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Economic assessment of primary frequency control with
electric vehicles in isolated systems

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1 Introduction

Electric vehicles are set to be one of the biggest revolution in the next thirty years. Climate change, environmental politics for better air quality and always more economical solution are all factors that are pushing towards a change of paradigm in the energy and transportation field. According to the “Global EV Outlook 2017”, written by the International Energy Agency (IEA), sales of electric vehicles reached 750 thousand in 2016, with more than 40% of them that has been sold in China. Also the infrastructures grew in number, increasing by 72% from previous year. The growth of the electric vehicles stock was around 60% in 2016, but anyway the stock size is still small: talking about light-duty vehicles, electric vehicles cover just 0.2% of the entire stoke. This numbers show how big is the increasing rate of this technology, and also how big is the potential that still it is possible to exploit. The spreading of this “new” technology (rediscovered, to better say) is now beginning to reshape the way that we move around, and the way that we intend the electric system in its overall. But this fermentation in the present goes hand in hand with a completely new-designed future, for which new studies and new discoveries are done each day. This work is obviously part of the interest that the present is giving to this technology, but it is also looking at the future and at the ways that will allow it to develop in a cleaner and more sustainable way.

The aim of this work is to economically evaluate the feasibility of the provision of Primary Frequency Control (PFC) services with a fleet of aggregated Plug-in Electric Vehicles (PEVs). The environment in which the evaluation is carried out is a small isolated system, like small Italian or Greek islands in the Mediterranean Sea or the Canary Islands in the Atlantic Ocean. The reasons why this specific environment is chosen will be found later in the document.

At first, a brief introduction about Primary Frequency Control is written. Then some researches are done, in order to run an analysis of which are the technical and economic aspects of PFC around Europe. Some nations are inspected, to see which are the standards that each one of them has and which differences they have among them. This is done to better understand the environment of the evaluation, that is lately set, after withdrawing some consideration, in the above-mentioned isolated system.

The case study, the overall scenarios and the impact that PEVs should have to allow the evaluation to be feasible, are all developed in Chapter 4, together with a description of the model that will be used later in the work for the modeling of the system.

Chapter 5 is the core of the work, where all the economic aspects are listed and carefully analyzed, explaining step by step the utilized method and the numbers behind it.

Finally, chapter 6 withdraws all the needed conclusions and elaborates the data calculated in the previous chapter, allowing to have some simple yet important results.

2 Primary frequency regulation

2.1 Introduction

Every electric system in the world is operated with a balance between generation and load. Since electric energy can't be stored without transforming it, there must always be a match between driving power produced and active power required. The indicator of this balance is the frequency of the network, or, to better say it, the deviation from a nominal frequency value previously chosen. Generally speaking, if the quantity of generated energy is lower than the quantity of absorbed energy, the frequency drops according to the gap entity because of the lack of driving torque in each generator; this is what can happen if a generation unit unexpectedly decreases its power (for failures or, in RES case, also for weather conditions) or if a big load is suddenly connected without having matching generation. On the other hand, if the quantity of generated energy is greater than the quantity of absorbed energy, the frequency will rise, also in this case according to the gap entity, because of the lack of resistant torque in each generator; this situation can happen if a generation unit unexpectedly increases its output (almost exclusive peculiarity of wind and photovoltaic plants) or if a big load is disconnected. Primary frequency control is the tool used to automatically stop the frequency oscillation, changing the power output of the generation units according to the frequency oscillation.

Avoidance of too many frequency oscillations is necessary for various reasons: first of all, every different load surely reacts differently at a frequency change, but all of them work in a worse way. Efficiency drops, angular speed changes and power output as well, with a relation more than linear with it. Second, auxiliary services of any power plant could be affected by the frequency change and not work properly, creating problems to the energy production and to the turbine speed. This could lead, in worst cases, to the interruption of the parallel with the grid.

Primary frequency control acts during the first 15-20 seconds after the network disturbance occurs, stabilizing the frequency to a new value that is different from the nominal one. At that point secondary frequency control comes in play, and in almost 100 seconds it brings the frequency back to its nominal value. Anyway, taking into account secondary control is not necessary for the developing of this work, so this particular argument will not be treated here. The correction of the generation unit output is practically done with a speed governor, that reads the grid frequency and changes the input power of the plant. This changes the driving

torque of the plant, to better match, together with all the other generators that participate at the regulation, the resistant torque that loads apply to the system.

In this chapter, it will be analyzed the simplified block scheme of primary frequency control and the utilization of batteries for doing it. All the formulation written in this chapter are widely and better discussed in [1].

2.2 Block scheme

The complete structure that is necessary for understanding how system variables change according to a power disbalance is messy and complicated. Working in time-domain doesn't simplify the work, like it doesn't the high number of elements in an electric system. That's why, under certain conditions and with some simplified assumption, it's useful to develop a block scheme in Laplace domain for understanding the mechanics of frequency control. A more precise model will be developed later for this work, but for the moment this simplified block scheme will be enough.

The block scheme will be analyzed in two parts: in the first, an intuitive schematization will be transformed in formulas, while in the second the block scheme will be completed.

2.2.1 First part

For understanding the nature of the block scheme that is used to model frequency response, it's possible to look at this merely intuitive scheme. Through an analogic visualization, the overall process of frequency control will be easily explained. What will be done in this subsection is the explanation of the analogic scheme, the extraction of the transfer functions, the analysis of each step and the modeling of the whole response.

As an example, the case of a Pelton-turbine generation unit will be examined. This is a little bit simpler because it's easier to visualize the change in power input, thanks to the mechanism used for this technology: a spear valve that regulates the water flow by being pushed nearer or farther the opening. Fig. 2.1 shows the working concept of a spear valve.

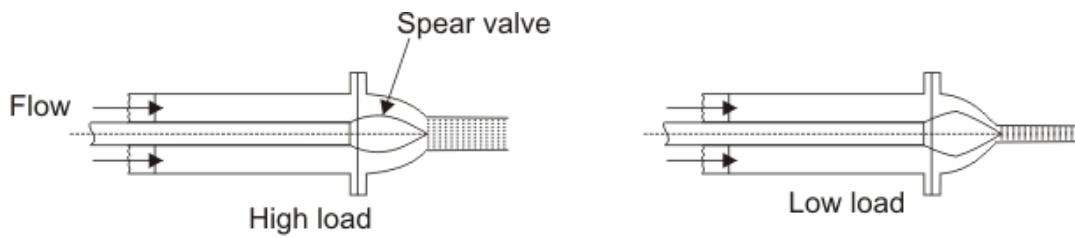


Figure 2.1 – Working concept of a spear valve

Every other type of generation unit can use the block scheme that will be implemented at the end of this subsection. This example just fits better for the explanation of the mechanisms of primary frequency control.

Qualitatively, the following scheme in Fig. 2.2 will explain the behavior of the regulator. It revolves around the movement of the points that are signed with capital letters, with the hinge B that can move only if the threaded sleeve (in light blue) moves along the rotating shaft t. The rotation of the two masses is related to the rotation of the generator. For the sake of simplicity, just the case of a frequency increase will be examined, because for a frequency decrease everything will be specular.

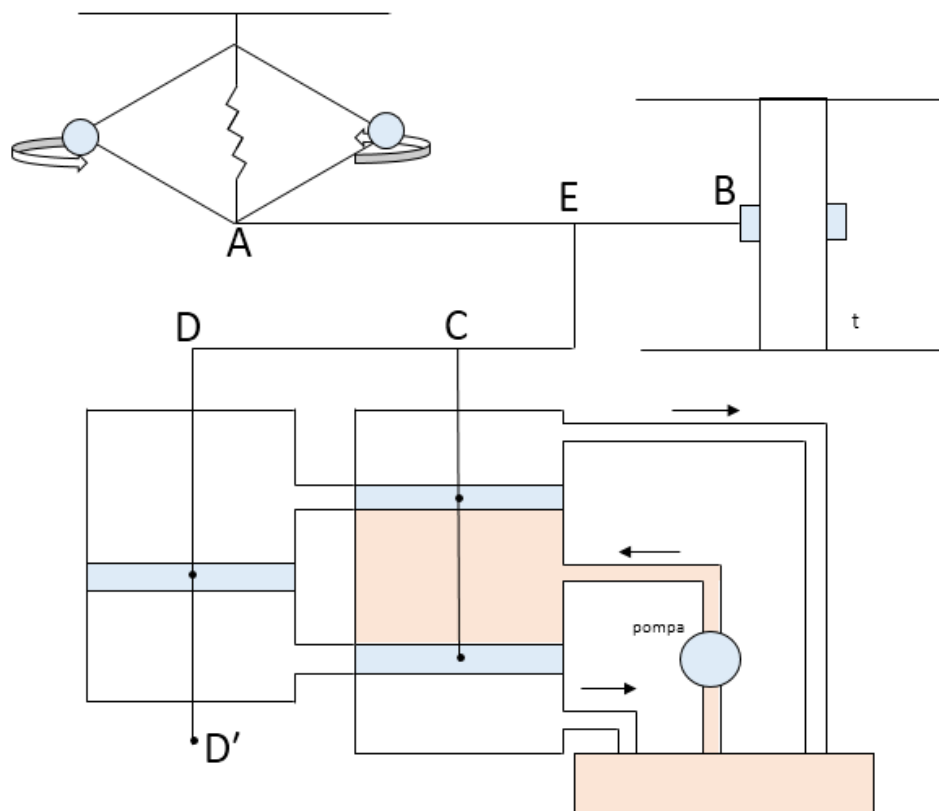


Figure 2.2 – Behavior of the regulator

When the grid frequency increases, the generator increases its rotating speed because a part of the resisting torque is missing. Given to this, the two rotating masses get away from their rotating axis, so that A gets higher and E gets higher as well, with B hinged. This movement makes C to get up and allows the under-pressure oil to flow in the last chamber, where D gets lower thanks to the oil that accumulates over the plate. In this way D' closes the spear valve, reducing the flow rate of the entering water and so allowing the turbine to slow down.

The same reasoning can be done for a decrease in frequency, which will finally lead to an increase of water flow rate.

Looking at the interaction between the points and the movements that they do, it's possible to write the following equations. The system is considered to be linear, or at least linear for small variations. Underneath each equation will be written the unit of measure of each variable, because later, if units of measure are clear, it will be easier to extract some information. The variables are the variations of each parameter (power, length, frequency). Variables in time-domain will be written with lowercase letters, while the same variables in Laplace domain will be written in uppercase letters.

$$\Delta p_i = K_i \cdot \Delta d \quad (2.1)$$

$$[W] = \left[\frac{W}{m} \right] [m]$$

$$\Delta d = -K \cdot \int \Delta c \cdot dt \quad (2.2)$$

$$[m] = [Hz][m][s]$$

$$\Delta c = K_a \cdot \Delta f + K'_a \cdot \frac{d(\Delta f)}{dt} - K_b \cdot \Delta b + K_d \cdot \Delta d \quad (2.3)$$

$$[m] = \left[\frac{m}{Hz} \right] [Hz] + \left[\frac{m}{Hz^2} \right] [Hz^2] - [adim][m] + [adim][m]$$

All K coefficients are positive. For writing the equation (2.1) transient phenomena in hydraulic pipelines were neglected and it was used the hypothesis of system linearity, which allows Δp_i to be considered proportional to the increasing opening of the distributor Δd ; for writing the equation (2.2) it was considered that the oil flow through the two channels would be

proportional to the value of Δc ; for writing the equation (2.3) the superposition of effect was used.

To simplify and to not work with differential equations, the domain is shifted from time to Laplace using the Laplace transformation. So, equations (2.1), (2.2) and (2.3) become:

$$\Delta P_i = K_i \cdot \Delta D \quad (2.4)$$

$$\Delta D = -K \cdot \frac{\Delta C}{s} \quad (2.5)$$

$$\Delta C = K_a \cdot \Delta F + K_a' \cdot s \cdot \Delta F - K_b \cdot \Delta B + K_d \cdot \Delta D \quad (2.6)$$

Mixing together equations (2.4), (2.5) and (2.6), the result is:

$$\Delta P_i = -\frac{K_i K_a}{K_d} \cdot \left(\frac{1 + s \frac{K_a'}{K_a}}{1 + s \frac{1}{K K_d}} \right) \cdot \Delta F + \frac{K_i K_b}{K_d} \cdot \frac{1}{1 + s \frac{1}{K K_d}} \cdot \Delta B \quad (2.7)$$

Some of the factors can be written in a more compact way:

$$\text{Regulating energy } K_r = \frac{K_i K_a}{K_d} \quad ([J] = \left[\frac{W}{m} \right] \left[\frac{m}{Hz} \right] = [W][s]) \quad (2.8)$$

$$\text{Accelerometric time constant } T_1 = \frac{K_a'}{K_a} \quad ([s] = \left[\frac{m}{Hz^2} \right] \left[\frac{Hz}{m} \right] = \left[\frac{1}{Hz} \right]) \quad (2.9)$$

$$\text{Regulator time constant } T_r = \frac{1}{K K_d} \quad ([s] = \left[\frac{1}{Hz} \right]) \quad (2.10)$$

$$\frac{K_i K_b}{K_d} = \frac{K_i K_b}{K_d} \cdot \frac{K_a}{K_a} = \frac{K_i K_a}{K_d} \cdot \frac{K_b}{K_a} = K_r K_B \quad \left([J] \frac{[Hz]}{[m]} \right) \quad (2.11)$$

Adding equations (2.8), (2.9), (2.10) and (2.11) in equation (2.7) it's possible to get:

$$\Delta P_i = -K_r \cdot \left(\frac{1 + s T_1}{1 + s T_r} \right) \cdot \Delta F + K_r K_B \cdot \frac{1}{1 + s T_r} \cdot \Delta B \quad (2.12)$$

From this last equation, it's clearer the fact that, to adjust the power output with respect to the frequency oscillation, two factors are working together: the one that lets the automatic governor do it and the one that acts on the rpm variator.

The block scheme right now can be pictured like in Fig. 2.3:

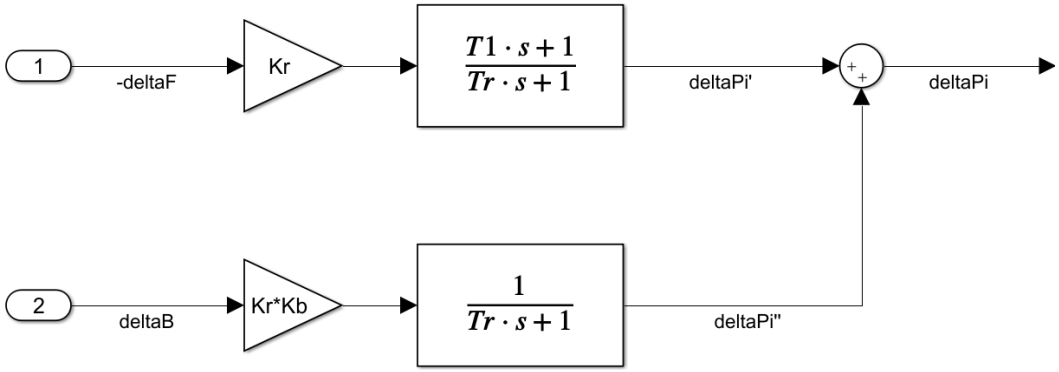


Figure 2.3 - Block scheme of primary frequency control (1)

The upper part of the block scheme is related to primary frequency control, while the lower part is related to secondary frequency control. Since that the time-period of everything that will be analyzed in this work is quite short, and the contribute of secondary frequency control can be neglected in that time-period, this scheme will be completed and used supposing a nil change of the rpm variator ($\Delta B = 0$).

2.2.2 Second part

What is missing from this incomplete block scheme is the contribution of other generators and of connected loads. The power input change will modify in some way everything that is connected to the grid, generating a change in the grid frequency that will return, in a closed chain, to the start.

Supposing for simplicity an efficiency $\eta=1$, the generators input power p_i equals the output power p_o , if no disturb occurs. So:

$$p_i = p_o \tag{2.13}$$

When a disturb occurs, the balance changes a little bit. In fact, it becomes:

$$p_i + \Delta p_i = p_o + \Delta p + \Delta p_u + \Delta p_a \quad (2.14)$$

The members are:

- Δp_i change in power that occurs when the frequency regulation chain acts on the generation unit. It coincides with the one shown in equation (1.12) in time domain, because it is assumed to be $\Delta B = 0$;
- Δp disturb that occurs in the grid;
- Δp_u variation in power absorption by loads, due to frequency changes;
- Δp_a accelerating power, connected to generators and loads inertia.

Given the fact that the amount of Δp is chosen by external factors, what is needed to know are the variation in power absorption Δp_u and the accelerating power Δp_a .

2.2.2.1 Variation in power absorption

To get Δp_u , the variation in load power absorption, it's possible to start from the evolution in time of p_u due to the variation in time of the grid frequency:

$$p_u(t) = p_u^* \cdot \left(\frac{f(t)}{f^*} \right)^\alpha \quad (2.15)$$

The factors are:

- p_u^* power absorbed by loads at nominal frequency;
- f^* nominal frequency;
- α parameter that reflects the proportionality between output power and rotating speed for each load. It depends on the nature of the load ($\alpha = 0$ for resistive loads, $\alpha = 1,2,3$ for rotating loads), so in literature it is always chosen the mean value, $\alpha = 1.5$.

The derivative of equation (2.15) with respect to frequency is:

$$\frac{d(p_u(t))}{df} = p_u^* \cdot \alpha \cdot \left(\frac{f(t)}{f^*} \right)^{\alpha-1} \cdot \frac{1}{f^*} \quad (2.16)$$

Which, simplifying and passing at finite variations, becomes:

$$\frac{\Delta(p_u(t))}{\Delta f} \cong p_u^* \cdot \frac{\alpha}{f^*} = K_u \quad (2.17)$$

K_u is the load regulating energy, because it has the dimension of an energy: $\frac{[W]}{[Hz]} = [W][s] = [J]$. The simplification from (2.16) to (2.17) was possible because $\frac{f(t)}{f^*}$ is very similar to 1 in a normally operated grid (even a disbalance of 500 *mHz* in both ways, which is very unlikely due to the laws in each state, would change very little in the analyzed ratio above because f^* is either 50 or 60 *Hz*). From equation (1.17), it's finally possible to extract what is Δp_u and directly write it in Laplace domain, given the fact that it has the exact same structure:

$$\Delta P_u = K_u \cdot \Delta F \quad (2.18)$$

It is important to notice that active loads have a positive influence in controlling frequency oscillation. In fact, if the frequency rises (falls) they absorb more (less) power, helping to stabilize the grid.

2.2.2.2 *Accelerating power*

To get Δp_a , the factor that keeps track of the inertia of generators and loads, it's possible to start knowing that Δp_a is the variation of the kinetic energy of the system, obviously with respect of time.

$$\Delta p_a = \frac{dw_{cin}(t)}{dt} \quad (2.19)$$

Kinetic energy's evolution in time depends, as for what has been discussed for power before, from frequency deviation in time:

$$w_{cin}(t) = w_{cin}^* \cdot \left(\frac{f(t)}{f^*}\right)^2 \quad (2.20)$$

The factors are the same of equation (15), with two differences: w_{cin}^* is the kinetic energy of loads at nominal frequency; α in this case is equal to 2, because the proportionality between kinetic energy and frequency is:

$$w_{cin} = \frac{1}{2} \cdot J \cdot \Omega^2 \quad (2.21)$$

With J moment of inertia and Ω rotating speed, directly proportional to f .

The derivative of equation (2.20) is:

$$\Delta p_a = \frac{dw_{cin}(t)}{dt} = 2 \cdot w_{cin}^* \cdot \left(\frac{f(t)}{f^*} \right)^{2-1} \cdot \frac{1}{f^*} \cdot \frac{df(t)}{dt} \quad (2.22)$$

Simplifying as done in equation (2.17) and regrouping, equation (2.22) becomes:

$$\Delta p_a = 2 \cdot w_{cin}^* \cdot \frac{1}{f^*} \cdot \frac{df(t)}{dt} = K_w \cdot \frac{df(t)}{dt} \quad (1.23)$$

Shifting to Laplace domain, equation (2.23) becomes:

$$\Delta P_a = K_w \cdot s \cdot \Delta F \quad (2.24)$$

Finally, it is possible to obtain the equation that will close the block scheme drawn in Fig. 2.3. This is possible by transposing equations (2.14) to Laplace domain and then adding to it equations (2.13), (2.18) and (2.24). The result is:

$$\Delta P_i = \Delta P + K_u \cdot \Delta F + K_w \cdot s \cdot \Delta F \quad (1.25)$$

Which, with some grouping, becomes:

$$\Delta P_i - \Delta P = (K_u + K_w \cdot s) \cdot \Delta F \quad (2.26)$$

Equation (2.26) is the one that closes the block scheme, because it transforms a power signal back in a frequency signal. In this way, the block scheme is complete and it becomes the one in Fig. 2.4, always keeping in mind that the contribute of secondary frequency control is neglected in this case ($\Delta p_i = \Delta p_i' + \Delta p_i'' = \Delta p_i'$).

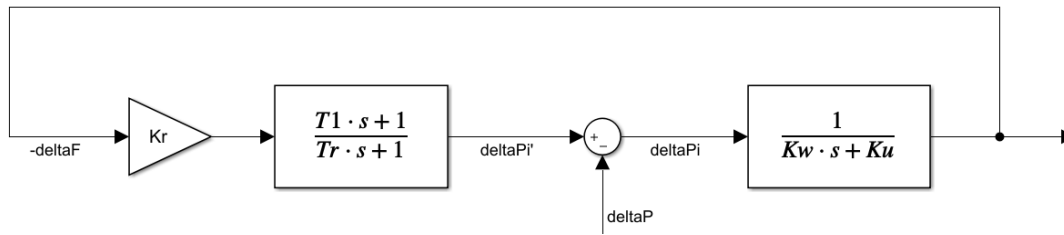


Figure 2.4 - Block scheme of primary frequency control (2)

It's important to underline that the model that will be used in chapters 4 and 5 is slightly different from the one drawn above, but the changes will be explained and motivated in that section.

