ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)
GRADO EN INGENIERÍA ELECTROMECÁNICA

Economic assessment of the impact of electricity storage on power quality in distribution systems

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'It is the combination of reasonable talent and the ability to keep going in the face of defeat that leads to success' Martin Seligman.

ECONOMIC ASSESMENT OF THE IMPACT OF ELECTRICITY STORAGE ON POWER QUALITY IN DISTRIBUTION SYSTEMS

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ABSTRACT

Nowadays electricity is one of the most important aspects of people's lives. Almost no one can imagine their day without checking their email, showering with hot water or going to work by train. We can affirm that electricity has become a really important product and, due to this, several quality requirements need to be fulfilled. Almost every country in the world, especially the European ones and the US, have laws that regulate the characteristics of power supply so that electrical companies provide their customers with the best electricity available in the market.

The main disadvantage of power is that it is produced in a different place where it is consumed. Electricity is produced in power plants where its main characteristics (like voltage value, frequency, harmonic's content…) are highly controlled. But, while electricity reaches its final customers, those characteristics may be disturbed. Those disturbances affect the quality of supply, that is the part of quality of electrical service that represents the measure of how an ideal power supply system should be.

Among the electrical disturbances that affect the quality of supply we can find the supply voltage variations, voltage dips, voltage swells, short interruptions and long interruptions. Their causes are various: variations of loads, line faults, incidents in the line's insulation… As we can see, not all the disturbances are caused by failures of the distribution companies but also because of a bad state of the equipment connected to the distribution network.

Of all the electrical disturbances long and short interruptions are the ones studied deeper in this project as they are the ones with highest probability of happening.

In order to measure them two indexes are mainly used: the SAIDI and the SAIFI. The SAIDI represents the average duration interruption of service for each customer of the electrical company. The SAIFI represents the average number of times that a customer experiences an interruption of power service. Spain is neither among the countries with the lowest values of SAIDI and SAIFI nor among the countries with the highest ones but in the middle. This means that we still that actions are still needed in order to improve the quality of service and, therefore, decrease the value of these indexes. Moreover, the ENS index is also important as it measures the quantity of energy that hasn't been supplied to customers in a certain region.

Furthermore, as disturbances imply a bad quality of service they have an economic impact. This is why electrical distribution companies carry out studies in order to know the opinion that customers have on this subject. For example, the AEMO developed the VCR (Value of Customer Reliability) that is in an index that represents the willingness of customers to pay in order to avoid disturbances. In this project we have considered a value of 10€/kWh for the cost of non-supplied energy.

Using the SAIDI, SAIFI, ENS and the cost of non-supplied energy we have obtained the amount of money that electrical distribution companies need to pay to customers when interruptions take place. As we have obtained that the total cost of the interruptions implies a big sum of money it is economically profitable to install storage systems in order to improve the quality of electricity.

Therefore, in order to reduce the number and length of interruptions several solutions are presented: Petersen coil, Uninterruptable Power Supply (UPS) System, flywheel, Dynamic Voltage Restorer (DVR) and Variable Frequency Drive (VFD). Among them, the flywheel and the UPS are the best solution in economic terms. If we study the advantages and disadvantages of these two solutions, we conclude that the UPS storage system is currently the best solution as it can provide energy for almost one hour while the flywheels only last for a few seconds.

Finally, we have studied the economic impact of the electrical disturbances in the distribution network in the future. We are living in the decade of the climate change, in a few years the average temperature of the planet and its precipitation patterns are going to change drastically. As a lot of electrical disturbances are caused by weather phenomena, the climate change will have a big impact on power quality by increasing the length and frequency of the electrical disturbances. Because of this we have studied the consequences that the climate change will have in the long and short interruptions. In order to do this, two scenarios have been presented: a gathered rural zone and an urban zone. In both cases we have analyzed the economic impact of the interruptions if its duration and frequency is multiplied by two, by five and by ten. By doing this, we have modeled the impact of the climate change on electrical disturbances. Moreover, the economic cost of the installation of an UPS storage system is analyzed.

In the gathered rural zone, even with a small population and a big number of electrical disturbances (because its configuration is a radial one) it is economically profitable to install an UPS storage system. Obviously, in an urban zone, with a bigger population and less disturbances (thanks to its netted configuration) it is also economically profitable to install the UPS not only in the future with the climate change but nowadays. In both cases the possibility of charging the customers the cost of the UPS storage system has been studied but we have concluded that it cannot be all charged to the customers as it implies a big sum of money.

In this project we can learn the importance that a good quality of electricity has on all the equipment connected to the electrical network. The problem is that not everyone is aware of the big consequences that electrical disturbances have. Therefore, it is important that we all learn about it in order to, as long as it is possible, avoid their causes.

ESTUDIO ECONÓMICO DEL IMPACTO DE SISTEMAS DE ALMACENAMIENTO EN LA CALIDAD DE ENERGÍA EN SISTEMAS DE DISTRIBUCIÓN ELÉCTRICA

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RESUMEN

Hoy en día la electricidad es uno de los aspectos más importantes en la vida de las personas. Casi nadie puede imaginar su día a día sin revisar su email, ducharse con agua caliente o ir a la oficina en tren. Podemos afirmar que la electricidad es un producto muy importante y, por lo tanto, tiene que cumplir unos requisitos de calidad. Prácticamente todos los países del mundo, especialmente los países europeos y Estados Unidos, tienen leyes que regulan las características del suministro eléctrico. De esta forma, los usuarios de la red eléctrica pueden estar seguros de que la energía que reciben es la mejor energía disponible en el mercado.

La principal desventaja de la energía eléctrica es que es producida en un lugar diferente al de su consumo final. La electricidad es producida en centrales eléctricas donde sus características principales (como el valor de la tensión, la frecuencia, el contenido en harmónicos…) son controladas. El problema que esas características se ven alteradas mientras la electricidad llega a los usuarios finales. Estas alteraciones reciben el nombre de perturbaciones eléctricas y afectan a la calidad de suministro. La calidad de suministro es una parte de la calidad del servicio eléctrico que se encarga de medir cómo ha de ser una red eléctrica ideal.

Entre las perturbaciones que afectan a la calidad de suministro encontramos las variaciones de voltaje, los huecos de tensión, los aumentos de tensión, las interrupciones largas y las interrupciones cortas. Las causas de estas perturbaciones son muchas: variaciones en la carga, faltas en las líneas, incidentes en el aislamiento… Como podemos observar no todas las perturbaciones eléctricas son debidas a fallos de las

compañías eléctricas sino también debido a un mal estado de los equipos conectados a la red de distribución eléctrica.

De todas las perturbaciones eléctricas, las interrupciones largas y cortas son las más estudiadas en este proyecto puesto que son los que tienen mayor probabilidad de suceder. Para medirlas se utilizan principalmente dos índices: SAIDI y SAIFI. El SAIDI mide la duración media de las interrupciones de servicio para un usuario de la red eléctrica. El SAIFI representa la frecuencia media de interrupciones de servicio. España se encuentra entre los países con valores medios de estos índices. Esto implica que aún es necesario actuar para mejorar la calidad de servicio y, por lo tanto, disminuir el valor de estos índices. Además, también se utiliza el índice ENS que mide la cantidad de energía que no ha sido provista a los consumidores en una región y debería haberlo sido.

Además, al suponer las perturbaciones eléctricas una mala calidad del servicio éstas tienen un impacto económico. Debido a esto, las compañías eléctricas centran muchos de sus estudios en conocer la opinión de los consumidores eléctricos sobre este tema. Por ejemplo, el AEMO desarrolló el VCR (valor de la fiabilidad del consumidor), éste es un índice que representa cuánto están los consumidores dispuestos a pagar para evitar las interrupciones de suministro eléctrico. En este proyecto hemos considerado un valor de 10€/kWh para representar el coste de la energía no suministrada.

Utilizando los valores de SAIDI, SAIFI, ENS y del coste de la energía calculada se ha obtenido la cantidad total de dinero que las compañías distribuidoras deben de pagar a los usuarios debido a las interrupciones de suministro. Puesto que se han obtenido valores muy elevados se ha concluido que es rentable la instalación de sistemas de almacenamiento de energía para mejorar la calidad de la energía.

Por lo tanto, para reducir la cantidad y duración de las interrupciones se han presentado las siguientes soluciones: bobina Petersen, Sistema de Alimentación Ininterrumpida (SAI), volante de inercia, Restaurador Dinámico de Tensión y un Variador de Frecuencia. Entre todas estas soluciones, el volante de inercia y el SAI son las mejores en cuanto a términos económicos. Si estudiamos las ventajas y desventajas de ambos podemos concluir que el SAI es, a día de hoy, la mejor solución ya que puede proporcionar energía durante casi una hora mientras que los volantes de inercia solamente por unos segundos.

Por último, se ha estudiado el impacto económico de las perturbaciones eléctricas en la red de distribución en el futuro. Vivimos en la década del cambio climático, en un par de años la temperatura media del planeta, así como el modelo de precipitaciones cambiarán drásticamente. Puesto que muchas de las perturbaciones eléctricas son debido a fenómenos meteorológicos, el cambio climático va a tener un gran impacto en la calidad de suministro eléctrico aumentando la duración y frecuencia de las distribuciones. Por este motivo se han estudiado las consecuencias que el cambio climático va a tener en las interrupciones cortas y largas. Para ello se han presentado dos escenarios: una zona rural agrupada y una zona urbana. En ambos casos se ha analizado el impacto económico de las interrupciones en el caso de que su duración y frecuencia se vea multiplicada por dos, por cinco y por diez. Con esto se consigue modelar el impacto que tendrá el cambio climático en las perturbaciones eléctricas. Además, el coste de instalar un SAI ha sido analizado.

En el caso de la zona agrupada rural, a pesar de que su población es pequeña y su cantidad de perturbaciones elevada (debido a su disposición radial) es económicamente rentable instalar un SAI actualmente y en el futuro. Obviamente, en la zona urbana, con una mayor población y menor número de perturbaciones (gracias a la disposición mallada de este tipo de redes) también es rentable en términos económicos instalar un sistema SAI no sólo en el futuro con el cambio climático sino también hoy en día. En ambos casos se ha estudiado la posibilidad de cobrar a los usuarios de la red el coste del sistema SAI, pero se ha concluido que esto no es posible ya que los consumidores tendrían que pagar una elevada suma de dinero por ello.

Este proyecto nos permite aprender la importancia que la buena calidad de energía eléctrica tiene sobre los equipos conectados a la red eléctrica. El problema es que no todo el mundo es consciente de las enormes consecuencias que las perturbaciones tienen. Por lo tanto, es importante que todos aprendamos sobre ellas para, en la medida de los posible, disminuir sus causas.

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)
GRADO EN INGENIERÍA ELECTROMECÁNICA

Economic assessment of the impact of electricity storage on power quality in distribution systems currently and in the future

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CHAPTER 1:

INTRODUCTION

1. INTRODUCTION

In this first chapter a general introduction to the project can be found.

Firstly, the importance of maintaining the quality of electricity will be expounded. The main aspects of electrical quality will be given: quality of the customer service, continuity of supply and power quality. The most representative aspects related to power quality that affect voltage waveform and voltage stability will be explained. Moreover, the regulation about quality of electricity is going to be presented.

Finally, the project's structure and its main objectives will be given.

1.1. Distribution system

The electric system is the group of the necessary installations to generate, transport and distribute the energy generated in the power plants to the consumers [1]. Therefore, it is composed by three different stages: generation, transportation and distribution.

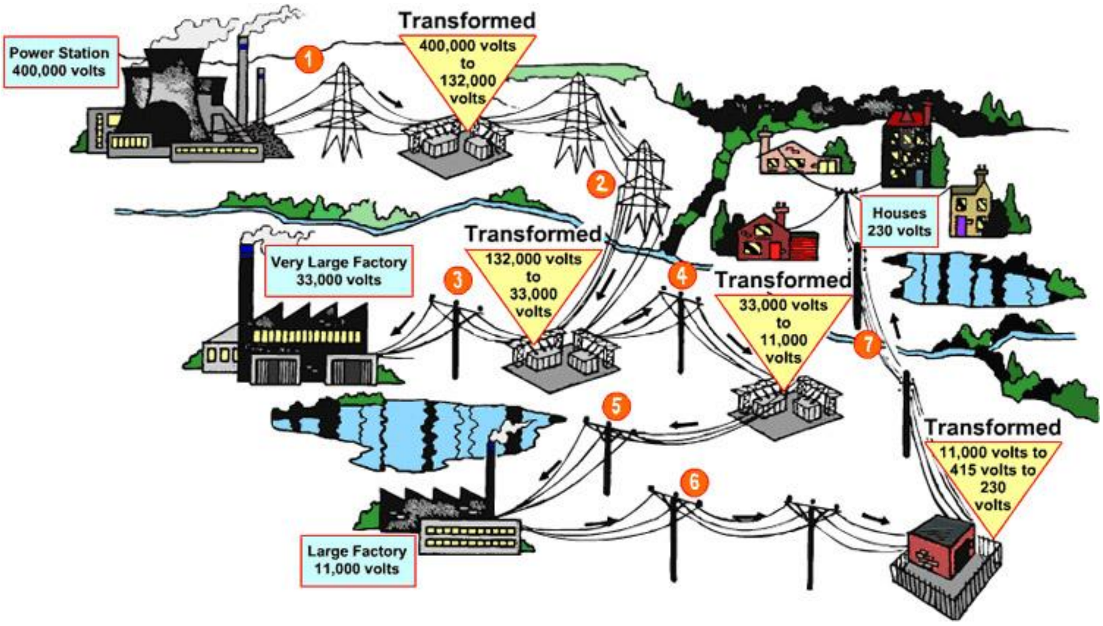


Fig. 1: Electric system **[2].**

An electric power distribution system is the final stage in the delivery of the electricity power. In this stage the voltage is firstly reduced and then delivered to retail customers that have no connection with the high voltage transmission system. The distribution of the electric power is done by distribution networks and, depending on the geographical location of the users, it can be done by overhead lines or by underground cables. The main difference between these two types of lines is the cost, underground cables are far more expensive than overhead lines so, underground cables are only used when overhead lines cannot be. Consequently, underground cables are normally used in large urban centers or in historical places, increasing network safety and lowering the negative landscape impact of overhead lines.

As electricity cannot be easily stored it is produced and delivered on real time. This means that, whenever and wherever electricity is consumed, it also has to be generated at that same moment and somewhere nearby. Therefore, it is strictly necessary to maintain a balance between the energy's production and the energy's consumption. It is usual to keep generation a little bit above demand so that, if more energy is demanded suddenly, the balance will not be highly altered and no outages will take place [3]. Moreover, the main power systems follow the N-1 or N-2 criteria which means they can work properly without one or two elements of the network.

Electricity is produced in power stations where its main characteristics (voltage, frequency, harmonics' content…) are highly controlled. The problem is that, while the power reaches the customer's supply terminals, some variations can occur. Those variations are caused by lightning, wind, pollution, user's equipment… and they can cause a big degradation in the performance of the electrical equipment. That's the main reason why, nowadays, every distribution company needs to maintain an electricity quality in order to be allowed to provide power [4].

1.1.1. Quality of electricity

Quality of electricity is a measure of how an ideal power supply system should be. There are various reasons why the quality of electricity has become a strategic issue for electrical companies, but the main ones are: the economic necessity of increasing competitiveness, the opening up of the electricity market and the widespread use of equipment that is sensitive to voltage disturbances [5]. That's why, the European Energy Regulator working through the CEER (Council of European Energy Regulators) has promoted the well-functioning and competitiveness of the EU energy markets. Therefore, consumers can get fairy prices, the widest choice of energy suppliers and the best possible quality.

As the possibility of storing electricity is very reduced nowadays, most of the energy is consumed at the same instant it is generated. Therefore, it is strictly necessary to measure its quality at the same point it is generated and while its being transmitted [6].

The quality of the electrical service can be divided in two main aspects: the quality of customer service or commercial quality and the quality of supply which includes power quality and continuity of supply. In order to measure the quality of the energy various indexes are used, the most important ones will be then explained [7]. Indexes allow us to compare the quality of different networks. They have to be kept to its minimum value (meaning with this low disturbances) and they need to be representative of the disturbance they are measuring.

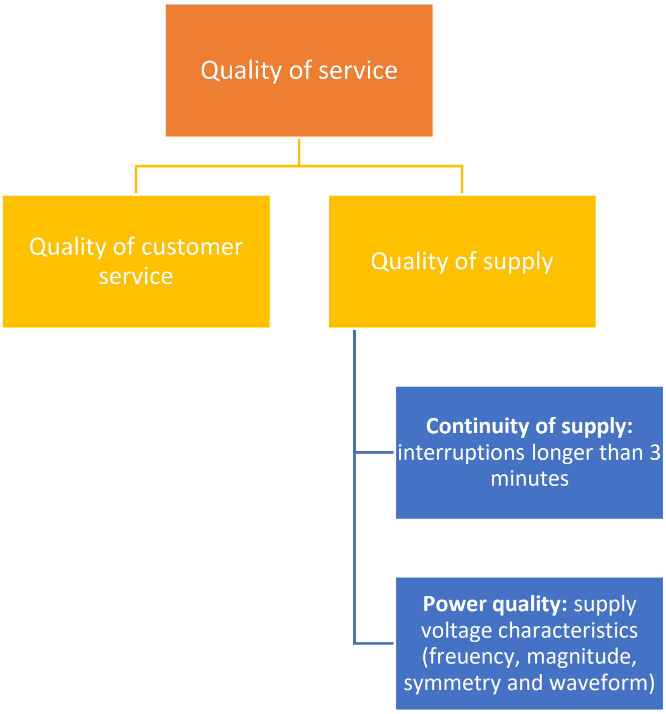


Fig. 2: Quality of service **[8]**.

1.1.1.1. Customer service

Quality of customer service or commercial quality refers to the treatment received by the customers from the distribution company. It includes different aspects of the relationship between the electricity companies and the users such as the supply, the sale of electricity and the contact between the company and the customer. The most concerning quality aspect is the timeliness of the service requested by the customers. Depending on the country the definition of ‘timeliness’ may vary [7]. Even though commercial quality is a very interesting index it will not be studied in this project.

1.1.1.2. Continuity of supply

Continuity of supply alludes to the interruption in electricity supply, those events in which the voltage drops to zero. Moreover, the continuity of supply implies that there is electricity available for all of the network users at all times.

Regarding to the nature of the interruption we can differentiate among planned, unplanned and exceptional interruptions:

1) Planned interruptions: interruptions for which network users are informed in advance. They usually happen when the system operator intentionally switches a circuit breaker leaving part of the network without energy [9]. In Spain, planned interruptions are the one declared by a distribution company 72 hours in advance to the Regional Government and authorized by them [7].
2) Unplanned interruptions: on the opposite to the planned ones, the users are not informed in advanced. They are due to unpredictable events like the failure of components.
3) Exceptional events: natural disasters like hurricanes or earthquakes.

Regarding to the duration of the interruption we can distinguish among short (less than three minutes), long (more than three minutes) and transient (few seconds) interruptions.

In order to measure the continuity of supply different indicators are used, the most used ones are the SAIDI, the SAIFI and the ENS. These indexes will be deeply explained in chapter number 2.

The indexes mentioned above are reliability indexes. We can understand by reliability the ability of a system to function for a concrete period of time under specific characteristics. So, the reliability of power support is related to the ability of providing customers with continuous and non-disturbed service.

In reliability engineering the bathtub curve is widely used to express how the electrical system and its components work with time.

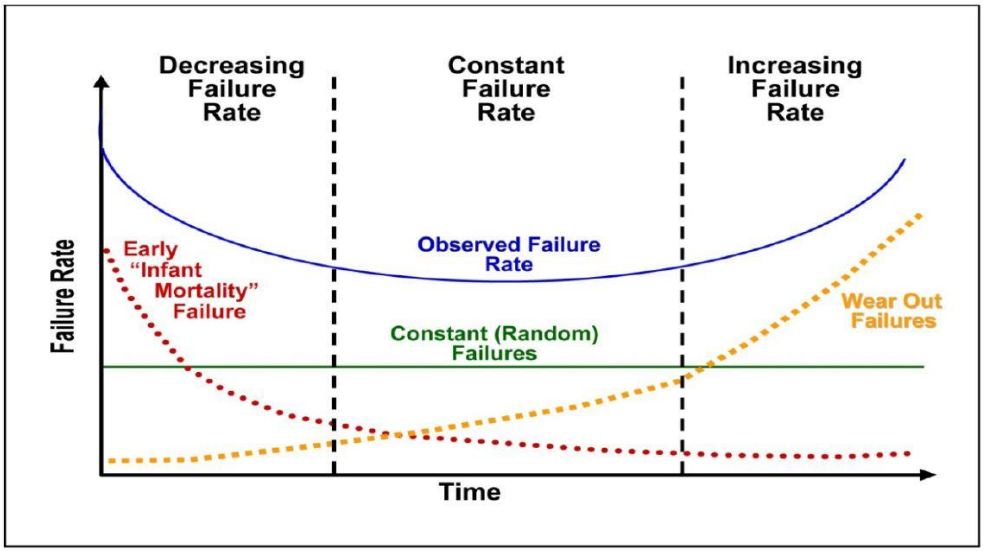


Fig. 3: Bathtub curve **[10]**.

This curve comprises three parts:

- Part I: this part is a rapidly decreasing failure rate. It receives the name of Burn-in period and it is characterized by failures due to manufacturing details. In the electrical power system this part of the curve can be due, for example, to a wrong installation of cables.
- Part II: this part is a constant failure rate due to random failures. This part of the curve represents the useful life of the electrical system. The failures that are represented in this part of the curve are failures due to random

events such as the falling of a tree, the impact of a lightning into an electrical line…

- Part III: this part represents an increasing failure rate. It is known as wear-out failures. It is caused by the aging and deterioration of the equipment. Modern electronic equipment is made up of semiconductor devices that have no real short-term wear out mechanism. Because of that, the part III of the bathtub curve of the electrical system is practically flat, as failures caused by electronic equipment don't have to be considered.

Consequently, we can consider that the reliability curve followed by the electrical power system is a bathtub curve with a flat third part.

Continuity of supply is a very important issue nowadays as an interruption of power in a city can be the cause several incidents, for example:

- Interruption of water supply in buildings, as the water pumps need electricity to function
- Stoppage of electrical vehicles such as trains
- Chaotic traffic as power is needed for the working of traffic lights
- Important economic impact as the production in industries may be totally stopped

Due to this we can affirm that continuity of supply is crucial. Interruptions of power supply, that affect continuity, will be studied in this project.

1.1.1.3. Power quality

Power quality is defined in the IEEE 100 Authoritative Dictionary of IEEE Standard Terms as "the concept of powering and grouping electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment. Utilities may want to define power quality as reliability" [11]. So, it refers to both the disturbances and the deviations in voltage magnitude or waveform from the optimal values.

Power quality includes the variation of voltage, current and frequency. Historically, most of the power equipment has worked, without big problems, with fluctuations of those three parameters. The problem is that currently most of the equipment used cannot function properly with those fluctuations as they are more sensible to them that the ones used before [12]. Therefore, power quality is an important matter for electricity consumers especially for industries and the services sector.

Moreover, as currently sensitive power electronic equipment and non-linear loads are used in industrial, commercial and domestic applications power quality is becoming one of the most technically-complex part of quality of electricity supply and it is also becoming one of the most important issues dealt with by the different countries [7]. It is estimated that the cost of the losses due to power quality comes to 150 billion € in Europe and 119-188 billion $ in US [13]. So, poor power quality has also a big economic impact.

Furthermore, power quality is a very complex matter of study as three parties are in charge of it:

1. Producer of energy and operator of the system: they are in charge of producing energy that satisfies the necessary requirements. They also need to meet instantaneously the energy demanded at each moment by the network users.
2. Manufacturer of electrical equipment: they need to provide the market with equipment that sends out the lowest level of disturbances to the network. Also, it is mandatory for this equipment to be robust enough to support the already existing disturbances in the network. The EN 61000 specifies that it is necessary to study the electromagnetic compatibility of the equipment so that, there is a limited generation of disturbance and tolerance towards a specified level of disturbance [8]. Manufactures, in order to know if they are doing it correctly, can then ask themselves 'How good is good enough for electrical equipment? This question is impossible to answer. As it may be

really easy to determine the behavior of the equipment against some disturbances like voltage dips it is not as easy to determine how it will react against other disturbances like harmonic distortion [14].

3. Network user: they are responsible for selecting and installing the necessary equipment to limit the disturbances introduced in the network. They are also responsible for installing equipment to prevent the interruption of the electrical energy (such as UPS) if it is necessary [15].

As it is stated the power quality depends on these three parties and the relation between them. Quality standards are fixed (they will be explained at the end of this chapter) and, in order to keep them, the supply system, the manufactures of the electrical equipment and the network users have to be coordinated.

Aspects related to power quality can be classified into two categories: voltage stability and voltage waveform.

