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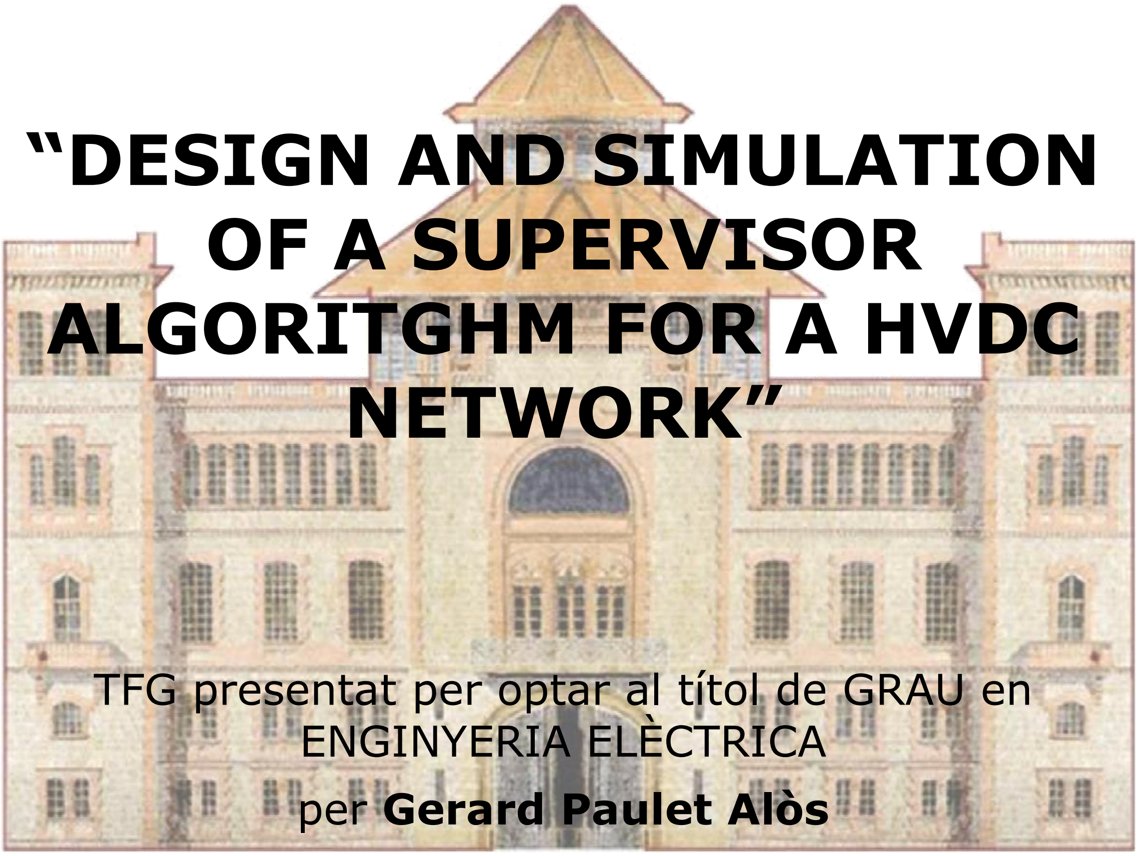
Project Report



"DESIGN AND SIMULATION OF A SUPERVISOR ALGORITGHM FOR A HVDC NETWORK"

TFG presentat per optar al títol de GRAU en ENGINYERIA ELÈCTRICA

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RESUM

Aquest projecte té com a objectiu la creació d'un algoritme que optimitzi els resultats d'una simulació del control d'una xarxa MTDC i convertir aquesta recreació en un procés automàtic. Una vegada aquest algoritme hagi estat implementat en el model de control i els resultats obtinguts s'hagin validat confirmant el correcte funcionament del mateix, el següent pas serà dur a terme varies simulacions per diferents topologies de xarxes i comparà els resultats obtinguts pels diferents casos, analitzant la resposta i el comportament de la xarxa davant de les diferents situacions d'explotació i els canvis desitjats.

RESUMEN

Este proyecto tiene como objetivo la creación de un algoritmo que optimice los resultados de una simulación del control de una red MTDC y convertir esta recreación en un proceso automático. Una vez este algoritmo haya estado implementado en el modelo de control y los resultados hayan sido validados confirmando el correcto funcionamiento del mismo, el siguiente paso será llevar a cabo varias simulaciones para diferentes topologías de red y comparar los resultados obtenidos para los diferentes casos, analizando la respuesta i el comportamiento de la red enfrente las diferentes situaciones de explotación i cambios deseados.

ABSTRACT

This project aims to create an algorithm in order to optimize the simulated results of a MTDC network control algorithm and turn this recreation in an automatic process. Once this algorithm is implemented in the control algorithm code and the results are validated which the optimizing control works, the next step of the project is doing simulations for different topologic MTDC network models and finally compare all the results, by studying and analysing the response as well as examine the progress of the network in front all the changing situations suggested.

CHAPTER 1: Introduction

1.1. Context and motivations

The standard of living of modern civilizations around the world, which the last few years has reached high levels of comfort, has increased the necessity of producing more electrical energy in order to keep this level at the same point nowadays. This is caused by the arrival of the technological systems, which makes the way of live easier for the society in exchange for electricity. To this necessity is added one new factor that gained strength in the recent years, the requirement of sustainability.

In the actual context, human civilization has the necessity to find new ways to produce electricity at a large-scale. The rudimentary methods with carbon and fuel central generation are not in a long-term sustainable technology. This is because these two primary material are limited, there are not renewable sources and the fear alarm of spending it all is starting to sound. According to this situation, the idea of producing electrical energy taking advantage of all the natural resources of energy the planet offers was born. The wind force, the solar radiation or the power of water are the most reliable examples of the ways that mankind can produce energy, taking advantage of these sources to avoid using finite and polluting materials. Nowadays, these methods represent an important part of the amount of electricity produced in most countries which promoted that instead of the traditional ways. Moreover, these technologies are still growing up and the modern society pretends to establish it as the unique way to get energy.

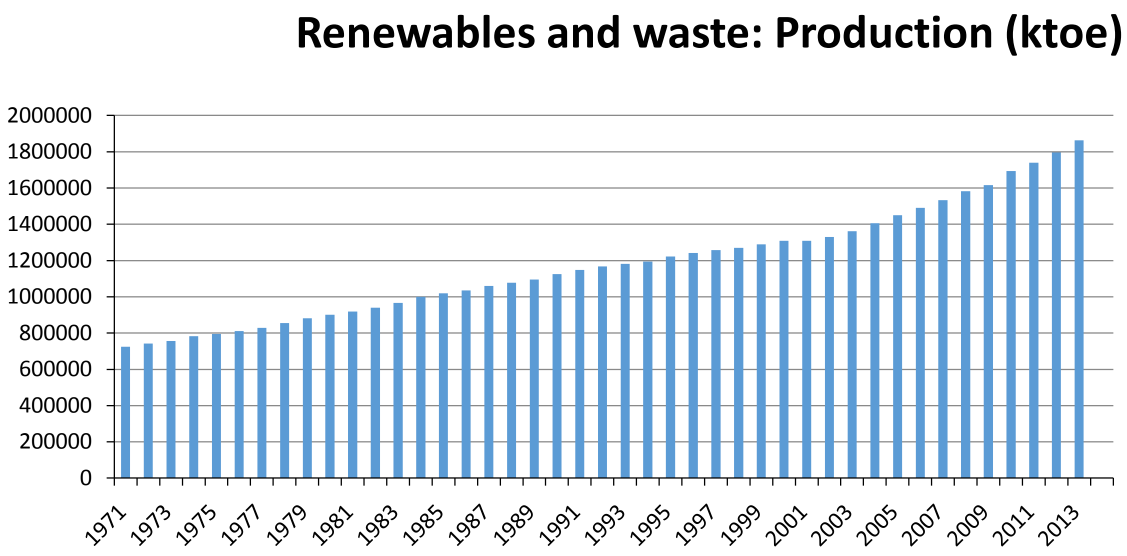

Figure 1.1: *Evolution of the world's energy production with renewables energies and waste expressed in kilotonne of oil equivalent in the last 42 years since 1971 (1 MWh = 0.086 toe). Source: IEA ©OECD/IEA 2015*

Probably, establishing the renewable energy systems as the only source of electricity in our planet is more a dream than a reality. The electrical system of any country needs to be stable and have a constant input of electrical energy all time the users demand it. To get these type of constant energy there is a need of constant material or sources both controlled by the producer. The only renewable technology, which is able to offer this possibility, is the hydroelectric. Around the world there are hydroelectric plants that can produce large amount of energy, but such structures would not be constructed anywhere because they have a special needs and make a big impact in the territory so the range of places being able to assume these constructions is reduced. Also taking into account that it depends on the emplacement, there is a necessity of different resources, in this case a huge quantity of water, and the power which would produce will not be that great if the hydroelectric plant is not constructed in a zone that would provide it with these quantity of water. Is for that reason that with the massive demand of energy of the population the electrical systems needs of other kind of technology process too.

However, it is known that the electrical demand is not constant. The system needs the technologies which can establish a constant flux of energy all the time but also needs at specific times, other sources of energy that would be able to produce electricity instantly to cover an increase of the energy request. This type of energy source is possible thanks to the renewable energies. These technologies can be installed in a vast extension of territory, making a similar function than other electrical plants, or in reduced spaces, in order to be such a complement. This possibility of the renewable energies of taking these two roles make them a huge weapon for the system and the new idea of it.

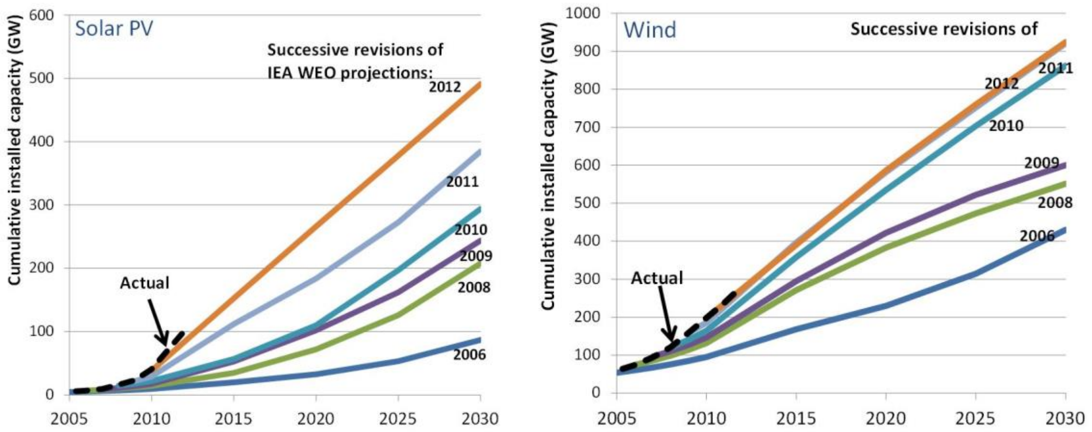

Figure 1.2: *The International Energy Agency has had to raise their forecasts of future solar and wind growth every year to keep up with current growth rates. Image from* http://rameznaam.com/

In recent years the idea of the Smart Cities has growth. This concept of the modern city prototypes involves the fact of renewable energies. The objective of Smart Cities is to create an electrical multi-terminal network whose generation and demand will be located in the same area, offering the consumers the possibility of producing their own energy. This strategy of energy production is only available using small installations of renewable energy around the expansion of the city, because the implantation of a big infrastructure near the people communities are not well seen. This model of city creates an electrical distribution and transmission network which can be extrapolated to a big scenario. The electrical interconnection between European countries will become a necessity if these prototypes of cities happen to be a reality in the continent.

One example of an interconnection between different countries by a multi-terminal network is the European Offshore Supergrid Proposal which intends to create a direct current network in order to interconnect various European countries and regions around Europe borders with a high-voltage direct current (HVDC) power grid. In the North Sea, some part of this project has already been built and has become an offshore multi-terminal with offshore wind generation, which is some kind of the idea that has been commented previously, in order to create an international network with the renewable energy for the implantation of the Smart Cities.

There are many HVDC power grid projects around the entire world. This DC networks allow to improve the efficiency of the electricity transport in better ways than the AC model networks at a certain length range. This technology would admitt of the construction of offshore wind farms. For countries like Sweden, Denmark, Germany or the United Kingdom the wind power has been the best way for start to close the rudimentary technologies and establish themselves as the example model for the rest of European states. The huge power installation of onshore and offshore wind farms in recent years is one of the causes of the growth on the importance of the renewable energy resources.

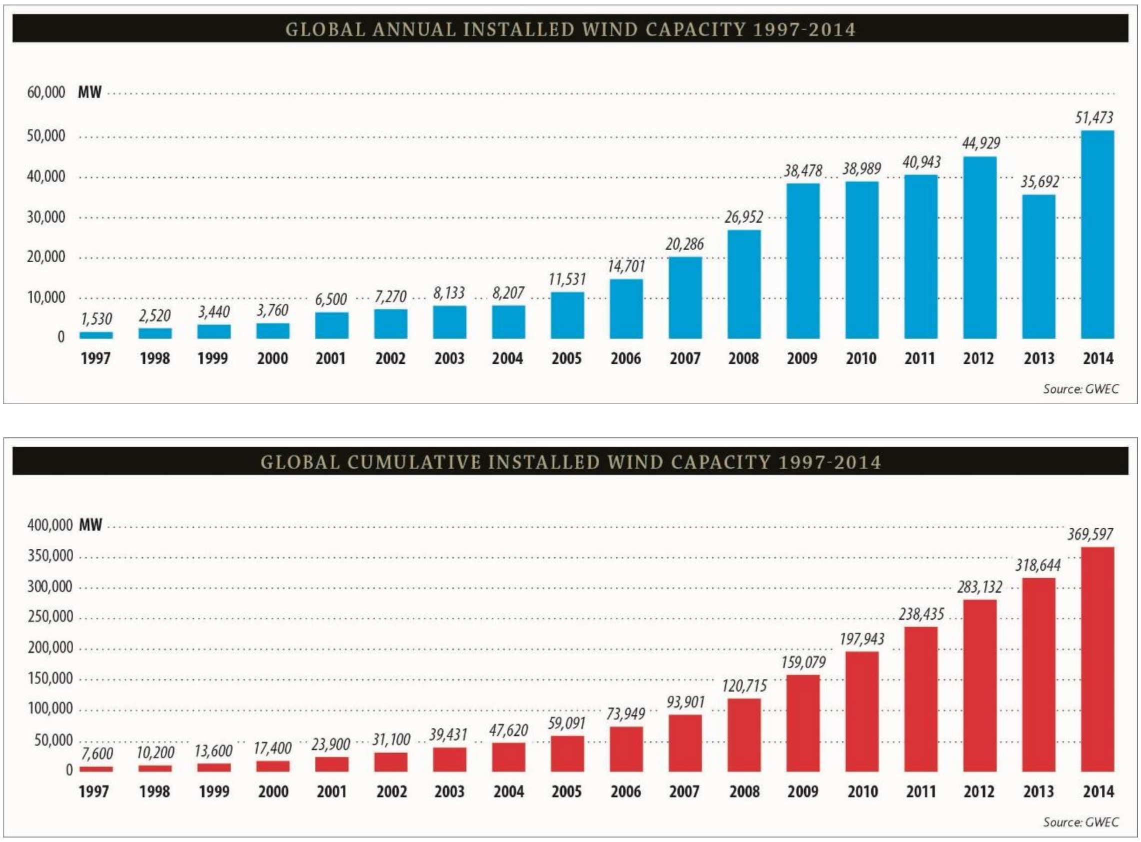

Figure 1.3: *Graphics of the global wind power installed per year since 1997 (blue) and the cumulative wind capacity of that installed wind power (red). Information from the Global Wind Energy Council.*

The steps of the more important governments established a route to the non-pollution politics. The preservation of the planet is one of the topics and concerns of the actual societies, and the growth of the renewable energies is a proof of it as well as the growth of the electrical and hybrid vehicle. The implantation of it would improve the expectancy of the small residential networks, which would be able to be controlled and performed on the best way.

1.2. Goals

There are multiple goals in the accomplishment of this document. On the one hand, practical and researching goals based on the wish of contributing, in the best of ways, in the creation of a MTDC network control algorithm, making any necessary changes and modifications so as to get the best results, going further with the making of an academic project, including a programing activity. On the other hand, educational goals based on the idea to improve my knowledge in the electrical field so as to be able to consider different ways to work which would lead me to reach an improvement in my programing formation in order to get a proper level.

CHAPTER 2: High Voltage Direct Current networks

2.1. Introduction to the High Voltage Direct Current Systems

The use of electricity as a way to transport energy started at the end of the 19th century. Since the outbreak of the industrial revolution energy turned out to be an essential asset. This need made people think about new methods to provide all the regions with it. At present time it is known the electricity takes a remarkable role in the established way of life. Nowadays the electricity as the basic and most accessible source of energy is implanted. The fundamental reason which contributes to the establishment of the electricity as the most used source of energy is the ease to transport it from one place to another. In addition to this facility, it has to be aggregated the high performance of the system, allowing to do the transfer of energy without significant loss. In this way, once discovered the advantages of the electricity, in the 1880's an epic dispute for the electrification of the United States of America which would mark the future of the transport and distribution traditional model was started. On this dispute, two of the greatest engineers and inventors of all time were involved. Thomas Alba Edison and Nikola Tesla were the two protagonists of this confrontation. Meanwhile one of them would defend the theory of distributing the electric energy in direct current was the best option, the other contradicted that idea urging the alternate current would be more efficient. The proponent of the use of direct current systems was Thomas Alba Edison, whose great success after the presentation of incandescent light bulb made him known worldwide therefore it was straightway adopted in Europe and North America. Edison would establish the direct current system because his company General Electric owned the patents. On the other hand, Nikola Tesla and George Westinghouse were the developers of the alternate current system which won the dispute. This was because the cost of the electricity transport with AC was less expensive. The cause of this is that the power losses in the transport defined in the Joule's law establish the current squared proportional to them. With the Tesla's and Westinghouse's system, which includes the transformer designed by Westinghouse, it was possible to decrease the value of current increasing the voltage just like determine the definition of electrical power ($P = V \cdot I$), thus obtaining a better efficiency because the less heat losses. This advantage of the AC systems tips the balance and temporally removed the DC transporting and distributing electrical systems.

