UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE
ELECTRIC POWER INDUSTRY

Master's Thesis

Voltage control regulation in systems with high penetration of renewables

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Madrid, July 2021

REGULACIÓN SOBRE EL CONTROL DE TENSIÓN EN SISTEMAS CON ALTA PENETRACIÓN RENOVABLE

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RESUMEN

En esta tesis se abordan de forma general dos aspectos de vital relevancia en materia de control de tensión. En primer lugar, se realizará un estudio, con su consiguiente descripción, sobre las estrategias y métodos de control de tensión aplicados en las principales tecnologías de generación renovable. En segundo lugar, un análisis de los marcos regulatorios actuales (España y Reino Unido) con el fin de encontrar deficiencias y proponer soluciones para aumentar la eficacia del control de tensión.

Palabras clave: Tensión, Reactiva, Potencia, Regulación, Control, Renovables, Energía

1. Introducción

Actualmente, uno de los principales objetivos de los sistemas eléctricos alrededor del mundo es garantizar la confiabilidad, seguridad de suministro y calidad de la energía a sus consumidores, el cumplimiento de este objetivo comienza con el control constante de ciertas variables del sistema que deben estar bajo los límites requeridos para mantener la estabilidad del sistema. Una de estas variables mencionadas son las tensiones de los nodos, que, a diferencia de la frecuencia del sistema, es una variable que debe ser controlada localmente. La principal variable que determina la variación de la tensión en un nodo determinado es la generación/absorción de potencia reactiva en ese nodo. Por ello, el mantenimiento de la tensión de los nodos dentro de los límites establecidos dependerá principalmente de la gestión por parte del operador del sistema de la cantidad de potencia reactiva inyectada en el nodo considerado. Debido a la gran influencia que tiene el control de la tensión en el correcto funcionamiento del sistema, muchos operadores del sistema han desarrollado diferentes mecanismos para mantener los valores de tensión dentro de los límites. Estos mecanismos suelen estar definidos dentro de los servicios auxiliares que se pueden ofrecer al sistema eléctrico en cuestión. Estos mecanismos auxiliares de control de la tensión implican a numerosos agentes del sistema, ya sean generadores, DSOs o TSOs, todos ellos juegan un papel importante en el éxito de este mecanismo. Actualmente, la mayor carga de este servicio auxiliar la llevan los generadores del sistema, ya que son los principales responsables de generar o absorber la potencia reactiva necesaria en cada momento. Debido a la gran importancia de los agentes de generación en el suministro de este servicio, el operador del sistema suele diseñar los mecanismos de control de tensión auxiliar de forma que los generadores deban cumplir ciertos requisitos obligatorios en función de las características de cada generador. En la actualidad, dependiendo del sistema eléctrico del que hablemos, se están implementando mecanismos auxiliares que complementan o transforman el servicio de control de tensión. En concreto, se están implementando diferentes mecanismos de mercado con la intención de aumentar la competitividad de este servicio auxiliar. Esta competitividad se verá incrementada gracias a la retribución del servicio, que convertirá al servicio de control de tensión en uno más de los muchos mecanismos que representan una fuente de ingresos para los agentes de generación, promoviendo y facilitando, un incremento de la inversión de los agentes externos en el sistema.

2. Alcance del proyecto

Aunque el control de la tensión no ha tenido gran relevancia en el pasado, debido principalmente a la naturaleza de las tecnologías de generación utilizadas, en respuesta al aumento de la penetración de las renovables, los sistemas eléctricos están en proceso de modificar sus marcos regulatorios para implementar nuevos mecanismos que se adapten a las necesidades actuales que requiere el perfil de tensión. Esta modificación no sólo responde a las necesidades técnicas del sistema, sino también a las directrices emitidas por la UE, que establecen, entre otras, la necesidad de asignar los servicios a través de mecanismos de mercado.

Los sistemas eléctricos más representativos que hasta ahora han modificado o están modificando e innovando sus marcos regulatorios para adaptar un nuevo servicio de tensión son el Reino Unido y España. Precisamente el principal componente innovador en estas normas reguladoras es la implementación de la asignación parcial del servicio a través de mecanismos de mercado. Aunque tanto el marco regulatorio británico como el español son muy similares en comparación con las normas establecidas en otros sistemas, existen diferencias significativas entre ellos que serán objeto de estudio y análisis durante la elaboración de esta tesis.

Aunque la parte más innovadora es la incorporación de los mercados al servicio, la parte más importante de la regulación consiste en las especificaciones técnicas que deben cumplir los agentes que participan en el servicio. En consecuencia, es de gran interés estudiar y analizar las capacidades actuales de las diferentes tecnologías para proporcionar el control de la tensión.

3. Metodología

Las metodologías aplicadas durante la elaboración del proyecto son diferentes y variadas en función de la parte del proyecto en la que se centran. Como se ha mencionado anteriormente, el proyecto tiene dos líneas principales de investigación, para las que se ha aplicado una metodología específica. La primera parte del proyecto consiste en una parte más descriptiva, por lo que la metodología aplicada se basa en los siguientes pasos

- Selección de las tecnologías renovables a estudiar, en función de su desarrollo, impacto y perspectiva de futuro en los sistemas eléctricos.

- Profundización e investigación de las principales estrategias y metodologías utilizadas para el control del perfil de tensión en las tecnologías seleccionadas.

- Análisis y evaluación de los procedimientos utilizados en cada tecnología para identificar los elementos diferenciales de cada una de ellas.

- Descripción exhaustiva y concreta de los elementos identificados en el paso anterior, combinada con un breve comentario sobre los mismos.

La segunda parte del proyecto consiste en el análisis y estudio del marco normativo; debido a las diferencias entre este apartado y el anterior, la metodología será diferente.

- Estudio y comprensión de los marcos regulatorios aplicados recientemente tanto en España como en el Reino Unido, con especial atención al español.

- Descripción de ambos marcos normativos de la forma menos técnica posible para facilitar una lectura comprensiva al lector.

- Incorporación de comentarios a la mayoría de los apartados de la normativa, aclarando o cuestionando las diferentes metodologías regulatorias aplicadas.

- Una vez adquiridos unos antecedentes coherentes sobre los marcos reglamentarios en cuestión, se realizará una comparación entre las dos normas reglamentarias.

- Por último, se propondrá un modelo de regulación que, a juicio del autor, es el óptimo, basándose en los marcos reguladores presentes hasta ahora.

4. Conclusiones

Las conclusiones obtenidas pueden dividirse en dos partes principales, asociadas a cada uno de los dos apartados principales del proyecto. En primer lugar, respecto a los marcos regulatorios estudiados, se ha determinado que el modelo óptimo a implantar en el sistema español sería una combinación de ambos marcos regulatorios, que consistiría básicamente en la correcta definición de las zonas eléctricas y la combinación de los modelos retributivos utilizados en ambos marcos regulatorios. En cuanto al resto de los aspectos definidos en ambos marcos regulatorios, se recomienda utilizar, en su mayor parte, la regulación establecida en el marco español, combinando únicamente las restricciones técnicas, siendo en algunos casos las emitidas en el P.O. 7.4 algo más exigentes que en el marco inglés.

En segundo lugar, en cuanto al comportamiento de las tecnologías bajo el control de tensión, se ha observado que tanto las tecnologías como las estrategias utilizadas en el control de tensión varían significativamente en función de la tecnología de generación que se analice, lo que previsiblemente tendrá un impacto en el futuro, dado que la investigación para mejorar el rendimiento de las diferentes tecnologías a la hora de controlar la tensión se realizará de forma descentralizada. De este modo, podría crearse un cierto desequilibrio entre las tecnologías a la hora de prestar el servicio, que debería ser tenido en cuenta en la regulación si la desventaja de unas tecnologías frente a otras se hace relevante.

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[1] Peter W. Sauer. "*Reactive power and voltage control issues in electric power systems"*. March 2006. University of Illinois, Urbana-Champaign.

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[4] National Grid, United Kingdom. *"Enhanced Reactive Power"*. 2019.

VOLTAGE CONTROL REGULATION IN SYSTEMS WITH HIGH RENEWABLE PENETRATION

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Supervisor: Rodríguez Domínguez, Venancio Javier.
Collaborating Entity: Endesa

ABSTRACT

This thesis generally covers two aspects of vital relevance in terms of voltage control. Firstly, a study will be carried out, with its consequent description, on the voltage control strategies and methods applied in the main renewable generation technologies. Secondly, an analysis of the current regulatory frameworks (Spain and UK) in order to find deficiencies and propose solutions to increase the effectiveness of voltage control.

Keywords: Voltage, Reactive, Power, Regulation, Control, Renewable, Energy.

6. Introduction

Currently, one of the main objectives of electrical systems around the world is to ensure the reliability, security of supply and quality of energy to their consumers, the fulfillment of this objective begins with the constant control of certain system variables which must be under required limits in order to keep the stability of the system. One of these mentioned variables is the nodes voltages, which, unlike the system frequency, is a variable that must be controlled locally. The main variable that determines the voltage variation at a given node is the generation/absorption of reactive power at that node. That is why maintaining the voltage of the nodes within the established limits will depend mainly on the system operator's management of the amount of reactive power injected to the node under consideration. Due to the great influence that voltage control has on the correct functioning of the system, many system operators have developed different mechanisms in order to keep voltage values within limits. These mechanisms are usually defined within the ancillary services that can be offered to the power system in question. These auxiliary voltage control mechanisms involve numerous system agents, no matter whether they are generators, DSOs or TSOs, they all play a major role in the success of this mechanism. Currently, the greatest burden of this auxiliary service is carried by the system's generators, since they are primarily responsible for generating or absorbing the reactive power required at any given moment. Due to the great importance of the generation agents in supplying this service, the system operator usually designs the auxiliary voltage control mechanisms in such a way that the generators must comply with certain mandatory requirements depending on each generator’s features. Nowadays, depending about which electricity system are we talking about, auxiliary mechanisms are being implemented to either complement or transform the voltage control service. Specifically, different market mechanisms are being implemented with the intention of increasing the competitiveness of this auxiliary service. This competitiveness will be increased thanks to the remuneration of the service, which will turn the voltage control service into another of the many mechanisms that represent a source of income for generation agents, promoting and facilitating, an increase in investment by external agents in the system.

7. Scope of the project

Although voltage control has not had great relevance in the past, mainly due to the nature of the generation technologies used, in response to the increase in renewable penetration, electricity systems are in the process of modifying their regulatory frameworks to implement new mechanisms that adapt to the current needs required by the voltage profile. This modification not only responds to the technical needs of the system but also to the guidelines issued by the EU, which establish, among others, the need to allocate services through market mechanisms.

The most representative electricity systems that have so far modified or are modifying and innovating their regulatory frameworks to adapt a new voltage service are the UK and Spain. Precisely the main innovative component in these regulatory rules is the implementation of the partial allocation of the service through market mechanisms. Although both the UK and Spanish regulatory frameworks are very similar in comparison with the rules established in other systems, there are significant differences between them that will be the subject of study and analysis during the preparation of this thesis.

Although the most innovative part is the incorporation of markets in the service, the most important part of the regulation consists of the technical specifications to be met by the agents participating in the service. Consequently, it is of great interest to study and analyze the current capabilities of the different technologies in providing voltage control.

8. Methodology

The methodologies applied during the preparation of the project are different and varied depending on the part of the project they are focused on. As mentioned above, the project has two main lines of research, for which a specific methodology has been applied. The first section of the project consists of a more descriptive part, consequently, the methodology applied is based on the following steps:

- Selection of the renewable technologies to be studied, based on their development, impact and future perspective in the electricity systems.
- In-depth study and investigation of the main strategies and methodologies used to control the voltage profile in the selected technologies.
- Analysis and evaluation of the procedures used in each technology in order to identify the differential elements of each of these technologies.
- Comprehensive and concrete description of the elements identified in the previous step, combined with a brief commentary on them.

The second part of the project consists of an analysis and study of the regulatory framework; due to the differences between this section and the previous one, the methodology will be different.

- Study and understanding of the regulatory frameworks recently applied in both Spain and the UK, with a special focus on the Spanish one.
- Description of both regulatory frameworks in the least technical way possible to facilitate a comprehensive reading for the reader.

- Addition of comments on most sections of the regulation, clarifying or questioning the different regulatory methodologies applied.

- After having acquired a consistent background on the regulatory frameworks in question, a comparison will be made between the two regulatory standards.

- Finally, a regulatory model will be proposed which, in the author's view, is the optimal one, based on the regulatory frameworks present so far.

9. Conclusions

The conclusions obtained can be divided into two main parts, associated with each of the two main sections of the project. First, with respect to the regulatory frameworks studied, it has been determined that the optimal model to implement in the Spanish system would be a combination of both regulatory frameworks, which would basically consist of the correct definition of the electricity zones and the combination of the remuneration models used in both regulatory frameworks. As for the rest of the aspects defined in both regulatory frameworks, it is recommended to use, for the most part, the regulation established in the Spanish framework, combining only the technical restrictions, being in some cases those issued in P.O. 7.4 somewhat more demanding than in the English framework.
Secondly, regarding the technologies behaviour under voltage control, it has been observed that both the technologies and the strategies used in voltage control vary significantly depending on the generation technology being analysed, which is expected to have an impact in the future, given that research to improve the performance of the different technologies when it comes to voltage control will be carried out in a decentralized manner. In this way, a certain imbalance could be created between technologies when providing the service, which should be taken into account in the regulation if the disadvantage of some technologies compared to others becomes relevant.

10. References

[1] Peter W. Sauer. "*Reactive power and voltage control issues in electric power systems".* March 2006. University of Illinois, Urbana-Champaign.

[2] IRENA (2019), Future of wind: "*Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation paper*)", International Renewable Energy Agency, Abu Dhabi.

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Chapter 1. INTRODUCTION

Currently, one of the main objectives of electrical systems around the world is to ensure the reliability, security of supply and quality of energy to their consumers, the fulfillment of this objective begins with the constant control of certain system variables which must be under required limits in order to keep the stability of the system. One of these mentioned variables is the nodes voltages, which, unlike the system frequency, is a variable that must be controlled locally. The main variable that determines the voltage variation at a given node is the generation/absorption of reactive power at that node. That is why maintaining the voltage of the nodes within the established limits will depend mainly on the system operator's management of the amount of reactive power injected to the node under consideration.

Due to the great influence that voltage control has on the correct functioning of the system, many system operators have developed different mechanisms in order to keep voltage values within limits. These mechanisms are usually defined within the ancillary services that can be offered to the power system in question, these services are divided into frequency and non-frequency ancillary services. As their name states, the frequency ancillary services are those in charge of restoring the frequency to its nominal value when an unbalance between demand and generation is taking place, some of these mechanisms are secondary or tertiary regulation reserves. On the other side, the non-frequency ancillary services are devoted to maintain other network variables within limits, such as voltage levels, having these variables no direct relation with frequency control. These auxiliary voltage control mechanisms involve numerous system agents, no matter whether they are generators, DSOs, TSOs or demand, they all play a major role in the success of this mechanism.

Currently, the greatest burden of this auxiliary service is carried by the system's generators, since they are primarily responsible for generating or absorbing the reactive power required at any given moment. Due to the great importance of the generation agents in supplying this service, the system operator usually designs the auxiliary voltage control mechanisms in such a way that the generators must comply with certain mandatory requirements depending on each generator's features. Nowadays, depending about which electricity system are we talking about, auxiliary mechanisms are being implemented to either complement or transform the voltage control service. Specifically, different market mechanisms are being implemented with the intention of increasing the competitiveness of this auxiliary service. This competitiveness will be increased thanks to the remuneration of the service, which turns the voltage control service into another of the many mechanisms that represent a source of income for generation agents, promoting and facilitating, an increase in investment by external agents in the system.

The first step will consist of a deep study and analysis of all the topics to be covered in the thesis. From the technical behavior of the different generation technologies when providing the system with voltage control to the regulatory aspects that mark the operation and restrictions that these units must comply with.

On the other hand, this project aims to analyze and evaluate the role that renewable energies will play in the new voltage control service. Not only from a technical perspective, which in itself presents a series of challenges that are also intended to be addressed in the thesis, but also its adaptation to the new regulatory framework that is presented. One of the main aspects that will be addressed in this part of the project, is the difficulty to implement market mechanisms for voltage ancillary services in nodes where several generating agents are participating in the service mentioned.

This previous step is mandatory as one of this thesis aim's is to assess and study how the voltage control service in power systems is going to evolve due the continuous changes that the energy mix is experimenting. As everyone knows, nowadays energy mix is evolving from a system based on CO_2 emitting technologies, to a system defined by an increase in the generation of renewable and sustainable energies committed with the environment and climate change. This sudden change presents several challenges at the time of ensuring the grid reliability and quality of supply. The renewable energies are known for their variability and uncertainty of supply, these features present a serious challenge to voltage control activity due to the difficulty of voltage regulating when big amounts of energy are generated suddenly, which creates major changes in the power flows, provoking unbalances which might lead to voltage instability scenarios. On the other side, some renewable units such as wind and solar are connected to the grid as non-synchronous generators, this is generally due to the presence of an inverter between the generation point and the grid connection point. This type of connection requires a different approach when performing voltage control which is not as developed as the automatic generation control (AGC) used in synchronous generation, given the fact that those two technologies have most of the generation production share, this new types of approaches for voltage control are of great interest in the power sector.

After studying the technical restrictions presented by the different technologies in terms of voltage control, we will proceed to analyze the regulatory framework that sets the guidelines to be followed when providing the voltage control service. First, we will study the new regulatory standard that REE plans to implement on voltage control, which presents major modifications with respect to the current regulatory framework. At the same time, we will study the regulatory frameworks of other countries that have a current regulatory format similar to the one to be implemented in Spain.

The main motivation for the development of this project is mainly due to the recent modification of the regulations by the system operator regarding the auxiliary service of voltage control. By modifying the current regulatory framework, REE has defined the voltage control service more specifically, reducing uncertainty on some aspects that where not regulated before. On the other hand, it is also considering the possibility of implementing a market for additional reactive power capacity in order to increase competitiveness and improve the quality of service. Note that voltage control is a fundamental service to ensure the gird reliability and quality of supply, without an effective and reliable voltage control service the electric power systems might incur in fatal disasters such as blackouts and outages which will materialize in large economic and social losses.

For example, in Northeast region of the US, August 2003 took place the second widespread blackout in history. Even that voltage instability was not the only cause of the blackout, it was documented as an important trigger for the outage. This blackout affected 55 million people during a period that lasted from 2h to 4 days depending on the location. This disaster affected different types of infrastructure such as power generation, water supply, transportation, communication and industry. The emergency services received 3000 fire calls and 80.000 calls for help[1].

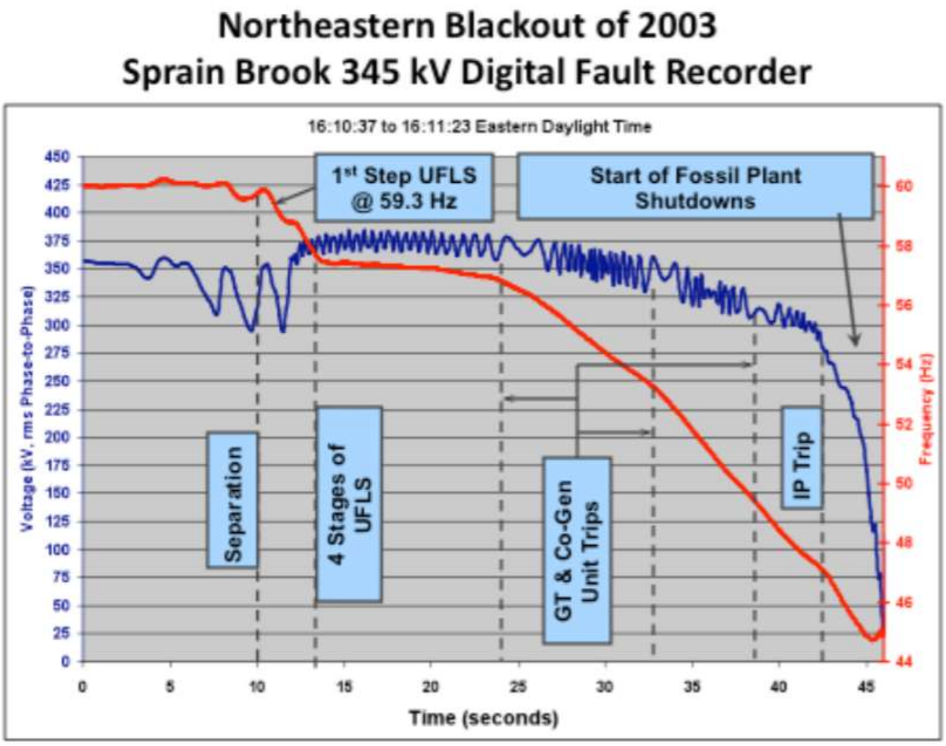


Figure 1-1: Voltage & Frequency Drop, Blackout 2003[2]

Apart from catastrophic failures and the consequences they can cause in the electrical system due to instabilities in the voltage profile, there are other occasions in which inefficient voltage control can cause losses in the system. When matching the daily electricity market, a certain process is followed. Firstly, the matching process is carried out between generation and demand bids, from a purely economic perspective, taking into account the restrictions that each agent defines in its bid. Next, the system operator checks that the dispatch obtained meets all the technical requirements demanded by the network, i.e., it ensures that there will not be any type of instability or technical impossibility. Generally during this process, it is usually found that the initial dispatch is not viable and therefore has to be modified, which results in market distortions that displace it from its state of perfect competitiveness. During this process, additional costs associated with this new redispatch are induced, adding the compensation to be provided to the agents involved. Although there are many types of technical restrictions, one of the most common and fundamental is due to voltage control.

Chapter 2. VOLTAGE CONTROL

2.1 INTRODUCTION

The main function of electric power systems is to transform natural sources of energy into electricity in order to transport it through the electrical network and supply it to energy consumers at the given distribution points. The main advantage of electricity, in comparison with other energy sources, is that it can be transported and partially controlled with a certain level of reliability and efficiency. Therefore, every single power system must fulfill a minimum number of requirements which might ensure the correct performance of all the elements in which the security of supply relay on, those minimum requirements are described below.