- **Voltage stability**

Voltage stability refers to the limits of voltage and frequency that cannot be overpassed. Among the disturbances that affect voltage stability we find:

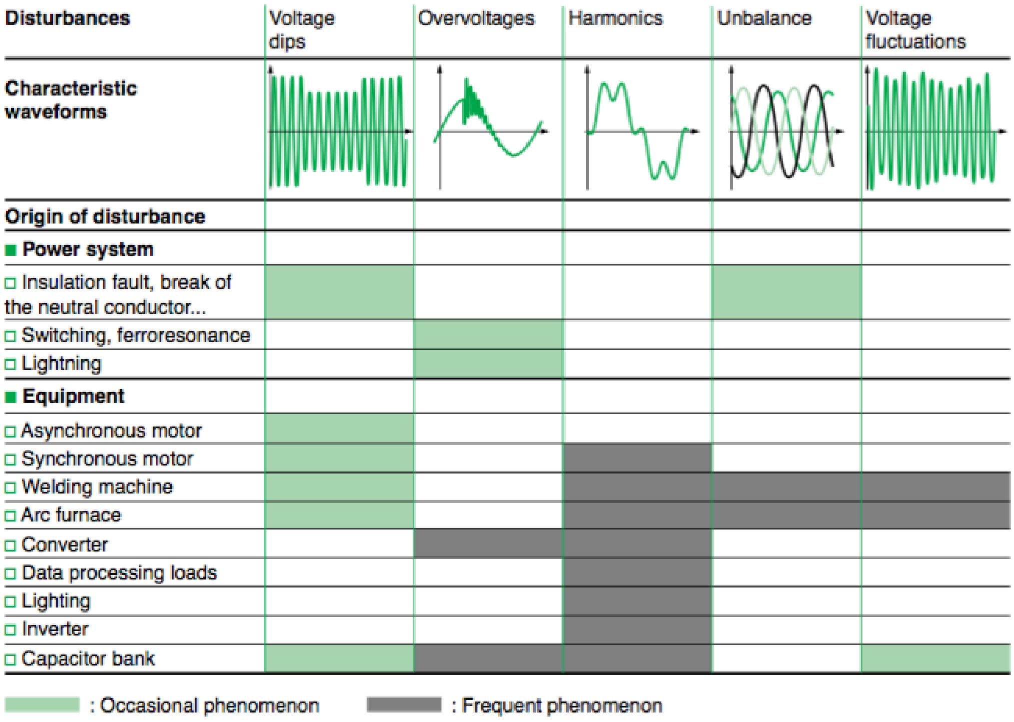
- *Over-voltage:* raising of the voltage above its upper designed limit caused by line faults and large load disconnections. Some of the effects caused are the malfunctioning of the elements connected to the system and the damaging of the insulation of the electric equipment [8].
- *Voltage Sag or Voltage Dip:* sudden and brief voltage drop caused by faults in order lines. Among its effects we can find the malfunctioning of electronic and protection equipment, the change in the speed of motors, faults and errors in computerized processes… [8].
- *Voltage Swell:* opposite of the voltage sag or voltage dip, it is an increase in voltage caused when a heavy load turns off in a power system.

- *Voltage fluctuations:* they are variations in the RMS value or in the peak value with an amplitude less than 10% of the nominal voltage. They are mainly due to rapidly varying industrial loads like arc furnaces or rolling mills [5].
- *Flicker:* changing in the intensity of the illuminated flow that affects the human vision. It is usually generated by fluctuations in the electrical network caused by loads whose active and reactive power demand change constantly.

- **Voltage waveform**

As its own name indicates, voltage waveform refers to the form of the voltage wave. The main disturbances that can affect this are:

- *Unbalance:* event that takes place when, in a three-phase system, the RMS values of each phase are different or their dephasing is different to $\pm 120^{\underline{o}}$. This can be caused by large single-phase loads, unbalanced three phase loads or unbalanced load distribution. It can be the cause of an increasing in the energy losses, the malfunctioning of electronic equipment, the reduction of power transfer and the braking torques and overheating of rotating machines [8].
- *Harmonics:* they are sinusoidal voltages with frequencies *k* times the fundamental frequency (50Hz). The origins of these disturbances are: loads with no sinusoidal currents, industrial loads such as rectifiers or arc furnaces and domestic loads like TV sets or fluorescent lamps. Its main effects are: the increasing of losses, electrical energy measurement errors, interferences in the telecommunication systems, overheating of motors and capacitates and the malfunctioning of control and protection electronic equipment [8].
- *Notch:* recurring power quality disturbance that occurs when current is commutated from one phase to another. It is caused by the normal operations of power electronic devices.



Disturbances	Voltage dips	Overvoltages	Harmonics	Unbalance	Voltage fluctuations
Characteristic waveforms					
Origin of disturbance					
■ Power system					
□ Insulation fault, break of the neutral conductor...	🟩			🟩	
□ Switching, ferroresonance		🟩			
□ Lightning		🟩			
■ Equipment					
□ Asynchronous motor	🟩				
□ Synchronous motor	🟩		▨		
□ Welding machine	🟩		▨	▨	▨
□ Arc furnace	🟩		▨	▨	▨
□ Converter		▨	▨		
□ Data processing loads			▨		
□ Lighting			▨		
□ Inverter			▨		
□ Capacitor bank	🟩	▨	▨		🟩

🟩 : Occasional phenomenon ▨ : Frequent phenomenon

Fig. 4: Some of the disturbances that affect voltage quality **[5].**

In order to study and fix these disturbances it is necessary to know their causes, effects and how to measure and avoid them. A deeper study on the most important disturbances can be found in chapter number 2.

1.2. Regulation

As electricity is a product it should satisfy some quality requirements. Therefore, it is desired that the electrical energy is supplied at a constant frequency and magnitude and with a perfect sine wave [15].

The EN 50160 is the European Standard in charge of establishing the voltage parameters of the electrical energy in public distribution systems. This standard establishes general limits for the supplier to maintain in public distribution systems.

It is important to clarify that the EN 50160 deals with the supply voltage whereas the EMC standard EN 61000 refers to the utility voltage. The supply voltage is the line-to-line or line-to-neutral voltage in the point of common coupling. The point of common coupling, PCC, is defined by the IEEE 519 "Standard Practices and Requirements for

Harmonic Control in Electrical Power Systems" as the interface between loads and sources in the electrical system. On the other hand, the utility voltage is the line-to-line or line-to-neutral voltage at the plug of the electrical device [6]. As this project refers to the supply voltage only EN 50160 will be presented.

In order to understand the EN 50160 standard is necessary to know the meaning of some parameters:

- *Supply voltage:* RMS value of the voltage at a given moment at the PCC, measured over a given time interval.
- *Nominal voltage of the system (U_n):* voltage by which a system is designated or identified and to which certain operating characteristics are referred.
- *Declared supply voltage (U_c):* it is normally the nominal voltage of the system.
- *Normal operating condition:* the condition of meeting a load demand, systems switching and clearing faults by an automatic protection system in the absence of exceptional conditions due to external influences or major events.
- *Voltage variation:* increase or decrease of voltage, due to variations of the total load of the distribution system or a part of it.
- *Supply voltage dip:* sudden reduction of the supply voltage to a value between 90% and 1% of the declared U_C, followed by a voltage recovery after a short period of time.
- *Supply interruption:* is a condition in which the voltage at the supply terminals is lower than 1% of the declared voltage U_C.
- *Temporary power frequency overvoltage:* overvoltages that have a relatively long duration, usually for a few periods. They are mainly originated from switching operations or faults, e.g. sudden load reduction, or disconnection of short circuits.
- *Transient overvoltages:* are oscillatory or non-oscillatory, highly damped, short overvoltages with a duration of a few milliseconds or less, originating from lightning or some switching operations, for example a switch-off of an inductive current.

- *Harmonic voltage:* a sinusoidal voltage with a frequency equal to an integer multiple to the fundamental frequency of the supply voltage.
- *Interharmonic voltage:* is a sinusoidal voltage with frequency between the harmonics, i.e. the frequency is not an integer multiple of the fundamental.
- *Voltage unbalance:* is a condition where the RMS value of the phase voltages or the phase angles between consecutive phases in a three-phase system are not equal [8].

Moreover, it is important to clarify that the EN 50160 only applies under normal conditions. Therefore, the following ones are excluded:

- Conditions arising as a result of a fault or a temporary supply condition.
- In the event of the failure of a customer's installation or equipment to comply with the relevant standards or with the technical requirements for the connection of loads.
- In the events of the failure of a generator installation to comply with relevant standards or with the technical requirements for interconnection with an electricity distribution system.
- In exceptional situations outside the electricity supplier's control such as:
    - Exceptional weather conditions and other natural disasters
    - Third party interference
    - Actions of public authorities
    - Industrial action (subject to legal requirements)
    - Force majeure
    - Power shortages resulting from external events

It is important to note that, during any of those abnormal conditions, the power supply should be maintained to as many customers as possible, even if some of the voltage characteristics are deteriorated. This if preferred to completely interrupting the supply.

All the information included in EN 50160 corresponds to the general limits that are technically and economically feasible for the energy supplier in a region. If, for any reason, a consumer requires tighter conditions then he will have to come to terms with the supplier.

The requirements included in the standard EN 50160 are presented in the following table number 1 and some of them are also shown graphically in figure number 5.

Number	**Parameter**	**Supply Voltage characteristics according to EN 50160**
1	Power frequency	LV, MV: mean value of fundamental measured over 10s $\pm 1\%\ (49.5 - 50.5\ Hz)$ for 99.5% of week $-6\%/+4\ \%\ (47 - 52\ Hz)$ for 100% of week
2	Voltage magnitude variations	LV, MV: mean value of fundamental measured over 10s $\pm 10\%$ for 99.5% of week, mean 10 minutes RMS value
3	Rapid voltage changes	LV: 5% normal 10% frequently $P_{lt} \leq 1$ for 95% of the week MV: 4% normal 6% frequently $P_{lt} \leq 1$ for 95% of the week
4	Supply voltage dips	Majority: duration <1s, depth<60% Locally limited dips caused by load switching on: LV: 10-50%, MV:10-15%
5	Short interruptions of supply voltage	LV, MV (up to 3 minutes): few tens-few hundreds/year Duration 70% of them <1s
6	Long interruptions of supply voltage	LV, MV (longer than 3 minutes) <10-50/year
7	Temporary, power frequency overvoltages	LV: <1.5 kV RMS

		MV: 1.7 U_c (solid or impedance earth) 2.0 U_c (unearthed or resonant earth)
8	Transient overvoltages	LV: generally, <6kV, occasionally higher; rise time: ms-µs MV: not defined
9	Supply voltage unbalanced	LV, MV: up to 2% for 95% of week, mean 10 minutes RM values, Up to 3% in some locations

Table 1: Supply voltage requirements of EN 50160. LV: Low Voltage (0-1kV), MV: Medium Voltage (1kV-30kV).

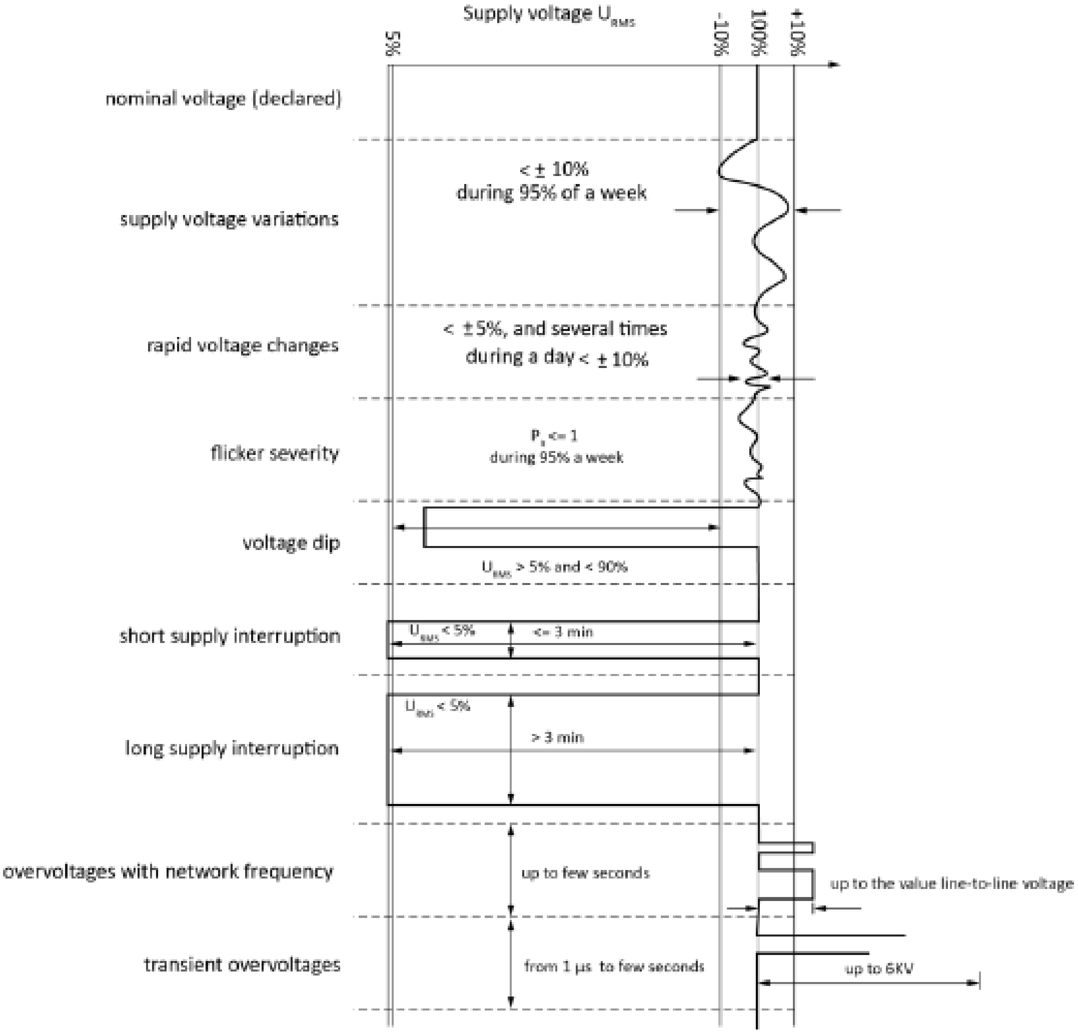


Fig. 5: The most important parameters of standard EN 50160 in graphical form **[15].**

1.3. Objectives

The main objective of this project is to analyze the technical and economic impacts that poor quality of electricity, and especially poor continuity of supply, have on the customers of electrical distribution companies. The current Spanish regulation on electrical supply quality will be reviewed too. Moreover, the different solutions to avoid electrical disturbances are also going to be studied.

An economic study of the impact of climate change on electrical disturbances will be carried out in order to study if the installation of an UPS storage system is economically profitable for electrical distribution companies or not.

1.4. Structure

The structure followed in this project will now be presented.

In this Chapter a general introduction to the quality of electricity and its regulation can be found.

In next Chapter, we will deeply study the electrical disturbances: definition, types, causes, effects and how to measure them. Who is responsible for them can also be found.

Then, in Chapter 3 the electrical disturbances from an economic point of view will be presented. We will study the cost arising from electrical disturbances and the cost of the different technical solutions to avoid them in order to determine which solution is the best in economic terms.

In Chapter 4, how the climate change will affect electrical disturbances will be studied. There, two scenarios will be presented in order to know the differences between them and if it is or not economically profitable to install a storage system.

In Chapter 5 the conclusions of the project will be exposed.

Finally, Chapter 6 and Chapter 7 are bibliography and annexes.

1.5. Conclusion

Once this chapter has been finished, the concept of power quality has been introduced. The quality of electricity is divided in two main aspects: the quality of the customer service and the quality of the power supply including the power quality and the continuity of supply. As it is an important feature of power it is regulated by the law.

As it is stated power quality has a huge impact not only economically but also technically as there are some devices that require a certain quality in order to work properly. So, if those requirements are not fulfilled, then introducing storage devices in the system may be necessary. Those devices will be studied in next chapter.

CHAPTER 2:

ELECTRICAL DISTURBANCES

2. ELECTRICAL DISTURBANCES

The two main objectives of quality of supply in a power system operation should be:

1. Security and stability of the system
2. Reliability and quality of the supply

Nowadays, almost every average consumer receives the amount of energy demanded but the quality and reliability of that energy may vary over time and depending on the region. Quality issues can be accepted in part or the world while in others the power quality requirements are increasing. So, currently some customers expect higher-quality and continuity of electrical power supply with reductions in the interruptions and other disturbances like harmonics [16].

Therefore, in order to fulfill these requirements, it is necessary to study the causes, effects and possible solutions that cause not accomplishing them.

An electrical disturbance is caused by a change in the normal conditions of the electrical power system. This change of conditions can be the result of accidental (a lightning’s impact on a transmission line) or scheduled (the disconnection of a hydro-electric power plant in order to improve it) events. Therefore, when studying electrical disturbances, it is important to distinguish between these two type of causes as, the effects caused by the intentional ones can be partly avoided. Moreover, if the interruption of power is due to premeditated causes the users should be informed in advance.

2.1. Definition of some electrical disturbances

As it has been mentioned before, quality of supply includes continuity of supply and power quality. Among all of the existing disturbances short and long interruptions, voltage dips and swells will be studied deeply in this chapter. Any interruption of power supply causes a change in the normal conditions of the electrical system so, there is a transient during which the electrical conditions of the system pass from one steadystate to another. The causes and effects of supply voltage variations will be also presented.

In figure number 6 we can find the different disturbances that are going to be analyzed in this chapter. They are classified depending on the area of quality of supply that is affected by them: voltage quality or continuity of supply.

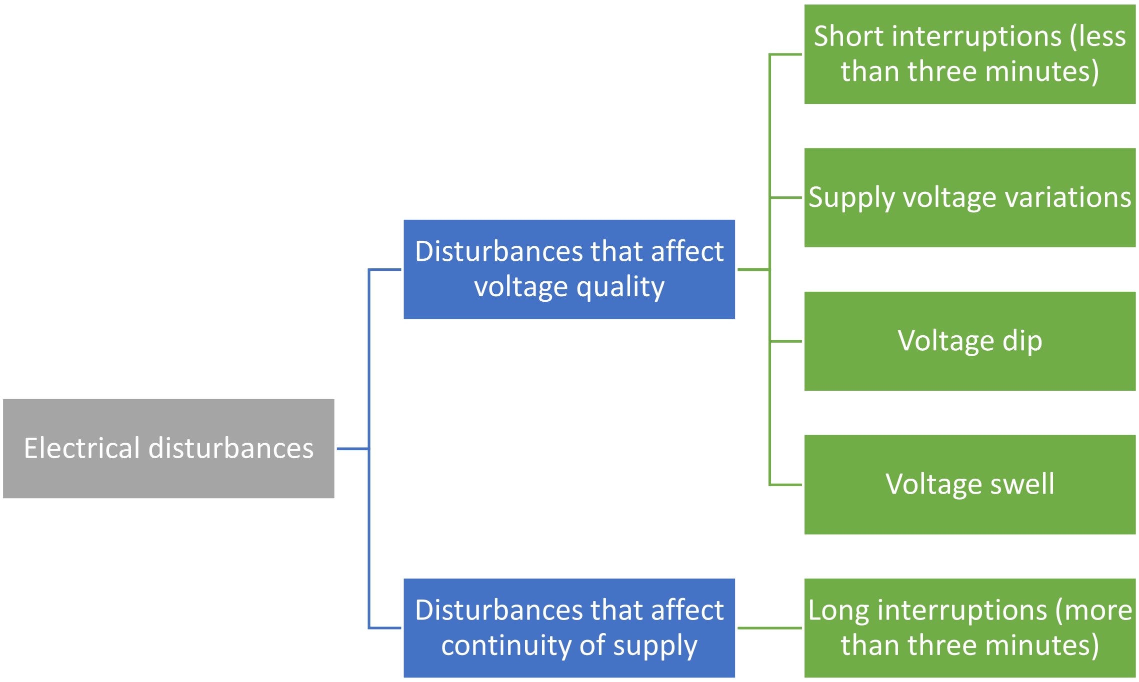


Fig. 6: Electrical disturbances that are going to be studied classified by the area of quality of supply that is affected by them.

2.1.1. Supply voltage variations

Supply voltage variations are increases or decreases of the voltage value. They are usually caused by load variations.

2.1.1.1. Causes

If the electrical system were perfect, the value of the voltage in the different points of the electrical system would only depend on the transforming relations of the transformers. But, as the lines and the transformers on the electrical network have an internal impedance, there is current that flows through those impedances. That flow of current produces voltage’s drops in the net. On the other side, if the loads were constant, the voltage drop would be constant too so there will not be voltage variations so the load's voltage would only depend on the AT voltage. The main problem is that the loads in the electrical network are variable, they change hourly depending on the exterior temperature, humidity, the hour of the day, if it's a weekday or a weekend day… These loads variations are the sources of the voltage variations in the different loads [17].

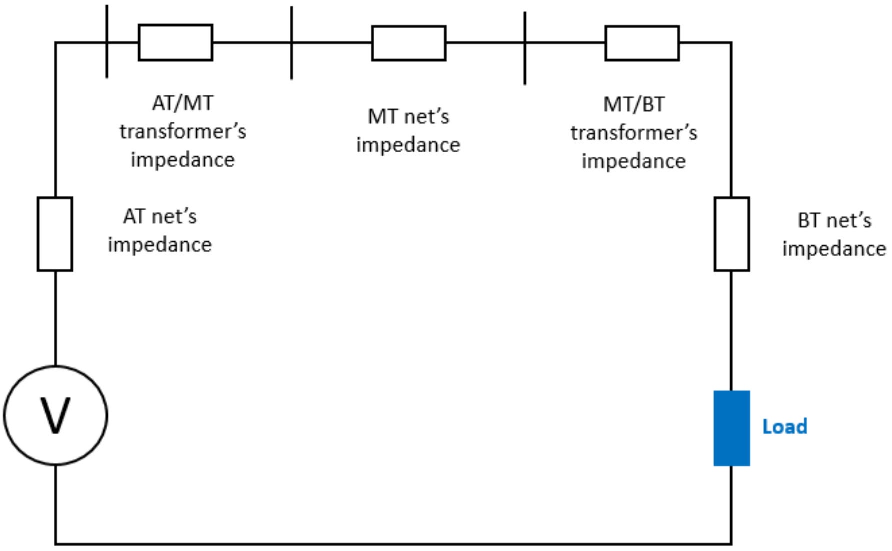


Fig. 7: Equivalent monophasic scheme of the electrical network.

2.1.1.2. Effects

The effects of voltage variations are numerous depending on the load. For example, if the load is a lamp, over-voltages will reduce its life while under-voltages will increase it. In induction motors it will cause alterations in its starting torque and percentage slip. It will also affect the amount of reactive power given by capacitors as it depends of the voltage [18] .

2.1.2. Voltage dips

A voltage dip or voltage sag is a sudden and brief reduction of the voltage in an or all of the electrical phases. It happens when the RMS of voltage decreases between its 10 and 90% of nominal voltage and it recovers after a short period of time (normally between 10ms and a few seconds).

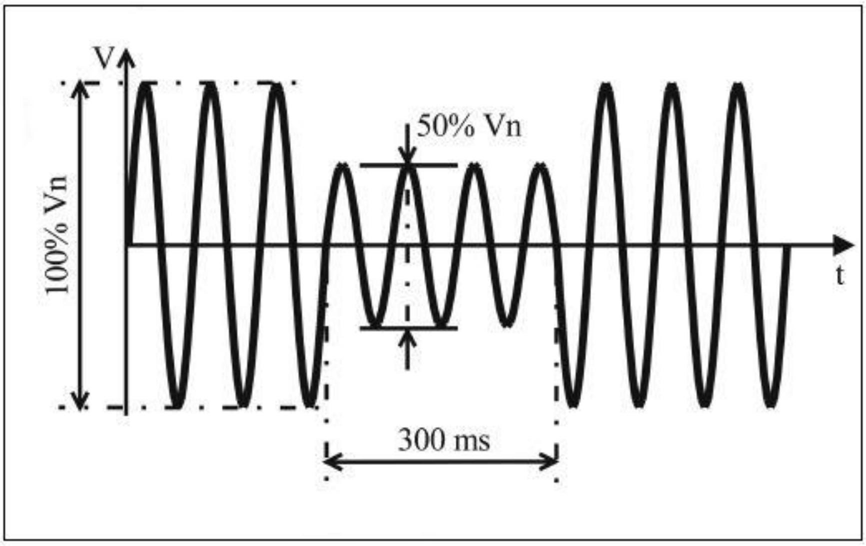


Fig. 8: Voltage dip **[19]**.

We can distinguish between balanced and unbalanced voltage sags. The first are the ones that affect equally to the three phases maintaining the 120º angle between them. When an unbalanced voltage dips occurs the fault affects differently to the three phases so the angle between them doesn't remain always the same. The unbalanced voltage dips are more frequent in the real world than the balanced ones.

It may seem obvious that the voltage dip takes place in the peak of the sine wave or near it as there is more energy at that moment. But, researches have demonstrated that the dip initiation is a random thing [16]. Moreover, depending on where the voltage dip takes place there may be a change in the voltage waveform. As we can see in figure number 9 if the dip happens in the zero crossing of the wave it will maintain its symmetry while it occurs somewhere else, it will not. There can also be a change in the phase of the sine wave depending on the fault's current and the value of the impedance of the transmission line where the voltage dip takes place.