2.3 Batteries and EVs providing primary frequency control

The provision of primary frequency control, and more broadly of ancillary services, has always been carried out with conventional power units. As it has been seen, the inertia given from all the generation units through their turbines is essential and very useful for frequency stability, allowing the grid to operate in better conditions. In the last decades although, the penetration of non-predictable sources has changed this paradigm. Given the enormous cost decrease for these technologic solutions and the priority of dispatch often given by regulating entities, the generation mix has suffered an enormous change during the last years, reducing the amount of classical spinning generation (powered with coal, oil and gas) in favor of renewable sources (like wind or photovoltaic generation).¹

Ambiental costs have surely decreased, while governments are facing new challenges such as mixing market-driven segments with regulated remuneration and new technical constrains. The main technical problem, as has been said previously, is frequency containment. Given the fact that generation from renewable and non-predictable energy sources has often the priority in dispatch, a lot of conventional generation plants stay out of the merit order for meeting the daily load, so being also unable to provide ancillary services. The non-predictability of the new sources destabilizes the grid, because there is more uncertainty on generated power and less inertia from generation units to fight against frequency fluctuations. For these reasons, a

¹ European Union has more than doubled its renewable share from 2000 to 2015. Source: OECD data on renewable energy, <https://data.oecd.org/energy/renewable-energy.htm#indicator-chart>

new solution has begun to spread worldwide: using Energy Storage Systems (ESS) to support power units powered with non-predictable energy sources. There already was a solution for storage and it was the pumped hydro storage, but the utilization of different and more specific things (like batteries, flywheel, fuel cells and supercapacitors) allows a better and more precise allocation of energy. Surely the most used solution is adding batteries to the power plant to create an Hybrid Power Unit, or even utilizing them as a stand-alone solution. All the conversion steps for making possible the interaction between grid and batteries are made with inverters.

There are quite a lot of examples about ESS used to help the power generation structures, and they are dislocated all over the world. Some of them are used as a test to see and estimate improvements, others are, or were, normally integrated in the power plant. Normally they are used for multiple tasks: peak-load reduction, load shifting, mitigation of voltage and frequency fluctuation, congestion avoidance, load-shedding avoidance, flattening of the output power curve (this happens especially for windfarms). Small grids like insular ones are perfect to experiment storage system solutions, given the special environment that they create, the fluctuation that they overcome and the renewable share that they usually can profit by. Given the fact that frequency regulation is the topic of this work, here following will be listed some examples of ESS that are helping in grid frequency regulation:

- In Spain, specifically in three of the Canary Islands, Enel has conducted a study on island systems storage support via its controlled spanish company Endesa [2]. They developed three different storage system types and they put them on three different islands, to see how they would have responded to the necessity of the grid. The three storage technologies were batteries, flywheels and ultracapacitors;
- In China, in the Shijingshan district of Beijing, a project was started in 2013 and was run for a year and a half [3]. In this project, a BESS was helping one of the generation unit in a thermal power plant, with the specific aim of enhancing frequency regulation;
- In the US, more specifically in Alaska, another BESS was integrated to the generation mix of an off-grid system [4].
- In Italy, on the island of Ventotene, a BESS was installed with the aim of baking up diesel generation and helping with frequency regulation [5].

These are just some examples of the technical solutions that companies are experimenting worldwide. But it's possible to go even further, and it's here where electric vehicles come to play. Since that electric vehicles are basically batteries in movement, it is possible to use their available capacity to do all the things thought for single ESS. Cars are parked for most of the time during a day, so during that time it is possible to connect them to the grid (talking about

only Plug-in Electric Vehicles, or PEVs, of course) and use them to exchange power in both direction. This solution is called “Vehicle to Grid”, shortened in V2G. A key role for exploiting this solution is played by the so-called “aggregator”: one single car represents a power quantity too small to be controlled singularly, so more PEVs are governed together in a way that allows control over a bigger pack of batteries, generating a virtual BESS (Battery ESS).

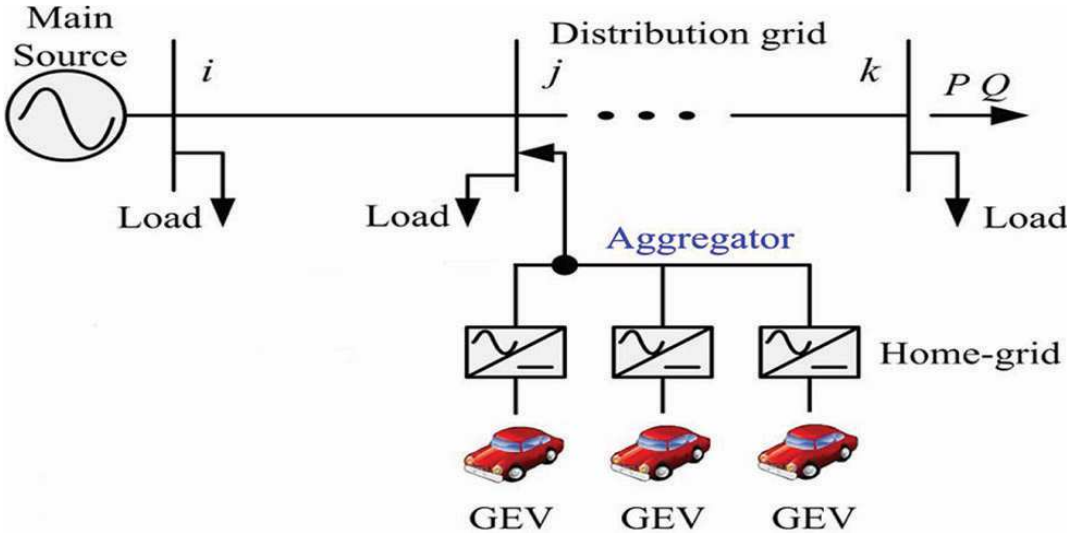


Figure 2.5 - Aggregation of PEVs for Vehicle to Grid technology

V2G is widely discussed in literature, which offers a very large compendium of researches and studies on the various aspects of the topic. Instead, not so many cases of practical examples can be found that are (or were) experimenting or actually running on the market of frequency control: in Denmark a big project is running for testing aggregation of PEVs, thanks to the partnership of Nissan, Enel, Nuvve (an American company founded by one of the pioneers of V2G) and many others²; In US, back in 2013 a small fleet of electric vehicle has managed to bid into PJM ancillary services markets ³, and PJM regulator has changed the minimum accepted bid to better fit this technology. Among the case studies, in [6] it is examined how frequency will change in a small system with a high penetration of renewable sources, considering two different situations: EVs just charging or participating in primary frequency control. In [7] is discussed a model for Load Frequency Control where every energy source is considered (including distributed generation and EV participation), with also a control for best coordination between EV and diesel generators. In [8] the strategies of energy dispatch that

² Website: <http://parker-project.com/>

³ “Electric Vehicle Start Selling Power Into PJM Grid”, 2 March 2013, Greentech Media website

include electric vehicles are analyzed and categorized, assessing problems and future researches.

On paper and in experiments, PEVs providing primary frequency control has always confirmed its positive results, but problems aren't missing. The biggest problem that this technology has to face right now, for what concerns economic feasibility, is regulation. Since the creation of a regulatory framework for transmitting and dispatching electric energy, one thing was always sure: that the flow of energy was unidirectional. The power generation was always centralized in big power plants, and only them had to meet the load power required from all consumers, which had no technical possibility of doing something else. But in the last 30 years, all of this has changed: flow of energy is not unidirectional anymore and consumers can have their own way to get energy, thanks to the powerful enhancement of solar panels and batteries. The regulatory framework has been adapted a little to meet these changes, but a lot is still needed to do. The absence of a clear regulation about aggregation, the missing of a clear definition about "storage system" and the shape of the current ancillary services markets prevent a little bit this technological solution to spread. This is why, in the next chapter, the regulatory framework for primary frequency control will be analyzed.

3 Regulatory framework of primary frequency control around Europe

3.1 Introduction

The primary control service, as for every other ancillary service, is carried out for each different nation by its own TSO (Transmission System Operator). From that, it's easy to understand how many differences there would be, in the frequency regulatory framework, between both technical and economic aspects.

These two aspects are really important in the overall calculation, especially since this work aims to find an economic evaluation of primary frequency control service, so a further investigation must be carried out. In this way, at least a general picture will be found, in which it's possible to dive into and explore.

The two aspects will be evaluated for some of the biggest European countries, including also UK, and the differences among the various states will be investigated. The nations that were taken into account for this overview are: Austria, Belgium, Denmark, France, Germany, Greece, Italy, Netherlands, Spain, Switzerland, Portugal and UK.

3.2 Technical aspects

For guaranteeing the best service for primary control, some requirements have been established by each TSO. They regulate aspects as obligation of primary control services, admissible gap of frequency in all the network, dead band and sensitivity of the frequency controller that is installed in the power generation unit, and others that will be discussed later. These features are what each TSO ask for maintaining the frequency at 50 Hz, controlling that each power plant fulfils the requirements. At first, an analysis of correlation between states and TSOs is carried out, then it will be given a closer look for each of them, examining what that feature is and how it is treated by each nation. Before starting to list the characteristics, it's important to say that it wasn't possible to find all the following features for all the countries, so some data is still missing.

- 1) Name and number of TSOs: in the 12 countries considered, there are 17 different TSO. Pretty much everywhere in Europe there is just one TSO per nation, with some exceptions described at the end. In Austria the TSO is Austrian Power Grid, or APG in short; in Belgium there is Elia; in Denmark there is Energinet; in France there is Réseau de Transport d'Électricité (RTE); in Greece there is Ανεξάρτητος Διαχειριστής Μεταφοράς Ηλεκτρικής Ενέργειας (ADMIE in latin alphabet); in Italy there is Terna; in Netherlands there is TenneT NL; in Spain there is Red Eléctrica de España (REE); in Switzerland there is Swissgrid; in Portugal there is Redes Energéticas Nacionais (REN). The exceptions are Germany and UK, with four and three operating TSOs respectively. In Germany there are 50Hertz, Amprion, TransnetBW and Tennet, all four with pretty similar size; in UK there are National Grid, Scottish Power and Scottish HET, with the first one predominant on the other two.
- 2) Obligation of primary control services: it concerns the obligation for the power plant to offer or not the service of frequency regulation. Some TSOs say that having availability of primary reserve is mandatory for some (or all) generation units, depending on the size of the unit itself. So, it means that each power plant who has mandatory requirements for primary control has to keep available a certain amount of power in both senses. This power quantity will eventually be furnished (or not furnished) depending on the frequency disturbance, with the power plant that will vary its output. This feature is usually in a strict relationship with the economic aspect of frequency regulation, as we will see later. This point will be examined going from the less to the most restrictive countries. At first, it's possible to see that TSO of Austria, Denmark, Netherlands and Switzerland do not ask for a mandatory service. Gradually shifting to Germany, the four TSOs present on the territory (working together to uniform requirements for the sake of a better service) oblige units above 100 MW to give frequency regulation services; from this duty, generation units powered with non-predictable sources are excluded. Then there is UK, with a situation similar to the German one but with different sizes decided by each TSO: primary control services are compulsory for plants above 100 MW for National Grid, above 30 MW for Scottish Power and above 10 MW for Scottish HET. For France, there is a mandatory provision threshold above 40MW for new units and above 120MW for old units. In Italy, mandatory primary control service is required to all the power units above 10 MVA, with the exclusion of those powered with non-predictable sources, and those units must be available to offer 1,5% of their nominal power in the interconnected

system and 10% in isolated systems (Sardinia and Sicily when not interconnected to the main land). More strictive rules in Greece instead, where every power unit over 2 MW must participate in frequency regulation, with an added constrain for thermal and hydro units above 100 MW: they have to let available at least 3% of the maximum power granted when operating between 50% and 97% of the maximum power. In the end, Spain and Portugal oblige all the power plants connected to the grid to furnish primary control service, maintaining available 5% of maximum power for it. Also, Spain specifically directs its attention also to his non-peninsular territories, and it's the only country that has a dedicated grid code part for them. REE (the Spanish TSO) deliberated that on each isolated system the primary regulation reserve must be at least 50% of the biggest power unit in activity in each time period.

- 3) Frequency gap: it's the maximum oscillation accepted around the optimal value of 50 Hz, in a normal working situation. Every generation plant must respond with its duty proportional share when oscillations from the optimal value occur. Pretty much everywhere this maximum fluctuation is imposed to ± 200 mHz. There are some exceptions, like Greece and Spain (± 150 mHz) and Italy (± 100 mHz). For the latter two it is important to make another differentiation, because of their peculiar territory. In fact, they include also islands in their borders, and requirements for those territories are different from inland ones. Since these systems are smaller and less interconnected than the inland ones, they have much less generation plants in their territory and their inertia is much smaller. Because of that, is more difficult maintain frequency between the normal gap. For Spanish islands like Balear Islands and Canaries Islands, the frequency can fluctuate in a range of ± 250 mHz with respect to the nominal value; in Italy for Sardinia (always) and Sicily (when not interconnected to the national grid) and in Portugal for the Madeira island, the oscillation can be ± 500 mHz.
- 4) Dead band: it is the maximum voluntary insensibility that generation plants can establish for not replying to frequency fluctuation. If the frequency stays in the range described, always with respect to the nominal frequency, no regulation is required. The most common is ± 10 mHz, used in Belgium, France, Switzerland and Portugal. For UK it is ± 15 mHz, while it is ± 20 mHz for Denmark and Greece. For the latter, in that gap is also included the intrinsic insensitivity of the frequency-recording device, something that will be examined in the next point. Special mentions for Germany, in which the dead band is decided between each generation unit and the respective TSO, and Italy, where the situation changes according to the type of generation unit: ± 10

mHz for hydroelectric and simple steam cycle plants, ± 20 mHz for natural gas and combined steam cycle plants. Finally, in Spain there is no dead band allowed.

- 5) Sensitivity: it is the structural measurement limit of the device that regulates the power output in response to frequency fluctuation. For the states in which it was possible to find information (Belgium, Denmark, France, Germany, Italy, Netherlands, Spain and Portugal) it is always ± 10 mHz. There are some differences for Italian, Spanish and Portuguese islands: in the firsts, for old power units (in which the insensitivity is usually already greater than ± 10 mHz) it is established that the sum of dead band and insensibility must not overcome ± 30 mHz; for the others, the insensitivity grows to ± 30 mH for Spanish and to ± 100 mH for Portuguese islands. The voluntary dead band for them remains nil.
- 6) Droop, or statism: it is defined as the opposite of the ratio between the frequency variation, expressed in per unit of the nominal value, and the consequent power variation, expressed in per unit of the nominal power of the generation plant. It is usually indicated in %.

$$\sigma_{\%} = - \frac{\frac{\Delta f}{f_n}}{\frac{\Delta P}{P_{nom}}} \cdot 100 \quad (3.1)$$

It indicates how strongly a power unit replies to a change in the frequency value. Low droop values mean that the system is very quick to respond, but it can also exaggerate in the amount of power response. On the other hand, high droop values mean that the system responds gradually to the change and can be easily corrected if it is giving (or subtracting) too much power, but it responds slowly. The optimal values are among the two extreme endings. This information is available for very few countries. In Italy, it varies from 4% in hydroelectric plants to 5% in thermal plants. In Spain instead, for the islands there are two different gaps according to the age of the power plant: from 2 to 5% if the generation unit is new, from 2 to 7% if the generation unit is old.

- 7) Activation and availability: they are the requirements for when activating the primary reserve and for how long it must be available. In Austria, Germany, Greece and Switzerland it is sufficient to allow availability of full reserve in the first 30 seconds after the frequency-changing event, and to maintain that amount of power available for the next 15 minutes (30 minutes for Austria). In Denmark, France and Italy it's the same but with an additional request: beside having the full reserve available in 30

seconds, it's also necessary to have half of the reserve available in the first 15 seconds. In the end Netherlands, Spain and Portugal require that, between those two steps, a discrete linear response is given (60% of the reserve in 18 seconds, for example). For UK it is completely different, because they require that the reserve must be available in the first 10 seconds and to be maintained for the next 20 seconds, where the secondary reserve gets involved.

These aspects are summed up in Table 3.1, where just the valuable information is reported. Each time that an information is mentioned in the table but not properly treated, an asterisk will sign the fact that the information is better explained in the part above. If a box is filled with the sign “/” it means that it was not possible to find information about it.

	<i>TSO</i>	<i>Mandatory service</i>	<i>Voluntary service (if fulfilling technical conditions)</i>	<i>Gap [mHz]</i>	<i>Dead band [mHz]</i>	<i>Sensitivity</i>	<i>Droop</i>	<i>Activation and availability (ΔP: amount of power from PFC)</i>	<i>Ref</i>
<i>AT</i>	APG	No	Yes	± 200	/	/	/	ΔP in $\leq 30s$ for 30 mins	[9] [10]
<i>BE</i>	Elia	No	Yes	± 200	± 10	± 10	/	/	[9] [11]
<i>DK</i>	Energinet	No	Yes	± 200	± 20	± 10	/	$\Delta P/2$ in $\leq 15s$, ΔP in $\leq 30s$, for 15 mins	[9] [12]
<i>FR</i>	RTE	Yes, over 40MW for old plants and 120MW for new ones	Yes	± 200	± 10	± 10	/	$\Delta P/2$ in $\leq 15s$, ΔP in $\leq 30s$, for 15 mins	[9] [13] [14]
<i>DE</i>	More than one *	No	Yes	± 200	Decided by each TSO	± 10	/	ΔP in $\leq 30s$, for 15 mins	[9] [15]
<i>GR</i>	ADMIE	Yes, over 2 MW *	No	± 150	± 20 with insensitivity	See above	/	ΔP in $\leq 30s$, for 15 mins	[9] [16]

<i>IT</i>	Terna	Yes, over 10 MVA excluding non-predictable sources *	No	± 100 *	Depends on the PU type *	Depends on age of PU *	4% hydro, 5% thermal	$\Delta P/2$ in $\leq 15s$, ΔP in $\leq 30s$, for 15 mins *	[9] [17]
<i>NL</i>	TennetNL	No	Yes	± 200	± 10	± 10	/	$\Delta P/2$ in $\leq 15s$, ΔP in $\leq 30s$, for 15 mins *	[9] [18]
<i>ES</i>	REE	Yes, for all power plants *	No	± 150 *	0	± 10 *	*	$\Delta P/2$ in $\leq 15s$, ΔP in $\leq 30s$, for 15 mins *	[9] [19]
<i>CH</i>	Swissgrid	No	Yes	± 200	± 10	± 10	/	ΔP in $\leq 30s$, for 15 mins	[9] [20]
<i>PT</i>	REN	Yes, for all power plants *	No	± 200 *	0	± 10 *	4-6%	$\Delta P/2$ in $\leq 15s$, ΔP in $\leq 30s$, for 15 mins *	[9] [21] [22]
<i>GB</i>	More than one *	Yes, for plants above: 100MW for NG, 30MW for SP, 10MW for SHET	Yes, in specific markets	± 200	± 15	/	3-5%	ΔP in $\leq 10s$, for the further 20s	[9] [23]

Table 3.1 - Technical aspects of Primary Frequency control in Europe

3.3 Economic aspects

They are referred to how the primary control service is remunerated in each nation. Being available to provide this type of service means that a part of the generation capacity is not used for the principal market, influencing the plans for plant remuneration. Given this, pretty much all the TSOs decided a remuneration of the service, choosing different ways to do so: call for tenders, fixed remuneration, a hybrid system between the two, etc. The analysis will be carried

out by similarity in the policy adopted and then singularly for each state, because the situations are really different from one another.

