steady state value.

When EVs participate in frequency control then this under damping situation disappears as EVs inverters have very small delays, participating actively in the frequency control either by injecting or absorbing active power. So, EVs interfaced with smart grid interfaces bring stability to the system just by reducing their level of consumption from 401 kW to 141 kW. Another visible phenomenon is that when frequency starts to drop in both cases the system evolves equally. This is due to the dead band in the EVs droop control, that avoids premature wear of the batteries but also prevents EVs reaction to smaller frequency deviations.

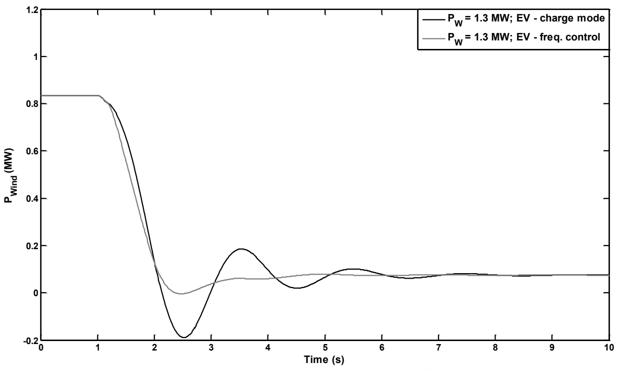

Fig. 8. Wind generators active power for scenario 1.

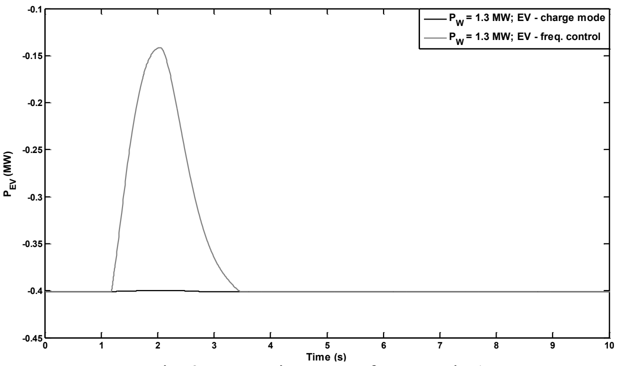

Fig. 9. EVs active power for scenario 1.

Since frequency deviations can be largely damped when adopting this kind smart EV grid interface, one can assume that wind generation can be increased without compromising power quality in terms of system frequency excursions. In order to evaluate the feasibility of this hypothesis an increase in wind power generation was considered for the scenario under analysis.

To perform the verification of this premise, a third wind generator, similar to the others, was then assumed to be in operation in the system. From the simulations performed, system frequency, in this case behaves as shown in Fig. 10. However, in EVs charging mode only the frequency drops to 49.13 Hz and, with EVs participating in frequency control, to 49.47 Hz.

Finally, the active power delivered by each of the generating units is shown in Fig. 11 to 13. Once again the system reacts similarly to scenario 1 results, as expected, with two main differences:

a) The first is that even though the initial generated active power was much larger than that of scenario 1, the final value after the wind shortfall is quite similar: 74 kW in scenario 1 against 112 kW in scenario 2. Such fact enforces the more demanding nature of scenario 2.

b) The second main distinction that can be made between both settings is that when EVs participate in frequency control, in scenario 2, they have to inject power into the grid. EVs work on a V2G basis instead of a purely controllable load approach. Nevertheless, the value it assumes, 6 kW, is very small (see Fig. 13). If a cap had been fixed for the EVs participation, then the system, under a controllable load approach, would have performed almost in the same way as in the vehicle to grid one.

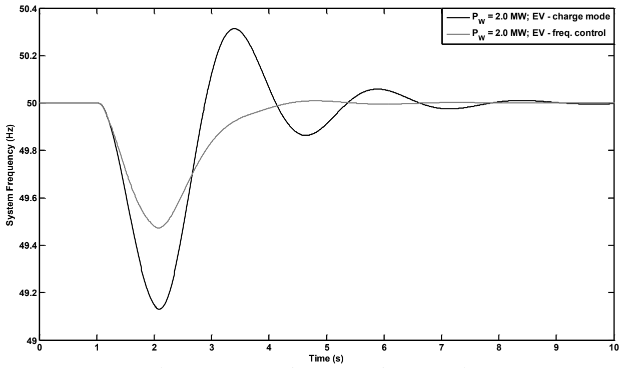

Fig. 10. System frequency for scenario 2.

