Electric Vehicles Contribution for Frequency Control with Inertial Emulation

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Abstract

This work proposes a novel primary frequency control technique with Electric Vehicles (EV), the combination of inertial emulation and droop control, for isolated systems. Being EV dispersed along the grids, the impacts of possible delayed actions is assessed. Islanded systems have reduced inertia and so load / generation imbalance situations may lead to large frequency deviations. Therefore, this paper focuses essentially on the EV contribution for primary reserves provision, in order to allow a safe integration of further intermittent Renewable Energy Sources (RES). An avant-garde generation dispatch was adopted for the test system used in this work, fully reliant on RES, mainly conventional hydro units and some wind generation. The studied disturbances include a rapid shortfall on wind power production and a sequence of consecutive events caused by the variability of the wind resource in an ordinary situation.

Keywords: Electric vehicles, Power system dynamics, Primary frequency control, Islanded systems, Inertial emulation, Droop control.

1. Introduction

There are countless frontlines that need to be tackled in the pursuit of sustainability. Environmental awareness and the instability of the crude oil markets are pushing

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modern world towards a future less dependent on fossil fuels. As alternatives, energy efficiency and Renewable Energy Sources (RES) are being more and more exploited. At a global level, regarding final energy consumption by sector of activity, it is verified that the transport sector is the one that leads, followed closely by the industry and only after the residential [1].

This paper is devoted to the exploitation of the impacts and potential benefits that the electrification of the vehicle fleet may provoke on isolated electric power systems, namely in what regards the expansion of intermittent RES. Regarding transportation, sufficient recharging facilities will have to be provided to Electric Vehicle (EV) owners, charging either at home or at public charging infrastructures. In any case, in the electricity sector, Distribution System Operators (DSO) will have to handle with a new load that before was not included in planning and operation.

In addition, as EV have a high potential to participate in several ancillary services, [2], this paper also addresses the grid operational management and control strategies that should be available with the presence of these new elements.

Whether providing peak load demand or participating in the spinning reserves or in frequency regulation, the potential to control EV charging process is new to the current structure of the electricity grids. In this way, the growing prospects of an EV market expansion may strengthen the concepts that aim at the active network management.

The work presented in [3-5] promoted the first steps into EV integration in power systems as controllable loads and set the path for the exploration of EV batteries as storage elements for the provision of several ancillary services to the electricity grid.

Four power markets with relevance for EV were analyzed in [6]: base load, peak, spinning reserves, and regulation. As EV main purpose while connected to the grid is to acquire energy to fulfill its transportation needs, the authors suggest that EV should initially provide regulation and spinning reserves. Another work, [7], addressed the participation in regulation by EV, performing a valuation of EV power for the provision of regulation up and down. The work presented in [8] addresses the technical grid related issues of using EV in regulation. Technical operation is alongside with market integration a pillar that supports EV advanced management techniques. EV were used in voltage support and frequency regulation with the application of control droops.

Stationary battery applications for frequency control have been studied, for instance in [9,10], but they always considered relatively large battery systems, which imply large investments costs in a dedicated asset for the grid. EV presence in electricity grids may be exploited for the same purpose, while avoiding the investment cost. Nevertheless, EV presence is not certain in time and space as the vehicles commute and may be plugged-in in different locations. In addition, the State-of-Charge (SOC) of the EV batteries is also variable for the system operator.

This work builds upon the research developed in [11], to assess the effectiveness of EV participation in frequency control in isolated system. These systems have reduced inertia and so imbalance situations between load and generation may lead to large frequency deviations. Therefore, EV contribution in these systems should focus on primary reserves provision. In this paper a novel control approach that emulates the generators inertia effects in combination with the previously described droop control loop that mimics conventional generators governing actions is proposed. In a second stage, this work tests the performance of the EV local frequency control units when their action is disturbed by delays that may differ with the EV charging equipment and control. The test system is a representation of a small islanded system, based on real data, with high potential for RES expansion, but with very low load conditions during valley and peak hours. For this reason the island has to depend on fossil fuels to guarantee quality to the power supplied to the consumers. The presented scenarios assume an avant-garde generation dispatch, fully reliant on RES, mainly conventional hydro units and some wind generation. As referred, the developed control techniques should be able to allow further integration of intermittent RES in these systems.

2. Methodology and Modeling

As it was explained in section 1, this paper aims at identifying new procedures and assessing the efficacy of EV in frequency control provision for isolated systems.

The European norm EN50160, [12], defines that the admissible operation conditions for isolated system and introduces a limit of ±1 Hz for frequency deviations.

To do so, a disturbance on Renewable Energy Sources (RES) power availability was defined in order to create a worst case scenario. To evaluate EV potential for frequency control the methodology presented next is as follows:

1. The isolated network dynamic model was characterized in terms of electricity grid and generation system.
2. With the defined disturbance, a dynamic simulation was conducted for the case where EV are regarded as simple loads.
3. The same simulation was conducted using EV to perform frequency control.

The obtained results allow analyzing the power system reaction in terms of frequency, the dispatched conventional units' power and torque and the EV load.

2.1 Control Scheme

In [11,13] a droop control that mimics the governors of conventional generators was adopted to implement primary frequency control on EV. In this paper, a novel control loop is proposed in addition to the droop control, the inertial control, which also emulates the behavior of conventional generator allowing EV to provide inertia to the system. This technique has been applied in different contexts, for instance in [14].

For both control loops frequency must be read locally and the reaction to frequency deviations is performed autonomously. This reaction should consist on providing new set-points for the electronic power converter that interfaces EV batteries and the electricity grid. As described in [15,16] the control scheme should be installed on individual Vehicle Controllers (VC), which should be located next to the vehicle charger, establishing the link with the smart electricity grid communication infrastructure. This allows upstream controllers to be logged about the activity of the VC concerning primary control provision and, if needed, redefine the droop control settings for the inertial emulation.