- 1) Tendering process: it is a complete market mechanism. The TSO decides the amount of capacity needed to match the system characteristics, then each participant makes an offer consisting of the amount of power that it can deliver as primary reserve and the price at which that power will be available. When the call for tender is over, an order of merit will be done listing the participants from the cheapest offer to the most expensive one. Each capacity bid will be added, until reaching the point where the sum exceeds the predetermined needed capacity for the system. The remuneration will be assigned to those that are involved in this last sum. Given this overview, each state adopts its own methodology:
 - a) Germany: since December 2007, German TSOs have decided to meet the need for a primary control reserve in a shared call for tenders, which happens in an online platform (nota: www.regelleistung.net). A weekly tender is done, with the minimum bid set at ± 1 MW. Each participant that is eligible of remuneration will receive the bid price (pay-as-bid). Beside this, the German tendering platform hosts also an international call for tender. It is used by Austria, Belgium, France, Germany, Netherlands and Switzerland to jointly allocate a share of their respective primary reserve, adding it all together and bidding for the whole joint system. Given that the platform is the same, also the tendering characteristics are the same. As for Belgium, France and Switzerland, over-the-counter transaction are allowed, meaning that the tendered capacity can be renegotiated with other suppliers that satisfy technical requirements;
 - b) Austria: for the big part of their allocation, see Germany. For the remaining part, the TSO organizes an intern call for tender on a weekly basis, minimum bid set at ± 1 MW with no possibility to separate the up-offer from the down-offer and a pay-as-bid remuneration;
 - c) Belgium: for part of their allocation, see Germany. For the remaining part, also Elia (the Belgian TSO) organizes a national call for tender. Although information about the characteristic of this tendering process is hard to find, it is possible to note that there is a distinction between primary control markets. Given that the frequency range in Belgium is ± 200 mHz, as said before, Elia distinguishes four different markets, two symmetric and two asymmetric. The first (R1 symmetrical 200mHz) requires the full activation of the contracted volume at a +200 mHz and

at a -200 mHz deviation from nominal frequency value, the second (R1 symmetrical 100mHz) is the same but with full activation at a +100 mHz and at a -100mHz deviation; also, the contracted volume must be fully available for -200 mHz/-100 mHz and for +100 mHz/+200 mHz frequency gaps. The third market (R1 upwards) involves contracted volume in the -200 mHz/-100 mHz frequency gap, requiring its full activation at -200 mHz, while the fourth market (R1 downwards) is similar but specular (+100 mHz/+200 mHz frequency gap, full activation at +200 mHz). The international tendering process happens two weeks before the targeted week, while the regional one happens one week before. In Fig. 3.1 it's visually explained which the boundaries of each market are. For simplicity, it is supposed a submitted bid of 1 MW (or -1 MW);

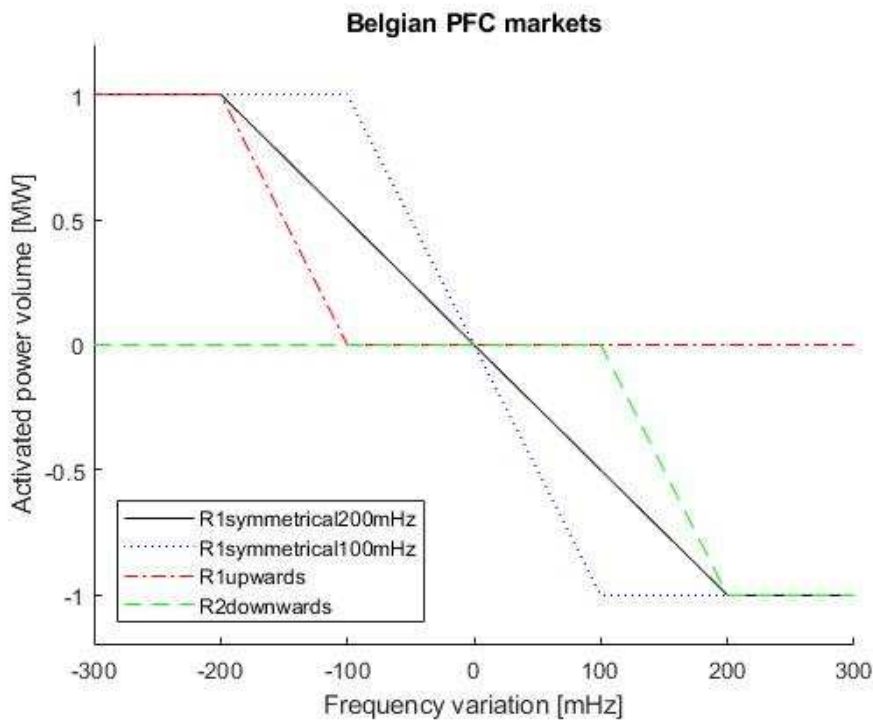


Figure 3.1 - Belgian markets for Primary Frequency Control

- d) Denmark: Energinet has organized its own call for tender, with a minimum bid of ± 0.3 MW and the possibility to differentiate between up or down offers. When the tender ends, each winner gets a remuneration price as the higher one accepted (i.e. the marginal cost);
- e) France: RTE has imposed mandatory primary control services for specific power plants. Anyway, in January 2017 France joined the big central-European-

countries group in the tendering system, so that every plant that has a mandatory request can trade the capacity on the German platform;

- f) Netherlands: as for Austria and other countries, the big part of their allocation is done with the international tendering process on the German platform (see Germany). The difference is that the same platform is used for the regional call for tender, made exclusively for Dutch participants, with the same rules;
 - g) Switzerland: all the needed primary control reserve is acquired participating to the international tendering process on the German platform (see Germany).
- 2) Regulated remuneration: in this case, the TSO sets standards for a mandatory provision of primary control reserve and remunerates the involved plants with a regulated price. It was the most common way for the TSOs to purchase primary control reserve, but with the liberalization of the market just few states still adopt this method.
- a) Greece: they have a hybrid system for providing primary control reserve. For what concerns capacity, generators are obliged to offer, in the internal market, a part of their capacity for ancillary services purposes. The bidding happens each hour, without the need of symmetric bid, and at the end they get the marginal price of the system. For the energy part of the service, generators are obviously obliged to let available the power bid, but they don't get explicitly remunerated for the energy that they provide for primary frequency service. In fact, there is no differentiation between energy dispatched for this purpose and energy injected for meeting the total load of the system;
 - b) Italy: TERNA asks for mandatory primary control services, and remunerates the energy with a fixed price that is different for up regulation and down regulation. This payment should cover also fixed costs for making available part of the generator capacity and the costs of installed instruments to guarantee primary frequency control.
- 3) No remuneration: in this last case, generation unit that provide primary control services don't get paid for doing it. This is the case of Spain and Portugal.

A special mention is required for UK, because it is by far the country that most differentiates between the markets of primary frequency regulation and the remuneration of each one. Nationalgrid has developed three different markets for frequency control: Mandatory Frequency Response, Firm Frequency Response and Enhanced Frequency Response. While the first two are remunerated by predetermined fixed price according to different parameters (energy delivered, disposal hours, capacity) and just the second has a mixture between regulated prices and tenders, the third one is the most interesting for the topic of this thesis. In

fact, while the first two don't make distinction for primary or secondary frequency control, the Enhanced Frequency Response is about providing frequency control in one second or less, pretty far from the ten seconds required by primary frequency response. It is suited for Electric Storage Systems, that can provide all the power that they can in a very short amount of time. The remuneration of this service is carried out with yearly tenders.⁴

These aspects are summed up in Table 3.2, where just the valuable information is reported. As for Table 3.1, each time that an information is mentioned in the table but not properly treated, an asterisk will sign the fact that the information is better explained in the part above. If a box is filled with the sign “/” means that it was not possible to find information about it or that it makes no sense to fill the box.

	Type of remuneration	Different market types	Components remunerated	Frequency of market clearing	Market clearing price	Minimum bid [MW]	Possibility to distinguish up or down reserve	Ref
AT	Tendering process	One national and one international (German market)	Capacity	Weekly	Pay as bid	±1 on international basis	No	[9] [24] [25]
BE	Tendering process	One national (*) and one international (German market)	Capacity	Weekly *	Pay as bid	±1 on international basis	Yes on national basis, no on international basis	[9] [11] [25]
DK	Tendering process	National	Capacity	Daily	Marginal price	±0.3	Yes	[9] [12] [25]
FR	Tendering process *	International	Capacity	Weekly	Pay as bid	±1	No	[9] [25] [26]
DE	Tendering process	International	Capacity	Weekly	Pay as bid	±1	No	[9] [25]

⁴ For further explanations it's possible to go on NationalGrid website, looking for “Frequency response services”: <https://www.nationalgrid.com/uk/electricity/balancing-services/frequency-response-services>

<i>GR</i>	Mandatory tendering process	National	Capacity *	Daily	Marginal price	/	Yes	[9] [13]
<i>IT</i>	Mandatory provision	/	Energy	/	Fixed price *	/	Yes	[9] [27]
<i>NL</i>	Tendering process	One national and one international (German market) *	Capacity	Weekly	Pay as bid	± 1	No	[9] [25] [28]
<i>ES</i>	Mandatory provision	/	No remuneration	/	/	/	/	[9] [13]
<i>CH</i>	Tendering process	International	Capacity	Weekly	Pay as bid	± 1	No	[9] [25]
<i>PL</i>	Mandatory provision	/	No remuneration	/	/	/	/	[9] [13]]
<i>GB</i>	Mandatory provision and tendering processes	Mandatory, firm, enhanced. All on national basis	Depends on the market type	Monthly for the 1 st , yearly the 3 rd	*	Depends on the market type	*	[9]

Table 3.2 - Economic aspects of Primary Frequency Control in Europe

3.4 Regulation in isolated systems

As briefly said at the end of the first chapter, isolated systems are a very interesting reality to study. Their particular environment and their peculiar generation mix are two of the aspects that create a natural stage for researches. This difference with the inlands is reflected also in regulation for operating them, because the norms and standards that are good for the big systems could not be so suitable for small ones. In the subchapters above, for both parameters it has been always clearly reported when there was a difference between regulation in inland systems and isolated systems. Anyway, there were differences in procedures and in remuneration that were difficult to catalog, and for this it's necessary to write something more

about the peculiar regulation that isolated systems have in some countries. UK has not been considered an isolated system, although being an island, due to its extension and its similarities with regular inland systems. The countries that have been further examined are the Southern Europe ones, because they can be more interesting to work on. Tourism and weather, in fact, are two of the major aspects that make them a more profitable solution to be studied. Their generation mix always includes massive diesel generation and poor renewable energy generation, because the small size of the system doesn't allow nowadays a high renewable penetration. In specific, the countries examined are Greece, Italy and Spain. The same countries will be analyzed also in the next subchapter.

- 1) Greece: the ensemble of Greek island is called the “Non-Interconnected Islands” system. There is one government entity that largely dominates energy generation and supply in all the country, inland and islands included. HEDNO is the entity that controls the dispatch in the “Non-Interconnected Islands” system, so it decides also about the primary service control, done vertically for each island. The consumers of all the country pay the same price for electricity. The extra-costs of producing energy in the non-interconnected system is recovered from the revenues of a surcharge in the electric bill, spread among all Greek consumers;
- 2) Italy: Beside Sardinia and Sicily, which are specifically cited in Terna's rule for primary frequency control and are almost part of the interconnected system (thanks to submarine cables), the Italian islands are mostly run by small local companies that own generation, dispatch and supply. Given that, they obviously decide on their own about frequency regulation. The remuneration is done on all energy produced, with no distinction between daily load and frequency control, via a standard cost approach. It means that it is set a fixed remuneration per energy unit, calculated by the regulatory entity depending on a sum of several factors, and each company will get that amount of money independently of being above or below that remuneration. As per Greece, there is a surcharge on all Italian electric bills for financing the power generation in little islands;
- 3) Spain: it is the country that has the most expanded regulation about insular and extra-peninsular territory, among those analyzed. Unlike Greece and Italy, also due to different morphology of the islands, the Spanish TSO follows transmission grid maintaining and developing in the insular system. Since in Spain there's no remuneration for primary frequency control service, there is no need to talk about a remuneration in isolated systems. Consumers in those systems get charged with the

same price that people on inland have, and like Greece and Italy there is a surcharge in the electric bill spread for all Spanish consumers. Companies in insular systems get remunerated by the difference between production cost and selling price.

3.5 Regulation about energy storage

Another topic that is interesting for this work is, of course, energy storage. Even if Energy Storage Systems are something that are continuously rising its importance for a better management of the electric grid, the regulation about them is not completely clear. The regulatory environment in which storage systems are growing is not the better because, as for new paradigms in power generation, regulation couldn't totally cope with the rising of this technical solution.

- 1) Greece: the only ESS type that is allowed to sell energy as a producer is the pumped hydro storage. Battery ESS are not allowed to participate in frequency regulation, but on the “Non-Interconnected Islands” system Hybrid Power Units are allowed. Those units are composed by any type of power generation, also renewables, coupled with a battery storage system, that allows more flexibility;
- 2) Italy: since May 2017 it is allowed for storage systems to participate in the balancing market (MSD) and to aggregate for doing it⁵. Given this, it is not possible for them to participate in other markets nor in frequency regulation;
- 3) Spain: like Greece the only ESS type that is regulated is the pumped hydro. For other storage systems, there is a barrier because there are two different registers in which a generation unit can be enrolled: one for buying and one for selling. Since pumping storage is regulated and has its own special rules, hydro power plants can split and have two different virtual units playing in different markets. But for others, which have no rules whatsoever, it's impossible to do so.

⁵ Delibera 300/2017/R/eel, 5th May 2017

3.6 Choosing isolated systems

Since the initial aim of this work was to economically evaluate the impact that electric vehicles could generally have in giving primary frequency control services, an overview has been carried out to better understand which boundaries would have been best to set. The goal was to have an overlook of the European situation, so that it could be possible to find a proper context in which was good to work.

From the overview it has been seen that, among national interconnected systems, there are plenty of different rules and different standards to cope with frequency oscillations. There are a lot of restriction to participate to the service, given the fact that the number of power plant participating is quite high, and it is possible to achieve a high degree of frequency quality. Also, each nation has decided its own generation mix according to a lot of different parameters, aiming at having the most reliable and cheap mix that it was possible.

Instead, in small isolated systems things are different. Islands have often developed step by step, just adding power generation when it was needed, and often that generation has been diesel generation. Diesel is easy to transport and to use, but it is a solution that neither is efficient nor economical. Also, the small size of the systems translates in a lack of inertia, given the small amount of generation that is needed to match the load, so frequency oscillates a lot more frequently and largely than in big interconnected systems. Given this, there is a much bigger margin of improvement for what concerns the frequency regulation service.

Economically speaking, it is more easy and interesting to see what happens if a fleet of PEV is added to the system of an island instead of a national network system. The impact can be bigger and the solution is surely more profitable, given the high costs that the operators of islands (which almost always is also the owner of the grid and the generation) have to face for properly run the system.

Another factor that strengthens the choice of this environment is also the concern about climate issues, to which islands give more attention than inlands giving their geographical situation. One clear example of this aspect is the decision of the Balearic Islands government, taken in late November 2017, to mandatorily have the entire rental car fleet on its islands composed by electric vehicles. The aim is set for 2030, with gradual increases of 10% each year starting in 2020. Rental car services are really common in small islands, since they are a touristic destination for people that cannot go there with their vehicle. This important example of legislation is not only something that is closely related to the aim of this work; it is also a sign of what is the islands' aim for the future, regarding their energy mix and their way to fight

climate change and pollution, something that further justifies the environment choice of this evaluation.

Anyway, for the purpose of a more complete work, at the end of this thesis it will also be analyzed how the final economic evaluation can be replicated and scaled, so that it can be taken as a starting point for future scenarios and different settings.

4 Evaluation setting

4.1 Introduction

To better understand what happens in an electric system when it suffers of over-frequency or under-frequency events, which are the things that are the interest of this work, the most obvious approach is to create an equivalent model of the network and play with the parameters to simulate the problem. This model, which usually is simplified in order to reduce the complexity of the overall structure, always includes the generation mix (with transfer functions related to the components of the power plant), the network lines and the load. In literature it is possible to find many examples of systems modeling, from small to big and from simplified to accurate. But this work also needs a modeling of the electric vehicle fleet that is connected to the distribution network, which is harder to find. Besides that, there is of course the necessity of a description of the island nature, status and running operation. These information require some assumption to be made, and some calculations with them.

In this section, at first will be explained from where the model of Plug-in Electric Vehicles (PEVs) is taken from. Then it will be given a quick explanation, analyzing singularly the blocks that it has inside.

After that, the data used for the case study will be shown and explained, preceded by some assumptions over the system and the use of PEVs for PFC and some calculation about the impact that PEVs must have on the system in order to have an equivalent one.

4.2 Model used and connection with chapter I

In literature, there are very few examples of models that take into account PEVs in all their complexity. A lot of parameters must be considered, like how many PEVs are connected at a specific moment, at what power are they charging in that moment, what is their SOC state, how much they can be available for power exchanges, and more other things.

The model that was used for this work reflects what has been written in the first chapter. Data for generators characteristics has been taken from [29], and something about secondary control (or Load Frequency Control) was added. For what concerns PEVs, the model is the one described in [30]. Of course, parameters and data from the case study have been modified to fit the purpose of this work. The peculiarity of this PEVs modeling, which makes it more

comprehensive than others, is the developing of a participation factor. This particular tool allows to involve in the considerations the minimum desired State Of Charge (SOC) of the vehicles, the power limitation of the drive train and the PEV battery charging modes, with constant current or constant voltage. For coping with the different situations of each PEV, it is used the averaging method.

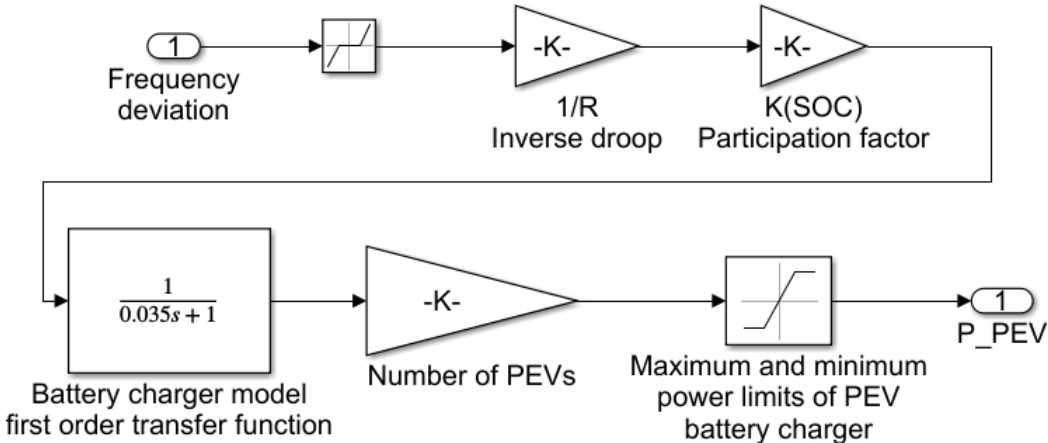


Figure 4.1 - Block scheme of PEVs' model

In Fig. 4.1 are shown the blocks that compose the PEVs' model. It is possible to see that all the initial parameters are referred to an average single vehicle, and afterwards the result is multiplied by the number of PEVs connected to the grid at the chosen moment. It is also possible to see that, for a given frequency disturbance as input, the model gives back a variation in the power output of the overall PEV fleet.

This section continues with the explanation of each block of the scheme in Fig. 4.1.

4.2.1 Dead zone

Like it has been said in subchapter 3.2, a dead zone (or dead band) is the maximum voluntary insensibility that generation plants can establish for not replying to frequency fluctuation. It is set for avoiding too much stress for generators, as they would always react to oscillations. For this model it has been set at ± 30 mHz, to better resemble the island parameters.

4.2.2 Inverse droop

Also the droop has been treated in subchapter 3.2: it was calculated in equation 3.1 and defined as the opposite of the ratio between the frequency variation, expressed in per unit of the nominal value, and the consequent power variation, expressed in per unit of the nominal power of the generation plant. Looking at the equation, it is possible to see that, if the aim is to find the power variation, it is necessary to multiply the frequency variation for the inverse of the droop. This is exactly what happens in the model. The droop was set to 0.5%, ten times lower (so a response ten times quicker) than the normal droop used for conventional generators. This solution was adopted because it has been seen that, with such a value replied for PEV, the response wasn't quick enough to give appreciable advantage nor to avoid load shedding.

4.2.3 Participation factor

The participation factor is the solution that allows such a simple model to be very effective. It is represented with k_i (the i stands for the i vehicle), and goes from 0 (no participation to PFC) to 1 (full participation to PFC) according to the PEV battery SOC. For a plug-in electric vehicle it's possible to distinguish among three different connection modes: disconnected, charging or idle.

- For disconnected mode it is obviously meant that the vehicle is not connected to the grid, being parked or driven around. The participation factor K in this mode is 0;
- For charging mode, it is meant when the vehicle is connected and the battery is charging. The usual charging mode of a Li-ion battery is shown in Fig. 4.2. It also includes the maximum and minimum limit for the battery, which will be treated later in this subchapter.

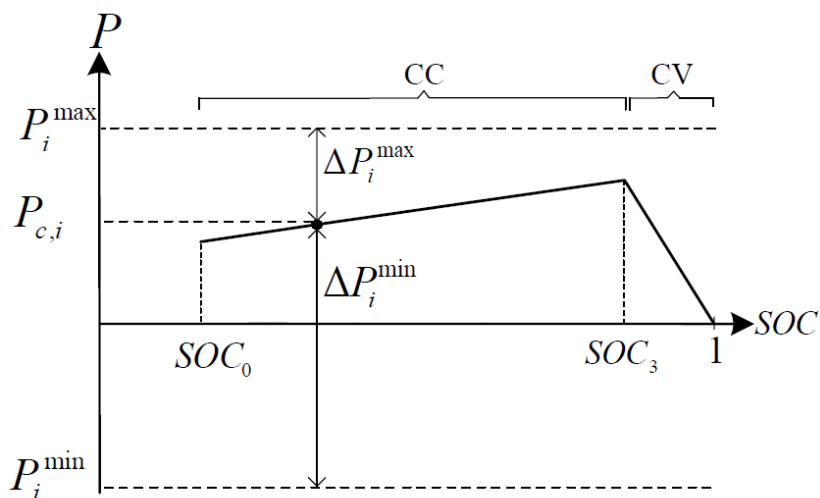


Figure 4.2 - Typical charging mode of a Li-ion battery [30]

The first part, from SOC_0 to SOC_3 , works with constant current and increasing voltage, so that the charging power slightly increases. After a certain point, where the maximum voltage allowable from the battery is reached in SOC_3 , the charging mode changes in constant voltage. The current decreases until reaching a nil value, and then the battery is fully charged. So, given the fact that these two steps have completely different control strategies, the SOC of the battery largely affects the possibility for the PEV to participate to PFC services. In Fig. 4.3 it is represented how this happens, showing the relationship between SOC and k_i^C .

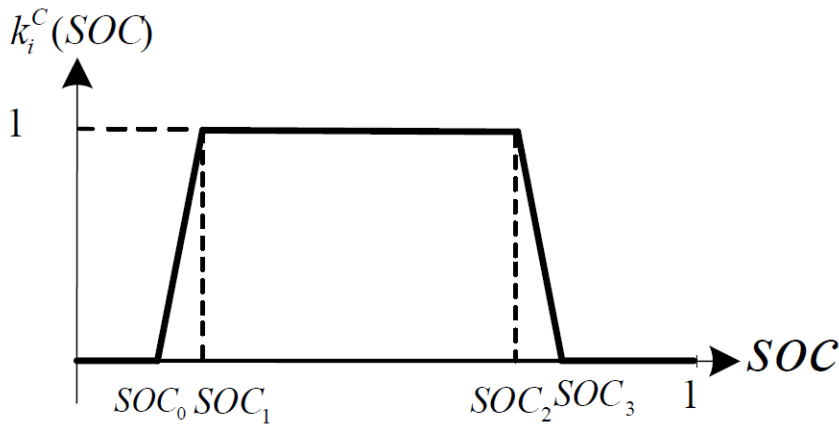


Figure 4.3 - Participation factor of PEVs in charging mode according to their SOC [30]

k_i^C stands for k_i in charging mode. It is important to note that the sudden changes are represented with high-slope ramps, not with abrupt changes. This happens to avoid abrupt changes in the participation factor function. So, the surpassing of the preferred SOC_0 has been replaced with a ramp from SOC_0 , the required lower level, to a hypothetical SOC_1 . The same happened for the start of the constant voltage charging mode, where the sudden change in SOC_3 has been replaced with a ramp from SOC_2 to SOC_3 . Between SOC_1 and SOC_2 the participation factor k_i^C is 1, because it is in constant current charging mode and the SOC is higher than the minimum required. Anywhere else, beside the ramps, the participation factor k_i^C is 0, because of either a low SOC of the battery or the constant voltage charging mode.

- For idle mode, it is meant when the vehicle is connected but the charging power is nil. It can happen when the charging process is finished, or even when it is stopped due to

particular charging management strategies. Also in this case, sudden changes are represented with high-slope ramps. Fig. 4.4 shows the correlation between SOC and k_i^I .