- Power systems are known for having continuous changes in demand load for both reactive and active power. As might occur with other primary sources of energy, electricity is not storable, which means that system generation must be adjusted constantly, in order to cover demand variations.
- Given that power systems formed by widespread facilities and are essential for the subsistence of people from all over the world, their service must be provided at minimum cost and causing the minimum ecological impact.
- Finally, the power provided to consumers must comply with a minimum quality standard regarding the following variables: Frequency, voltage and reliability level.

During the last years there has been a large effort for understanding the behaviour and techniques of voltage control. In principle, this research focused on voltage control through the production or absorption of reactive power in the system, as we will see later, reactive power is the main variable used to control voltage rises and falls. During the past years, where thermal generation has been the most predominant technology, accounting for a large part of the production, voltage control has been relatively easy to carry out, thanks to the great flexibility of this type of generation units together with the automatic voltage controls that allow maintaining the required setpoint at the grid connection point. However, the impact of renewable technologies on voltage control has to be taken into account more and more, since unlike thermal units, they lack flexibility and therefore cannot regulate the voltage at their will[3].

As stated before, achieving minimum requirements for voltage, and therefore, for reactive power is necessary in order to keep efficiency and reliability in the operation of power systems. In order to meet these optimal operation values of voltage and reactive power, the following objectives must be fulfilled.

- Voltage values at all system nodes must be within limits. Maintaining the voltage within the established standards is imperative to ensure the correct operation of the equipment involved in the transmission network. The lack of voltage control for a prolonged period can cause permanent damage to system equipment, and in extreme cases, a total blackout.
- Improving system stability is one of the main concerns of system operators, in this aspect both voltage and reactive power are key elements to improve efficiency of the transmission network.
- One of the main characteristics of reactive power flows is the impact they have on losses in the transmission network. The higher the reactive power transported by the network is, the higher the losses of both reactive and active power in the network. Therefore, it is a task of great importance to supply/absorb sufficient reactive power to keep the voltage within limits, while minimizing the reactive power flows through the network, and thus its losses.

The main problem in maintaining voltage control is that generation and demand imbalances that generate voltage instabilities occur continuously along numerous points of the transmission network. Since voltage is a local variable, meaning that the voltage at each node of the network takes a different value, it has to be controlled by reactive power generation/absorption at the node in question. Moreover, as mentioned above, transporting reactive power over long distances through the network is extremely inefficient.

Consequently, it is a great challenge to place voltage control systems at strategic points in the network in such a way as to provide a fast response, while avoiding losses in the transmission network.

2.2 *REACTIVE POWER*

In electric power systems reactive power is defined as the energy that flows back from its initial destination into de grid while operating an AC current system. While in DC power systems, load and voltage are static variables, which means that the energy flows in one direction, in AC systems different phases are found, these phases might vary depending on the elements connected to the grid. Another way to define reactive power is as the resulting power when in an AC system, the current waveform is not in phase with the voltage waveform, which means that the load either is capacitive or inductive.

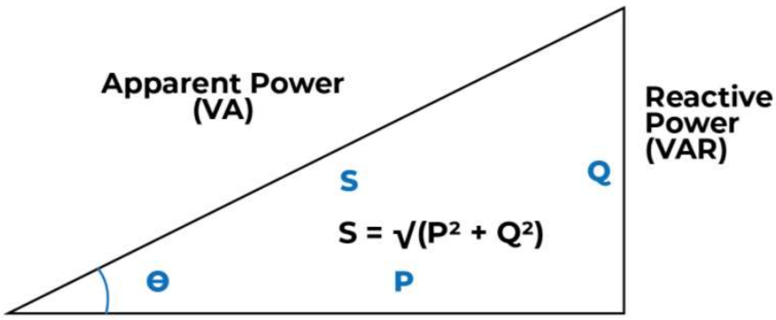


Figure 2-1: Active & Reactive Power

As shown in the previous figure, there are 3 different types of power. In the first place, the active power stands for the number of watts (W) destinated to feed the system loads. The reactive power results in the dissipated power in volt-amperes reactive (VAR), resulting from both capacitive and inductive loads. The apparent power is the combination of both reactive and active power, is calculated as stated in the figure and is measured in volt-amperes (VA)[4].

The reactive power has an important role across energy power systems, while active power supplies most of the loads such as motors, heater, or illuminates electric light bulb, reactive power has the function of regulating voltage. Both types of powers are essential for their optimal operation, if the system voltage is not high enough, then the system will be unable to supply the active power. Likewise, if the reactive power does not keep the voltage within limits, the efficiency of the system in providing reactive power will be far from optimal. In addition, reactive power is essential to control power flows within the network, for example, to transport active power from the transmission network to the distribution and ultimately to the consumers.

As we have already mentioned, the need for reactive power in power systems is of great importance for the correct operation and reliability of the system. The reactive power controls the voltage levels, and consequently is responsible for preventing damage to the system equipment by operating outside the nominal values for which they were designed. Usually, both consumer and system equipment are designed to operate in a range of ±5% of their nominal value, when such equipment is operating significantly below its nominal value, it worsens its performance and increases the risk of overheating, on the other hand, when operating above the established nominal value, the equipment usually suffers overloads that decrease the useful life of the equipment. It also has the power to minimize the fluctuations of the voltage vectors of the network, maintaining the voltage values within the established limits for as long as possible, thus minimizing the power losses generated by the power flow through the network. Finally, voltage stability is considered another determining factor in the correct operation of electrical systems, since as with other types of stabilities such as angle or frequency, they determine whether the system is within standards or on the contrary there is the possibility of suffering a large-scale collapse, voltage stability is achieved by maintaining the voltage of a node within a range established according to the characteristics of each node. In short, reactive power has the capacity to regulate the voltage, when the voltage of a node is too high, reactive power has to be absorbed to reduce it, in the same way, if the voltage of a node is too low, reactive power has to be generated to compensate it[3].

At the same time, it must be taken into account that voltage control without continuous monitoring of the evolution of the network may cause collateral effects. In cases where the origin of the reactive power used to control the voltage is from the node itself, a cyclic process could occur in which, when an attempt is made to reduce the voltage by absorbing reactive power, the system is forced to increase the current to maintain the level of power supplied, causing the network to consume more reactive power due to losses and therefore further reducing the voltage. This effect can cause significant faults in the line, putting it out of service, and it usually causes a cascade effect that affects more parts of the network.

A similar process occurs when a generator disconnects from the grid to protect itself, such a case usually occurs when the generation agent notices a drop in the voltage of its connection node, when this voltage drop endangers the operation of the installation, the agent disconnects to avoid damage to its assets. When the generation agent disconnects, in addition to further decreasing the voltage, it removes from the network one of the major assets to generate reactive power and control the voltage, i.e. the generator itself. As if that were not enough, as the voltage continues to drop, the elements integrated in the network whose capacity to produce or generate reactive power depends on the voltage of the network, reduce their power of influence as the voltage decreases, leading to a chain process that can cause line failures and blackouts.

The transmission network is not a linear consumer of reactive power, it depends on the distribution of both loads and generation units. In general, a system that has a low load level is injecting reactive power to the grid, in the same way, when such a system has a high load level, it usually absorbs reactive power from the grid. So that in both cases the voltage profile does not go out of limits, the transmission grid must be equipped with elements that are capable of absorbing or generating reactive power when necessary, not only in scenarios in which the grid increases or decreases its load level due to imbalances between generation and demand, but also when there is a drastic variation in the load level, for example, when a line is disconnected or when a generator is out of service.

The main elements present in the transmission grid that in some way regulate the system voltage by absorbing or generating reactive power are summarized below.

- Synchronous generators can absorb or generate reactive power depending on their degree of excitation, when they are operating overexcited, they generate reactive power, on the contrary, when they operate in an under excited condition, they consume reactive power. Generally, synchronous generators are equipped with automatic voltage regulators (AGC) that automatically adjust the excitation, thus controlling the voltage in the most optimal way possible.
- The overhead lines have the ability to both absorb and generate reactive power depending on their load level, the line is above its natural load level, it will be absorbing, while if it is below, it will be injecting reactive power to the network. Subway lines are characterized by having a high capacitance, which translates into a very high natural load level, consequently, subway lines are permanently generating reactive power. The transformers continuously absorb reactive power from the network, independent of their load level.
- Demand loads always tend to consume reactive power, although the degree of consumption depends on many factors and changes practically on a daily basis, in general they always consume. The compensating devices are implemented in the network in order to control the voltage profiles, these devices have the ability to inject or absorb reactive power from the network as they wish[5].

The different voltage control elements present in the network can be classified according to the conditions under which these devices are activated to provide the system with reactive power generation/absorption. This classification distinguishes between static or dynamic voltage control elements. Dynamic voltage control is the one carried out during the occurrence of a fault, an overload or a service failure in a generation unit, i.e., it is that control which acts instantaneously to bring voltage levels to a zone of stability, some elements that carry out this type of control could be capacitors or generators. On the other hand, the static voltage control is one that is carried out both before and after a transient in which the dynamic control has acted, i.e. the static control is permanently active under normal conditions. The elements that carry out the static voltage control have a more limited response capacity since its main function is to correct small deviations from the nominal value, some of the elements that provide this type of control are capacitors, reactors, tap changes.

2.3 MAIN ELEMENTS

- ***Shunt Reactors:***

  Generally, shunt reactors are used to compensate for the high level of capacitance present in the lines, so that when the line is in open circuit or operating at low load, the rise over the voltage profile that would be caused by a highly capacitive line can be limited. Normally such devices are used on long overhead lines (over 200km) due to the lack of elements to regulate the voltage if necessary. They are also used on shorter lines whose supply comes from a weak system, that is, with a low short-circuit ratio.

  Those shunt reactors with a high capacity should be permanently connected to the line in order to avoid temporary over voltages, 1 second maximum. Such shunt reactors are also used to limit energization over voltages during transient switching. In addition, shunt reactors are used on lines with a low load factor, however they must be equipped with circuit-breakers to be able to deactivate them in case of a sudden increase in the line load factor.

  For lines connected to systems with high technical robustness (high short-circuit ratio), it is recommended that the shunt reactors are connected by switching devices. In some cases, shunt reactors with tap-change voltage control devices are also used, in order to control the level of reactive power injected to the network in a more continuous way[3].

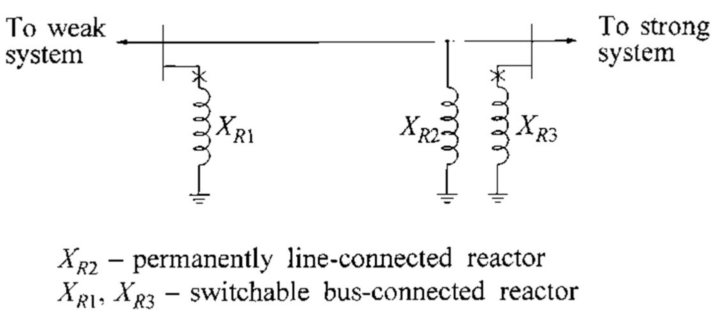


Figure 2-2: Shunt Reactor Scheme

- ***Shunt Capacitors:***

  Shunt capacitors have the main function of supplying reactive and boosting the voltage profile. Devices of different sizes are used throughout the system depending on the needs of the network. At first, shunt capacitors were used to correct the power factor, but due to their large size and high cost, their operation was limited during the early 1990s. However, since 1930, thanks to the discovery of more affordable dielectric materials, the size and cost of shunt capacitors could be reduced, becoming a very competitive device for voltage control. Shunt capacitors have the advantage of being very flexible and adaptable to any part of the network, both distribution and transmission. On the other hand, the reactive power production is proportional to the square of the voltage, therefore, when there is a voltage drop, just when the reactive power supply is needed, the devices have less capacity to control the voltage.

  Shunt capacitors are very commonly used in the distribution network, their main functions are to regulate the power factor and to control the voltage at the power taps. Devices located in the distribution network usually require greater flexibility in their use, and therefore are often equipped with a switching system that responds to network disturbances that may cause voltage instability events. The main purpose of providing a certain power factor is to facilitate the absorption of reactive power from the grid by the loads connected to it. Since each load has a different power factor, shunt capacitors need great flexibility to adapt to this requirement. In order to supply this reactive power factor accurately, shunt capacitors are used, both permanently connected to the distribution network and with switch devices, as well as being distributed among the different voltage levels along the distribution network. Another function of the shunt capacitors is to control the voltage feeders, the necessary devices are placed along the feeder to maintain the voltage requirements established.

  On the other hand, shunt capacitors are also an element of the transmission network, mainly used to mitigate losses due to the Joule effect and ensure the correct operation of the system when overloads occur. They are connected at high voltage, and as in the distribution network, they have the option of disconnecting and connecting, either manually or following a voltage setpoint. Usually, a network study is carried out in order to identify the points where the shunt capacitors should be placed, as well as the characteristics that these devices should have, specifying size, maximum and minimum voltage values[3].

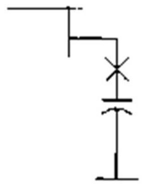


Figure 2-3: Shunt Capacitor Scheme

- ***Series Capacitors:***

  The series capacitors are generally connected in series with the voltage lines, with the main purpose of compensating the reactance of the same. Compensating the line reactance results in an increase of the maximum power transportable on the line and in a significant reduction of reactive losses. Series capacitors are not elements specifically designed for voltage control, since they do not have a control mode that allows them to absorb or produce reactive power as needed, but only produce more reactive power the higher the power carried by the line. Series capacitors have different operational modes depending on their application.

  The series capacitors have applications in medium and low voltage, either in the distribution network or in industrial consumers' sockets. The main reasons why these devices are able to operate in these voltage ranges are, first of all, the limitation provided by these devices on voltage variations during initial operating states. Secondly, they are characterized by a fast response to variations in load current. However, they present other problems that have discouraged the use of these devices in MV and LV networks. The main drawback of series capacitors is their technical impossibility to protect themselves against possible system current faults, however, nowadays they are used in the sub transmission network where they still have applications that can be beneficial for the system.

As mentioned above, series capacitors are devices that provide higher performance when connected to the transmission network, thanks to their ability to provide stability to the network and distribute the load level across parallel lines are considered elements of great benefit. Due to the above mentioned, the series capacitors have become elements that allow to increase the load level of the lines in a very economical way.

However, it is important to keep the line compensation level under minimum levels. If the line is compensated to 100% means that the effective reactance will be zero, in those cases where the line compensation is very high the operational difficulty of the line will increase, compromising the stability and reliability of the same. Regarding the distribution of the series capacitors along the line, it is neither practical nor effective to place the devices individually along the line, therefore, they are usually placed in groups at scattered points along the network.

The main challenges posed by the series capacitors are described below:

Spontaneous voltage surges, either due to increases in current or high load levels, can push series capacitor banks to their technical limits causing permanent system failures. In order to avoid them, the series capacitors must be prepared to withstand such surges, there is also the option of designing the topology of the line in a preventive way, preventing the occurrence of such voltage levels.

The series capacitors are connected to the network to a small percentage of the nominal voltage of the same and therefore have been designed for these voltage values, however, when there is a fault in the network downstream of the device, the voltage in bars of the bank of series capacitors becomes equivalent to that of the line, ie, a voltage for which it is not prepared. To solve the problem, and since it would not make sense to design a series capacitor to withstand such voltages, a by-pass system is used to disconnect the device when a fault of the above characteristics is detected. This by-pass disconnects the series capacitor from the line in order to prevent it from being damaged by operating outside its voltage range, and quickly reconnects it to the grid when the fault has been overcome, helping to improve the transient after the fault.

Series capacitors can be placed anywhere on the lines, but this does not mean that depending on their placement, different levels of cost, effectiveness, quality of service, voltage profile, etc. are incurred. There are two main forms of distribution. The first form of distribution known as mid-point consists of placing the device, as the name suggests, in the middle of the line in question. This arrangement has the advantage of needing few relaying requirements when the degree of compensation of the line is around 50% and of having a lower short-circuit current, on the other hand, it has the disadvantage of being a point that is not very accessible, and therefore makes maintenance, monitoring and safety tasks more difficult. The second way of distribution consists of placing the capacitor banks at the ends of the lines, contrary to the mid-point distribution, the main advantages in this case are those of great accessibility, which facilitates maintenance, monitoring and safety tasks. However, in this distribution there are high degrees of compensation and high short-circuit currents[3].

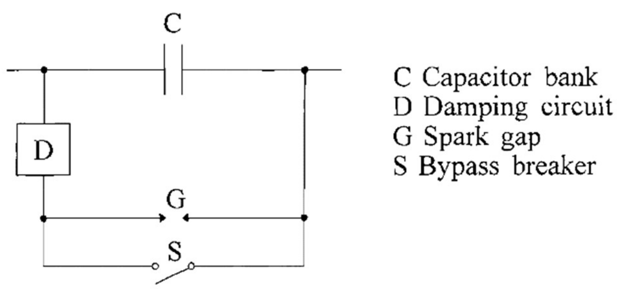


Figure 2-4: Series Capacitor Scheme

- ***Synchronous Condensers:***

  Synchronous condensers are synchronous rotating machines that operate without supplying any active load. By controlling the excitation magnetic field, the desired output of both absorption/reactive power generation can be maintained, thus becoming very important elements for voltage control. Generally, these generators have an automatic voltage regulator that generates or absorbs the necessary reactive power at each moment to maintain the voltage within the required limits. These generators absorb practically no active energy from the network to compensate the losses of the installation.

Synchronous capacitors have been used for many years in the transmission and sub-transmission areas, however, during the last few years they have been replaced by static var compensators due to their high investment, maintenance and operation costs. Despite them, there are still some old synchronous compensators operating in the system since they do provide a great voltage control service.

Despite the cost difference, synchronous compensators have a series of advantages of great relevance with respect to static compensators, they contribute to the reinforcement of weaker systems by providing short-circuit capacity. Unlike other voltage control elements, the reactive power production of synchronous compensators does not depend on the grid voltage, i.e. they can generate high levels of reactive power even if the voltage at their connection node is very low. During large power swings, which usually result in voltage instabilities, synchronous compensators have the capacity to supply reactive power above its nominal value, which is of great help for system recovery, and can be maintained in this production state for approximately 30 minutes. Finally, and linked to the second advantage already mentioned, synchronous compensators, thanks to their independence from the grid, can be coupled to the grid when it is under minimum voltage levels (after a blackout, for example)[5].

- ***Static Var Systems:***

  Static var compensators (SVC) are quality power devices, which use power electronics to control the reactive power of the node to which they are connected. As a result, the SVC system provides the electrical system with reactive power compensation very quickly and efficiently wherever there are variations in the voltage profile. The SVC systems have their outputs set to produce current, either capacitive or inductive, to perform their control function on system variables, mainly on the voltage of the node to which they are connected. The term static included in SVC, specifies the absence of rotating elements present in its operation, such as synchronous machines.

Static power compensators are primarily used to mitigate unwanted voltage variations. unwanted voltage variations, these systems are currently used in numerous industries, although steel plants stand out for their use in electric arc furnace installations. arc furnaces. In addition, SVCs are usually installed strategically at points in the electrical system where they will be most effective, i.e., where they will transmit greater stability to the voltage plane when subjected to an unbalance. It is necessary to emphasize that through the variations caused in the voltage by the SVCs, the active power can also be controlled to stabilize the oscillations it may suffer. The SVCs, acting as automatically regulated impedances, have the advantage of tending to approximate the power factor to unity[8].

Other benefits provided by SVCs:

- Maximizes power compensation.
- Virtually instantaneous response to voltage variations.
- Increased economic benefits.
- Elimination of harmonics and reduction of voltage variation.
- Load balancing on three-phase systems.

The highlighted SVC configurations are explained as follows:

- ❖ Thyristor controlled reactors with fixed capacitors (TCR/FC), the design of the SVC consists of two parallel branches. SVC design consists of two parallel branches connected in the secondary part of a transformer, one of the branches is connected to the secondary part of a transformer. transformer, one of the branches consists of AC thyristor-controlled reactors. AC thyristor-controlled reactors, and these reactors are also connected in a delta for three-phase for three-phase application. The other branch usually consists of fixed capacitors or sometimes shunt filters. The reactive power variation is realized by the activation of thyristors, which cause current flow to the node.

- Capacitors with thyristors (TSC), in this configuration the capacitors are phase-phase connected to the thyristors. It is due to this type of configuration that the reactive power that this system can provide is variable, not continuous as in the TCR. as was the case in the TCR. Nevertheless, by providing a considerable number of such configurations of such configurations, the required reactive power variation can be supplied. required.
- Thyristor controlled reactors and thyristor capacitors (TCR/TSC), this configuration is the combination of the two previous ones. control of this configuration is based on measuring the value of the reactive component of the load current at the initial time. current at the initial instant. This component is then used to the angle necessary for the SVC to inject or absorb the current required to maintain the balance. current required to maintain the balance. The shortcoming of this control is that there is a significant time interval between the measurement of the reactive component and the action of the control, which the action of the control, which makes it inefficient in some cases.

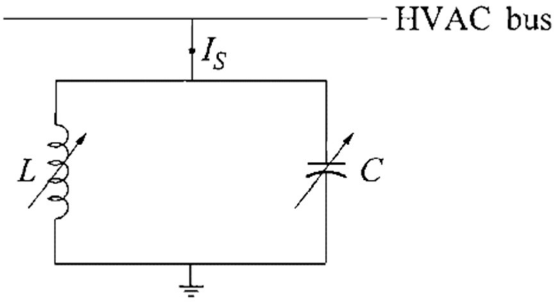


Figure 2-5: SVC Scheme

- ***Tap Changing Transformers:***

  Tap-changing transformers are an important tool to control the voltage profile, mainly in the transmission and sub-transmission network. Autotransformers are used to switch voltage levels from one system to another, sometimes these elements are equipped with tap-changing devices that can be operated either manually or automatically.

Transformer taps facilitate control over reactive flows, which can be used to maintain voltage levels and avoid both active and reactive losses. However, the effectiveness of voltage control by tap-changing transformers is highly dependent on the topology of the system, including location of generation and demand agents, and some interpenetration between the various transformers in the system during voltage control is necessary if a significant effect is to be achieved.