After the imposition of the HVAC systems for the electricity transmission, it was not until the 1954 that a direct current system was used again for the transport of electricity. Once in the world large HVAC grids and long power lines were built, several problems on the operation of the AC grids were detected. The synchronism which must have all the connected assets in an AC system is a limitation. This limitation would be supplied with the implantation of HVDC systems. In the nineteenth century the obstacle of the direct current system was the unability to increase the voltage level in order to reduce the Joule's effect. This operation must be done with an AC system because it is the only way to make the Westinghouse power transformer work. Now, after the AC systems were implemented and it could be possible to increase the operating voltage transmission levels, the DC systems turned in a better option in certain situations. Therefore, it is possible to install HVDC systems operating with voltage levels previously modified by a HVAC system, mitigating the 1880's HVDC systems troubles. So as to make this interconnection possible, a power electronics converters had to be installed. These converters would transform the AC into DC and vice versa. Since the invention of these converters, the technologies for building them have evolved and now there are many power electronics systems and configurations to design the inverter and the rectifier of a HVDC-HVAC interconnection.

2.2. High Voltage Direct Current Technologies

The main purpose of the power converters is to make the transformation between AC and DC on both sides of the interconnection. In order to make these converions in the AC/DC interconnections different HVDC systems have been designed (Teixeira Pinto 2014) and (Frau and Gutiérrez 2005). The classical technology is the LCC (Line Commutated Converter). This technology is based on the use of devices such as diodes, thyristors or SCR (Silicon-

Controlled Rectifiers). The use of thyristors results in a converter made of semiconductor switching elements. As it is known, the semiconductor devices have the capacity of commuting depending on the polarization. If the thyristor is directly polarized, it would permit the pass of current. Although, if it is inversely polarized, the thyristor would become an open circuit blocking the current flow. As a consequence of this characteristics, the classical technology only permits the selection of the turned on control action if thyristors are used, it offers the possibility of control when they are directly polarized. The turned off control action will be uncontrolled and it would happen when the switching device become inversely polarized. This behaviour of the converter is responsible of the control limitations of the Line Commutated Converter. With this technology only the active power could be regulated. However, the reactive power of the system could not be controlled and would depend on the active power provided (Teixeira Pinto 2014) and (Frau and Gutiérrez 2005). The advantage presented by the Line Commutated Converter is that this technology has the inherent capability of preventing short-circuits in the DC side, as well as a lower power loss because of the semiconductor switching system. Nevertheless, owning to the electronic conversion type, this system injects harmonic currents in the AC network. These harmonics would have to be limited by the installing of harmonics filters, which makes the installation of the LCC more expensive. Moreover, it is indispensable the supply of reactive power and alternate voltage to the converter. These requirements make essential the robustness of the AC network where these devices are connected. It must have a high short-circuit power (Red Eléctrica Española (Bola Merino, D. Juan) 2012).

Alternatively to the Line Commutated Converter technology, the VSC (Voltage-Source Converters) system was invented. Thanks to the technology progress other type of semiconductor devices were discovered. Due to the implementation of this technology through devices like IGBT’s (Insulated-Gate Bipolar Transistor) or GTO’s (Gate Turn-Off thyristor), the independent control of both power magnitudes is possible (Teixeira Pinto 2014) and (Frau and Gutiérrez 2005). These devices are fully controllable switches by way of control signals, which leads to this control possibility. Thereby, now with this technology reaching almost sine waves is plausible, so the harmonic content of the injected into the alternating current side is lower, which reduces the harmonic overload in transformers and in some cases it makes AC filtering dispensable. Moreover, the independent control of the different powers permits the VSC technology to operate weaker grids which would have lower short-circuit power. Furthermore, this system is able to energize an electrical grid from a blackout or re-establish a weak scheme, which is so useful to provide remote places. Otherwise, this technology cannot prevent the DC system to a fault. In this case, the interconnection would have to be disconnected through the AC switches (Red Eléctrica Española (Bola Merino, D. Juan) 2012). In addition to this disadvantage the highly power loss compared with the LCC technology is added, due to the huge number of commutations made in a cycle (Van der Feltz 2016).

In spite of the last presented disadvantages of the VSC systems, they are located as the best option to implement the conversion process of an AC/DC interconnection in a Multi-terminal HVDC network (Teixeira Pinto 2014). This is because in VSC the voltage has fixed polarity. The change in the direction of power flow is done by the current which permits a better management of the grid through the voltage values, as well as the control of the power using this technology is complete (Teixeira Pinto 2014) and (Red Eléctrica Española (Bola Merino, D. Juan) 2012).

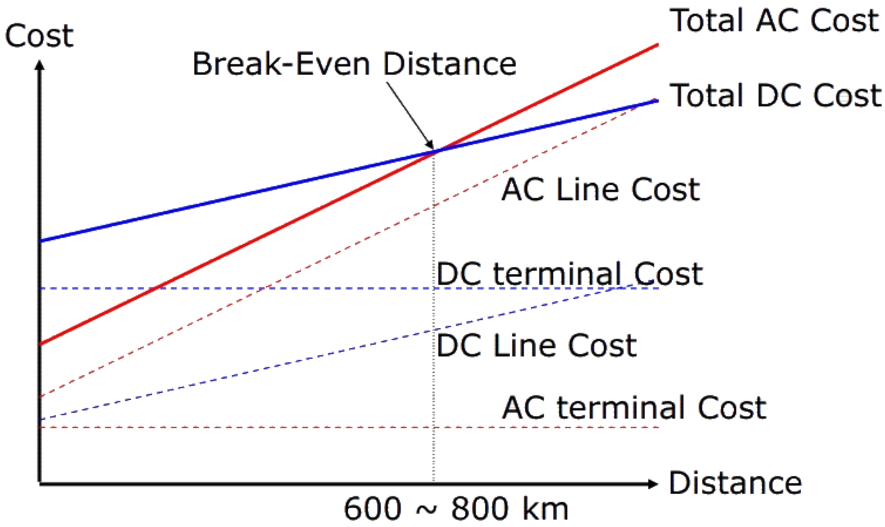

Figure 2.1: *Cost comparison between HVAC systems against HVDC based on the length of the installation. Image obtained from http://komhedos.com/hvdc-high-voltage-direct-current/*

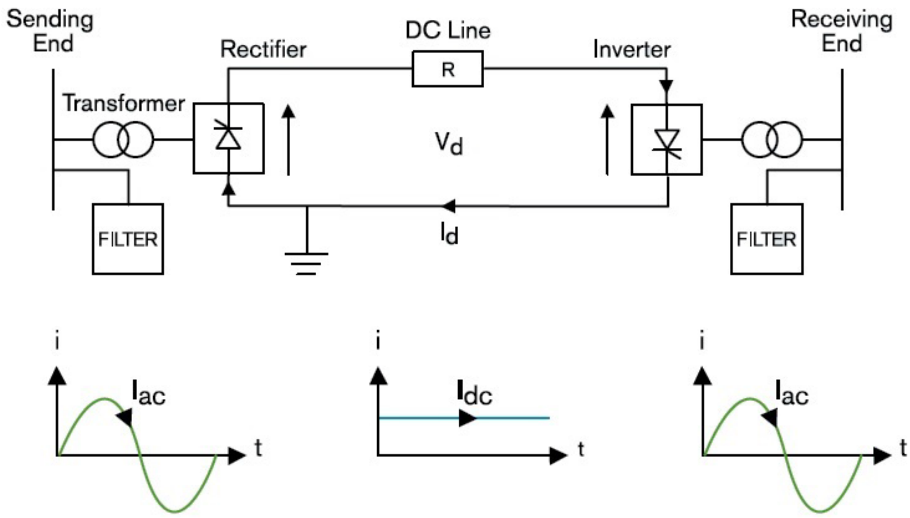

Figure 2.2: *Scheme of an interconnection between to HVAC systems through a HVDC system. Image obtained from (Van der Feltz 2016)*

2.3. High Voltage Direct Current Characteristics

Even though the AC in the start of the world's electrification surpassed the DC, the improvement of the recent technologies opened the door to the use of DC systems. With the new forms to generate electricity and the computerization of the majority of the process and devices, as well as the starting growth of the electrical vehicle the DC systems turned themselves into an essential mechanisms. Entering in an era where the distributed generation is starting to make a space for itself through the renewable generation systems, the MTDC networks as the future configuration of the transport and distribution grid is considered like an option. HVDC networks provides a range of possibilities thanks to its advantages in certain situations regarding to the HVAC systems that could ease the implementation of new ideas.

The use of Direct Current instead of Alternate Current offers better solutions for certain infrastructures. When Alternate Current is used for energy transmission it appears the named skin effect in the power lines. This fact means a rise of the power lines resistance, increasing the Joule's losses. The skin effect is basically the non-uniform current density along the surface of the wire. Seeing that the variation of the magnetic field on the epicentre of the wire is much higher, the inductive resistance there is higher too, supposing a lower current flow in the centre and a higher in the periphery. In addition the more frequency levels operates the grid the more evident would become this effect. The fact that the current density would not become homogeneous it will produce a decrease of the used surface, bringing about the increase of the wire resistance. This effect does not appear in the DC because it does not mean a variation of magnetic field. To generate a fixed magnetic field the impedance of the line is just resistive and remain constant. With a constant resistance the current flow happens uniform along the wire surface. As a result of it, the power losses in the DC transmission are lower than the obtained in an AC system. Furthermore, it is known that in AC cables there is a high electrical capacitance which makes the capacitive charging current become significant (Van der Feltz 2016). Added to the fact that in very long lines the current transmission capacity would decrease because the inductive effects, as well as the length of the line which would lead to a much higher resistivity than a shorter line, increasing the temperature of the wire. As a consequence of a wire temperature growth, the current capacity of the cable will drop, reducing the amount of real power that can be transmitted. This trouble is alleviated by the installation of electrical substations (Van der Feltz 2016). Finally, depending on the length of the power line, the inductance could produce a phase difference that would entail into a non-stability of the system. It is for these reasons that the HVAC systems are not a good fit for the offshore electrical transmission. The non-necessity of electrical substations, the non-effect of the inductance and the lower transmission power losses make the HVDC systems a much better option for electrical marine transport. Moreover, the cost of the HVDC systems would be less expensive if the system were sufficiently long. Although the necessity of installing the converter systems, which is the reason that the HVDC would be more expensive for a short length systems, the lower necessity of power lines and supports (being aerial lines) decrease the economic cost of the installation regarding the HVAC systems. It is because the transmission with DC is made with monophasic in front the three-phasic system used in the HVAC systems. This concludes into a necessity of only two cables regarding the three cables required in the AC systems. Consequently the electricity pylon of the AC systems are much bigger than the used in the DC systems, as well as the servitude zone of them (Frau and Gutiérrez 2005). This last advantage added at the previously commented makes the HVDC system a much better option to use in the building of point-to-point connections. Understanding point-to-point connection an infrastructure to interconnect a remote generating plant to the main grid without any intermediate power load (Teixeira Pinto 2014). This is what was used in the Nelson River DC Transmission System in Canada to transfer the electric power generated by the several hydroelectric power stations along the river to the populated areas in the south across the wilderness of the region. The infrastructure is configured in bipolar transmission. It means that it has two sets of high-voltage direct current transmission lines. The first has a total length of 895 km and a power rating transmission capacity of 1,620 MW. The second one has a total length of 937 km and a power rating transmission capacity of 1,800 MW. This HVDC system constructed to provide the city of Winnipeg is part of the Nelson River Hydroelectric Project recorded on the list of IEEE Milestones which represents key historical achievements in electrical and electronic engineering.

On the other hand, the HVDC systems could be used for other purposes. One of the most popular services given by the HVDC systems is the separation of HVAC system. It is known that in view of an HVAC system could be interconnected with another one is necessary that both of them would stay at the same frequency and the same phase. Without such conditions the interconnection is impossible to make. Thereby, the installation of an HVDC system between them would make this interconnection possible despite not having the proper conditions. This is because in the DC interconnection the frequency and the phase of any AC system would not take any impact. The frequency and the phase of both systems will be defined in the AC side by the power inverter and could be different. This characterise is why HVDC systems are used for interconnect HVAC grids in order to prevent that an unstable situation in one of the HVAC networks would affect in the operation of the other. This is why an interconnection between France and Spain was built. This infrastructure has doubled the electricity exchange capacity between France and Spain, resulting in greater security and stability in the two electrical systems. These facts are because the implementation of an HVDC system contribute to the betterment of the grids stability. The stabilization of the connected network is possible because of the independence in the control of the energy delivery and the power load. Thanks to the active and reactive power as well as the possibility of control both sides voltage levels, make the HVDC systems a great option for interconnect different electrical markets. Also, these type of systems increase the energy exchange capability between two systems, improving the electric power transmission capacity of the power lines as consequence of the non-affectation of the inductive effects.

Finally, HVDC infrastructures offers one last advantage related to the new generation era. The implementation of the renewable energies in the system is a fact that could be well executed with DC systems. As it is known, depending on the renewable production system the energy would be produced in different ways. Furthermore viewing the location of the device or installation, the use of HVAC systems is not feasible, for example in the case of offshore generation previously commented. In this way, HVDC systems could benefit the implantation of renewable generation. The distributed generation as the new model of energy productions may be interconnected with DC systems. This would provide the interconnection of the different points with a major stability system as well as in the case of certain renewable generation systems such the solar photovoltaic would not be necessary the immediately transformation to AC. In other cases such the offshore generation, the better fit undersea of the HVDC systems in front of the HVAC offer the opportunity of increment these type of activity. Actually there seems to be a general agreement on the evolution to the Smart Grid prototype. These ideal includes the Smart City concept where the distribution generation and the implementation of the electrical vehicle are the key of its success. This turns the city into a multi terminal network inside another multi terminal network. Anyway, the different multi terminal networks would have to be controlled and HVDC systems are a good option for doing it, keeping in mind that most of the distributed generation may be photovoltaic generation in DC.

2.4. Multi Terminal Direct Current networks

Once the advantages and the characteristics of the HVDC systems are presented, the configuration of the grids using this technology could be different and may offer different advantages. An MTDC transmission system consists of a number of generating energy points, usually renewable energy stations such as offshore wind farms, which are connected to a main AC power grid through a meshed DC grid, and with VSC converters transforming the DC electrical power into an AC waveform, or vice-versa. Previously, the Nelson River DC Transmission System was presented as a Point-to-Point infrastructure. This construction was made to transport the energy generated from a remote place in Canada to the south of the country. This was implemented in DC due to the long length characteristics offered by the HVDC system. The concept of remote generation in Canada is the same as what happens in the North Sea of Europe. The remote generation and the fact that it is offshore make the DC system much better option. The question is how better it is to implement this infrastructure keeping in mind the huge project planned. Thinking about the amount of wind generators that might be constructed in different locations of the sea, seems not feasible to implement a Point-to-Point connection between the Grid Side Converters situated in the civilization. The Point-to-Point infrastructure works in Canada owning to between the generation in the Nelson River and Winnipeg there is not any power load. Otherwise, in the North Sea and the European zone beside it would be possible to implement a Multi Terminal Network. As previously mentioned, a Multi Terminal infrastructure would stimulate and progress the connection of renewable sources into the main grid. It is known that the generation of the renewable sources is variable and the recognition of the exact amount of energy which would be generated is nearly impossible. However, this complication could be solved with the construction of a Multi Terminal Grid which connects all the renewable generating points. As a consequence of the interconnection of all of them, a system which could cover the deficiency of energy generated in some places by some renewable sources with the energy generated by other technology in that moment would be established. This infrastructure will make the renewable energies become much more reliable sources through the stability offered by the DC system (Van der Feltz 2016). With this ideal, returning to the North Sea example, the implementation of a MTDC grid there could offer all these advantages. Firstly, the construction of the system would become less expensive thanks to the unnecessity to implement a couple of converters for each Point-to-Point interconnection. Furthermore, the demand of certain regions would be covered by all the generation of the place and not for a part of it as would be happened in a Point-to-Point infrastructure. Without a multi terminal grid, there may occur a blackout due to the impossibility of cover the fault of generation. With a multi connection system it would be possible to cover the decrease of generation of one zone with the other generation points. Finally, the AC systems of the different countries connected to the multi terminal grid would become more stable thanks to be provided by the DC network.

Moreover, it would be a good idea to extrapolate this concept emerged for big infrastructures to smaller markets with lower voltage levels. It would be the case of a city or a not very vast extended territory. The multi terminal concept could be used anywhere where a generation and a demanding of energy occurs at same time. However, the realization of an MTDC network requires of a much more sophisticated and exhaustive control system than a Point-to-Point installation. Depending on the number of nodes connected to the main grid the difficulty of running it in a correctly working mode in order to cover the demand increases considerably. For this reason the best method to establish a great control on the grid is implementing it with VSC converters, due to they offer a better control of the power and the voltage levels of each node.

CHAPTER 3: Model and control of MTDC networks

The operation and control of a multi terminal direct current transmission system consists of the configuration of three control levels. Firstly, a supervisor algorithm which will set the voltages required for all the converters connected to the grid. This supervisor would be called Secondary Control. Secondly, after the definition of the desired voltage levels, a mid-level voltage control scheme that regulates the voltages of each VSC capacitor, which would be defined as the Primary Control. Finally, a lower-level current controller providing the switching policy to inject or extract the required current (Dòria-Cerezo, Olm and Scherpen 2015).

In this way, this review outlines the creation of a secondary control in order to optimize the power flow in a MTDC network model with a control algorithm already implemented. In the next script it is going to be described the entire mathematical model used for the configuration of the simulated network prototype. Also, the bases of the optimal power flow algorithm system and the concept of the working point area would be presented. Thereby, this research will try to adjust the performance of a controlled MTDC grid to the optimal operation whenever would be possible. Furthermore, the MTDC higher-level supervision relies on calculating the equilibria of the network. This task requires a communication system that constantly updates the state of each VSC controller. This feedback would try to be implemented in the simulations making a changing model that recreates the new state communication of the grid.

3.1. Mathematical Model of a Multi Terminal Direct Current network

To be able to recreate the performance of an MTDC and the control of that an approximated model of it is needed. In order to approach accurately the model into a real MTDC system, it is important to take into account the principles of electronics. In this way, both nodes and power lines will have to be defined with a schematic electrical representation. Keeping in mind that an MTDC grid could be seen as a certain quantity of generation nodes connected to some HVAC systems through power lines and VSC converters, it is possible to modulate the nodes of the grid such as a VSC converter and (Dòria-Cerezo, Olm and di Bernardo, et al. 2016). Meanwhile, the power lines would be configured as a typical structure of an electrical transmission line.