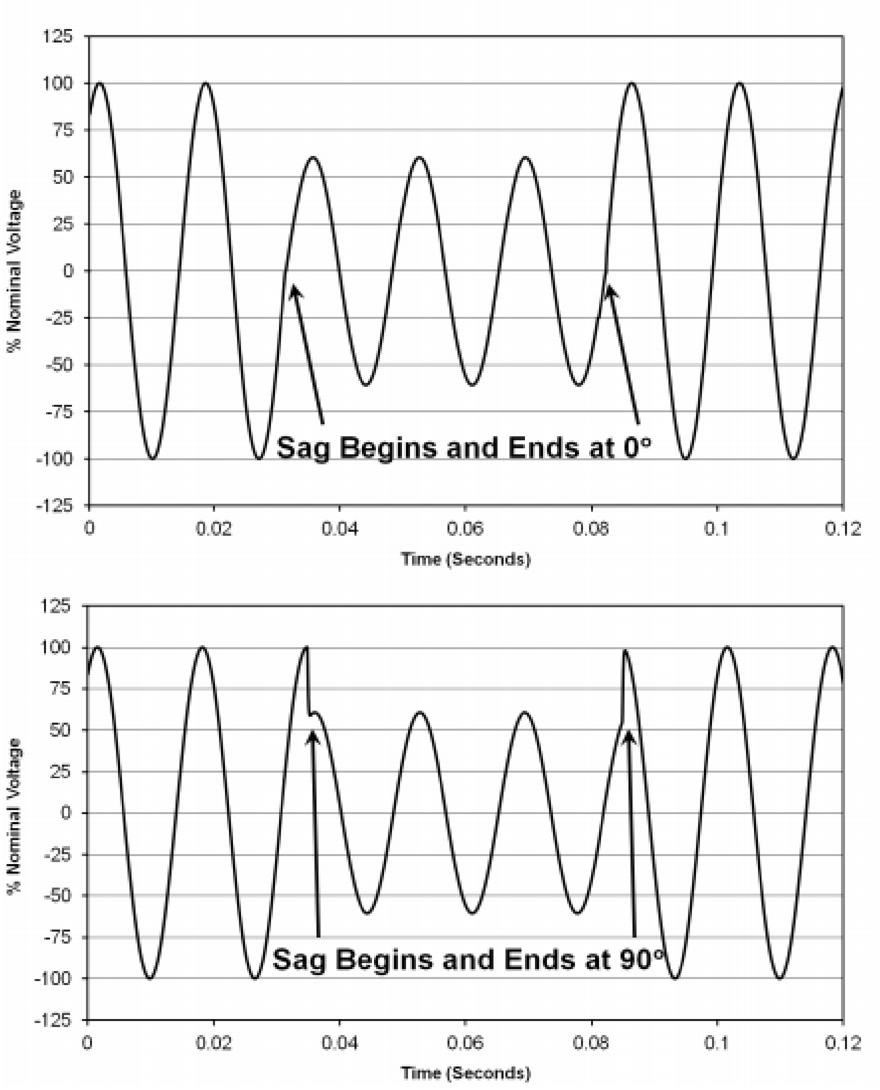


Fig. 9: Waveform change in two voltage dips starting at a different moment **[16]**.

2.1.2.1. Causes

The electrical power system has a non-zero impedance therefore, any increase in the current's value causes a reduction in the voltage's value (Ohm's law). These reductions are usually small hence the voltage remains within the regulated tolerances. The problem is that, when there is an increase in the current or in the value of the system's impedance, the voltage can drop considerably. It is more unlikely for the impedance to increase than for the current so, voltage dips are usually caused by increases in the second one. Therefore, the main causes of increasing the current (and consequently of voltage dips) are:

- Starting a large load, usually industrial ones like motors
- Defective wiring
- Faults caused by lightning, tree contact, birds… in the transmission lines

As we can assume from the information shown above, the majority of the voltage dips are caused in the distribution and transmission lines so, they are responsibility of the energy supplier.

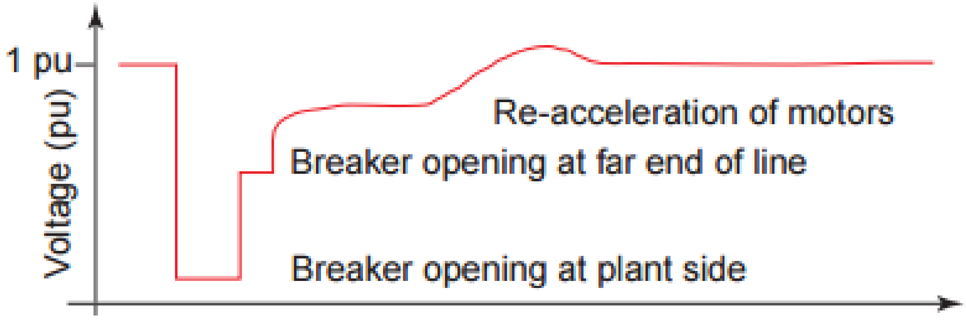


Fig. 10: Voltage dips with its different causes **[20]**.

In order to describe the power system's behavior is usual to compare it to a tree: the trunk is the substation where the voltage is fixed, the branches are the transmission lines and the leaves are the customer's loads. Any voltage dip in the trunk or in any of the branches leading to the leaf will have a negative effect in the leaf (the customer's load). Similarly, if there is any problem in one of the loads or one of the distant branches, this could cause a decrease in the voltage of the trunk, provoking also a voltage dip in the leaves. So, even faults that take place far in the tree can cause a voltage dig in a leaf on the other side of the tree [19].

Whenever a fault takes place the electrical protections are in charge of recognizing the fault and isolating it in a short amount of time. During the time that it takes them to clear up the fault the voltage dips occurs so, the extent of voltage dips depends on the reclosing capability of the protections.

2.1.2.2. Effects

The effects of the voltage dip in the power systems are various and more harmful when the decrease of the voltage is deeper. As the voltage dip is a brief disturbance, only the sensitive equipment will be affected by it. During a voltage dip the energy that is supposed to reach the loads doesn’t reach them so, depending on the type of load the consequences may or not be important. For example, if a motor doesn’t receive the required energy it will obtain it from the inertia of the drive, causing its stalling.

Other effects are the tripping of sensitive equipment, instantaneous dimming of lamps and the resetting of control system [14].

2.1.1. Voltage swell

A voltage swell is rapid increase in the RMS value of the voltage, usually phase to neutral, above its nominal value ranging from 1.1pu to 1.8pu and that last for half a cycle up to one minute. We can say that they are the opposite to voltage dip but much less common.

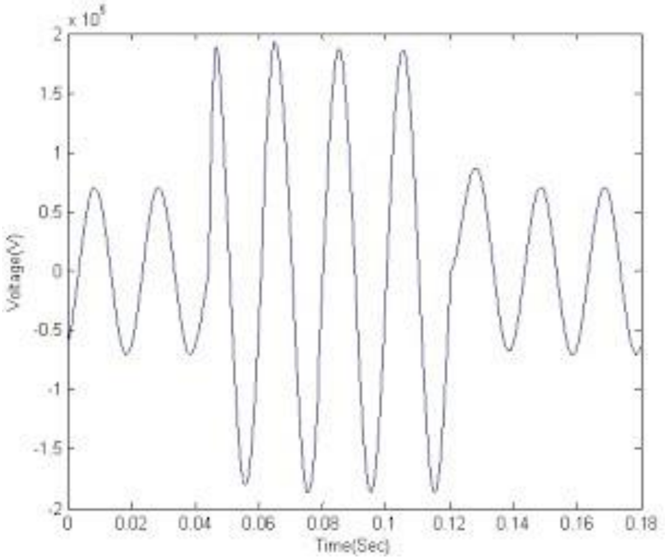


Fig. 11: Voltage swell **[21]**.

Depending on its magnitude and duration voltage swells can be subdivided in three categories:

Type of voltage swell	Magnitude	Duration
Instantaneous	1.1-1.8pu	0.5-30 cycles
Momentary	1.1-1.4pu	30 cycles-3s
Temporary	1.1-1.2pu	3s-1min

Table 2: Types of voltage swells **[22]**.

2.1.1.1. Causes

The main causes of voltage swells are the line faults, switching off and on large loads and the energization of capacitor banks.

2.1.1.2. Effects

The effects of the voltage swells are often less noticeable but more destructive than the voltage dip ones. Consequences from voltage swells are: malfunctioning of electrical equipment, control problems and hardware failure in the equipment and possible damaging of the equipment's insulation due to its overheating.

2.1.2. Shorts interruptions

A short interruption of the voltage supply includes a supply voltage under 10% for a period less than three minutes [8]. This is a more general definition than the given by the standard EN50160 that considers short interruptions the ones with a supply voltage under 1% of the declared voltage supply.

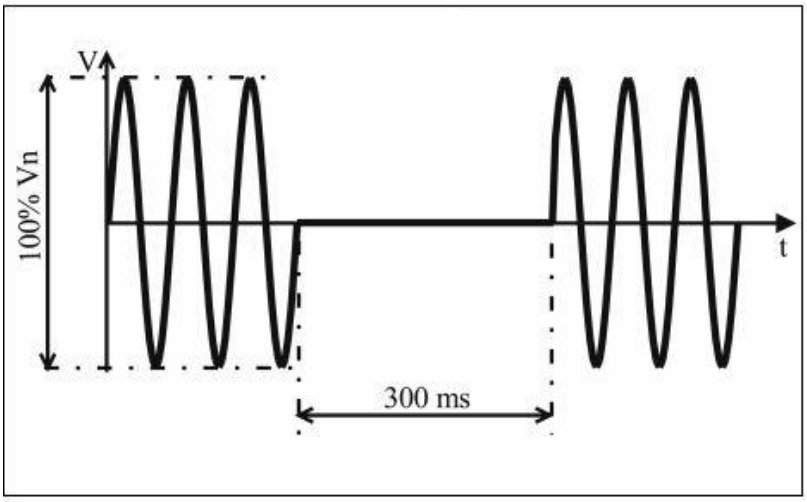


Fig. 12: Short interruption of power supply in which the voltage drops to zero **[19]**.

2.1.2.1. Causes

A short interruption is similar to a voltage dip where, instead of the RMS decreasing between the 10%-90% of its nominal value, the decrease is complete. Short interruptions are usually accidental and caused mainly by short-circuits. They can also be caused by electrical overloading but this is not so common. The causes of the short-circuits can be divided into two sections:

- Incidents in the lines' insulation: they depend on the characteristics of the place. As it has been mentioned at the beginning of this project underground lines are usual in large urban centers or in historical places while overhead ones are used in more rural environments. As the insulation of the underground cables can only be damaged by drillings or excavators, overhead lines are the ones that suffer more incidents in their insulation. Those incidents are caused by contamination, gales, falling of trees, high salinity…
- Overvoltages that overtake the networks' insulation: the main origin of these overvoltages are the storms' lightings. The overvoltages produced by lightings can be of millions of volts [17].

2.1.2.2. Effects

The consequences of short interruptions are similar to the ones caused by voltage dips. Therefore, they may cause the following issues:

- Stoppage of sensitive equipment like PLC, computers…
- Tripping of protective devices
- Loss of data
- Problems in motors start-up
- Arc lightning switch off
- Malfunctioning of data processing equipment
- Overheating of engines producing an accelerated aging of its insulation

2.1.3. Long interruption

Long interruptions occur when the voltage drops to zero during a period of time longer than three minutes.

2.1.3.1. Causes

The causes of long interruptions are always the outage of equipment. This outage can be due to three different reasons:

- Fault that occurs in the electrical system and needs human intervention in order to fix it.
- Incorrect intervention of a protection causing a component outage.
- Operator action: currently it is possible to do live-line working in order to maintain the continuity of supply while fixing some of the components of the electrical network. But, due to security reasons, there are certain works than cannot be done by live-line working so, during those events is necessary to isolate the section where the maintenance work is taking place. As it has been mentioned before, the distribution system should follow the N-1 or N-2 criterion. So, even if one of the elements is not available the power supply shouldn't be

interrupted. The problem is that it is not always possible to constantly maintain all the power supply.

If these events take place in a part of the system that is not redundant (so the necessary energy cannot be provided to the customers by another part of the system) a number of pieces or equipment will not have power while the problems is being solved [23].

2.1.3.2. Effects

The consequence of a long interruption will be the stoppage of all the equipment as they don’t receive the necessary energy to work.

2.2. How frequent are electrical disturbances?

As it has been previously presented during the last few years the amount of disturbances in power supply have highly increased. This is due, mainly, to the widespread use of electronic equipment that doesn’t fulfill the necessary requirements to avoid the generation of disturbances. Even though, all these electric disturbances have a big economic impact as they mean losses, not all of them are equally common. Therefore, in order to make an accurate economic evaluation it would be necessary to assess the expected number of disturbances in a specific period of time. This assessment can be done by three different ways:

- Predicting the amount of disturbances and its length. In order to do so, Stochastic prediction methods are used. The accuracy of these methods depends on the accuracy of the model and data used. As some of the electric disturbances are caused by random phenomena, the data used in this type of models is not always the most precise.
- Uninterrupted monitoring in order to measure at all times the characteristics of the voltage: frequency, harmonics, vale… Monitoring is a method used to detect voltage variations such as flickers, harmonics, voltage unbalances… In Spain the law requires to monitor the voltage levels at all times.

- Trigger-mechanism that starts recording when the relevant characteristics exceed a specific value, for example, when a sudden reduction of the voltage takes place. This mechanism is mainly used for detecting voltage dips, swells and transient over-voltages [24].

As it may seem obvious neither the probability of the electric disturbances nor the importance of its effects is the same. In table number 3 we can find the different electrical disturbances studied before according to their probability and the importance of their effects.

	Importance of its effects	**Probability**
Supply voltage variations	Low	Low
Voltage dip	Medium	Very high
Voltage swell	Medium	Low
Short interruption	High	High
Long interruption	Very high	Medium

Table 3: Classification of electrical disturbances according to their probability and importance of its effects **[17]**.

As we can see in the table number 3 supply voltage variations have a low probability of occurring and their effects are not as dangerous as the effects caused by the other disturbances. So, even though they impose costs on customers, its economic impact will not be studied as the costs of the other disturbances are much severe. Moreover, voltage swells will not be analyzed in deep detail because they rarely occur and the impact they have is not very important.

It has been previously explained that we can divide the quality of supply into three main aspects: continuity of supply, voltage quality and commercial quality. Depending on the type of disturbance the area of quality of supply affected is different. Therefore, we will classify the disturbances by this criterion. Voltage dips, voltage swells and short interruptions affect the voltage quality while long interruptions affect the continuity of supply.

2.3. How to measure continuity of supply

Continuity of supply is the area of quality of supply that studies how the long interruptions (understanding by long interruptions the ones that last longer than three minutes) affect the quality of the electricity. Therefore, continuity of supply represents the availability of energy; if electricity is not available at a certain moment then we refer to it as an interruption. It has been explained before that the electric power system is a reliable one, this means that the duration of interruptions is just some hours per year, so the system achieves its function the majority of time. Even so, electrical distribution companies use indexes in order to measure how reliable the system is. Then, once the indexes have been calculated, they use them to implement new strategies in order to improve the continuity. Among the strategies we can find: a change in the topology of the system, reinforcement of some elements…

We can distinguish to main types of indexes: individual or client indexes and system indexes.

Individual indexes reflect the quality level that an individual client experiments. Even though these indexes represent perfectly the state of the system they are not commonly used as they require a high volume of calculations. Electrical companies are starting to use these indexes as they represent better the singular quality of each client so that the company can perfectly know if all of the clients have the correct quality.

On the other hand, system indexes reflect the quality of the whole power system in a particular region. They are usually a weighted average of the individual indexes of the clients in that region so, they represent in a compact and easy way the behavior of the electrical system. But, there are also disadvantages when using these indexes because, as they are an average, there may be clients with quality levels much lower than the average and that cannot be accepted [25].

Among the system indexes we can find the ones that were presented in the first chapter of this project. Those indexes are: SAIDI, SAIFI and ENS. They will be explained above.

The different distribution companies are in charge of providing information to the government of each country in order to calculate the value of these indexes to know how reliable is the energy in each country. Details on the value of these indexes in Spain can be found below but before that it is important to clarify that the Spanish regulation divides the Spanish territory in four types of zones:

- Urban: towns with more than 20.000 points of supply.
- Semi-urban: towns with a number of points of supply between 2.000 and 20.000.
- Gathered rural: towns with a number of points of supply between 200 and 2.000.
- Scattered urban: towns with less than 200 points of supply and points of supply located outside of the population centers that are not industrial nor population sites.

The Spanish territory is divided in zones depending on the population as the electrical network is configured in a different way depending on the location. The rural network is characterized for being arranged like a tree where each customers receives the energy from only one source of supply. By contrast, customers of the urban network usually receive the power from different sources that work in parallel.

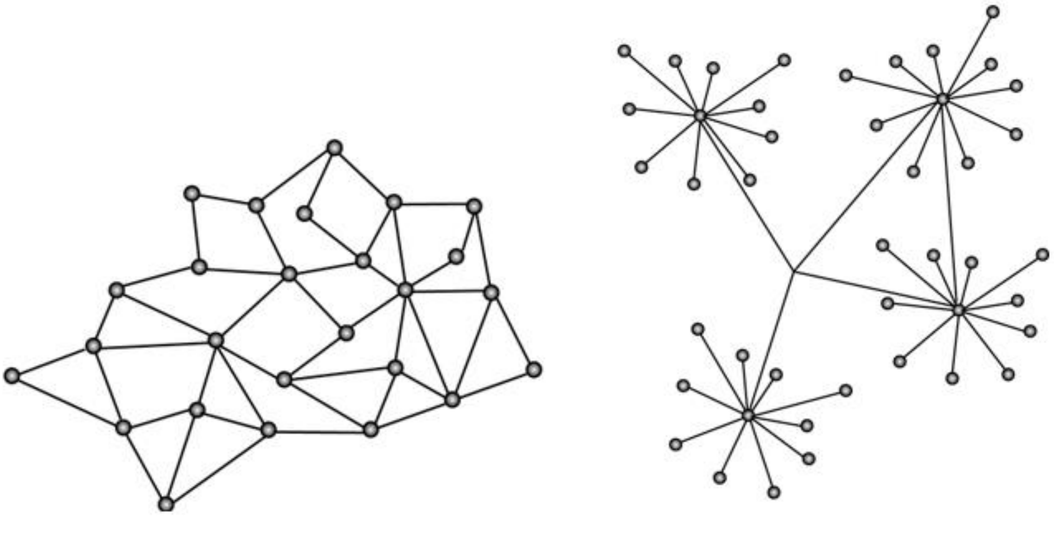


Fig. 13 : Urban network on the right side of the image and rural network on the left side **[26]**.

2.3.1. SAIDI

SAIDI (System Average Interruption Duration Index) is the average duration interruption of service for each customer of the electrical company [27]. The SAIDI is usually calculated monthly or yearly but it can actually be calculated for any period of time. This index is usually measured in hours.

$$SAIDI = \frac{sum\ of\ all\ customers'interruption\ duration}{total\ number\ of\ customers\ served} = \frac{\sum U_i * N_i}{\sum N_i}$$

Where U_i represents the annual failure rate and N_i the number of clients in point *i*.

So, this index represents the average amount of time during which energy was not supplied to the customers in a certain period of time.

In the table number 4 and figure number 14 we can find the value of the SAIDI index from 2003 to 2014 in Spain depending on the zone. We can also find its average value over those years and a 'total' value of each of the indexes that is calculated by doing a weighted average depending on the population of each zone.

		Zone				
Year	**Total**	**Urban**	**Semi-urban**	**Gathered rural**	**Scattered rural**	
2003	2,861	1,714	3,285	4,159	7,881	
2004	2,422	1,541	2,464	3,589	6,373	
2005	2,186	1,444	2,306	3,127	5,008	
2006	2,044	1,194	2,161	3,797	4,587	
2007	1,930	1,224	2,018	3,409	4,206	
2008	1,628	0,932	1,765	2,877	4,014	
2009	2,369	1,077	2,790	4,851	5,693	
2010	2,495	1,205	2,928	4,362	7,725	
2011	1,120	0,671	1,163	1,982	3,364	
2012	1,053	0,656	1,063	1,843	2,539	
2013	1,623	0,616	1,241	3,658	3,508	
2014	1,056	0,594	1,002	1,375	3,202	
	1,899	1,072	2,016	3,252	4,842	**Average**

Table 4: Values of the SAIDI index over the last years depending on the type of zone **[28]**.

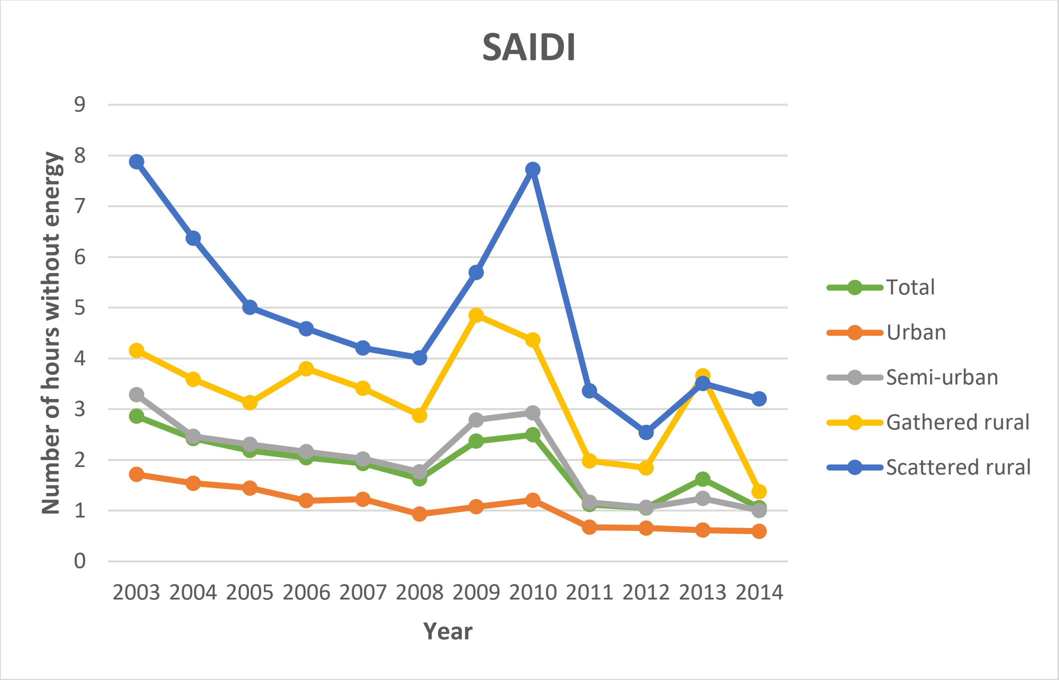


Fig. 14: Progress of the SAIDI index over the las few years.

From the information presented above we can obtain the following conclusions:

- The progress of the SAIDI index is descending, except for a big peak in 2010. This is thanks to the improvements in the power distribution system: automatization of the processes, usage of high efficiency equipment, monitoring of the electric signals…
- The urban zone is the one with the smallest SAIDI's values. As it has been explained before the urban customers receive the power from different sources so, if any of these sources fails, they can still receive the power from elsewhere.
- The scattered rural zone and the gathered rural are the ones with the highest SAIDI's values. This also due to the disposition of this type of network where the clients receive power only from one source. So, when there is a problem in that source, they cannot receive energy from elsewhere as it happens with the urban zones.

- As the population in the rural zones is much less than the population in the urban zones, installing in the rural areas a more interconnected network doesn't economically compensate the electrical companies.

2.3.1.1. SAIDI in different European countries

In figure number 15 we can find the progress of the SAIDI index (or the corresponding index used in each country in order to measure the amount of time without power supply) in different European countries over the last few years. As we can see Spain (in light green color) is not among the countries with less minutes lost per year but it has been improving over the last years.

Moreover, we can perceive that the most industrially developed countries, such as Germany and the Netherlands, are the ones with less minutes lost per year while the less industrially developed ones, like the Slovak Republic, are the countries with more minutes lost per year.

It is also important to note that the countries located in the center of Europe (Germany, Romania, France…) are the ones that have loss the less minutes per year. This can be due to the existing interconnections between these countries and their neighbors. These interconnections can be used to supply power to different zones in the country when the country itself cannot provide it. Obviously, this is a payed service.

Spain, instead, is not located in the center of Europe so it only has interconnections with Portugal, France and Morocco. This limits the amount of energy that can be demanded from other countries as a big number of Spanish regions don't border other countries.