The voltage control strategy for tap-changing transformers depends, of course, on the system load level. In high-load scenarios, the voltage level is kept as high as possible, so that the voltage control elements integrated in the network (shunt capacitors, for example) are producing reactive power close to their maximum capacity, thus minimizing the reactive power requirements of other agents that would incur a higher cost if they had to provide such energy. This operational procedure involves constant monitoring of voltage levels to avoid instabilities. Likewise, when the system is operating under a light load level, it is required to reduce the voltage level to avoid under excitation of some generators.

Although tap-changing transformers have the ability to control voltage in the short term (days, hours or minutes), it is advisable to perform a long-term study to evaluate their location, factors such as increased demand or future network expansion plans may be decisive to achieve an efficient operation of the transformer[3].

- ***Transmission Side:***

  As mentioned above, the transmission network plays an important role in controlling the voltage profile. Generally, power lines have a capacitive characteristic, which makes them 'generators' of reactive power by default, however, this reactive power contribution to the network has no control by default. Consequently, to establish a control over the voltage profile, some of the devices explained above are used, such as series or shunt capacitors, static var compensators, etc. Some of the strategies and topologies used to maximize the efficiency of these elements during their reactive power production are detailed.

- Compensation by switched shunt capacitors provides the system with an economical way to control reactive power injection into the network, and thus keep the voltage profile within limits. Due to their characteristics, switched shunt capacitors are mainly used to compensate the line, reducing the characteristic impedance of the line, however, it must be taken into account that the disproportionate use of these devices may incur stability and voltage control problems.
- The series capacitors are elements that are automatically regulated, contributing more reactive power to the network the higher the load level of the line. Mainly these devices provide the system with a higher level of natural load, improving both stability against small disturbances and voltage regulation. It is very common to find these elements in the network, improving stability and balancing the load division between parallel lines. However, the use of these devices can bring negative consequences to the system, in the form of resonance problems that will require special attention, as well as extra protections on the line.
- A combination of the two strategies discussed above is often an efficient solution to voltage compensation and regulation problems in the network. This combination allows a modelling of both the characteristic impedance and the line loading angle.
- Static var systems are used in situations where fast and effective tension control is required. Comparing them with series capacitors, we can state that they have different ways of regulation, while series capacitors require a direct connection to the line, shunt elements, such as static var compensators, are connected to the corresponding node. Consequently, series capacitors end up incurring more costs than SVCs. Although static var systems are designed to transfer power over long distances, one must not forget the effects that such a device could cause if it reaches its technical limit. When an SVC is operating below its capacitive limit, it becomes a simple capacitor, so that it is not able to control the voltage by itself, but becomes dependent only on the square of the voltage of the node to which it is connected. Consequently, those systems that rely excessively on SVC elements in terms of voltage control may be susceptible to voltage collapse when the system is under a high level of load, hence

the capacity of the SVC should be determined through studies on the possible scenarios of high load level[3].

- ***Distributed Generation:***

Regarding voltage control in the distribution network, there are two main points of application: voltage control at the substation nodes and voltage regulation at the feeders. Voltage control in distribution substations is mainly based on the presence of tap-changing transformers, which always allow secondary voltage regulation. Generally, these transformers have automatic voltage regulators in each of the three phases of the system, in order to adequately manage networks that are characterized by operating under a certain unbalance.

As for the feeders, their voltage regulation is carried out by means of automatic voltage regulators, it is possible to place a regulator in each phase or simply work in single-phase, the latter being the most common option. If possible, there could be cases in which several feeders with the same load characteristics connected to the same substation are operating under the same automatic voltage regulator. When feeders have a long length, in order to support the automatic regulators in voltage control, shunt devices are usually installed along the feeder to keep the voltage profile within limits.

In addition, another influential factor in voltage control in the distribution network today is distributed energy. Although sometimes generation facilities connected to the distribution grid do not have the capacity to control voltage, different connection strategies have been designed and implemented to provide generation facilities with some capacity to control reactive power supply. Induction generators are a very interesting option for these cases, they are very cheap and besides not needing synchronization, they provide mechanical characteristics to the network. Generally, these generators demand reactive energy from the grid, being this demand variable to the primary energy input (in overhead generators, the wind). Therefore, these generators cause a certain instability in the voltage profile that can be compensated by means of grid connection strategies using power devices to regulate the injection of reactive power to the grid[3]. Something similar happens with photovoltaic energy installations connected to the distribution grid, which, as they produce continuous energy, require power converters to be able to inject the energy into the grid, and these converters are accompanied by power electronics devices similar to STATCOMs, which provide stability to the system voltage profile.

2.4 RENEWABLES

Numerous forecasting studies state that global energy consumption will continue to increase exponentially over the next few years, with the EIA forecasting a 50% increase in energy consumption by 2050[6]. In response to this global energy increase and the commitment that the electricity sector is demonstrating to all sustainability goals, the increase in energy production from renewable sources must continue to grow. This prediction of an increase in renewable generation presents a series of challenges regarding the integration of these technologies and the technical requirements they will have to meet, which are issues of great interest and concern within the sector. The main reasons for this concern lie in the variability and non-controllability of renewable generation, which brings some uncertainty about the quality of the product that these generation facilities can provide to consumers, this quality being the set of features such as efficiency, reliability, quality of the system.
Although electricity generation from renewable sources has great advantages such as reduced energy costs and reduced emissions, it also has great operational disadvantages due to its production variability, which can lead to voltage rise, voltage imbalances and even overloads in the network that can cause faults or blackouts.

Consequently, it is necessary to review and analyse the impact that this increase in renewable penetration has on the grid, in order to improve it and adapt it to the new challenges posed by these circumstances. Specifically, the main variable that is affected by this increase in renewables is voltage, making it necessary to implement new control methods or elements to maintain voltage within limits and meet reliability, security and quality requirements. This drawback is of great interest to the sector, since it is one of the few prevailing challenges that prevent renewables from a full integration free of cost overruns.

The problem related to the integration of new renewable generation into the grid has generated more uncertainty in the distribution network, due to the great impact it has had on the grid characteristics, mainly due to the effect of distributed generation. As previously mentioned, the increase in distributed energy is currently one of the greatest challenges in the distribution grid, mainly due to the stability and control problems that it causes on the voltage profile, in addition to the power reflows that it provokes. Another drawback of distributed energy is that, in the case of wind turbines, if high wind gusts are reached, the turbine would automatically disconnect for safety reasons, which would cause sudden drops in production without prior warning. In certain systems where distributed energy makes up an important part of the total energy generated in the system (EU proposes 20%), the aforementioned unplanned shutdowns can cause serious problems to the system, even outages. In summary, we can say that the increased penetration of renewable energy in the distribution grid, mainly solar and wind, with other less relevant technologies, is causing instabilities in the voltage profile, compromising the efficiency, reliability and quality requirements that are mandatory for grid managers.

Voltage levels at the consumer's supply point must maintain minimum levels, as a general rule the voltage must be within ±10% of the nominal value. As distributed generation increases, it is more complicated to keep within the before mentioned voltage ranges. The main factors that influence the impact of distributed generation at a connection node are the location of the renewable generation source and the configuration of both the feeder and the capacitor banks connected to the supply node. As previously mentioned, the high degree of variability of renewable energies causes the load level of the lines to vary abruptly, causing in many cases problems of instability in the voltage profile. When the system is faced with sudden variations in voltage on a regular basis, the system equipment ends up being affected by a considerable reduction in their useful life.

The following is a general description of the different voltage control methods used in the distribution network when the voltage profile is compromised by high levels of renewable generation. There are two main quantitative approaches used[7]. The first approach proposed is to actively monitor the grid with a centralized strategy in order to smooth the distributed integration to the grid. This approach allows DSOs to implement the different changes and strategies they deem convenient by means of real-time communication tracking, monitoring and control of the grid through reactive power injection/absorption elements such as those explained in the previous section. The second approach consists of making sure that the voltage profile is within limits by means of intelligent control of distributed generation and different network parameters. In this second approach it is of vital importance to study the grid points where distributed generation is to be implemented, since the effectiveness of this method depends to a large extent on the integration of distributed generation in the feeder.

Finally, the main methods for monitoring the voltage profile in the distribution network are described. The more traditional methods, which are mainly based on using elements such as tap-transformers, switched capacitors and SVCs to control the voltage profile, have already been discussed in the previous section. Therefore, we will proceed to describe the most current methods used in the distribution network to normalize the voltage profile.

- The reduction of distributed energy generation in off-peak periods to control voltage is a method employed by DSOs, however, it is not a method that favours the system as a whole since it forces certain generators to spill energy, which causes significant economic losses for certain agents.
- In generation technologies such as wind and solar, present in the distribution grid, generally require an inverter at their grid connection point, such inverter can be used as a tool to control the voltage by reactive power injection/absorption.
- Promoting greater flexibility in both generation and demand is expected to avoid imbalances that could cause problems in the voltage profile.
- Energy storage is considered an asset when it comes to voltage regulation, as it allows energy to be absorbed during off-peak periods and injected into the grid during peak

periods, thus compensating for possible imbalances that may cause undesirable variations in voltage.

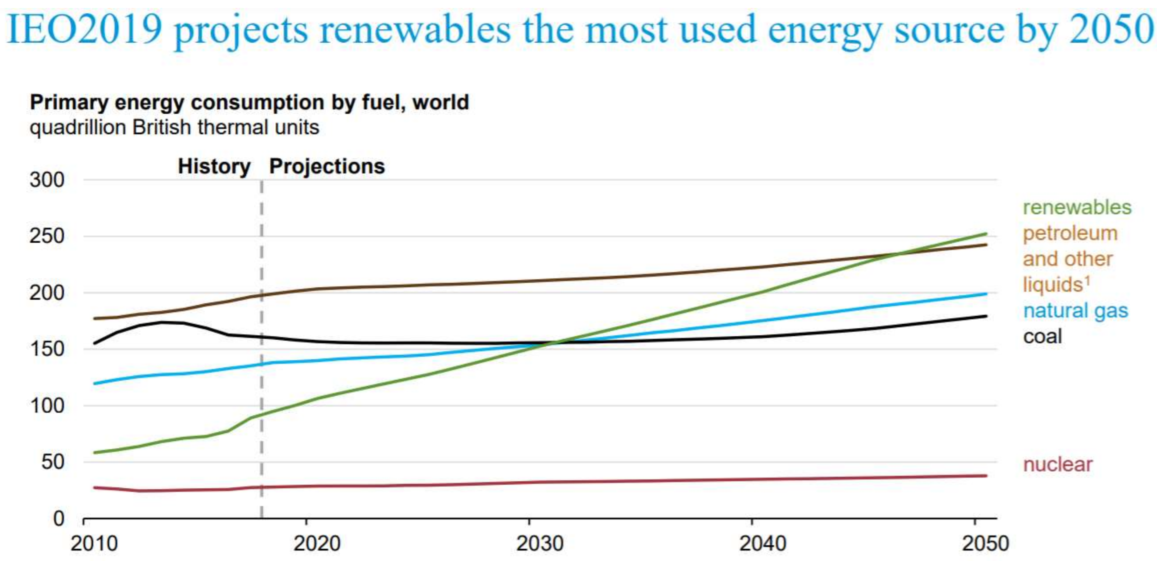


Figure 2-6: Primary Energy Consumption Forecast 2050[9]

Chapter 3. TECHNOLOGIES BEHAVIOR

3.1 INTRODUCTION

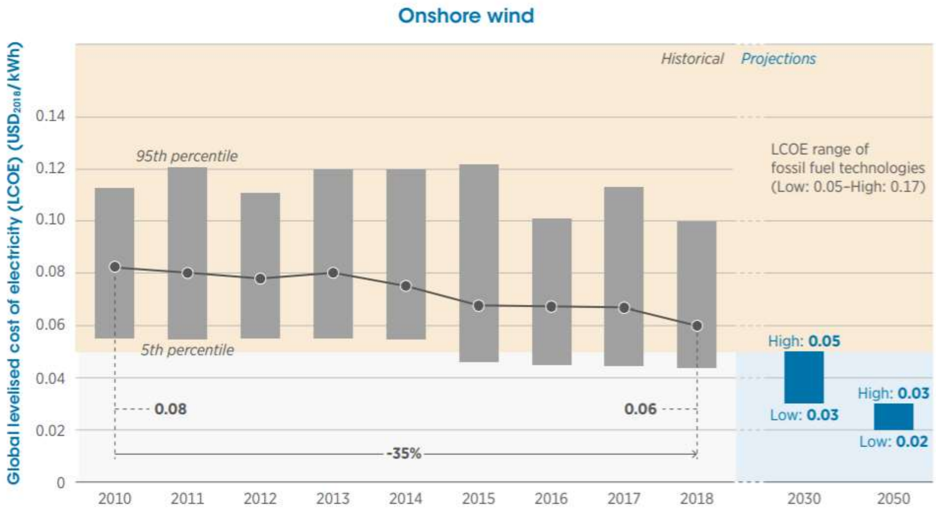
This third chapter of this project aims to analyze the behavior of the different technologies in terms of voltage profile control. As can be seen below, the technologies chosen to carry out the research do not correspond to conventional generation cycles but are focused on new technologies. This is due to the large increase in generation that these technologies are contributing to the grid in recent years. At first, they were not required to maintain strict voltage control since their level of penetration was considered negligible, but now, however, they make up a significant share of total generation and are therefore obliged to meet certain minimum requirements to contribute to the stability of the voltage profile. The main problem is that these technologies generally have a highly variable and uncontrollable generation profile due to the origin of their primary energy, hence their contribution to voltage control presents major challenges. Furthermore, unlike conventional power plants, the technologies to be studied in this chapter are composed of small generation modules that together make up the declared generation unit, which implies an individual control of each module in order to monitor and control the voltage that the installation as a whole contributes to the grid. Another problem to be addressed in this chapter is that the technologies to be analyzed in this chapter are relatively modern, which means that they have undergone a great development during the last years, in other words, the performances provided by the current technologies are completely different from those that can be provided by the old technologies. This analysis of the evolution in the performance of the different technologies will also be the subject of study in this chapter. In the next chapter of this project, the previous problem connected with the new regulatory framework will be addressed in greater depth. Simply to introduce it, we will comment that the new regulatory framework[10] that REE intends to implement in Spain in November 2021, presents a series of requirements in voltage control that will be difficult to be covered by many generation agents of a certain age, which, given that they are mandatory requirements, will cause large investments in voltage control mechanisms. That is why it is considered a task of great importance to maximize the accuracy of voltage control with the currently available ones, thus correctly interpreting the investment signals and at the same time avoiding unnecessary investment cost overruns.

3.2 WIND

3.2.1 INTRODUCTION

Wind energy is currently the renewable energy source with the largest presence in the generation sector. Due to its current great importance within the Spanish electricity system, and its expected growth, wind energy is expected to play a very important role in the future energy mix led by renewables. In Spain, wind energy is responsible for producing 21.9% of the total energy, which makes it the second most productive technology after nuclear energy, and the first in renewable production with an abysmal difference with respect to solar energy. This notable presence in the total generation has led the system operator to specify certain operating procedures that require wind power generation facilities to maintain dynamic control over the voltage profile to ensure the operation of the grid.

Regarding the evolution that wind technology has undergone, leaving aside the notable increase in capacity over the energy mix, we can observe other indicators that reflect and point out the path that has led this technology to become one of the predominant technologies in the generation mix. Firstly, the experience acquired by wind turbine manufacturers over the years has resulted in a marked decrease production costs, which is a great indicator for assessing the maturity of the technology, which in turn is an investment incentive. Secondly, the evolution of the infrastructures used to produce wind energy has evolved massively, increasing exponentially both in size and capacity, which has resulted in an increase in MW produced per square meter, i.e., in a better use of space. Finally, both the turbines and the controls used in wind turbines have improved over the years, adapting to provide the grid requirements at the point of connection and improving operating and production efficiency.



Source: Historical data based on IRENA, 2019c and future projections based on IRENA's forthcoming report: Solar and wind cost reduction potential to 2030 in the G20 countries (IRENA, n.d.).

Figure 3-1: Onshore wind LCOE[11]

The following is a brief description of the main types of wind turbines currently in use[12].

- ***Squirrel-cage single-speed or two-speed induction generator:***
  This type of wind turbine is known for having a simple and inexpensive construction and maintenance process thanks to the fact that it is one of the most mature technologies, in addition, it can be connected directly to the grid thanks to the frequency values for which it was designed. On the other hand, it needs to absorb reactive power to cover certain operating losses, it needs starting devices to smooth the high starting currents, and it is only applicable in turbines operating at fixed speed and requires a gearbox.

- ***Doubly-fed induction generator:***
  The doubly-fed induction generator is characterized by a reduced power ratio and a low-cost converter, and unlike squirrel-cage turbines, reactive power is compensated by the power converter, and does not need to be obtained from the grid. This type of wind turbine has the ability to regulate speed to optimize power generation, hence it

can operate in both a sub-synchronous and super-synchronous state. On the other hand, it is a more delicate technology and has higher maintenance costs. In addition, due to its complexity, it is complicated to control the entire turbine and consequently its connection to the grid is more difficult.

- ***Synchronous generator with rotor excitation winding:***
  These turbines present a remarkable simplicity in their control, emphasizing the importance of such control over the generation/absorption of reactive power, besides having the capacity to operate in a wide range of speeds. On the other hand, these wind turbines require a power converter of the same nominal power as the machine, together with the fact that they need a special excitation system and that maintenance tasks have to be carried out with a certain frequency, the cost overrun with respect to other technologies can be considerable. There are two types of synchronous generators.
  Direct-drive generators, which do not have a gearbox and are highly efficient, although they also have problems during construction, transport and maintenance due to their size and weight.
  The generators that have a gearbox have much smaller dimensions that reduce construction costs thanks to the use of standard processes. On the other hand, these types of generators induce considerable costs due to the losses they present, as well as the constant maintenance required by the gearboxes.

- ***Synchronous permanent magnet generator:***
  This type of turbine is characterized by having a considerably simple rotor, with parts that are not prone to wear, which translates into a reduction of rotor losses. Although it is true that it presents notorious disadvantages such as a high cost for the permanent magnets, possibility of demagnetization, which could jeopardize the operation of the turbine, and finally, the little experience of the sector in developing both the construction and installation of this type of turbines generates some uncertainty making it a riskier choice. As in the previous case, this type of turbine may or may not have a gearbox, and consequently there are two types.

Direct-drive generators, which do not have a gearbox, are highly efficient and they have very simple maintenance procedures, although, they also have problems during construction, transport and maintenance due to their size and weight.

The generators that have a gearbox have much smaller dimensions that reduce construction costs thanks to the use of standard processes. On the other hand, these types of generators induce considerable costs due to the losses they present, as well as the constant maintenance required by the gearboxes.

3.2.2 CONTROL STRATEGIES

The most common voltage control strategies employed on wind farms are described as follows[13]:

- ***Centralized Voltage Control:***

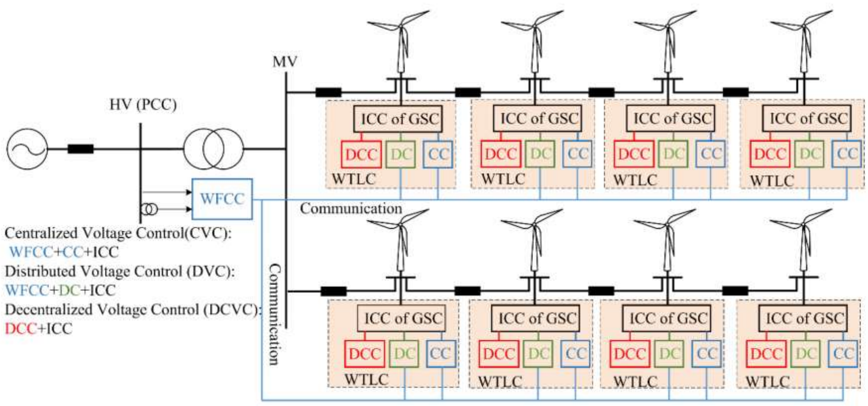
  The centralized voltage control model corresponds to a hierarchical control, in this context, the voltage control is carried out by a WFCC (Wind turbine centralized control), while the reactive power setpoints are sent to the WTLC (Wind turbine local control). This type of control requires a communication network between the different turbines that make up the wind farm. Another important fact that defines the strategy in this type of control is that, when there are large changes in generation due to intermittent wind speed, the voltage undergoes changes that must be corrected by the voltage control of the plant. As the plant is made up of a multitude of turbines coordinated by an extensive communications network, the response to voltage variations suffers certain delays, which is an element to be taken into account during the design of the control. In the study of the implementation of these controls, the SCR (Short circuit ratio), which indicates the degree of stability of the network, must be taken into account. High values can lead to long response times, while low values indicate stability problems. Finally, it is worth mentioning that centralized strategies use a PI with an anti-winding integrator.

- ***Decentralized Voltage Control:***

  As with centralized control, decentralized control is hierarchical in nature. However, this control is based on a secondary voltage control, where a primary voltage control is carried out independently in the WTLC, while a secondary control is carried out in the WFCC to eliminate the steady-state error in the voltage control. As with centralized control, the system requires a complex communication network connecting all the turbines in the wind farm, which induces delays in voltage control that must be taken into account during its design. In the decentralized context, the control is carried out individually in each of the turbines of the wind farm, being in this case, a proportional control used to maintain the reactive setpoint, thus avoiding the elimination of the steady-state error.

- ***Distributed Voltage Control:***

  Distributed voltage control combines certain characteristics of the two aforementioned strategies, which makes it a very interesting and innovative strategy for certain systems. The main difference with the decentralized control is the outer loop of voltage control in WTLC, in this case, the estimated voltage at the connection point is controlled in the WTLC. The outer control loop corresponds to a PI that eliminates the steady-state error. In addition, unlike both the centralized and decentralized strategies, this strategy has no communications system, which makes it faster and more efficient when acting on voltage controls.



3.2.3 TECHNOLOGIES COMPARISON

This section aims to analyse the behaviour of two different types of wind turbine technologies when their voltage control is improved. This analysis is based on a real experiment carried out in some wind power generation facilities in the Iberian Peninsula[14]. This experiment is motivated by the announcement of a P.O. (Proposal of Operation) by REE, which has as main objective to renew the regulatory aspects that until now defined the voltage control in the Spanish electrical system. One of the defining characteristics of the new voltage control is the improvement in the quality and accuracy of voltage control when voltage is destabilized by disturbances. In order to examine the performance of this new voltage control, two experiments will be carried out, the first one will involve a layout for DFIG(Doubly-fed induction generator) based technology, while the second one will involve a SCIG(Squirrel cage induction generator) based technology.