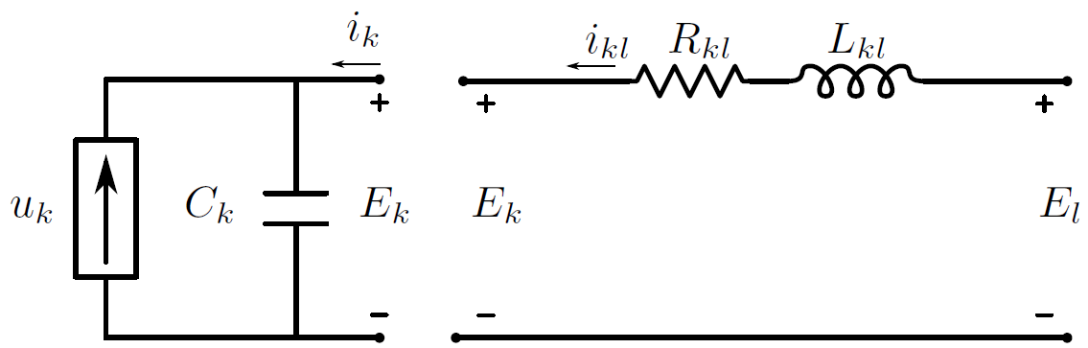

Figure 3.1: *Electric schematic of the MTDC nodes (left) and the transmission lines (right). Image from (Dòria-Cerezo, Olm and Scherpen 2015)*

Thereby, the VSC converter and the transmission lines could be configured as it is presented in the Figure 3.1. The nodes of the grid would be considered like a current source in parallel with a capacitor meanwhile the power lines might be represented as a resistance connected in series with an inductance. Once determined it, a signs agreement is needed. As a rule, the node which will be injecting current to the MTDC grid would have a positive sign. Otherwise, if the node were demanding power the sing would be negative.

The dynamics of both VSCs and DC transmission lines are obtained from Kirchhoff Currents Law and Kirchhoff Voltages Law as presented in (Dòria-Cerezo, Olm and Scherpen 2015), (Dòria-Cerezo, Olm and di Bernardo, et al. 2016) and (Pons Perelló 2015). In this way, the dynamics of each Grid Side Converter responds to

$$C_k = \frac{dE_k}{dt} = u_k(E_k) + i_k \qquad (3.\ 1)$$

Where E_k is the voltage across the capacitor C_k, and $u_k(E_k)$ is the current injected (or consumed) by the power converter. The incoming current i_k into the capacitor can be described as the sum of all the currents flowing into the node k from the interconnected nodes with it

$$i_k = \sum_{l=1}^{n} b_{kl} \cdot i_{kl} \tag{3. 2}$$

Where i_{kl} is the current flowing from node l to node k. b_{kl} is the position of the B matrix which indicates the connections of the network between nodes. If the node k is connected with the node $b_{kl} = 1$, if not $b_{kl} = 0$. Finally N is the number of nodes of the grid.

Now applying Kirchhoff Voltages Law in the transmission power line model, the dynamics of a transmission line connecting nodes k and l is given by

$$E_l = E_k + R_{kl} \cdot i_{kl} + L_{kl} \cdot \frac{di_{kl}}{dt} \tag{3. 3}$$

Where R_{kl} and L_{kl} are the resistance and inductance of each line, respectively. Notice that $i_{kl} = -i_{lk}$

Letting $d \in \mathbb{N}$ stand for the total number of transmission lines, it is defined the line currents vector

$$i = i_{kl} \in \mathbb{R}^d \tag{3. 4}$$

Where $k, l = 1, \dots, n$ with $k < l$, if $b_{kl} \neq 0$, as the line currents vector. Then, the VSC dynamics can be written in a matrix form as

$$\boldsymbol{C} \cdot \frac{dE}{dt} = -\boldsymbol{B} \cdot i + u(E) \tag{3. 5}$$

Where $E = (E_i) \in \mathbb{R}^n$, the voltages in the nodes. $u = (u_i) \in \mathbb{R}^n$, the control variable in each node for the current consumed or injected to the network by the VSC converter. $C = diag(C_i) \in \mathbb{R}^{nxn}$, a diagonal matrix with the capacitance values in the VSC in Farads and $B = (B_{kj}) \in \mathbb{R}^{nxd}$ as the incidence matrix, where

$$B_{kj} = \begin{cases} 1 \; if \; line \; j \; connects \; from \; line \; k \\ -1 \; if \; line \; j \; connects \; to \; line \; k \\ 0 \; if \; the \; lines \; are \; not \; connected \end{cases} \tag{3. 6}$$

In a similar way the dynamics of the transmission lines could be presented in matrix form as well as the VSC dynamics. Defining the $\mathbb{R}^{dxd}$ inductance and resistance matrices $L = diag(L_{kl})$, $R = diag(R_{kl})$, respectively, a matrix description of the overall transmission lines dynamics is:

$$L \frac{di}{dt} = -\boldsymbol{R} \cdot i + \boldsymbol{B}^T \cdot E \tag{3. 7}$$

Therefore, the MTDC general dynamics could be written as

$$\frac{d}{dt}\begin{pmatrix} E \\ i \end{pmatrix} = \begin{pmatrix} \mathbb{O}_n & -\boldsymbol{C}^{-1} \cdot \boldsymbol{B} \\ \boldsymbol{L}^{-1} \cdot \boldsymbol{B}^T & -\boldsymbol{L}^{-1} \cdot \boldsymbol{R} \end{pmatrix} \cdot \begin{pmatrix} E \\ i \end{pmatrix} + \begin{pmatrix} \boldsymbol{C}^{-1} \\ \mathbb{O}_{dxn} \end{pmatrix} \cdot u \tag{3. 8}$$

With $\mathbb{O}_n$ and $\mathbb{O}_{dxn}$ denoting $n \; x \; n$ and $d \; x \; n$ null matrices, respectively.

Thereby, the change of voltages and currents in a MTDC transmission system could be described by the presented mathematical model. The state variables are the voltages and currents and the input u is the current injected or consumed in the Grid Side Controller. The dynamics are dependent on the inductance and resistance in the lines, the capacitance in the nodes and the topology of the network.

3.2. Control for a Multi Terminal Direct Current network

As it was defined in the system description introduction, the control system proposed consists of a multiple hierarchical control algorithms. In the Figure 3.2 it is possible to view the distribution of the different control mechanisms previously commented.

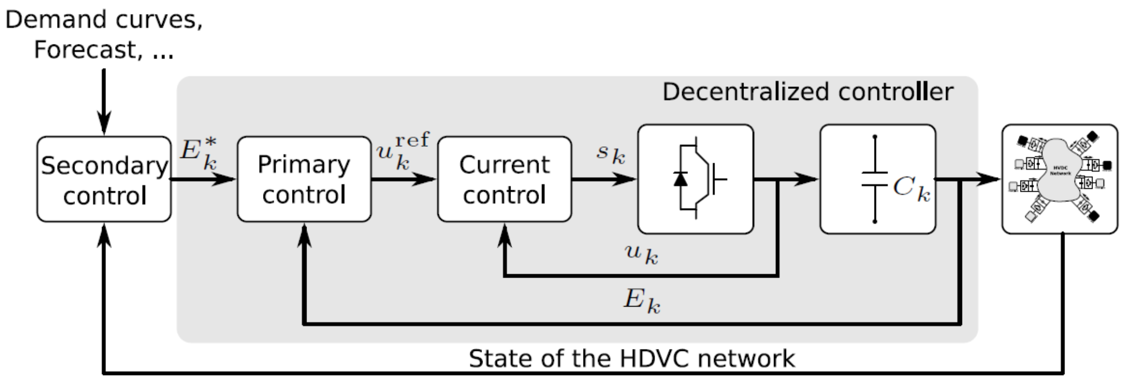

Figure 3.2: *Hierarchical configuration of a MTDC control system. Image from (Dòria-Cerezo, Olm and Scherpen 2015)*

The main purpose of this research is to create a Secondary Control which provides the Primary control already implemented in the model with the grid voltage configuration in order to stablish the optimal power flow. The primary control regulates the voltages in each node using decentralized control laws. This control level needs to independently control the system and ensure that it remains stable even without communication. The reason the primary control manages the power fluctuation through the voltage levels is because in DC grids the current can only flow if a voltage difference between two nodes is stablished. In AC systems this control is based on the management of the frequency of the current magnitude, which is not a variable in the DC systems. In this way, the Primary control would govern the current flow determining the voltage level of each node (Egea-Alvarez, et al. 2010). Notwithstanding, the Primary control needs a reference of which voltage configuration could cover the power necessities of the grid. This control would try to establish the voltage references input that it would have at the beginning of the control activity. However, the voltage configuration informed to the primary control should be one that ensures the equilibrium of the grid. In a specific scenario more than one possible voltage configuration may be valid. Although, only one would entail the minimum power losses in the transmission of the energy to the converters. Due to these two determinant factors, hence a Secondary control has to be implemented. With the implementation of the Secondary control, the Primary control would be provided of its necessary voltage references as well as these references will ensure the stability of the network and its optimal performance. This is because the Secondary control would analyse the situation of the grid through a feedback. Once the information of the grid is given, the Secondary control would determine which would be the best operating point for each node, basing this study in the compliance of maximum and minimum boundaries for each node magnitude and the minimization of the transmission power losses of the grid during the power fluctuation. After defining all the working points of all nodes, it will communicate its selection to the primary control to adjust the management of the grid to the determined parameters.

CHAPTER 4:

Optimal Power Flow

4.1. Non linear optimization

In mathematics, statistics, computational science or economy mathematical optimization is the selection of a best element with regard to some criteria from some set of available alternatives. In the simplest case, an optimization problem consists of maximizing or minimizing a real function by systematically choosing input values from within an allowed set and computing the value of the function. Thereby, the mathematical optimization is used to maximize the efficiency of a system either to maximize the performance of a process or minimize the consequence of a counter-productive effect. Depending on the purpose and the type of function that determines the behaviour of the system to optimize the problem would differ. This is because it would not be equal the methodology of maximize the total value of a certain process than minimize it, as well as that would not be the same if the function is convex or is concave. These named examples are the base of what is called Convex programming or Convex optimization. This subfield of optimization can be viewed as a particular case of nonlinear programming or as generalization of linear or convex quadratic programming. The nonlinear programming is the process of solving an optimization problem defined by a system of equalities and inequalities, collectively termed constraints, over a set of unknown real variables, along with an objective function to be maximized or minimized, where some of the constraints or the objective function are nonlinear. For the resolution of optimizing problems defined by a system of inequalities as the one which would have to be implemented for the optimization of the MTDC grid (Jiménez Carrizosa, et al. 2015), it would have to been satisfied the KKT conditions. The compliance of the KKT conditions ensure the resolution of a problem to obtain the optimal result (Paredes Hernández 2007).

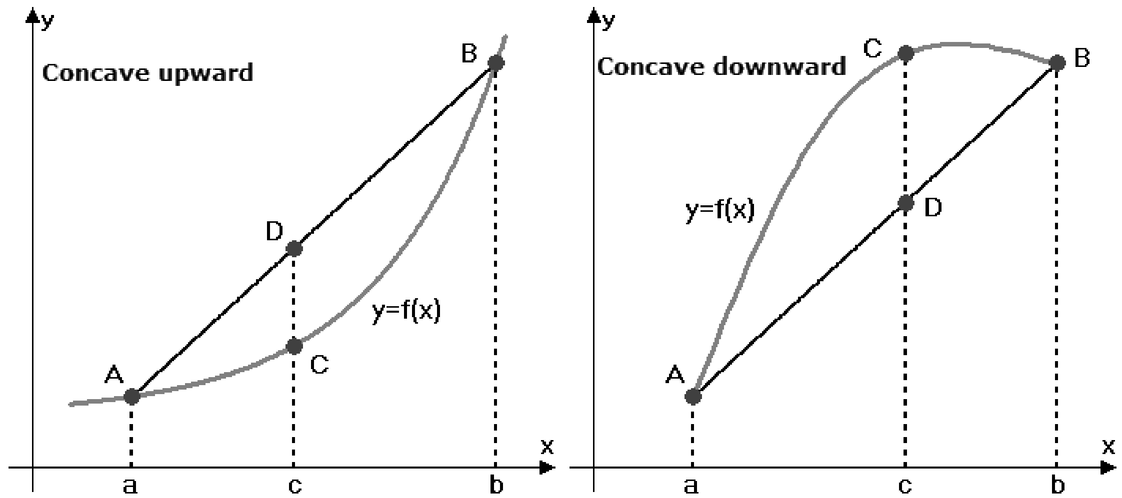

Figure 4.1: *Example of a convex function (left) and a concave function (right). Image from* *http://www.emathhelp.net/*

In this way, the KKT approach to nonlinear programming being an extension of the Lagrange multipliers method. The Lagrange multipliers method permits to encounter the maximum or the minimum values of functions with multiple variables subjected to an equally constraint.

Therefore, considering a problem such

$$\min f(x)$$
$$h_i(x) = 0; i = 1, \dots, l \qquad (4.\ 1)$$

Where $f(x)$ is the objective function and $h_i(x)$ are the l equality constraints the function is subjected to.

According to the Lagrange multipliers method, being $f : \mathbb{R}^n \to \mathbb{R}$ and $h_i(x) = 0; i = 1, \dots, l$, if the restrictions are completely satisfied the objective function would be defined as

$$\min f(x, \lambda) = f(x) + \sum_{i=1}^{l} \lambda_i \cdot h_i(x) \qquad (4.\ 2)$$

Where $\lambda_i(x)$ is the Lagrangian multiplier.

The minimum of $f(x)$ could be determined by finding the stable points. These stable points can be found resolving the $\nabla_x f(x) = 0$, which would determine the roots of the gradient of the function. This would establish the first optimality condition

$$\nabla_x \mathcal{L}(x, \lambda) = \nabla_x f(x) + \sum_{i=1}^{l} \lambda_i \cdot \nabla_x h_i(x) = 0 \qquad (4.\ 3)$$

Moreover, in order to imply $h_i(x) = 0$ it has to be solved the $\nabla_x f(x) = 0$ too. By forcing the derivatives of the equality functions to zero, the solutions are limited to a set where the constraints are satisfied.

$$\nabla_\lambda \boldsymbol{\mathcal{L}}(x,\lambda) = \sum_{i=1}^{l} \nabla_\lambda \lambda_i \cdot h_i(x) = \sum_{i=1}^{l} h_i(x) = 0 \tag{4. 4}$$

In this way, the method of Lagrange multipliers is defined as the compliance of

$$\nabla_{x,\lambda} \boldsymbol{\mathcal{L}}(x,\lambda) = 0 \tag{4. 5}$$

To summarize

$$\nabla_{x,\lambda} \boldsymbol{\mathcal{L}}(x,\lambda) = 0 \Leftrightarrow \begin{cases} \nabla_x \boldsymbol{\mathcal{L}}(x,\lambda) = -\sum_{i=1}^{l} \lambda_i \cdot \nabla_x h_i(x) \\ \sum_{i=1}^{l} h_i(x) = 0 \end{cases} \tag{4. 6}$$

However, if the objective function is subjected to some inequality constraints, the Lagrange multipliers method could not solve it. So as to be able to find an optimal point in these type of problems, the Karush–Kuhn–Tucker (KKT) conditions, which are a generalize of the Lagrange multipliers, have to be used. Therefore, as described in (Paredes Hernández 2007) and considering a problem such

$$\begin{gathered} \min f(x) \\ h_i(x) = 0; i = 1, \dots, l \\ g_j(x) \leq 0; j = 1, \dots, m \end{gathered} \tag{4. 7}$$

Where $f(x)$ is the objective function, $h_j(x)$ are the equality constraints and $g_i(x)$ are the inequality constraints, with l and m the number of equalities and inequalities restrictions, respectively.

Supposing that the objective function and the constraint functions $f, h_i, g_j : \mathbb{R}^n \to \mathbb{R}$. Being continuously differentiable at a point x^*, it will be possible to affirm that $x^*$is an optimal point if and only if $\exists\ \lambda_i (i = 1 \dots m) \in \mathbb{R}$ and $\mu_j (j = 1 \dots m) \in \mathbb{R}$, called KKT multipliers, such that the following requirements would be accomplished

Stationarity condition

$$\nabla_x \boldsymbol{\mathcal{L}}(x,\mu,\lambda) = \nabla_x f(x^*) + \sum_{i=1}^{l} \lambda_i \cdot \nabla_x h_i(x^*) + \sum_{j=1}^{m} \mu_j \cdot \nabla_x g_j(x^*) \tag{4. 8}$$

Primal feasibility

$$h_i(x^*) = 0; for\ all\ i = 1, \dots, l \tag{4. 9}$$

$$g_j(x^*) \leq 0; for\ all\ j = 1, \dots, m \tag{4. 10}$$

Complementary slackness

$$\mu_j \cdot g_j(x^*) = 0; for\ all\ j = 1, \dots, m \tag{4. 11}$$

Dual feasibility

$$if\ CKKTMin\ \Leftrightarrow\ \mu_j\ \geq 0 \quad with \quad j = 1, \dots, m \min f(x) \tag{4. 12}$$

Or

$$if\ CKKTMax\ \Leftrightarrow\ \mu_j\ \leq 0 \quad with \quad j = 1, \dots, m \tag{4. 13}$$

From the Complementary slackness it is deduced that if the inequality restriction is no active in the solution point, the Karush-Kuhn-Tucker multiplier would be equal to 0. The points x* $\in \mathbb{R}^n \cap \Omega$, being Ω the feasible set of the problem which compliance the stationary conditions, are the named critic points or stationary points (Paredes Hernández 2007). To conclude, the KKT points could be found solving the mathematical system compound by the stationarity condition, the equality primal feasibility condition and the complementary slackness condition or taking the derivative of the objective function with respect to the decision variables, x; λ; μ.

At last, if the system to be optimized presents an objective function or any constraint which establishes it as a non-linear system, there would be another condition to be accomplished in order to find an optimal solution (Paredes Hernández 2007). According with the Newton's method

$$\boldsymbol{\mathcal{H}\mathcal{L}}(x, \mu, \lambda) = \boldsymbol{\mathcal{H}}\, f(x^*) + \sum_{i=1}^{l} \lambda_i \cdot \boldsymbol{\mathcal{H}} h_i(x^*) + \sum_{j=1}^{m} \mu_j \cdot \boldsymbol{\mathcal{H}} g_j(x^*) \tag{4. 14}$$

Therefore, if the system contains any equation whose inclusion makes it does not satisfy the superposition principle, which will mean that the output is not directly proportional to the input, the optimal solution would compliance the named second-order conditions.

Because the objective function of the MTDC optimization makes the system nonlinear, the optimizing process would have to accomplish the Hessian condition too. So, to be able to solve the optimization problem would be necessary the use of nonlinear algorithms or convex optimization algorithms (Aragüés-Peñalba, et al. 2012).