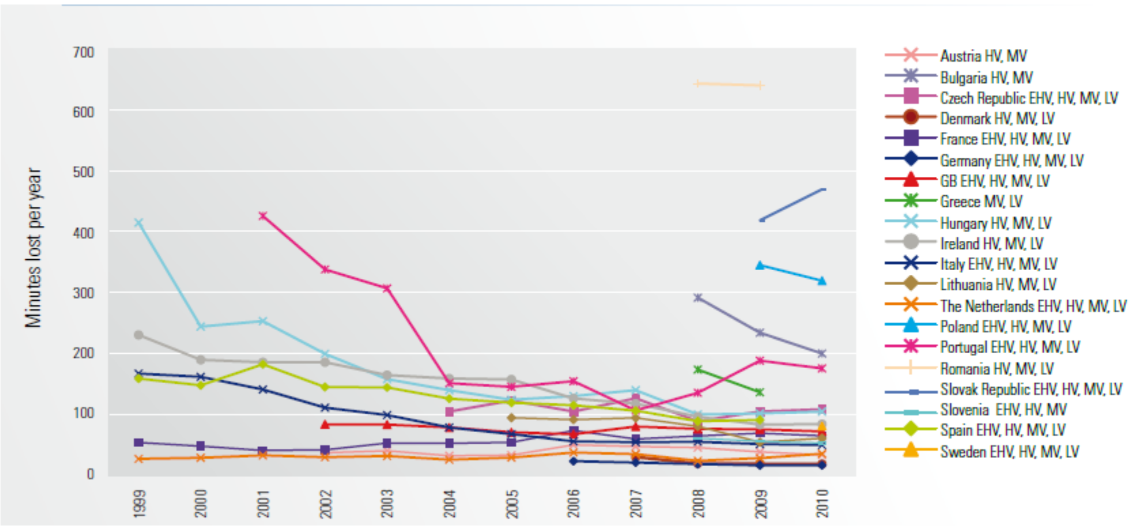


Fig. 15: Minutes lost per year in different European countries over the last years **[7]**.

2.3.2. SAIFI

SAIFI (System Average Interruption Frequency Index) is the average number of times that a customer experiences an interruption of service in a year.

$$SAIFI = \frac{total\ number\ of\ customer\ interruptions}{total\ number\ of\ customers\ served} = \frac{\sum \lambda_i * N_i}{\sum N_i}$$

Where λ_i represents the failure rate and N_i the number of clients in point *i*.

Therefore, this index represents the average number of interruptions suffered by each customer during a specific period of time.

In the table number 5 and figure number 16 we can find the value of the SAIFI index from 2003 to 2014 in Spain depending on the zone. We can also find its average value over those years and a ‘total’ value of each of the indexes that is calculated by doing a weighted average depending on the population of each zone.

		Zone				
Year	Total	Urban	Semi-urban	Gathered rural	Scattered rural	
2003	2,992	2,296	3,292	3,714	5,896	
2004	2,711	2,141	2,757	3,479	5,173	
2005	2,402	1,759	2,623	3,209	4,308	
2006	2,459	1,765	2,660	3,808	4,122	
2007	2,318	1,669	2,531	3,561	3,849	
2008	2,067	1,424	2,284	3,124	3,921	
2009	2,253	1,484	2,520	3,532	4,527	
2010	2,016	1,313	2,218	3,322	4,483	
2011	1,474	1,015	1,599	2,323	3,193	
2012	4,533	0,934	3,740	1,908	4,187	
2013	1,338	0,889	1,584	1,442	3,240	
2014	1,198	0,804	1,243	1,210	3,203	
	2,313	1,458	2,421	2,886	4,175	**Average**

Table 5: Values of the SAIFI index over the last years depending on the type of zone **[28]**.

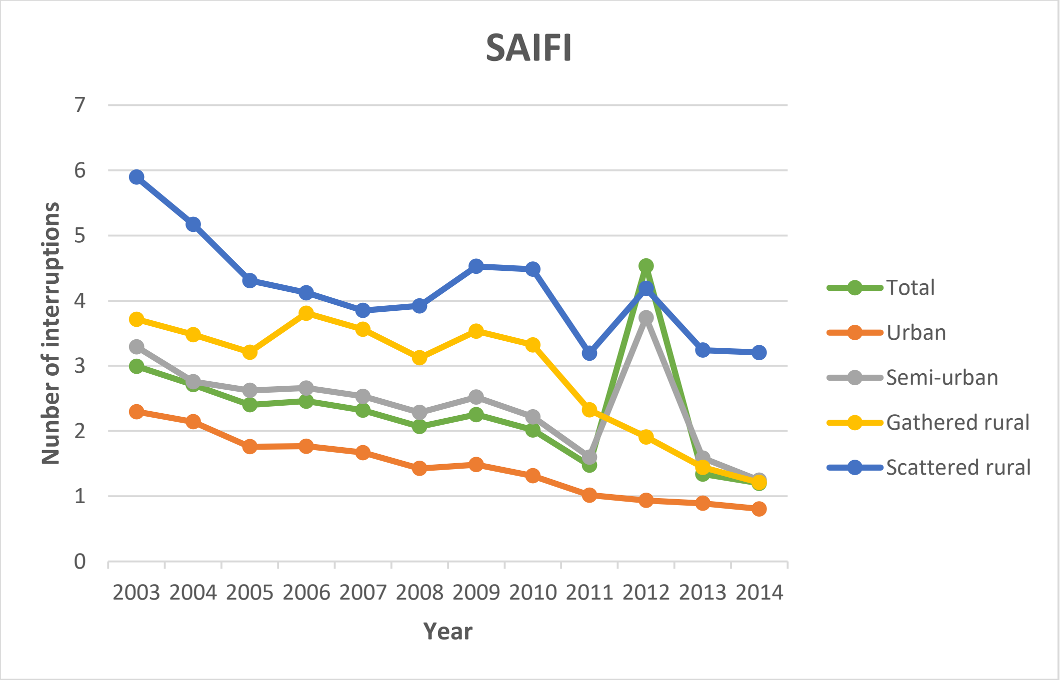


Fig. 16: Progress of the SAIFI index over the las few years.

From the information presented above we can obtain the following conclusions:

- The progress of the SAIFI is similar to the progress of the SAIDI: descending thanks to the improvements on the distribution system. In this case, we can distinguish a peak in 2012 in the semi-urban, gathered rural and scattered rural zones.
- Just like what happened to the SAIDI, the urban zone is the one with the smallest SAIFI's values. This is also due to the distribution of the urban network, where clients can receive power from different points of supply. So, if one point of supply fails its clients will not have their power interrupted as they will be receiving energy from another point of supply.
- Because of the rural disposition of the network, the scattered rural and the gathered rural zones are the ones with the highest SAIFI's values as they cannot receive power from other sources if their usual point of supply fails.

2.3.2.1. SAIFI in different European countries

The number of interruptions per year over the last few years in different European countries can be found in figure number 17. The conclusions that can be obtained from this graphic are similar as the ones obtained from the SAIDI graphic in figure number 15. As we can see Spain (in light green color) is among the countries with more interruptions per year even though this figure has been decreasing over the last years.

Besides, the countries that border more countries, as the Netherlands and Germany, are the ones with the best values of interruptions per year with an average of 0.5 approximately.

As the SAIFI's evolution is correlated with the SAIDI's evolution we can observe that the countries that are more industrially developed are the ones with less interruptions per year.

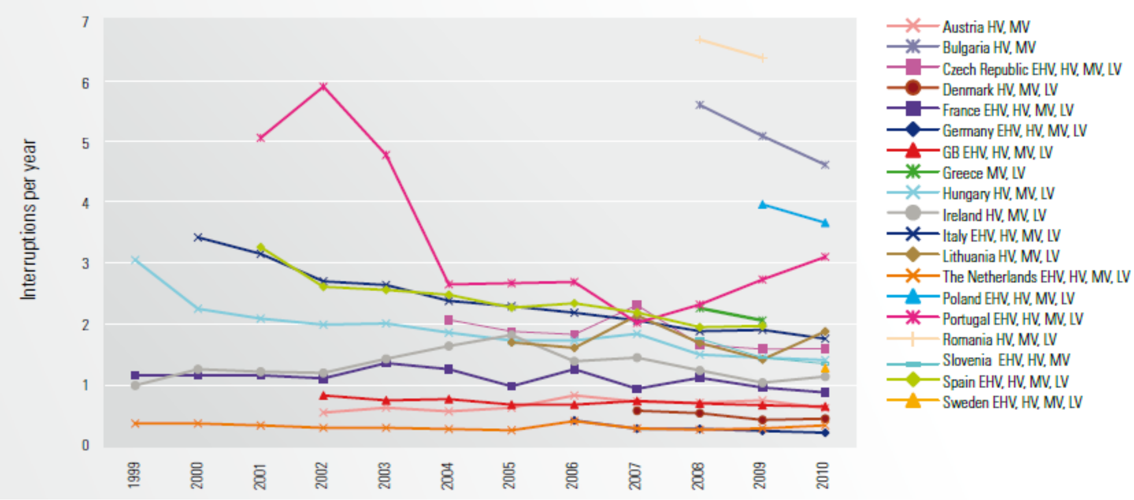


Fig. 17: Number of interruptions per year in different European countries over the last years **[7]**.

2.3.3. SAIFI and SAIDI

In figure number 18 the progress of both indexes can be observed. Even though these indexes measure different things (so they cannot be really compared as they are measured in different units) we can observe that their progression is descendant over the last years. Implicitly, this means that the quality of the energy is Spain is improving as less and shorter interruption are taking place.

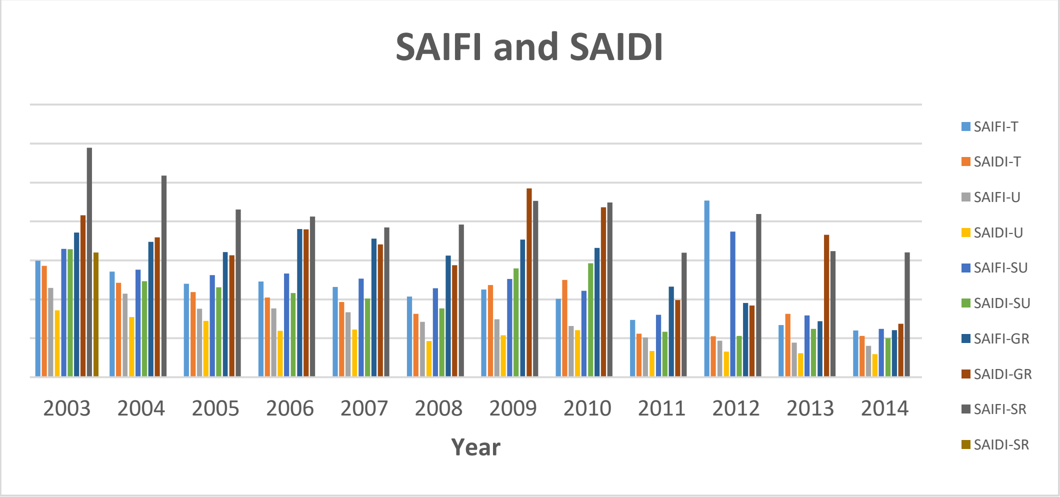


Fig. 18: SAIFI and SAIDI index in the last few years. T: total, U: urban zone, SU: semi-urban zone, GR: gathered rural zone and SR: scattered rural zone.

2.3.4. ENS

ENS (Energy Not Supplied) is an index that measures the quantity of energy that has not been supplied for a year in a certain region.

$$ENS = \sum La_i * U_i$$

Where La_i represents the average energy demanded at knot i and N_i the number of clients in point i.

So, ENS models the energy that wasn't supplied to the customers during a certain period of time due to failures of the system.

In the table number 6 and figure number 19 we can find the values of the ENS index from 2011 to 2015 in Spain. We can also find its average value over those years.

Year	**ENS (MWh)**	
2011	336	
2012	150	
2013	1240	
2014	281	
2015	89	
	419,2	**Average**

Table 6: Values of the ENS index over the last years **[29]**.

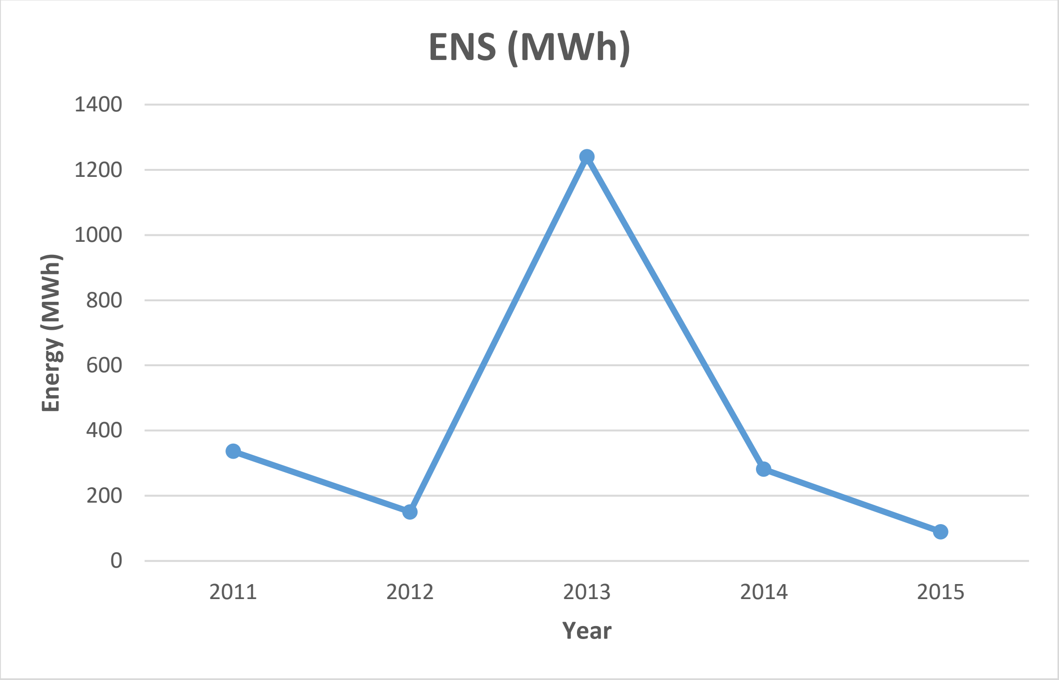


Fig. 19: Progress of the ENS index over the las few years.

From this information on the ENS index we can conclude that its progress is also descendant. As it happened with the SAIFI and SAIDI indexes this implies that the Spanish distribution system is becoming more reliable as more targets on continuity of supply are being accomplished.

2.4. How to measure voltage quality

Voltage quality is the area of quality energy supply that analyses the voltage waveform. Among the disturbances that affect voltage waveform we will focus on voltage dips, voltage swells and short interruptions.

Whenever any of the disturbances mentioned before take place there is a change in the RMS value of the voltage. The RMS value is the square root of the mean value of the squared function of the instantaneous values of the voltage. It represents the amount of AC power that produces the same heating effect as an equivalent DC power.

$$V_{RMS} = \sqrt{\frac{1}{T} * \int_0^T [v(t)]^2 dt}$$

Where *v(t)* represent the voltage waveform and *T* its period.

When a voltage dip or a short interruption takes place the RMS voltage value drops below a threshold. On the other hand, when a voltage swell takes place the RMS voltage value increases above a threshold. These durations last until the RMS voltage value recovers.

Disturbances that affect voltage quality are disturbances that affect a random number of clients; unlike long interruptions that affected a large number of customers. Thus, the level of voltage quality needs to be measured at the point of connection of each client to the distribution. So, a specific voltage quality recorder needs to be installed. This recorder is expensive so, as of today, measuring voltage quality for every single customer on a distribution network is not economically feasible. What is currently done is that voltage quality is measured just on some points of the network [24] .

Among the different indexes used in order to measure the voltage sags and short interruptions (it is important to note that a short interruption is a voltage sag where the voltage drops until zero value) the most used one is the SARFI index. Instead, there are no defined indexes used to measure the voltage swells.

2.4.1. SARFI

The SARFI (System Average RMS Variation Frequency Index) is a count of voltage sags or short interruptions below a certain threshold.

$$SARFI_{\%V} = \frac{\sum N_i}{N_T}$$

Where *%V* represents the voltage threshold, N_i the number of customers experiencing a RMS voltage value below that threshold and N_T the total number of customers [30].

2.5. Responsibilities

As we have seen before of power supply, voltage dips, voltage sags… have several origins. Electrical disturbances are not only caused by distribution companies but also clients can affect them. Therefore, it is important to identify the origin of the disturbances in order to know who is responsible of them. As this is quite difficult to accomplish, distribution companies are normally responsible for all the costs associated to disturbances even though they aren't always responsible of them.

In Spain the RD 1995/2000 establishes that the interruptions of supply in MV (1kV-36kV) cannot exceed the values shown in table number 7.

Type of zone	Number of hours	Number of interruptions
Urban	3.5	7
Semi-urban	7	11
Gathered rural	11	14
Scattered rural	15	19

Table 7: Total number of hours and interruptions accepted in MV (1kV-36Kv) in Spain depending on the type of zone according to the RD 1995/2000.

If those values are exceeded the RD 1995/2000 declares that the distribution company in responsible for the unfulfillment. Therefore, they will have to compensate the customers economically if they do so. Depending on the type of client, the length of the interruption and other aspects the amount of money payed will be different.

It is important to note that the exceptional events (hurricanes, earthquakes, tsunamis…) are considered as irregularities so the regulation doesn't count them as interruptions.

2.6. Conclusion

In this chapter we can find a deep study of the electrical disturbances. We have seen that some of them have worse effects than others.

Furthermore, we have studied different indexes in order to measure them: SAIDI, SAIFI and ENS. In order to calculate these indexes Spain is divided into four main areas depending on the amount of customers in each area. We have seen that Spain is among the countries with average number and length of interruptions which means that we still have to progress in order to acquire a better quality of electricity.

CHAPTER 3:

ECONOMIC STUDY UNDER CURRENTLY QUALITY LEVELS

3. ECONOMIC STUDY UNDER CURRENT QUALITY LEVELS

3.1. Introduction

As it has been mentioned before the disturbances have several effects. So, the cost of the damage produced by them can range from a few euros to millions of them. A study made in 2001 in the United States declared that “data suggest that across all business sectors, the U.S. economy is losing between $104 billion and $164 billion a year to outages and another $15 billion to $24 billion to PQ phenomena” [31].

Good quality of supply can assure an enormous reduction of the expenses caused by electrical disturbances. So, sometimes improvements are needed in order to achieve a better quality of supply. Nevertheless, it is important to know if the investment is worth the improvement in quality of supply; so, it is important to quantify the economic impact that the disturbances have on the customers.

In this chapter an economic study of the electrical disturbances can be found. Firstly, the costs implied by these disturbances will be exposed and then different solutions will be analyzed. Moreover, a study of the people responsible for the disturbances can be found.

3.2. Costs arising from electrical disturbances

The economic impacts due to poor quality of supply are wide and various so, the costs arising from electrical disturbances are not easy to calculate. It is important to know that the damage caused by disturbances can be obvious, like the damaging of the equipment when voltage sags take place. But it can also be not so obvious to identify if the damage takes longer to manifest, like the ageing of the equipment.

Considering this we can divide the cost arising from electrical disturbances in three types: direct economic impact, indirect economic impact and social economic impact. The direct economic impact includes the costs due to the interruptions by themselves. The indirect economic impact represent the costs associated to the consequences provoked by the interruptions. Finally, the social economic impacts are a type of indirect economic impact that includes the consequences that the interruptions have on people.

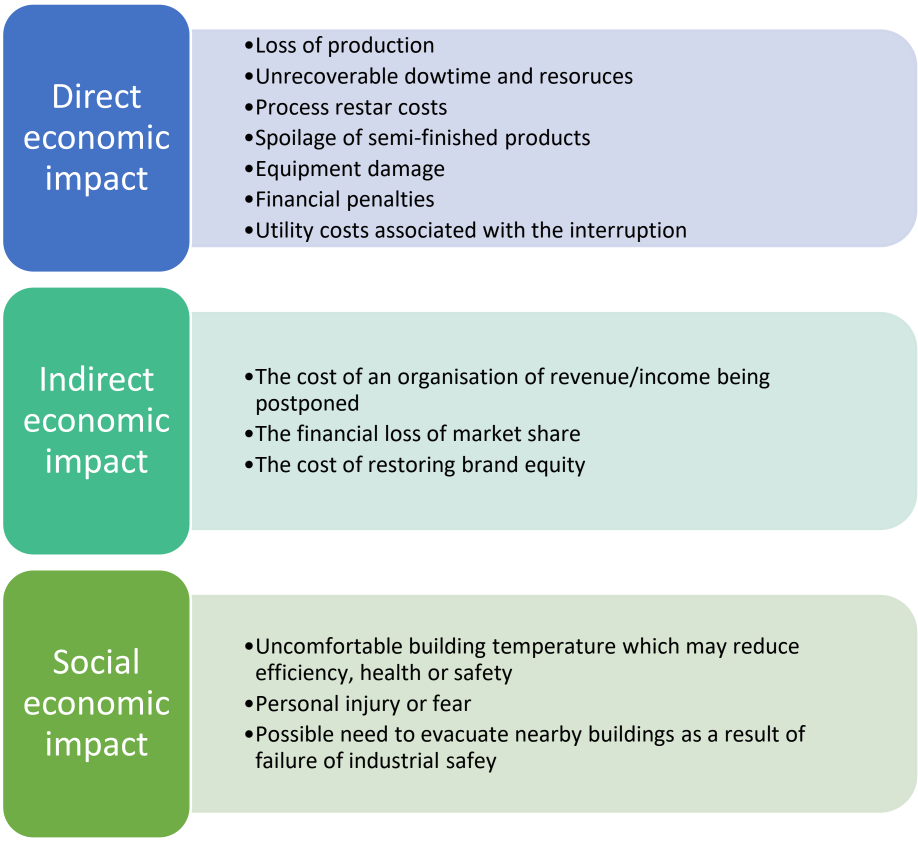


Fig. 20: Cost arising from electrical disturbances **[32]**.

Among all the disturbances presented in this paper the costs associated to interruptions and voltage sags are the ones that will be studied in this chapter. As it has been explained before we can consider a short interruption as a long voltage sag and a long interruption as a long short interruption but, it is important to clarify that the relationship between the length of these disturbances and its impact is not directly proportional. The cost of the electrical disturbances doesn't only depend on the duration of the interruption but in other factors like the frequency of the interruptions, the day of the week when the interruption takes places, the moment of the day, the season…

As not all the customers of a distribution company use the electricity with the same objective it is relevant to group the clients depending on their activity. So, in order to do a cost-estimating study we will classify the clients into the following groups:

- Residential: clients that use the energy in their houses to light them up, wash their clothes, watch TV…
- Agriculture: clients that use the energy in the countryside in order to fulfill agricultural activities such as cereal milling, irrigation systems, pumping water…
- Commercial: clients that use energy in order to sell their products like shops, pharmacies, shopping malls…
- Industrial: clients that use energy for industrial activities like the ones that take place in refineries, paper mills, chemical plants…

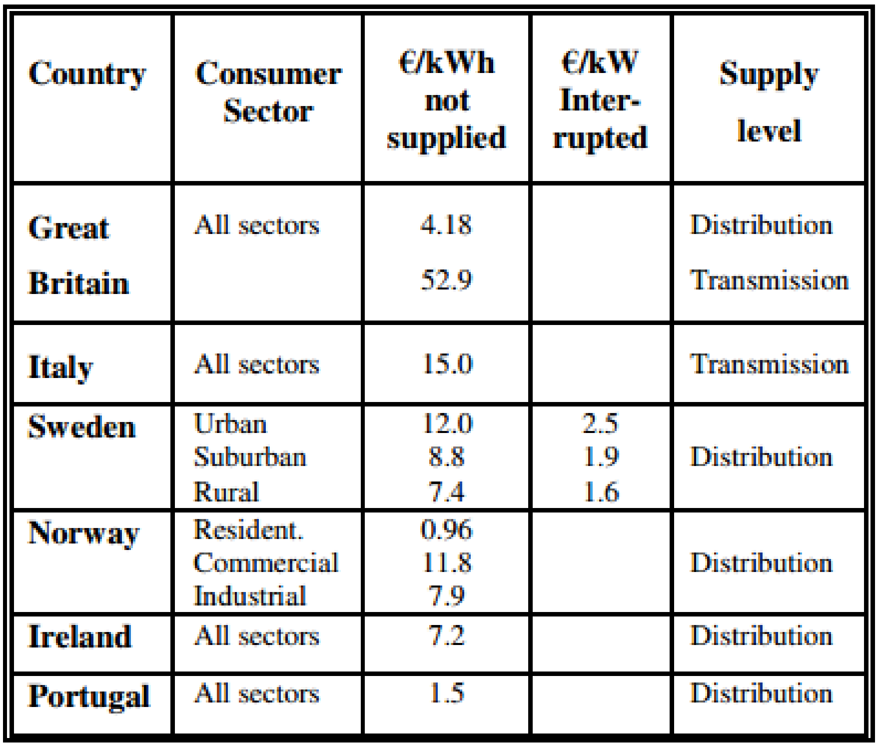
It is important to understand that the consequences of an electrical interruption are not the same, for example, for an industrial client (he could lose millions of euros if he isn't able to produce his product) than for a residential client (an interruption for him could mean not being able to watch TV for a couple of hours).

3.2.1. Cost of non-supplied energy

As we have seen whenever an interruption occurs server consequences happen. Therefore, the cost of non-supplied energy is related to the economic consequences incurred by consumers whenever an interruption of power supply takes place.

Different studies have tried to quantify the economic impact of the loss of electricity supply. In document [33] we can find a summary of different interruption cost studies. In them we can find some of the indexes that have been used in order to measure the willingness of customers to pay in order to obtain a better quality of electricity. Most of these studies are based on customers' surveys and this can present some problems because it is very difficult to directly specify the value placed on reliability of the electrical distribution network. Due to this, clients my give higher values to interruption costs than the ones they really have.

In figure number 21 we can find the value of the VOLL index for different European countries. The VoLL (Value of Lost Load) is an index used to measure the cost of non-supplied energy that provides an estimation cost of the damage incurred by customers because of interruptions of power supply.