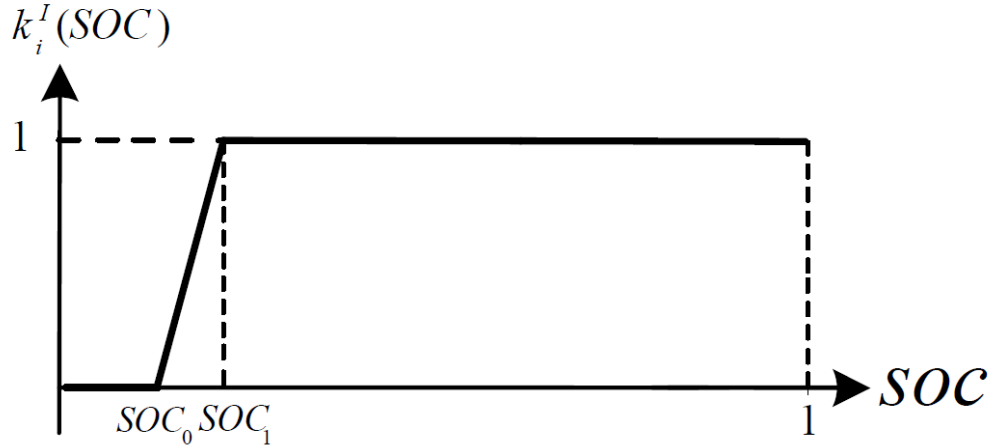


Figure 4.4 - Participation factor of PEVs in idle mode according to their SOC [30]

It is possible to see that it doesn't take into account the difference between constant current and constant voltage modes. In idle mode, the voltage is always the one at the terminal of the battery.

Knowing the profile of each connection mode, it is possible to calculate the average participation factor $k_{avg}(SOC_{avg})$, function of the average battery State Of Charge SOC_{avg} that can largely vary over time. This value allows to consider the entire connected PEV fleet as composed by vehicles with the same average participation factor. The calculation is shown in (4.1)

$$k_{avg}(SOC_{avg}) = \int_0^1 [\alpha^I k^I(SOC) + \alpha^C k^C(SOC)] \phi_{SOC_{avg}} d(SOC) \quad (4.1)$$

The factors in the equation are:

- α^I share of total PEV that are connected in idle mode, assumed to be 75%;
- k^I participation factor of an idle mode connected vehicle depending on its SOC;
- α^C share of total PEV that are connected in charging mode, assumed to be 25%;
- k^C participation factor of a charging mode connected vehicle depending on its SOC;

ϕ_{SOC} probability distribution of PEV's battery SOC, assumed to be a normal distribution with a variance of $\sigma^2 = 0.0075$ and SOC_{avg} as mean value.

The levels of SOC_0 , SOC_1 , SOC_2 and SOC_3 mentioned above are set to 0.2, 0.25, 0.85 and 0.9. If necessary, further explanations can be found in [30].

As a result of (4.1), the relationship between k_{avg} and SOC_{avg} is the one in Fig. 4.5:

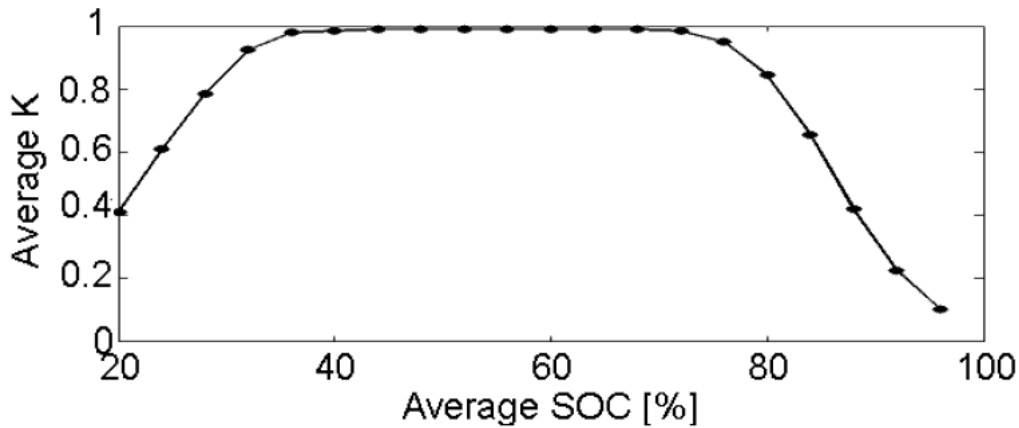


Figure 4.5 - Relationship between participation factor and State Of Charge [30]

This graph is needed to later translate the average SOC of the vehicles connected to the grid in the participation factor that will be put in the model.

4.2.4 Battery charging model

The response of the battery of each vehicle is modeled with a first order function. The time constant is set at 35 ms, as the best example in [31].

4.2.5 Number of PEV

The number of vehicles N_h that is inserted in the model is the amount of PEV connected to the grid. It is not the total number of vehicles that are present in the system, but just those that could be available to offer PFC services. This is also possible to be noticed from the calculation of k_{avg} , where the disconnected vehicles are not considered. So, for the specific moment of the day that is chosen, it is necessary to know the SOC_{avg} (to calculate the participation factor) and the N_h number of vehicles connected to the grid. N_h can largely vary during the day.

4.2.6 Maximum and minimum power limits

These limits are dictated by two factors: the number of connected PEV and their average charging power, both at the chosen moment for the simulation. What is necessary to do is to find the average charging power of the vehicles, to be multiplied by the number of PEV connected to the grid. The relationship with the charging power at that moment (nominal charging power, half the nominal charging power, something in between) gives the maximum and minimum limits for the total power that the PEV fleet can either give or absorb, respectively ΔP_{max} and ΔP_{min} .

At first, it's important to know the battery charger's typologies. Different types of vehicles and different necessities in charging time are the reasons why several levels of charging typologies are adopted. Of course, taking as reference the same charging time, battery chargers with lower nominal power inject less energy in vehicle's batteries; but also vehicle's batteries themselves can be dimensioned with different parameters, that would require different charging methods to correctly operate. Another thing that is really crucial for the evaluation is the moment of the day in which this is run, because from it depends the number of connected PEVs (that largely vary during the day) and the average SOC of the vehicles, that decide the participation factor as it has been seen before. The average charging power P_c can be calculated as in (4.2):

$$P_c = P_{avg} \cdot k_{avg} \cdot N_h \cdot q \quad (4.2)$$

The factors in the equation are:

- P_{avg} average power of the charging station according to their share;
- k_{avg} average participation factor at the moment of the evaluation;
- N_h number of total PEV that are connected to the grid at the moment of the evaluation;
- q factor that keeps track of the charging vehicles share, the idle-connected vehicles share and the power at which these ones are charged; it goes from 0 to 1.

The maximum power limit P_{max} and the minimum power limit P_{min} are calculated as in (4.3) and (4.4):

$$P_{max} = P_{avg} \cdot k_{avg} \cdot N_h \quad (4.3)$$

$$P_{min} = -P_{max} \quad (4.4)$$

The factors in the equation have been already explained for equation (4.4). The final relationships are shown in (4.5) and (4.6):

$$\Delta P_{max} = P_{max} - P_c \quad (4.5)$$

$$\Delta P_{min} = -P_{min} + P_c \quad (4.6)$$

It's important to notice that both ΔP_{max} and ΔP_{min} are positive, since they are differences.

4.3 Case study

As it has been told before, the environment for this economic evaluation is a small isolated system. The characteristics of the system are really important for the reliability of the study, so the data have been hypothesized according to the typical and most common values that it had been possible to find. Also some assumption about the system will be made, followed by some calculation on the role of PEVs and the descriptive table of the island overall situation.

4.3.1 Data of the island

The surface of the island is 25 km², with a population of 3300 people and a density of 132 inhabitants/ km². These data are similar to a lot of small islands in southern Europe, as it is possible to see in Table 4.1:

Island (nation)	Density (inhab/ km²)
Elba (IT)	139
Sant'Antioco (IT)	133
Pantelleria (IT)	92
San Pietro (IT)	127
Lanzarote (ES)	176
La Palma (ES)	116
Sao Miguel (PT)	188
Terceira (PT)	140

Table 4.1 - Population density of some european islands

During summer, although, population notably rises for the touristic nature of this kind of islands, reaching 10000 people. This phenomenon is well known in such islands, who thanks to their environment, topology and morphology are likable to be chosen as holiday places. This effect creates two different scenarios in the span of a yeartime, being possible to be subdivided in peak touristic days and off-peak touristic days. In the first one the population remains almost constant at 3300 people, while in the second it varies along the days and it can reach 10000 people. Due to this variation in people on the island, the oscillation between minimum and maximum load is stronger than usual: common values are almost 0.33 MW for person for minimum load and 1 MW per person for maximum load, but there are heavy variations between how many people are on the island in peak and off-peak periods. This brings the minimum load to 1 MW, because it happens in off-peak period, and the maximum load to 10 MW, because it happens in peak period. If the off-peak number of inhabitants was considered, the maximum load is 3MW for person. This helps to understand the peculiarity of such systems.

The power mix of this kind of islands is often particular too, because the difficult and remote geographical position, combined with a low inertia of the electrical system due to small dimensions, exclude many possibilities for the generation power. The generation in the islands has often developed chasing the increasing maximum load, so that it was not possible an efficient strategic planning of the mix. Typically, diesel generation is the choice made by the owner of the system, that controls generation and distribution at the same time. Fuel shipping and technical necessities are among the reasons why diesel fuel is the main energy source for small islands, but these benefits are possible sacrificing efficiency and a clean generation mix. On the island there are seven diesel generators with a nominal power of 2.5MW, in a way that allows to cope with the maximum load in peak periods and to have some redundant generator.

The droop for all of them is 5%, and the minimum power that they can manage to generate is 0.3 MW.

The evaluation will distinguish between two different scenarios: a scenario where PEVs are present on the island but they are not providing PFC services, called “no PEV” scenario, and a scenario where PEVs are present and providing PFC services, called “PEV” scenario. The second scenario will modify the first in some parameters, allowing to compare the two cases and see what the changes are. The situation in the island will be described starting from the load of the system: with a step of 0.1 MW, the description of the system will be developed for each load, from the minimum to the maximum, and for each of the two scenarios. The data will be about the number of active generators, the power share and the efficiency of each generator, the time that the total load is at least the one indicated in the row and the probability to have that load.

Later in the work, an exhaustive table with all the data will be show. Before that although, there is the necessity of the introduction of some general assumptions and some calculation about the weight of PEVs in the system, that are fundamental for table construction and explanation. These assumptions will be justified, and together with calculations they will help build the island case study.

4.3.2 General assumptions

The assumptions helps to build the evaluation, they represent some common situations and are explained properly.

- Chargers installation and PEVs purchase are considered already installed in the system

This evaluation is conducted from the point of view of the system operator. The two scenarios are differentiated by PEVs providing or not providing PFC services, so for sure there are costs for going from one scenario to another. The focal point of the evaluation is to see what the economical differences are when the already existing PEVs on the island are switching from not giving PFC services to giving PFC services. Given this, the base of the scenarios will already include battery chargers and PEVs, but there can be a cost of adapting the already existing infrastructure for allowing PEVs to participate. This will be included in the evaluation.

- All battery chargers on the island in the “PEV” scenario are bidirectional

Usually, what batteries do is to withdraw electric energy from the system and transform it in chemical energy, storing it and charging the battery. With the right power electronic however, it is also possible to have the opposite energy flow: the energy stored in battery can be withdrawn from the system, discharging the battery. Applying this to the electric vehicle

world, it means that every charger at which PEVs is connected in the island allows this bidirectional energy flow. This is far better and simpler for offering services with PEVs, because it enhances the possibility of helping the grid having more freedom about the changes of involved power. With unidirectional battery chargers, the lowest power that can be made available is 0, meaning that all connected PEVs are simply disconnected. With bidirectional battery chargers however, power can also be negative, because batteries can also be discharged. Of course this type of battery charger is more expensive, and that is taken under consideration in the evaluation.

- For “PEV” scenario, the shares of battery chargers are 5% of 20 kW chargers, 39% of 7 kW chargers and 56% of 3 kW chargers

The average charging power, weighting each charging value with its share, is $P_{avg} = 5.41 \text{ kW}$. This value can also be found in [30], calculated more carefully and considering different types of vehicles, but doing the same reasoning from charger’s side is equivalent. The island is quite small, so there is no need for a big number of fast chargers because the traveled distances are never high, and the batteries aren’t discharged so much.

- Charging power of PEVs is 50% of the maximum PEV reserve

In equation (3.2) there is an element that allows to understand which the level of charging power is between 0 and the maximum available, that is every connected vehicle charging at the nominal power of the charging station. It is the factor q , and it is fixed at 0.5. This assumption can be justified thinking that the two more likely scenarios are either a lot of connected vehicles charging at low power (night) or some connected vehicles charging at high power (day).

- The system in “no PEV” scenario is operated supposing an increased secondary reserve of 15% of the load

This typically happens in small systems, where the reserves are much higher than in bigger interconnected systems because disturbs can be much higher. Also, there is more need for system inertia and this way of running the system allows it to be higher, because more generators are active with respect to the same load and more increasing and decreasing power can be utilized to stabilize the system. The value of 15% is reasonable, since normally in interconnected systems secondary reserve has a value around 3% and isolated systems need more reliability.

- PEVs can act as secondary reserve only for five minutes for each disturb

For an electric vehicle, what happens in five minutes is not so important in the overall count of the absorbed or given power, because a charging event happens in the order of hours. The

limit is set to five minutes because it is the time in which a diesel generator can be started-up to supply the missing generation to meet the load.

- The droop for PEVs is set at 0.5%

The conventional droop for CGUs is around 5%, which is the value used in this evaluation for diesel generators. For PEVs however, the droop can be previously decided thanks to power electronics, and it has been set to a quicker value because it enhances frequency response for them.

4.3.3 Calculation

These calculations regard the duty and the limits that PEVs can have towards the system when they're aggregated. The first is the minimum required number of PEVs that can allow a substitution of one CGU's duty in primary frequency control, the second comes from the first and is about how many PEVs are necessary to cover and substitute that 15% value of higher secondary reserve. The point is that, thanks to the connection of PEVs, the system can be enhanced enough to be run more according to the real load of the system, and with these calculations it will be calculated the minimum number of PEVs for doing so. For the calculations, the profiles of State Of Charge SOC, participation factor k_{avg} and number of connected vehicles N_h are drawn in Fig. 4.6 and Fig. 4.7.

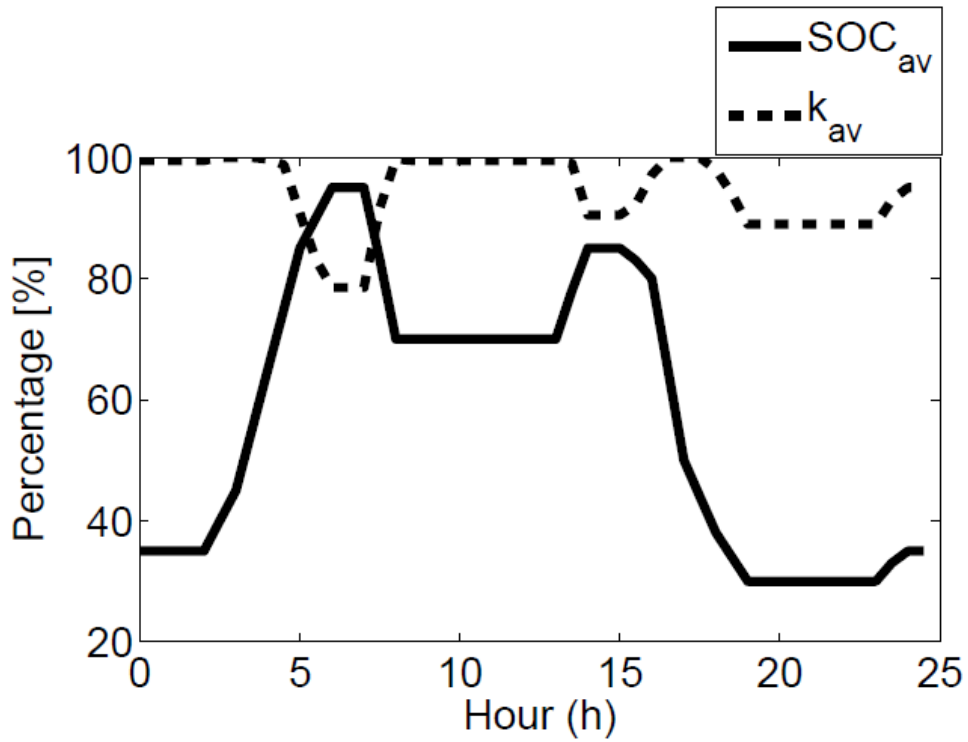


Figure 4.6 - SOC and k_{av} according to the hour of the day [30]

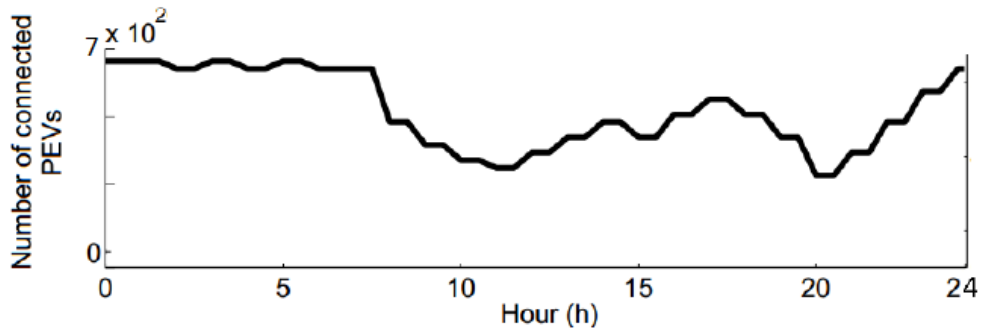


Figure 4.7 - Number of connected vehicles according to the hour of the day [30]

- PEVs and primary frequency control

Just the after-the-transient response is going to be evaluated, because time constants of batteries are way smaller than the ones of generators and so the transient is quicker and smaller. Equation (4.1), if written for a diesel generation unit and elaborated, becomes:

$$\Delta P = -\frac{\Delta f}{f_n} \cdot \frac{100}{\sigma_{\%}} \cdot P_{nom} \quad (4.7)$$

Supposing $\Delta f = 1 \text{ Hz}$ and having $P_{nom} = 2.5 \text{ MW}$, $\sigma_{\%} = 5\%$ and $f_n = 50 \text{ Hz}$, it's easy to see that a frequency variation of 1 Hz causes an opposite power variation at regime of the generator of 1 MW . With connected PEVs, to see how many are necessary to substitute a diesel generator, it must happen the same. This time the unknown is P_{nom} , the equivalent power that must be available from PEVs.

$$P_{nom} = \left| \Delta P \cdot \frac{\Delta f}{f_n} \cdot \frac{100}{\sigma_{\%}} \right| \quad (4.8)$$

ΔP , Δf and f_n are the same, while $\sigma_{\%}$ is 0.5% for PEVs. The result of (4.8) with the previous data is $P_{nom} = 250 \text{ kW}$. This is the maximum reserve P_{max} that PEVs must let available. Equation (4.3) shows how that power is obtained, so it's possible to use (4.3) to calculate N_h . For k_{avg} it is taken the worst value shown in Fig. 4.6, to be sure that all cases are covered, so $k_{avg} = 0.8$. For P_{avg} , it is 5.41 kW . This gives a number of 58 PEVs that at least must be connected to cover PFC duty of one diesel generator.

- PEVs and secondary frequency control

The two reasons for having the increase in secondary reserve are more inertia available and more secondary reserve. Now the second hypothesis will be controlled, to see what is possible to do with PEVs, and after that it will be evaluated what happens with the first hypothesis.

It's already been said that the increase for secondary reserve is 15% of the island load. So, for cutting that share from diesel generators and still maintain an equivalent system, it is necessary that connected PEVs let available the same amount of power. What is trying to be shed is upwards secondary reserve, so it means that if connected PEVs can offer the same amount of upwards secondary reserve everything is ok. So the system is equivalent if, from the charging point, PEVs can invert their flow and become generators, offering enough power to the grid. In equations, this means that ΔP_{min} in (4.6) must be at least 15% of the load. Combining equations (4.3), (4.4) and (4.6), and keeping in mind that in the new scenario the load increases for the presence of PEVs, it's possible to obtain, in pu with the reference load as base power, (4.9):

$$\Delta p_{min} \left(1 + \frac{P_c}{P_{refload(kW)}} \right) = \frac{-P_{min} + P_c}{P_{refload(kW)}} \quad (4.9)$$

Developing (4.9), it is possible to get (4.10):

$$\Delta p_{min} = \frac{-P_{min} + 0.85 \cdot P_c}{P_{refload(kW)}} = \frac{P_{avg(kW)} \cdot k_{avg} \cdot N_h \cdot (1 + 0.85q)}{P_{refload(kW)}} \quad (4.10)$$

The unknown is $\frac{N_h}{P_{refload(kW)}}$, which transforms (4.10) in:

$$\frac{N_h}{P_{refload(kW)}} = \frac{\Delta p_{min}}{P_{avg(kW)} \cdot k_{avg} \cdot (1 + 0.85q)} \quad (4.11)$$

Knowing that $\Delta p_{min} = 0.15$, $P_{avg} = -5.41 \text{ kW}$, $k_{avg} = 0.8$ to always consider the worst case and $q = 0.5$, it's possible to see that $\left| \frac{N_h}{P_{refload(kW)}} \right| = 0.02432$, or more clearly that $\left| \frac{N_h}{P_{refload(MW)}} \right| = 24.32$. This is the minimum ratio, so everything that makes it higher than this value is acceptable. In the end, if there are at least 25 connected PEVs for each MW of the load, secondary reserve problems are satisfied. This means that, for the maximum load that the system can have (10 MW), there must be at least 250 PEVs connected.

To see if this value is reasonable, some typical data can be checked. Typical and reasonable values for knowing the number of cars that are available and circulating in a place can go from one over two inhabitants to past one over five inhabitants, so a middle way of one over four is taken. With one vehicle over four inhabitants, when 10000 people are present in the island it means that almost 2500 vehicles of all kind are available. Assuming that half of them are electric vehicles of all kind, and half of all electric vehicles are plug-in electric vehicles (PEVs), this brings the number of useful vehicles to 625. In the worst moment of the day although, it can happen that just half of them are connected to the grid as it is possible to be seen in Fig. 4.7, so the number of available PEVs drops to 313.