4.2. Working Area and Optimal Power Flow

So as to keep the system stabilized there it is necessary to operate the nodes into their individual determined maximum and minimum limitations. These limitations would be firstly determined as the nominal values. These nominal values would indicate the boundaries which each node normally operates. Along the simulation and with the proposed changes the definition of these boundaries would determine the new demands and constraints of the grid as well as the new working points policy which means that is the supposed feedback provided to the Secondary control would vary these limitations in order to change the operation of the grid and view how it performance. Thereby, the limitations would be imposed because the electrical elements characteristics of the installed devices or there must be stablished a certain power demand, a certain current fluctuation or a specific voltage for a node. These changes would determine the work area of each node. The currents and voltages and their resulting power should be within these operational bounds as were expressed in the equations (4.15), (4.16) and (4.17) as described in (Aragüés-Peñalba, et al. 2012) and (Benedito, et al. 2016). The operational bounds are bounded by a maximum and minimum for the currents, voltages and power in each node as is seen in the Figure 4.2.

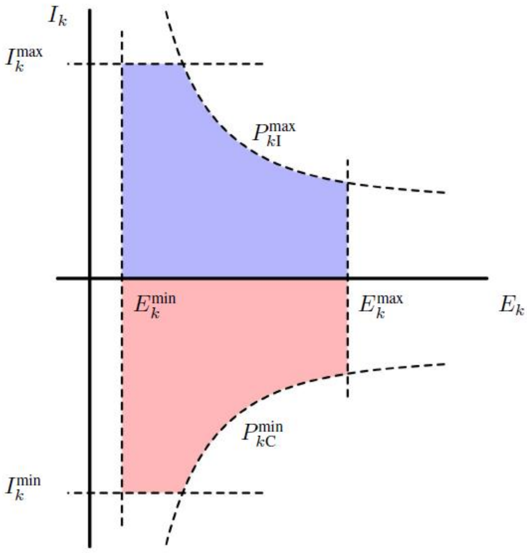

Figure 4.2: *Working area defined for the maximum and minimum level bounds for a MTDC node. Image from (Dòria-Cerezo, Olm and di Bernardo, et al. 2016)*

$$E_{min,k} \leq E_k \leq E_{max,k} \qquad (4.\ 15)$$

$$u_{min,k} \leq u_k \leq u_{max,k} \qquad (4.\ 16)$$

$$P_{min,k} \leq E_k \cdot u_k \leq P_{max,k} \qquad (4.\ 17)$$

The compliance of all the constraints is a crucial factor to the correct operation of the grid. It is for this reason that the Secondary control would always try to fulfil all of them as long as the proposed scenario will have a solution. Unless the scenario has a solution, the Secondary control could not ensure the stabilization of the system because one or more restrictions will be unfulfilled. The noncompliance of the constraints could entail into a non-stabilized operation and a non-cover of the power demand. Then happens that the Secondary control is unable to define one or more working points of some nodes into their configured area. Depending on where this point is designed, the node could start to oscillate in order to arrive to the determined location, but because this is out of bounds the system would never reach it making possible the oscillation of the system. Otherwise, it is possible that the grid does not entry in an oscillation period despite the assigned point do not compliance the restrictions. It is possible that the grid could encounter a stable point in spite of non-cover the whole demand. This is because the control system is able to reach a point that achieve the equilibrium conditions. The equilibrium point of the MTDC network as presented in (Benedito, et al. 2016) is given by

$$0 = -\boldsymbol{B} \cdot i + u(E) \tag{4. 18}$$

$$0 = -\boldsymbol{R} \cdot i + \boldsymbol{B}^T \cdot E \tag{4. 19}$$

Which yields in the relationship

$$u = \boldsymbol{G} \cdot E \tag{4. 20}$$

Where $\boldsymbol{G}$ is the conductance matrix, defined as

$$\boldsymbol{G} = \boldsymbol{B} \cdot \boldsymbol{R}^{-1} \cdot \boldsymbol{B}^T \tag{4. 21}$$

It is important that the system must reach the equilibrium point in every scenario programmed. If the equilibrium is not reached, the voltages of some nodes will probably oscillate. These oscillations would make the performance of the grid impossible as well as an increase in the power losses of the grid. These oscillations could appear during the transitory change of scenarios meanwhile the system is reaching the new working points assigned. If these oscillations are not much noticeable, the performance of the grid would not probably be affected and the operation of it could continue without any problem. Alternatively, if these oscillations records several increases of the voltage level and makes it during an appreciable period, the grid would be unworkable entailing into a blackout. Because of this, it is important that the system operates safely within these bounds, taking into account a safety margin.

Therefore, if the system remains stable it is clearly a good idea to optimize the operation of the grid. Optimizing methods have been a great implementation in many systems, for example in wind turbines and photovoltaic solar systems with the enforcement of the MPPT (Maximum Power Point Tracking) to maximize power output. In this case the objective function is based on the minimize of the transmission power losses occurred in the power lines. Keeping in mind that the power losses on the lines in DC are produced just by resistive effect, transporting the power over relatively shorter distances or at higher voltages should minimize them (Van der Feltz 2016). This is because the resistance of the line is proportional to its length as well as the Joule effect is quadratic proportionally to the current flow. As it was commented in the introduction, thanks to increasing the operation voltage the current flow could be decrease. Therefore, taking into account the Ohm law, $E = I \cdot R$, and the expression of the power in DC, $P = E \cdot I$, it is possible to extract the Joule's law through a combination of both

$$P_{loss} = R \cdot I^2 \tag{4. 22}$$

Modelled in matrix form as presented in (Benedito, et al. 2016)

$$P_{loss} = i^T \cdot \boldsymbol{R} \cdot i \tag{4. 23}$$

However, in this way it is not possible to control directly the power loss in the operation of the grid through the determining of the voltage levels. In this way, the expression has to be restructured like

$$P_{loss} = R \cdot I^2 = \frac{E^2}{R} = E \cdot G \tag{4. 24}$$

Implementing it for the totality of the nodes as indicated in (Aragüés-Peñalba, et al. 2012) and (Benedito, et al. 2016)

$$P_{loss} = \sum_{k=1}^{n} \sum_{l=1}^{n} \boldsymbol{g}_{kl} \cdot (E_k - E_l)^2 \tag{4. 25}$$

Where E_k and E_l are the voltages in node k and l, respectively and g_{kl} is the conductance between node k and l. This can be rewritten as

$$P_{loss}(E) = E^T \cdot \boldsymbol{G} \cdot E \tag{4. 26}$$

The implementation of all these theoretical for the creation of the Secondary control will be presented next.

4.3. Initial program

To start the optimizing algorithm creation, it was first needed to have established a network model to simulate and a control algorithm for handle it correctly. The primary model consisted of following the same kind of topology system idea implemented in the final model. This archetype consists of the definition of each point, determining the type of point it is, either is a Wind Farm established as a generation point or a Grid Side converter listed as a consuming point of energy. After it, the primary model needs the determination of other parameters like the maximum power which each point can provide to the network or the maximum demand could consume, depending on the former definition of them. This type of affectation parameter was detected automatically by the programme and turned it valid or opposite, which is kind of limited option. The capacitance and the initial voltage of the capacitor which form the patron of the nodes, the maximum current in each point and the constant K for the controller are the other parameters which would have to be determined. Besides the definition of all points which are part of the network, connections between them must be determined, because it will establish the topology of the network to complete. For decrease these connection lines, the program has the inputs of for each line, the starting and final point, the resistance and the inductance of the specific line, which are determined by the length of each one and the global parameters of resistance per kilometre as well as the inductance per kilometre. It is also necessary to indicate the starting current value of the line. These inputs were the basic data in order to define a network to simulate a scenario. With all these parameters defined, it may be determined the only final input necessary for the function of this primary model. This final input is the array of voltages for all nodes in each change to those who the performance of the grid would has to be addressed by the control. Once these voltage parameters were introduced with the others, the simulation shows the results like the figure 4.3.

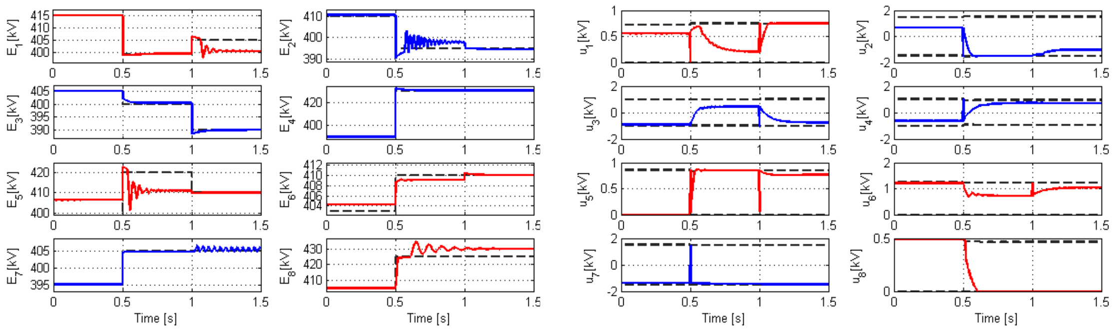

Figure 4.3: *Example of simulation results of voltage (left) and current (right) magnitudes on a specific scenario with the old model.*

Nevertheless, this model has some issues which made him improbable. First at all, this simulation process do not worry about the optimum point of work. This fact makes the solution given by the algorithm not the best one in terms of power losses. In the field of power transmission, the most important factor is the minimization of the Joule's losses, which would be a serious problem if it do not be controlled correctly. Control appropriately the factor of the transmission power losses would make the difference between benefit of almost the totality of the energy produced, or make a wasteful processing of these generated energy.

Then, the first model only allows an exact simulation in three different scenarios. This restriction forces to define only a specific set of probabilities, limiting the user to simulate other type of scenarios. Moreover, these changes only can only be determined by the voltage value, making it impossible to adjust the power generation or the power demand, as well as the maximum and the minimum current of the nodes.

Finally, the last issue of this model is the input value possibility. As previously noted, the input data in this old system is a handicap. Allowing to define the possible scenarios only through the determination of the voltage values is not a full opportunity of shape a certain example. This constraint is relevant with the first mentioned. Foremost, only allowing the establishment of the voltage values for each scenario instead of offering the possibility of determine an accurate intervals for the power, current and voltage, makes it impossible the option of optimizing the result, because it is forcing the simulating to operate at a certain voltage value which probably, would not be the perfect one. Furthermore, with this input standard, it is impossible to impose a node to generate or demand a specific amount of power or current, being subjected to the algorithm criterion. This is another limitation in the simulation option.

Table 4.1: *Input data model of the primary simulation system.*

WF(1) or GS(0)	P_{max} [MW]	C [uF]	iniC [KV]	I_{max} [kA]	k	t0	E_0 [KV]	t_1	E_1 [KV]	t_2	E_2[KV]
1	300	75	400	1	1	0	415	0,5	399	1	405
0	600	75	400	1,5	1		410		395		395
0	400	75	400	1,3	1		405		400		390
0	400	75	400	1,5	1		390		430		430
1	350	75	400	1,2	1		393		420		410
1	500	75	400	1,4	1		403		410		410
0	600	75	400	1,5	1		395		405		405
1	200	75	400	1	1		405		425		425

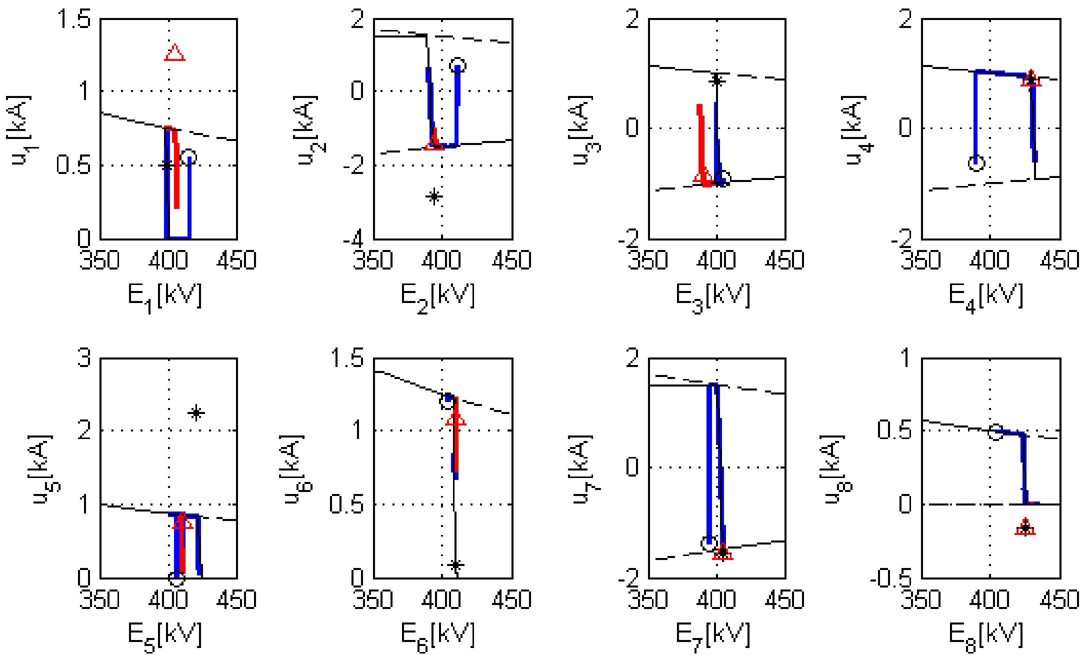

Figure 4.4: *Evolution of the work point in the possible workspace for a specific scenario in the old model.*

Once all the possible improvements have been detected, the next step is to make changes so as to build up this simulation algorithm to a programme which offers the opportunity of simulate all the potential scenarios demanded by the users, and returning the best of the infinite solutions the proposal network has.

4.4. Programing the OPF algorithm

For the creation and implementation of all the possible potential improvements detected in the first model, it was decided to reconfigure the network inputs. At the beginning, the optimizing algorithm was implemented in a simple network model without impedance and capacitance elements, establishing a non-dynamic system. Therefore, the only elements which produce some power losses in the grid on this model are the line resistances. In consequence of all these parameters, this process only dictates the best work point for the network model and state.

In order to increase the simulation possibilities of the model it was determined the input data prototype. The optimizing algorithm provides the best voltage level for each node in determined intervals of maximum and minimum values of all the electrical magnitudes. This system offers the possibility to force an exact value for one of the magnitude of each node, leaving the optimizing algorithm assign the rest numerical values for the other magnitudes through the voltage level, making the situation optimal with the imposed magnitude. That is to say, it is possible to impose an exact value of power, intensity or voltage making equal the maximum and minimum bounds. If the data input imposes a power or intensity value, the algorithm is going to establish all the voltage levels for each point, in order to define the optimal operation. Otherwise, there is a chance of impose the voltage value. If the data input imposes all the voltage levels for each points, it will be impossible for the optimizing algorithm establish the best operation option, as the scenario has already been defined by the imposition of the voltage levels and there would not be any possibility of making it any changes. However, it is possible to establish many voltage values for some nodes and, if the user agree, it can be combined with other impositions provided that only one magnitude is restricted per node. If many voltage values are imposed, the algorithm will maintain these values and search the best option for the other voltage nodes levels in order to minimize the total power losses of the network.

Table 4.2: *New input data model of the final simulation system.*

N	P_{max} [MW]	P_{min} [MW]	E_{max} [KV]	E_{min} [KV]	E_0 [KV]	I_{max} [KA]	I_{min} [KA]
1	-200	-300	420	400	415	1	-1
2	400	0	420	400	405	1	-1
3	400	0	420	400	410	1	-1
4	-150	-150	420	400	440	1	-1
5	-200	-400	420	400	385	1	-1

Once the input data prototype was changed, the optimizing algorithm using the *fmincon* MATLAB function could be created. To perform the function correctly it is necessary to define first a value which contains the initial conditions, and after that, to determine the constraints functions introduced to the *fmincon* through the *c(x)* and *ceq(x)* functions. At last, in an exclusive file like the constraints would be defined the objective function. This file would be indicated to the *fmincon* as the expression which its result has to be optimized.

$$\min_{x} f(x) \; such\ that \begin{cases} c(x) \leq 0 \\ ceq(x) = 0 \\ A \cdot x \leq b \\ Aeq \cdot x = beq \\ lb \leq x \leq ub \end{cases} \qquad (4.27)$$

```
[V,FVAL,EXITFLAG,OUTPUT]=fmincon(@OPFof,V0,[],[],[],[],lb,ub,'OPFnlc',
options);
```

Thereby, the first demand that makes the *fmincon* function is the mathematical expression which is needed to minimize its outcome. In this case, the aim it is to minimize the losses in the transmission of the energy from the generation points to the demand points. This concept is expressed in the Joule's law defined in (4.26):

So, the specific file for the Objective Function is implemented in a MATLAB file like:

```
function Ploss = OPFof(V)
global AiRA
Ploss=V'*AiRA*V;
```

Whereas *V* is the variable to optimize, which stores the optimizing process results and creates a voltages vector with a size like the number of nodes that the network has, and the *AiRA* variables is the conductance matrix of the network.

Therefore, with the assignation of the *V* variable in the *fmincon* definition, and the implementation of the Objective Function depending on the *V* variable, the optimizing process interprets correctly which variable has to modify, and knowing the relationship between the variable and the power losses, this is defined with the equation in the code, it manages to optimize the network performance. As well as with Objective Function, it is necessary to say to the *fmincon* function which restrictions it has to tolerate. These constraints are the maximum and minimum power and current bounds. The maximum and minimum voltage bounds are demanded by the function in the main definition, with the *lb* and *ub* variables. To be able to introduce the current and power limitations, it has to be done through the *c* and *ceq* functions of the *fmincon* function. As the algebraic definition of the *fmincon* MATLAB function indicates, the equations referenced to the *c* variable are going to be inequalities, where the expression assigned would have to be equal or lower than zero after the *V* variable values assignation. Meanwhile, the equations which will be referenced at the *ceq* function, are going to be declared as mathematical equal to zero. So that, as the constraints only want to delimit the value of the variables and not to fix them, all the restrictions equations will be referenced at the *c* function. Therewith, the general restrictions equations for the optimizing algorithm, which were described in functions (2.9), (2.10) and (2.11), would be implemented as:

For the power limitations

$$(P_1, \dots, P_n) - (P_{max_1}, \dots, P_{max_n}) \leq 0 \quad (4.28)$$

$$-(P_1, \dots, P_n) + (P_{min_1}, \dots, P_{min_n}) \leq 0 \quad (4.29)$$

With

$$(P_1, \dots, P_n) = (V_1, \dots, V_n) \cdot (I_1, \dots, I_n) \quad (4.30)$$

For the current limitations

$$(I_1, \dots, I_n) - (I_{max_1}, \dots, I_{max_n}) \leq 0 \quad (4.31)$$

$$-(I_1, \dots, I_n) + (I_{min_1}, \dots, I_{min_n}) \leq 0 \quad (4.32)$$

With $(I_1, \dots, I_n)$ as was defined in (4.20)

$$(I_1, \dots, I_n) = G_{nxl} \cdot (V_1, \dots, V_n) \quad (4.33)$$

Implementing these equations on MATLAB in a matrix form and assigning them to the c variable:

```
function [c,ceq]=OPFnlc(V)
global Pmax Pmin AiRA n Imax Imin
 %Limit of maximum and minimum power for all vertex
 for i=1:n
    y(i) = V(i) * (AiRA(i,:) * V) - Pmax(i);
 end
 for i=1:n
    z(i) = -V(i) * (AiRA(i,:) * V) + Pmin(i);
 end
 %Limit of maximum and minimum current for all vertex
 for i=1:n
     q(i) = (AiRA(i,:) * V) - Imax(i);
 end
 for i=1:n
     w(i) = -(AiRA(i,:) * V) + Imin(i);
 end
c=[y;z;q;w];
ceq=[];
```

These restrictions force the algorithm to select a point of work which is in the workspace of each node, making the system stable. Obviously, the best performing point will be in a stable point because a non-steady point of work will produce important oscillations which would decrease the grid performance.