So, apart from an eventual set-point imposed by an EV market aggregating entity, named Aggregator, as proposed in [15], or by local control actions, the load value of the EV may be influenced by one of or both the control loops. Equation (1) presents the active power change requirement for the EV due to the influence of the droop. The load will change by an amount that is obtained by multiplying a proportional gain by the actual frequency change. While a frequency error is sustained the proportional controller will always impose a change in the load of the EV.

Equation (2) provides the amount of active power change, in case of a load/generation imbalance, that results from the inertial emulation implementation in the controllers of EV. In this case the load will change by an amount equal to the product of a gain by the derivative of frequency change in respect to time. The derivative gain is a measure of the sensitivity of the controller to the rate of change of frequency, expressed in units of power per units of frequency per unit of time. The influence of this type of control is bigger for periods when frequency is changing fast and will be null when frequency stabilizes, independently of how big the absolute frequency error may be. The action of this control is mainly noticeable in the initial moments succeeding a disturbance.

$$\Delta P_{Droop} = k_p \cdot \Delta f \quad (1)$$

$$\Delta P_{Inertial\,Emulation} = k_{in} \cdot \frac{d}{dt} \Delta f \quad (2)$$

Where

- ΔP_{Droop} is the load change provoked by the droop control
- $\Delta P_{Inertial\,Emulation}$ is the load change provoked by the inertial emulation control
- k_p is the proportional gain
- k_{in} is the derivative gain of the controller
- Δf is the frequency deviation

However, EV should not react to every small mismatch in power and so a dead band must be added and a fixed power rating should be maintained whenever possible. The dead band should be considered to guarantee longevity of the batteries and thus a beneficial synergy between parties, the grid operator/Aggregator and the EV owners. The charging reference power, P_{ref}, may be defined in different ways:

- Set-point from the Aggregator or the DSO for EV that adhere to smart charging schemes, depending on the strategies for minimizing charging costs and the occurrence of possible grids technical violations
- Or, by local decision of EV owners who do not adhere to smart charging

A margin between the actual power rating and the maximum power rating may be imposed to EV participating in primary frequency control, in order to allow the participation in downwards regulation. The maximum power rating is the nominal charging power of the EV, whereas the minimum power rating is the nominal discharging power, zero, a value between the minimum and maximum power ratings or even a value below zero if drawing power from the EV batteries is allowed.

As to the inertial emulation loop, it may be wise to introduce a saturation following the derivative of the frequency deviation to block positive rates of change and consequently prevent the action of the inertial emulation loop for periods where generation exceeds load. Such fact is due to the most severe events being linked to generation capacity loss, due to either variability of primary resource or tripping of generation units.

2.2 Dynamic Simulation Model for Primary Control Provision

To perform dynamic simulations the model for EV participation on primary frequency control was developed for the Eurostag simulation software [17].

For the purpose of dynamic simulation, EV charging can be modelled, as any load, as constant power load, constant current load, constant admittance load or a combination of those. It is common to assume that all loads are considered to be constant admittance or current. Yet, EV load is in this case distinguishable from the conventional load. Therefore, the known EV charging profile, constant current constant voltage charging process for a lithium-ion battery cell, [18], was taken into account. The analyzed scenarios refer to relatively short periods, with small voltage variations in the EV buses, and so EV may be considered constant power loads.

Figure 1 presents the block diagram of the control loop that will define the active power set-point of the EV power electronic interface. The reactive power component is always set to a constant value equal to zero. The active power set-point is composed by the summation of three different signals with a saturation block to assure that the requested power for the EV is within its operation limits:

- Droop control, ΔP_{Droop} – The frequency deviation signal, Δf, goes through a dead band block to prevent EV charging from being disturbed by minor frequency changes and gets multiplied by the proportional gain, k_p, Figure 2.
- Inertial emulation control, $\Delta P_{Inertial\,Emulation}$ – The input signal derivative, the frequency deviation, Δf, is calculated, then the result goes through a saturation block to limit the rates of change and the derivative gain is applied, k_{in}.
- EV load set-point, $P^{EV}_{Set-Point}$ – defined by EV owner or the Aggregator.

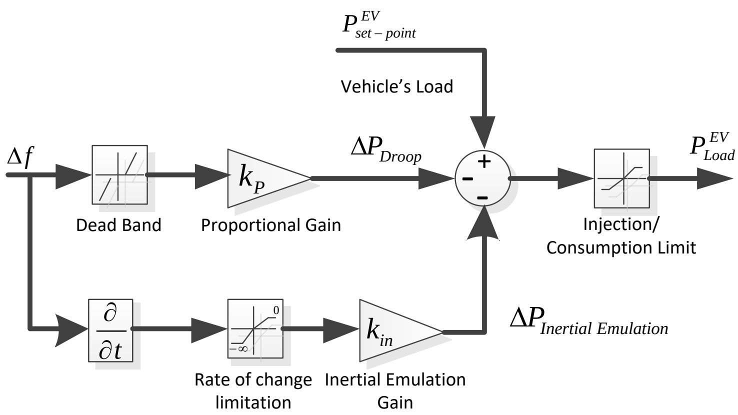

Figure 1: Active power set-point control for the power injector

The active power limitation in a real implementation would depend on the contract established between EV owners and Aggregators, being possible to block battery power drawing.

Some assumptions should be made to implement this model:

- Battery SOC is in the range of 0-100%, but never with a fully charged / depleted battery, thus allowing neglecting SOC monitoring for small simulation periods.
- State of health is neglected as it is assumed that batteries do not suffer significant damage in ancillary services provision.
- As the time periods being studied are of the order of a few seconds the storage elements can be modeled as constant DC voltage sources using DC/AC inverters, to couple them to the grid. These devices act as controllable AC voltage sources (with very fast output characteristics) to face sudden system frequency changes.
- It is considered that there is no requirement for a 15 seconds delay for changing the battery charging rate as imposed by IEC 61851, [19]. Such a large delay could prevent the usage of EV in primary frequency control, as this delay could cause instabilities in the system.