Country	Consumer Sector	€/kWh not supplied	€/kW Inter-rupted	Supply level
Great Britain	All sectors	4.18 52.9		Distribution Transmission
Italy	All sectors	15.0		Transmission
Sweden	Urban Suburban Rural	12.0 8.8 7.4	2.5 1.9 1.6	Distribution
Norway	Resident. Commercial Industrial	0.96 11.8 7.9		Distribution
Ireland	All sectors	7.2		Distribution
Portugal	All sectors	1.5		Distribution

Fig. 21: VoLL values in different European countries **[34]**.

Moreover, in order to calculate the costs that arise from electrical interruptions the AEMO (Australian Energy Market Operator) developed the VCR (Value of Customer Reliability). The VCR represents, in dollar terms, the estimated aggregated valued that customers place on the reliable supply of electricity [33]. So, it stands for the willingness of consumers to pay in order to avoid interruptions. Therefore, the VCR can be used to calculate the costs due to bad continuity of supply caused by long interruptions. In table number 8 we can find the value of the VCR depending on the customer group. It can be found in dollars (calculated by the AEMO) and in euros ($1=0.90€).

Customer group	**VCR ($/kWh)**	**VCR (€/kWh)**	
Residential	25,95	23,41	
Agriculture	47,67	43,00	
Commercial	44,72	40,34	
Industrial	44,06	39,74	
	40,60	36,63	**Average**

Table 8: Values of the VCR in dollars and in euros depending on the customer group **[32]**. [1]

For this project we will use 10€/kWh for all consumers for the cost of energy non-supplied as it represents an average of the different indexes presented above.

3.2.1.1. Average cost of long interruptions in Spain

As the regulation of the cost of energy non supplied hasn't always existed in this chapter we will calculate the amount of money not earned by distribution companies when an interruption takes place, because as no energy is being powered no money is being earned and this can be considered as a "loss", and the money that electrical distribution companies need to pay to customers when an interruptions tales place. In order to do this, the values of the SAIDI, SAIFI and ENS in Spain between the years 2011 and 2014 will be used.

We will start by calculating the money "lost" by distribution companies when interruptions occur.

We can find information about the average demand of energy and its price in Spain during those years in table number 9.

---

[1] The values of the VCR may seem very high compared to the values of the VoLL represented above. This can be because the VCR is an index used in Australia while the VoLL is an index used in the European Union. Therefore, as prices of the electricity are different is this places, the value of these indexes is different too.

	Demand (MWh)	Price (€/MWh)	
2011	41822	60,2	
2012	41141	59,6	
2013	38681	57,8	
2014	37843	55,0	
	31897,4	46,5	**Average**

Table 9: Demand and price of the electricity in Spain between years 2011 and 2014 **[29]**.

Furthermore, we will only consider the values of the SAIDI, SAIFI and ENS indices between the years 2011-2014 in order to do our calculations. Instead of taking into account the SAIDI's and SAIFI's values we will use their 'total' values presented above as they are a weighted average depending on the population of each type of zone and, therefore, a good approximation to reality.

	ENS (MWh)	SAIFI (number of interruptions)	SAIDI (hours)	
2011	336	1,474	1,12	
2012	150	4,533	1,053	
2013	1240	1,338	1,623	
2014	281	1,198	1,056	
	502	1,198	1,213	**Average**

Table 10: ENS, SAIDI and SAIFI indexes in Spain in years 2011-2014 **[29]**- **[30]**.

The procedure followed in order to calculate the cost of interruptions of power supply in Spain between years 2011-2014 will be the following:

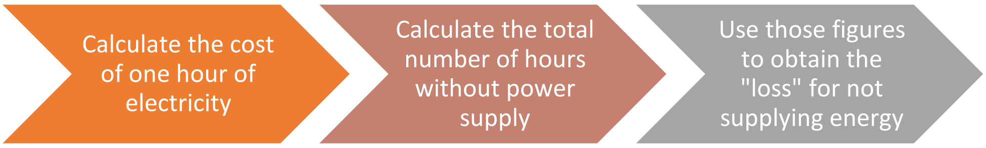


Fig. 22: Procedure that will be followed in order to calculate the "loss" due to interruptions of power supply in Spain between the years 2011-2014.

So firstly, we will calculate the cost of one hour of electricity in Spain over that period of time, which is the amount of money payed electricity by the Spanish for one hour of supply. As we have just explained when an interruption takes place this sum of money is not earned by the electrical distribution company so we can consider it as a "loss of money". In order to do so we will multiply the demand by the price payed for the electricity. This represents the cost of an hour of electricity the years 2011-2014.

$$Cost_{hour} = \frac{Demand * Price}{Number\ of\ hours\ in\ one\ year}$$

Year	Cost (thousands of €)	
2011	0,287	
2012	0,280	
2013	0,255	
2014	0,238	
	0,265	**Average**

Table 11: Cost of one hour of electricity in Spain between the years 2011-2014.

Now the total time without power supply will be calculated. In order to do so we will use the SAIDI index (average duration of the interruptions) and the SAIFI index (average amount of interruptions).

$$Total\ time = SAIFI * SAIDI$$

Year	Total time (hours)	
2011	1,650	
2012	4,773	
2013	2,172	
2014	1,265	
	2,465	**Average**

Table 12: Total number of hours without power supply in Spain between 2011-2014.

We will now combine the information shown in tables number 11 and 13 in order to determine the amount of money not earned by the distribution companies due to interruptions of power supply in Spain between the years 2011 and 2014. To do so, we will multiply the total time without power supply by the cost of one hour of power supply.

$$Money\ not\ earned_{interruptions} = Cost_{hour} * Total\ time$$

Year	Cost (millions of €)	
2011	4,16	
2012	11,70	
2013	4,86	
2014	2,63	
	5,72	**Average**

Table 13: Money not earned by distribution companies due to interruptions of power supply in Spain between 2011-2014.

As we can conclude from the figures in table number 13 the average amount of money not earned by distribution companies due to interruptions of power supply in Spain between the years 2011-2014 is 5,72 million of euros.

Even though it hasn't always worked this way, nowadays whenever an interruption takes place the electrical companies need to pay the customers a sum of money to compensate them for not being able to use power while the interruption last. We will now use the average value of the cost of non-supplied energy and the ENS to estimate the amount of money lost by distribution companies when interruptions occur. Since the cost of energy non-supplied represents the cost of non-supplied energy when interruptions occur and the ENS is the amount of energy not supplied in a year we will combine both numbers to obtain the total that electrical distribution companies need to face when an interruption occurs.

$$Total\ cost_{\ interruptions} = Cost\ of\ energy\ non - supplied * ENS$$

Year	Total cost (millions of €)	
2011	3,36	
2012	1,50	
2013	12,4	
2014	2,81	
	5,02	**Average**

Table 14: Total cost of interruptions that electrical companies have to pay.

In figure number 23 we can find a comparison between the total cost that electrical distribution companies have to face because of interruption of power supply and the money not earned by distribution companies due to interruptions of power supply. As we can see, the money that electrical distribution companies need to pay to customer when an interruption of power supply takes place is very high compared to the amount of money not earned by them (that can be considered as a loss) when an interruption takes place.

Therefore, as the total sum of money lost by electrical distribution companies because of interruptions of power supply is very high, the distribution companies should improve the distribution system in order to decrease as much as possible, the number and length of the interruptions. In chapter number 3 we can find a study of the different solutions that distribution companies can apply in order to reduce the length and number of power supply interruptions.

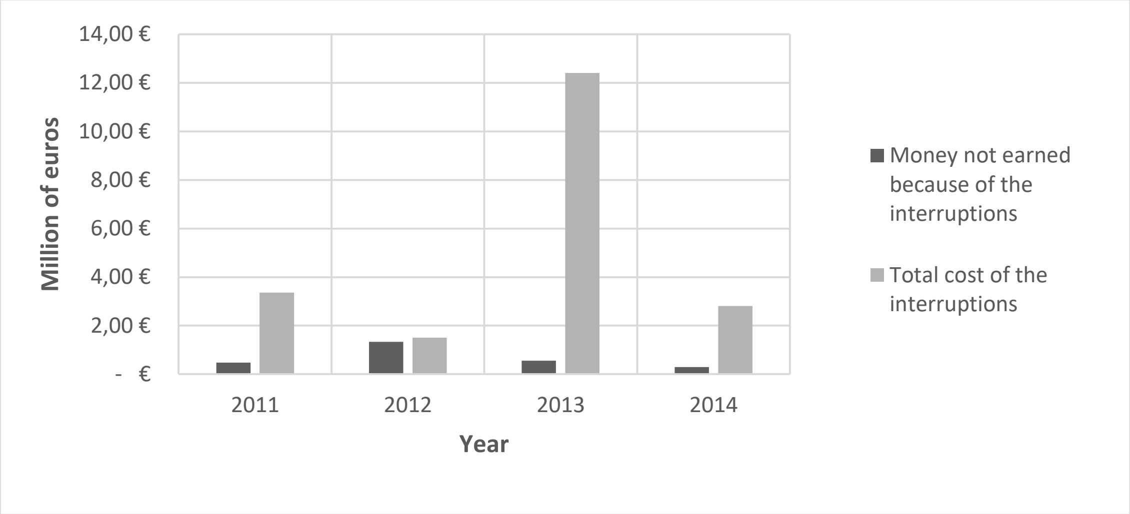


Fig. 23: Comparison between the total cost due to interruption of power supply and the money not earned by distribution companies due to interruptions of power supply.

3.2.2. Cost due to poor voltage quality

As it has been explained before the cost of non-supplied energy is a measure for long interruptions. Therefore, it represents the cost of non-supplying energy for a period over three minutes. These interruptions affect continuity of supply but not voltage quality. It is more difficult to calculate costs provoked by bad voltage quality (due to voltage sags, voltage swells and short interruptions) as there is not many information available about this topic. Therefore, we will only analyze briefly how to measure voltage quality.

Voltage sags are the costliest of all power quality disturbances mainly because they can affect users in greater than a 100km radius from causing the event. Normally, voltage sags are caused by faults so, voltage sags last until the fault lasts.

It is important to know that if the relationship between the duration of a voltage sag and is cost begins at 0€ and then increases linearly with time. Several studies have concluded that a one-second outage provokes, approximately, 20% of the cost of one-hour outage. Therefore, the relationship between the cost and the duration of a voltage will be the following:

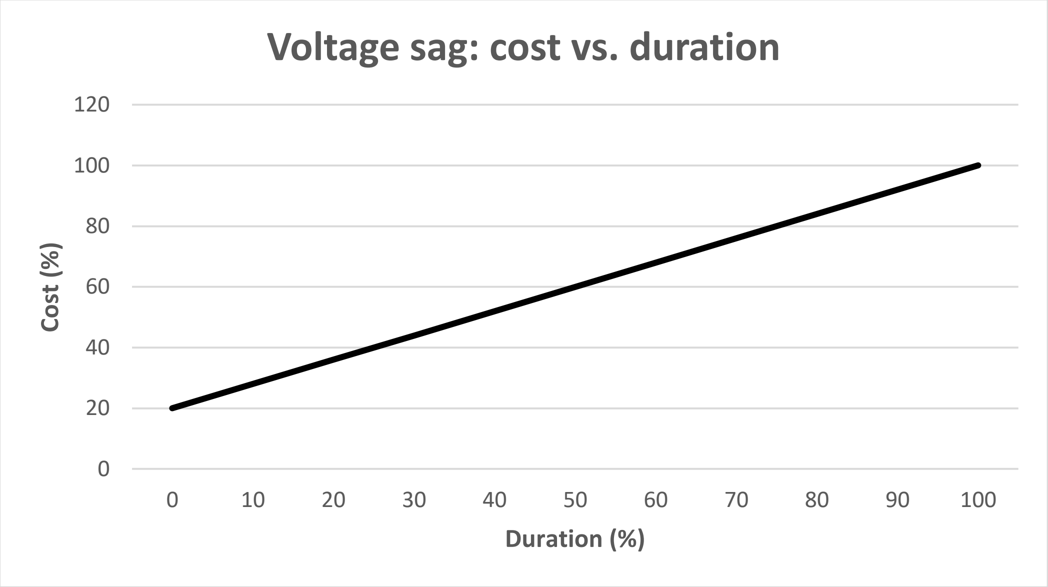


Fig. 24: Relation between the cost of the voltage sag and its duration.

Voltage sag can be considered a short interruption that last only a few seconds.

In the Australian case, where the cost of long interruptions is measured using the VCR, the cost of voltage sags is determined by using that same data. By doing so, we will obtain the VCS (Value of Customer Sags) as the 20% of the VCR [32].

Customer group	VCS ($/kWh)	VCS (€/kWh)
Residential	5,19	4,68
Agriculture	9,53	8,59
Commercial	8,94	8,06
Industrial	8,81	7,94

Table 15: Values of the VCS in dollars and in euros depending on the customer group **[32]**.

3.3. Solutions to avoid electrical disturbances

The consequences of a poor quality of supply are various are severe. It is important, therefore, to try to maintain the best quality in distribution systems in order to avoid electrical disturbances. As we have seen, the VCR values prove that customers want to cease those disturbances even if they have to pay more money to electrical distribution companies to achieve it. In this section of the project we will approach some of the solutions to avoid disturbances and their effects. We will then choose the best solution according to economic and quality terms.

Obviously the best and cheapest solution consists in a correct maintenance of the electric lines and all the devices that are used to distribute electricity. Firstly, it is important to assure a proper cleaning of the insulators. Over time solid particles are deposited in the electrical insulators decreasing their efficiency. This cleaning is especially relevant in coastal regions, deserts and places with high contamination levels.

Fig. 25: Power line insulator cleaning operation **[34]**.

Moreover, it is important to assure a minimum distance between the trees and shrubs and the power lines and the electric towers. By doing so, disturbances caused by faults can be avoided. Also, protections against electric shocks need to be installed to guarantee proper shielding. It is relevant too to maintain the proper operation temperatures and confirm that the ground wiring of the circuits is the correct one as the ground wiring is responsible for diverting the power surges.

Even though a correct maintenance is really important when avoiding electrical disturbances some of them are caused by random phenomena so we cannot be totally sure that they will not harm our distribution system. This is why, some equipment is installed in the system in order to minimize the harm caused by the disturbances that cannot be avoided. We will now study the most common solutions to electrical equipment: Petersen coil, UPS, flywheel, dynamic voltage restorer and variable frequency drive.

3.3.1. Petersen coil

Petersen coils are used in order to limit arcing currents during earth faults. It is a variable ballast that is connected between the earth and the star point of the substation transformer in a three phase system.

In an ungrounded three-phase-system when a phase-to-earth fault takes place, the phase voltage of the phase where the fault occurs is reduced to the earth potential (the capacitance of this line is discharged where the fault happens); while the phase-to-earth voltage of the other two phases is multiplied by $\sqrt{3}$. When this happens, a charging current 'I_C' flows between these phase-to-earth capacitances. This current is three times the charging current of each phase-to-earth and continues to flow via the path created by the fault until the fault disappears.

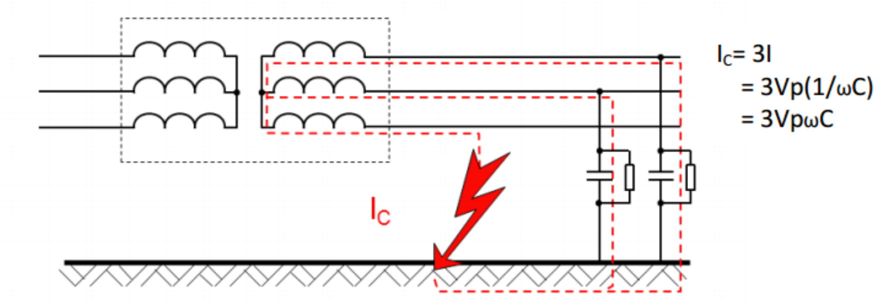


Fig. 26: Isolated distribution system where I_c is the discharge current due to capacitance of the healthy phases **[35]**.

When a Petersen coil is installed and a fault takes place, the I_c is neutralized by a current (I_L) that flows from the coil, with equal magnitude but with a change of phase of 180º. By doing this, it counteracts the capacitive current I_c by an inductive one I_L so that the value of the current where the fault takes place is extremely reduced [35].

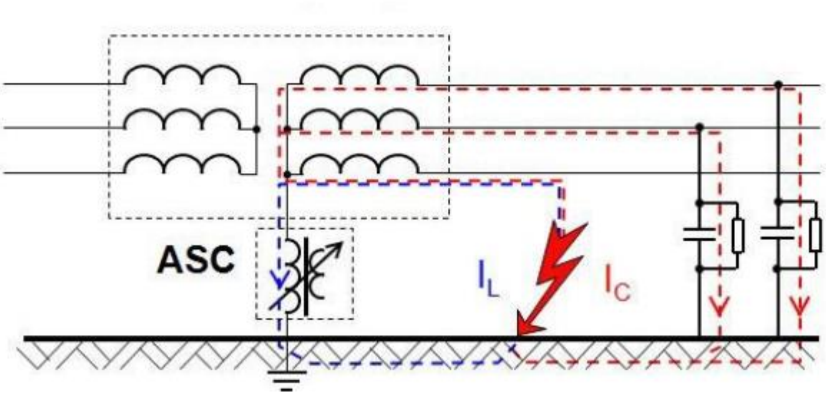


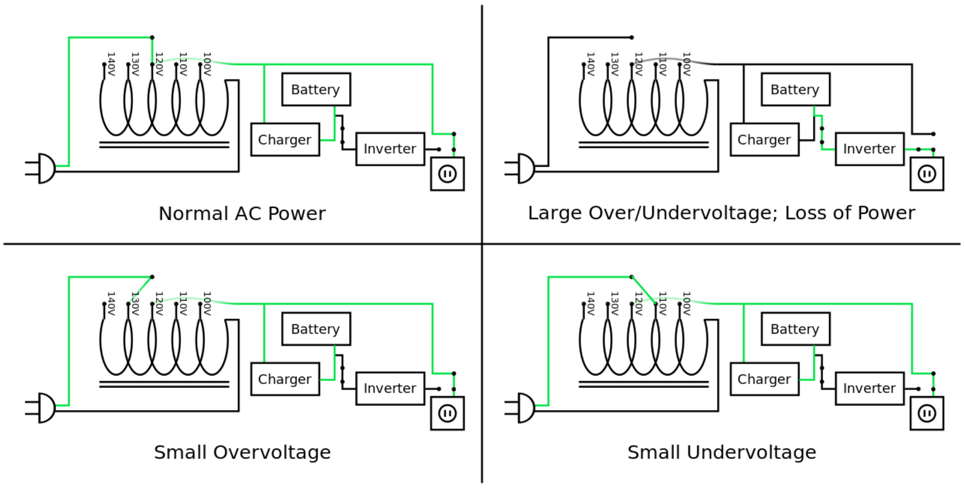
Fig. 27: Compensated system where I_L counteracts I_C **[35]**.

The main advantage of the Petersen coil is that it avoids the activation of the electrical protections so that the system can still work when the fault occurs.

3.3.2. UPS

An UPS (Uninterruptable power supply) is an electrical device that provides power to a load in an emergency situation when the main power fails. When the system is correctly working it uses its energy to power a battery system through a converter. Just as soon as the electrical disturbance occurs the UPS provides the power stored in the battery system. Currently, we can find in the market different types of batteries depending. Using one type or another depends on the application and the needs. We can find more information about batteries in Annex A.

So, UPSs are used to protect equipment or hardware to which an unexpected power stoppage can cause serious injuries. We can find UPSs in data centers, hospitals, telecommunication equipment…



Normal AC Power

Large Over/Undervoltage; Loss of Power

Small Overvoltage

Small Undervoltage

Fig. 28: An UPS system. The green light represents the power flow **[36]**.

3.3.3. Flywheel

A flywheel is a mechanical device that stores rotational energy, we can compare it to a ‘mechanical battery’.

Fig. 29: Flywheel **[37]**.

Basically, it is a big wheel that needs a big force to spin around. As it is very heavy or very big it is necessary to push very hard to make it spin. And, as a lot of force is needed to make it spin, a lot of force is also needed to stop it. Because of this, when it is spinning at high speed it wants to keep on doing so (it has a lot of angular moment), so it can store a lot of kinetic energy.

The kinetic energy is:

$$E_k = \frac{1}{2} * I * \omega^2$$

Where *I* represent the moment of inertia and ω the rotational speed of the rotating disc. The moment of inertia of a cylinder is:

$$I = \frac{1}{2} * r^2 * m$$

Where *m* represents the mass of the cylinder and *r* its radius.

From the equations shown above we can conclude that the kinetic energy of the flywheel increases with its mass, radius and angular speed.

The functioning of this mechanism is very simple: energy is transferred to the flywheel by the application of a torque. So, when the rotational speed of the torque grows, more energy is stored in it. Then, as soon as the energy is needed, the flywheel releases it by applying a torque to a mechanical load. Moreover, when this is done it increases its own rotational speed.

As flywheel can store kinetic energy they are used to reduce disturbances. The system (shown in figure 30) includes an engine and a generator installed into the same axis. As the electrical network powers the motor the axis spins. The axis is also connected to a generator that produces the electrical energy. Therefore, electrical energy is converted into mechanical energy and, after then into electrical energy again. So, in this system a flywheel can be installed between the motor and the generator. Thanks to this, the flywheel spins at the engine’s speed acquiring inertia. So, when a disturbance occurs, the flywheel is able to maintain the spin with its inertia for a few seconds providing power [38].

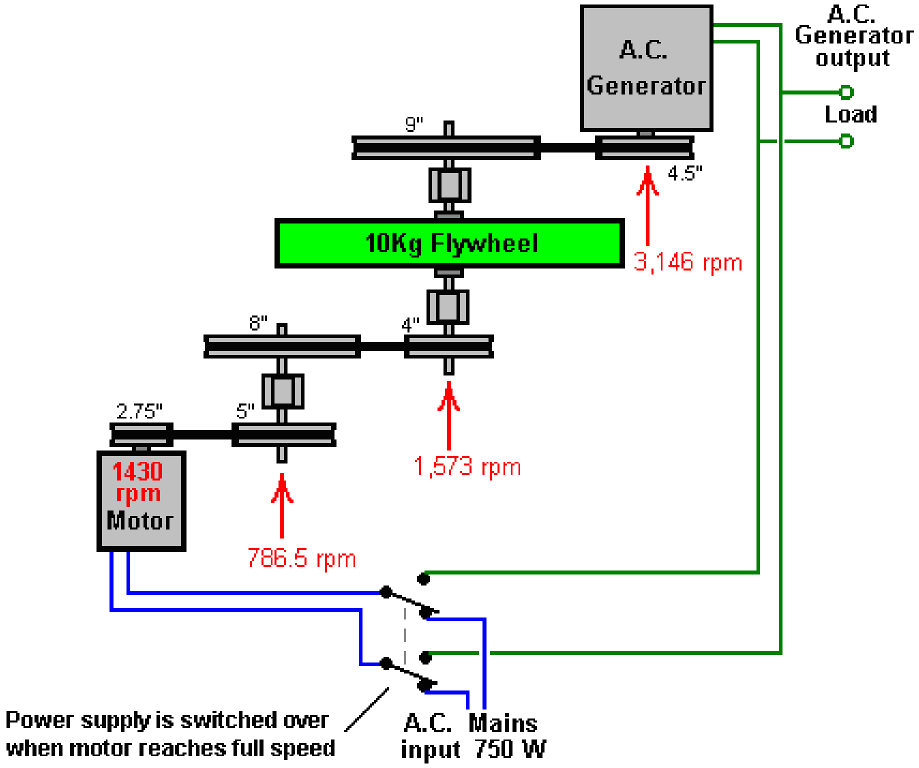


Fig. 30: Flywheel energy storage system **[39]**.

One of the main disadvantages of flywheels is its safety. As the energy contained in them has to be released very quickly the flywheel may break or fall off its axle. So, investigations are now being carried out in order to find their perfect material and design.

3.3.4. Dynamic Voltage Restorer

A Dynamic Voltage Restorer (DVR) is a device used to compensate voltage sags by injecting a 3-phase voltage in series and in synchronism with the distribution voltage feeder. It represents a fast, flexible and efficient solution for this type of disturbances.

When a voltage sag takes place the DVR injects voltage in order to restore the load supply voltage. To do so, an energy source is needed. This energy can be obtained either from a storage device like a battery or from the incoming supply through a shunt converter [40].