The last but not least parameter which the *fmincon* function wants, is the array of the initial values of the variable which is going to be optimized. Without initial conditions, the algorithm is not able to start the optimization. Normally these values are the nominal voltage of the nodes or values close to it.

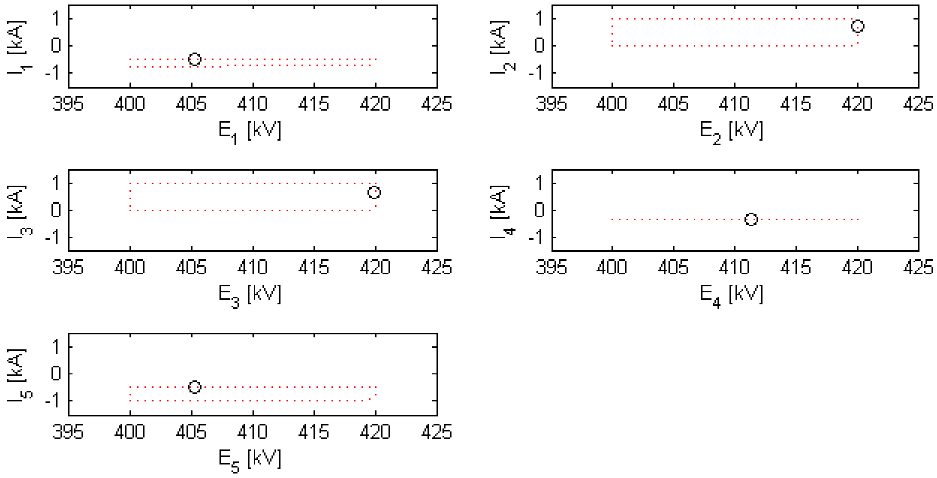

Figure 4.5: *Work point selected by the algorithm in the non-dynamic model for a specific network configuration.*

4.5. Selection of the best solver algorithm for the fmincon function

It has been specified all the input parameters which the *fmincon* function needs to start the optimization process. However, apart from the parameters, in the function settings there is the option to indicate which solver the user wants to implement in the process. This definition would be made by the *options* input. The *options* of the function allow to configure the specific settings of them. In the *fmincon* options, there is the possibility to select the solver algorithm which will be used in the simulation process. These solver algorithms are better or worse depending on the type of problem, being more accurate and fast on specific model problems. These model problems are catalogued depending on the difficulty to solve them, and many algorithms are defined depending on the type of problems. There are two different modalities clasified, the Large-scale algorithms and the medium-scale algorithms.

Large-Scale algorithms

- Linear algebra that does not require to operate on full matrices, does not need to store.
- Sparse linear algebra whenever possible.

Medium-Scale algorithms

- Dense linear algebra and complete matrices.

- High memory usage for the storage of the complete matrices.
- It may require a high runtime.

It is possible to use a Large-Scale algorithm for a minor problem. This would lead to a minor use of memory and consequently a faster simulation. However, the use of a Large-Scale algorithm may incur in less accurate results. The *fmincon* function has four possible algorithms to use. To decide which of them algorithms would be the best option, it is necessary to present them and compare the results.

Table 4.3: *Possible algorithms solvers for the fmincon function.*

INTERIOR-POINT
Solves large scattered problems and small dense problems. Satisfy limits for all iterations. Can recover from NaN and Inf calculation results. Large-Scale algorithm.
SQP
Satisfy limits for all iterations. Can recover from NaN and Inf calculation results. Not a Large-Scale algorithm. Medium-Scale algorithm.
ACTIVE-SET
Big steps. More velocity. Can recover from NaN and Inf calculation results. Not a Large-Scale algorithm. Medium-Scale algorithm.
TRUST-REGION-REFLECTIVE[1]
Requires to provide a gradient on the objective function, and allows only bounds or linear equality constraints, but not both. Large-Scale algorithm.

In order to accomplish the comparison and selection process of the *fmincon* best resolution algorithm for the optimizing model, different scenarios of a specific topologic network are going to be simulated. The factors which would determine what algorithm is the best option they will be determined by:

- The EXITFLAG *fmincon* output, which indicates the success of the simulation process and the accomplishment of the specified constraints.
- The elapsed time in the optimizing process.
- The minimization of the final value of the objective function.

Table 4.4: *Topologic configuration of the network which will be used for the comparison process.*

N_{start}	N_{end}	L [km]	R [Ω/km]	R [Ω]
1	2	150	0,2	30
1	5	100	0,2	20
2	5	300	0,2	60
4	5	120	0,2	24
3	4	70	0,2	14

[1] The trust-region-reflective algorithm will be discarded for the comparison process because is not able to simulate the problem with the constraints specified in this model.

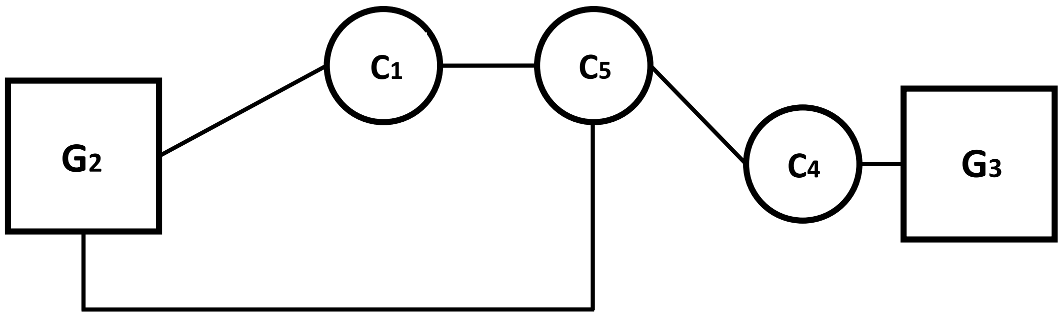

Figure 4.6: *Schematic representation of the topological constitution of the network simulated.*

So as to view the differences between the three possible algorithms to use, it is going to be simulated the same type of grid in a different scenarios and plotting the final results of each algorithm, comparing them offering the possibility to see which the best option is. Forcing the algorithms to choose the optimal solution in some extreme cases would show which algorithm tolerates the assigned constraints better. It prevents from breaking more restrictions and magnitude limits being capable of guarantee the less power losses in a tough operation situation.

These extreme scenarios will be determined first by a power and current bounds modifications, making a first simple case, and after making a second and a third cases which are going to be in one, a demanding limitation of power with more flexible bounds of current, and the other case unlike this, with a demanding current limitation and more reasonable generation and demanding power. After these types of scenarios it would be interesting to carry on a similar study, but in this case limiting the voltage bounds and forcing an exact voltage value in some nodes. Probably in all these cases, the algorithms are not going to be able to make a perfect selection which abide all the restrictions, however, these results will show which of them will assign a nearer or a further value of the limitations previously imposed. This aspect will be an important one because it is fundamental that the system works in the working area delimited by the user, and an algorithm which defines distant points of this area would not be a good choice.

4.5.1. Comparison and selection experimental study

<u>Input data for each case</u>

Case 1

N	P_{max} [MW]	P_{min} [MW]	E_{max} [KV]	E_{min} [KV]	E_0 [KV]	I_{max} [KA]	I_{min} [KA]
1	-100	-300	420	400	415	1	-1
2	400	0	420	400	405	1	-1
3	400	0	420	400	410	1	-1
4	-150	-150	420	400	440	1	-1
5	-200	-400	420	400	385	1	-1

The first case which was simulated was not an extreme scenario. The idea of simulating this type of scenario was to observe which of the three solver algorithms was the fastest and the differences among them. Moreover, the no resolution of this scenarios would be the discard of that algorithm.

CASE 1	Interior-Point	SQP	Active-Set
EXITFLAG	1	1	0
Time	0,792307	0,564529	1,235985
Plosses	1,13E+07	1,13E+07	1,13E+07

Once the scenario is simulated, it was possible to realize that the three algorithms have led to the same solution of the problem, the optimal one obviously, and it was viewed in the Power losses results, which were the same at each algorithm results. In the EXITFLAG factor, only the Active-Set solver has not obtained a perfect simulation, because output 0 represents that the number of iterations exceeded the options maximum iterations limit or number of function evaluations exceeded options maximum function evaluations limit. Finally, the aspect of the time reveals that the SQP seems to be at first sight, the one that fits better the programme, being a 40% faster than the Interior-Point and a 118% faster than the Active-Set algorithm, which has made the maximum number of iterations possible.

Case 2

N	P_{max} [MW]	P_{min} [MW]	E_{max} [KV]	E_{min} [KV]	E_0 [KV]	I_{max} [KA]	I_{min} [KA]
1	-300	-300	420	400	415	2	-2
2	200	0	420	400	405	2	-2
3	800	0	420	400	410	2	-2
4	-150	-150	420	400	440	2	-2
5	-400	-400	420	400	385	2	-2

In the second scenario simulated, the aim is to view the voltage assignment of the different solvers for a case of a strict exact demand of power. In this case, the working region has been limited for the consumer points to the power curve assigned, making it more difficult for the algorithm to assign voltage values that tolerates all the system constraints.

CASE 2	Interior-Point	SQP	Active-Set
EXITFLAG	-2	-2	0
Time	1,504689	0,491679	1,034679
Plosses	1,62E+07	1,65E+07	2,20E+07

In this case stricter than the first, any solver could reach an optimal solution which respects all the restrictions. Nevertheless, as it was previously mentioned, these results in extreme conditions would show which algorithm had a better behaviour in difficult scenarios. In this simulation, once again the SQP algorithm was the fastest, and this time being 2 times faster than the Active-Set and 3 times faster than the Interior-Point. In reference at the optimization power losses results, the SQP and the Interior Point solvers were at the same level, while the Active-Set was worse than the other two, being apparently the worst option.

Case 3

N	P_{max} [MW]	P_{min} [MW]	E_{max} [KV]	E_{min} [KV]	E_0 [KV]	I_{max} [KA]	I_{min} [KA]
1	-200	-300	420	400	415	0,5	-1
2	400	0	420	400	405	0,5	-1
3	400	0	420	400	410	0,5	-1
4	-150	-150	420	400	440	0,5	-1
5	-200	-400	420	400	385	0,5	-1

In the last case which it is going to be changed power and current bounds, the limitations comes in the maximum current that the generation points can give. It is highly probably that the current limits in the second and third nodes are not going to be respected, but there is the expectation to view which of the algorithms can tolerate the power limitations, choosing the cage assignation for this system configuration. Knowing that when the optimizing algorithm is implanted in the dynamic model with the control algorithm will be this which would control that the network will not to surpass the current and power limitations. This scenario is based on viewing the algorithms tolerate priorities.

CASE 3	Interior-Point	SQP	Active-Set
EXITFLAG	-2	2	-2
Time	0,957895	0,585075	0,838995
Plosses	1,10E+07	1,80E+07	1,25E+07

At the end of the simulation, the general results show the differences on the priorities for the different solvers. First of all, only the SQP algorithm is to prevent the EXITFLAG = -2, which indicates that it has not been possible to find a feasible point. The EXITFLAG = 2 indicates that the iteration process has been stopped because the change in the variable which should be optimized is less than the tolerate value assigned in the configuration. Secondly, the relations between the solvers in the time wasted in the simulation process seems to be the same as in the other two simulations. Finally, because the priorities in the tolerance on the constraints, the SQP solver obtains the worst Power losses results. This is because this solver has prioritized the power restrictions in front the current restrictions like the Interior Point did. These results can be viewed in the presentation of the total evaluation.

Case 4

N	P_{max} [MW]	P_{min} [MW]	E_{max} [KV]	E_{min} [KV]	E_0 [KV]	I_{max} [KA]	I_{min} [KA]
1	-100	-300	420	400	415	1	-1
2	400	0	425	425	405	1	-1
3	400	0	440	420	410	1	-1
4	-150	-150	420	400	440	1	-1
5	-200	-400	420	420	385	1	-1

Since the fourth scenario, the limitation idea in the inputs change. Now, the restrictions will come from the voltage magnitude predominantly, maintaining the current limits and restructuring the power demanded and generated. In this first case, the power and current bounds will keep like the first case, and there will be imposed one voltage in one generation point and another one in a demanding point.

CASE 4	Interior-Point	SQP	Active-Set
EXITFLAG	0	-2	0
Time	3,894265	0,419422	1,029622
Plosses	1,77E+06	3,04E+06	3,61E+06

Once the fourth scenario is simulated, it is possible to view that two of the three solvers have spent a lot of time because they have used all the possible iterations. Otherwise, the SQP solver algorithm has used lesser time because it detected that there was not a feasible point to solve the problem. The Interior Point algorithm, which wasted almost four seconds to do the iteration process, has concluded with the best Power losses, but because the order of the power losses for this case, the difference between the other two solutions is not as big as in previous cases. Notwithstanding it, continues being the best result. In reference to the other two solvers in terms of power losses, their results were higher considering the Interior Point obtained, but for the SQP, it may be explained because it tried to accomplish the constraints and selected the closest point to the limitations.

Case 5

N	P_{max} [MW]	P_{min} [MW]	E_{max} [KV]	E_{min} [KV]	E_0 [KV]	I_{max} [KA]	I_{min} [KA]
1	-300	-300	420	400	415	1	-1
2	400	0	410	410	405	1	-1
3	400	0	420	420	410	1	-1
4	-150	-150	420	400	440	1	-1
5	-200	-200	420	400	385	1	-1

In order to continue the study with the variation in the voltage limits, in the fifth case there has been imposed the exact voltage levels in the generation points, and also fixed in the other nodes the power demand which were going to consume, making this case a restrictive extreme scenario. This case has the difficulty for the solver algorithms that the voltage levels of the generation points are not greatly high, and it will mean that the solver will have to decrees the voltage levels of the demanding points closer to the minimum in order to stablish the correct current fluctuation.

CASE 5	Interior-Point	SQP	Active-Set
EXITFLAG	-2	-2	0
Time	0,752695	0,441286	0,952367
Plosses	1,36E+07	1,59E+07	1,58E+07

In this fifth scenario, the general results for all three solvers were practically identical. Like all the previous cases, the SQP was the faster solver, and the Interior Point obtained the best result in the power losses parameter. With this non conclusive general results, all the conclusions for this case will become from the EXITFLAG results and the fulfilment of the constraints, which will determine which solver selects the more stable solution.

Case 6

N	P_{max} [MW]	P_{min} [MW]	E_{max} [KV]	E_{min} [KV]	E_0 [KV]	I_{max} [KA]	I_{min} [KA]
1	-200	-500	410	410	415	1	-1
2	400	200	430	410	405	1	-1
3	300	200	430	410	410	1	-1
4	-100	-250	410	410	440	1	-1
5	-300	-500	410	410	385	1	-1

Finally, in the last case scenario, the fixed values have been the voltages of the demanding points, and it is obligated the generation points to produce a minimum of energy, making the scenario more restrictive. In order to make the case possible, the power demanding has been configured a little more flexible. In this last case, the ability of each solver to stablish a good scenario with less possibilities of making changes is evaluated, as there is only the chance to switch two of total five values of the voltage variable.

CASE 6	Interior-Point	SQP	Active-Set
EXITFLAG	-2	-2	-2
Time	1,627175	0,47166	0,84592
Plosses	2,19E+07	2,06E+07	2,27E+07

After comparing the individual case results, with the final case it can be affirmed that the SQP algorithm is the fastest of all three possible solvers. In terms of power losses, it seems that the Interior Point algorithm has been the best option in the rest of the cases, however in this one it was the SQP solver which gave better iteration results. Moreover, with all the results exposed and as seen in the general results, the Active-Set solver is not a real possibility and could be discarded without doubt. In this situation, the only worry is which of the other two algorithms is the best to use in the optimizing algorithm to implement it in the dynamic model. To accomplish this problem and select which of these two algorithms is the most indicated it was created an evaluating algorithm with these general results and the EXITFLAG results subjected to certain ponderation values, giving priority to the more important factors assigning a mark for each case.

4.5.2. General results. Evaluating algorithm

Once all the results for each scenario have been presented, it is necessary to choose which solver algorithm is the most appropriate to make the iteration process of the optimizing algorithm. To do so, it has been configured an evaluating algorithm, which assigns marks in the specific factors that have been presented, to compare the results of each solvers and obtaining general marks in each case, to determine which algorithm is the best option for that case.

Before presenting the evaluation algorithm results, all the general results are going to be exposed in many graphic presentation in order to understand and interpret better the results which have been obtained in each case. These graphics would give a better point of view of the results and the degree of difference between the purposes of the three solvers, making it easier the detection of which are the factors that each algorithm has a better performance and are the proposals for being selected.