The presented model has also included, in a second stage of the developed work, a delay in frequency measurement, in order to represent the delay incurred by the phase-locked loop that measures frequency in the power electronic interface. Figure 3 presents the frequency measurement delay, where T_D is the time delay introduced for the measurement period.

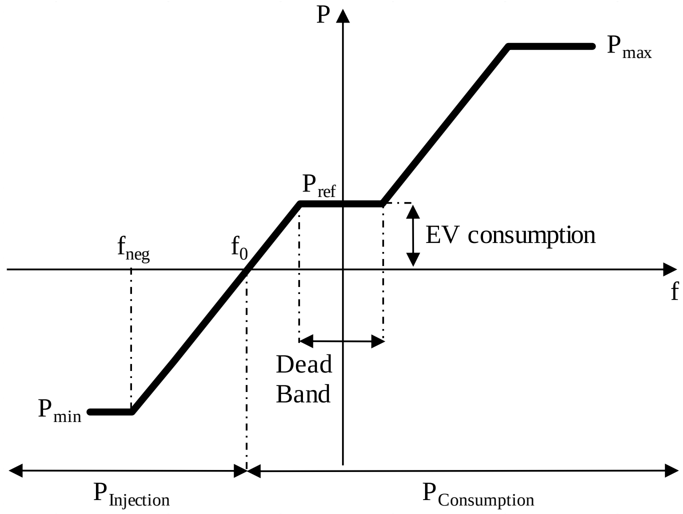

Figure 2: Proportional gain characteristics

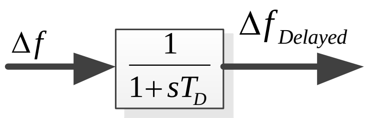

Figure 3: Frequency measurement delay block

2.3 Grid Modeling

As in [13], the dynamic behavior of the isolated power system was simulated using the Eurostag software.

A complete representation of the MV distribution network was made, including the step-up transformers from the existing generation units. Conventional loads were modeled as constant admittance in their active and reactive components.

In terms of generation system, the hydro turbines were modeled by synchronous generators represented by a 4th order model, [20]. Governors with transient droop compensation and IEEE type 1 voltage regulators were considered. The governors were also equipped with proportional and integral control loops to enable the hydro units to perform primary and secondary frequency control.

The wind turbines were modeled by variable speed synchronous generators. The model was created as a controllable active and reactive power source, using a first-order model representing a spinning mass connected to a voltage-source converter that presents controllable electrical torque as presented in [21,22]. Due to the presence of a simple power electronic interface there is a decoupling between the mechanical behavior of the variable speed wind turbine and the electrical grid, which is not contributing for adding additional inertia in such small system. There is no droop control imposed to the wind turbine model.

The developed models do not consider the initial subtransient phenomena as these are not crucial for the load-frequency analysis performed in this study.

The complete list of dynamic parameters and the block scheme of the hydro units is provided in Appendix (Figure 16, Table 3 and Table 4). The block scheme of the wind turbines is based on the one provided in [21].

3. Test System

The case study chosen for testing EV capability of performing primary frequency control is based on the power system of a small island based on real data. This island has a 15 kV distribution network with two substations, each located in one of the two existing generation plants, as described in Figure 4. In 2009, the annual peak load was 2200 kW and the minimum valley load was 750 kW. The generation system is composed by four diesel generators with the nominal power of 625 kVA, two wind turbines of 330 kVA and four hydro units, three of 370 kVA and one with 740 kVA.

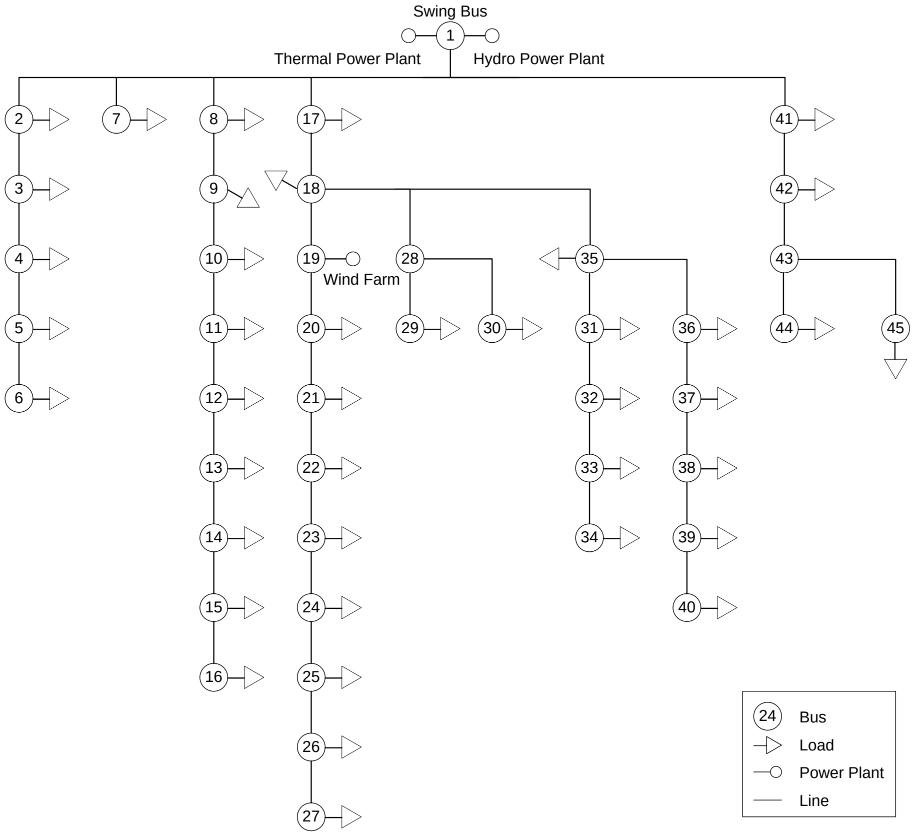

Figure 4: Single line diagram of the isolated system case study

In this network, the most critical operation period is the load valley. The rather small number of generation units dispatched is associated with small system inertia. Therefore, frequency stability issues may be expectable, especially when there are good wind resource conditions. In fact, the island could explore more of its endogenous resources, wind and hydro power, but operational restraints prevent this occurrence.