It's important to notice that these hypotheses are done in the worst-case scenario, supposing at the same time that $k_{avg} = 0.8$ on one side and that the number of connected PEVs is half the total availability on the other, two scenarios that never happen together, as it is possible to see in Fig. 4.6 and Fig. 4.7. Anyway, even if the hypotheses are conservative, the data can be considered reasonable.

Putting together the results of the two calculations, it is possible to say that there is no need for keeping the increased secondary reserve if there are connected at least 25 PEVs for MW and at least 58 PEVs in general. In fact, there is no need for more inertia if there are enough PEVs to provide PFC services and there is no need for more secondary reserve if there are enough PEVs to provide it. So, for both scenarios it is considered to have 25 PEVs for MW of

load, with the difference that in the “no PEV” scenario they are not offering any service while in “PEV” scenario they are. This is the minimum requirement to guarantee the equivalence of the system, so it is the number of vehicles connected to the grid for each scenario. Everything above that just helps the evaluation. Also, according to the load it is not possible to substitute any diesel generator with connected PEVs until the load is at least 2.4 MW, because in that case the number of PEVs connected will be 60 ($2.4 \cdot 25$). But it will be seen that it is not possible to substitute anyway a CGU’s PFC duty below that share because otherwise it would not be possible to meet the requested load.

4.3.4 Data used for the evaluation

Table 4.2, shown in the next pages, offers a complete view over the situation of the island.

Ref load	N° gens (no PEV, +15% load)	N° gens (PEV)	Generated power (no PEV)				Generated power (PEV)				Efficiency (no PEV)				Efficiency (PEV)				Secondary reserve with respect to load (no PEV)	Secondary reserve with respect to load (PEV)	Hours for load	Probability for load (%)
1	2	2	0,5	0,5			0,5	0,5			0,161	0,161			0,161	0,161			400%	415%	8760	0,342
1,1	2	2	0,55	0,55			0,55	0,55			0,172	0,172			0,172	0,172			355%	370%	8700	1,027
1,2	2	2	0,6	0,6			0,6	0,6			0,182	0,182			0,182	0,182			317%	332%	8580	1,769
1,3	2	2	0,65	0,65			0,65	0,65			0,192	0,192			0,192	0,192			285%	300%	8390	2,477
1,4	2	2	0,7	0,7			0,7	0,7			0,201	0,201			0,201	0,201			257%	272%	8146	3,517
1,5	2	2	0,75	0,75			0,75	0,75			0,209	0,209			0,209	0,209			233%	248%	7773,75	4,249
1,6	2	2	0,8	0,8			0,8	0,8			0,217	0,217			0,217	0,217			213%	228%	7401,5	4,249
1,7	2	2	0,85	0,85			0,85	0,85			0,225	0,225			0,225	0,225			194%	209%	7029,25	4,249
1,8	2	2	0,9	0,9			0,9	0,9			0,232	0,232			0,232	0,232			178%	193%	6657	4,249
1,9	2	2	0,95	0,95			0,95	0,95			0,238	0,238			0,238	0,238			163%	178%	6284,75	4,249
2	2	2	1	1			1	1			0,244	0,244			0,244	0,244			150%	165%	5912,5	4,249
2,1	2	2	1,05	1,05			1,05	1,05			0,25	0,25			0,25	0,25			138%	153%	5540,25	4,249
2,2	2	2	1,1	1,1			1,1	1,1			0,255	0,255			0,255	0,255			127%	142%	5168	4,249
2,3	2	2	1,15	1,15			1,15	1,15			0,26	0,26			0,26	0,26			117%	132%	4795,75	4,249
2,4	2	2	1,2	1,2			1,2	1,2			0,265	0,265			0,265	0,265			108%	123%	4423,5	4,249
2,5	2	2	1,25	1,25			1,25	1,25			0,269	0,269			0,269	0,269			100%	115%	4051,25	4,249
2,6	2	2	1,3	1,3			1,3	1,3			0,273	0,273			0,273	0,273			92%	107%	3679	4,249
2,7	2	2	1,35	1,35			1,35	1,35			0,277	0,277			0,277	0,277			85%	100%	3306,75	4,249
2,8	2	2	1,4	1,4			1,4	1,4			0,281	0,281			0,281	0,281			79%	94%	2934,5	3,837
2,9	2	2	1,45	1,45			1,45	1,45			0,284	0,284			0,284	0,284			72%	87%	2634,5	3,196
3	2	2	1,5	1,5			1,5	1,5			0,287	0,287			0,287	0,287			67%	82%	2374,5	2,626
3,1	2	2	1,55	1,55			1,55	1,55			0,29	0,29			0,29	0,29			61%	76%	2174,5	2,055
3,2	2	2	1,6	1,6			1,6	1,6			0,293	0,293			0,293	0,293			56%	71%	2014,5	1,712
3,3	2	2	1,65	1,65			1,65	1,65			0,296	0,296			0,296	0,296			52%	67%	1874,5	1,541
3,4	2	2	1,7	1,7			1,7	1,7			0,298	0,298			0,298	0,298			47%	62%	1744,5	1,398
3,5	2	2	1,75	1,75			1,75	1,75			0,3	0,3			0,3	0,3			43%	58%	1629,5	1,233
3,6	2	2	1,8	1,8			1,8	1,8			0,302	0,302			0,302	0,302			39%	54%	1528,5	1,09
3,7	2	2	1,85	1,85			1,85	1,85			0,304	0,304			0,304	0,304			35%	50%	1438,5	0,987

3,8	2	2	1,9	1,9			1,9	1,9			0,306	0,306			0,306	0,306			32%	47%	1355,5	0,873
3,9	2	2	1,95	1,95			1,95	1,95			0,308	0,308			0,308	0,308			28%	43%	1285,5	0,771
4	2	2	2	2			2	2			0,31	0,31			0,31	0,31			25%	40%	1220,5	0,696
4,1	2	2	2,05	2,05			2,05	2,05			0,311	0,311			0,311	0,311			22%	37%	1163,5	0,611
4,2	2	2	2,1	2,1			2,1	2,1			0,312	0,312			0,312	0,312			19%	34%	1113,5	0,531
4,3	2	2	2,15	2,15			2,15	2,15			0,314	0,314			0,314	0,314			16%	31%	1070,5	0,474
4,4	3	2	1,467	1,467	1,466		2,2	2,2			0,285	0,285	0,285		0,315	0,315			70%	29%	1030,5	0,485
4,5	3	2	1,5	1,5	1,5		2,25	2,25			0,287	0,287	0,287		0,316	0,316			67%	26%	985,5	0,508
4,6	3	2	1,533	1,533	1,534		2,3	2,3			0,289	0,289	0,289		0,317	0,317			63%	24%	941,5	0,491
4,7	3	2	1,567	1,567	1,566		2,35	2,35			0,291	0,291	0,291		0,318	0,318			60%	21%	899,5	0,474
4,8	3	2	1,6	1,6	1,6		2,4	2,4			0,293	0,293	0,293		0,319	0,319			56%	19%	858,5	0,462
4,9	3	2	1,633	1,633	1,634		2,45	2,45			0,295	0,295	0,295		0,32	0,32			53%	17%	818,5	0,457
5	3	2	1,667	1,667	1,666		2,5	2,5			0,296	0,296	0,296		0,321	0,321			50%	15%	778,5	0,457
5,1	3	3	1,7	1,7	1,7		1,7	1,7	1,7		0,298	0,298	0,298		0,298	0,298	0,298		47%	62%	738,5	0,457
5,2	3	3	1,733	1,733	1,734		1,733	1,733	1,734		0,299	0,299	0,3		0,299	0,299	0,3		44%	59%	698,5	0,457
5,3	3	3	1,767	1,767	1,766		1,767	1,767	1,766		0,301	0,301	0,301		0,301	0,301	0,301		42%	57%	658,5	0,457
5,4	3	3	1,8	1,8	1,8		1,8	1,8	1,8		0,302	0,302	0,302		0,302	0,302	0,302		39%	54%	618,5	0,428
5,5	3	3	1,833	1,833	1,834		1,833	1,833	1,834		0,304	0,304	0,304		0,304	0,304	0,304		36%	51%	583,5	0,4
5,6	3	3	1,867	1,867	1,866		1,867	1,867	1,866		0,305	0,305	0,305		0,305	0,305	0,305		34%	49%	548,5	0,4
5,7	3	3	1,9	1,9	1,9		1,9	1,9	1,9		0,306	0,306	0,306		0,306	0,306	0,306		32%	47%	513,5	0,388
5,8	3	3	1,933	1,933	1,934		1,933	1,933	1,934		0,307	0,307	0,307		0,307	0,307	0,307		29%	44%	480,5	0,371
5,9	3	3	1,967	1,967	1,966		1,967	1,967	1,966		0,308	0,308	0,308		0,308	0,308	0,308		27%	42%	448,5	0,354
6	3	3	2	2	2		2	2	2		0,31	0,31	0,31		0,31	0,31	0,31		25%	40%	418,5	0,331
6,1	3	3	2,033	2,033	2,034		2,033	2,033	2,034		0,311	0,311	0,311		0,311	0,311	0,311		23%	38%	390,5	0,308
6,2	3	3	2,067	2,067	2,066		2,067	2,067	2,066		0,312	0,312	0,312		0,312	0,312	0,312		21%	36%	364,5	0,285
6,3	3	3	2,1	2,1	2,1		2,1	2,1	2,1		0,312	0,312	0,312		0,312	0,312	0,312		19%	34%	340,5	0,274
6,4	3	3	2,133	2,133	2,134		2,133	2,133	2,134		0,313	0,313	0,313		0,313	0,313	0,313		17%	32%	316,5	0,251
6,5	3	3	2,167	2,167	2,167		2,167	2,167	2,166		0,314	0,314	0,314		0,314	0,314	0,314		15%	30%	296,5	0,211
6,6	4	3	1,65	1,65	1,65	1,65	2,2	2,2	2,2		0,296	0,296	0,296	0,296	0,315	0,315	0,315		52%	29%	279,5	0,177
6,7	4	3	1,675	1,675	1,675	1,675	2,233	2,233	2,234		0,297	0,297	0,297	0,297	0,316	0,316	0,316		49%	27%	265,5	0,126
6,8	4	3	1,7	1,7	1,7	1,7	2,267	2,267	2,266		0,298	0,298	0,298	0,298	0,317	0,317	0,317		47%	25%	257,5	0,068
6,9	4	3	1,725	1,725	1,725	1,725	2,3	2,3	2,3		0,299	0,299	0,299	0,299	0,317	0,317	0,317		45%	24%	253,5	0,04
7	4	3	1,75	1,75	1,75	1,75	2,333	2,333	2,334		0,3	0,3	0,3	0,3	0,318	0,318	0,318		43%	22%	250,5	0,034
7,1	4	3	1,775	1,775	1,775	1,775	2,367	2,367	2,366		0,301	0,301	0,301	0,301	0,319	0,319	0,319		41%	21%	247,5	0,04

Table 4.2 - Island parameters with respect to reference load

7,2	4	3	1,8	1,8	1,8	1,8		2,4	2,4	2,4		0,302	0,302	0,302	0,302		0,319	0,319	0,319		39%	19%	243,5	0,046
7,3	4	3	1,825	1,825	1,825	1,825		2,433	2,433	2,434		0,303	0,303	0,303	0,303		0,32	0,32	0,32		37%	18%	239,5	0,051
7,4	4	3	1,85	1,85	1,85	1,85		2,467	2,467	2,467		0,304	0,304	0,304	0,304		0,32	0,32	0,32		35%	16%	234,5	0,057
7,5	4	3	1,875	1,875	1,875	1,875		2,5	2,5	2,5		0,305	0,305	0,305	0,305		0,321	0,321	0,321		33%	15%	229,5	0,063
7,6	4	4	1,9	1,9	1,9	1,9		1,9	1,9	1,9	1,9	0,306	0,306	0,306	0,306		0,306	0,306	0,306	0,306	32%	47%	223,5	0,068
7,7	4	4	1,925	1,925	1,925	1,925		1,925	1,925	1,925	1,925	0,307	0,307	0,307	0,307		0,307	0,307	0,307	0,307	30%	45%	217,5	0,074
7,8	4	4	1,95	1,95	1,95	1,95		1,95	1,95	1,95	1,95	0,308	0,308	0,308	0,308		0,308	0,308	0,308	0,308	28%	43%	210,5	0,086
7,9	4	4	1,975	1,975	1,975	1,975		1,975	1,975	1,975	1,975	0,309	0,309	0,309	0,309		0,309	0,309	0,309	0,309	27%	42%	202,5	0,097
8	4	4	2	2	2	2		2	2	2	2	0,31	0,31	0,31	0,31		0,31	0,31	0,31	0,31	25%	40%	193,5	0,103
8,1	4	4	2,025	2,025	2,025	2,025		2,025	2,025	2,025	2,025	0,31	0,31	0,31	0,31		0,31	0,31	0,31	0,31	23%	38%	184,5	0,103
8,2	4	4	2,05	2,05	2,05	2,05		2,05	2,05	2,05	2,05	0,311	0,311	0,311	0,311		0,311	0,311	0,311	0,311	22%	37%	175,5	0,108
8,3	4	4	2,075	2,075	2,075	2,075		2,075	2,075	2,075	2,075	0,312	0,312	0,312	0,312		0,312	0,312	0,312	0,312	20%	35%	165,5	0,114
8,4	4	4	2,1	2,1	2,1	2,1		2,1	2,1	2,1	2,1	0,312	0,312	0,312	0,312		0,312	0,312	0,312	0,312	19%	34%	155,5	0,12
8,5	4	4	2,125	2,125	2,125	2,125		2,125	2,125	2,125	2,125	0,313	0,313	0,313	0,313		0,313	0,313	0,313	0,313	18%	33%	144,5	0,131
8,6	4	4	2,15	2,15	2,15	2,15		2,15	2,15	2,15	2,15	0,314	0,314	0,314	0,314		0,314	0,314	0,314	0,314	16%	31%	132,5	0,137
8,7	5	4	1,74	1,74	1,74	1,74	1,74	2,175	2,175	2,175	2,175	0,3	0,3	0,3	0,3	0,3	0,314	0,314	0,314	0,314	44%	30%	120,5	0,143
8,8	5	4	1,76	1,76	1,76	1,76	1,76	2,2	2,2	2,2	2,2	0,301	0,301	0,301	0,301	0,301	0,315	0,315	0,315	0,315	42%	29%	107,5	0,148
8,9	5	4	1,78	1,78	1,78	1,78	1,78	2,225	2,225	2,225	2,225	0,302	0,302	0,302	0,302	0,302	0,316	0,316	0,316	0,316	40%	27%	94,5	0,154
9	5	4	1,8	1,8	1,8	1,8	1,8	2,25	2,25	2,25	2,25	0,302	0,302	0,302	0,302	0,302	0,316	0,316	0,316	0,316	39%	26%	80,5	0,148
9,1	5	4	1,82	1,82	1,82	1,82	1,82	2,275	2,275	2,275	2,275	0,303	0,303	0,303	0,303	0,303	0,317	0,317	0,317	0,317	37%	25%	68,5	0,126
9,2	5	4	1,84	1,84	1,84	1,84	1,84	2,3	2,3	2,3	2,3	0,304	0,304	0,304	0,304	0,304	0,317	0,317	0,317	0,317	36%	24%	58,5	0,103
9,3	5	4	1,86	1,86	1,86	1,86	1,86	2,325	2,325	2,325	2,325	0,305	0,305	0,305	0,305	0,305	0,318	0,318	0,318	0,318	34%	23%	50,5	0,091
9,4	5	4	1,88	1,88	1,88	1,88	1,88	2,35	2,35	2,35	2,35	0,305	0,305	0,305	0,305	0,305	0,318	0,318	0,318	0,318	33%	21%	42,5	0,086
9,5	5	4	1,9	1,9	1,9	1,9	1,9	2,375	2,375	2,375	2,375	0,306	0,306	0,306	0,306	0,306	0,319	0,319	0,319	0,319	32%	20%	35,5	0,08
9,6	5	4	1,92	1,92	1,92	1,92	1,92	2,4	2,4	2,4	2,4	0,307	0,307	0,307	0,307	0,307	0,319	0,319	0,319	0,319	30%	19%	28,5	0,08
9,7	5	4	1,94	1,94	1,94	1,94	1,94	2,425	2,425	2,425	2,425	0,308	0,308	0,308	0,308	0,308	0,32	0,32	0,32	0,32	29%	18%	21,5	0,051
9,8	5	4	1,96	1,96	1,96	1,96	1,96	2,45	2,45	2,45	2,45	0,308	0,308	0,308	0,308	0,308	0,32	0,32	0,32	0,32	28%	17%	19,5	0,017
9,9	5	4	1,98	1,98	1,98	1,98	1,98	2,475	2,475	2,475	2,475	0,309	0,309	0,309	0,309	0,309	0,321	0,321	0,321	0,321	26%	16%	18,5	0,011
10	5	4	2	2	2	2	2	2,5	2,5	2,5	2,5	0,31	0,31	0,31	0,31	0,31	0,321	0,321	0,321	0,321	25%	15%	17,5	0,006

The “no PEV” and “PEV” tag help to distinguish to which scenario the column is referring to. Now each column is better explained and commented:

1. Reference load: this is the load of the system that is taken for reference for each row of the scenario. As it has been said previously, it goes from the minimum load of 1 MW to the maximum load of 10 MW with a step of 0.1 MW.
2. Number of generators (no PEV): as it has been said in the assumptions, in the “no PEV” scenario the generators are run taking in consideration an added 15% of the load as secondary reserve, to have more inertia and more reserve available. So the equivalent load that is used for deciding how many generators must be active is the load written in column 1 +15%. Also, it never happens that the load of the island is met by one single generator.
3. Number of generators (PEV): thanks to the calculation above, it is shown that it is possible to set aside the 15% increase and to run the generators according to the actual load. The load that they must meet is always the one in column 1, but this time no constrain is added. As for the previous column, it is not possible to meet the island’s load with just one generator. It is possible to notice that there are different steps at which the number of generators increases.
4. Generated power (no PEV): each row has as many sub columns as how many generators are running according to column 2. The power is then almost equally divided among the generators.
5. Generated power (PEV): the same reasonings of column 6 are applied in this section, keeping as reference column 3 instead of column 2.
6. Efficiency (no PEV): each previous generator power share in column 4 is linked with a running efficiency. The efficiency curve is the one shown in Fig. 4.8 below.
7. Efficiency (PEV): the same reasonings of column 8 are applied in this section, keeping as reference column 5 instead of column 4.
8. Secondary reserve with respect to load (no PEV): it shows the amount of secondary reserve that it is available in the “no PEV” scenario. It is calculated with respect to the load, because secondary reserve is always linked with disturbs and those are always correlated with the load. The available remaining generation power is calculated, and then it is divided by the reference load. In normal interconnected systems, there is small to no difference between calculating secondary reserve with respect to nominal power of the generators or to the load; in isolated systems instead, there are strong differences.

9. Secondary reserve with respect to load (PEV): the same reasonings of column 8 are applied in this section, with one difference: a 15% of the load is added, to take into consideration the availability coming from PEVs' aggregation.
10. Hours of load: it shows for how many hours in a year the load is at least the one written in the correspondent row. The load curve is represented in Fig. 4.9 below. Since the hypothesis for the "PEV" scenario says that the power of the system is just scaled when the charging power of the minimum required PEVs is added, it's possible to say that the load curve stays the same for the two scenarios. The load curve is a little bit different from the typical ones, that are peculiar of large interconnected systems. It has been said that the excursion of the load is stronger than normal for this case study, given the nature of the system, therefore the load curve has a different weighting of the values.
11. Probability for load: this column shows how likely it is to be in the load share written in column 2 or 3 when analyzing the overall power distribution. The starting and the ending point where weighted half then all the others, because every discrete step is approximating half the difference that it has with the previous one and half the difference that it has with the following one.

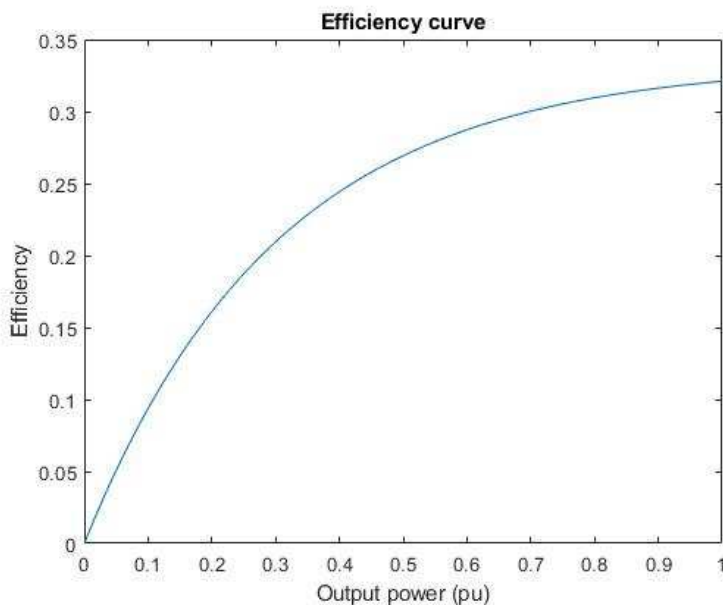


Figure 4.8 - Efficiency curve of a diesel generator

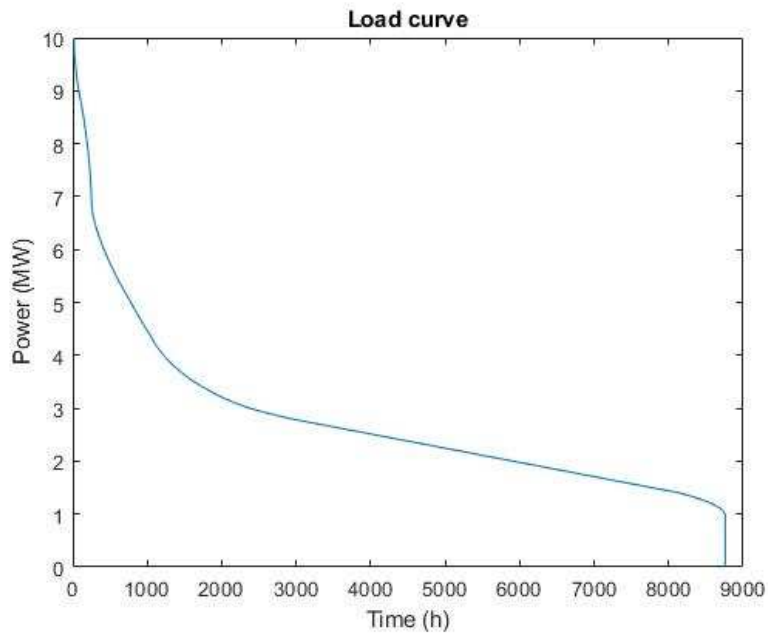


Figure 4.9 - Load curve of the island

These are the starting information the hypothesis needed for running the evaluation. Just to give an example of what happens in the two scenarios, in Fig. 4.10 down below will be represented what happens with the frequency of the system when the reference load is 4.5 MW and a disturb of 0.15 pu occurs.