- ***Voltage Controller for DFIG:***

  In DFIGs, the main improvement to be implemented to improve voltage control at the connection node consists of improving the communications system used to receive and send instructions between the different agents involved in voltage control. The communications system involved in this process is made up of 4 main components:

  - Remote central controller: It receives instructions from the grid manager regarding the values of both active and reactive power required by the grid and communicates them to the wind turbines.
  - Wind farms PLC controller: It manages the commands received from the remote central controller and issues its own commands to the wind turbines according to the evolution at the connection point, while optimizing the operation of the wind turbines.
  - Communication system: Connects the remote central controller with the wind farms PLC controller and the latter with the wind turbines.
  - Grid analyser: Processes measurements at the point of connection to the grid making them processable by the PLC.

The implementation of the before mentioned components is aimed at establishing improvements in the following aspects. In the first place, improving the reactive power absorption/generation range at any active value. Secondly, optimizing the control over the reactive setpoints and adding new algorithms to manage the reactive power production, thus increasing the dynamic reactive power capabilities.

Another important fact to comment on is that the Spanish regulation currently requires a monitoring of the power factor generated by the installation to verify the voltage profile levels, which is not entirely efficient since in some cases it limits the supply of reactive power, which is really the variable capable of directly affecting voltage levels.

The results obtained in this field experiment can be summarized in the following points. After analysing the data obtained on the voltage profile, it can be assured that they have always been within the required limits, taking into account that the control is based on a proportional structure which provides a steady-state error. The second observation is the variation of the capacity to supply reactive power depending on the level of active power that the turbine is providing to the grid. If the level of active power provided is low, the level of reactive provided decreases accordingly, so that there is no longer control over the voltage profile, moreover, in these situations the steady-state error presented by the control is considerable. However, when the reactive power level is medium-high, a maintained control over the voltages is observed, added to a practically insignificant error in permanent regime provides a great efficiency to this control strategy.

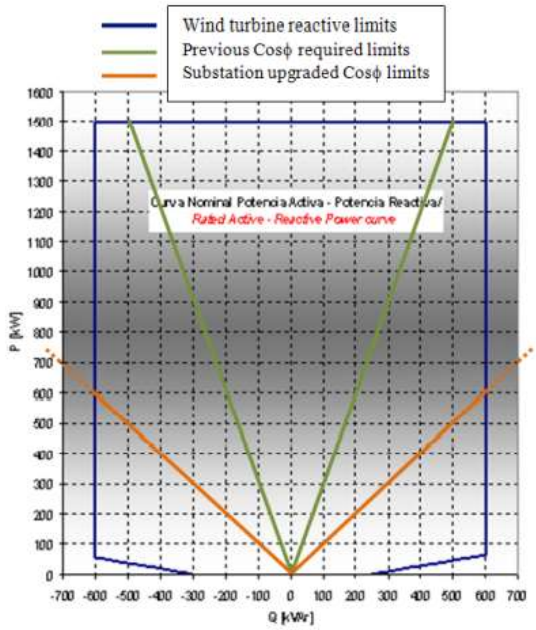


Figure 3-2: Reactive Power Limits in DFGI[14]

- ***Voltage Controller for SCIG:***

  This voltage control strategy is based on establishing a global control that jointly coordinates all the capacitor banks belonging to the system by means of a closed loop. Generally, capacitor banks are located at different levels within the installation, usually there is a group of capacitor banks on the low side of the substation and another one inside the wind turbines. As mentioned in other sections of this project, capacitor banks are elements that have a number of very useful capabilities when carrying out voltage control, these elements combined with controls that allow the conditioning of capacitor banks as required by the network at all times, make a powerful tool to carry out the voltage control. This provides the system with extra flexibility to meet the requirements of the system operator. Two stages of voltage control regulation can be distinguished, which are mainly differentiated by which capacitor banks are involved in the process. The first control stage is carried out by the capacitor banks present on the low side of the substation. This control is characterized by the presence of an open loop that connects or disconnects the capacitor banks depending on the active power being supplied, thus regulating the busbar power factor of the substation.

The second control stage consists of the activation or deactivation of the capacitor banks in order to adjust the reactive power supply with the first stage and obtain the most accurate results possible. For this purpose, the control uses the PLC of the wind turbines to receive reactive power production/absorption setpoints, thus being more precise when supplying reactive power.

After analysing the data obtained in the test, it can be concluded that the proposed control system has a high control capacity over the voltage profile, in addition to a fast response. However, it shows a lack of capacity when supplying high/low levels of reactive power when the active power at the operating point reaches high/low levels.

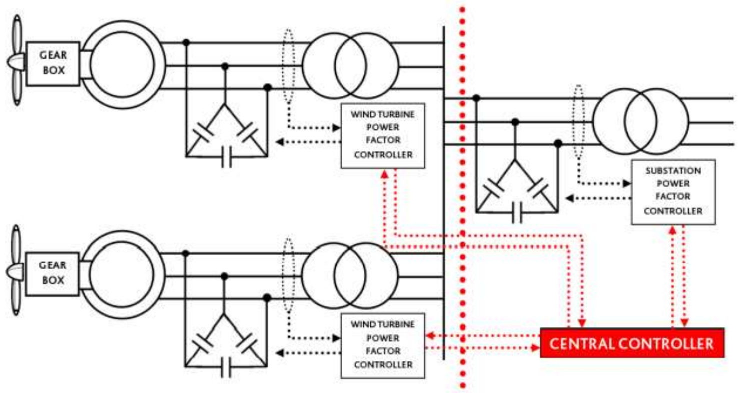


Figure 3-3: SCIG Control Scheme[14]

3.3 SOLAR PV

In response to the decarbonization process that is currently taking place in the energy sector, numerous renewable generation facilities are being commissioned, taking on more and more relevance within the sector. Solar photovoltaic energy is no exception; thanks to its constant technological development, its share of generation within the electricity systems has grown exponentially. In 2013 the energy capacity contributed by solar PV was 55,43 GW[15], while in 2019 it reached 290,86 GW. However, solar PV shows certain shortcomings due to some of its defining characteristics. The primary energy that allows solar PV to produce energy (the sun), presents a large degree of uncontrollable variability, which translates into constant uncertainty about when and how much energy the installation will produce. Furthermore, unlike synchronous generators, the nature of solar PV installations prevents them from contributing inertia to the system, partly because they are connected to the grid by means of a static DC/AC converter. Being connected to the grid via a DC/AC converter reduces the ability of the installation to respond dynamically when a fault occurs in the system. In addition, the converter provides a low level of response to disturbances that can cause instabilities, which is a significant problem if the installation is located in a weak area of the system. All of the above can have a negative impact on power quality, flows and system stability. As a result, and thanks to the great development of this technology, system operators are increasingly demanding more and better performance from photovoltaic installations, such as voltage control at the point of connection.

As mentioned above, one of the quality controls of vital importance is that carried out to ensure that voltage levels are within limits so that instabilities do not occur. In this case, the DC/AC converter has this ability, and in photovoltaic installations it is usually the main responsible for controlling the voltage profile, although it is true that its effectiveness varies depending on the strategies applied[16].

As explained above, the main element with the capacity to regulate the voltage in photovoltaic installations is its DC/AC converter, which acts in a very similar way to a STATCOM. Generally, the reactive requirements are effective at the POI (Point of Connection), hence the converter is responsible for ensuring that the voltage profile at the POI is maintained within the established range of values. However, it must be taken into account that normally the DC/AC conversion point is considerably far from the point of connection to the transmission grid, combined with the fact that reactive power cannot be transported over long distances, which implies losses that have to be taken into account when calculating the reactive setpoint given by the converter. To perform the above process as effectively and efficiently as possible, a closed-loop plant control is usually applied to calculate the most appropriate voltage profile for the POI. To improve the accuracy of the process, a measuring instrument is usually installed at the POI, so that the generating agent has a constant flow of measurements from the connection point, thus being able to adjust the reactive levels if necessary, all in real time.

As in any part of the network, in photovoltaic installations, voltage control by means of reactive power production/absorption is divided according to the nature of its response, which can be dynamic or static. A static response corresponds to the one provided by those elements routinely to satisfy the reactive needs of the grid, on the other hand, a dynamic response is characteristic of those elements with the capacity to provide reactive power suddenly and for short periods of time. Emphasize the importance of finding a balance between static and dynamic response elements so that the voltage profile is not impaired. In relation to the above mentioned, it is intended to emphasize the importance of correctly considering the capacity of the different elements connected to the network and intended to supply reactive power. It is necessary to be extremely careful when connecting or disconnecting elements with reactive capacity, normally the capacity of the converter to provide reactive power should be exploited to the maximum before connecting other elements such as capacitor banks. Even when support elements are to be connected, it is very important to correctly evaluate the needs of the network before venturing to over-connect reactive power that may later cause equipment failures[16].

Photovoltaic installations are designed to operate within a range of voltage values. This range of voltage values, in turn, delimits the reactive power values under which the installation must operate in a standard operating state. When the installation is operating outside any of the established limits, it is considered that the installation requires voltage regulation. The regulation can follow different set points, generally the most distinguished are voltage set point, reactive power set point or power factor set point. One of the challenges in the voltage control of these installations lies in the choice of the setpoint type to follow in order to maintain the voltage profile.

The importance of the existence of a power plant controller has already been described above; however, the intention is to emphasize the need for coordination between the different elements of the installation involved in voltage control. This coordination is carried out by means of the power plant controller. The power plant controller receives real-time instructions from the POI, making it the main responsible for interpreting these instructions and reacting to the needs that arise at the connection point, always minimizing the effect that such changes may have on the active supply. On the other hand, the power plant controller must manage the connection and disconnection of elements with reactive capacity when necessary, in this process special care must be taken not to exceed the necessary reactive capacity, as this could cause stability problems, as well as losses in the equipment.

Finally, the performance of the solar panels during the voltage control process is affected by variables such as solar irradiance, ambient temperature, or the voltage of the socket to which the installation is connected. The effect of these variables on voltage control is discussed below[17].

- Ambient temperature has a significant effect on the reactive capacity of the converter. Consequently, it is advisable to oversize the converter so that even if its reactive capacity is reduced by the ambient temperature, it can cover the reactive requirements. Another option would be to implement the temperature variable in the model used to calculate the reactive capacity from the beginning. Currently, in the Spanish electricity system, the temperature variable is proving to be of vital importance for the correct design of solar photovoltaic projects that are being submitted to the administration for approval.
- The geographical location directly affects the performance of photovoltaic installations when it comes to providing reactive power. Generally, hotter geographical areas cause more deficiencies in the converter, which implies higher costs. However, cooler areas do not require estimations or oversizing because the converters operate as expected.
- The effect of losses caused by ambient temperature is more significant the larger the installation, hence large-scale PV installations require more exhaustive environmental

studies to determine the appropriate sizing for the AC/DC converters, thus ensuring that the minimum reactive capacity requirements will be met.

3.3.1 BATTERY (BESS)

Given the known variability characteristics of the different renewable generation plants, energy storage systems are taking on an important role when combined with renewable installations, minimizing the impact of the variability of generation presented by these on the grid. The most widely used energy storage systems are currently the BESS (Battery Energy Storage System), which mainly differ from storage systems in that they are equipped with power electronics systems and a converter, which allow the storage system to provide a series of services to the grid very quickly. Apart from the main source of value provided by the storage systems (load shifting), they also provide important benefits at the grid level, including frequency control and voltage control. Although BESSs commonly participate in frequency services, they also have the capacity to provide the system with voltage control support, mainly through the controlled reactive power production that can be provided by the DC/AC converter. Such control over reactive power production has characteristics and technical constraints very similar to those of the DC/AC converter of photovoltaic installations, explained above.

3.4 SYNCHRONOUS GENERATOR

Synchronous machines are made up of two independent windings: the inductor or excitation winding fed by direct current and the armature winding, which is three-phase and is driven by alternating current. For the powers used in power plant generators, the inductor is located in the rotor and the armature in the stator. The power required by the excitation system is between 0.2 and 3% of the rated power of the machine, so that excitation voltages of up to 1 kV and currents of a few kA are used. The excitation system of the generator can be of the traditional type, in which the direct current of the exciter field comes from a direct current generator or exciter mechanically linked to the turbine and the alternator, so that its output is applied to the rotor of the alternator by means of slip rings and brushes[18].

Depending on the shape of the rotor of the synchronous machine, generators are classified as either salient pole or cylindrical rotor generators. In the first case, the rotor windings are located on the poles of the magnetic circuit, while in the second case the windings are distributed in small slots of the rotor.

Synchronous machines with protruding poles are mainly used in generators coupled to a driving machine with a low rotational speed, such as hydraulic turbines, which have a better performance at low or moderate speed. As a consequence, these generators usually have a large diameter with respect to their axial dimension.

On the other hand, synchronous generators driven by steam turbines, have high efficiency when operating at high speeds, consequently, in these cases cylindrical rotors are used since the protruding pole rotor would have great difficulties to withstand the mechanical voltagees caused by centrifugal force. These generators are also called turbogenerators, and unlike the salient pole generators, those with cylindrical rotors have an axial dimension considerably larger than the rotor diameter[18].

The simplified equivalent scheme of a synchronous generator is shown below:

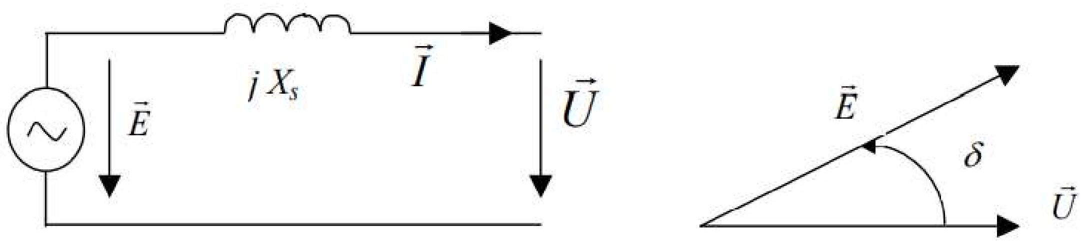


Figure 3-4: Synchronous Machine Scheme[18]

Where:

E: No-load voltage

U: Voltage at machine terminals

I: Current supplied by generator

X_s: Generator synchronous reactance

δ: Angle between U and E.

Any electrical network can be represented by its Thevenin equivalent as an ideal voltage generator representing the open-circuit network voltage in series with an impedance. As the short-circuit power of the network increases, the value of the impedance of the equivalent circuit decreases, so that for infinite short-circuit power, the equivalent impedance becomes zero. An infinite power network represents a large number of generators connected in parallel in the same electrical system, so that as a whole, they are capable of maintaining both the voltage and frequency of the system within limits in the event of any type of incident, such as the disconnection of a generator or a large demand agent.

Regarding the production of both active and reactive power, it is convenient to mention that the production of both powers is independent, being the production of active power dependent on the power delivered by the turbine that moves the generator, while the production of reactive power depends mainly on the excitation current. More specifically, it can be stated that if the electromotive force of the machine (E) is ahead of the machine terminal voltage (U), the machine works as a generator giving active power to the grid, while if the opposite occurs, i.e. U is ahead of E, the synchronous machine will be absorbing energy from the grid. On the other hand, something similar happens with the reactive power, when the product of the electromotive force (E) by the cosine of (δ) is greater than the terminal voltage of the machine (U), it is said that the machine is overexcited and is generating reactive power. When the opposite occurs, it is said that the machine is under-excited and consequently it is absorbing reactive power from the network. Consequently, if a generator connected to an infinite power network were to have its excitation current modified, the active power would not be affected, while the reactive power would be.

In conclusion, a synchronous machine can operate as a motor, absorbing power, or as a generator, yielding power, depending on whether the mechanical torque applied to its shaft is driving or resistant. Whether the synchronous machine is operating as a generator or as a motor, it can absorb or generate reactive power depending on its excitation current[18].

The operating limits of synchronous machines are delimited by what is called p-q abacus. This graph consists of the representation of the technical limits presented by the generators as a function of the active power and reactive power they are consuming/generating. The increase of nominal power of these machines is conditioned by the correct application of cooling techniques that allow the increase in size with admissible heating of the inductor and armature windings. On the other hand, the turbines of the generators do not adequately withstand sustained overloads, which is an operational limit caused by the rated power of the driving machine. In addition, synchronous machines have their excitation regulator circuits in order to adapt the excitation level to the voltage variations carried out at the terminals with the network. Additionally, protections are installed to limit the minimum excitation current, so that in case of any loss or decrease of the excitation current, the torque angle does not increase until the dynamic or static limit of stability of the machine is reached.

Summarizing, the main operational limits affecting the p-q abacus are defined below:

- Maximum current limit on stator and rotor windings.
- Power limit of the turbine or in general of the driving machine.
- Minimum admissible value of the excitation or current in the rotor.
- Torque angle below the static and dynamic stability limit.

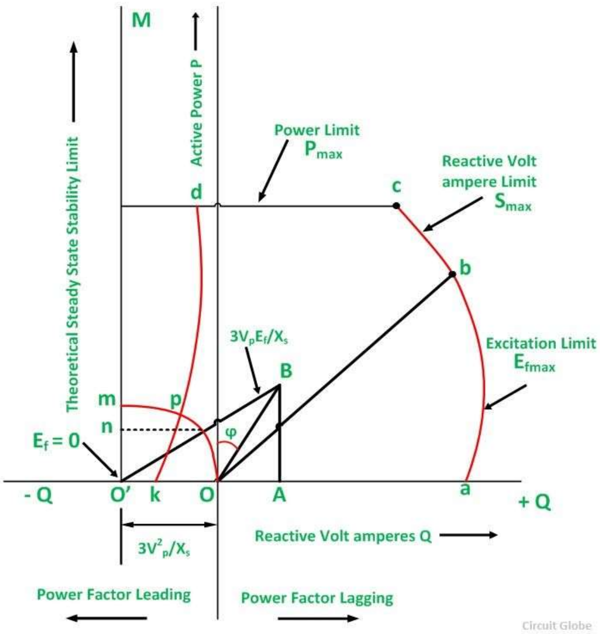


Figure 3-5: Synchronous Machine Operational Curve (Abacus P-Q)[19]

Synchronous generators usually have an automatic voltage regulation (AVR) system. Generally, this control is characterized by being relatively simple and fast. Voltage controls can be discrete; as it could be when disconnecting capacitors, tap transformers, or continuous; as in the case of generator regulation.

The voltage values at the nodes of electrical systems depend to a large extent on the power flows in the system lines. As explained above, the correlation between reactive power flow and voltage is strongly local, i.e. reactive power flows do not affect the voltage of those nodes that are at a considerable distance. The automatic voltage control (AVR) aims to maintain the generator terminal voltage by continuously controlling the electromotive force generated by the synchronous machine. In order to manipulate the internal electromotive force of the machine, the excitation current of the generator must be controlled. As mentioned before, the response of these regulators is considerably fast, in the order of seconds.

The voltage control process follows the following process, first the voltage measured at the generator terminals is transformed into a DC signal proportional to the original RMS value, this conversion is performed by a rectification and filtering process. The signal obtained in direct current is compared with a reference value, the difference between the two being the voltage error. This difference considered voltage error is amplified to send a setpoint to the generator, so that the error is corrected by a variation in the excitation of the synchronous machine.

Although it is not the subject of this section of the project, it is intended to make a small mention to the participation of synchronous generators in the market of technical restrictions, in many cases due to voltage control needs.

Based on the Iberian market, it can be stated that the purpose of the technical restrictions market is to adapt the electricity generation programmed in the sessions managed by OMIE to the quality, reliability and safety requirements that must govern the electricity system. Once OMIE has carried out the matching of the daily market, REE puts its system power flow model into operation in order to evaluate which technical restrictions would prevent the current established dispatch. Once these restrictions have been detected, the technical restrictions market is opened. The current regulation (P.O 3.2)[21] allows both generation and demand agents to participate in this market. However, in order to avoid insufficient supply, agents with thermal, biomass, waste, nuclear, large hydroelectric and pumped-storage plants will be obliged to introduce bids to increase or reduce their production/consumption programs as much as possible, which results in the mandatory participation of many participants. The fact that this is not a market characterized by competitiveness, which in the end results in a significant cost to the system, makes many agents reflect on the efficiency of this market[20].

Chapter 4. VOLTAGE CONTROL REGULATORY FRAMEWORKS

This fourth chapter of this project aims to address the main and most innovative regulatory trends in terms of voltage control. First of all, the new voltage service that will come into force in November 2021 by REE will be presented. This service will mean a great number of modifications with respect to the current regulatory framework and, consequently, it is expected to have a great impact on the different agents involved in the peninsular electricity system. The idea is to analyze and describe the P.O. 7.4 in such a way that it can be easily understood and interpreted by any individual regardless of their previous background. Secondly, it is intended to investigate different regulatory frameworks associated with voltage control that are being used in other liberalized electricity systems, in order to compare and evaluate the regulatory framework to be implemented in Spain. It is true that in Great Britain, National Grid has implemented a new regulatory framework regarding voltage control, which is very innovative and similar to the one to be implemented in Spain[10]. Consequently, it is very likely that the UK case will be further developed.

4.1 SPAIN

1. **Application Aspects:**

   This new voltage control is intended to regulate the following areas of application:

   - Service provision
   - Allocation of the service
   - Service validation
   - Additional reactive capacity markets
   - Qualification tests for these markets

   As explained at the beginning of this project, voltage control is essential to ensure reliability, security and power quality within the power system.

2. Scope of Application:

Participating agents: System operator (SO), transmission grid, distribution grid, generation and demand control centers, generation facilities, generation facilities with auto consumption, demand facilities, storage facilities.

Comments: The range of agents involved in this new operating procedure has increased considerably, mainly due to the entry of new players in the electricity system, such as self-consumption facilities, storage systems or unified aggregators in the generation and consumption control system.