Graphic implementation of all the results of the different cases

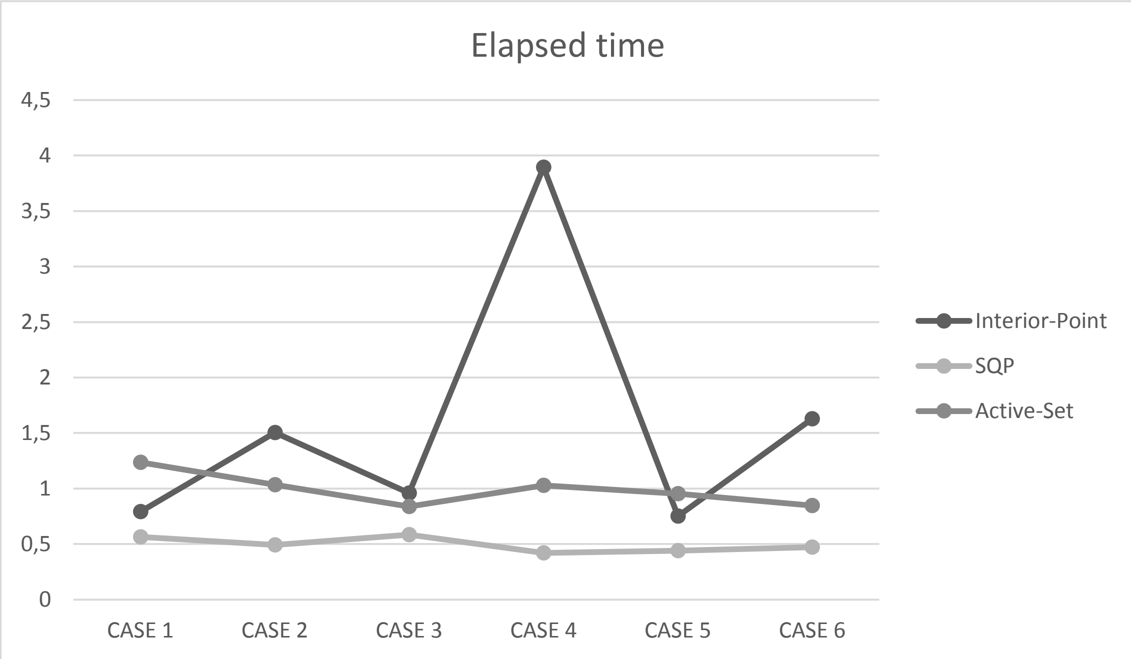

Figure 4.7: *Time elapsed results of the three solvers for all the cases simulated plotted in the same graphic.*

The Figure 4.7 confirms the conclusions obtained in the individual presentations on the factor of time. It is possible to view that the SQP algorithm is by far the fastest algorithm on doing the iteration process, avoiding the long iterations and obtaining results always in approximately the same amount of time, which makes it the most constant option. It seems that the SQP algorithm has more facility to detect when the problem has a feasible point of work and so when it has not a possible solution, avoiding long searches through determining a point which minimizes maximally the non-accomplishment of the constraints. According to the other two algorithms, in terms of time it seems that the Active-Set algorithm would be the second best option, because when it enters in a maxim iteration process, it makes the process faster than the Interior Point. However, along the individual studio was seen that the Active-Set does not seem to be a good option for the fulfilment of the restrictions. Nevertheless, the Active-Set will be evaluated in the same way as the other two solvers so as to make sure that it is a good sense. Finally despite spending more time, it seems that the Interior-Point is the most robust option. It probably minimizes better the power losses.

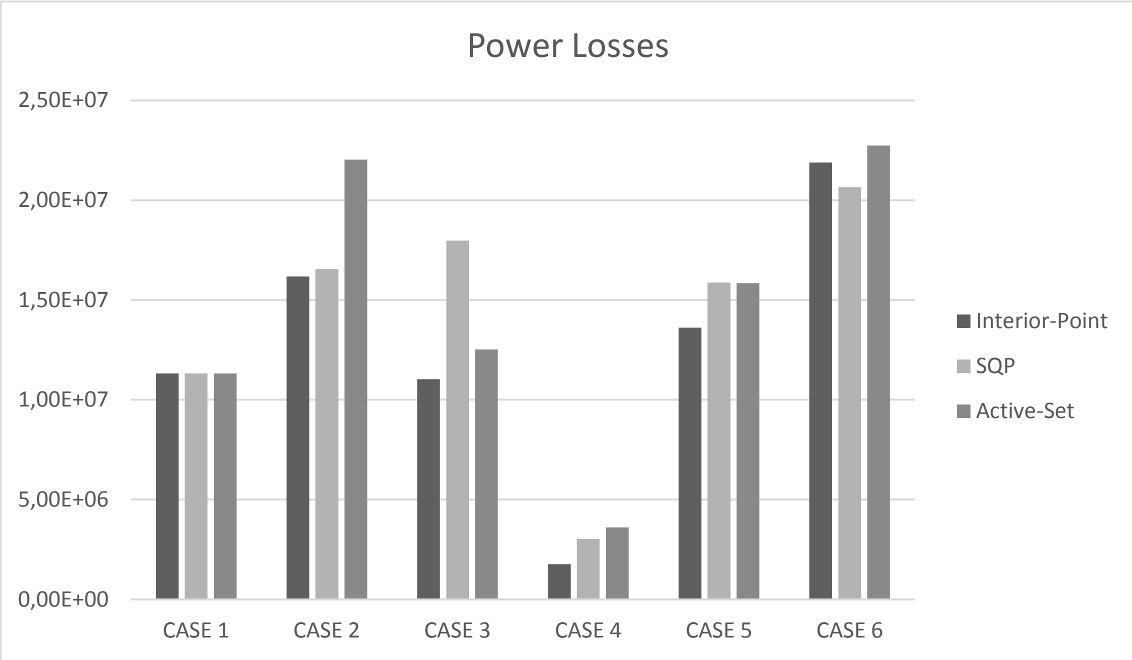

Figure 4.8: *Power losses results of the three solvers for all the cases simulated plotted in the same graphic.*

In the power losses minimization, except in the last case, it was the Interior Point the solver which had the best results. Discarding the first case, which was solved perfectly by the three algorithms, in four of five cases the Interior Point despite of wasting more time it was able to minimize the objective function better. These results shows that the Interior point algorithm is the best option to find a point which is supposed to produce less power losses. However, these results must go with a correct EXITFLAG evaluation. The further the work point selected by the algorithm of the work area, the less stable will be the system and the more power losses would entail.

This studio it is only an extreme scenario evaluation in order to determine the priorities of the algorithms when the work conditions purposed by the user are not feasible. Obviously, it is known that if this scenario is simulated in the global model, the power losses will be different, because the optimizing algorithm will only determine the perfect voltage values for the model, and the driving of all the variables will be performed by the control system, which would be unable to stablish the desired values because it would have to delimit the current or power to the maximum or minimum level. Thereby, these results have to be interpreted like a theoretical value, only used to have an approximated idea of which algorithm performances better and priorities the optimization of each factor.

Nonetheless, returning to the theoretical study, it is viewed that the Interior Point will probably obtain the best marks in the power losses aspect. Seeing of the other two solvers, the results of both are quite similar. Depending on the case, the results are far from each other, but in the global compute, their marks will probably be at the same point. The only difference between these two algorithms will be in the EXITFLAG evaluation. Meanwhile the Active-Set has not been able to tolerate the constraints of the system, the SQP algorithm is the solver which had performed with the maximum respect to the restrictions of the problem. That fact puts it in a much better position in the evaluation and makes the obtained results more appropriately for the control of the system.

Table 4.5: *Marks assigned by the Evaluation Algorithm for all the general results of the three solvers for each case.*

GENERAL RESULTS EVALUATION						
	Interior-Point		SQP		Active-Set	
	Time	Plosses	Time	Plosses	Time	Plosses
CASE 1	8	10	8	10	6,5	10
CASE 2	5	10	10	7,5	6,5	0
CASE 3	8	10	8	0	8	7,5
CASE 4	0	10	10	2,5	6,5	0
CASE 5	8	7,5	10	2,5	8	4
CASE 6	5	4	10	7,5	8	4

Table 4.6: *Accomplishment of the problem constraints in the different cases for each algorithm.*

EXITFLAG SUCCESS									
	Interior-Point			SQP			Active-Set		
	V Limits	I Limits	P Limits	V Limits	I Limits	P Limits	V Limits	I Limits	P Limits
CASE 1	YES	YES	YES	YES	YES	YES	YES	YES	YES
CASE 2	YES	YES	NO	YES	YES	NO*	NO	YES	NO
CASE 3	YES	NO**	NO	YES	NO	YES	NO	NO	NO
CASE 4	YES	YES	NO*	YES	YES	NO**	NO	YES	NO
CASE 5	YES	YES	NO*	YES	YES	NO**	NO	YES	NO
CASE 6	YES	YES	NO	YES	YES	NO**	NO	NO	NO

Table 4.7: *Marks assigned by the Evaluation Algorithm in reference to the accomplishment of the problem constraints.*

EXITFLAG SUCCESS EVALUATION									
	Interior-Point			SQP			Active-Set		
	V Limits	I Limits	P Limits	V Limits	I Limits	P Limits	V Limits	I Limits	P Limits
CASE 1	10	10	10	10	10	10	10	10	10
CASE 2	10	10	0	10	10	2	0	10	0
CASE 3	10	4	0	10	0	10	0	0	0
CASE 4	10	10	2	10	10	4	0	10	0
CASE 5	10	10	2	10	10	4	0	10	0
CASE 6	10	10	0	10	10	4	0	0	0

Explication of the Numeric Evaluation Algorithm

In order to have an analytic tool to estimate which of the three algorithms fits better in this system, a numeric evaluating algorithm that would assign certain marks depending on the results of each algorithm on each case has been implemented. To obtain the mark of every single algorithm for one specific case, the Numeric Evaluation Algorithm would evaluate, using different systems for each factor, one mark since 0 until 10 depending on the success related with the other results of the other two solvers or in reference to a specified criterion.

- TIME

So as to evaluate the time factor there was established a high quality scale classified in specifics intervals of time. Depending on the amount of time wasted for the iteration process of a certain algorithm, this time would be classified in a spot which would determine the mark. These intervals go in steps of 0.5 s since 0, where a fewer time of 0.5 s would get a grade of 10, until 2 s, where a time larger than this limit would receive a rating of 0. A time result comprised in the interval since 1.5 s to 2 s, will receive a rating of 5, and this mark will be increased in 1.5 points according as the result would be included in the next intervals of lower maximum value. For example, a time result of 1.25 would receive a mark of 6,5 points. This is because 1.25 is included in the interval [1, 1.5), which receive a mark 1.5 lower than the [0,5, 1), which is the next lower interval after the maximum grade assignation.

- POWER LOSSES

According to the method implemented to evaluate the minimization of the power losses, it contemplates all the results of the algorithms and makes a relationship in order to evaluate them considering the distance between them. Firstly, it is necessary to choose which reference point will be. In this evaluation algorithm was chosen use the average of the three results like the limit between a good result and a bad one. Thereby, if the subtraction between the average and a specific result is positive, it will indicate that this result is lower than the global average, showing that it deserves a good rating. On the other hand, if the result of the subtraction is negative, it will be the opposite signal and the result of the optimization process will be bigger than the average, so that will mean a lower mark than 5. Once it is determined were would be classified the power losses result of the algorithm, it is important how much far away it is from the reference point. Obviously, depending on the nearness of the point in reference to the average the obtained rating would be different, because it will indicate how much better or how much worst was the result about the others.

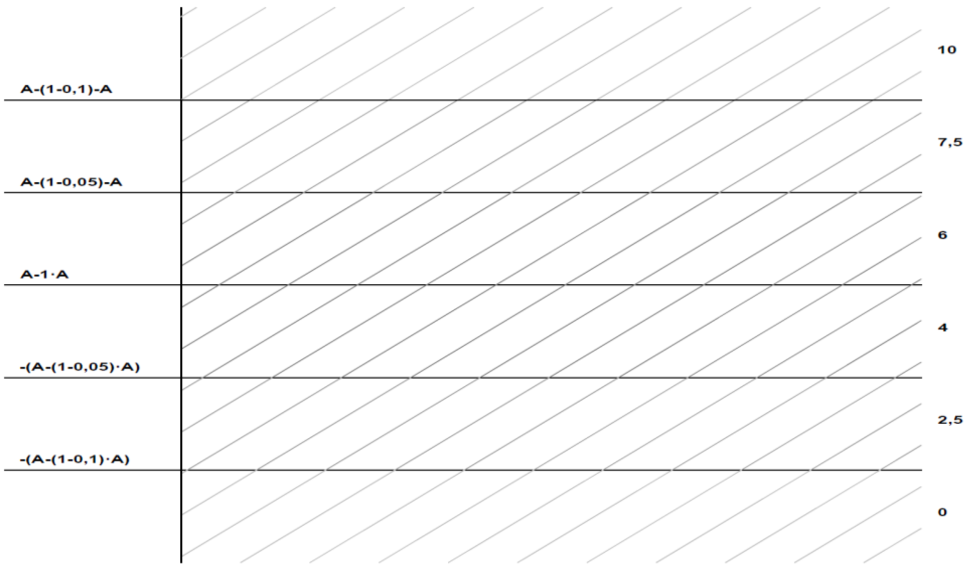

Figure 4.9: *Graphical representation of the evaluation method based on the percentage of the subtraction between the average and the obtained result.*

The remoteness identification system was created using a method of comparing the same subtraction used in the previous detection idea. The result of this subtraction is the difference between the reference point and the obtained result, which is the exactly remoteness of this point respecting the reference point. If the obtained point is related to the average is possible to locate it. This relation will be made using percentages and the idea of intervals used in the time evaluation, with the difference that in this case it will be possible to have negative results. As is possible to view in the figure 4.9, the reference point will be the $O = A - 1 \cdot A$, where the A variable is the average of the three power losses results. This expression is equal to 0, but is expressed like this because goes in consequence with the general idea of this comparison. The other limit reference points will be situated at some specific percentages. Therefore, the positive limits will be expressed like $R = A - (1 - 0{,}05) \cdot A$ and $R = A - (1 - 0{,}1) \cdot A$, meanwhile the negative limits will be the same as the positive multiplied by -1, making it a symmetric system. These expressions will locate the limits at the 5% and the 10% of the average. The comparison makes it possible to relate the result of the R expression with the subtraction between the average and the result obtained, being expressed as a percentage of A like the $Obtained\, Result = (1 - x) \cdot A$, where this 1 – x expression will be a certain percentage lower or higher than 1, depending whether the subtraction is positive or negative. Then, the relationship is stablished as $R = A - (1 - x) \cdot A$. With this percentage determined, it is possible to situate the obtained result respecting the average in the comparison system. Regarding to the evaluation, the ratings of the negative results are awarded reverse as in the positive case. If the related percentage result is larger, the rating will be worse whereas the positive case, a larger related percentage will indicate that the result obtained is much lower than the average.

- EXITFLAG SUCCESS

Because it is not a realistic analysis result and it is prioritizing the conduct of the algorithms depending on the scenario, an evaluation process for study and appreciate the selected way chosen by each algorithm was implemented, in order to express it into a possible evaluation data. The fulfilment of the system constraints marks with a good optimization of the complete success of the process. For that reason it is really necessary to evaluate that procedure and make it a crucial factor in the selection process. In order to carry on this evaluation in all the simulations the accomplishment of the defined limitations and impositions were revised. Depending on the degree of compliance of these restrictions, the rating that will obtain the algorithm will vary. The evaluation algorithm will extract the numerical results according to the Table 4.6. The only passing grade that will be assigned will come from a total accomplishment of the constraints, and will be a 10. On the other hand, if the algorithm is not capable of accomplish the totality of the restrictions, its passing grade will be lower than five. However, there is a fundamental differential in the non-accomplishment of the constraints based on the selected way of the algorithms previously mentioned. If the final results do not tolerate one of the all constraints in all nodes, this results will obtain a NO, which is synonym to a mark equal to zero. But if the solver is able to get the accomplishment of any constraints in some nodes, this NO would become a NO* or NO**, which would indicate the partially success of the restriction toleration on the simulation process, making it a more realistic solution. With this conversion the evaluation mark will change into a 2, if the new assigned reference is a NO*, or in a 4 if it were a NO**. This model will be implemented only in the power and current limitations. The non-compliance of the voltage restriction levels is not allowed and it will be a zero. This is because in the dynamic model, the control algorithm cannot succeed in preventing that the voltage value will not surprise the limits like makes with power and current magnitudes, which makes it necessary to establish the desired voltage value in the permitted interval.

Table 4.8: *Final marks of the Evaluation Algorithm referenced to the EXITFLAG results for each case subjected to specific ponderations*

EXITFLAG EVALUATION			
	Solver Algorithms		
	Interior-Point	SQP	Active-Set
CASE 1	10	10	10
CASE 2	7	7,6	1
CASE 3	6,4	9	0
CASE 4	7,6	8,2	1
CASE 5	7,6	8,2	1
CASE 6	7	8,2	0

With the final purpose of highlight the importance of the accomplishment of each limitations, the EXITFLAG obtained results of each case will be subjected to a ponderation criteria, which will mean a difference on the ratings that will determine which algorithm choose in general the best simulation way respecting the priorities stablished.

Firstly, in this situation and with the importance of the accomplishment of the voltage constraints, the rating obtained in the voltage results will count as a 60% of the total mark. Secondly, the next most restrictive magnitude in this studio was the power limitations and impositions. The accomplishment of the power demand defined in the model is a difficult and an important task, because it determines the behaviour of the grid and the success of the simulation. The rating assigned to the power limitations results will count as a 30% of the total. Finally, the last 10% will be assigned to the current restrictions accomplishment. It is known that the control of the current values is an important factor that must to be successful and always tolerate the maximum levels of permitted current fluctuation. This is because a huge increment of current fluctuation could entail the destruction of the power lines, which would entail the impossibility of transport the energy among nodes or to a specific node. The reason that these important factor is not considered as much as important as it deserves is because it is not the aim and the responsibility of the optimizing algorithm to control this hypothetical problematic situation. The system is controlled by the general control algorithm, which would try to carry the finally assignation voltage value to the desired value defined by the optimizing algorithm. Therefore, the system is controlled by the voltage levels, but will be the general control algorithm which is the responsible of manage it and define the exact value in each instant of time. Accordingly to, the current and power values will be a consequence of the assignation of the voltage values. These voltage values will be linked to the power demands and current limitations because of the implanted constraints in the optimizing process, which will indirectly assign the correct values if it is possible. It is meant that the accomplishment of the demand is more important that the compliance of the maximum currents levels because this is a task for other control system. Evidently, if the control should limit the current fluctuation to a maximum, the power offered or consumed would be resentfully, increasing the insufficiency of energy provided to a node. In conclusion, because the current limitations accomplishments becomes a responsibility of the general control algorithm, this factor is the less important in the evaluation process. It is important to remember that the optimizing algorithm does not define which the exactly point of work of each node of the grid will be. This algorithm will establish the best reference point in the voltage management on a specific scenario, giving the control the competence of operate freely in order to accomplish all the demands on the input data. Obviously, if the result of the optimizing algorithm tolerates all the constraints, this result will be the best and the implemented by the control algorithm.