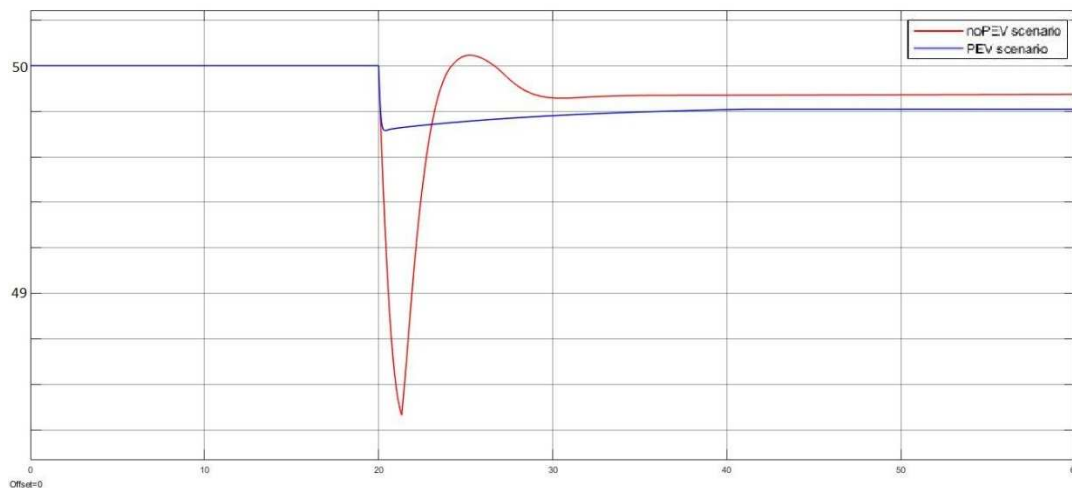


Figure 4.10 - Frequency oscillation in "no PEV" and "PEV" scenarios

5 Economic evaluation

5.1 Introduction

The difference between the “no PEV” scenario and the “PEV” scenario is the participation of the electric vehicles to the duty of Primary Frequency Control. The electric vehicles are already existing and charging in both scenarios, but in the second one they also participate in the services for enhancing the stability of the grid. This is what is being evaluated with this work, and it’s going to be analyzed through an estimation of the benefits that the participation of PEVs can bring and the costs of allowing such participation. Given the fact that the load is the same for both scenarios, it is clear that the connection to the grid of a certain number of PEVs is an already established thing. Charging stations and purchases of electric vehicles aren’t considered as a cost because of that, but to allow the provision of PFC services some components must be substituted, upgraded or added to the charging stations.

In this chapter, an analysis of benefits and costs is carried out. They are listed and singularly analyzed, making clear the assumption for each one of them.

Final numbers are calculated, which will be discussed in the next chapter.

5.2 Explanation and assumptions about benefits

Comparing the two scenarios shown in Table 4.2, it’s obviously possible to see that parameters change in every row. Each one of those changes can be translated in an economic value, that alters the economy of the system. In this sub chapter, benefits coming from PEVs’ intake in the system are listed and evaluated. For this last task, it is also necessary to make some assumption regarding various aspects of lifetime of components, costs and other things. Everyone was done according to the typical values obtained by experience and researches.

The benefits for this evaluation are:

- Lower degradation of the generators
- Lower start-up costs
- Energy savings due to higher efficiency
- Environmental considerations
- Lower amount of shed load

5.2.1 Lower degradation of the generators

As it was possible to see, in the “PEV” scenario generators can more easily follow the load of the island. All these things allow generators to generate power more efficiently, fact that is translated in a longer lifespan for each generator. In this case, the savings will be evaluated as a lower share of amortization each year for the diesel generators, since that they obviously have purchasing, shipping, installation and maintenance costs.

The assumptions are:

- The lifetime of a diesel unit is 40000 working hours;
- The purchase price of a 2.5 MW diesel unit is 250000 €, which must be multiplied by 3 to cover shipping and installation;
- A full maintenance intervention costs 5% of the purchase price, a partial maintenance intervention costs of 1% of the purchase price;
- The number of start-ups is 1 every 100 hours;
- Every 20 start-ups a partial maintenance intervention is needed, every 100 start-ups a full maintenance intervention is needed;
- The total number of generators $n^{\circ}gen$ is 7.
- Each generator has the same number of working hours, since they have the same size

The top line of Table 4.2 is reported here in Fig. 5.1, just for the sake of clarity. Afterwards the evaluation is developed.

Ref load 1	N° gen (no PEV) 2	N° gen (PEV) 3	Gen pow er (no PEV) 4	Gen pow er (PEV) 5	Efficien cy (no PEV) 6	Efficien cy (PEV) 7	Seconda ry reserve (no PEV) 8	Seconda ry reserve (PEV) 9	Hour s for load 10	Probabili ty for having the load 11
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Figure 5.1 - Columns of Table 4.2

The evaluation of this point starts multiplying all the values in column 2 or 3, according to the scenario, by the respective value in column 11 and by 8760h. Then all the products are summed up to get the yearly overall number of working hours $n^{\circ}wh_{noPEV}$ and $n^{\circ}wh_{PEV}$.

$$n^{\circ}wh_{noPEV} = (2 \cdot 0.342 + \dots + 5 \cdot 0.006) \cdot 8760 = 18896.2 \text{ h} \quad (5.1)$$

$$n^{\circ}wh_{PEV} = (2 \cdot 0.342 + \dots + 4 \cdot 0.006) \cdot 8760 = 18433.7 \text{ h} \quad (5.2)$$

The next step is to divide $n^{\circ}wh_{noPEV}$ and $n^{\circ}wh_{PEV}$ by the number of total generators, getting the average yearly hour-charges per genset yh_{noPEV} and yh_{PEV} :

$$yh_{noPEV} = \frac{n^{\circ}wh_{noPEV}}{n^{\circ}gen} = \frac{18896.2}{7} = 2699.5 \text{ h} \quad (5.3)$$

$$yh_{PEV} = \frac{n^{\circ}wh_{PEV}}{n^{\circ}gen} = \frac{18433.7}{7} = 2633.4 \text{ h} \quad (5.4)$$

The expected lifetime of a diesel generator is divided by these two values, getting the expected lifetime expressed in years ely_{noPEV} and ely_{PEV} :

$$ely_{noPEV} = \frac{\text{expect life}}{yh_{noPEV}} = \frac{40000}{2699.5} = 14.82 \text{ y} \quad (5.5)$$

$$ely_{PEV} = \frac{\text{expect life}}{yh_{PEV}} = \frac{40000}{2633.4} = 15.2 \text{ y} \quad (5.6)$$

The difference between the two is evaluated as a lower share of amortization, so it's necessary to spread the initial cost of diesel generators over the lifetime and add the maintenance costs, which are linked to the number of start-ups. The number of start-ups nS_{noPEV} and nS_{PEV} is calculated multiplying the average yearly hour-charges per genset $n^{\circ}wh_{noPEV}$ and $n^{\circ}wh_{PEV}$ by the rate of start-ups:

$$nS_{noPEV} = n^{\circ}wh_{noPEV} \cdot \text{startup rate} = 18896.2 \cdot \frac{1}{100} \cong 189 \quad (5.7)$$

$$nS_{PEV} = n^{\circ}wh_{PEV} \cdot \text{startup rate} = 18433.7 \cdot \frac{1}{100} \cong 184 \quad (5.8)$$

Knowing from the assumptions when and how maintenance is done, it's possible to calculate the annual expense for maintenance me_{noPEV} and me_{PEV} :

$$\begin{aligned} me_{noPEV} &= \left[\frac{nS_{noPEV}}{100} \cdot 0.05 + \left(\frac{nS_{noPEV}}{20} - \frac{nS_{noPEV}}{100} \right) \cdot 0.01 \right] \cdot 250000 \quad (5.9) \\ &= 45000 \text{ €} \end{aligned}$$

$$me_{PEV} = \left[\frac{n_{S_{PEV}}}{100} \cdot 0.05 + \left(\frac{n_{S_{PEV}}}{20} - \frac{n_{S_{PEV}}}{100} \right) \cdot 0.01 \right] \cdot 250000 = 45000 \text{ €} \quad (5.10)$$

They are the same because there is a similar number of start-ups and rounding is necessary, given the fact that the number of maintenance intervention must be integer. Adding it to the yearly amortization of the fixed costs and comparing the two scenarios, the benefit for lower degradation B_{ld} is:

$$B_{ld} = \left(me_{noPEV} + \frac{gen \text{ cost}}{ely_{noPEV}} - me_{PEV} + \frac{gen \text{ cost}}{ely_{PEV}} \right) \cdot n^{\circ}gen = 8672.4 \text{ €} \quad (5.11)$$

5.2.2 Lower start-up costs

Since in some particular power-share a lower number of generators is needed, it is obvious to notice that there is less necessity to start up a generator for matching the load. This is a potential saving that must be considered.

The assumptions are:

- The number of start-ups is 1 every 100 hours;
- The start-up cost is 500 €.

In the previous point it was already calculated the number of start-ups in a year $n_{S_{noPEV}}$ and $n_{S_{PEV}}$. The cost of all start-ups in a year is calculable as the product of $n_{S_{noPEV}}$ and $n_{S_{PEV}}$ with the assumed start-up cost, getting the yearly start-up costs $y_{SC_{noPEV}}$ and $y_{SC_{PEV}}$:

$$y_{SC_{noPEV}} = n_{S_{noPEV}} \cdot 2000 = 94500 \text{ €} \quad (5.12)$$

$$y_{SC_{PEV}} = n_{S_{PEV}} \cdot 2000 = 92000 \text{ €} \quad (5.13)$$

The comparison of the two costs gives the benefit from lower start-up costs B_{lsc} :

$$B_{lsc} = y_{SC_{noPEV}} - y_{SC_{PEV}} = 2500 \text{ €} \quad (5.14)$$

5.2.3 Fuel savings due to higher efficiency

As it has been seen, in “PEV” scenario efficiencies of the generators are higher than the ones of the same row in “noPEV” scenario. This means that there is less input fuel needed to have the same output, and this is the benefit that will be evaluated in this section.

The assumptions are:

- Diesel Lower Heating Value (LHV) is 0.0119 MWh/lit;
- The purchase cost of the fuel is 4.5 €/lit.

Once again, the top line of Table 4.2 is reported here in Fig. 5.2, just for the sake of clarity. Afterwards the evaluation is developed.

Ref load 1	N° gen (no PEV) 2	N° gen (PE V) 3	Gen pow er (no PEV) 4	Gen pow er (PEV) 5	Efficien cy (no PEV) 6	Efficien cy (PEV) 7	Seconda ry reserve (no PEV) 8	Seconda ry reserve (PEV) 9	Hour s for load 10	Probabili ty for having the load 11
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Figure 5.2 - Columns of Table 4.2

In “no PEV” scenario, for each row of Table 4.2 each value in column 4 is divided by its matching value in column 6, getting the total input power for the load share of the row. Those values are added up and multiply by the respective value in column 11 and by 8760, getting the input energy ie_{noPEV} for having the power outputs in column 4:

$$ie_{noPEV} = \left(\frac{0.5}{0.161} + \frac{0.5}{0.161} \right) \cdot 29.96 + \dots + \left(\frac{2}{0.31} + \dots + \frac{2}{0.31} \right) \cdot 0.53 \quad (5.15)$$

$$= 89968.3 \text{ MWh}$$

In “PEV” scenario something similar happens, but with column 5 instead of column 4 and column 7 instead of column 6. The result is the input energy ie_{PEV} :

$$ie_{PEV} = \left(\frac{0.5}{0.161} + \frac{0.5}{0.161} \right) \cdot 29.96 + \dots + \left(\frac{2.5}{0.321} + \dots + \frac{2.5}{0.321} \right) \cdot 0.53 \quad (5.16)$$

$$= 89344.5 \text{ MWh}$$

The next step is to divide ie_{noPEV} and ie_{PEV} by the diesel LHV value, getting how many liters of fuel are used, $n^{\circ}lt_{noPEV}$ and $n^{\circ}lt_{PEV}$:

$$n^{\circ}lt_{noPEV} = \frac{ie_{noPEV}}{0.0119} = 7560368.8 \text{ lt} \quad (5.17)$$

$$n^{\circ}lt_{PEV} = \frac{ie_{PEV}}{0.0119} = 7507944 \text{ lt} \quad (5.18)$$

Multiplying by diesel's purchase cost it is possible to calculate the total fuel costs fc_{noPEV} and fc_{PEV} , with the related benefit B_{es} that comes from the difference between the two:

$$fc_{noPEV} = n^{\circ}lt_{noPEV} \cdot 4.5 = 34021660 \text{ €} \quad (5.19)$$

$$fc_{PEV} = n^{\circ}lt_{PEV} \cdot 4.5 = 33785748 \text{ €} \quad (5.20)$$

$$B_{es} = fc_{noPEV} - fc_{PEV} = 235911.30 \text{ €} \quad (5.21)$$

5.2.4 Environmental considerations

Given the fact that a lot of parameters between the two scenarios change, it is important to check what happens with polluting emissions. Since that it is too difficult to calculate both direct and indirect costs of the entire pollution and that there are many different polluting agents, there is going to be a partial evaluation for this point. Just CO2 emissions will be taken in consideration, evaluating them according to the actual European Union Emission Trading Scheme (EU ETS). In reality, no island's system operator participates in the EU ETS, so this evaluation is just a translation of environmental indirect costs.

The assumptions are:

- 1 lt of diesel fuel emits 2650 g of CO2;
- 1 tCO2 costs 10 €.

From the previous point the quantities of used fuel $n^{\circ}lt_{noPEV}$ and $n^{\circ}lt_{PEV}$ are known. Multiplying $n^{\circ}lt_{noPEV}$ and $n^{\circ}lt_{PEV}$ by the emission per liter and by the cost of CO2 it's possible to have the emission total costs etc_{noPEV} and etc_{PEV} , while the difference between the two is the benefit B_{ec} :

$$etc_{noPEV} = n^{\circ}lt_{noPEV} \cdot 2.65 \cdot 10^{-3} = 200349.8 \text{ €} \quad (5.22)$$

$$etc_{PEV} = n^{\circ}lt_{PEV} \cdot 2.65 \cdot 10^{-3} = 198960.50 \text{ €} \quad (5.23)$$

$$B_{ec} = etc_{noPEV} - etc_{PEV} = 1389.30 \text{ €} \quad (5.24)$$

5.2.5 Lower amount of shed load

In small isolated systems, one of the worst threats is load shedding. Since that the size of the system is small and the inertia is quite low, each disturb that occurs to the system is a danger for loads, because frequency deviations can be so high that a load curtailment can be needed. Load shedding is one of the most drastic way to restore nominal frequency, and it comes at a high cost. With PEVs although, things can be different. Time constants of batteries, in fact, are much lower than diesel-generator time constants, and this helps to have smaller frequency deviations when a disturb occurs.

To evaluate this point, firstly different disturb size are identified, and it is hypothesized a probability for each one of them. They are under-frequency disturbs, so they are equivalent to an injection of load or a loss in generators. The maximum disturb that it's possible to have is considered to be 0.5 pu, also because generators are always giving half of the required power at maximum. The base power of each case is the reference load of the load share.

The assumptions are:

- There is no peculiar moment in which a load shedding event can occur;
- The possibility of having two broken generators at the same time is not considered;
- The probability of CGU failure is 3% of time in a year;
- The VoLL is 10000 €/MWh;
- Each generator has the same number of working hours, since they have the same size;
- The disturbs go from 0.05 pu to 0.5 pu with a step of 0.05 pu;
- The probabilities for having each particular disturb are summed up in Table 5.1:

0.05 pu	0.1 pu	0.15 pu	0.2 pu	0.25 pu	0.3 pu	0.35 pu	0.4 pu	0.45 pu	0.5 pu
30%	23%	15%	10%	8%	5%	4%	3%	1%	1%

Table 5.1 - Probability of disturbance

- Thresholds and parameters used for load shedding evaluation are similar to the ones used in [29], and they are summed up in Table 5.2:

Triggering frequency [Hz]	Time delay [s]	Shed load [pu]
48.81	0.6	0.071
48.81	0.9	0.006
48.66	1.3	0.145
48.66	1.8	0.036
48.66	2.3	0.073
48	2.3	0.2

Table 5.2 - Parameters of load shedding

For each load share and for each disturb size a simulation of the system is run, using the model cited in chapter 3 and the data in Table 4.2. The simulation has the purpose to calculate how much load is shed according to the occurred disturb and caused by frequency deviation. Then it is weighted according to the disturb probability $probdist_{noPEV}$, the right time span of generator failures t_{fail} and the number of active generators n (because the disturb can occur to each one of the generators), obtaining, for each simulation, the energies not served $enssim(i)_{noPEV}$ and $enssim(i)_{PEV}$. In (5.25) it is reported an example where 0.071 pu of load gets shed with a disturb of 0.1 pu when three generators are running. There is no distinction among scenarios because it is an example that can happen for both:

$$\begin{aligned}
 enssim &= slsim \cdot probdist \cdot t_{fail} \cdot n = 0.071 \cdot 0.23 \cdot 0.03 \cdot 8760 \cdot 3 \quad (5.25) \\
 &= 12.88 \text{ MWh}
 \end{aligned}$$

The sum, for each share, of each $enssim_{noPEV}$ for “no PEV” scenario and $enssim_{PEV}$ for “PEV” scenario is multiplied by the probability of load share $probload$ written in column 11 of Table 4.2 and by the VoLL, obtaining the cost for load shedding over a year sl_{noPEV} and sl_{PEV} . Since that load shares go from 1 MW to 10 MW with a step of 0.1 MW, the $enssim$ parameters are 91 for each scenario. The benefit B_{ec} is the difference between the two:

$$sl_{noPEV} = \left(\sum_{i=1}^{91} enssim(i)_{noPEV} \cdot probload(i) \right) \cdot VoLL = 389600 \text{ €} \quad (5.26)$$

$$sl_{PEV} = \left(\sum_{i=1}^{91} enssim(i)_{PEV} \cdot probload(i) \right) \cdot VoLL = 94383.82 \text{ €} \quad (5.27)$$

$$B_{last} = sl_{noPEV} - sl_{PEV} = 295216.18 \text{ €} \quad (5.28)$$

In order to have a clearer look at what happens in the two scenarios for the evaluation of the shed load, Table 5.3 shown down below information, for both scenarios and for each load share, about the minimum disturb that will cause load shedding and how likely it is to have a disturb in the system that is equal or higher than that. From this table, the improving of the system is once again really clear.

Ref load	Minimum disturb to have shed load (no PEV, [MW])	Probability of having the disturb (no PEV, %)	Minimum disturb to have shed load (PEV, [MW])	Probability of having the disturb (no PEV, %)
1	0,25	0,22	0,45	0,02
1,1	0,275	0,22	0,44	0,05
1,2	0,3	0,22	0,48	0,05
1,3	0,325	0,22	0,52	0,05
1,4	0,28	0,32	0,49	0,09
1,5	0,3	0,32	0,525	0,09
1,6	0,32	0,32	0,56	0,09
1,7	0,34	0,32	0,595	0,09
1,8	0,36	0,32	0,63	0,09
1,9	0,38	0,32	0,665	0,09
2	0,4	0,32	0,7	0,09
2,1	0,315	0,47	0,735	0,09
2,2	0,33	0,47	0,66	0,14
2,3	0,345	0,47	0,69	0,14
2,4	0,36	0,47	0,72	0,14
2,5	0,375	0,47	0,75	0,14
2,6	0,39	0,47	0,78	0,14
2,7	0,405	0,47	0,81	0,14
2,8	0,42	0,47	0,84	0,14
2,9	0,435	0,47	0,87	0,14
3	0,45	0,47	0,9	0,14
3,1	0,465	0,47	0,93	0,14
3,2	0,48	0,47	0,96	0,14
3,3	0,495	0,47	0,99	0,14
3,4	0,51	0,47	1,02	0,14
3,5	0,525	0,47	1,05	0,14
3,6	0,54	0,47	1,08	0,14
3,7	0,555	0,47	1,11	0,14
3,8	0,57	0,47	1,14	0,14
3,9	0,585	0,47	1,17	0,14
4	0,4	0,7	1,2	0,14
4,1	0,41	0,7	1,23	0,14
4,2	0,42	0,7	1,26	0,14

4,3	0,43	0,7	1,29	0,14
4,4	0,66	0,47	1,32	0,14
4,5	0,675	0,47	1,35	0,14
4,6	0,69	0,47	1,38	0,14
4,7	0,705	0,47	1,175	0,22
4,8	0,72	0,47	1,2	0,22
4,9	0,735	0,47	1,225	0,22
5	0,75	0,47	1	0,32
5,1	0,765	0,47	1,53	0,14
5,2	0,78	0,47	1,56	0,14
5,3	0,795	0,47	1,59	0,14
5,4	0,81	0,47	1,62	0,14
5,5	0,825	0,47	1,65	0,14
5,6	0,84	0,47	1,68	0,14
5,7	0,855	0,47	1,71	0,14
5,8	0,87	0,47	1,74	0,14
5,9	0,885	0,47	1,77	0,14
6	0,6	0,7	1,8	0,14
6,1	0,61	0,7	1,83	0,14
6,2	0,62	0,7	1,86	0,14
6,3	0,63	0,7	1,89	0,14
6,4	0,64	0,7	1,92	0,14
6,5	0,65	0,7	1,95	0,14
6,6	0,99	0,47	1,98	0,14
6,7	1,005	0,47	2,01	0,14
6,8	1,02	0,47	2,04	0,14
6,9	1,035	0,47	2,07	0,14
7	1,05	0,47	1,75	0,22
7,1	1,065	0,47	1,775	0,22
7,2	1,08	0,47	1,8	0,22
7,3	1,095	0,47	1,825	0,22
7,4	1,11	0,47	1,48	0,32
7,5	1,125	0,47	1,5	0,32
7,6	1,14	0,47	2,28	0,14
7,7	1,155	0,47	2,31	0,14
7,8	1,17	0,47	2,34	0,14
7,9	1,185	0,47	2,37	0,14
8	0,8	0,7	2,4	0,14
8,1	0,81	0,7	2,43	0,14

8,2	0,82	0,7	2,46	0,14
8,3	0,83	0,7	2,49	0,14
8,4	0,84	0,7	2,52	0,14
8,5	0,85	0,7	2,55	0,14
8,6	0,86	0,7	2,58	0,14
8,7	1,305	0,47	2,61	0,14
8,8	1,32	0,47	2,64	0,14
8,9	1,335	0,47	2,67	0,14
9	1,35	0,47	2,7	0,14
9,1	1,365	0,47	2,73	0,14
9,2	1,38	0,47	2,76	0,14
9,3	1,395	0,47	2,79	0,14
9,4	1,41	0,47	2,35	0,22
9,5	1,425	0,47	2,375	0,22
9,6	1,44	0,47	2,4	0,22
9,7	1,455	0,47	2,425	0,22
9,8	1,47	0,47	2,45	0,22
9,9	1,485	0,47	1,98	0,32
10	1	0,7	2	0,32

Table 5.3 - Data about load shedding with respect to reference load

5.2.6 Total benefit

The overall benefit is the sum of all the points calculated above:

$$\begin{aligned}
 B_{tot} &= B_{td} + B_{sc} + B_{es} + B_{ec} + B_{last} \\
 &= 8672.40 + 2500 + 235911.30 + 1389.30 \\
 &\quad + 295216.18 = 543689.18 \text{ €}
 \end{aligned}
 \tag{5.29}$$

5.3 Explanation and assumptions about costs

The second part of the evaluation involves the calculation of the costs that the system is experiencing for the PEVs' capability of furnishing PFC services. As it has already been said, chargers and PEVs are considered to be already inserted in the scenarios. What is needed to keep in mind although is the improvements that are necessary for letting PEVs available to

provide PFC. One of the assumptions is that all chargers are bidirectional, but there is no certainty that the chargers that are already on the island have already that characteristic. Also, the ability to interact and communicate between chargers and between vehicle and charger have to be implemented. All of the chargers are operating in mode 3, which require type 2 sockets that are the EU standard. Also for this part of the evaluation, costs will be listed and analyzed, making some assumptions for each one of them.