Current operational practices always include at least one diesel unit to perform load following and frequency control, but the existing hydro units could in theory replace the diesel units in this task. However, the high head height and long conduit impose a long water starting time, [20]. Long water starting times may lead to larger frequency fluctuations and the mechanical wear and tear on the turbines is bigger due to the fast governing actions.

To test the primary frequency control techniques described in Section 2.1, a valley hour with a total conventional load of 731 kW, where the load from EV was added to the conventional load, was considered. It was assumed that 25% of the island's vehicle fleet (2000 vehicles), was replaced with EV and all of them adhered to smart charging schemes that follow the methodology presented in [23]. The driving patterns of the EV owners influence the availability of EV in frequency control participation throughout the day. The EV fleet considered was composed by three vehicle types, 20% of which with 1.5 kW of rated power for battery charging and 6 kWh capacity, 40% with 3 kW and 12 kWh and 40% with 6 kW and 24 kWh. A full charge cycle of 4h was assumed. EV SOC, charging power per consumption node and flexibility of the EV were determined as follows:

- Location: EV were sorted randomly across the nodes with conventional loads.
- SOC: determined by a normal distribution with an average value of 70%, standard deviation of 30% and limited to the range of values [10%, 100%].
- Normal charging rate: 0.8C.
- All vehicles that are charging assume the normal charging rate before the disturbance.
- Controllability range: charging rate change possible between 0.2C and 1.0C, if SOC is below 100%.

Table 1 presents the load of the considered scenario, the range of possible load values for EV in response to frequency deviations and the EV controller parameters.

In order to match the load of the island during the defined period, the following generation dispatches were created:

- Basic scenario – A full renewable dispatch was performed exploiting the existing hydro and wind resources.
- Wind generation expansion scenario – More wind power installed capacity was included. Identical to the basic scenario, it included more generation from wind

and less generation from hydro units.

Two disturbances on the wind resource availability were considered.

Table 1: Conventional and EV load of the considered scenario and EV controller parameters

Conventional load (kW)	731
Required EV load at 0.8C (kW)	964
Total load (kW)	1695
EV maximum power consumption at 1.0C (kW)	1200
EV minimum power consumption at 0.2C (kW)	250
EV Proportional Gain (kW/Hz)	P_{Rated}
EV Inertial Emulation Gain (kW.Hz^{-1}.s)	$5*P_{Rated}$
EV Dead band (Hz)	±0.1

First, a shortfall on wind resource availability was considered leading to the loss of 40% of the total wind power, 200 kW in 10 s, as depicted in Figure 5.

Second, a chain of events based on the variability of the wind resource was created for both generation dispatches over a period of 15 minutes. The wind resource variability is the same for both generation dispatches, but has different repercussions on the wind farm output power, Figure 6.

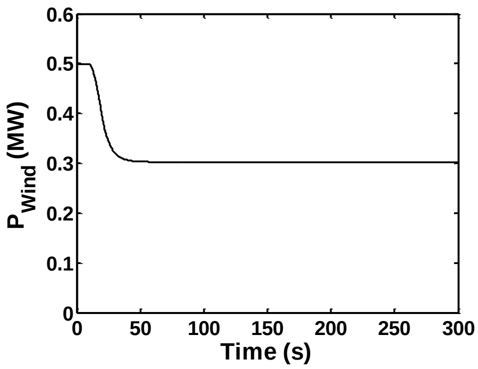

Figure 5: Shortfall on wind resource availability

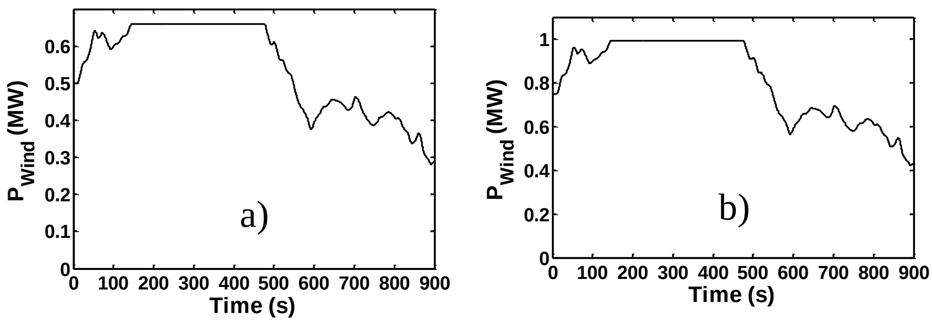

Figure 6: Chain of events due to the variability of wind resource in: a) basic dispatch scenario; b) wind generation expansion scenario

The two control techniques described before should be tested separately first, compared with each other and if beneficial for the system tested for combined effect. Additionally, there may be some influences of possible delays in the reaction of the EV electronic grid interfaces and so this situation must also be addressed for the different generation dispatches. The existence of delays may lead to the asynchronous reaction of the EV, leading to EV reactions in different moments, which may cause instability in the system. Thus, there is a multiplicity of scenarios that were addressed and are presented in Table 2. However, in section 4, only a selected number of scenarios (highlighted in bold in the table) is presented, illustrating the most representative scenarios to evaluate the performance of the EV control techniques.