Table 4.9: *Final obtained marks by the Evaluation Algorithm in consideration of all the described factors.*

FINAL EVALUATION			
	Solver Algorithms		
	Interior-Point	SQP	Active-Set
CASE 1	9,6	9,6	9,3
CASE 2	7,5	8,05	1,8
CASE 3	7,8	6,1	3,85
CASE 4	6,8	6,85	1,8
CASE 5	7,65	6,85	3,3
CASE 6	5,7	8,35	2,8
TOTAL	7,51	7,63	3,81

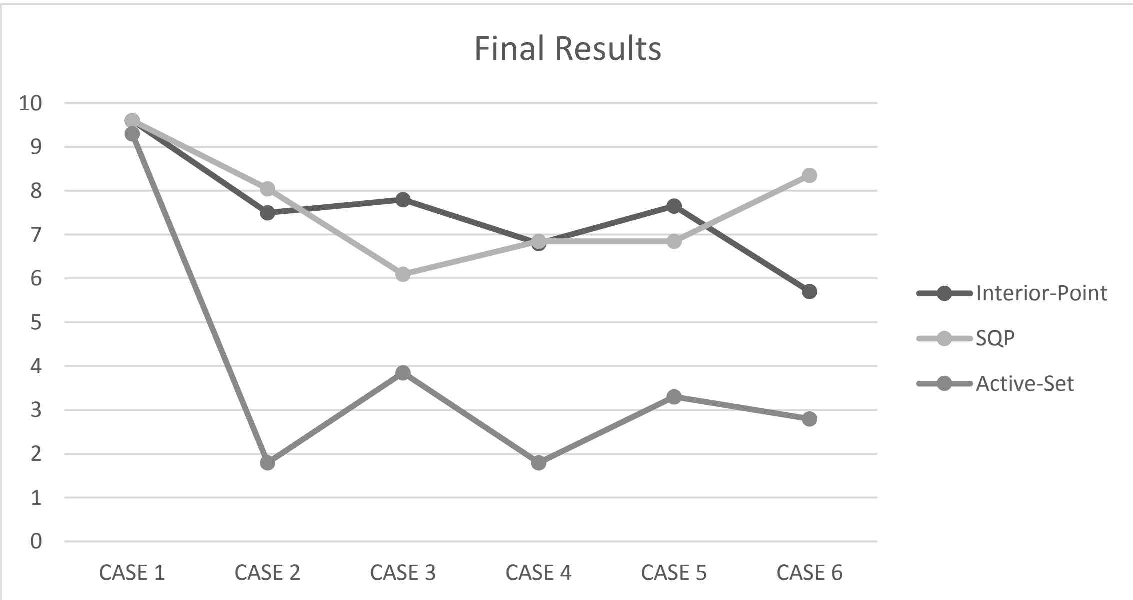

Figure 4.10: *Evaluation results of the three solvers for all the cases simulated plotted in the same graphic.*

Once the final results have been revealed, it is possible to view that the Active-Set algorithm is the worst option of the three solves and it is immediately discarded, confirming what was said in the previous individual case analysis. In the numerical results, on the total value it is noted that just for a bite the SQP evaluation is better than the Interior Point. This occurs because the SQP, which had worst power losses optimization results than the Interior Point solver, could manage the accomplishment of the constraints in the majority of the cases better than the Interior Point did. Knowing that the ponderation of the better management of the compliance of the constraints (50%) is higher than the ponderation for the minimization of the power losses (30%), and considering that ratings are much lower in the EXITFLAG evaluation in comparison with the marks which are assigned in the power losses evaluation, these results shows that both algorithms are suitable fits for the programme. These last quickly argumentation creates the idea that the Interior Point solver is much better than the SQP algorithm in terms of minimizing the objective function being reasoned in the individual case studio, meanwhile the SQP solver manages much better the accomplishment of the system constraints than the Interior Point algorithms, which is probably the most important factor for the correct operation of the global system. Nonetheless, there are two cases where the equality in the evaluation of the simulation process is showed quite differentiated. For this reason, and in order to determine which of these two solvers is the best, the third and sixth case in order to obtain a more conclusive results are going to be studied.

Final comparison and conclusions

The general results have clearly showed that the Active Set algorithm is not an option for this system, but do not solved the doubt on which of the two left solver algorithms fits better. It is sure that both of them will probably be good enough, however it is only needed one, it is necessary to determine which the best choice for this problem is. For doing so, the final results showed two cases where the algorithms were graded a bit differently. The study of these cases and the analysis of why one solver had much better mark than the other in each case will contribute the sufficient information for decide manually which solver is the best option to use.

The first one to be analysed will be the third. In this case the limitations of the input conditions were coming from the maximum current that the generation points were be able to give. Limiting the maximum current provided by the generation nodes is an indirect limitation to the power which the system is able to produce and offer, as well as a limitation for the cover of the demand. So, only limiting the current generation exit, the system looks practically limited in all the magnitudes. Once observed the results of this case for each algorithm, in terms of time the two algorithms have received the same mark, because both stablished their wasted time in the interval [0,5, 1), but those two marks were close into the limits of this interval by the both sides. Meanwhile the SQP receives a 8 for a time equal to 0,585 s approximately, the Interior Point received the same mark for a time approximately of 0,958 s. In base of these results and how it is possible to view in the Elapsed time graphic, the SQP is better than the Interior Point in this case, which would mean that these equal marks used for the general evaluation have to be different in this particular studio. Otherwise, seeing that to the evaluation of the power losses for this case, the marks assigned for the Evaluation Algorithm were completely opposite. Meanwhile the Interior Point was prized with the maximum rating, the SQP optimizing result was the worst of the three in terms of power losses amount, obtaining an evaluation result of 0. This result of the SQP algorithm which is far from the Interior Point obtained result by 7 MW will be probably explained by the fact that the SQP algorithm prioritized the cover of the power demand instead the accomplishment of the current restrictions.

Table 4.10: *Results of the two solver algorithms and comparison with the input limitations for the Case 3.*

CASE 3			
Interior-Point	SQP	Restrictions	
E results [KV]	E results [KV]	Emax [KV]	Emin [KV]
405,13	402,81	420	400
415,16	416,81	420	400
420,00	420,00	420	400
413,00	410,66	420	400
405,22	403,40	420	400
I results [A]	I results [A]	Imax [A]	Imin [A]
-338,45	-496,51	500	-1000
500,02	690,13	500	-1000
500,13	667,44	500	-1000
-175,89	-365,27	500	-1000
-485,81	-495,78	500	-1000
P results [MW]	P results [MW]	Pmax [MW]	Pmin [MW]
-137,12	-200,00	-200	-300
207,59	287,65	400	0
210,05	280,32	400	0
-72,64	-150,00	-150	-150
-196,86	-200,00	-200	-400

With the presented results in the Table 4.10 it is possible to view the different priorities of each algorithm. Meanwhile the results of the SQP for the current did not respect the maximum current levels, the Interior Point adjusted the operation of the grid in order to carry the currents of the nodes 2 and 3 into the margins specified. However, this compliance of the current restrictions carries the Interior Point to be unable to accomplish the minimum demand of power for all the three consumer nodes, which is completely logical. On the other hand, the SQP was totally able to accomplish the power demand caused by it did not limited the current injection to the defined input limitations. Having reached this point, the only significant difference is the power losses optimization, given that the unfulfilment of the one or other limitations will be related. This relationship would come when the general control algorithm decides to stablish the maximum current given by the generation points to the level assigned in the input data. This control strategy would become the scenario proposed by the SQP probably into the Interior Point proposed scenario. This hypothetical event is only an expected happening based on the current and power saturation implemented in the control system, since the saturations of the current and power magnitudes are performed by the establishment of the current into the specified input bounds. Therefore, attended to these reasoning, it seems that the Interior Point obtained the best result in this case, accordingly to with the evaluation determined by the Evaluation Algorithm. However, the proposed solution by the SQP not seems wrong because is able to accomplish all the power demand, which is quite interesting, but the fact that these scenario will not fit better than the Interior Pont scenario with the control saturation makes it a worse solution.

Once the third case was studied, it will continue with the analysis of the sixth case. This last case consisted of the fixation of all the demanding nodes to the same voltage level and the imposition of a minimum energy generation to the generation nodes. This scenario is more focused on the capacity of the solvers to arrive to an optimal solution with less options to play with. So, this case probably will have more importance in the studio than the last one because the results obtained in this case probably will be completely accepted by the general control, without being conditioned by the current saturation instead the last case.

Table 4.11: *Results of the two solver algorithms and comparison with the input limitations for the Case 6.*

CASE 6			
Interior-Point	SQP	Restrictions	
E results [KV]	E results [KV]	Emax [KV]	Emin [KV]
410,00	410,00	410	410
430,00	428,66	430	410
415,13	416,73	430	410
410,00	410,00	410	410
410,00	410,00	410	410
I results [A]	I results [A]	Imax [A]	Imin [A]
-666,67	-622,12	1000	-1000
1000,00	933,19	1000	-1000
366,28	480,41	1000	-1000
-366,28	-480,41	1000	-1000
-333,33	-311,06	1000	-1000
P results [MW]	P results [MW]	Pmax [MW]	Pmin [MW]
-273,33	-255,07	-200	-500
430,00	400,02	400	200
152,05	200,20	300	200
-150,17	-196,97	-100	-250
-136,67	-127,54	-300	-500

In the general factors in this case was the SQP which obtained the best results as much in the power losses optimization and the wasted time factor, where was a lot faster than the Interior Point. In reference to the first factor, this time the SQP solver obtained a better result than the Interior Point in the optimization of the power losses of the grid. It is true that only in this scenario the SQP was able to obtain a better optimization than the Interior Point. This circumstance was reasoned and analysed previously. In spite of being unable to improve the results of the Interior Point in the optimization process, the SQP solver could obtain the best result in the most demanding case, which demonstrates that works better with low operation possibilities. In the aspect of time, the SQP proved be the fastest option in all cases and in this las case was more than 1 second faster than the Interior Point, which leaves no doubt in this evaluation facet. Finally, in the accomplishment of the constraints both solvers could tolerate the voltage and current bounds, but meanwhile the Interior Point was only able to achieve two of five nodes in bounds, the SQP could cover the demand of the same two nodes and was able to stablish the generation energy points almost perfectly. Only the fifth node which is in the grid the most interconnected point would receive the minimum power demanded. It is logical because it was connected at the same voltage level which impossibilities the current flow between these interconnections, making only possible supply this node from the generation node 2. With these results is obviously that in this case the best fit was the SQP algorithm, which was capable to obtain the best results with less time and accomplishing much more constraints than the Interior Point.

In this way and after being analysed both cases, it seems that the best option is the SQP. In the first case, the reason why the SQP obtained a worse result than the Interior Point in terms of power losses was its priority to fulfil all the possible constraints in all possible nodes. Obviously, if the generation points provide the system with less energy, the power losses will be lower than if the system receives more energy for cover the demand. This is what happens in the first case between the two scenarios proposed. The SQP scenario had more power losses because it provides the grid with all the necessary energy although do not accomplish the current constraints. Otherwise, the Interior Point model had less power losses but had less power injection to the network, which explains the best result in this factor. Perhaps in all the study the Interior Point had better results than the SQP solver because of it, that is why the SQP had worse power losses results in the majority of the cases. Moreover this, the SQP proposed scenario is equally adaptable like the Interior Point scenario to the general control saturation, which should not be a problem for this case and any other similar. Finally, in the last case the SQP demonstrated a better way to work with limited operation tools, obtaining a better accomplishment result, a better optimization process and making it faster. With these conclusions it is completely possible to affirm that the best algorithm solver fit for the optimizing algorithm is the SQP.

Nevertheless, the selection of the SQP as the best fit for the optimizing process does not mean that the Interior Point will not be a good fit. How was said previously, both algorithms could be used without any problem.

After this analysis it could be that the idea of which the Interior Point obtains the best optimizing results was wrong because the reasoned fact in the previous analysis. However, the evaluation system has the tools to relate this power losses with the constraint accomplishment, pondering with the 50% of the mark the better fulfilment of the restrictions and with a 30% the better power losses results, making decrease the final rating for not accomplish the restrictions and balancing it avoiding a misinterpretation of the obtained results.

4.6. Programming of the unlimited scenario algorithm and explanation of the operation method

Finally, the last aspect which was previously described as improbable with the data input and the optimization of the operation magnitudes was the possibility of recreate the desired number of different scenarios in one simulation, making the optimizing algorithm and the general control adopting the correct and necessary changes in order to operate optimal the network in a new situation. So as to undertake the programming of this idea, firstly it was decided the method which will be used for be able to define different scenarios and the program could recognize the input data of each scenario separately. The best way to do it and making the definition of the data easier and feasible was using the possibility of create multiple sheets on an Excel document. Establishing the first two sheets as one for the topological definition of the grid and the other one as the nominal values of it, the rest of the created sheets would become the different scenarios and changes that would has to bear and adapt the network.

Once decided how to make it work, was necessary to express it into a code which would make it possible. To do what was established it will be necessary read the Excel file in other form like was read in the start. At the beginning of the code was used the *xlsread* function for import all the data information. Now, since the new method is implemented, the data for the changes would have to be read sheet by sheet when the simulation period starts after the end of the simulation of the initial conditions, which will receive the data like always. In order to read only one sheet of the Excel file, first it will be necessary to have all the information of how many sheets will have the file and what name will receive each sheet in order to distinguish them. The tool which permits to obtain this desired information was the *xlsfinfo* Matlab function.

This function is able to obtain a text array of all the sheets names. With this array obtained is possible to know all the information that was needed. First, with the name of the sheets it is now possible distinguish all the different scenarios. The unique change that would have to be done is pass this text array to a string characters. To do that, into the *for* loop that is necessary to separate the simulation of the different scenarios a code line will be configured to extract the name of the sheet of the scenario that will be simulated and convert it into a string character.

Otherwise, the number of sheets that will have the Excel file, will be possible to know with the Matlab functions *size* or *length* about the text array obtained by the *xlsfinfo* function. After that, the number of scenarios will be the total number of sheets minus one, because the first sheet defines the topologic characteristics of the grid. With these calculations, the number of scenarios will be the nominal values scenarios plus so many scenarios that it is wished make.

```
[type,sheetname] = xlsfinfo('OPFvar.xlsx');
m=size(sheetname,2);
% Start of the loop which separate the different scenarios
for(k=2:1:m);
  [...]
% Converting process to a string variable and creation of the
scenario data reading it from the principal Excel file.
Sheet = char(sheetname(1,k)) ;
matrix = xlsread('OPFvar', Sheet);
```

With this simple method now is possible to separate the different scenarios and simulate them separately, making many changes as scenarios was defined. Once in the loop, which goes from the second sheet, where are determined the nominal parameters, to the determined length *m* of the text array, which is the total number of sheets, the definition of all the changing input data variables will be necessary. This definition will come from the reading of the *matrix* variable created in the *xlsread* linked to the specific sheet, which will contend all the information of the scenario. Once the input changing variables will be defined, it is time to make the optimization process and obtain which are the best voltage levels for each node in each new scenario. When the optimizing iteration process ends for the first scenario, the next will start at the point where the last one was finished. This strategy is built here in order to link correctly the scenarios in the dynamic model. So, it is supposed that the next scenario to optimize will be the changing situation after a period of time operating the network on the last optimal assignation.

That is why the start point for the next optimizing process will be the last point evaluated on the network the time before start the new optimization, and that time would be assigned as the start time for the next scenario. In the non-dynamic model, were this idea is firstly implemented, the next optimization simulation will start from the optimization previously made, establishing the idea that will be extrapolated to the dynamic model. Once the iteration process and the definition of the next initial conditions were made, it is time to calculate and present the results. Now, the plots will stand into the for loop because the information of the input data for the scenarios will overwrite along the advancement of the loop process. Therefore, at the end of the simulation now it is presented many figures like many scenarios were simulated. Operating the same network and making different scenarios changing only the power demand is obtained.

Table 4.12: *Magnitudes nominal values established for the operation of the network.*

N	P_{max} [MW]	P_{min} [MW]	E_{max} [KV]	E_{min} [KV]	E_0 [KV]	I_{max} [KA]	I_{min} [KA]
1	-100	-300	400	380	415	1	-1
2	400	0	400	380	405	1	-1
3	400	0	400	380	410	1	-1
4	-150	-150	400	380	440	1	-1
5	-200	-400	400	380	385	1	-1

Table 4.13: *Power variation for each different scenario simulated ordered from the first to the last respectively.*

N	P_{max} [MW]	P_{min} [MW]
1	-100	-100
2	400	0
3	500	0
4	-50	-150
5	-300	-400

N	P_{max} [MW]	P_{min} [MW]
1	0	0
2	350	0
3	350	0
4	-250	-250
5	-300	-400

N	P_{max} [MW]	P_{min} [MW]
1	-200	-300
2	400	0
3	400	0
4	-50	-150
5	-200	-300

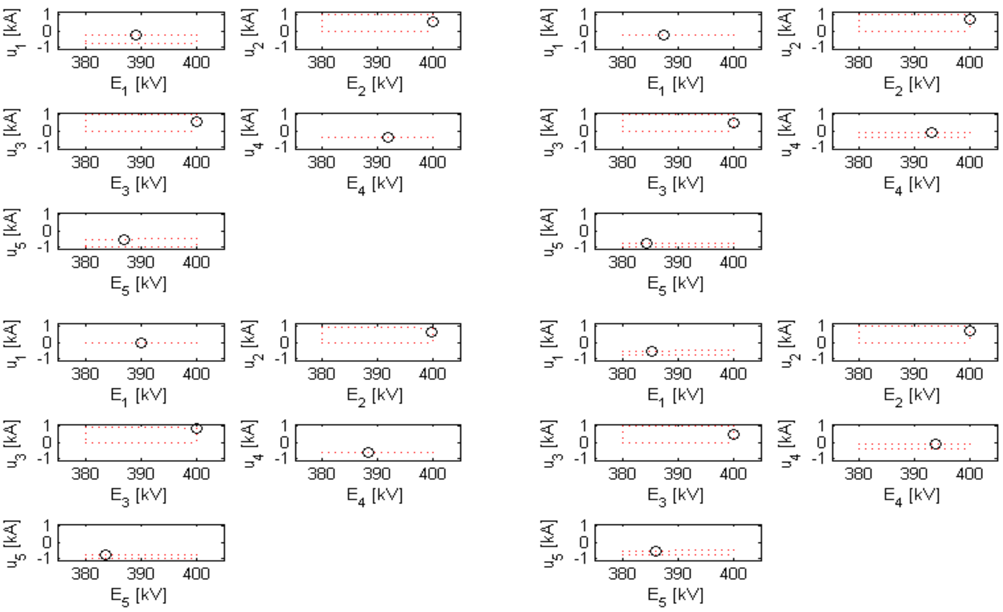

Figure 4.11: *Representation of all the work points selected by the Optimizing algorithm for each node in all the changing scenarios programmed.*

At the end of the simulation it is possible to observe how the optimizing algorithm has been changing the voltage levels of all the nodes for change the workpoint in order to adapt the grid to the different situation purposed in the changing situation. In this case, only changing the power demand and generation was possible to implement another complete different situation of operation. In the general model, it will be possible to change any magnitude in any scenario in order to establish a specific value in a determinate moment of the simulation, and once this scenario was finished, have the possibility of return it to its nominal range. In the last simulated model, the only variable that would be changed by the user along the simulation was the power. If at the start of the simulation, in the input data was imposed that a certain node had to remind in a specific voltage value imposing it, along the simulation this node will be operate at this voltage level, without the possibility of changing it. However, this model is not the wanted. The idea of making the input data like was explained is to offer the possibility of manage all the variables which affects to the network and changing them and the potential impositions whenever the user wants. To be able to do that, the voltage and current readings would have to be included in the for loop as in this model were the power data lectures. With this modification it would be possible manage the grid manipulating not just the power generation and demand but also changing the voltage and current levels and intervals too.