The costs for this evaluation are:

- Chargers improvement (shipping, installation and maintenance)
- Aggregation (shipping, installation and maintenance)

5.3.1 Chargers improvement

It is not obvious to have the capability of allowing bidirectional power flow, because the main purpose of battery chargers is of course to just charge the batteries that are attached to them. In the worst-case scenario, all chargers previously installed on the island are unidirectional, which means that all of them should be updated to bidirectional battery chargers in order to allow bidirectional power flows. This is the case that is considered. To evaluate it, it is assumed that the electronic that is already built in the chargers is substituted with power converters of a suitable power size.

The assumptions are:

- The costs for power converters are 350 € for 3 kW, 600 € for 7 kW and 1000 € for 20 kW;
- Costs triples for shipping and installation;
- Maintenance costs are 6% each year for a 25-years lifetime

The number of battery chargers has of course a relationship with the number of PEVs circulating in the island. The maximum value is considered, to be sure that there will be enough charging points even in the worst situations. It is chosen a value of one charger every two vehicles, so that for 625 PEVs (as it was calculated before for evaluating the secondary reserve assumption) the number of charging points is 315, including all home and road chargers. This reflects a ratio of one charger each two PEVs, considered a common value as it can be seen from Table 5.4. Some states have been taken as examples.

Country (data of 2015)	Chargers/100000 inhabitants	Total chargers	Total PEVs	PEV per charger
NL	145.5	24735	88991	3.6
DE	15.9	13038	48669	3.73
UK	20.4	13260	53524	4.04
FR	47.5	31825	74294	2.33
SE	44.4	4440	16996	3.83

Table 5.4 - Data about chargers and PEVs in some countries

It is hypothesized some degree of redundancy, because in a touristic island it's very likely for people to do activities in the same moment of the day (being with the car parked in hotels during the night and near the beach during the day). Therefore, the value of the ratio is a little bit lower. Also, this means that some chargers will not be utilized in certain moment of the day, while others will be heavily working. From the general assumptions it comes that there are 16 20-kW chargers, 123 7-kW chargers and 176 3-kW chargers. Multiplying each one for the cost of the relative power converters and amortizing everything for the supposed lifetime, it is possible to get the fixed costs $F_{C_{ci}}$:

$$F_{C_{ci}} = \frac{(16 \cdot 1000 + 123 \cdot 600 + 176 \cdot 350) \cdot 3}{25} = 18168 \text{ €} \quad (5.30)$$

The variable costs $V_{C_{ci}}$ are due to maintenance works, which are quite expensive due to climate. $V_{C_{ci}}$ are:

$$V_{C_{ci}} = (16 \cdot 1000 + 123 \cdot 600 + 176 \cdot 350) \cdot 0.06 = 9084 \text{ €} \quad (5.31)$$

The overall yearly cost for chargers' improvements C_{ci} is the sum of the two values:

$$C_{ci} = F_{C_{ci}} + V_{C_{ci}} = 27252 \text{ €} \quad (5.32)$$

5.3.2 Aggregation

“Aggregation”, in the field of electric vehicles, means the capability of reducing many different charging points to something smaller and easier to manage. Normally, electric vehicles are not able to communicate between them or with the grid, sharing information about SOCs and other things. The process of aggregation, among other more important things, adds this possibility. The principal aim of aggregation is to join and control together a big number

of small charging points as if they were just one big unit from the point of view of the generation. Later, it allows to singularly control the small charging points according to the fixed values required from the system. This has obviously a cost, which is calculated here.

The assumptions are:

- The cost for aggregation is 300 € for each charger;
- Costs triples for shipping and installation;
- Maintenance costs are 10% each year for a 15-years lifetime.

Given the fact that the total number of battery chargers is known, it is possible to find the fixed costs for implementing aggregation and the variable costs for the maintenance. Fixed costs Fc_a are:

$$Fc_a = \frac{315 \cdot 300 \cdot 3}{15} = 18900 \text{ €} \quad (5.33)$$

As for chargers' improvements, variable costs Vc_a are due to maintenance works, which are more expensive because of climate and of delicate parts. Vc_a are:

$$Vc_a = 315 \cdot 300 \cdot 0.1 = 9450 \text{ €} \quad (5.34)$$

The overall yearly cost for aggregation C_a is the sum of the two values:

$$C_a = Fc_a + Vc_a = 28350 \text{ €} \quad (5.35)$$

5.3.3 Total cost

The overall cost is the sum of all the points calculated above:

$$C_{tot} = C_{ci} + C_a = 27252 + 28350 = 55602 \text{ €} \quad (5.36)$$

6 Results and considerations

6.1 Introduction

The estimation of all the aspects of the economic evaluation has already been completely carried out. What are missing now are just the final results, that will show the nature of the investment according to the assumptions and to the methodologies that have been used. The small isolated system allows to think in a certain way and permits to have an economic evaluation that is far better than in interconnected systems. In fact, just being a small portion of land instead of a massive area, a lot of things are simplified. Also, costs are higher in everything, and this is something that helps the changes between the two scenarios that are taken into consideration.

At first, the resulting profit for the investment is shown. Then some economic parameter is calculated, to have a better and more objective look at the overall investment.

Finally, some considerations about the replicability and the scalability of the project are done.

6.2 Results

The previous chapter has shed light on the magnitude of benefits and costs of the evaluation. The profit comes, of course, from the difference of these two values. Comparing the values in equations (5.29) and (5.36), it can be found that P_{tot} is:

$$P_{tot} = B_{tot} - C_{tot} = 543689.18 - 55602 = 488087.18 \text{ €} \quad (6.1)$$

The resulting profit is high, but it means little if it is not compared with other important voices. Anyway, it is already possible to say that this is the basic profit for the system operator given the assumptions made before. The two scenarios that compose the evaluation can be considered equivalent even if the two scenarios are different in many voices, but it is important to underline one particular point: in the “PEV” scenario, primary and secondary frequency control services are partially covered by final customers and private companies, which means that they are offering a service that they weren’t giving in the “no PEV” scenario. This can be

resolved in two different ways. One way can be that it is considered a mandatory and not remunerated service that all PEV owners have to provide in order to maintain grid stability. In Spain and Portugal, for example, power plants are already having a mandatory, non-remunerated duty of providing PFC services, and load shedding in islands is something that today happens really often, being possible to consider it as a mandatory service by households. The savings for private customers could come from less shed load during the year, as it has already been demonstrated that the amount of shed load in “PEV” scenario would be much lower.

But another way can be to have the system operator that provides some kind of remuneration, that, for having an overall net positive income of implementing the service, must be lower than the profit P_{tot} previously calculated. This second possibility is better studied in subchapter 6.4.

6.3 Economic indexes

In every economic evaluation, some indexes are described to have a better look at the investment that has been proposed. Also for this work, some of them are written and analyzed, to see more objectively how much this investment is feasible. The economic indexes that are included in this section are:

- Pay-back time, or PB;
- Return On Investment, or ROI;
- Net Present Value, or NPV;

6.3.1 Pay-back time

The Pay-Back time, or PB, is an index that shows how much time is needed in order to cover the initial investment and reach the break-even point. It is not very accurate, because it doesn't take in consideration time and what happens after the moment that the investment is recovered, but it gives an overview of the situation and it is easy to calculate. It's calculated dividing the total initial investment I_0 for the annual financial cash flow D . The initial investment I_0 is given by the total cost previously calculated with a small difference: maintenance must not be calculated, so equations (5.30) and (5.33) will be used. The annual financial cash flow D is the difference between the total benefit calculated in (5.29) and the annual costs A , calculated thanks to equations (5.31) and (5.34):

$$I_0 = Fc_{ci} \cdot 25 + Fc_a \cdot 15 = 737700 \text{ €} \quad (6.2)$$

$$D = B_{tot} - A = B_{tot} - (Vc_{ci} + Vc_a) = 525155.18 \text{ €} \quad (6.3)$$

With these data, it is possible to calculate the Pay-Back time PB :

$$PB = \frac{I_0}{D} = 1.4 \text{ years} \quad (6.4)$$

6.3.2 Return On Investment

The Return-On-Investment rate, or ROI, is the ratio between the yearly average net income and the initial investment done to have those incomes. The initial investment is always I_0 , the yearly average net income U is the difference between D and the annual amortization share C_{am} :

$$C_{am} = Fc_{ci} + Fc_a = 18534 \text{ €} \quad (6.5)$$

$$U = D - C_{am} = P_{tot} = 488087.18 \text{ €} \quad (6.6)$$

With these data, it is possible to calculate the Return On Investment rate ROI :

$$ROI = \frac{U}{I_0} = 66.2\% \quad (6.7)$$

6.3.3 Net Present Value

The Net Present Value, or NPV, is a more reliable economic index for an investment. It is obtained by discounting all the yearly profits to the present moment, taking into consideration also time, and comparing them with the initial investment I_0 . It is necessary to estimate a value of the interest rate according to the risk of the investment and the opportunity cost of money. It is assumed a 6% interest rate. The number of years for the evaluation is fixed at 15, because both aggregation and diesel generators have a lifetime of almost 15 years and, after that period, some other investments must be made. The NPV is calculated as:

$$NPV = \sum_{i=1}^{15} \frac{D(n)}{(1+a)^{-i}} - I_0 = 4362738 \text{ €} \quad (6.8)$$

6.4 Tariff example

This evaluation work, as it was clear, did not consider a remuneration to the PEV owner for the services of primary and secondary frequency control. This was not implemented because at the moment there are no example in the market for such a peculiar solution. There are tendering rules that can be considered good and adapted to the case study, like the ones that is possible to see in Table 3.2 for Germany, Denmark and other countries, but without having the certainty of the possible implies of such solution, it has been chosen to not include it. Anyway, something that is now possible to do is see, assuming some remuneration rules and including all actors in it, which remuneration tariff can't be surpassed, because otherwise the cost for the system operator would be higher than the benefits that the implementation of the solution would provide. So, setting the limit for the cost of this remuneration to the total profit calculated in (6.1), it is calculated now the remuneration that, if surpassed, would provide a negative profit for the implementation.

First of all, since that both services of primary and secondary frequency control are needed, the two services are not separated for the remuneration. Also, the remuneration is given to the aggregator, that will share it with the connected electric vehicles according to the time and power size that the owners let available. Here although, since that the rules for aggregation and sharing are not created yet, it is calculated the equivalent revenue for each PEV. Since that it has been established that PEVs offer the secondary frequency control service for just five minutes, the time that is necessary for starting-up a new diesel generator, the tariff should take it under consideration for the time span that it's remunerating.

Calculating the secondary reserve needed for each load share (15% of the load), and the time in minutes that that secondary reserve is needed (according to the load curve), it is possible to find the amount of kW that must be let available and the number of minutes for which those amounts must be available. So, considering Table 4.2, multiplying column ... for 0.15 and column ... for $8760 \cdot 60$, it's possible to find the power in kW for secondary reserve $P_{sr(n)}$ and the time span $t_{sr(n)}$ for each load share. Down below, in equations (6.9) and (6.10), it is shown an example for the 6.4 MW load share:

$$P_{sr(6.4)} = 6.4 \cdot 1000 \cdot 0.15 = 960 \text{ kW} \quad (6.9)$$

$$t_{sr(6.4)} = \frac{0.251}{100} \cdot 8760 \cdot 60 = 1319,256 \text{ min} \quad (6.10)$$

Multiplying each element $P_{sr(i)}$ for the corresponding load-share element of $t_{sr(i)}$ the overall secondary reserve quantity SR_{tot} is found:

$$SR_{tot} = \sum_{i=1}^n P_{sr(i)} \cdot t_{sr(i)} = 218342334,2 \text{ kW} \cdot \text{min} \quad (6.11)$$

The tariff is calculated per kW·min, meaning that it is the remuneration for letting available 1 kW of power for 1 minute. Dividing the profit calculated in () for SR_{tot} , the tariff X is found:

$$X = \frac{P_{tot}}{SR_{tot}} = \frac{488087,18}{218342334,2} = 0.223 \frac{\text{c€}}{\text{kW} \cdot \text{min}} \quad (6.12)$$

This means that, if a PEV's owner lets available 3 kW of power for an accumulated time of 2.5 hours, its remuneration is almost 1 €. This has to be compared with the price that owners have to pay to recharge their PEV: considering an electricity price of $0.31 \frac{\text{€}}{\text{kWh}}$ and a battery capacity of 30 kWh, both typical values, a complete charge would take around 9 €. It is important to remember that this is a limit case, because the tariff that has been calculated is the maximum tariff that could possibly be implemented in order to have a positive profit.

6.5 Considerations

In all models and evaluations, two considerations must be done: if the model is replicable and if the model is scalable. The first one is really helpful in order to see which are the critical aspects that influence this particular evaluation. If this evaluation will be repeated for other different cases, it is important to underline which are the key aspects that must be payed attention at, aspects that are different from this one and may result, after all the calculations, in different endings. The second one helps a lot for thinking what happens if an evaluation like this is applied to a bigger system. A lot of aspects can change, because some parameters are

not the same for small and big systems (the equivalent inertia of the grid H is an easy example). Some assumption will be no longer true and even regulation can be much different.

6.5.1 Replicability

First of all, the characteristic of the island can heavily influence the economy of this evaluation. For some of the points, it was assumed that the costs were tripling with respect to the normal case. But this factor can be higher or lower depending on the island accessibility, morphology and position. Prices for shipping things are, of course, dependent on the distance that the ship has to cover, so this aspect must be controlled. Also installations of generators and chargers depend on the morphology of the ground, so if the island is flat it is easier to do things than an island with a lot of reliefs. It is worth of notice also the fact that this work was carried out thinking to a physical island, surrounded by sea. But it could be possible, with the right adjustments, to consider also those areas that are on the mainland but are operated as isolated systems, due to difficult morphology of the ground or to the remoteness of the region. There are for examples areas in Canada where the snow doesn't allow an easy communication and connection with the interconnected system, and so they are provided with diesel generators that are totally similar to those present in this evaluation. For sure there could be more restriction on the use of vehicles, but this work can for sure be a starting point.

In this case study, the generation was supposed to be coming exclusively from diesel generation sets, as it is usual for a lot of small island. Even those islands that have a great potential for exploiting renewable energy sources like solar, wind and hydro-electric, run for a big time-period with few or nil share of renewable generation. If some renewable source would have been implemented in the system, before reasoning on what could have happened to the evaluation it must be checked how those sources would interfere with the PFC service. For hydro-electric plants, there would be no problem for providing PFC duties, since there can easily be a control over the power of the unit. For wind and solar although, there are some problems. For the first one, even if there is a synchronous generator that rotates and has a certain inertia, there is a decoupling from the grid due to the transformation from DC to AC. For the second one, there isn't anything in the system that rotates and can furnish inertia to the grid. This causes a lot of troubles in terms of system inertia, meaning that, with these types of generation allowed to furnish power to the grid, the capability of replying to frequency deviations is weakened. There are studies about giving synthetic inertia through power converters, but at the moment those solutions are not common in the market.

With respect to the evaluation, if some diesel generation is substituted by renewable generation, it is necessary to distinguish between hydro-electric generation and wind and solar generation:

- Hydro-electric: the main difference between diesel and hydro generation is CAPEX. While for a diesel generator there is an average ratio of around 100 €/kW, for hydro-electric power plants this ratio can largely vary from 1300 €/kW to almost 8000 €/kW for small plants [32] (small island are still the purpose of the work, so the size of the plants can't be big). Given this, the part of the evaluation that would change more would surely be the one for lower degradation, because everything related to hydro power would be a lot bigger than diesel generation. For the part of start-up costs, it would probably not be existing for hydro-power plants because they are usually considered for serving base load, so that they suffer less about on and off switching. Environmental considerations would also be different, simply because a hydro-power plant is usually emission-free while operating. Of course, if pumping technologies are present in the power plant they have to be taken into account, because unclean energy might be used for pumping up water to the basin;
- Non-synchronous generation (wind and solar): for sure the capability of the PFC service would be smaller, because there is the substitution of some generation that can provide PFC with another type of generation that can't. In this case, utilizing PEVs for providing PFC can have a much bigger impact on the system. In fact, with respect to the case study analyzed above, the frequency deviation and the overall dynamic of the system would be worse in the "no PEV" scenario, allowing a higher profit in "PEV" scenario thanks to the participation of added PFC services. The minimum needed number of connected PEVs might be higher.

Economically although, there is an opposite side to be taken into consideration. Given that a part of diesel generation is substituted with something else, almost all the calculation done for the benefits that would result from PEVs providing PFC have a smaller weight in the overall evaluation, according to the share that is replaced.

Another thing that must be considered in a possible replication of this work is the set of diesel generators that provide the island with the needed power to meet the load. For example there can be a different number of generators, or different sizes of them. Taking as a fixed value the load and the total generating capacity of the system, and supposing a different size of the single generators, there would surely be a difference in the lifetime of each generator. Talking for both scenarios, if the size of the generators is bigger (smaller) the amortization shares and the maintenance costs for each generator would be higher

(lower), but the number of generators for which is needed to think to those costs is lower (higher), so a careful calculation must be rolled out. The number of start-ups would be smaller (higher). The overall efficiency of the system would be worse (better) because it would be more difficult (easier) to meet the load of the system having bigger (smaller) generation steps and the plants would work further (closer) to the high-efficiency points. Also, it would be necessary to have more (less) electric vehicles to substitute a CGU's PFC duty.

At last, also the amount of secondary reserve with which the system is run is important to be considered, because from that value depends the minimum number of connected PEVs and the size of all benefits downwards. If just that parameter is changed, it is easy to see that the difference among the two scenario changes, becoming smaller if the secondary reserve is decreased and becoming bigger if the secondary reserve is increased.

6.5.2 Scalability

The scalability of this model implies the passage from a small isolated system to an interconnected system, where the land analyzed is bigger and so is the load. This is translated in a higher number of generators, probability distributions of higher precision and easier possibility to reply to disturbs.

The first restriction that this work would find if it was scaled up and applied to bigger systems is regulation. As it has been seen in chapter 3, regulation for PFC in interconnected systems has precise technical requirements that have to be satisfied and not so clear regulations about aggregation of electric vehicles and storage in general. Isolated systems allow to have a higher degree of freedom, because their particular nature and necessities require to do everything that would preserve the operation of the system. Normally the generation, distribution and operation of the system is vertically integrated and run by just one company, that work differently from those companies that operate in big interconnected systems and have to deal with market competition. Summing up, for this point it would be more difficult to introduce something new as PEVs providing PFC, because it would be necessary for regulation to follow the technical solution and allow such change.

For PEVs standards, it has already been said that all chargers of the island are considered to be working in mode 3. This charging mode requires a type 2 socket, one of the most common available in the market for PEVs and the EU standard. So, for models implemented in interconnected systems, there would be no problem on this point.

The minimum number of connected PEVs should be higher, according to the size of the power plant that is being replaced for PFC duty. For example, a plant of 500 MW can be replaced by almost 11600 PEVs, according to equations (4.7) and (4.8). This number can be too high for the moment (in all Europe, at the end of 2015, there were about 425000 plug-in electric vehicles on the street, distributed not homogeneously among the countries), but given the policies that nations are applying to fight climate change and to increase environmental sustainability, together with the market that is continuously growing, it's a number that can easily be met.

The real problem is the profitability of this solution, that is far less convenient than in isolated systems, where the dynamics help the development of such new approach. PFC services can be furnished more easily and more conveniently, thanks to a high number of power plants connected to the system and the higher rotating inertia of CGUs. Also, the provision of fuel of every nature is cheaper in interconnected systems, making the profit shrink.

In conclusion, there are still possibilities to have a profitable solution, but the size of the profit would be smaller.