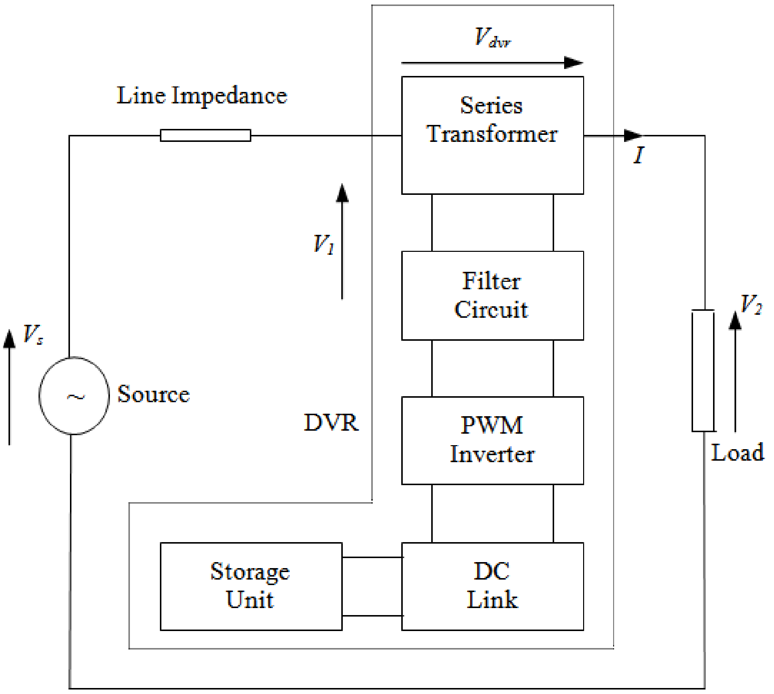


Fig. 31: Simplified circuit of a Dynamic Voltage Restorer (DVR) **[41]**.

Figure number 31 is a simplified circuit of a DVR in the distribution system. Whenever a fault takes place the load's voltage suddenly drops to zero experiencing a voltage sag. The DVR compares voltage V_1 with the load's predetermined voltage and, as they are not the same, it injects the necessary voltage in order to maintain constant the value of the load's voltage V_2. This device allows to control the magnitude and the phase of the voltage achieving a perfect control of the load's voltage and the active and reactive power exchanged with the distribution system.

3.3.5. Variable frequency drive (VFD)

One of the worst effects of the interruption of voltage is the decrease of an engine's speed. In order to avoid this variable frequency drives (VFD) are installed.

An VFD is an adjustable speed drives that allows to control the AC motor speed by varying the input frequency and voltage of the motor.

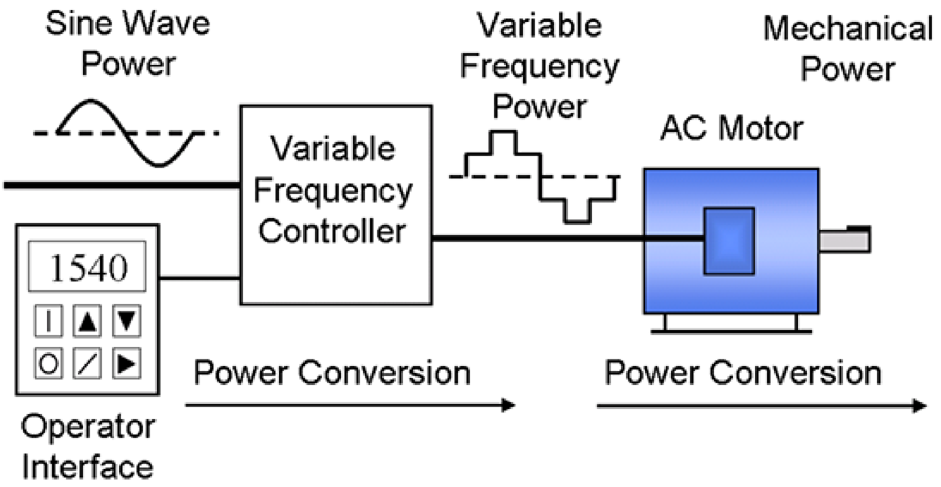


Fig. 32: Functioning of a VDF **[42]**.

This device has a simple working principle. It converts an input sinusoidal AC voltage to a DC voltage and then back to an AC one. In order to do this its uses IGBTs that are continuously switched on and off.

VFDs are used in various applications but they only solve the effect that interruptions of voltage have in motors. So, even though VDFs have been presented they will not be economically studied as they only counteract the effects of the disturbances in the motors.

3.4. Economic study of the solutions

We have studied before on this project the economic impact of the electrical disturbances and the amount of money that customers are willing to pay in order to avoid them. We will now compare the amount of money needed to solve the voltage interruptions by using the different devices already presented. It is important to note that, depending on the characteristics of the distribution network and its needs, the solution device used may differ. Nowadays it is also relevant to study the environmental impact of the different alternatives. In order to do so, a viability study is necessary.

In table number 16 we will find information about the initial investment needed to install the different solution devices. Moreover, data about their yearly maintenance costs can also be founded.

Solution	Initial investment	Yearly maintenance cost (% respect to the initial investment)
Petersen coil	1.000 €/kW	7%
Uninterrupted Power System	400 €/kW	15%
Flywheel	450 €/kW	7%
Dynamic Voltage Restorer	550 €/kW	20%

Table 16: Initial investment and yearly maintenance cost of the different solutions presented.

Using the information on table number seventeen we will reject the Petersen coil as a solution to our problem due to its expensive price. Moreover, even though the dynamic voltage restorer has a slightly more expensive price than the other two solutions it has a higher yearly maintenance cost. Because of this, we will also discard this solution.

Now we will try choose the best solution (in general terms because, as it has been mentioned before, in order to choose the best device a deeper study has to be done) among the other two mentioned above. It is also important to note that UPS can be made of different types of batteries so, depending on the type of battery, its characteristics will be different. The high maintenance that the UPS requires is caused the batteries as, even though the rest of the elements of the UPS can last longer, batteries need to be replaced several times during the life of the UPS. But, as the storage element of the UPS are the batteries it doesn't make sense to compare the UPS with the flywheels but the batteries with them. Therefore, we will directly compare the batteries with the flywheels.

As not only the economic cost of the different types of storage is important we can now question ourselves what qualities make an energy storage better than the rest. So, in order to answer this, we will study five qualities of the two possible solutions left [43]:

- Being able to occupy a small space even when storing a lot of energy
- Long lifespan
- Releasing the energy quickly

- Low losses when transferring and absorbing energy
- Little environmental impact

Firstly, we will study the amount of energy that both batteries and flywheels can store and the speed at which they release energy stored. In order to compare both technologies we will talk about energy density and power density. Energy density refers to the amount of energy stored per unit of volume or mass. Power density refers to the amount of power stored per unit of volume or mass. So, while energy density represents the capacity of storing energy, power density represents the ability of delivering it faster.

Figure number 33 shows a comparison between different storage systems (including batteries and flywheels) according to its power and energy density. As batteries have been in the market for more decades than flywheels they have improved more than them in general terms. Thanks to this, we can now find batteries that store a lot of energy when occupying a small place. But their main disadvantage is that they are not able to deliver it really fast. On the other side and even though flywheels can deliver energy faster than batteries, they also occupy a bigger space. This is why batteries have a higher energy density than flywheels but a smaller power density.

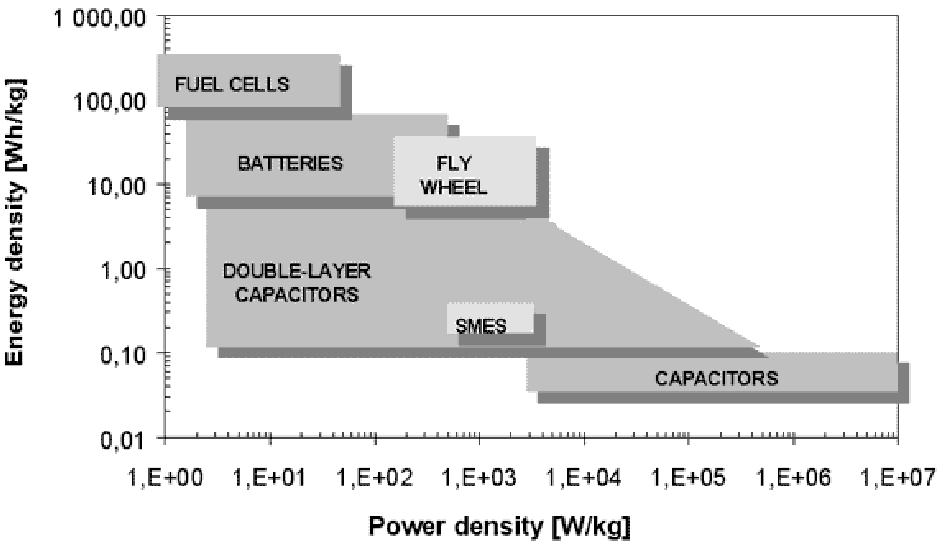


Fig. 33: Comparison between different energy storages according to its energy and power density **[44]**.

If we compare the life of both technologies, we find out that the lifespan of the flywheels is higher (10.000 cycles) than the lifespan of the batteries (3.000 cycles). The problem is that, while the batteries can last for that long, the mechanical components of the flywheels may fail shortening its life duration. Furthermore, one of the advantages of flywheels is that their life duration and performance isn’t affected by changes of temperature while it does affect batteries. Thanks to this, flywheels are able to operate at a wider temperature range.

When talking about batteries its self-discharge may vary from a 1-2% monthly to a 30-40% monthly, depending on the type of battery. But, flywheels also loose energy when transferring and absorbing it, an average value of losses between a 5-15% due to friction.

Finally, if we compare the environmental damaged caused by both technologies we will find that batteries have a lower carbon footprint than flywheels. The reason to this is that the carbon emissions caused to operate the flywheel are greater. But, on the other hand, flywheels don’t contain any hazardous material while the batteries are made of chemicals that can be toxic.

Summarizing, from all the information above it may seem difficult to choose between batteries and flywheels as they both seem to have disadvantages and advantages. But, when choosing between them it is important to consider that, while some batteries can provide energy for almost one hour, the typical energy storage time of flywheel is only between 8-30 seconds. That amount of time is sufficient to cover short interruptions or voltage sags but doesn’t work for long interruptions. Therefore, even it is necessary a further technical study in order to choose between these two, we can conclude that in order to solve the problems caused by short interruptions, long interruptions and voltage sags, UPS (with batteries as their storage device) may be better than flywheels nowadays.

3.5. Conclusion

As we have seen the electrical disturbances have an economic impact in the users of the electrical system and in the distribution companies. In particular, we have studied the implications of the short and long interruptions.

Using the information of several surveys we have stated that the money lost by electrical distribution companies is very high. This is because whenever an interruption takes place electrical distribution companies need to pay a big sum of money to the users. In this study we have considered the cost of non-supplied energy 10€/kWh as an average of the different indexes used to measure this cost. The problem is that, depending on the cost of non-supplied energy, the figures obtained in this type of project can vary a lot.

After analyzing the advantages and the disadvantages of the different storage solutions we have concluded that the best one is the UPS system. Nevertheless, when installing a storage device, a deeper technical and economic study will always be necessary.

CHAPTER 4: ECONOMIC STUDY UNDER FUTURE QUALITY LEVELS

4. ECONOMIC STUDY UNDER FUTURE QUALITY LEVELS

4.1. Introduction

In this chapter we can firstly find a theoretical introduction to the climate change and the impact it will have on the electrical disturbances. As a lot of disturbances are due to weather conditions, the climate change will highly increase them.

Then, two cases of study are presented: a gathered urban zone and a rural zone. We will study the cost that the increase of electrical disturbances will have on these two types of zones and the cost of installing an UPS storage system in order to avoid them.

4.2. Climate change

When we talk about climate change we understand it as a change in the Earth's overall climate. So it can refer to a change in its average temperature and/or a change in its typical precipitations patterns. This changes in the Earth's climate have happened before, the Earth has suffered warmer and cooler periods. So, as this has happened before we are sure human behavior is not the only cause of the climate change. Scientifics have assured that some causes of climate change are natural like changes of the Earth's orbit, the amount of energy coming from the sun, volcanic eruptions…

Currently the Earth is becoming warmer. The main problem is that the rate at which Earth's temperature is increasing is very big and this is not only due to natural causes but also to the actions of human beings. Nowadays a lot of fuels are burned generating heat-trapping gases, known as greenhouse gases, like the carbon dioxide.

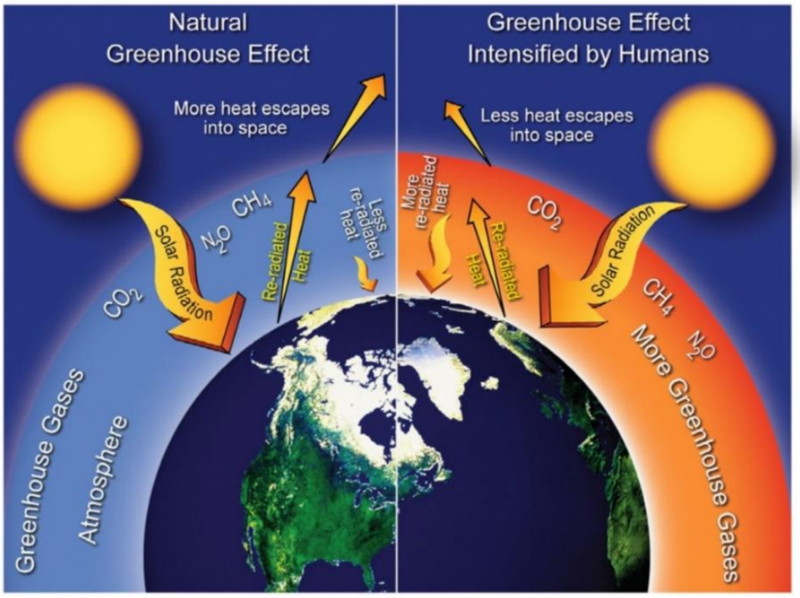


Fig. 34: Natural and intensified greenhouse effect **[45]**.

As it is shown in figure number 34 sunlight goes through the atmosphere and warms the Earth during the normal greenhouse effect. Part of this radiation is given off by the Earth, other part escapes to the outer space and the remaining radiation is trapped by gases in the air to keep the Earth warm enough to sustain life. Those gases are the greenhouse ones. The problem is that, as we have released so much greenhouse gases, our atmosphere is now like a heat-trapping blanket. The result to this is the climate change which provokes a general warming of our planet [46].

The effects of climate change are various and severe. Among them we can find the following ones:

- Rising of the sea level, 17cm over the last century
- Global temperature rising, an average 0.6ºC over the last century
- Warming of the oceans, 0.1ºC over the last century
- Increasing of the sea level, 3mm over the last decades
- Acidification of the ocean
- Melting of the arctic icecap
- Increasing number of extreme events like hurricanes or tsunamis

The worst aspect of climate change is that it is only starting. So, if we keep on producing the amounts of greenhouse gases that we are currently producing the effects will be much worse. Figure number 35 shows graphically the impacts that different raises of temperature would have.

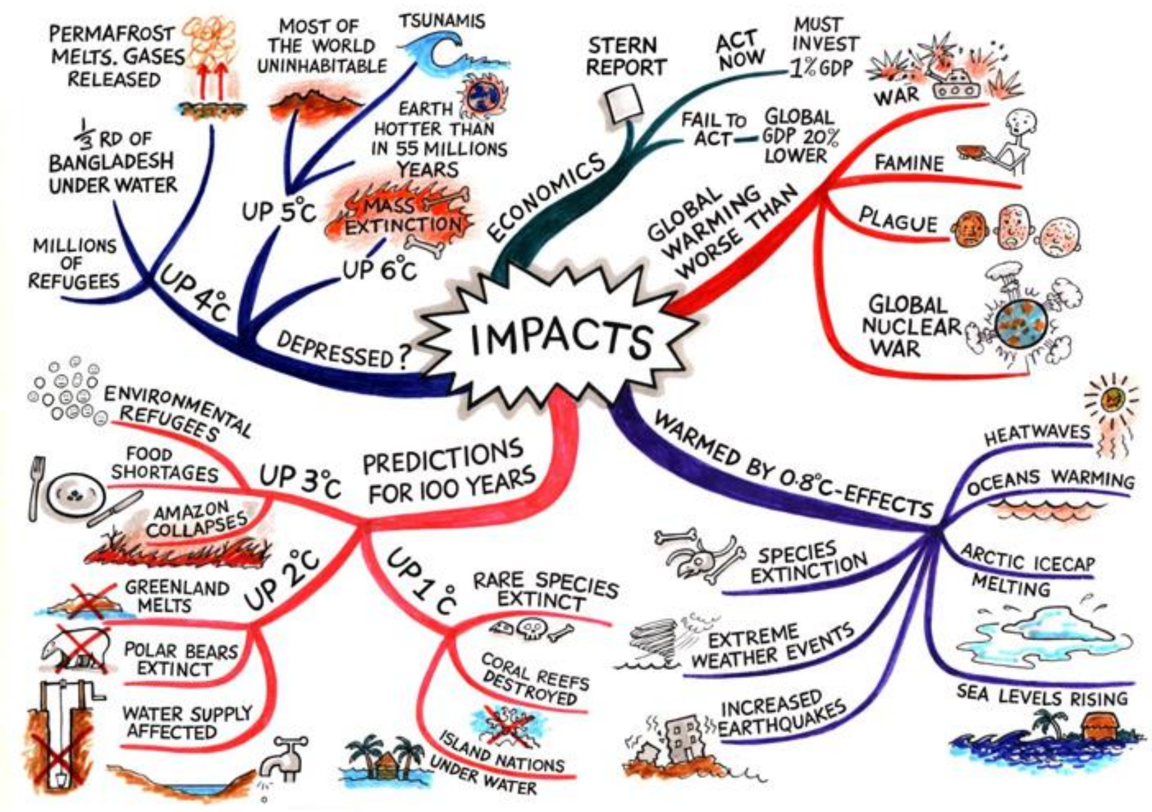


Fig. 35: Impact of the climate change depending on the increase of temperature **[47]**.

Even though electrical disturbances may seem to have nothing to do with climate change that is not true. The Edison Electric Institute has stated that 70% of power outages in the US are caused by weather phenomena such as lightings, snow, ice, temperature, hurricanes… As due to climate change all this weather events will increase in intensity and in frequency, they will affect the quality of electricity supply. For instance:

- High winds can blow tree branches into power lines provoking a voltage sag or even an interruption
- The accumulation of snow and ice on power line insulators can provoke flash-overs

- Lightning strikes in power lines and towers cause voltage sags
- An increasing in the global temperatures provokes a growing in the electrical demand because of the higher demand for air conditioning and refrigeration systems
- The temperature rise also produces a higher evaporation of water, decreasing the chance of using that water in order to generate electricity
- Need of moving or elevating infrastructures due to the rise of sea level making them more expensive
- Aging of the electrical equipment because of extreme heating
- Extreme events like tornados destroy elements of the electrical system such as cables or power tower [47] [48]

The main problem is that traditionally the electrical infrastructure (substations, cables, power towers…) hasn't been designed to bear extreme meteorological events as it is not economically profitable. This is why some actions have to be taken now in order to prepare the electrical system for the future impacts the climate change may provoke. Among the solutions we find the followings:

- Constant measuring of the power through the different power lines in order to know if their temperature limits are being exceeded
- Elevating or relocating electrical equipment in order to avoid accidents like the fall of branches over a power line
- Reduction of the energy demand nowadays so that less greenhouse gases are emitted
- Evaluation of the risks of climate change to electricity infrastructure in cities, counties, states…
- Strengthen clean energy policies in order to lower the amount of greenhouse gases emissions
- Installing equipment to mitigate the effects of climate change (like UPS) in order to reduce power outages, interruptions and voltage sags

- Upgrading electricity equipment so that renewable energies are more integrated [50]

In the solutions shown above we find that the installation of UPS or other storage device may be useful in the future in order to avoid some of the effects that the climate change will have in electrical disturbances. We have studied before in this project both the economic cost of UPS and its advantages and disadvantages.

Now, we will examine if it is economically profitable the installation of UPS in the distribution system in order to prevent interruptions of power supply. In order to do this several scenarios will be presented. We will vary the type of zone, the number of interruptions and its length. In order to do this, we will double the value of the SAIDI and SAIFI indexes to model the impact that climate change will have in interruptions of power supply. Therefore, in our study two scenarios can be found: a rural zone and a gathered rural zone. We will study the economic impact by multiplying the amount and duration of interruptions by 2, by 5 and by 10. We will study as well the worthiness of the installation of an UPS in the distribution system. Then, both scenarios will be compared.

When we are multiplying the values of the SAIDI and the SAIFI by 2, by 5 and by 10 we are not only considering the impact of the climate change on the electrical disturbances but other facts that may increase their value. For example, if the electrical equipment is old it may be not as precise as it is when it is new. This implies that it will not clear the faults as it clears them when the equipment is new, increasing the time that it takes an interruption to be solved. Moreover, the extreme events (like hurricanes or tornados) can destroy a big number of electrical equipment. As the number of these extreme events is going to increase in the future, more electrical equipment will be destroyed so more and longer interruptions will take place.

4.3. Scenario I: Gathered rural zone

For this scenario we will consider a Spanish municipality called Pedraza. It is located in the province of Segovia and it has a population of 416 inhabitants. It is a fortified medieval village.

Fig. 36: Map of Segovia where we can see where Pedraza is located **[51]**.

As it has less than 2.000 inhabitants but more than 200 it is considered a gathered rural zone. In table number 17 we can find the average value of the SAIDI and SAIFI indexes in the gathered rural zone over the last few years. This table also those indexes multiplied by different constants in order to model the impact of climate change in those indexes.

	Average value of interruptions	**Average value of interruptions x 2**	**Average value of interruptions x 5**	**Average value of interruptions x 10**
SAIDI (hours)	3,252	6,504	16,26	32,52
SAIFI (number of interruptions)	2,886	5,772	14,43	28,86

Table 17: Different values of the SAIDI and SAIFI indexes in a gathered rural zone (average value, average value multiplied by two, average value multiplied by five and average value multiplied by ten).

Moreover, the average demand of electricity of Spanish customers over the last years is 31897,4 MWh with a price of 46,5€/MWh. Even though Spain has 46,5 million people they may not be all customers of the distributions companies. We will use a ratio

1:4 so, the total number of customers of electrical distribution companies in Spain will be:

$$Number\ of\ customers_{Spain} = \frac{Number\ of\ habitants}{4} = 11{,}6\ million\ ^{2}$$

We will now obtain the electrical demand of one single Spanish customer:

$$Electricity\ demand_{one\ customer} = \frac{31897{,}4\ MWh}{11{,}6\ million} = 2749\ Wh$$

Even though Pedraza has 416 inhabitants, if we use the 1:4 ratio, its number of electrical customers are:

$$Number\ of\ customers_{Pedraza} = \frac{Number\ of\ habitants}{4} = 104$$

The total electricity demand of this village will be:

$$Total\ electricity\ demand\ _{Pedraza} = 2749\ Wh * 104\ inhabitants = 285{,}4\ kWh$$

Now, following the procedure presented in chapter 2 we will calculate the cost of not providing one hour of electricity in Pedraza due to interruptions. As, whenever an interruption takes place, the distribution companies have the pay an amount of money of 10€/kWh, the cost of one hour with non-supplied energy will be:

$$Cost_{hour} = Demand * Price = 285{,}4\ kWh * \frac{10€}{kWh} = 2854€/hour$$

Therefore, 2854€ represent the amount of money that electrical distribution companies have to pay to customers when a one-hour interruption takes place.

We will calculate the total time without energy supply by multiplying the value of the SAIDI index by the value of the SAIFI index.

---

[2] In Spain the number of electrical customers is approximately 22 million. The figure used in this project is different as we are considering a ratio of 1:4, meaning by this that each electrical customer includes four habitants. This ratio is usually only used for residential customers but, in this project, we are using it for all the customers. Nevertheless, the amount of customers used in this project doesn't affect the results of the project.

$$Total\ time = SAIFI * SAIDI$$

	Total time (hours)
Average value of the interruptions	9,385
Average value of interruptions x 2	37,541
Average value of the interruptions x 5	234,632
Average value of interruptions x 10	938,527

Table 18: Total number of hours without power supply in Pedraza's scenario with different values of the interruptions.

The SAIDI and SAIFI represent the frequency and length of the interruptions for only one customer. Therefore, in order to calculate the total cost of the interruptions we will have to multiply the cost of one hour of power by the average number of hours without energy supply by the total number of customers.

$$Cost_{interruptions} = Cost_{hour} * Total\ time * Number\ of\ customers$$

	Cost (€)
Average value of the interruptions	2.791.327
Average value of the interruptions x 2	44.661.244
Average value of interruptions x 5	279.132.777
Average value of interruptions x 10	1.116.531.111

Table 19: Total cost of interruptions of power supply in Pedraza's scenario in one year with different values of the interruption.

Once we are aware of the total cost of interruptions of power supply in Pedraza in one year we will figure out if it compensates economically to install UPS in their distribution system. From the information on table 16 we know that the initial investment in order to install an UPS system is approximately 400€/kW with a yearly maintenance cost of 15% of the initial investment.

As we are studying the climate change the interruptions will increase not currently but in the future. We have just presented the current initial investment and yearly maintenance cost. But, as we are studying a future event, we will suppose that the initial investment of the batteries and its maintenance cost will decrease in the future that is when those events will take place.

In order to simplify our calculations, we will suppose that the transition from the current value of the interruptions to the future value of them will be direct (meaning with this that it will jump from its current value to its value multiplied by two, by five or by ten).

As we are not really certain of how the UPSs' cost will progress, we have estimated them. Figures number 37 and 38 show us the evolution of the initial investment cost of installing an UPS system and the evolution of its yearly maintenance cost.