Table 2: Summary of studied cases

EV electronic interface		Without Delay	With Delay
Shortfall on wind and chain of events in the basic dispatch scenario			
Without EV Droop Control	Without Inertial Emulation	**Case 1**	Case 3
	With Inertial Emulation	**Case 5**	Case 7
With EV Droop Control	Without Inertial Emulation	**Case 2**	Case 4
	With Inertial Emulation	**Case 6**	**Case 8**
Chain of events in the wind generation expansion scenario			
With EV Droop Control	With Inertial Emulation	-	**Case 9**

4. Results

This section presents the results of the dynamic simulation of the behavior of the electric power systems of the island, when the flexibility of EV load is explored to provide primary frequency control. This section is divided in 5 sub-sections based on comparison of scenarios.

First, the EV droop control (case 2) is compared to the case of inexistence of EV control (case 1). Second, the differences between the usage of EV with droop control (case 2) and the usage of inertial emulation (case 5) are evaluated. Third, the two control techniques proposed for EV are combined (case 6) and the simulation results compared to the base case where EV are uncontrollable loads (case 1). The benefits of having both controls (case 6) in relation to having just EV droop control (case 2) are also compared. Then, the effects of possible delays in EV reaction were addressed. So, the case with droop control and inertial emulation were compared with (case 8) and without (case 6) delay. Finally, a wind expansion scenario where EV provide both controls (case 9) was compared to the base scenario with both EV controls (case 8) and without EV control (case 1) for a chain of disturbances.

4.1 Droop Control with Electric Vehicles

Figure 7 depicts the system frequency and the evolution of the total EV load for the event of a shortfall on wind power. If the system is operated without EV participation on frequency control and using a full renewable based generation dispatch, frequency drops to a minimum value of 48.39 Hz. In opposition, when the EV droop control is considered, frequency does not fall below 49.78 Hz. There are two factors influencing this discrepancy: the slow dynamic reaction of the hydro generation units and the fast reaction of EV to frequency deviations. In terms of EV participation on frequency control the total charging power temporarily changes from the original 964 kW to 824 kW, resulting in a reduction of 3.6% in the energy absorbed by the batteries of EV during the 300 s of simulation. The participation of EV not only sustains the frequency drop but also avoid the oscillations verified in the frequency response without EV.

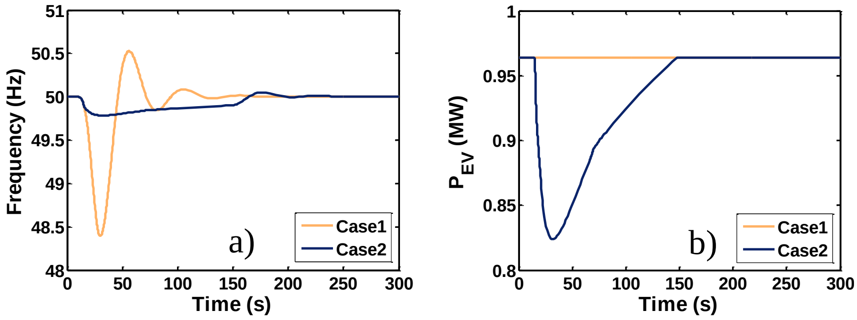

Figure 7: Without EV control versus EV droop control: a) Frequency; b) Active power of EV

4.2 Droop Control Versus Inertial Emulation

From Figure 8 it is possible to observe that the droop control is more effective than the inertial control. In fact, this would be an expected result. A careful analysis shows that inertial emulation manages to hold frequency drop more efficiently in the first seconds following the disturbance. Only about 20 s after the disturbance does the droop control perform better than the inertial control. Both strategies are quite effective with some overall advantage for the droop control, while the inertial emulation addresses more properly the initial moments that follow a disturbance. In terms of load variation the initial decrease in EV load is evidently faster with inertial emulation, following a period where both techniques evolve side-by-side. When the rate of change of frequency decreases the contribution of EV with inertial emulation also decreases, whereas the droop control accompanies the absolute error on frequency. EV contribution is sustained until frequency enters the dead band of the controller. For the tested event the inertial control lets EV charge 2.9% more energy than the droop control. Yet, the combination of both methods is expected to provide the best results.

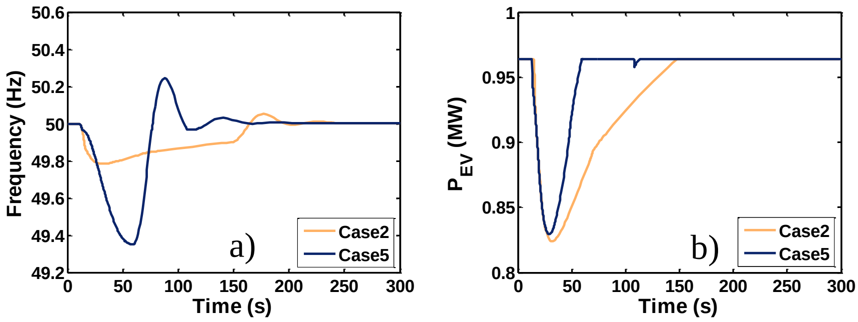

Figure 8: EV droop control versus inertial emulation with EV: a) Frequency; b) Active power of EV

4.3 Combined Effect of Droop Control and Inertial Emulation

Figure 9 shows the evolution of frequency and EV load. Frequency falls to a minimum value of 49.78 Hz, a similar value to the case with droop control only. Yet, it performs better in the initial seconds of the disturbance. The droop control case would follow during these initial instants the base case frequency, whereas in this case the benefits of inertial control are present and the system gains additional robustness. Regarding EV participation, their load gets reduced by 10 kW more than the case with droop control. Regarding energy consumption the case presented in this section manages to charge EV batteries by 0.05% more than the droop case.