7 Conclusions

This work aims to find an economic evaluation that can help system operators of small islands to decide the usefulness and the feasibility of PEVs providing PFC services. Two scenarios are considered: in the first, PEVs are present on the island but not providing PFC; in the second, PEVs are present and providing PFC. The evaluation considers an investment from the system operator, that aims at changing the grid in such a way that also PEVs can provide PFC and tries to see which the benefits and the costs of improving the system are.

In Chapter 2 some overviews about primary frequency control theory are written, together with some generalities about batteries and electric vehicles.

Chapter 3 explores technical and economic aspects of PFC duty around Europe, talking about nations and their big interconnected systems. After their analysis, it is decided that the focus of the work should be just in small isolated systems, because the impact of PEVs providing primary frequency control can be bigger and more profitable. Generators are often run at low efficiency to guarantee a good response in terms of PFC or secondary reserve, and PEVs can enhance that behavior. Also, islands' government regulation is often strongly aiming at increasing PEVs' penetration.

In Chapter 4 it is explained the model that will be used to simulate the island system and, more precisely, the block that represents the aggregation of PEVs that will provide PFC. Later, some assumptions are made for simplifying the problem, and calculations are done in order to understand what is the support that PEVs should give in order to have an equivalent system. It appears clear, from those calculations, that secondary control can't be unlinked from primary frequency control and must be considered as well, since that a reduction in active generators' number results also in a drop of secondary reserve. It is calculated that, according to data and assumptions, 25 PEVs for MW of load can offer the required secondary reserve and that 58 PEVs can substitute a diesel generator's PFC duty. Finally, the characteristics of the island and the technical data that will be used for the evaluation are shown.

Chapter 5 goes at the heart of the work, calculating benefits and costs of the implementation of the investment. Assumptions are done for each point and final numbers are obtained, calculating that the two main sources of benefit for an investment like the one analyzed in this work are fuel savings due to higher efficiency and lower amount of shed load. Also a table is shown about this last topic, showing the effective improvement of the system after having switched from "no PEV" scenario to "PEV" scenario.

Chapter 6 extracts the results from the previous chapters, comparing them and calculating also some typical economic index, to have an objective idea of the investment. It is shown that the investment has a Pay-Back time of 1.4 years and a Return On Investment of 66%, with a Net Present Value of 4362738 €. A maximum tariff is hypothesized, since at the moment there is no regulation about something like what happens in this work. Finally, some considerations about the replicability and the scalability of the project are done.

8 Acknowledgements

This master thesis has been the purpose of the last five months of my life, as it is the conclusion of that wonderful journey that has been my university experience. But the help that I received, and the possibilities that I had, go far beyond this time span, as they head back, in some case, to when I was born. So let me spend a few words of thanks to all the people that, crossing my life, helped to make it better and allowed me to make this work and finish this adventure.

First of all, I would like to thank my supervisors: Prof. Pablo Frías Marín, responsible of my internship at the “Instituto de Investigacion Tecnológica” (IIT) in Madrid, and Prof. Pablo García González, co-supervisor. Their constant help and your profound knowledge of the topic allowed me not only to complete this work, but also to learn many new things about both technical aspects and research works. I would also like to thank Prof. Arturo Lorenzoni, the relator of this thesis, for letting me have the possibility to experience a wonderful internship. Without these three people, surely this work would not have seen the light.

I would like to thank my family, and specifically my parents and my brothers, for all the possible and imaginable types of support that they gave me, moral and economic above all. I feel really lucky to have them as my family. About my parents, I know that everything that I have accomplished, included this work, and everything that I will accomplish in the future, is and will be mainly amenable to their teachings, and I will never be grateful enough for their help. Mum, Dad, I hope to be like you in the future.

I would like to thank my girlfriend Francesca, who has been at my side for two and a half years now, even more since we met for the first time. The support that she gave me every time I was down has been unique, and she contributed to my happiness more than anyone else has ever did in my life. She always makes me think, discuss and grow, offering me a different point of view that I would have never taken in consideration. I love you Fra.

I would also like to thank all my friends. I thank those that lived the “Padua experience” with me, for helping to build wonderful memories that will never go away and to feel Padova as a second home. This experience has ended, but we’ll keep having a bond that will connect us for the rest of our lives. I thank those that are from Castelleone di Suasa, for having accompanied me through the first twenty years of my life. You make me feel always at home when I come back, and this is something that only someone special can do. I thank those that

guided me through my experience in Madrid, for transforming a five-months internship in something that made me grow as an engineer and, even more, as a person. Special thanks to all the people on the fourth floor in IIT, that helped to create a nice work environment. I have few words for you: next challenge is the Pisa tower.

I would like to thank LEDS – L'Energia Degli Studenti and the people that compose it. They have been part of my academic experience since the second year, where I started to get interested and began to think about joining them. The environment that was built to discuss about energy-related topics was, and still is, something almost unique. I ask you: please don't stop what you're doing, keep spreading the word and the interest about energy world and, above all, never stop caring. Changes comes often slowly and always from people who care.

Last, and least, I would like to thank Word Office 2016. Its continuous attempts in showing me stupid problems that I had to solve was really inspiring, and it helped to keep my brain on training. It has not been a pleasure working with it, and I hope that we'll never see each other again.

I strongly believe that we are the sum of the relationship that we build in our lifetime, each one weighted according to their importance. This is why I tried to spend a word for each one of the meaningful people that crossed my path: because this scientific work requires knowledge, but before that it requires a person that has that knowledge. And everything that allows a person to acquire knowledge, environment included, is worth a mentioning. I thank everyone once again, I don't know how the future will affect me but I know one thing for sure: the problems that I have right now are nothing compared to the smile that I'll have when I'll look back to these days.

Giucci out.

9 Annexes

9.1 Simulink model of the island

In this subchapter, it is shown the Simulink model that has been used to calculate frequency deviations in both scenarios and evaluation of shed load in subchapter 5.2.5.

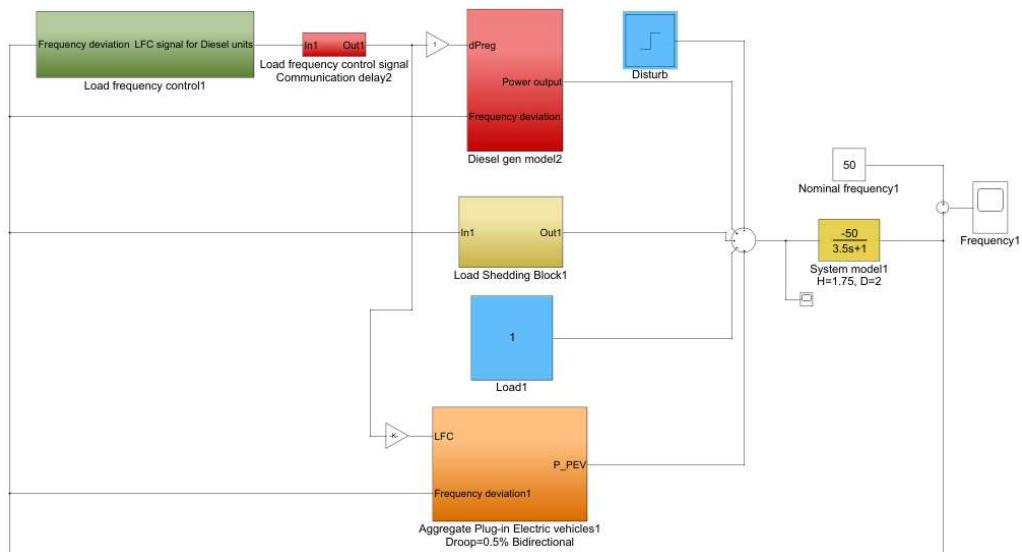


Figure 9.1 - Simulink model

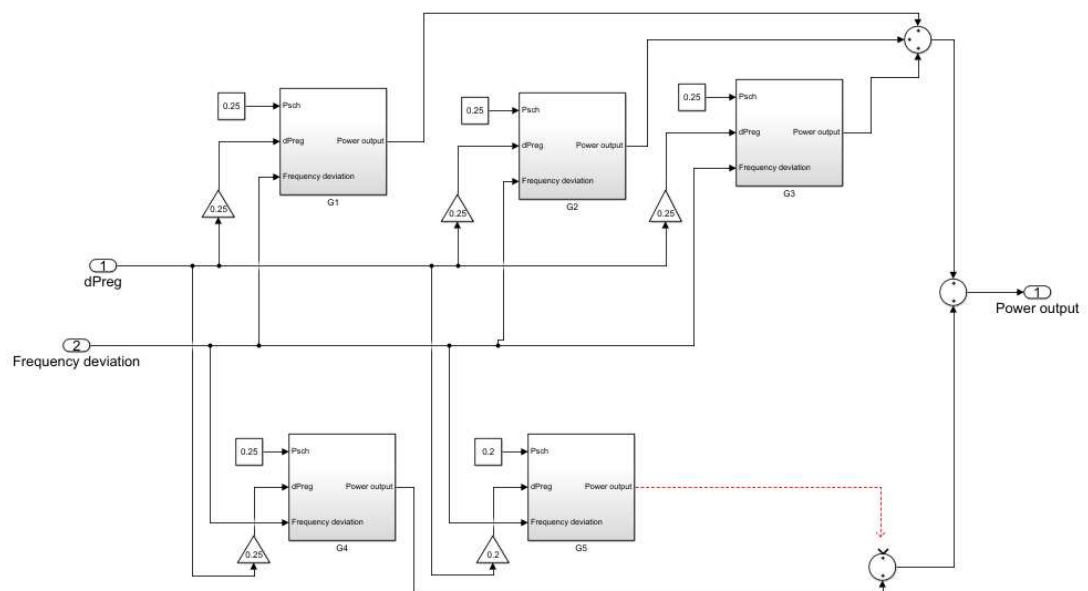


Figure 9.2 - Generation model

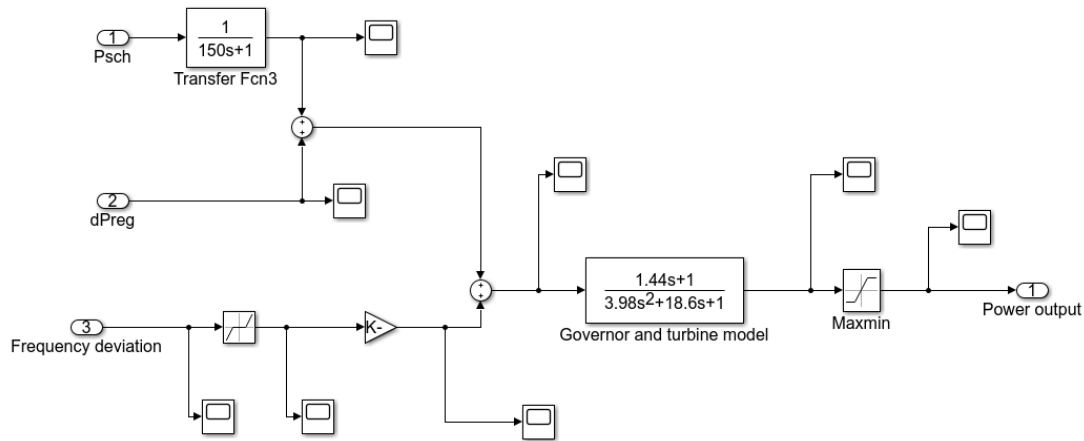


Figure 9.3 - Diesel generator model

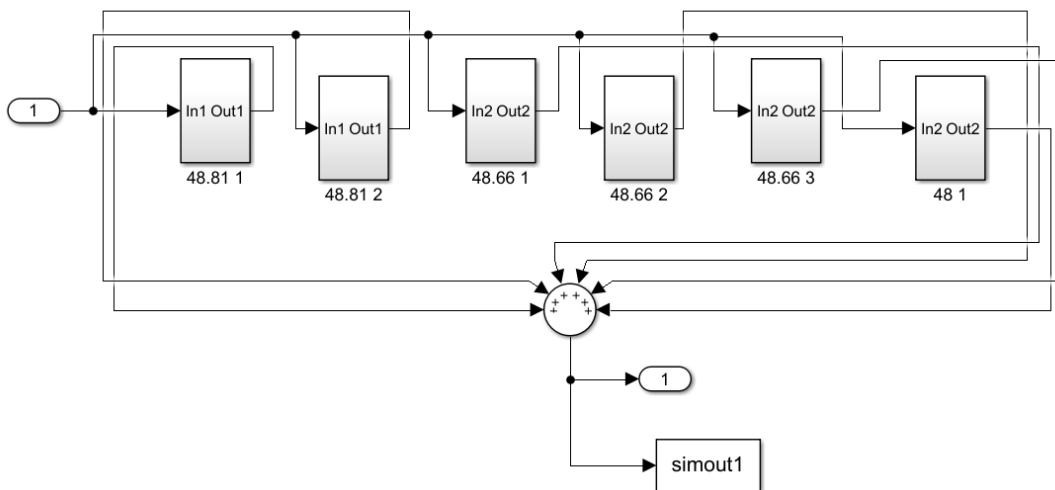


Figure 9.4 - Load shedding blocks

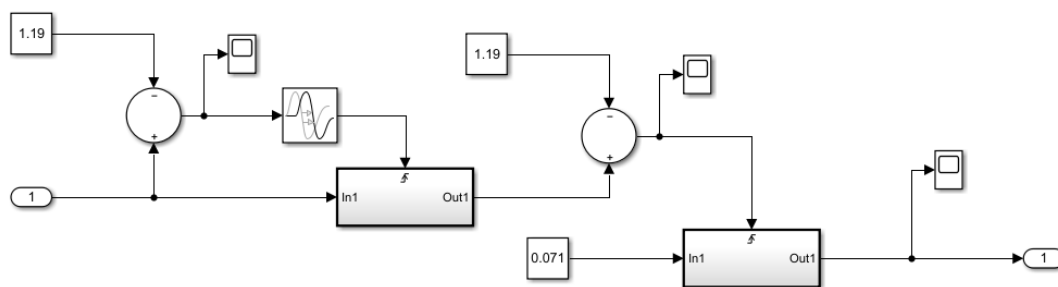


Figure 9.5 - Example of load shedding block with triggering under-frequency deviation of 1.19 Hz

9.2 Matlab scripts

In this sub-chapter the Matlab scripts used in the evaluation are shown. They are utilized for evaluating the lower amount of shed load in subchapter 5.2.5, as it was necessary to run ten

simulations for each load share and see how much load was shed in each one of them. There are four scripts, two main and two recalled by the main ones. The main scripts are used respectively when, between the two scenarios, the numbers of active generators for the load share under consideration are equal and when the same numbers are different.

9.2.1 Main script n°1

```
% Script that has to be run when the number of generator between the
two
% cases is equal. I must change values in generators each time that i
% start this.
% Since this is repeating for each share, after the first time that
the
% model is run all the things besides load_system can be deleted.
[num]=xlsread('eval_benefits.xlsx','Fogliol','A16:W106');
refload=num(:,1);
ngennopev=num(:,2);
ngenpev=num(:,3);
prob=num(:,23);
clear num;
%Data for load shedding
fail=0.03; %probability of failure over one year
voll=10000; %eur/MWh
l=length(refload);
costnp=0; %total cost of energy not served no pev
costp=0; %total cost of energy not served pev
%Developing
i=1;
dist=0.05:0.05:0.5;
ldist=length(dist);
o=zeros(ldist,1); %load shed for each disturb in one row in nopev
oo=zeros(ldist,1); %load shed for each disturb in one row in pev
mindistnp=zeros(1,1); %minimum disturb that causes shed load nopev
mindistp=zeros(1,1); %minimum disturb that causes shed load pev
probshednp=zeros(1,1); %probability of having at least that disturb
nopev
probshedp=zeros(1,1); %probability of having at least that disturb
pev
pd=[0.3 0.23 0.15 0.1 0.08 0.05 0.04 0.03 0.01 0.01]; %Prob of disturb
%Comment everything until this point when repeating the script
load_system('PFCcopy');
for i=i:l
    if ngennopev(i,1)==ngenpev(i,1)
        pb=refload(i,1);
        n=ngennopev(i,1);
        m=ngenpev(i,1);
        maxpow=2.5/pb;
        minpow=0.3/pb;
        gain=maxpow*20/50;
        ensnp=0;
        ensp=0;
        run nopev.m; %sets parameters for nopev scenario
        run pev.m; %sets parameters for pev scenario
        for k=1:ldist
            d=dist(1,k);
```

```

        set_param('PFCcopy/Disturb','After','d');
        siml=sim('PFCcopy'); %run simulink model
        slnp=max(simout); %shed load in no pev scenario
        slp=max(simout1); %shed load in pev scenario
        o(k,1)=slnp;
        oo(k,1)=slp;
        pensnp=slnp*pd(1,k)*fail*n; %partial energy not served no
pev
        pensp=slp*pd(1,k)*fail*m; %partial energy not served pev
        ensnp=ensnp+pensnp;
        ensp=ensnp+pensp;
    end
    p=find(o,1);
    pp=find(oo,1);
    mindistnp(i,1)=dist(1,p)*pb;
    mindistp(i,1)=dist(1,pp)*pb;
    for t=p:ldist
        probshednp(i,1)=probshednp(i,1)+pd(1,t);
    end
    for t=pp:ldist
        probshedp(i,1)=probshedp(i,1)+pd(1,t);
    end
    costnp=costnp+ensnp*prob(i,1)*8760*voll/100;
    costp=costp+ensp*prob(i,1)*8760*voll/100;
    prof=costnp-costp;
else
    break
end
end
end

```

9.2.2 Main script n°2

```

%Script that has to be run when the number of generator between the
two
%cases is different. I must change values in generators each time that
i
%start this
load_system('PFCcopy');
%Developing
for i=i:1
    if ngennopev(i,1)==ngenpev(i,1)
        break
    else
        pb=refload(i,1);
        n=ngennopev(i,1);
        m=ngenpev(i,1);
        maxpow=2.5/pb;
        minpow=0.3/pb;
        gain=maxpow*20/50;
        ensnp=0;
        ensp=0;
        run nopev.m; %sets parameters for nopev scenario
        run pev.m; %sets parameters for pev scenario
        for k=1:ldist
            d=dist(1,k);
            set_param('PFCcopy/Disturb','After','d');

```

```

siml=sim('PFCcopy'); %run simulink model
slnp=max(simout); %shed load in no pev scenario
slp=max(simout1); %shed load in pev scenario
o(k,1)=slnp;
oo(k,1)=slp;
pensnp=slnp*pd(1,k)*fail*n; %partial energy not served no
pev
pensp=slp*pd(1,k)*fail*m; %partial energy not served pev
ensnp=ensnp+pensnp;
ensp=ensp+pensp;
end
p=find(o,1);
pp=find(oo,1);
mindistnp(i,1)=dist(1,p)*pb;
mindistp(i,1)=dist(1,pp)*pb;
for t=p:ldist
    probshednp(i,1)=probshednp(i,1)+pd(1,t);
end
for t=pp:ldist
    probshedp(i,1)=probshedp(i,1)+pd(1,t);
end
costnp=costnp+ensnp*prob(i,1)*8760*voll/100;
costp=costp+ensp*prob(i,1)*8760*voll/100;
prof=costnp-costp;
end
end
% %UNCOMMENT THIS JUST AT THE LAST STEP OF REPETITION
% xlswrite('eval_benefits.xlsx',mindistnp,'Fogliol','AI16:AI106');
% xlswrite('eval_benefits.xlsx',mindistp,'Fogliol','AY16:AY106');
% xlswrite('eval_benefits.xlsx',probshednp,'Fogliol','AJ16:AJ106');
% xlswrite('eval_benefits.xlsx',probshedp,'Fogliol','AZ16:AZ106');
% xlswrite('eval_benefits.xlsx',costnp,'Fogliol','AK16');
% xlswrite('eval_benefits.xlsx',costp,'Fogliol','AX16');

```

9.2.3 Recalled script n°1 (noPEV.m)

```

set_param('PFCcopy/Diesel gen model2/G1/Gain1','Gain','gain');
set_param('PFCcopy/Diesel model2/G1/Maxmin','UpperLimit','maxpow');
set_param('PFCcopy/Diesel model2/G1/Maxmin','LowerLimit','minpow');
set_param('PFCcopy/Diesel gen model2/G2/Gain1','Gain','gain');
set_param('PFCcopy/Diesel model2/G2/Maxmin','UpperLimit','maxpow');
set_param('PFCcopy/Diesel model2/G2/Maxmin','LowerLimit','minpow');
set_param('PFCcopy/Diesel gen model2/G3/Gain1','Gain','gain');
set_param('PFCcopy/Diesel model2/G3/Maxmin','UpperLimit','maxpow');
set_param('PFCcopy/Diesel model2/G3/Maxmin','LowerLimit','minpow');
set_param('PFCcopy/Diesel gen model2/G4/Gain1','Gain','gain');
set_param('PFCcopy/Diesel model2/G4/Maxmin','UpperLimit','maxpow');
set_param('PFCcopy/Diesel model2/G4/Maxmin','LowerLimit','minpow');

```

9.2.4 Recalled script n°2 (pev.m)

```
set_param('PFCcopy/Diesel gen modell/G1/Gain1','Gain','gain');
set_param('PFCcopy/Diesel modell/G1/Maxmin','UpperLimit','maxpow');
set_param('PFCcopy/Diesel modell/G1/Maxmin','LowerLimit','minpow');
set_param('PFCcopy/Diesel gen modell/G2/Gain1','Gain','gain');
set_param('PFCcopy/Diesel modell/G2/Maxmin','UpperLimit','maxpow');
set_param('PFCcopy/Diesel modell/G2/Maxmin','LowerLimit','minpow');
set_param('PFCcopy/Diesel gen modell/G3/Gain1','Gain','gain');
set_param('PFCcopy/Diesel modell/G3/Maxmin','UpperLimit','maxpow');
set_param('PFCcopy/Diesel modell/G3/Maxmin','LowerLimit','minpow');
set_param('PFCcopy/Diesel gen modell/G4/Gain1','Gain','gain');
set_param('PFCcopy/Diesel modell/G4/Maxmin','UpperLimit','maxpow');
set_param('PFCcopy/Diesel modell/G4/Maxmin','LowerLimit','minpow');
set_param('PFCcopy/Diesel gen modell/G5/Gain1','Gain','gain');
set_param('PFCcopy/Diesel modell/G5/Maxmin','UpperLimit','maxpow');
set_param('PFCcopy/Diesel modell/G5/Maxmin','LowerLimit','minpow');
```

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