3. Service Providers:

- Generation and storage facilities connected to the network with more than 5MW of capacity.
- Demand and self-consumption facilities connected to the transmission grid with more than 5MW of capacity.

Generation facilities: The mandatory operating ranges for these installations are defined below, subject to the technology used and the date of commissioning (Regulation (EU) 2016/631, Order TED/749/2020, RD 413/2014 or any subsequent regulation to that effect). Those facilities that cannot supply the system with the minimum requirements will have to submit a report to the CNMC justifying their maximum operating ranges. If the operating levels of an installation are not sufficient to compensate for reactive consumption, the installation must cover reactive losses up to the point of connection to the grid. In the case of an installation consisting of several generation modules, each module will have to comply individually with the reactive requirements demanded by the standard.

Demand facilities: The following operation requirements are set.

Period	Cos ρ

Peak (1)	0,95 capacitive < Cos ρ < 0,95 inductive
Valley (6)	Cos ρ inductive
Flat (2,3,4,5)	0,98 capacitive < Cos ρ < 0,95 inductive

Table 1: Cos ρ requirements

Generating self-consumption facilities: Generation facilities associated with self-consumption must comply with the same operating ranges as demand facilities, except for those facilities that are required to install a meter for generation, in which case they will have to comply with the ranges specified for generation facilities.

Storage facilities: Same requirements as for generation facilities, except that the control levels for the maximum operating point will be applied to the entire operating range.

Hybrid facilities: Since they are considered as generation facilities formed by groupings of generation modules (MGEs), the same requirements will be applied to them as to generation facilities, taking into account the technologies of each of the MGEs.

Comments: The minimum power values to participate in the voltage control have significantly decreased compared to those established in the previous P.O., which implies a considerable increase in the number of agents obliged to participate in the new voltage control. This is expected to have a positive effect on the system, since there will be more agents with the capacity to support the control of the voltage profile of the network and taking into account that the intention of the SO is to implement a liberalized market, this will be a positive factor in order to increase competitiveness. At the same time, although this is a beneficial change at a global level, many agents will be forced to make significant investments in order to meet the requirements. Without going any further, demand agents have seen an increase in their requirements to provide the new tensioning service with respect to the previous P.O. For storage facilities there hasn't been developed a specific regulation that defines the minimum voltage requirements, that is why the generation facilities requirements are applied to the storage ones.

4. TSO Functions:

- The transmission operator has the function of calculating and issuing the different voltage setpoints required for the correct operation of the system. These setpoints will be sent to both the distribution grid managers and to those agents directly connected to the transmission grid.
- The system operator must manage the correct operation of the additional reactive capacity market, defining the different zonal markets, establishing the additional capacity requirements, calculating the payment and collection rights and carrying out the qualification tests for this market, always under the supervision of the CNMC.
- Finally, the system operator has technical responsibilities related to the communication of the impossibility of evacuation at points in the network or the allocation of losses in the network by means of sensitivity coefficients. Also, the SO has the responsibility of operating the voltage control elements of their own property.

Comments: The TSO is the agent that will require the new service, however, some involvement in the process is missing. It does not seem fair to ask for demanding requirements from different system agents as long as the system operator's contribution lies in "Managing the voltage control elements it owns". In conclusion, some conflicts between the functions of the TSO and the DSOs are observed, in addition to the lack of direct involvement in voltage control of the TSO is remarkable. On the other hand, it is known that the SO has an infrastructure plan which contains a section dedicated to investments in equipment to improve voltage control in the transmission network. However, many agents question the effectiveness and efficiency of both the investments themselves and their subsequent operational management, and propose a free market system to determine which agent should provide the voltage control service in the transmission grid, which was initially going to be provided by SO-owned equipment. This ensures that both investment and operational costs are as low as possible.

5. DSO Functions:

- One of the functions of the DSOs is to transmit voltage setpoints through the SO to the generation and demand control centers (GDCs).
- They also have tasks regarding the operation of the market such as establishing the additional reactive capacity requirements, defining the electrical zones associated with each zonal market and carrying out the enabling tests for the market.
- Finally, the DSOs also have technical responsibilities such as following the TSO's instructions when managing voltage control through the transformers bordering the transmission grid, managing the voltage control elements owned by them, and assigning losses to each agent by means of sensitivity coefficients.

Comments: Most of the DSOs functions are similar to the TSO ones, however, as happened with the TSO, there is a lack of involvement from the grid managers in the voltage control service in terms of investments. Also, some conflicts with TSO and DSO functions are noticed.

6. Functions of the Generation and Demand Control Centers:

- The main function of the generation and demand control center is the dispatching of consignments. This process is bi-directional, i.e., the CCGD sends both the instructions from the agents assigned to it to the SO, and from the SO to the CCGD, which are then received by the corresponding agents. The sending of the instructions must have a refresh time of less than 4 seconds.
- Another function of great controversy is that the CCGDs are responsible for managing the distribution of the setpoints to be followed by the different agents that are jointly providing voltage, so that at the point of connection to the transmission grid, the setpoint required by the OS is being provided.

- Finally, the CCGDs have the obligation to communicate as soon as possible the impossibility of evacuation and therefore to comply with the voltage requirements established by the SO.

Comments: (Definition of CCGD: Purely management or administrative entities, which serve as intermediaries between the SO and the different agents participating in the market, mainly to facilitate and expedite the dispatch of consignments). The generation and demand control centers are intermediary agents between the service providers and the SO, which have a continuous involvement and are vital to streamline the process and thus reduce response times. Since the present operation procedure requires very low response times, it is imperative that the intermediary, in this case CCGD, does not hinder the process. On the other hand, it plays a very important role in the process of joint participation in PPS; this way of providing the service will be explained later on, but it presents certain cases of uncertainty.

7. **Measures for coordinated voltage control in transformers at the border of the transmission network with the distribution network:**

The measures apply to those frontier transformers that:

- Ability to regulate on-load taps.
- Remote control of the automatic-manual tap regulator.
- Connection to a meshed distribution network, i.e. a distribution network that connects or can connect at least two nodes of the transmission network, at least two nodes of the transmission network.

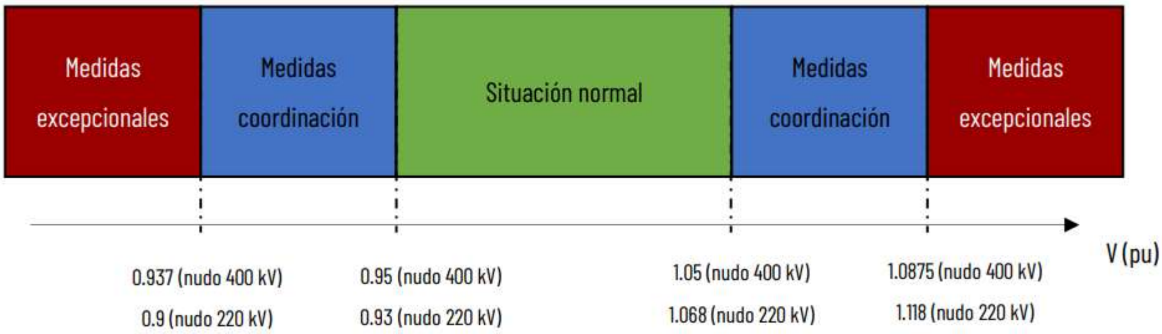


Figure 4-1: Transformers operational range

The measures apply to those frontier transformers that:

Measures	Overvoltage	Undervoltage
Coordination	Blocking of automatic regulators Minimize active injection	Blocking of automatic regulators Minimize reactive absorption
Exceptional	Transformer tap blocking	Transformer tap blocking

Table 2: Frontier transformers voltage mitigation measures

8. Provision of Mandatory Service:

The new voltage control service establishes minimum levels of participation that must be provided by all agents that have the capacity to participate in voltage control (specified in point 3). Failure to comply with these requirements will result in a financial penalty. However, in general, suppliers will be obliged to participate according to modality A, the other modalities being optional. Agents will be exempted from providing the service through modality A as long as there is a justification presented to the CNMC, being able to provide the service through any other modality. The time response to voltage variations must be lower than 1 minute. There are two main ways of providing the service.

- Individual participation in central bars:
  - Mode A: Real-time voltage setpoint monitoring. In this mode, the agents will have to follow the voltage setpoint sent to them by the CCGD by means of the necessary modifications in reactive production, according to the regulations applicable to the technology used. Response times to voltage variations must be less than 1s.
  - Mode B: Real-time reactive setpoint monitoring. In this mode, the agents will have to follow the reactive power setpoint sent to them by the CCGD by means of the necessary modifications in reactive production, according to the regulations applicable to the technology used.

- Mode C: Real-time power factor range tracking. In this mode, the agents will have to follow the power factor setpoint sent to them by the CCGD by means of the necessary modifications in reactive production, according to the regulations applicable to the technology used.
- Mode D: Power factor range tracking according to hourly periods. In this mode, the agents will have to follow the power factor setpoint according to what described in section 3, by means of the necessary modifications in reactive production, according to the regulations applicable to the technology used.

- Joint participation in PPS:

  Those service providers that share the same PCR (Point of Connection to the network) may benefit from joint participation in PPS (Point of Service Provision) in any of the modalities described above, provided that all agents downstream of the PPS are assigned to the same control center. The CCGD will be in charge of assigning the corresponding setpoints to each agent assigned to its control center, in order to provide the desired service in PPS.

Comments: First of all, some necessary definitions.

Central busbars (BC): point of connection to the installation's network, it is considered the most "downstream" point at which the agent can provide voltage control. When there is only one installation connected at the same BC point, this point is considered to be on the high voltage side of the transformer. On the other hand, if there is more than one installation connected to the same BC point, the point at which service is required is on the low voltage side of the transformer and is different for each installation.

Point of connection to the grid (PCR): Point of evacuation to the transmission grid. It is considered the most "upstream" point at which voltage control can be provided.

Point of Service Provision (PPS): Alternative point to provide voltage control, which must be located between the BC and PCR points. Its purpose is to facilitate the joint provision of the service of several agents, having these agents to be located "downstream" of the PPS and attached to the same CCGD.

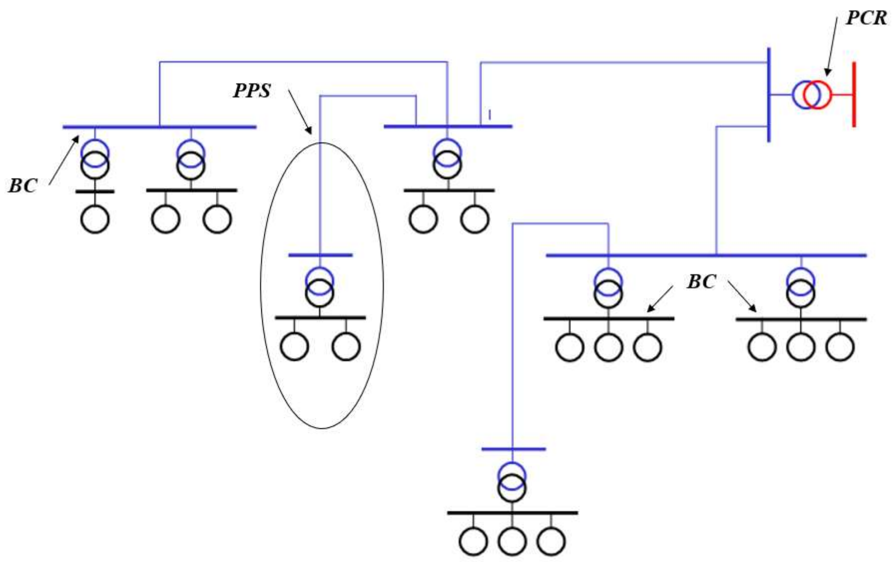


Figure 4-2: Network Scheme (PCR, PPS, BC)

A lack of specification is detected in some aspects of the service depending on the different modalities proposed by the system operator; this issue will be addressed in more detail in the last section of this thesis. In general terms, it is considered that the fact of allowing the agents to provide the service through different modalities provides flexibility and ease to the agents when carrying out the voltage control. On the other hand, this flexibility poses a problem for the control centers and the system operator since they would have to adapt to having to send up to 4 different types of setpoints, and given that in large-scale data processing standardization is rewarded, this procedure would not be the most efficient.

The joint participation service is considered a beneficial tool for the system, since on the one hand, it streamlines the system operator's functions by delegating them to the CCGD, while on the other hand, the fact of providing the service together with other agents promotes beneficial synergies for the different facilities attached to the same control center. This new service aspect of voltage control will also be developed more exhaustively in the next chapter of the thesis as certain aspects that generate uncertainty about this form of voltage control are detected.

9. Zonal Markets for Additional Reactive Capacity

- Characteristics of zonal markets for additional reactive capacity: Grid operators shall communicate to the SO the additional reactive capacity requirement for each of their electric zones, each of these zones being associated to a zonal market. The definition of these zones is established by the system operator. Two independent auctions will be presented, one for reactive absorption and the other for injection. These auctions will be carried out in accordance with Annex 3 mentioned below. The system operators will be able to make real time allocations if violations of the security criteria are detected. The bid allocation criteria are described in the fifth paragraph of this section.

  Comments: The criteria used to define the electric zones associated with the zonal markets for additional reactive capacity is significantly questioned, and this issue will be discussed in depth in the next chapter of the thesis.

- Communication of additional reactive capacity requirements: n the day prior to the call of the zonal markets, the grid managers will communicate to the SO the additional reactive capacity and in which zonal market it is required. The communication limit is set as 30 minutes after the publication of the reactive band.

  As mentioned before, additional reactive capacity can be allocated in real time, specifying quantity, zonal market and hourly period. In this case, a very demanding response speed is required; these specifications are described in Annex 3 of this chapter.

  Comments: It is pointed out that in most cases the reactive capacity that an agent can provide to the system depends on the active power it has assigned, consequently, there should be a sufficient time window for reactive bids to be prepared taking into account the characteristic capacity of each technology. In addition, the possible investments to be made in communications systems to comply with the demanding response times established by the SO must be taken into account.

- Reception period of bids for additional reactive capacity: As explained above, the bid publication period will be open until 30 minutes after the allocation of the secondary regulation band of active power; this period may be modified by the SO on an exceptional basis. The bids not assigned at the beginning, could be assigned either in real time or 15 minutes before the beginning of the delivery.
- Characteristics of additional reactive capacity offers: Bids are made at the service provision unit level. Bids must be divisible, i.e., a block of capacity is bid at a price and any capacity value equal to or less than the capacity bid may be assigned. Further details on the bids are discussed in Annex 3. Each bid must contain the following information:

  1. Area market to which the offer is sent.
  2. Participation mode: A, B, C, D.
  3. Block number: in correlative order from 1 to the maximum number of blocks listed in Annex 3.
  4. Block capacity (Mvar): The capacity offered must be effective capacity, taking into account the sensitivity coefficients of the physical units that will provide the service.
  5. Block price (EUR/Mvar): The offer price will be limited by the maximum price established by the CNMC/MITECO.

  Comments: Clear and defined structure on the information to be provided on the offer blocks.
- Allocation of additional reactive capacity offers: The reactive capacity offered is the effective capacity, which is that absorbed or generated in the PCR by the bidding agent. The difference between the power absorbed/generated in PCR with that provided in BC/PPS is determined by the sensitivity coefficients. The SO will assign the bids prioritizing the modality used, being that prioritization order from A to D. In general, the most economic bids will be assigned in order to minimize the cost of the service; whenever two bids have the same price, the one that has been submitted earlier will be assigned. The assignment of bids ends when the sum of assigned capacities coincides with that required by the system.

Comments: It is important to clarify the definition of effective power and the application of the sensitivity coefficients, which are explained in detail in Annex 4.

- Communication and publication of additional reactive capacity results: The results obtained in the allocation of bids will be communicated to market participants once the process has concluded, and always through the established information exchange channels.
- Communication of breakdowns of scheduling units into physical units of additional reactive capacity: The different market participants will have the obligation to provide the system operator with a breakdown of the effective capacity assigned in the physical scheduling units. Said breakdown will be considered correct when the sum of the capacities assigned to the different physical units coincides with that of the scheduling unit. Said breakdowns shall be updateable up to 15 minutes before the start of the delivery; moreover, any capacity incorrectly broken down or without breakdown shall be considered invalid and therefore penalized.

  Comments: It is very important that the breakdown of scheduling units is effective given the influence that the geographic location of agents has on the voltage control performance.
- Penalty for non-compliance with additional reactive capacity: The allocation of capacity offers is considered firm and will be subject to a validation process. If this process is not satisfactory, the agent in question will be subject to a series of penalties defined below.
- Limitations established by the network manager due to security criteria: In the event that, due to technical restrictions, the SO limits the capacity of any agent to comply with an assigned reactive offer, the agent may request the SO to designate capacity in order to comply with all the established requirements.

10. Qualification testing for additional Capacity Zonal Markets

In order for agents to participate in the zonal markets for additional reactive capacity, they will have to pass qualification tests for these markets where the additional capacity to the mandatory capacity they have available is certified.

The service providers requesting the qualification in modality A will have to take the tests described below:

- Phase 1: The grid manager sends a voltage set-point that implies a zero reactive output.
- Phase 2: When the voltage stabilizes, a new voltage setpoint is sent which is higher than the previous one and which provides a reactive supply within the service's mandatory limits.
- Phase 3: Once the voltage is stabilized, the maximum voltage setpoint is sent in such a way as to saturate the reactive power generation output.
- Phase 4: Once the voltage is stabilized, the grid manager sends the required voltage setpoint in the first phase.
- Phase 5: When the voltage stabilizes, a new voltage setpoint is sent which is lower than the previous one and which provides a reactive supply within the service's mandatory limits.
- Phase 6: Once the voltage is stabilized, the maximum voltage setpoint is sent in such a way as to saturate the reactive power absorption output.
- Phase 7: Finally, the voltage setpoint of the first phase is sent again.

The third and sixth phases will determine the additional capacity that each agent can offer in the market. The qualification tests for modalities B, C and D will be analogous to those described above but following the instructions of the corresponding variables in each modality.

11. Validation of Service Delivery Performance

The system operator must validate, on an hourly basis, the tele-measurements sent by the CCGDs and the compliance with both the mandatory and additional service.

- Service provider availability: For each hour one of the following states is established, D1; evacuation is not declared impossible, and D2; evacuation is declared impossible.
- Validation of active and reactive power remote measurements: This validation is only performed if the suppliers are in D1 status. Also on an hourly basis, the M1 status is

established as long as the following two conditions are met for the active and reactive power tele-measurements.

- Less than 10% of the measurements are of erroneous.
- The deviation of the integral of the remote measurement with respect to the recorded hourly energy must be less than 10%.

On the other hand, status M2 is assigned in all other cases, i.e., when the minimum power requirements are not met. In this case, the agent is charged with a penalty for the whole power band assigned for both the mandatory and additional modes.

- Validation of service delivery: Only for those agents that are under M1 status, a random and hourly sampling of the tele-measurements associated with the corresponding variable will be analyzed according to the chosen modality. If more than 75% of the samples analyzed meet the service, the corresponding agent is assigned status S1, while if the previous condition is not met, it is assigned status S2.

  The following are the different ways of verifying the tele-measurements according to the technologies, operating modes or operational status.

  - Validation of Modality A: synchronous technology-based suppliers
  - Validation of Modality A: other service providers
  - Validation of Modality B
  - Validation of Modalities C and D

  If the sample is not valid the agent will have to check its reactive power values with the mandatory and additional capacities it had committed to in order to determine one of the following options.

  - No saturation: The power provided is less than the mandatory.
  - There is saturation of the mandatory capacity: The power provided is greater than the mandatory but less than the sum of the mandatory and additional power.
  - There is saturation of the obligatory and additional capacity: The power provided is greater than the sum of the obligatory and additional power, in which case, the service is fulfilled.

- Supervision of compliance with voltage control at the frontier point: The system operator shall verify that the setpoints sent to the border transformers between the distribution grid and the transmission grid comply with the established requirements. These revision processes are carried out every ten minutes until the measures are deactivated.

12. Service Payment

The mandatory provision of the service will not entail any financial remuneration, while it will be associated with a financial penalty in the event of non-compliance. The allocation of additional reactive capacity will have an associated collection right, while in the event of non-compliance it will also have an associated financial penalty. The three items subject to settlement are defined below.

- Remuneration for additional allocated capacity: The allocation of the additional capacity offers will be based on the offer price for each delivery period, being the price expressed in EUR/MVar. The additional capacity allocated will be remunerated at the weighted average price of all the additional capacities allocated from the same scheduling unit for each delivery period and direction (absorption/generation).
- Penalty for non-compliance with the mandatory provision of voltage control service: Non-compliance with the mandatory voltage service is determined by the status associated with each facility; those facilities that are in M2 or S2 status are in non-compliance with the mandatory service and are therefore subject to penalties. The other form of non-compliance is through reactive power restrictions by the network operator.
- Penalty for non-compliance with the additional provision of voltage control service: The price associated with default is calculated as the weighted average price of default multiplied by a penalty factor defined in Annex 3.

13. Annex 1: Mandatory operating range in BC depending on PCR voltage of existing synchronous generation technologies.

The operating rules for synchronous generation technologies that delimit the present operating procedure are detailed below.