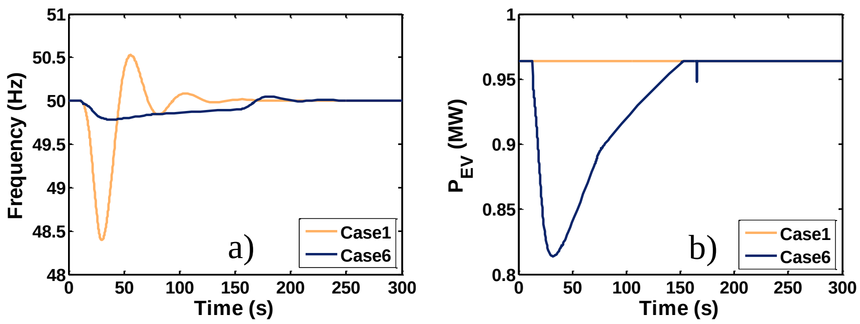

Figure 9: Without EV control versus EV droop control and inertial emulation with EV: a) Frequency; b) Active power of EV

The biggest advantage of combining the two techniques when a large disturbance occurs is related with the reaction of conventional generation units. The presence of the droop control and the inertial emulation provide the smoother ramping and the most damped responses of all the presented cases.

This is particularly noticeable by observing the plots of the electrical and mechanical torques. Figure 10 presents the evolution of the torques (mechanical – T_M – in the dashed line and electrical – T_E – in full) in the first 50 s period of the simulation. The two periods of EV action are quite visible. First, the fast response of the derivative gain that makes inertial control loop is able to attenuate the effects of the water starting time of the hydro units. This effect makes the hydro units respond in opposition to the governing actions in the initial moments after the governor request. This means that without the inertial emulation the hydro units, as expected, instead of immediately increasing the torque decrease it for a while and only after will it compensate for the disturbance. Second, the droop control loop with is proportional gain sustains frequency control during the time that the conventional generation units need to compensate for the generation loss caused by the shortfall on wind availability, similarly to what happened in the case without inertial emulation. During this second stage the derivative control driven contribution is almost null. As it was mentioned while presenting the case study of the island, nowadays a full renewable energy generation dispatch is likely to be more rarely adopted. The system may get unstable, problem that can be solved with the adoption of EV droop control, and the hydraulic phenomena may be very abrupt and lead to premature exhaustion of the hydro turbine and the mechanical equipment that performs the gate opening control. The inertial control may help prevent this premature exhaustion from happening and become the missing piece to make renewable based dispatches a current practice in the operation of systems with high renewable energy availability, when sufficient EV penetration is present.

Another interesting analysis that can be performed confronts the case where the EV only have droop control to the case where both controls are active. Figure 11 shows the frequency response in both scenarios, first for the single disturbance and then for the chain of events. It is visible that with little additional effort the inertial control manages to hold frequency drop a while longer. Yet, it is in the event of a series of disturbances that the combined effect of the droop control and the inertial emulation is most relevant. Frequency presents fewer oscillations with the both controls, managing, in most of the events, to reduce frequency drops. Nonetheless, the minimum frequency is nearly identical. The benefits of the combined effects of both control measures are obtained at the cost of a negligible increase on consumed power of 0.4%.

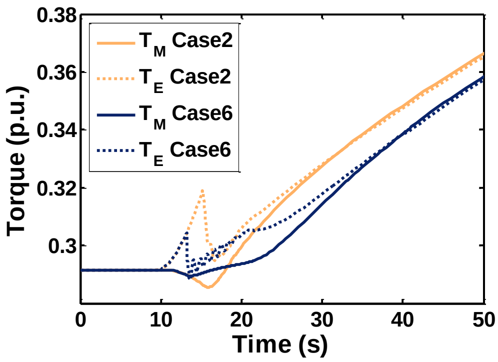

Figure 10: Without EV control versus EV droop control and inertial emulation with EV: Mechanical and electrical torque of hydro unit 4

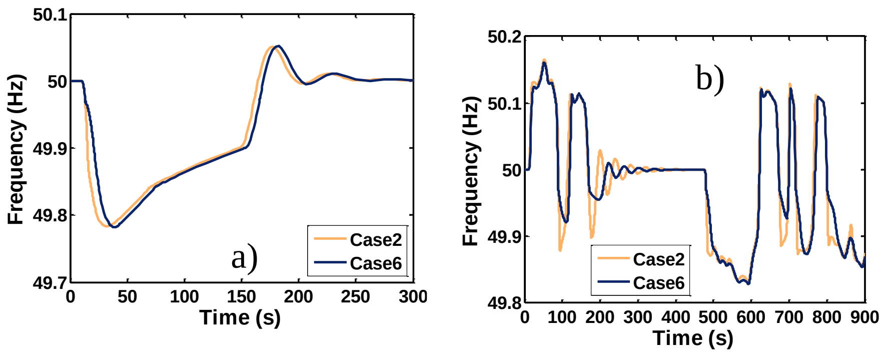

Figure 11: EV droop control versus both EV controls: a) Single disturbance; b) Chain of events

4.4 The Effect of Delays in Frequency Measurement and Electronic Interface

The value for delays in EV battery response may depend among other factors on the type of measurement scheme and the equipment manufacturer or model. Consequently, it is not expected to be uniformly distributed by all the EV and so a normal distribution was used to attribute different delays to each aggregation node on the MV distribution grid. An average value of 150 ms was considered with lower and upper limits of respectively, 100 ms and 200 ms. The considered range of values is intended to address a worst case scenario as the overall delay of an EV is not expected to be so large. Figure 12 presents a histogram with the distribution of considered delays and their frequency. As the number of load nodes and inherently EV aggregations is rather reduced the histogram does not tend to the perfect bell shaped form of the normal distribution.

The results of the simulation are presented next, placing side-by-side the cases of droop control and inertial emulation with and without delay. Figure 13 shows that the frequency response is practically equal in both cases and also that the reaction of the EV is the same, indicating that the performance of the control system should not be jeopardized by possible desynchronized controller actions. There is just a minor difference after the first overshoot, where the EV without delay suddenly reduce their load and re-establish it immediately after. In the case with delay the EV do not react. This is probably related with the duration of event that is smaller than the delay period of the EV grid interface.