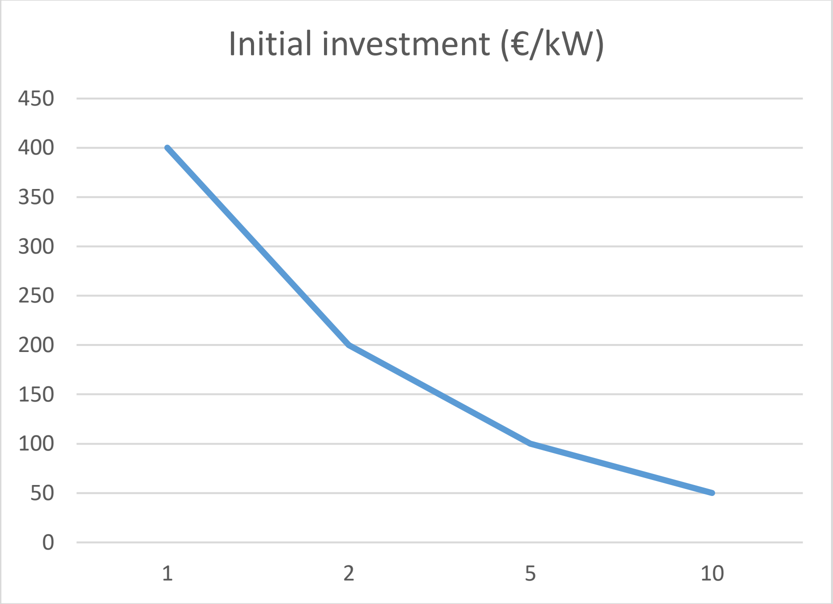


Fig. 37: Evolution of the initial investment cost of installing an UPS storage system.

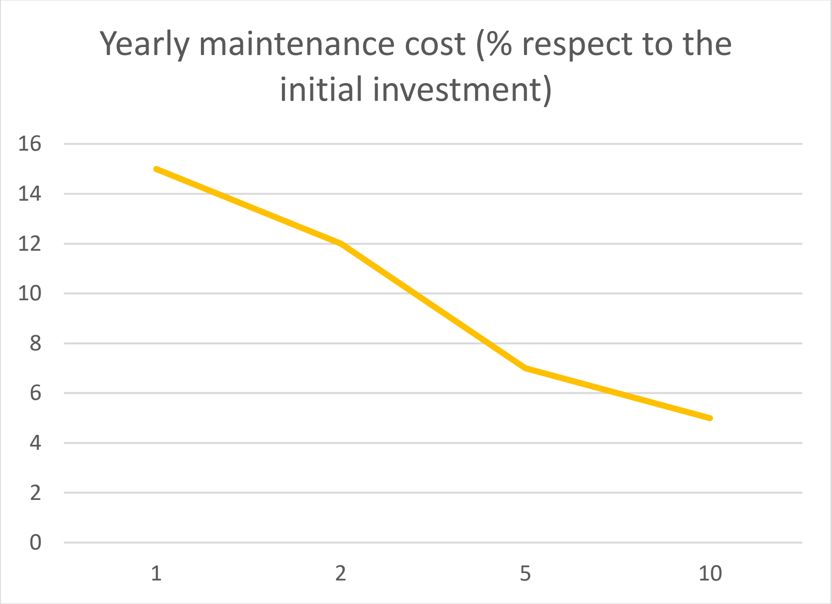


Fig. 38: Evolution of the initial yearly maintenance cost of installing an UPS storage system (%respect to the initial investment).

The following values of the initial investments to install and UPS system and its maintenance will be used:

	Initial investment (€/kW)	**Yearly maintenance cost (% respect to the initial investment)**
Average value of the interruptions	400	15
Average value of interruptions x 2	200	12
Average value of the interruptions x 5	100	7
Average value of interruptions x 10	50	5

Table 20: Future initial investment and yearly maintenance cost for an UPS system.

Furthermore, we know that the total electricity demand in Pedraza is 285,4kWh. If we multiply this figure by the total number of hours without power supply, we obtain the amount of kW that we need our UPS to provide.

$$Total\ kW_{UPS} = Total\ electricity\ demand\ _{Pedraza} \\ * Total\ number\ of\ hours\ without\ power$$

	Energy needed from the UPS (kW)
Average value of the interruptions	2.678
Average value of interruptions x 2	10.712
Average value of the interruptions x 5	66.954
Average value of interruptions x 10	267.819

Table 21: Energy needed from the UPS system in one year with different values of the interruption.

In table number 22 we can find the total cost of the UPS system. In order to calculate the total maintenance cost of the storage system we have considered that it will have a life of ten years. Then, in table number24, we can find a comparison between the initial investment and the yearly maintenance cost of installing an UPS storage system depending on the length and duration of the interruptions. We can conclude that, while at the beginning the maintenance covers the biggest part of the total cost, at the end it is the other way round. This is an important conclusion as distribution companies should consider this when including in their budgets the cost of the UPS system.

	Average value of the interruptions	**Average value of the interruptions x 2**	**Average value of the interruptions x 5**	**Average value of the interruptions x 10**
Initial investment (€)	1.071.279	2.142.558	6.695.493	13.390.985
Total maintenance cost of the ten years (€)	1.606.918	2.571.069	4.686.845	6.695.493
Total (€)	2.678.197	4.713.627	11.382.337	20.086.478

Table 22: Initial investment and maintenance costs linked to the installation of an UPS system in Pedraza's scenario.

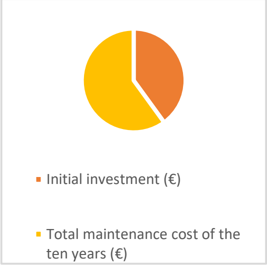
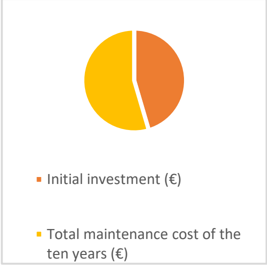
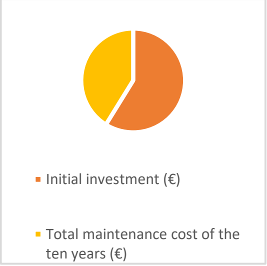
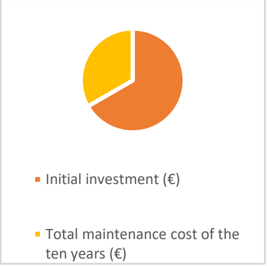
Average value of the interruptions	Average value of the interruptions x 2	Average value of the interruptions x 5	Average value of the interruptions x 10
			

Table 23: Comparison of the initial investment and maintenance cost over ten years depending on the length and duration of interruptions.

To sum up, we will compare the costs associated to the installation of an UPS storage system to the cost of interruptions in a period of time of ten years.

	Average value of the interruptions	Average value of the interruptions x 2	Average value of the interruptions x 5	Average value of the interruptions x 10
Total cost of interruptions (€)	27.913.277	446.612.444	2.791.327.778	11.165.311.115
Total cost of the installation of an UPS storage system (€)	2.678.197	4.713.627	11.382.337	20.086.478

Table 24: Comparison between the total cost of interruptions and the total cost of the installation of an UPS system in Pedraza's scenario.

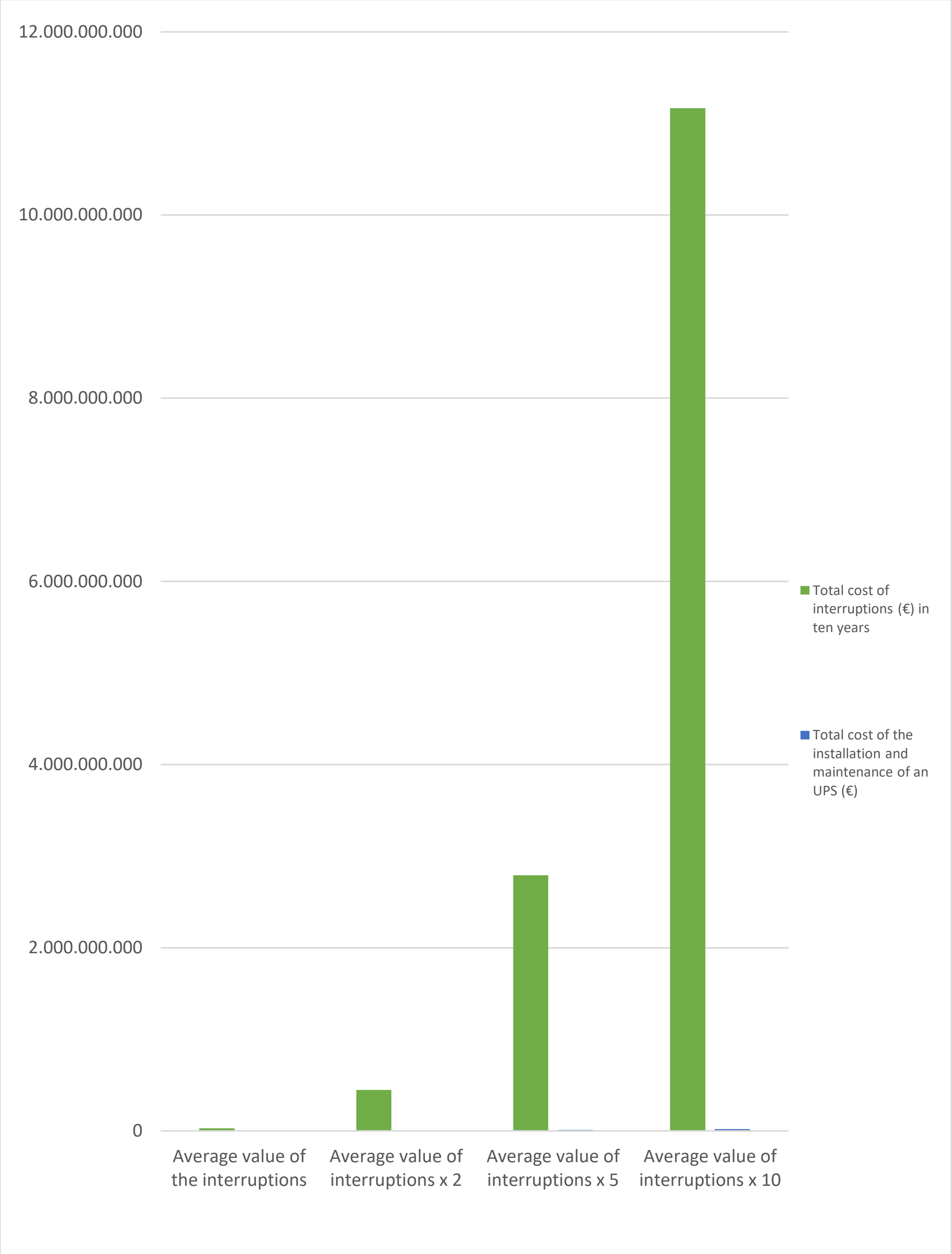


Fig. 39: Graphical comparison between the total cost of interruptions and the total cost of the installation of an UPS system in Pedraza's scenario.

Figure number 39 and table number 24 demonstrate that installing an UPS storage system in a gathered rural zone as Pedraza is currently profitable. Moreover, we can also observe that if the total cost of the interruptions increases while the cost of the installation and maintenance of an UPS decreases, so it will be even more profitable to install this storage system in the future. Therefore, by installing an UPS system the number and length of interruptions will decrease so that electrical distribution companies will not need to pay those big sums of money to customers when interruptions take place.

4.3.1. Cost for each customer

In this section we will study how much will each customer need to pay if the electrical distribution company decided to charge them for the installation of the UPS storage system meaning by this an improvement in the quality of their power.

In order to do this, we will divide the total cost of the installation of the UPS by the number of electrical customers in Pedraza. We will consider that the customer will pay the same amount of money every year, i.e., the distribution company will need to be aware that the first year they'll not receive all the money spent initial investment and first-year maintenance but a proportional part of the total cost. Then, as the customers usually pay the electrical companies every two months we will calculate the amount of money they'll pay.

	Average value of the interruptions	**Average value of the interruptions x 2**	**Average value of the interruptions x 5**	**Average value of the interruptions x 10**
Yearly cost (€)/customer	2.581	4.542	10.968	19.356
Cost (€)/customer every two months	430	757	1.828	3.226

Table 25: Yearly cost and two-monthly cost that each customer has to pay for the UPS's installation in Pedraza's scenario.

From table number 25 we can conclude that the installation of the UPS storage system will cost the customers a lot of money. Even if they want to improve the quality of their power the distribution company will need to pay for part of the storage system.

4.3.2. Sensitivity analysis

For our sensitivity analysis we will consider what happens if we equal the cost of the UPS storage system to the cost of the energy not supplied. We will carry out the sensitivity analysis only in the present where the value and length of the interruptions is the average one.

$$Cost_{UPS} = Cost_{ENS}$$

$$Initial\ investment_{UPS} * Energy\ needed = ENS * Cost\ of\ non - supplied\ energy$$

The average value of the energy needed from the UPS is 2678kW and the average value of the energy not supplied is 419.2MWh.

If we maintain the value of the initial investment of the UPS to 400€/kW we obtain that the cost of non-supplied energy should be:

$$Cost\ of\ non - supplied\ energy = \frac{Initial\ investment_{UPS} * Energy\ needed}{ENS}$$

$$= \frac{400 * 2678}{419200} = 2{,}5€/kWh$$

The average cost of non-supplied energy used in this project is 10€/kWh. If we compare this with the figure we have just obtained, we can conclude that it is worth for companies to install UPS systems while the cost of non-supplied energy is more than 2,5€/kWh (considering that the initial investment of the UPS is fixed) in a gathered rural zone.

If we maintain fixed the cost of non-supplied energy, we obtain that the initial investment of the batteries is:

$$Initial\ investment_{UPS} = \frac{ENS * Cost\ of\ non - supplied\ energy}{Energy\ needed} = \frac{419200 * 10}{2678}$$

$$= 1565€/kW$$

The figure obtained means that, if the cost of non-supplied energy stays fixed, it will be profitable for electrical distribution companies to install storage technologies whose initial investment is less than 1565€/kW in a gathered rural zone.

4.4. Scenario II: Urban zone

We will use Spain's capital, Madrid, as the urban zone studied in this scenario. It is the most populated city of Spain with 3.141.991 habitants and located in the center of the country. It is the third largest city of the European Union after London and Berlin.

Fig. 40: Map of Spain where we can see Madrid's location **[52]**.

Madrid is considered an urban zone as it has more than 20.000 habitants. The average value of the SAIDI and SAIFI indexes for this type of zone can be found in table number 26. As we did with the gathered urban zone scenario, the values of these indexes can also be found multiplied by some constants in order to model the impact of the climate change on the electrical disturbances.

	Average value of interruptions	**Average value of interruptions x 2**	**Average value of interruptions x 5**	**Average value of interruptions x 10**
SAIDI (hours)	1,072	2,144	5,36	10,72
SAIFI (number of interruptions)	1,458	2,916	7,29	14,58

Table 26: Different values of the SAIDI and SAIFI indexes in an urban zone (average value, average value multiplied by two, average value multiplied by five and average value multiplied by ten).

As we calculated in the Pedraza's scenario, the electricity demand of one Spanish electrical customer has an average value of 2749Wh. Considering the population of Madrid we will now obtain the amount of customers of electrical distribution companies in it:

$$Number\ of\ customers_{Madrid} = \frac{Number\ of\ habitants}{4} = 785497$$

Using this information, we obtain that the total electricity demand of this city is:

$$Total\ electricity\ demand\ _{Madrid} = 2749\ Wh * 785479\ inhabitants$$
$$= 2159331\ kWh = 2159\ MWh$$

Now, following the procedure presented in chapter 3 and as we did in the Pedraza's scenario we will calculate the sum of money that electrical companies have to pay for not providing one hour of electricity in Madrid.

$$Cost_{hour} = Demand * Price = 2159331\ kWh * \frac{10€}{kWh} = 21599331\ €/hour$$

$$Total\ time = SAIFI * SAIDI$$

	Total time (hours)
Average value of the interruptions	1,563
Average value of interruptions x 2	6,252
Average value of the interruptions x 5	39,074
Average value of interruptions x 10	156,298

Table 27: Total number of hours without power supply in Madrid's scenario with different values of the interruptions.

In order to calculate the total cost of the interruptions we will have to multiply the cost of one hour of power by the average number of hours without energy supply by the total number of customers.

$$Cost_{interruptions} = Cost_{hour} * Total\ time * Number\ of\ customers$$

	Cost (€)
Average value of the interruptions	26.517.922.402.477
Average value of the interruptions x 2	106.071.689.609.908
Average value of interruptions x 5	662.948.060.061.927
Average value of interruptions x 10	2.651.792.240.247.710

Table 28: Total cost of interruptions of power supply in Madrid's scenario in one year with different values of the interruption.

Once we are aware of the total cost of interruptions of power supply in Madrid in one year we will figure out if it compensates economically the installation of UPS in their distribution system. In order to do this, we will use the values of the initial investment and yearly maintenance cost that appear on table number 20.

As we know that the total electricity demand in Madrid is 2159MWh. If we multiply this figure by the total number of hours without power supply, we obtain the amount of kW that we need our UPS to provide.

$$Total\ kW_{UPS} = Total\ electricity\ demand\ _{Madrid} * Total\ number\ of\ hours\ without\ power$$

	Energy needed from the UPS (kW)
Average value of the interruptions	3.375.939
Average value of interruptions x 2	13.503.755
Average value of the interruptions x 5	84.398.467
Average value of interruptions x 10	337.593.868

Table 29: Energy needed from the UPS system in one year with different values of the interruption.

Finally, in table number 30 we can find the total cost of the UPS system. In order to calculate the total maintenance cost of the storage system we have considered that it lasts ten years.

	Average value of the interruptions	**Average value of the interruptions x 2**	**Average value of the interruptions x 5**	**Average value of the interruptions x 10**
Initial investment (€)	1.350.375.474	2.700.750.947	8.439.846.709	16.879.693.419
Total maintenance cost of the ten years (€)	2.025.563.210	3.240.901.136	5.907.892.697	8.439.846.709
Total (€)	3.375.938.683	5.941.652.083	14.347.739.406	25.319.540.128

Table 30: Initial investment and maintenance costs linked to the installation of an UPS system in Madrid's scenario.

Now we will calculate the costs associated to the installation of an UPS storage system to the cost of interruptions in a period of time of ten years to sum up.

	Average value of the interruptions	**Average value of the interruptions x 2**	**Average value of the interruptions x 5**	**Average value of the interruptions x 10**
Total cost of interruptions in ten years (€)	265.179.224.024.771	1.060.716.896.099.080	6.629.480.600.619.270	26.517.922.402.477.100
Total cost of the installation of an UPS storage system (€)	3.375.938.683	5.941.652.083	14.347.739.406	25.319.540.128

Table 31: Comparison between the total cost of interruptions and the total cost of the installation of an UPS in Madrid's scenario.

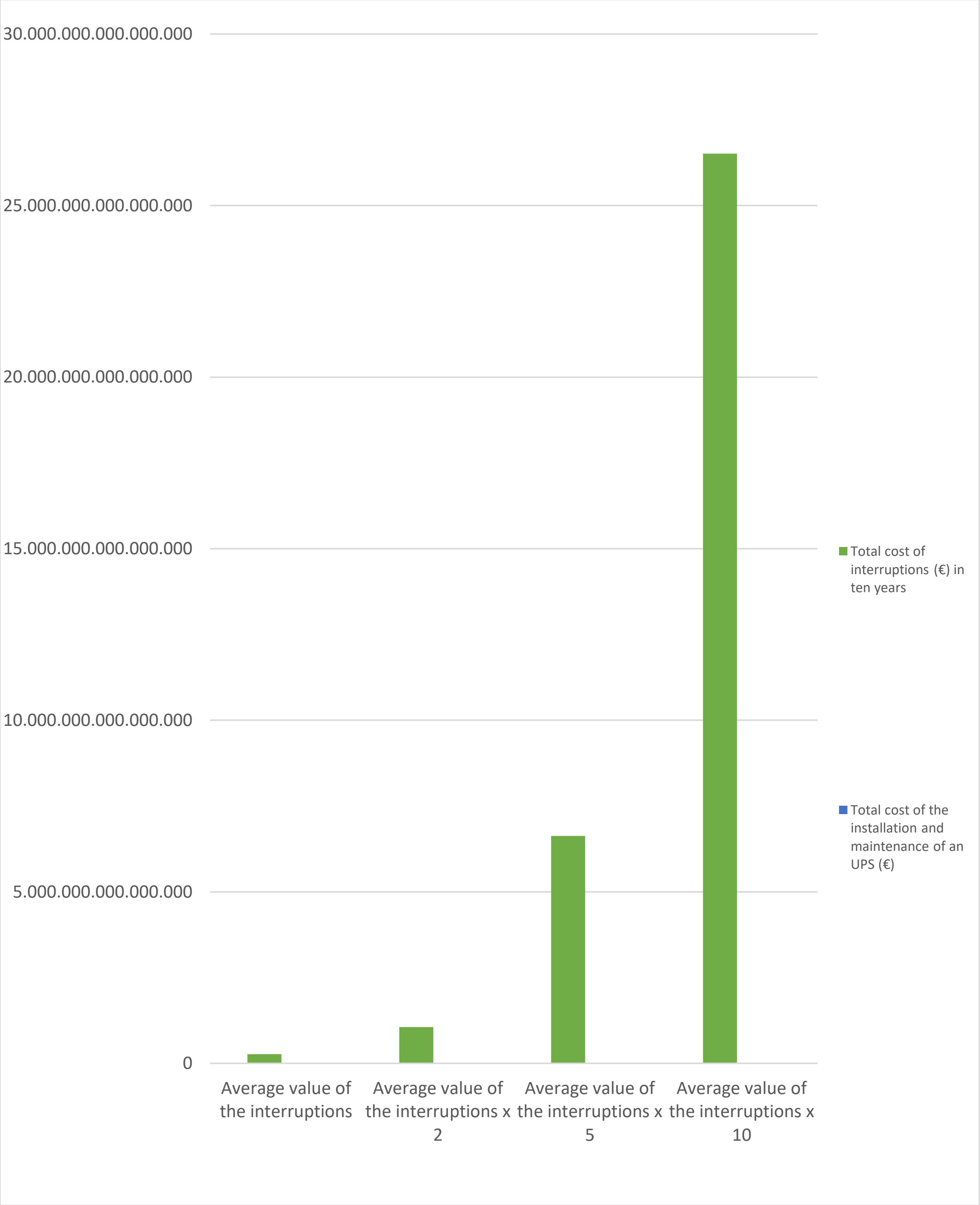


Fig. 41: Graphical comparison between the total cost of interruptions and the total cost of the installation of an UPS system in Madrid's scenario.

Figure number 41 and table number 31 demonstrate that installing an UPS storage system in an urban zone as Madrid is economically profitable. Even nowadays, when the number and length of interruptions is not very high, the electrical distribution will earn money by installing an UPS storage system in their distribution network. In addition, when there is an increase in the length and amount of interruption and a decrease in the cost of the UPS system, installing this storage equipment is even more profitable.

Moreover, a technical study of the installation of the UPS system may be necessary in order to assure the benefits of this measure.

4.4.1. Cost for each customer

As we did in the last scenario, it this section we will calculate the amount of money that needs to be payed for each customer in cade the electrical company wanted to charge them the total cost of the installation of the UPS.

In table number 32 we can find the yearly and two-monthly costs that the customers of the Madrid scenario will have to pay in order to install the UPS storage system. As we can see, the amount of money needed is a lot for the clients to afford. Therefore, the distribution companies would need to pay part of the installation by themselves.

	Average value of the interruptions	**Average value of the interruptions x 2**	**Average value of the interruptions x 5**	**Average value of the interruptions x 10**
Yearly cost (€)/customer	430	756	1827	3223
Cost (€)/customer every two months	72	126	304	537

Table 32: Yearly cost and two-monthly cost that each customer has to pay for the UPS's installation in Madrid's scenario.

4.4.2. Sensitivity analysis

As we did in the Pedraza's scenario we will carry out a sensitivity analysis for this scenario too.

$$Cost_{UPS} = Cost_{ENS}$$

$$Initial\ investment_{UPS} * Energy\ needed = ENS * Cost\ of\ non - supplied\ energy$$

The average value of the energy needed from the UPS in an urban zone is 3375939kW and the average value of the energy not supplied is 419.2MWh.

If we maintain the value of the initial investment of the UPS to 400€/kW we obtain that the cost of non-supplied energy should be:

$$Cost\ of\ non - supplied\ energy = \frac{Initial\ investment_{UPS} * Energy\ needed}{ENS}$$

$$= \frac{400 * 3375939}{419200} = 3221€/kWh$$

The average cost of non-supplied energy used in this project is 10€/kWh. If we compare this with the figure we have just obtained, we can conclude that, in order to cover the initial investment of the UPS system the cost of non-supplied energy that electrical distribution companies should pay is very high. If we just considered this figure we would conclude that it is worth for electrical distribution companies to install an UPS system because, if they don't do so, they'll need to pay a big cost for the non-supplied energy.

If we maintain fixed the cost of non-supplied energy, we obtain that the initial investment of the batteries is:

$$Initial\ investment_{UPS} = \frac{ENS * Cost\ of\ non - supplied\ energy}{Energy\ needed} = \frac{419200 * 10}{3375939}$$

$$= 1{,}25€/kW$$

The figure obtained means that electrical companies save a lot of money by installing the UPS storage system. Therefore, it will compensate them economically to install any storage system in an urban zone whose initial investment cost is above 1,25€/kW.