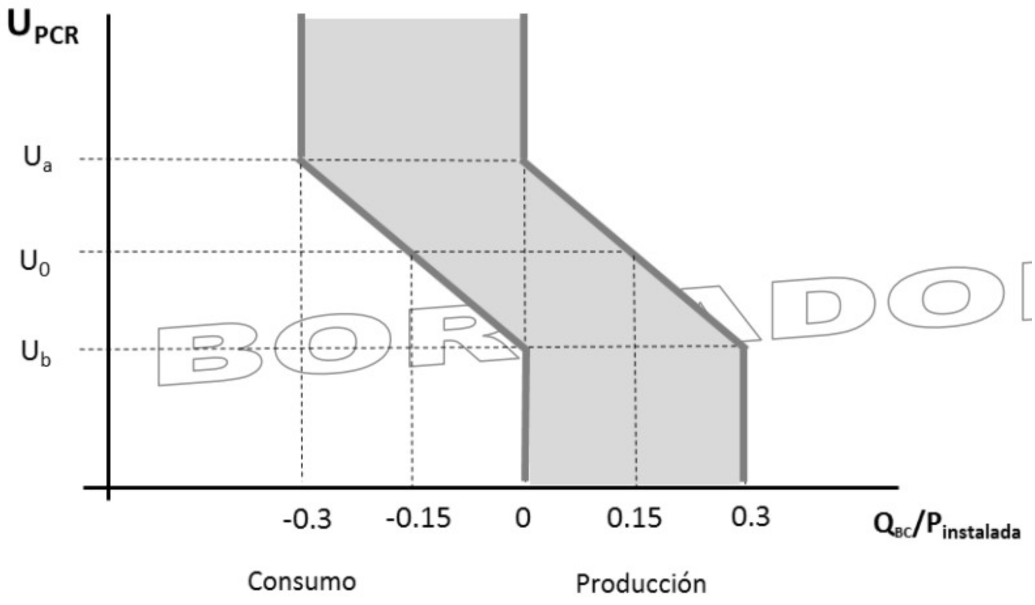


Figure 4-3: Synchronous Generators operational range

	400kV Network	220kV Network	Distribution Network
Ua	420kV	235kV	1.05 pu
U0	400kV	220kV	1 pu
Ub	380kV	205kV	0.95 pu

Table 3: Voltage values definition

A relevant clarification established in the regulation that affects the aforementioned synchronous generators, already discussed in previous sections of this project, is the fact that they can participate in the service as synchronous compensators, i.e., without producing any active energy. This participation will therefore consist of a pure reactive power contribution, which allows them to enter directly into the additional reactive power market.

Comments: Since these are synchronous generators, which, as explained above, have a high degree of control over their voltage output, the standard requires them to have specific operating ranges for their technology. These ranges, as can be seen in the table, are adapted to the needs of the system at any given moment. When the voltage is above its nominal value, the operating range limits the generator to only make consumption contributions. On the other hand, if the voltage is below the nominal value, the generators are obliged to contribute reactive power to the system.

14. Annex 3: Main characteristics of the additional reactive capacity markets

CONTRACTING SCHEME	Market. Participation is optional
ALLOCATIONS	**On day D-1**: for each zonal market and for each delivery period, one auction for reactive generation capacity and another for reactive absorption.
	In real time: only for the zonal market, delivery period and direction indicated by the grid manager.
SUPPLIERS	Only installations with installed/contracted power greater than 1 MW.
MINIMUM CAPACITY BID	0.1 Mvar
PRICE RESOLUTION	0.01 EUR/Mvar
REMUNERATION	Pay as bid
TYPES OF BIDS ACCEPTED	Simple fully divisible bids
DELIVERY PERIOD	Each of the 24 hours of the day D
PRODUCT SYMMETRY	No. "x" Mvar to be generated and "y" Mvar to be absorbed can be offered.
MONITORING	Real time
ALLOCATION TOLERANCE	± 10 %.
ACTIVATION TIME ACTUAL TIME ALLOCATIONS	10 minutes
MAXIMUM NUMBER OF BLOCKS PER OFFER	10
INCORRECT BREAKDOWN TOLERANCE	± 0.1 Mvar
PENALTY COEFFICIENT Kad	Will take the value 1.2

Table 4: Reactive capacity market bid characteristics

Comments: The methodology for offering additional reactive capacity in the market is considerably well defined and specified.

15. Annex 4: Methodology for sensitivity coefficients calculation

Sensitivity coefficients are of vital importance to correctly assess both the capacity to provide the service and the allocation of bids. The sensitivity coefficient denotes the ratio between the power absorbed/generated by the supplier in PCR to that absorbed/generated by the supplier in BC or PPS. These coefficients are calculated taking into account the different agents connected downstream of PCR and who also act as voltage control service providers, so that a fair distribution of responsibilities is established. Consequently, the sensitivity coefficient will be modified each time the network topology changes, new agents are added or the capacities of the existing agents are modified. Independent coefficients are calculated for both generation and absorption.

$$\boldsymbol{C_{abs} = Q_{abs2}/Q_{abs1}}$$

Being:

$Q_{abs1}(Mvar)$: Mandatory absorption capacity of reactive power.

$Q_{abs2}(Mvar)$: Q_{abs1} + reactive power absorbed by the evacuation system - reactive power generated by the evacuation system.

$$\boldsymbol{C_{gen} = Q_{gen2}/Q_{gen1}}$$

Being:

Q_{gen} $(Mvar)$: Mandatory generation capacity of reactive power.

$Q_{gen2}(Mvar)$: Q_{gen1} − reactive power absorbed by the evacuation system + reactive power generated by the evacuation system.

4.2 OTHER COUNTRIES (UK)

This part of the project aims to analyse and study the different mechanisms present in electrical systems to control and regulate voltage requirements. Regulation with respect to voltage control in international terms has followed a considerably static trend. However, it is true that some system operators have been more aware of it than others, mainly due to the characteristics of each one of them. In many cases this special attention has been caused by the increase of renewable energies in the system.

After an exhaustive analysis of the different regulatory frameworks present in the electricity systems, it has been found particularly interesting to emphasize the voltage control service in the United Kingdom. The main reasons for this fixation in the UK are described below.

- Firstly, the new voltage control service in the UK has very similar characteristics to the regulatory framework to be implemented in Spain, which makes the UK a very interesting option to study. In this way it will be possible to compare and analyse the differences between the two regulatory frameworks.
- Secondly, this service is a pioneer in its field worldwide, and has been in operation for a few years, which means that there is relevant information on the performance it is giving. Adding that it has been modified and improved over the years, it is definitely a very valuable source of information to advise on the new voltage control to be implemented in Spain.
- Thirdly, it has been detected that the United Kingdom has regulatory specifications on certain aspects that are not well defined in the Spanish case, and that are intended to be addressed in the last chapter of the project, thus providing a series of possible guidelines to be followed.

As in the Spanish regulatory framework, the voltage control service is divided into a mandatory part and an improvement or additional part to complement the service. The mandatory service is further divided into two regulatory standards depending on the technology used to provide the service (synchronous or non-synchronous).

- **Reactive Power – Obligatory *(Synchronous Generation)***:

  The Obligatory Reactive Power Service (ORPS)[22] is the provision of a specific mandatory reactive output, under any operating point the generators could be obliged to provide a reactive output in order to support the voltage profile of their area. According to the grid code, all those generators whose power is equal to or greater than 47MW will have the obligation to provide the mandatory service.

  The generators are obliged to supply the assigned setpoint in a response time of less than two minutes. This setpoint has to be within the operational limits of the synchronous generator, which will depend on its active power output, an abacus p-q is shown below as an example.

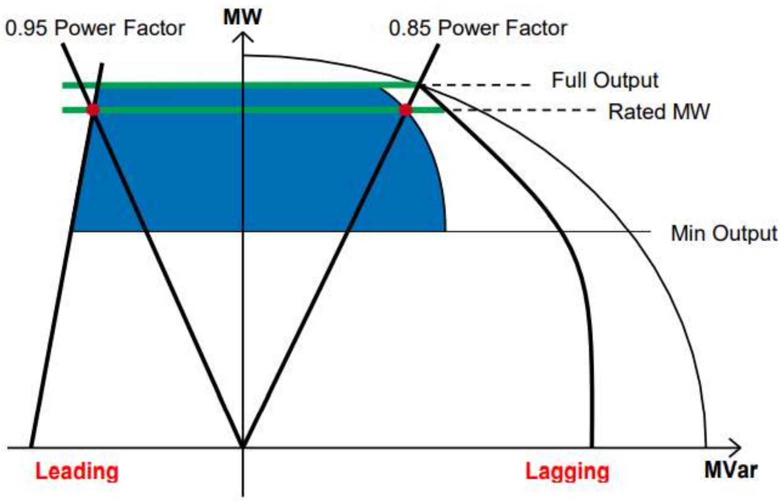


Figure 4-4: Synchronous Generators operational requirements

Reactive power setpoints are issued by the system operator (National Grid) directly to the generators through Electronic Dispatch Logging (EDL).

The minimum requirements to be met by the generators that provide the mandatory voltage control service are summarized in the following points.

- Be able to maintain their power output between a power factor of 0.85 lagging and 0.95 leading at the point of connection.
- Have a short-circuit ratio at the connection point less than 0.5.
- Maintain the full range of reactive power capacity fully available as long as the voltage is within 5% of rated voltage.
- Have an automatic voltage regulator (AVR) that provides constant voltage regulation at the point of connection, always avoiding any point of instability during the entire operational range.

The method of payment to the service providers is established through the Default Payment Mechanism, whereby National Grid pays the providers by the degree of utilization in £/MVArh. The price paid per utilization is updated on a monthly basis according to the relevant market indicators. The provider will begin receiving payments as soon as the Mandatory Service Agreement (MSA) has been signed. Such payment will be made regardless of whether the SO assigns them a mandatory power to generate/absorb, since the supplier will probably be producing or absorbing reactive rather than staying at the point of zero reactive output.

Comments: The minimum capacity established to participate in the mandatory service is 47 MW, being the Spanish one 5MW. In addition to the fact that the service is oriented only to generation agents, it can be deduced that the total number of participants in the UK is considerably lower than in Spain, with all the consequences that this entails. On the one hand, the scarcity of participants in the mandatory service could lead to inefficient allocations and therefore to poor results in controlling the voltage profile. At the same time, the fact of having such a high minimum power increases the chances that the agents that will provide the mandatory service will have adequate equipment to meet the SO requirements, if we add to that the fact that the mandatory service is subject to remuneration, we can conclude that the treatment of suppliers is considerably favourable compared to that provided in the Spanish case.

As for the minimum technical requirements, as in the Spanish regulatory framework, one of the main restrictions is the power factor, which is considerably stricter in Spain. In the UK a maximum short circuit ratio is required, in P.O. 7.4 no restriction is mentioned in this respect, however such restrictions can be found in the network code. Regarding the remaining two requirements, they are not explicitly mentioned in the Spanish regulation, however they could be considered as implicitly included.

As for the payment format and penalties, it is similar to the one used in the Spanish framework, i.e. the amount of reactive energy contributed or subtracted is evaluated. However, there is a major and important difference between the two systems in that in the Spanish case there is no remuneration but there is a penalty, while in the UK there is both the right to charge and the right to pay.

- **Reactive Power – Obligatory *(Non-Synchronous Generation)***:

  The Obligatory Reactive Power Service (ORPS)[23] is the provision of a specific mandatory reactive output, under any operating point the generators could be obliged to provide a reactive output in order to support the voltage profile of their area. In the case of synchronous generation, the network codes established a minimum participation power of 47MW, this limit is the same established for non-synchronous generation.

  As with synchronous generation, the time margin to reach the setpoint sent by the SO is set at approximately 2 minutes. The operating range of non-synchronous generators is also limited by technical restrictions, these restrictions limit the reactive output depending on the active power being generated, hence, depending on the active power generated, a certain reactive output may be required. These limits are shown in the following graph.

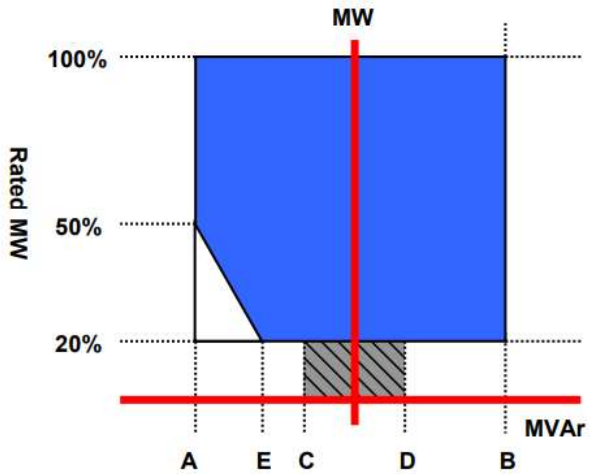


Figure 4-5: Non-Synchronous Generators operational requirements

The following table defines the amount of reactive power required at each of the points marked on the graph.

Point	Equivalent in MVAr
A	0.95 leading Power Factor at Rated MW output
B	0.95 lagging Power Factor at Rated MW output

C	-5% of Rated MW output
D	+5% of Rated MW output
E	-12% of Rated MW output
20% Rated MW	No obligation to provide Reactive capability

Table 5: Graph points definition

The main technical requirements of the network codes for non-synchronous generators are defined below.

- Be able to maintain their power output between a power factor of 0.95 lagging and 0.95 leading at the point of connection.
- Have a short-circuit ratio at the connection point less than 0.5.
- Maintain the full range of reactive power capacity fully available as long as the voltage is within 5% of rated voltage.
- Have an automatic voltage regulator (AVR) that provides constant voltage regulation at the point of connection, always avoiding any point of instability during the entire operational range.
- They must be able to maintain a zero reactive power output for all active power values as long as they are operating at rated voltage conditions.

The method of payment to the service providers is established through the Default Payment Mechanism, whereby National Grid pays the providers by the degree of utilization in £/MVArh. The price paid per utilization is updated on a monthly basis according to the relevant market indicators. The provider will begin receiving payments as soon as the Mandatory Service Agreement (MSA) has been signed. Such payment will be made regardless of whether the SO assigns them a mandatory power to generate/absorb, since the supplier will probably be producing or absorbing reactive rather than staying at the point of zero reactive output.

Comments: The regulatory structure applied to non-synchronous generators is very similar to that applied to synchronous generators, hence not all regulatory requirements will be discussed. However, there are certain changes that are worth commenting on.

First of all, it is quite surprising to see how the power factor requirements increase for non-synchronous generators with respect to synchronous generators, the latter having an older and more advanced technology, which allows them to have greater precision and flexibility when providing a specific power factor. On the other hand, in the previous paragraph to this comments section, the SO states that the supplier will receive remuneration as long as it produces/absorbs reactive power, regardless of the fact that the SO has not assigned a mandatory setpoint. In the first instance, the latter makes no sense, since it could be the case that the service provider is providing a reactive output that is unnecessary and even detrimental to the system, and is receiving remuneration for it.

- **Enhanced Reactive Power:**

  The main differences that separate the mandatory service (ORPS) from the optional service (ERPS)[24] are, firstly, as its name indicates, the ERPS service is completely optional, as opposed to the ORPS, which is mandatory. Secondly, the optional service allows the participation of any agent that can absorb or generate reactive power, while the mandatory service requires a minimum power to participate. Finally, it is imperative to emphasize that the optional service (ERPS) has the function of complementing, but never substituting the mandatory reactive service (ORPS).

  The optional service (ERPS), like the mandatory service, has the function of supporting the stability of the voltage profile. This service is usually defined as that provided by those facilities that exceed the minimum requirements of the mandatory service (ORPS) and that have the capacity to continue providing reactive support to the grid, an example could be a synchronous facility that has sufficient capacity to meet the mandatory requirements, and therefore once these services have been provided, the agent can continue to support voltage control through the optional mechanism. Although such a definition of the optional service is true, it is not complete, since the optional reactive service allows the participation of any agent that is capable of absorbing/producing reactive, even if such agents have not had the obligation to provide the mandatory service, e.g., demand agents.

The minimum technical requirements of the network codes those providing the optional reactive power service are defined below.

- Be able to maintain their power output between a power factor of 0.85 lagging and 0.95 leading at the point of connection.
- Have a short-circuit ratio at the connection point less than 0.5.
- Maintain the full range of reactive power capacity fully available as long as the voltage is within 5% of rated voltage.
- Have an automatic voltage regulator (AVR) that provides constant voltage regulation at the point of connection, always avoiding any point of instability during the entire operational range.

The optional reactive service is provided every 6 months through a bidding session, the service providers are obliged to participate in the service for 12 months, being this period extendable in periods of 6 months in 6 months. In addition to the assignment in the bidding session, service providers must meet all the requirements established in the network codes in order to be finally assigned to the auxiliary reactive service. If these requirements are not met, the agent in question will be limited to the mandatory reactive service.

Finally, in the payment structure of the optional service, there are three different factors that the agents can include in their offers, each of them complementary and non-exclusive.

- Available Capability Price (£/MVar/hr): It is understood as the payment associated with the agent's available capacity to supply a certain amount of reactive power.
- Synchronised Capability Price (£/MVar/hr): Payment associated with the costs incurred by the agent when it is disconnected and therefore has to synchronize with the network to be able to provide the service.

- Utilisation Price (£/MVar/hr): The latter payment corresponds to the remuneration paid to the agents for each unit of energy used to support the voltage profile.

Comments: The optional reactive service is a great incentive for agents to participate, despite having the same technical restrictions required in the mandatory service for synchronous generators, it has no minimum power restriction, from which a greater participation is deduced, which improves the competitiveness and efficiency of the service. At the same time, the service defines a bidding and allocation session every 6 months, i.e. it is a medium term provision of the service, which is not considered very recommendable given the difficult prediction of instabilities in voltage profiles. In this aspect, the framework applied in the Spanish case is recommended, where the service is provided on a daily basis, which promotes efficiency and reduces the economic loss due to payments to suppliers for services that are not used by the system operator. Finally, this service has a payment structure that takes into account all the costs incurred by the agents when providing the service, which is considered an advantage compared to the Spanish case, given that its payment structure only takes into account capacity payments.

- **Voltage Control Market Zones:**

  As mentioned earlier in this project, one of the main characteristics that define voltage is the fact that it is a local variable, which means that it has to be controlled locally or, in other words, by means of mechanisms that are geographically close. Other variables, such as frequency, are global, and can be controlled by agents at any point in the system; this characteristic of the voltage profile presents a great challenge for its correct control. For example, a problem in the voltage profile located in Madrid cannot be solved by means of reactive injection/absorption in Barcelona, due to its geographical distance.

  Hence, when it comes to assigning control services on the voltage profile, the geographical location of the agents is a factor of great importance.

In order to ensure that the service providers will have sufficient impact on the problem that is occurring in the voltage profile, the so-called voltage control market zones have been created, whose main objective is to define a geographic zone within the system. This zone will delimit the service participants to those currently within the voltage zone in question. The creation of such zones is a challenge for system operators given all the requirements they must meet in order to operate efficiently.

As part of the reactive service is subject to liberalized market mechanisms, the more agents that form part of the zonal market, the greater the competitiveness and consequently the better the market behaviour will be, thus avoiding abuses of power by some agents.

At the same time, the geographical limits of the zonal market cannot be extended indefinitely, since, as mentioned above, the agents must be able to act effectively on the voltage profile, which would be impossible if they were too far away from the point of conflict.

Finally, the reactive requirements to improve the voltage profile on the power systems are constantly changing, i.e., the geographical zones in each zonal market should not be designed taking into account only the current state of the voltage profile, but should also consider the fact that this profile will change over time. In the annexes section, different drawings are attached that define the state of the voltage control zones defined in the UK.

- **Voltage Costs:**

This section aims to show in a clear and visible way the evolution of the different costs incurred by the system operator in the UK due to the proposed reactive service. More specifically, it was decided to study this evolution over the last 3 years, given the events that occurred during those years and the volume of data obtained, it is considered that the sample is significantly representative.

This first graph shows the total costs incurred by the system operator during the provision of the reactive service. As can be seen, the graph contains information on the last three years of operation, as well as on synchronization and utilization costs. In 2018 a lower volume of costs is observed with respect to the rest of the years, specifically the graph shows a jump in the cost from 2018 to 2019, which then stabilizes in 2020. This could be due to the fact that the implementation of the voltage control service through reactive injection/absorption was carried out in 2019, therefore it is logical that voltage costs were increased. Firstly, a regulatory change such as this one usually has an impact on practically all the agents involved in the service, which requires a period of adaptation, which in turn is perfectly logical to cause a higher volume of costs. Secondly, the proposed service is of course characterized by the numerous incentives proposed to agents. This type of regulatory framework seeks to ensure that the proposed signals encourage agents to invest in the first instance, i.e. to expose themselves to a higher cost, and then to achieve a degree of efficiency and reliability that allows them to operate at a minimum variable cost. In fact, in 2020 a decrease in the total cost incurred can be observed, without further data it is difficult to certify, but this decrease could be due to an improvement in the adaptation of the service by the agents.

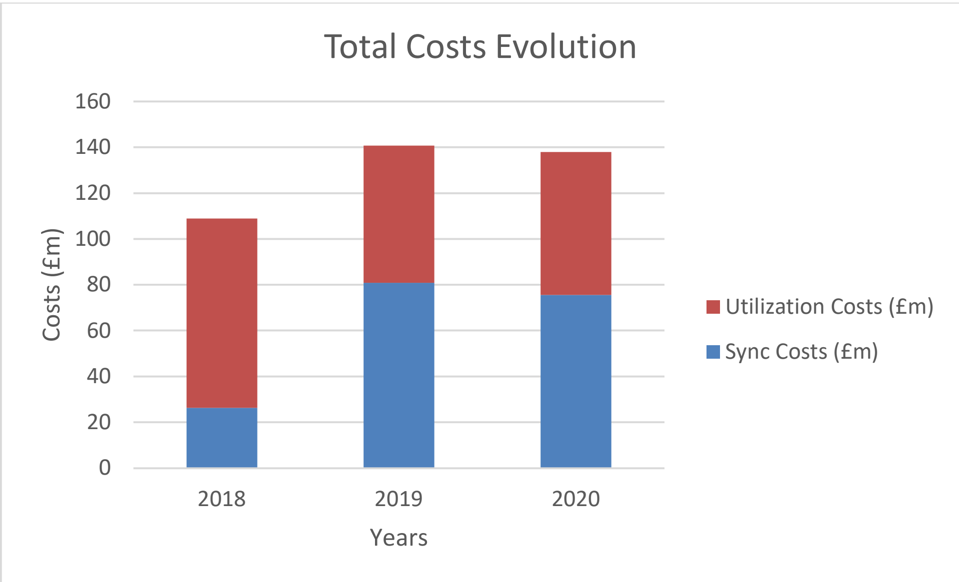


Figure 4-6: Total Costs Evolution

This second graph shows the evolution of the costs incurred on a monthly basis, throughout the 36 months that make up 2018/2019/2020, in this case also showing separately the synchronization and utilization costs, which as can be seen follow a fairly clear and defined pattern. This pattern consists mainly in the fact that the evolution of synchronization costs has practically the same curve as that of utilization costs, the latter being considerably higher in terms of economic volume, but having exactly the same shape as the former. Considering the definition of both costs, this pattern seems to indicate that the reactive power control service is provided by plants that are usually in a state of non-operation, hence both curves move in the same way, every time there is a need to cover some deficiency in the voltage profile, both synchronization costs are incurred, since the plant has to be coupled with the rest of the system, and utilization costs, to cover the costs of reactive power provided.