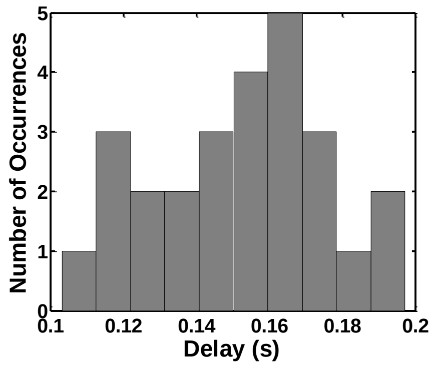

Figure 12: Histogram of EV grid interface delays

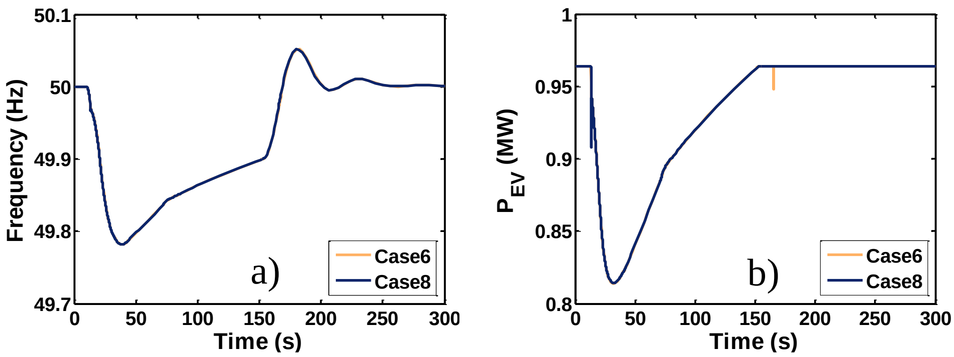

Figure 13: With versus without EV response delay: a) Frequency; b) Active power of EV

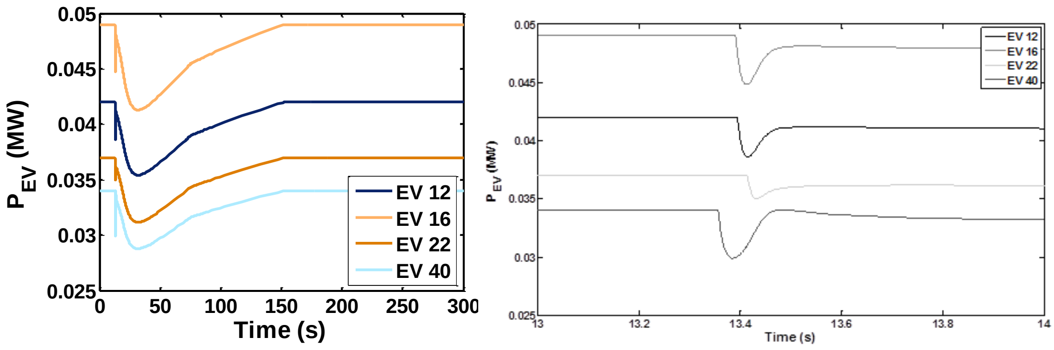

Figure 14: EV response delay: aggregated power of EV in nodes 12, 16, 22 and 40 (a zoom between seconds 13 and 14 is shown on the right)

Zooming into the participation of an aggregated set of EV (EV in nodes 12, 16, 22 and 40), the effect of the delay is visible, being perceivable that their reaction is not synchronized (Figure 14). Such delay disparity would likely be acceptable in a real world implementation of these concepts and would have no harmful effects in the system response.

4.5 Wind Generation Expansion

Having demonstrated the efficacy of the proposed control techniques and their robustness, even when considerable delays are introduced in EV operation, the possibility of expanding the share of wind generation and keeping a full renewable based dispatch is also tested. In this sense, an extra wind turbine is considered, with the same characteristics of and located near to the existing wind generation units. The new generation unit also shares the connection point of the other units. For the simulation, the same wind availability and variability conditions are assumed and so the generation dispatch has to be slightly modified. Being unfeasible to operate the network with the four hydro units, only three of the units are dispatched. It is also considered that EV participate in primary frequency control with droop control and inertial emulation, while suffering the effects of the previously introduced delays.

Figure 15 compares the performance of the system with wind generation expansion and both EV control techniques to the base case without EV control, when a chain of events is applied as disturbance. It is noticeable that even with more demanding conditions the presence of EV contributing for frequency control enables the integration of the extra wind turbine. In fact, it would possibly be feasible to go even further and the system would still be able to cope with the variability of the wind resource, in what respects frequency control.

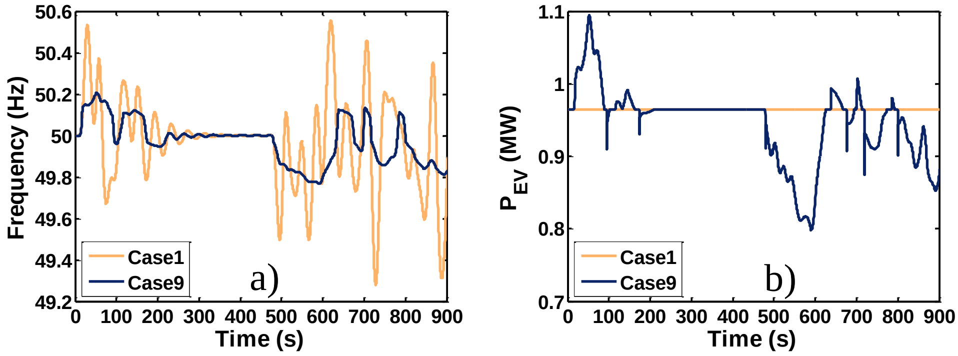

Figure 15: Comparison between the case with two wind turbines and no EV control and the case with three wind turbines, EV droop control and inertial emulation: a) Frequency; b) Active power of EV