4.5. Comparison of both scenarios

Comparing the both study cases we can conclude that it is more profitable to install an UPS storage system in an urban zone like Madrid than in a rural gathered one like Pedraza. This is mainly because, while the average amount of interruptions in an urban zone is smaller and its population bigger, in a gathered rural zone the average amount of interruptions is bigger with a much smaller population.

Therefore, even if the cost of the UPS system in Madrid's scenario is higher than in Pedraza's, the cost of the interruption is also higher in this first city. This implies that it is more profitable to install a storage system in Madrid than in Pedraza. This can also be concluded by studying the costs of the installation to the customers.

In table number 33 we can find a comparison between the initial investment of an UPS system when we maintain fixed the cost of non-supplied energy and the cost of non-supplied energy when we maintain fixed the initial investment of the UPS system in a gathered rural and urban zone.

	Gathered rural zone	**Urban zone**
Cost of non-supplied energy (€/kWh)	2,5	3221
Initial investment UPS (€/kW)	1565	1,25

Table 33: Comparison between the initial investment of an UPS system when we maintain fixed the cost of non-supplied energy and the cost of non-supplied energy when we maintain fixed the initial investment of the UPS system in a gathered rural and urban zone**.**

From the information shown in the table above we can conclude that the cost of non-supplied energy should be more in the urban zones and less in the rural ones. On the other side, regarding the initial investment of the UPS system and due to the savings it provokes, the UPS system should cost more in a gathered rural zone than in an urban one.

Besides, even though we have studied the scenarios for separate, the distribution companies usually power different types or zones (not only gathered rural or urban). So, it will be necessary to study both scenarios together in order to obtain a more global vision of the situation.

4.6. Conclusion

From this chapter we can conclude that the climate change will have severe consequences in duration and length of the electrical disturbances. As we have seen, a lot of electrical disturbances are caused by weather phenomena and, as weather will change with the climate change, electrical disturbances will too.

Moreover, from the two scenarios presented we can affirm that installing a storage system like an UPS will be economically profitable. Therefore, electrical distribution companies should study this option from an economic and a technical point of view.

On the other hand, we have considered that, while the number and length of the interruption increase, the initial investment and yearly maintenance cost of the UPS system decreases. We are assuming that the technology advancement on batteries will reduce the cost of the UPS system but this will may not be the case. Therefore, it is important to consider this in future studies.

Nevertheless, it is important to consider that the UPS storage systems are installed in the electric power transforming centers. And, depending on the type of zone, the characteristics of the transformers are different. For example, while a transformer of an urban zone has an average power of 1MVA as it has to supply a big number of customers, the power of a rural transformer has an average power of 150kVA as the number of customers is smaller. In this project we have considered that the power is provided by a “big UPS system” that is able to provide all the necessary energy. But, in real life these UPS systems don’t exist. Therefore, in order to quantify more precisely the total cost of the UPS system this has to be considered as various UPS system will be installed with a different value for each of them depending on the type of zone.

We have concluded that it is economically profitable if both situations the installation of a storage system like an UPS. It is important to note that in a country like Spain the quality of electricity is very good. Thanks to this, we have very low values of SAIDI and SAIFI in we compare them with other countries in the globe (because, as we have seen, in Europe there are countries with better quality indexes than us). This is why, currently, not all the distribution companies install storage systems as they consider their networks good enough. But, in other countries of the globe their quality indexes are not as good. We can compare the values of the indexes when multiplying the SAIDI and SAIFI by 2 and by 5 to the indexes of the east of US where tornados are hurricanes are quite usual. There, the installation of storages systems even in individual households is quite usual. Moreover, the values of the indexes of developing countries like the Dominican Republic, Nigeria or India; are very close to the value when we multiply the SAIDI and SAIFI index by ten. In those countries the amount and length of the interruptions of power supply is very high (they can even be without energy for days in a monthly basis) so the installation of batteries or other storage system in becoming an usual practice nowadays.

And, finally, it is important to clarify that this has only been an economic study but in order to probe the feasibility of installing the storage system, a technical study is necessary too.

CHAPTER 5:

CONCLUSIONS

5. CONCLUSIONS

In this project we can find an economic study of the electricity storage on power quality in distribution systems.

We have studied all the aspects related to the quality of electricity: customer service, continuity of supply and power quality. Among those aspects we have focused our study in the continuity of supply as interruptions on power supply are among the electrical disturbances with higher economic impact. In order to measure the disturbances indexes are used and we have studied the most important indexes: SAIDI (average duration), SAIFI (average frequency) and ENS (average energy not supplied). Spain isn't among the European countries with the best values on those indexes. Therefore, in order to improve them, storage devices are used.

We have used the indexes mentioned above in order to measure the amount of money that electrical distribution companies have to pay to customers when interruptions of power supply take place. To do that, a cost of non-supplied energy of 10€/kWh has been used. This figure represents the amount of money that distribution companies have to pay for each kWh of energy not supplied to customers. In this project we have used an average value of it but, it is important to note that the cost of non-supplied energy depends on a lot of factors like the country or the type of client. Therefore, if we change the value of the cost of non-supplied energy the conclusions obtained in the project may vary.

Among the storage devices we have centered our attention into five: Petersen coil, UPS, flywheel, DVR and VFD. We have studied their advantages and disadvantages in order to conclude that currently the best solutions are the UPS system and the flywheel. As UPSs use batteries in order to store their energy and this element has been on the market for a lot of time its improvements are more than the improvements in flywheels. That is why UPSs are nowadays able to store a lot of energy while flywheels are only able to store a bit. This is the main reason why we have chosen UPS over the flywheels.

Finally, we have studied if it is economically profitable to install an UPS system nowadays and in the future. We have considered that, due to the climate change, the electrical disturbances including the interruptions will highly increase. Because of this, a storage device like the UPS will be necessary in order to assure customers that they have the best possible power supply. With the economic study we can affirm that, depending on the area of living of the customers, it is currently profitable or not the installation of the UPS. But, in the future it will be highly profitable the installation of the as the number and length of electrical disturbances will increase. As electrical distribution companies don’t power just a village but a lot more (so different types of zones are included) we can conclude that electrical distribution companies should install storage systems to avoid the cost of electrical disturbances.

5.1. Limitations of analysis and future research

This project can be considered as a research work in order to know the viability that different storage systems when reducing the impact of electrical disturbances in electrical distribution networks.

It is important to know that, mainly due to the short amount of time given to carry out this study, some limitations have been involved. Anyone doing a future research of this topic may wish to consider the following aspects:

- Studying the impact of electrical disturbances currently and in the future for other zones
- Considering another storage technologies
- Varying the value of the cost of the ENS in order to compare the results
- Varying the value of the cost of non-supplied energy depending on the type of customer
- Considering the cost of different UPS systems instead of the cost of just an UPS system that power the whole zone
- Not varying the cost of the UPS system with time

CHAPTER 6:

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6. BIBLIOGRAPHY

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ANNEX A:

BATTERIES

7. ANNEX A: BATTERIES

It has been already explained that the batteries are the main element of the UPS storage system as they are the ones in charge of storing the energy. So, in order to further our knowledge in batteries in the annex we can find a theoretical study of them. In it, different technologies that are currently used in storage will be studied with its benefits and disadvantages. Moreover, the need of using an DC/AC inverter will be explained.

7.1. Batteries

A battery is an electromechanical cell which can be used to deliver current or to power a load [37]. Therefore, the battery allows to release energy at a desired time. The improvements in the battery world have been very slow. The main problem is that, theoretically, the energy that can be provided by batteries is ten times higher than the commercial equivalent [38].

Its nominal voltage is determined by the number of cells connected in series and its discharge capacity rate is mainly determined by its size. But, how do batteries really work? A chemical reaction called electrolysis takes place. During this reaction an ionic bond is formed: the atoms of one element possess an excess of electrons and the atoms of another element lack of electrons. The bond is formed because of the electrostatic attraction between these two charges. When the ionic bond is formed from neutral atoms the electrons are transferred from one element two the other providing electrical current. The atom that gains the electron is said to be reduced while the atom that releases it is said to be oxidized. In order to facilitate the reaction a chemical mixture called electrolyte is used [39]. During this reaction the following events occur:

- Electrons from a DC load enter the cathode and are collected by the positive ion (the PbO_2 in the example shown in figure 42)
- The positive ion is neutralized by the electrons
- At the same time electrons from a negative ion are released (the Pb in figure number 42)

- The electrons follow the circuit and continue the reaction

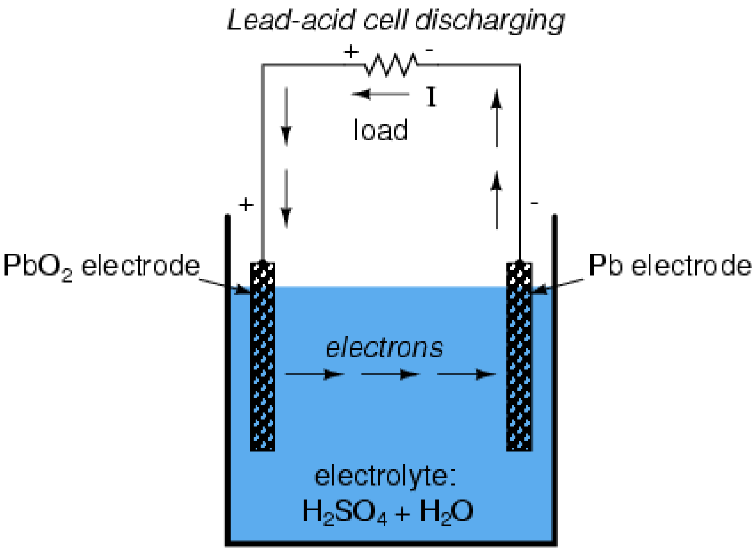

Fig. 42: Example of the reaction that takes place in a Lead-Acid battery **[39]**.

During a battery chemical reaction water is produced, the electrolyte is weakened and lead sulfates are formed on the electrodes. The effect that this causes in the battery is its discharge. Also, hydrogen gas and oxygen are produced during the electrolysis. These gases need to be releases from the battery cells and, in order to do that, ventilation is required [40]. If the ventilation is not correct the gas can be ignited causing serious explosions.

The state of charge of batteries describes how full a battery is. Temperature is important as, cold batteries will show a lower voltage than hot batteries when they are fully charged. Moreover, the depth of discharge (DOD) describes how deeply a battery is discharged. If the DOD is 0% its means that the battery is 100% full while, if the battery is empty, the DOD will be 100%.

The battery storage capacity is measured in Amp-hour (Ah); this is the amount of energy charge in a battery that will allow one ampere of current to flow for one hour.

$$Ampere - hours = ampere * discharge\ hours$$

The quantity of current that can be delivered by a battery depends, not only on its battery storage capacity, but also in the speed the battery has to release that current.

As a fluid stored in a container, the energy of a battery can be dispensed slower over a long period of time or faster over a short period of time [38].

A battery system is made up of different cells configured in series/parallel arrays in order to obtain the amount of voltage and current that are required by the system. The electricity obtained in the batteries needs to be modified so that it is suitable for the loads in the system. Therefore, this process is followed:

- Adjusting the current and voltage to maximize power output
- Converting the DC power to AC power using an inverter
- Matching the converted AC electricity to a utility's AC electrical network
- Halting the current flow from the system into the grid during the utility outages to safeguard utility personnel

The introduction of batteries in the electrical system will help improving the continuity and quality of supply. As the continuity is measured by indexes that count the number and/or duration of the outages, the inclusion of batteries will reduce its figures as the outages will take shorter (while the outage is being solved the batteries will proportionate the necessary energy).

Depending on how they make the chemical energy to electrical energy conversion we can find three main types of batteries:

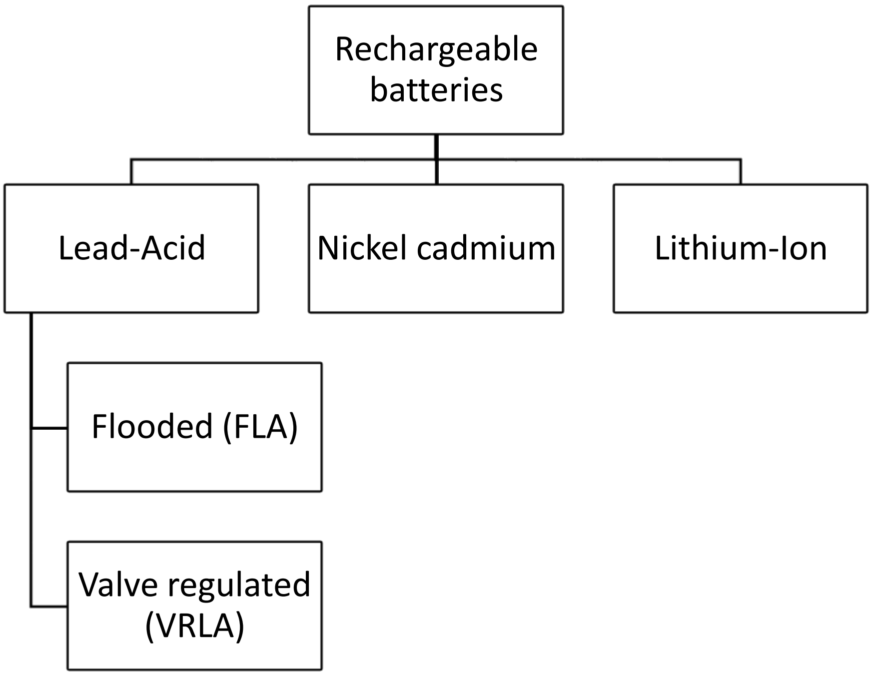

Fig. 43: Types of rechargeable batteries.

Although we can find different types of batteries in the market they all have one thing in common: they can also last for a certain amount of cycles. Therefore, battery replacement is always needed. The idea of an uninterrupted energy source is still a dream [38].

7.1.1. Lead-Acid batteries

Lead-Acid batteries are the oldest ones; they were invented in 1859 by the French physicist Gaston Planté. As it is shown in figure number 44 its electrodes are made of lead metal and lead oxide and its electrolyte consists in a diluted sulphuric acid solution. During its discharge the electrodes turn into lead sulphate while the electrolyte becomes water. [41]

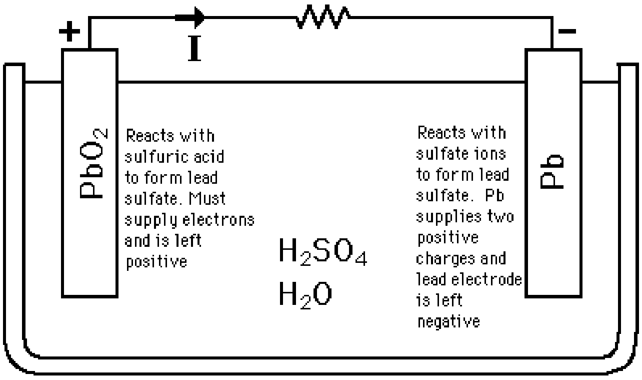

Fig. 44: Reaction that takes place in the lead-acid batteries. **[42]**.

The cost-benefit ratio of this batteries is quite good since they have relatively low costs, high reliability and efficiency (75%-80%). Moreover, their self-discharge rates are very low (<0.1%). Their lifespan is very limited as it consists in 1200-1800 cycles. Among their disadvantages we can find the fact that they cannot be discharged completely because, leaving these batteries discharged causes sulfation (phenomena during which amorphous lead sulfate converts to stable crystalline and deposits on the negative plates). Also, they have negative impact on the environment because of the lead processing, very low temperature performance, very low self-discharge rates and its life shortens if the battery is discharged below 30%. Its optimum operating time is 25ºC and temperature represents an important role in its behavior (a rise of 8 degrees will reduce its lifespan in half).

They can be found installed in uninterruptible power systems (UPS), renewable power systems and distribution systems.

We can distinguish two categories of lead-acid batteries: flooded lead-acid (FLA) and valve regulated lead-acid (VRLA).

7.1.1.1. Flooded Lead-Acid batteries

They are also made of lead but, while its positive electrode is made of lead dioxide the negative one is made of thinly divided lead.

The FLA batteries' batteries have the longest life and the least cost per amp-hour. Their principal inconvenience is that they need a strict maintenance. They are the most common ones as they entered the marketplace first. These batteries have a wide range of applications including solar and wind electric systems.

7.1.1.2. Valve-Regulated Acid batteries

These batteries, instead of having a liquid electrolyte have a Gel or AGM (Absorbed Glass Mat) electrolyte. The venting of the products of electrolysis is controlled by reclosing pressure-sensitive valve; therefore, no ventilation is required and no constant maintenance is needed.

The disadvantages of VRLA batteries are that they are less robust than FLA and have a shorter life. Moreover, its subsystem may need to be replaced more frequently than with FLA making them more expensive.

VRLA batteries are the most used ones because of their high power density and ease of use. They can also be used in reduced spaces as no ventilation is required. Among their applications are electronics, wheelchairs, motorcycles…

7.1.2. Nickel-Cadmium batteries

Nickel-Cadmium batteries are a type of batteries that use nickel oxide hydroxide as the positive electrode and metallic cadmium as the negative one, its electrolyte consists in an alkaline potassium hydroxide KOH.

These batteries have the disadvantage of having a higher initial cost than lead-acid ones but, in contrast, they have a longer life (>3500 cycles). They also have quick charge and discharge capabilities.

In comparison with lead-acid these batteries have a higher resistance to temperature. As it was mentioned before, lead-acid batteries reduce their lifespan by 50% with an increase of temperature of 8ºC above 25ºC while Ni-Cd batteries reduce their lifespan only by 20%. Moreover, Ni-Cd batteries' plates don't suffer degradation because the alkaline electrolyte used protects them from corrosion [43]. Another problem with NiCd batteries is that they lose charge even when they are not being used, around 1% per day. They also have low efficiency (60%-70%).

Nowadays, they are losing power because of their memory effect. This memory effect is that, if a Ni-Cd battery is recharged repeatedly after being discharged for example, 60% , it will become incapable of delivering more than 60% of its capacity [44]. So, the battery will “think” that it is fully charged when it is really only 60% charged. The memory effect is caused by a change in the crystalline formation of the Cadmium from a small size to a big size. The large crystal increases the cell impedance and cause the self-discharge of the battery. Therefore, as the cadmium is the element behind the memory effect Ni-Cd batteries are now being replaced by Nickel-Metal Hydride (NiMH) batteries.

Their main use currently is the domestic one. They can be found in portable electronics (such as solar garden lights) and toys. Ni-Cd batteries are also used in photographic equipment, emergency lighting and wireless telephones.

7.1.3. Lithium-Ion batteries

Lithium-Ion batteries are a type of rechargeable batteries. Its positive electrode is made of lithium metallic oxide while its negative electrode is made of a carbon material. The electrolyte used is a lithium salt in an organic solvent. During charging, lithium ions flow from the positive electrode tot the negative one trough the electrolyte. In the negative electrode electrons and ions combine so lithium is deposited there. The flow of ions is interrupted when the battery is fully charged. This same process, the other way round, takes place when the battery is discharging.

This type of batteries has a lot of advantages such as high energy density, fast charge and high round trip efficiency (80%-90%). Moreover, they have a long cycle life, around 3000 cycles. They are more expensive than NiCd ones but they operate over a wider temperature. Compared to NiCd batteries their self-discharge rate is much lower as it is only 2% per month, while in NiCd it was almost 30% per month.

Their main disadvantage is that they are currently very expensive. This is due to the special packaging required and the internal overcharge protection that the circuits need. Moreover, as they need less volume to generate more energy their price rises even more. They also have a short life, approximately 3 years, even if they are or they are not used.

Li-Ion batteries are the most demanded ones in the mobile phone market due to their huge energy/weight ratio. Also, in the last years Li-Ion batteries have been installed in electric vehicles.

7.1.4. Comparison of batteries

In the following table we can found a comparison between the three main types of batteries. The most important characteristics are the ones shown.

Cell type	**Lead-Acid**	**Nickel-Cadmium**	**Lithium-Ion**
Voltage (V)	2.0	1.2	3.0
Power density	Moderate	Moderate	Very high
Specific energy (Wh/kg)	30-40	50-60	130-200
Self-discharge (%per month)	4-8	20-30	1-2
DOD (V/cell)	1.75	1.0	3.0
Life cycles	1200-1800	>3500	3000-3200
Weight comparison for the same capacity	4	2	1
Size comparison for the same capacity	3.5	1.8	1
Cost	Moderate	Moderate	High

Table 34: Comparison of the different types of batteries.

7.1.5. Advancements in batteries

Even though we are living in the technological era the advancements in batteries during the last decades have been very shots. Batteries have several limitations: they are heavy, they have a short life span and they can only storage a small amount of power. Moreover, the smaller the battery, the higher its cost. So, currently, there are two main fronts of advancement in batteries: increasing its specific energy in order to obtain longer runtimes and increasing its specific power to obtain high-current load requirements. In figure number 45 we can find the relationship between these two improvements according to the battery type.

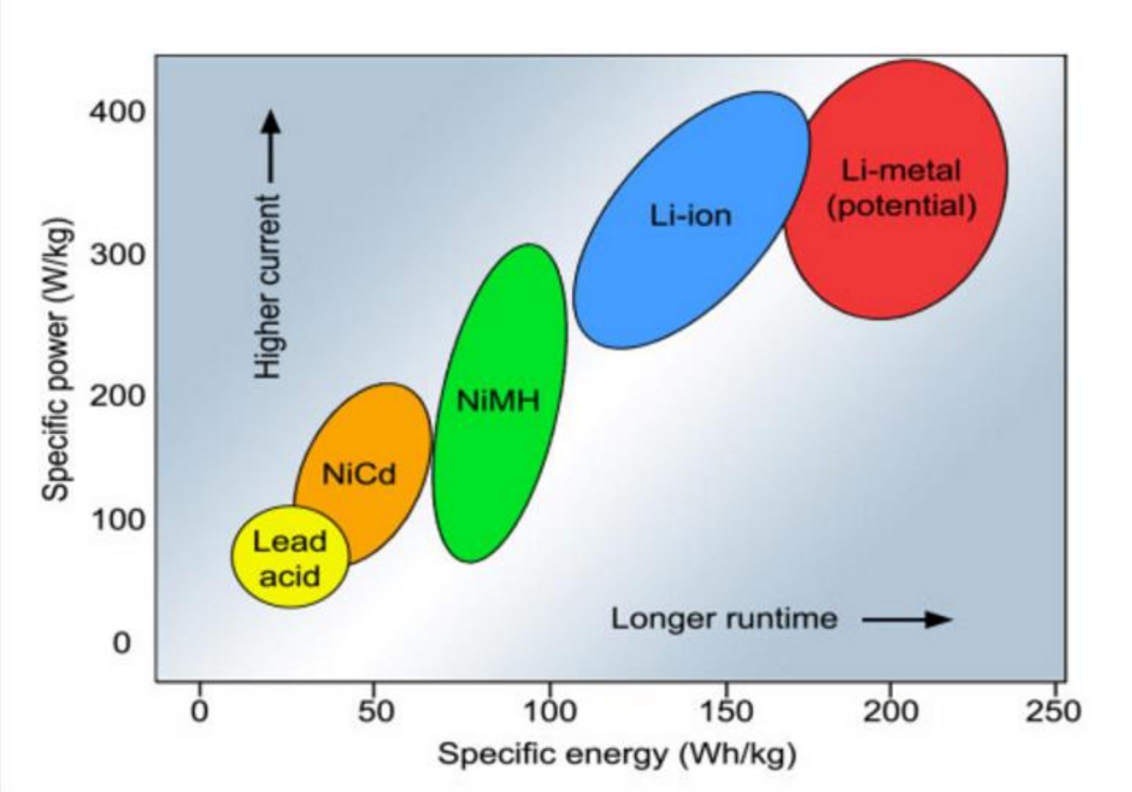

Fig. 45: Values for the specific energy and specific power of different types of batteries **[38]**.

7.2. Inverters

Direct current is very useful but batteries can provide only a very low voltage DC power, that's why the inverters are used. An inverter is an electronic device that converts DC power in AC power using power electronics. Therefore, they can produce the AC waveform needed from the batteries that are a DC power source. In order to produce the AC waveform switching elements such as IGBT or BTO are used.

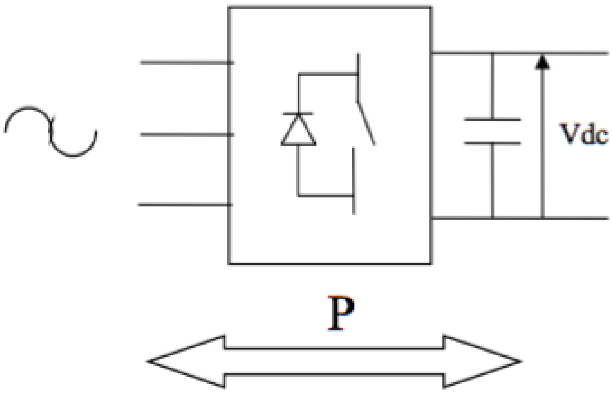

Fig. 46: Inverter **[45]**.

Depending on the requirements of the network the inverter needs to work within voltage and frequency margin. A filter is usually inserted in the system to reject the switching frequencies that could deteriorate the power quality. Moreover, modulation (adjusting the switching of the elements) will help by reducing the harmonic distortion.