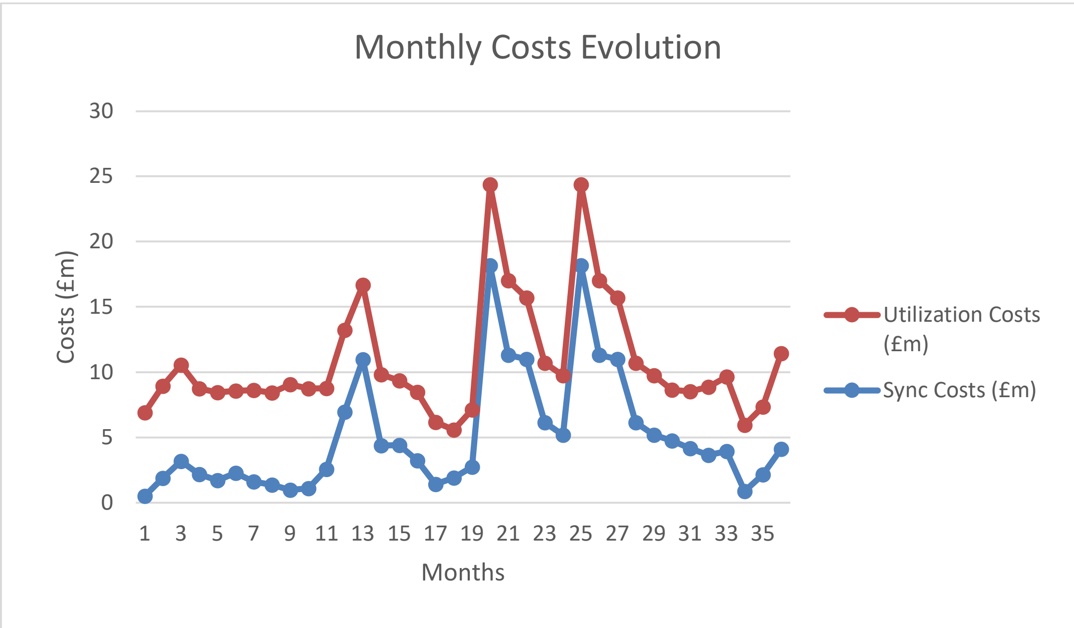


Figure 4-7: Monthly Costs Evolution

The following two graphs show the evolution of the synchronization and utilization costs during the 36 months that make up 2018/2019/2020, for each of the voltage zones defined in the UK by the SO. Although the graphs contain a lot of information and it is complicated to collect concrete information about each of the voltage zones, it is possible to highlight certain aspects that characterize the different costs with respect to the voltage zones. First of all, it can be observed that synchronization costs are generally lower than utilization costs, however, this type of costs have periods of large peaks that far exceed utilization costs. These peaks in synchronization costs are generally characterized by the same voltage zones; this comparison will be evaluated later. However, during the last three years, certain periods can be detected where the incidence of cost peaks increases considerably; these peaks are located between the months 11-15, 19-22 and 24-28, approximately. As for utilization costs, we can observe that they have a considerably constant evolution, without such marked peaks as occurs with synchronization costs, and without notable patterns of increases/decreases in the volume of cost over time. It is worth highlighting and commenting on both graphs the disparity between the volume of costs between the different voltage zones, which will be discussed and analysed later.

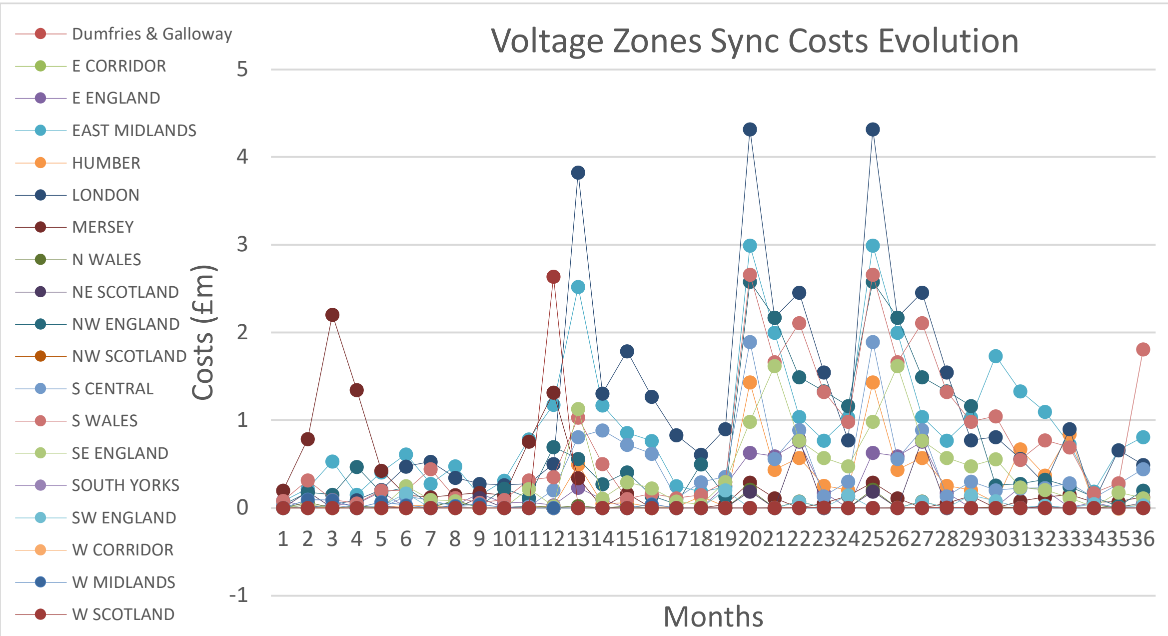


Figure 4-8: Voltage Zones Sync Costs Evolution

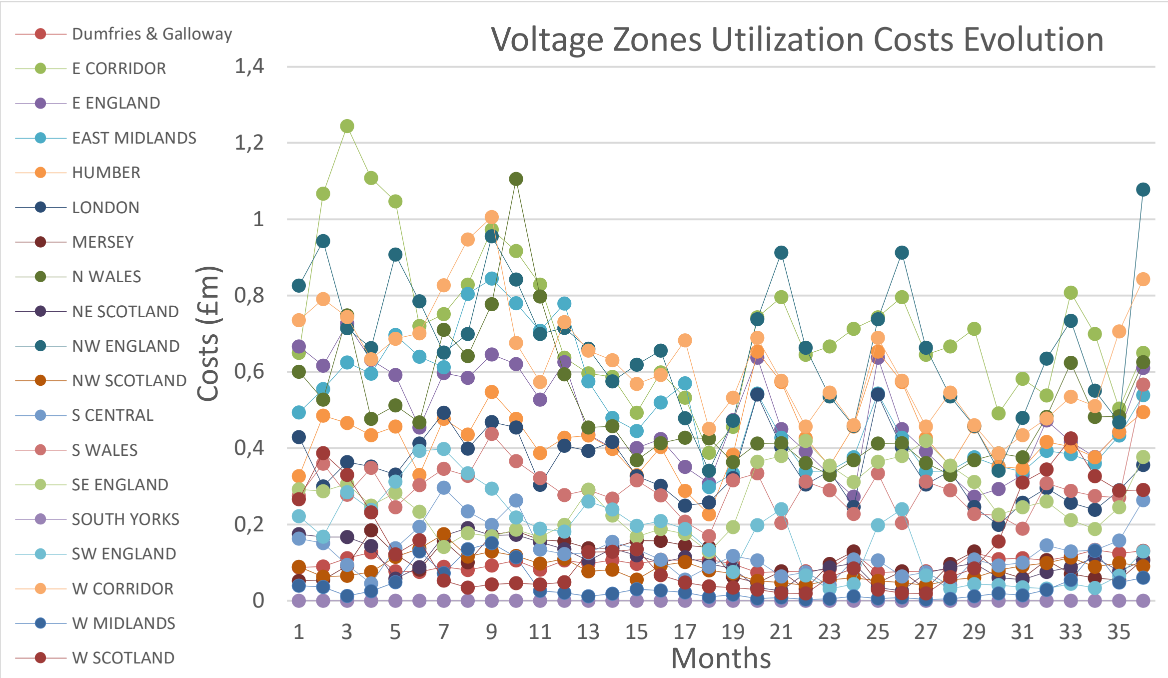


Figure 4-9: Voltage Zones Utilization Costs Evolution

The following graph shows a grouping and comparison of the different total costs incurred in each voltage zone, differentiating between synchronization and utilization costs, reflecting the percentage of cost associated with each of the voltage zones. This graph shows the fact that the percentage of costs for each of the voltage zones is the same for both synchronization and utilization costs, which is strange at first glance, but makes more sense after analysing the Figure 4-6, where a strong correlation between both utilization and sync costs is shown.

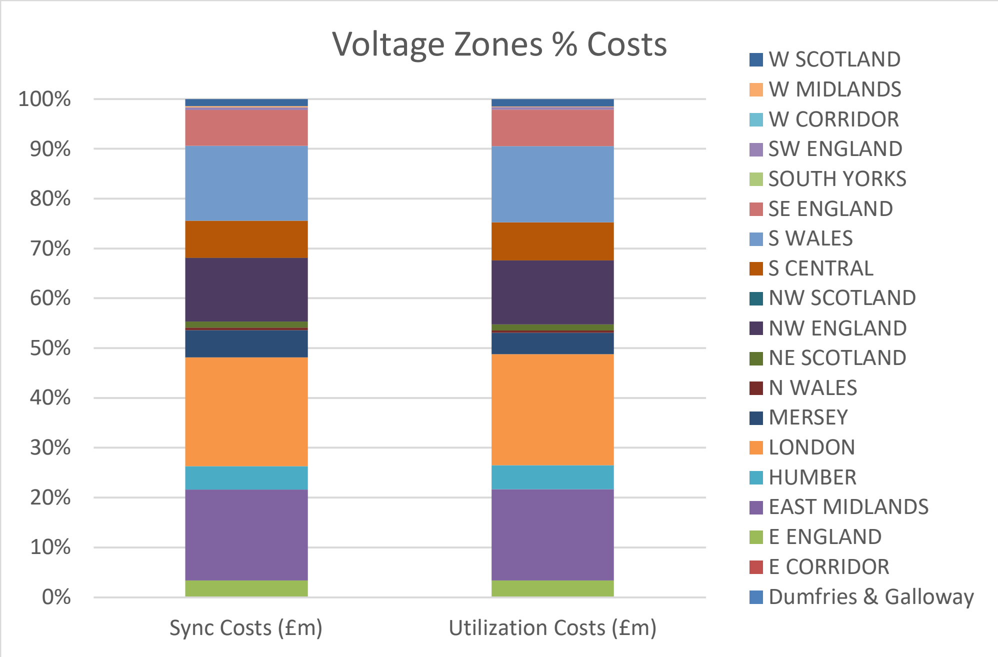


Figure 4-10: Voltage Zones % Costs

In this last graph, the comparison of the total costs incurred by each voltage zone are shown, also an average line has been drawn in order to identify which zones are the ones making a higher impact in the voltage costs. As explained before in Figure 4-7 there are some voltage zones which have high outlier peaks compared to the other voltage zones, as expected, those zones are the ones which's total costs are above the average. Most of the voltage zones have an acceptable cost level under the average line, some of them even have zero expenses, on the other side there are four voltage zones with total cost levels largely above the average line, from which we might deduce that in those zones the voltage profile stability is under constant threat and therefore more agents must be paid in order to provide the system with reactive power support.

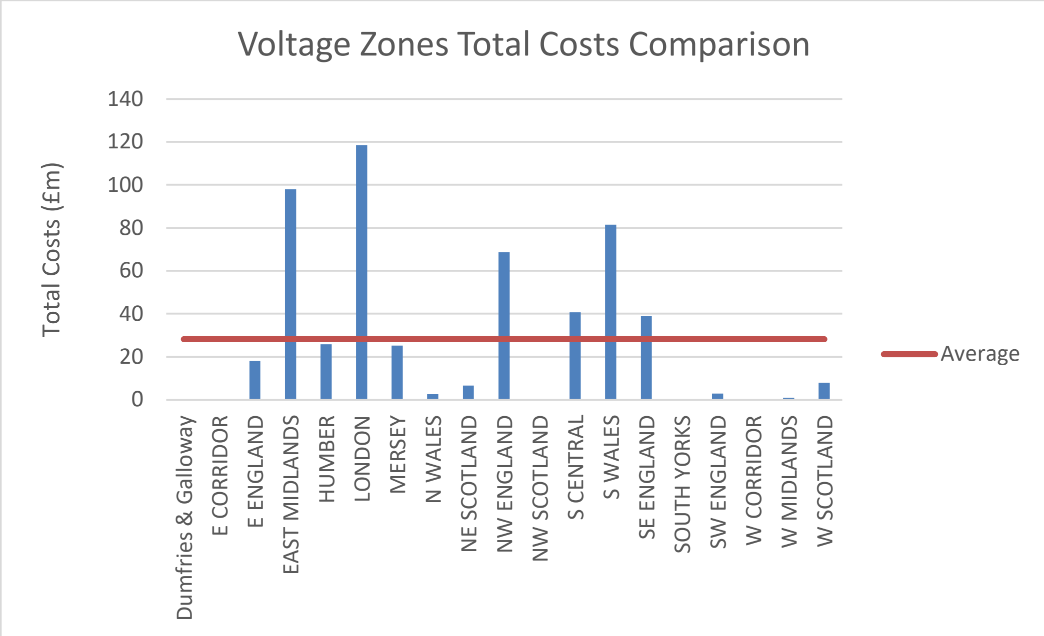


Figure 4-11: Voltage Zones Total Costs Comparison

Chapter 5. PROBLEMS IN THE SPANISH FRAMEWORK

5.1 REMUNERATION MODELS FOR VOLTAGE CONTROL

As explained above in 4.1, the remuneration model used in the new voltage control service issued by REE in Spain consists of a mandatory part and an optional/additional part. This first mandatory part of the service consists of the monitoring of a certain setpoint, which implies a reactive energy emission (MVarh), in addition, this service has associated penalties in the event of non-compliance, but does not have any type of remuneration in the event of a correct and efficient provision of the service. The second part of the service, which is optional/additional, involves the provision of a certain reactive power capacity (MVar). In this case, the allocation involves both remuneration for a correct provision of the service and a penalty in case of non-compliance.

As for the mandatory part of the service, it does not seem fair to make the provision of the service mandatory and without remuneration, even more so considering that the minimum requirements demanded by the SO in this new service far exceed those established so far. It is considered that such remuneration mechanism does not give sufficiently solid and fair investment signals to the agents. In this case, it would be recommended to opt for a remuneration model similar to the one used in the UK, where the mandatory service is characterized by having a penalty in case of non-compliance and remuneration in case of a correct provision of the service, in addition, the provision of the service and therefore its remuneration/penalty are linked to a quantity of reactive energy (MVarh).

The second part of the service, which is optional, has both remuneration and penalties associated with it in the event of correct or incorrect provision of the service, respectively. In this case, the model proposed by the SO is considered acceptable, since it does provide correct investment signals for the agents; however, since this service goes hand in hand with the mandatory part, it is considered that the investment signal provided by the optional part is not sufficient to encourage adequate investment in both parts of the service. In this case, the payment made is only for the allocated capacity, this payment structure is perhaps too simplified since it does not take into account all the costs incurred by the service providers. For example, in the UK, bids split their costs into synchronization, utilization and capacity, thus bringing transparency to the allocation and bidding process. Such a method is considered more successful in accounting for all costs incurred and bringing transparency to the market mechanism employed.

Finally, the allocation of bids in the new voltage control service will be carried out on a daily basis in harmony with the rest of the daily markets, on the other hand, the provision of the service in the UK is carried out every 6 months. In the first instance, it can be deduced that a long-term allocation of the service promotes investment signals since it ensures a certain level of remuneration, which would promote the participation of new agents in the provision of the service, the latter being very beneficial for a correct operation of the service. On the other hand, a daily service allocation promotes flexibility in the provision of the service and increases efficiency and cost reduction by avoiding over- or under-allocation of bids. Taking into account the current trend in the electricity sector markets to carry out most transactions in real time, a daily allocation of bids, as proposed in the Spanish regulatory framework, would be recommended. However, taking into account that the implementation of markets to allocate the voltage control service is very innovative and has no precedent in practically any country in the world except the UK, the option of implementing a long-term market to incentivize investments in the reactive service is also considered interesting. Given the current trend in the markets towards real time allocation, a mix between both approaches is proposed, so that the agents have a certain investment signal, but at the same time the system has a certain level of efficiency when allocating the offers.

5.2 NODE SHARING BY RENEWABLE UNITS

The problem of nodes shared by several generation facilities is mainly based on the fact that, if the same voltage setpoint is assigned to several agents connected to the same node and these agents try to reach this voltage in the same period of time, the results obtained will be far from the expected ones. For example, having in a random node of the network 3 generators capable of providing the voltage control service, imagine that a total energy of 5 MVarh is required to reach the voltage setpoint required in that node. If all three generators were to produce reactive power to meet this requirement, without any synchronization between them, there would end up being more reactive power than necessary, which would generate reactive power backflows and therefore instabilities in the voltage profile, which is what the SO wanted to avoid in the first place.

That is why there is a need to establish a certain degree of synchronization between the different agents that are providing the voltage control service downstream of a point of connection to the transmission grid. In P.O. 7.4, REE has partially taken this problem into account, and has proposed a system for issuing instructions that synchronizes the provision of the service by the different agents.

An agent that is essential for the allocation of setpoints to be carried out satisfactorily is the generation and demand control centers (DCGC). As explained above, the different service provider agents must be assigned to a DCGC so that it can supply them with the voltage setpoint that they will have to provide.

As explained above, the new voltage control service provides a new option for providing the service, which consists of providing the service jointly, or as defined in the service in PPS (4.1). This format establishes that the SO will provide the service setpoint at a point in the network chosen by the agents downstream of that PPS, provided that all the agents downstream of the PSS are assigned to the same CCGD. The main advantage of this new service provisioning format is that the agents can support each other according to their individual circumstances. For example, if they were providing the service individually, each agent would have to comply with its instructions regardless of the situation in which it finds itself, on the other hand, if several agents are providing the service jointly, it provides greater flexibility to the agents to provide the service, if by any chance the conditions of an agent prevent it from providing assistance to the tension control, the other agents could provide an extra to cover the deficiency caused by this first one and thus avoid incurring a penalty. The network structure that defines what a PPS is, is detailed in Figure 4-2.

Depending on the groupings formed to provide voltage control in a given area, the agents may be faced with different cases or forms of grouping, which largely determines their operating procedure for providing voltage control service. The different cases in which an agent may find itself are described below.

Firstly, the agent may find itself providing the service jointly or in PPS, as explained above. This case is considered the optimal one due to the flexibility and reliability it provides both to the system and to all the agents involved, although it is true that all the agents downstream of the PPS must accept this form of operation.

Secondly, the agents can provide the service individually, being individually connected to the grid by means of a transformer, in which case, the reactive setpoint required is on the high voltage side.

Finally, the agents can provide the service individually, being connected to the network through a transformer, but in this case, not individually, i.e., there are several agents connected to the low side of the same transformer. In this case, the setpoint required by the SO is on the low voltage side.

In relation to the establishment of service setpoints, there are certain aspects that must be specified to ensure the correct operation of the service, these aspects are described below.

First of all, it is necessary to specify the procedure to be carried out to establish the voltage setpoints for each agent. Part of P.O. 7.4 specifies that the setpoints for each agent or set of agents will be calculated starting from the PCR and distributing the voltage requirement among all the agents downstream of said PCR according to the sensitivity coefficients previously calculated for each of the agents involved. Such a procedure seems adequate a priori, but on its own it might be insufficient, so it should be combined with other procedures. For example, suppose that an agent is providing the service as described in case 3, where it is required a setpoint on the low voltage side since it shares a transformer with other generators. In this case there is no topological difference between one generator and another, so the sensitivity coefficients would be the same and there would be no a priori difference between the setpoints assigned to each agent. It is in these cases where an explanation of how and on what basis the voltage setpoints are to be assigned to each generator connected on the low voltage side to the same transformer is required. Since it does not specify the setpoint assignment in the specified case, two scenarios can be assumed. The first scenario, where the SO establishes a fair distribution of requirements according to the capacities of each agent, so that the setpoint required by the SO is provided equally by the agents connected to the transformer. The second scenario would be one where the SO assigns the same voltage setpoint for all the agents connected to the transformer, i.e. it does not make a correct distribution of the voltage requirements, in which case there would be reactive recirculations on the low side of the transformer, which could cause instabilities in the voltage profile, i.e. higher costs for the system. If this was the case, the new voltage control service would be considered highly inefficient.

The second aspect that requires further specification by the OS is related to both the modes of operation and the groupings of agents to provide the service. In the section defining the operation modes, the restriction is established that only when the agents meet the requirements to provide the service through the voltage setpoint mode, they will be able to perform the qualification tests for the other modes. However, it seems appropriate for the SO to place restrictions on the operation mode depending on the way of grouping to provide the service. It is considered that the agents that are providing the service in the same point of the network should do it under the same operation mode, since it is considered a significant and additional complication to the procedure the fact that each agent would operate under a different mode. The fact of calculating different setpoints for each agent providing the service at the same point implies a waste of time and an increase in the complexity of the process, added to the fact that the response times required by the SO are extremely small, it is considered that enabling this mode of operation is detrimental to the system. In response, it is proposed that all the agents that are providing the service at the same point in the network operate in the same mode.

5.3 *VOLTAGE CONTROL MARKET ZONES*

Voltage control zones can be defined as geographical segmentations of the system to delimit which agents will be able to provide the voltage control service in a specific area. As explained above, voltage is a local variable, which implies control by agents that are geographically close to each other. The definition of these geographical zones is a challenge for system operators given the complicated requirements that must be met to ensure the correct and efficient operation of voltage control. Some of the requirements for voltage control zones are defined below.