5. Conclusions

It was possible to verify that EV may gain a crucial role in the operation of isolated systems by participating in primary frequency control. The EV presence in islanded systems may benefit the system operation in different ways. The fact that a new load is integrated in the electricity grids is naturally beneficial for the resilience of this kind of system that tends to have low load values, especially during valley hours. EV add up to the pre-existing load and allow the dispatch of an increased number of generators. Yet, reserves still have to cover for any losses of generation or for the variability of the primary sources of RES based generation. This requirement may lead to limitations to the maximum installed RES based generation capacity as dispatches deeply rely on thermal units, fossil fuel based, to perform regulation and load following. If EV are considered active participants in primary frequency control, the reserve requirements can be met resourcing to loads instead of just generation. The dependence on the conventional reserve providers is reduced and the possibility of increasing the share of

RES is enabled.

It was verified that EV participation in frequency control in an isolated test system reduced the frequency oscillation band of the system, with a small effort for EV in terms of consumed energy. Evidently, by responding to frequency deviations with the reduction or increase of load, EV consumed energy changes. However, given that the charging period of an EV may take several hours, the substantiated 1% decrease of the consumed energy may represent just a few extra minutes to charge the vehicle. The main conclusions concerning the studied test system may be generalized to other isolated systems that have to deal with the same challenges. However, for quantifying the actual results and benefits, simulations have to be performed to analyze each case.

In addition, it was demonstrated that EV can effectively contribute for a better exploitation of the endogenous resources of isolated systems, while keeping the system robustness of operation. Yet, proper control schemes to enable the EV participation in primary frequency control should be implemented.

Two local control techniques, with different action principles, were described and applied to perform primary frequency control with EV. Both evidenced improvements in the power system dynamic behavior of islanded systems. On the one hand, inertial emulation has a predominant impact on the first moments that follow a disturbance, reacting very fast to the rate of change of frequency, and then its action fades. On the other hand, EV droop control is slightly slower on the initial reaction, as it reacts proportionally to the frequency error and particularly due to the action of the dead band, but sustaining a more durable effect that accompanies the disturbance until frequency error is eliminated. So, it is when both control techniques are combined that the performance of the system is best, as isolated systems typically have low inertia that may be compensated by the inertial emulation and require sufficient primary reserves to face possible disturbances granted by the EV droop control. Furthermore, the effects of possible desynchronized action of the controllers were evaluated and the local control system proved to be very resilient and with a good performance even when different reaction delays were considered.

Ultimately, this work supports the discussions being held in isolated areas or with weak links to stronger networks, such as the case of Northern Ireland, where a working group currently discusses possibilities of requiring the participation of demand in primary frequency control, [24]. Regulatory changes are required to create a proper framework to consider EV in ancillary services provision. In more general terms, in isolated regions with high availability of RES it may be economically sound to accelerate EV uptake through the introduction of dedicated acquisition programs. However, thorough cost benefit analyses are required to weigh benefits and potential deformities introduced to electricity and energy markets as well as to the transportation sector.

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Appendix

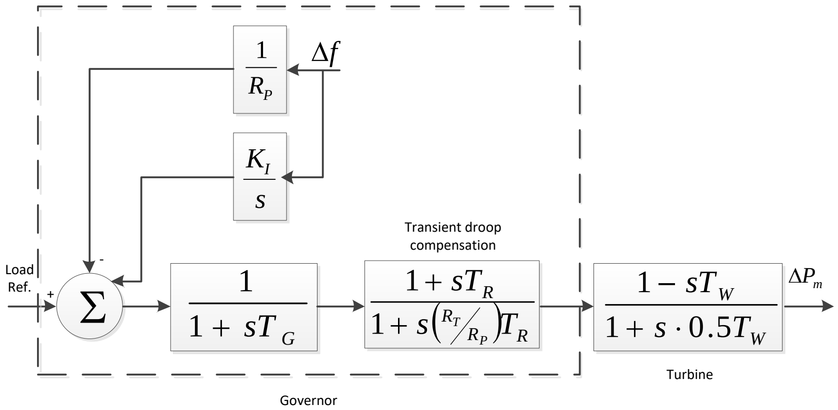

Figure 16: Hydro governor and turbine block diagram

Table 3: Parameters of the hydro units

Hydro units 1 to 3 (Electrical Machine and Speed governing system)	**Sb (MVA)**	**Ub (kV)**	**H (s) (machine base)**	**D (p.u./Hz)**	**Xd (p.u.)**	**Xq (p.u.)**	**X'd (p.u.)**	**T'd (s)**	
	0.37	0.4	8.3	0.005	0.444	0.266	0.067	3.5	
	KI	**R**	**Tg (s)**	**Tw (s)**					
	1	0.1	1	4					
Hydro unit 4 (Electrical Machine and Speed governing system)	**Sb (MVA)**	**Ub (kV)**	**H (s) (machine base)**	**D (p.u./Hz)**	**Xd (p.u.)**	**Xq (p.u.)**	**X'd (p.u.)**	**T'd (s)**	
	0.74	0.4	16.7	0.005	0.384	0.23	0.058	3.5	
	KI	**R**	**Tg (s)**	**Tw (s)**					
	1	0.05	1	4					
All hydro units (Voltage Regulation)	**Ka**	**Ke**	**Ks**	**Ta (s)**	**Te (s)**	**Tr (s)**	**Ts (s)**	**Vmax (p.u.)**	**Vmin (p.u.)**
	400	0.5	0.035	0.05	0.9	0.02	1	7.3	-7.3

Table 4: Parameters of one wind generator

S (MVA)	U (kV)	H	Xm	Rr	Rs	Xr	Xs
0.33	0.69	2.675	3.936	0.01218	0.0067	0.1256	0.095

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