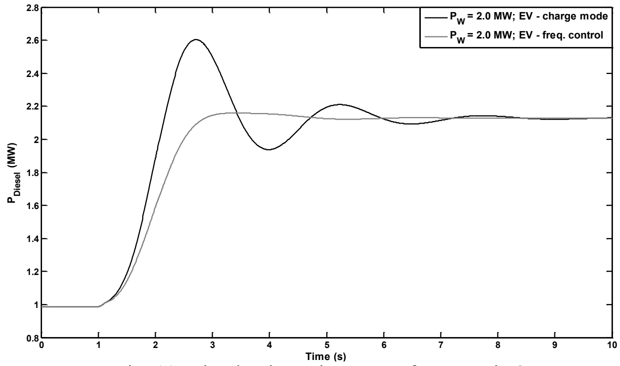

Fig. 11. Diesel units active power for scenario 2.

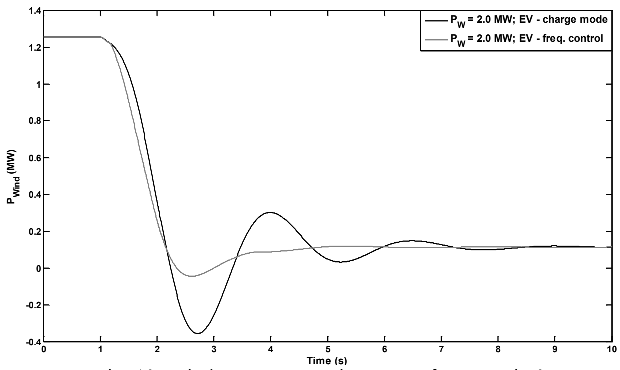

Fig. 12. Wind generators active power for scenario 2.

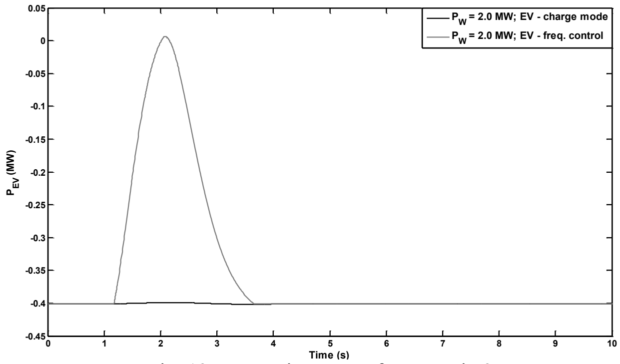

Fig. 13. EVs active power for scenario 2.

IV. CONCLUSIONS

Electric vehicles interfaced with the grid in a smart way can increase robustness of operation to power system dynamic behaviour. From a purely technical level, the use of batteries, like those that serve as storage for EVs, together with power electronic interfaces that are capable of responding very fast to frequency deviations improve considerably the global system dynamic behaviour regarding participation in primary frequency control.

The presence of a considerable amount of storage capability connected at the distribution level also allows the operation of isolated distribution grids with large amounts of IRES and/or microgeneration units connected to it. In fact the presence of storage devices will allow load following to take place in such conditions, since the batteries of the EVs will provide energy to fast balance these grids, thus maximizing the amount of IRES that can be exploited without compromise grid robustness. In an ultimate analysis, EVs and the V2G concepts can be faced as two key supports to boost the IRES usage, allowing at the same time to improve the overall performance of the electricity networks either functioning interconnected or in isolated mode.

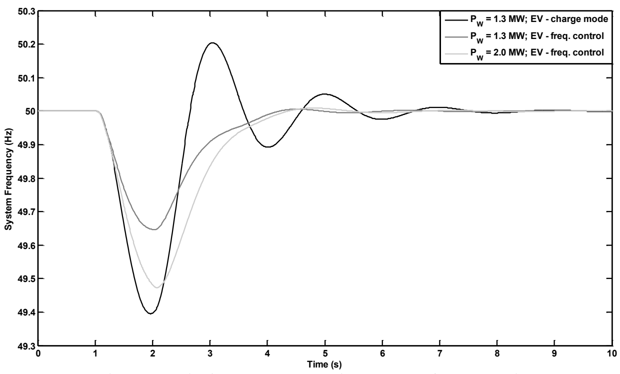

Fig. 14. Wind generators active power for scenario 1.

From the work developed in this paper, it is possible to verify that this system, which complied with the international standards for isolated systems under the norm EN50.160, improved dramatically its performance when EVs were used for frequency control. It was even possible to integrate one extra wind generation unit with improved performance as can be verified in Fig. 14.

Further sensitivity analysis is still needed to identify the best control parameters for the droop control mode of the electronic grid interface used by the EVs.

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V. BIOGRAPHIES

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