- Competitiveness: Each of the voltage zones associated with each zonal market must ensure competitive behaviour, through market mechanisms, when assigning voltage control bids. Therefore, the defined geographic zone must have the largest possible number of agents to favour competitiveness when it comes to bidding, giving correct market signals and thus ensuring market efficiency. Competitiveness is a matter of great concern given that, to date, voltage control was not a service provided by a large number of agents, hence, in many cases, the auxiliary service of voltage control has been subject to episodes of abuse of power.
- Technical restrictions: Although in general the most efficient way to use liberalized markets is for them to have the largest number of participants, in the case of voltage control services there are certain restrictions that prevent them from maintaining a very high number of participants. Another condition that must be met by the agents integrated in the voltage control zones is that they must be able to provide fast and efficient voltage control at any point in the zonal market in which they are integrated, as mentioned above, this ability to provide the service depends significantly on the distance the agent is located from the point of conflict in the voltage profile.

- Zone evolution: The design of voltage zones must take into account that the points of conflict in the voltage profile are not constant over time; on the contrary, they are very changeable and difficult to predict. Consequently, the zonal design has to be carried out not only taking into account the current state of the voltage profile, but also the possible evolution that this profile could undergo, given that predicting the behaviour of this profile is very complicated, the definition of the zones has to be carried out in the most general way possible.

Regarding the current status of the definition of the voltage control zones in the Spanish regulatory framework, there are certain comments issued by the system operator that are not extremely rigorous in relation to the current conditions of the system.

Firstly, the SO clearly indicates in P.O. 7.4 that the agent in charge of defining the voltage zones associated with the zonal markets are the network operators in question, network operators meaning distribution network operators. However, in the last webinar held to continue the consultation process on 7.4, the SO stated that they would have an important role in defining the voltage zones. Transparency is therefore required in the definition of this aspect, mainly as a consequence of the inconsistency between several comments issued by the SO. Leaving aside the fact that a clarification is needed regarding which system operator is going to be in charge of defining the electric zones and assuming that the one in charge of performing such task will finally be the distribution system operators (they are those mentioned for such task most of the times in the SO documents), it is not understood how it is going to be possible that each system operator is able to define an electric zone associated to a zonal market within its jurisdiction as a system operator. In Spain there are around 330 network distributors, according to the documents issued by the SO, each operator should define an electricity zone associated to a zonal market within its network jurisdiction, fulfilling all the necessary conditions mentioned at the beginning of the section for the implemented market to be efficient and competitive. The SO states that in the event that an electric zone does not have available more than twice the reactive power required for the voltage zone, the market mechanism will be discarded and the technical restrictions procedure used so far will be followed. On the basis that the Spanish SO wants to update its regulatory framework in line with the guidelines issued by the EU, which indicate that priority will be given to the use of market mechanisms, this decision taken by the SO is considered unfortunate given the following reasons:

- Firstly, establishing 330 reactive capacity markets in the Spanish region makes no sense, in addition to the fact that many of them would not meet the necessary conditions to operate as an efficient and competitive market, the cost incurred by the system would be disproportionate to the benefit obtained. Furthermore, as mentioned above, the key to defining the tension zones is based on achieving a balance between competitors and technical restrictions, such balance would not occur in most established zonal markets, and although in some cases it could occur, a higher degree of balance could be achieved with another distribution.
- Secondly, the dimensions of each of the 330 distribution network operators are completely different, which deeply favours an imbalance between the number of consumers and the fulfilment of technical requirements of each agent, when the jurisdiction of the network operator is small, there will be no technical problems, but there will be competitiveness problems, while if the voltage zone associated with the network operator is large, it is more likely that technical problems will flourish rather than competitiveness problems.

Regarding the definition of the person in charge of defining the associated voltage zones, it is recommended that the SO be the agent that performs this function, as is done in the UK. The SO in Spain is as such the agent that requires the voltage service, in addition, it has information of the system at a global level, which facilitates the function of defining the zones depending on service provider agents, technical restrictions or problems in the voltage profile. In this aspect, it is recommended the application of a model similar to the one used in the UK in which the SO defines the voltage zones independently of the distribution network managers.

The second point to be addressed is that the SO has stated that the voltage zones associated with the zonal markets will be dynamic and public. The fact that the tension zones will be public is considered necessary to comply with the transparency requirements demanded by the EU, and in this aspect, there is conformity with the chosen choice, on the other hand, the fact that the zones will be dynamic causes uncertainty on certain issues. Understanding the stated dynamism as the relatively frequent change of the geographic boundaries defining the zones of tension, it is required to define concretely how often the zones are intended to be changed and what the geographic scope (in short, displaced agents) will be. In the event that the specified dynamism would imply a continuous modification in the zonal markets, such action would be discouraged given the distortions in the markets that could be caused, in addition to the costs that the SO would incur to carry out such a change process. The same would be true if the number of agents removed/added from a market were significant.

Lastly, it is worth mentioning that as of July 2021 there is no signal or indication of the parameters to be used to define the voltage zones associated with the zonal markets, when the new voltage service is scheduled to come into operation in November 2021.

Chapter 6. CONCLUSIONS & FUTURE DEVELOPMENTS

As stated at the beginning of this thesis, voltage control is an auxiliary service of electrical systems that has followed a clear trend of stagnation during the last decades, but thanks to the recent development and evolution that electrical systems are experiencing, it has taken the relevance it deserves. The main trigger for this increased attention to the voltage profile is undoubtedly the increase of renewable energy penetration in power systems. This increase in renewable generation has created numerous episodes of instability in the voltage profile, which has undoubtedly forced the system to incur substantial costs, which ultimately have not brought any benefit to the system and are therefore a focus of attention for the SO. If we also add the fact that the regulation present so far has numerous shortcomings that cause the system to incur unnecessary costs once again, voltage control has become a problem of considerable importance. For example, in Spain the regulation regarding voltage control has been very lax since the old P.O. 7.4 was issued in 2000, and until the technical restrictions market was put into operation, no real requirements regarding voltage control were reflected. However, if the technical restrictions market has been defined by anything, it is the lack of competitiveness and abuses of power, which at the end of the day, means more cost overruns for the system.

Regarding the impact of renewable technologies on voltage control, as explained above, renewables are characterized by a significant dependence on primary energy sources with a highly variable and unpredictable production profile. Since the ability of renewable generation facilities to support the voltage profile depends significantly on their active power output, there is some complexity in maintaining a relatively constant reactive power output, that is why the main part analysed in this project has consisted of the strategies and technologies used to comply with the requirements that SOs request from system agents. In this aspect, it has been observed that both the technologies and the strategies used in voltage control vary significantly depending on the generation technology being analysed, which is expected to have an impact in the future, given that research to improve the performance of the different technologies when it comes to voltage control will be carried out in a decentralized manner. In this way, a certain imbalance could be created between technologies when providing the service, which should be taken into account in the regulation if the disadvantage of some technologies compared to others becomes relevant.

The second part of this project consists of an analysis of the current regulatory framework that includes all the requirements related to voltage control. In this part, special attention has been paid to the new P.O. 7.4 that REE is going to put into operation in November 2021. In addition, the regulatory frameworks of different countries have been evaluated in order to make a comparative analysis between the different regulatory standards, paying special attention to the voltage control service in the UK, due to the great degree of similarity with the Spanish one. After having carried out this analysis, the conclusions obtained from the Spanish regulatory framework are as follows.

Firstly, it is considered that the new service proposed by the SO is in line with some of the European guidelines, to establish new services through market mechanisms and of an innovative nature, in a fair way for the agents involved and always under efficiency standards. In many aspects the operational development of the new service is very specified and therefore there is no uncertainty about its procedure, however, there are other aspects that are not defined as they should be, several of these aspects are discussed in Chapter 5. The main shortcomings detected in the new voltage control are related to the definition of the electric zones associated to the zonal markets and the established remuneration model. On the other hand, there are other aspects of the service that are correctly specified, such as the minimum technical requirements, operation modalities, communication channels...

Regarding the regulatory framework established in the UK, it is considered that precisely the shortcomings found in P.O. 7.4 are correctly defined and specified, they have documents that define the electricity zones associated with the zonal markets, and they also have a remuneration model that covers the shortcomings of the Spanish model (discussed in Chapter 5.). On the other hand, the UK regulatory framework lacks specifications regarding many essential issues, such as the structure of the offers, communication channels, agents participating in the service...

From a general perspective, it has been determined that the optimal model to implement in the Spanish system would be a combination of both regulatory frameworks, which would basically consist of the correct definition of the electricity zones and the combination of the remuneration models used in both regulatory frameworks (explained in Chapter 5.). As for the rest of the aspects defined in both regulatory frameworks, it is recommended to use, for the most part, the regulation established in the Spanish framework, combining only the technical restrictions, being in some cases those issued in P.O. 7.4 somewhat more demanding than in the English framework.

Finally, we would like to contribute with some topics of interest that have emerged from the present project, so that future developments can be carried out to complete or continue with the work proposed in this thesis.

- Conduct a study at all levels (technical-economic) that provides sufficient knowledge and the right signals to define the electrical zones associated with the zonal markets.
- Study different ancillary services markets with greater development than the one used for the voltage service, in order to assess and modify the current remuneration models applied, which are very different from one another.
- Conduct a study to clarify the implications of the use of the different modalities proposed by the SO for the efficient provision of voltage control.
- Consider and analyse the operating conditions that occur in the nodes where several renewable facilities are connected (Modalities of service provision, allocation of slots).

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ANNEX

VOLTAGE CONTROL MARKET ZONES

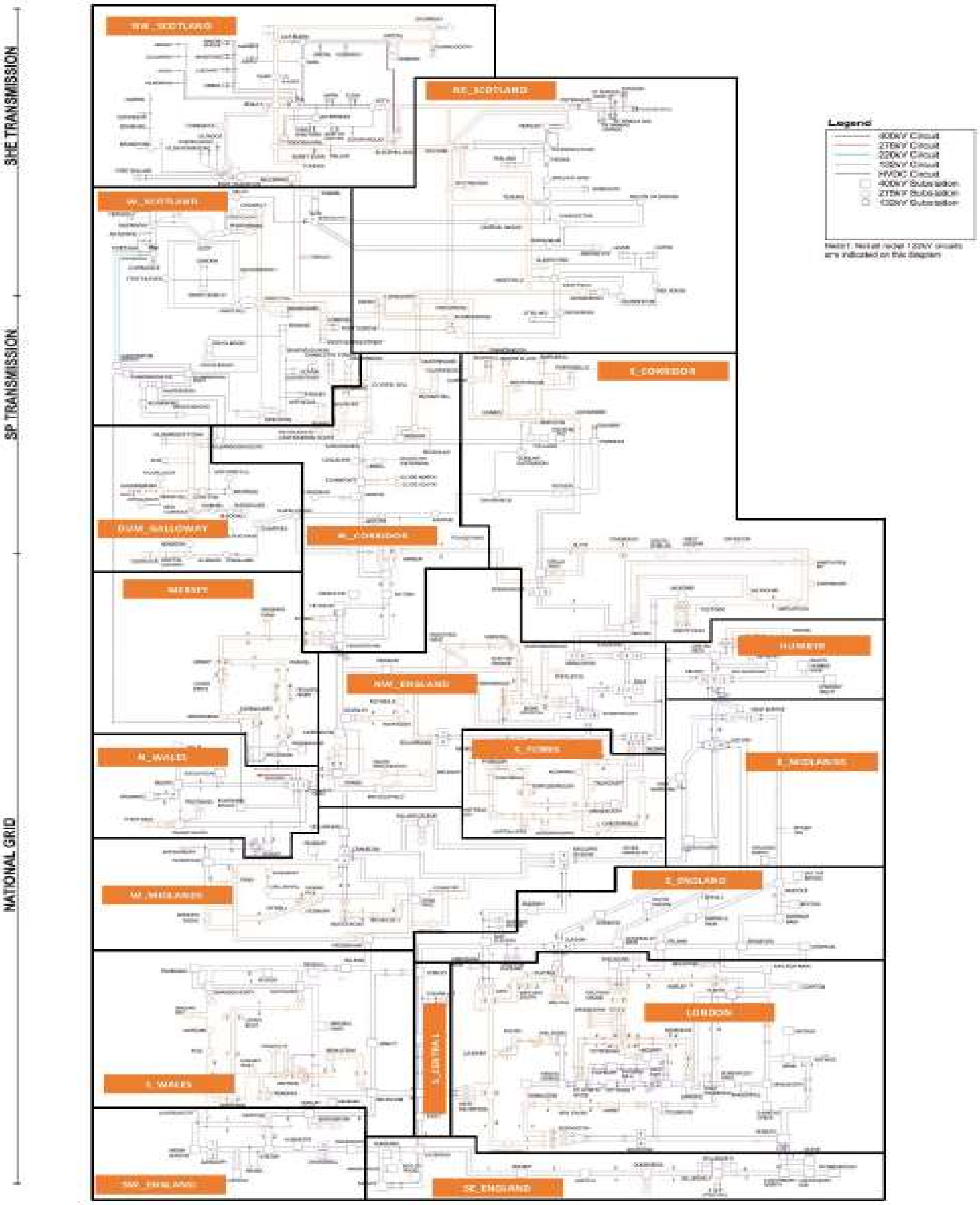

Figure 0-1: Voltage Zones Definition UK

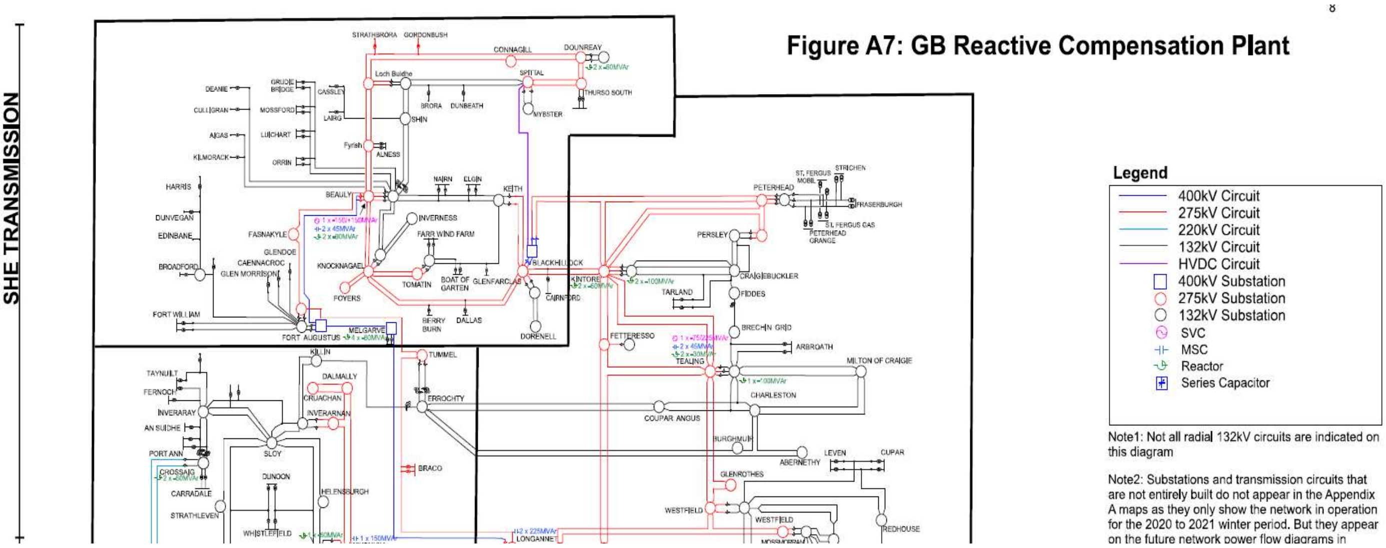

Figure 0-2: Voltage Zones Definition "She Transmission"

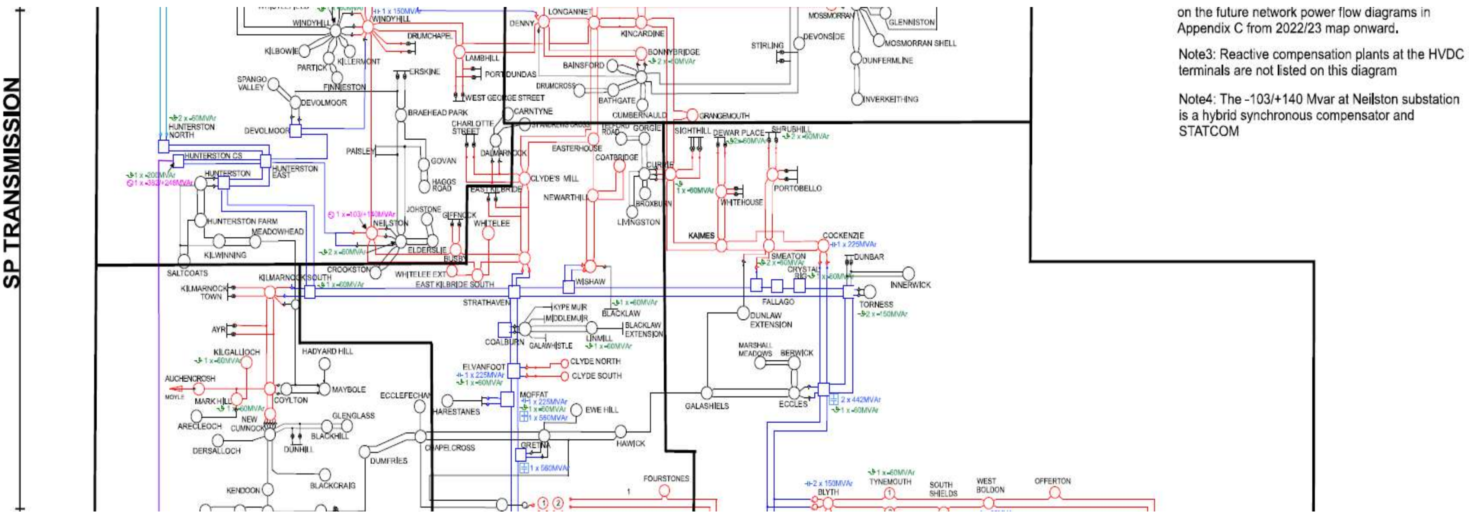

Figure 0-3: Voltage Zones Definition "Sp Transmission"

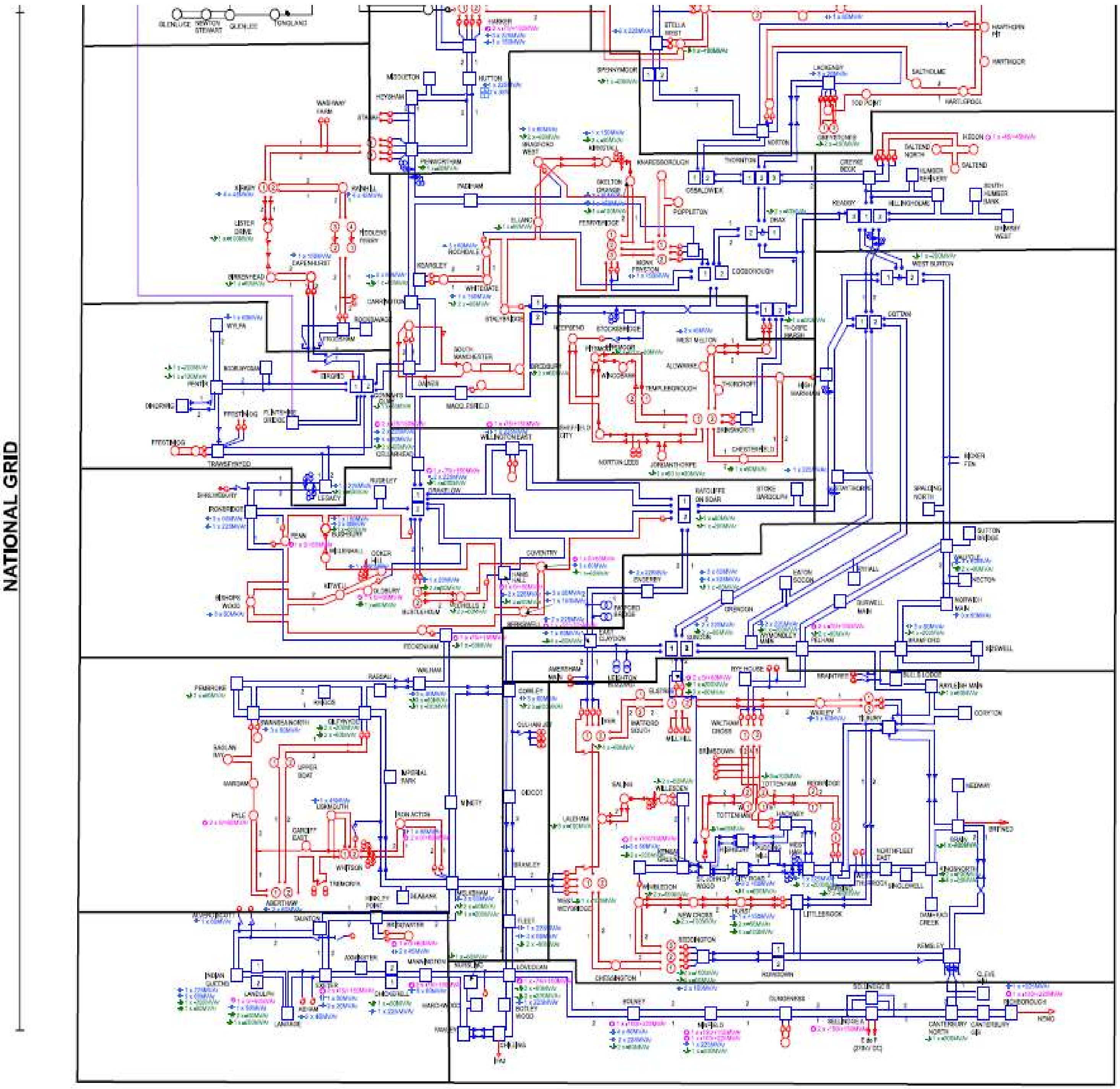

Figure 0-4: Voltage Zones Definition "National Grid"