In conclusion, once this mechanism is implemented in the general dynamic model with the specified modifications, there will be possible to manage the simulating process like the user want, variating the operating situations with complete freedom, and linking perfectly the scenario changes with the definition of the initial conditions at the end of the loop, making the model continuous and realistic.

4.7. Implantation of the Optimizing Algorithm created in the dynamic model

Once the building process of the optimizing algorithm has ended and all the detected improvements have been made, it is time to introduce all these improvements and modifications into the model which simulates the network realistically and control it. To could do it, it will be completely necessary introduce all the simulation mechanisms of the generic model into the for loop created in the scenario changing system. Therefore, until the optimizing part the code and the steps will be the same inside the loop with one added necessary specification. Now being a dynamic simulation, it is necessary to specify at which instant of time the scenario will end and start the next one. This specification will be implemented as the reading of the other parameters that will change along the simulation. When the optimizing process will end and the desired voltage for the scenario will be defined, which is the process that was made in the non-dynamic model, it is time to inform the general control of the results obtained by the optimizing algorithm. For doing that it is only necessary assign a relationship between the desired voltage variable of the general control *Eo* and the result variable of the optimizing algorithm *V*. Assigning the results of the variable *V* to the *Eo* variable, will finish the optimizing process in the dynamic model for the scenario. Now after have determined the best working points, it is time to the general control to manage the grid to them if it is permitted. The control will carry the voltage values to the desired values assigned by the algorithm once the grid will be stablish. If it is not possible, the control will determine a point which would compliance the current constraints and will be stable. This scenario would entail the worst situation because it would indicate that the desired scenario will not have a solution that accomplishes all the constraints, which is what was studied in the solver selection. In this case, the optimizing algorithm will define the working points depending on the priorities that were viewed in the solver selection part and after that, the general control would saturate the current flow into the limitations and variate the voltage if it were necessary. This saturation current of the control would entail a non-cover of the power demand of a node or some nodes, meanwhile a change of voltage levels would entail a non-optimal operation. Nevertheless, the control of current is necessary to prevent incidences, so with the control activated, if the variation of the operation levels does not vary so much, this will continue to be the best situation attended to the make compliance of the specified current levels. On the other hand, if the purposed scenario has a solution, the control will have not to have any problem with the assignation and will have to implement the solution of the optimizing algorithm, which would make the network remind stable and with the lowest power losses, which would be the best managing situation. Once the simulation process of a scenario will be concluded, it will be necessary save all the data outputs in order to represent them in the final results. It is a new necessity because when another scenario will start, all the previous results saved in the used variables in the calculus will be overwritten with the new results of the new scenario simulation. Without saving the results after a scenario simulation, it will be impossible to graphic and visualize the grid evolution. This saving process will entail a much waste of time for the simulating process, but turns necessary since the implementation of the scenario changing method. To sum up the final voltage levels obtained in the last instant of time in that scenario will be declared as the initial points of the next scenario.

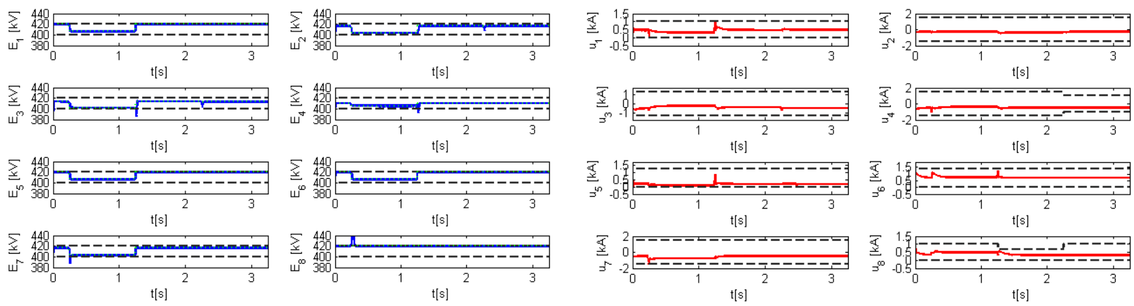

Figure 4.12: *Example of simulation results of voltage (left) and current (right) magnitudes with different changing scenarios in the new model.*

CHAPTER 5: Numerical Simulations

Once ended the implementation of the optimizing algorithm created, is time of view the results and the improvements this tool and the other modifications made in the primary model have provided the entire control system. For doing and analyse that it will be defined a specific model which will be used along the chapter in the regular simulations. Due to the improvement of the input data method, it is complicated establish the same scenario simulated with the old model. This is because in the old model only were delimited the maximum levels of the nodes magnitudes and there was not the possibility of determine a specific intervals. If is intended to implement the scenario of the old model in the new model, stablishing only the maximum levels upper and under zero, because one of the limits of the node will always be at zero for all the nodes. the system will conclude that the best power losses result will be that all the nodes will remain at zero current flow. This scenario was possible to simulate in the old model because the voltages were imposed by the user. Now, the voltage levels are chosen by the optimizing algorithm in relationship with the minimization of the power losses. For this reason, the comparison with the same scenario of the old model is discarded and it will make a studio independent of the old model, because the unique form of doing it implicates restringing the voltage limits and it will minimize the optimizing algorithm efficiency. Otherwise, if the new model is applied, the system would carried at the minimum voltage difference in order to stablish the low current flow and it will not have any similarity with the old model scenario. Without the possibility of compare the same scenario with all the security that it will be the same, below it is shown how it looks and in which form it is a better programme and a better simulating tool.

5.1. Presentation of the final result

Now on the dynamic model, following the electrical lines schematic established, there will be necessary to determine the resistance, as well as in the network model of the optimization algorithm, and the inductance values. These values will be proportional with the length of the line. Being possible to view them in the schema represented on the Figure 5.1.

Table 5.1: *Topologic configuration of the network which will be simulated with the new simulating model.*

N_s	N_a	R [Ohm]	L [mH]	iniL [KA]	Lenght [km]	rdc [Ohm/km]	ldc [mH/km]
1	2	8	764	0,5	40	0,2	19,1
2	3	6	573	0,6	30	0,2	19,1
2	5	20	1.910	-0,4	100	0,2	19,1
2	6	60	5.730	-0,1	300	0,2	19,1
4	7	35	3.342,5	-0,1	175	0,2	19,1
4	8	30	2.865	-0,3	150	0,2	19,1
5	6	10	955	0,1	50	0,2	19,1
6	7	6	573	0,6	30	0,2	19,1

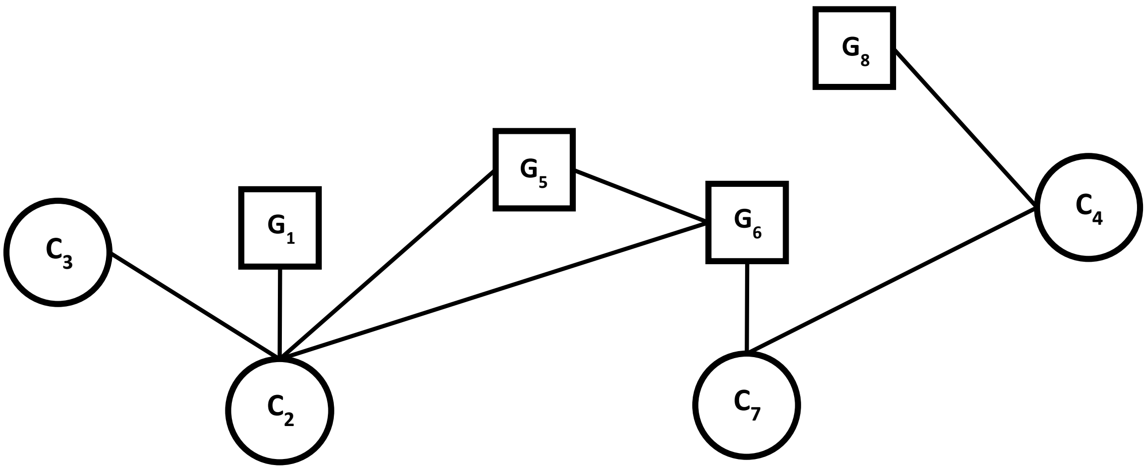

Figure 5.1: *Schematic representation of the topological constitution of the network simulated.*

Now the grid that will be operated is bigger than the used for the proves of the optimizing algorithm, which would implicate a more difficult model. This topological configuration is the same which was simulated with the old model. The difference now will be that it is completely possible control all the magnitudes values, and establish some different scenarios with the possibility of define which is expected to happen.

Table 5.2: *Definition of the nominal nodes delimitations, values of the constituent components and network control parameters.*

N	P_{maxN} [MW]	P_{minN} [MW]	I_{maxN} [KA]	I_{minN} [KA]	E_{maxN} [KV]	E_{minN} [KV]	E_0 [KV]	C [μF]	iniC [KV]	k
1	500	0	1	0	420	400	400	75	400	1
2	-100	-300	1,5	-1,5	420	400	417	75	400	1
3	-200	-300	1,3	-1,3	420	400	409	75	400	1
4	-200	-400	1,5	-1,5	420	400	413	75	400	1
5	350	0	1,2	0	420	400	400	75	400	1
6	500	0	1,4	0	420	400	405	75	400	1
7	-200	-600	1,5	-1,5	420	400	400	75	400	1
8	600	0	1	0	420	400	410	75	400	1

Table 5.3: *Definition of the limitations for the first changing scenario desired.*

N	P_{max} [MW]	P_{min} [MW]	I_{max} [kA]	I_{min} [kA]	E_{max} [kV]	E_{min} [kV]
1	400	0	1	0	420	400
2	-100	-150	1,5	-1,5	420	400
3	-100	-300	1,3	-1,3	420	400
4	-100	-400	1,5	-1,5	420	400
5	200	0	1,2	0	420	400
6	500	300	1,4	0	420	400
7	-300	-600	1,5	-1,5	420	400
8	600	200	1	0	420	400

Table 5.4: *Definition of the limitations for the second changing scenario desired.*

N	P_{max} [MW]	P_{min} [MW]	I_{max} [kA]	I_{min} [kA]	E_{max} [kV]	E_{min} [kV]
1	500	0	1	0	420	400
2	-150	-300	1,5	-1,5	420	400
3	-150	-300	1,3	-1,3	420	400
4	-200	-400	1,5	-1,5	420	400
5	350	0	1,2	0	420	400
6	500	0	1,4	0	420	400
7	-200	-600	1,5	-1,5	420	400
8	600	0	0,7	0	420	400

Table 5.5: *Definition of the limitations for the third changing scenario desired.*

N	P_{max} [MW]	P_{min} [MW]	I_{max} [kA]	I_{min} [kA]	E_{max} [kV]	E_{min} [kV]
1	500	0	1	0	420	400
2	-100	-300	1,5	-1,5	420	400
3	-200	-300	1,3	-1,3	420	400
4	-200	-400	1	-1	420	400
5	350	0	1,2	0	420	400
6	500	0	1,4	0	420	400
7	-200	-600	1,5	-1,5	420	400
8	600	0	1	0	420	400

Table 5.6: *Instants of time defined for the end of the scenario and the change of operation configuration.*

Table of time			
t_0 [s]	t_1 [s]	t_2 [s]	t_3 [s]
0,25	1,25	2,25	3,25

In the above tables presented the nominal defined values of grid as well as the different scenarios that are wanted to be simulated can be seen. As shown on the tables easy scenarios without heavy requisites are about to be simulated. This is only for analyse and view the first impression of the new system in front of the results and the behaviour of the previous model. In the first change it is obligated to some generation nodes to generate a minimum power, meanwhile the minimum power demand of some demanding nodes is lowered. In the second change the majority of the nodes return to their nominal power intervals except for the second, whose minimum demand is 50 MW higher than the nominal. Increasing to 50 MW the minimum demand respect the previous scenario in the third node but continues to be a lower level than its nominal value. On the other hand, the current flow in the generation point number 8 is limited to 0,7 KA. Finally, on the third scenario all the values and limitations return to the nominal levels.

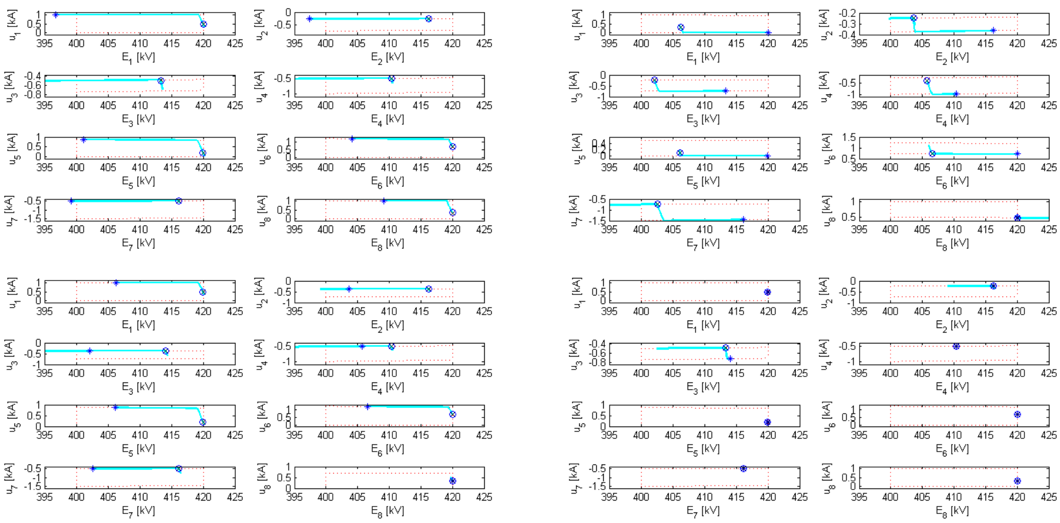

Figure 5.2: *Evolution of the workpoint along the simulation period for each node in all the scenarios. The start point is indicated by a diamond mark, meanwhile the final point is marked by a circle. The cross mark indicates the desired point of work defined by the optimizing algorithm. Order: 1st Scenario: Top Left; 2nd Scenario: Top Right; 3rd Scenario: Bottom Left; 4th Scenario: Bottom Right.*

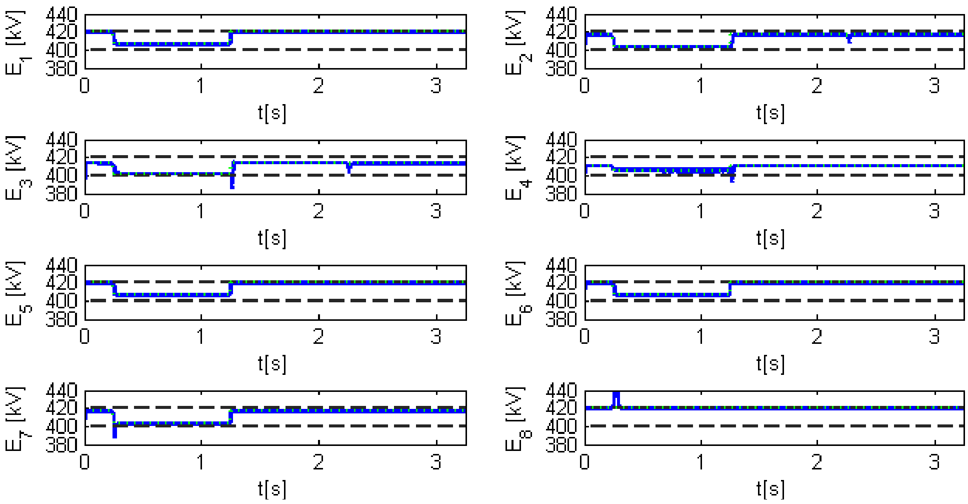

Figure 5.3: *Evolution of the voltage levels for each node along the simulation of all the programmed scenarios.*

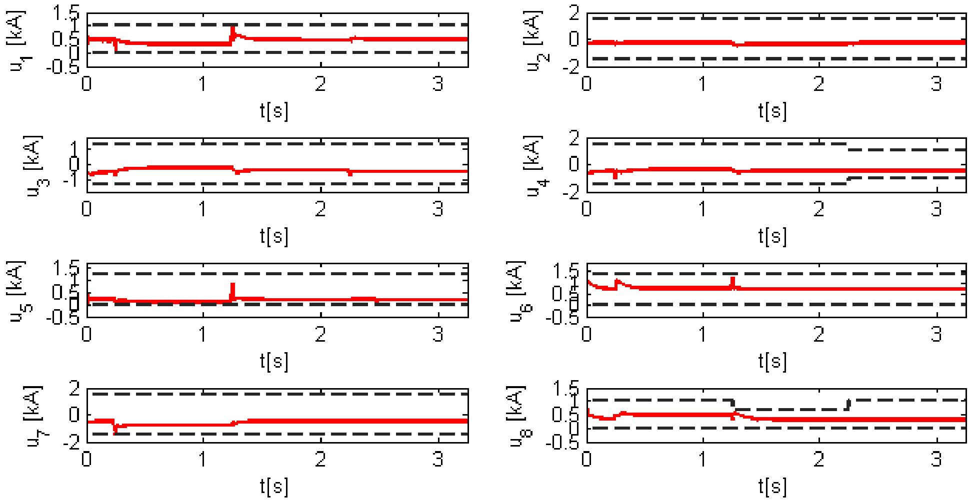

Figure 5.5: *Evolution of the current levels for each node along the simulation of all the programmed scenarios.*

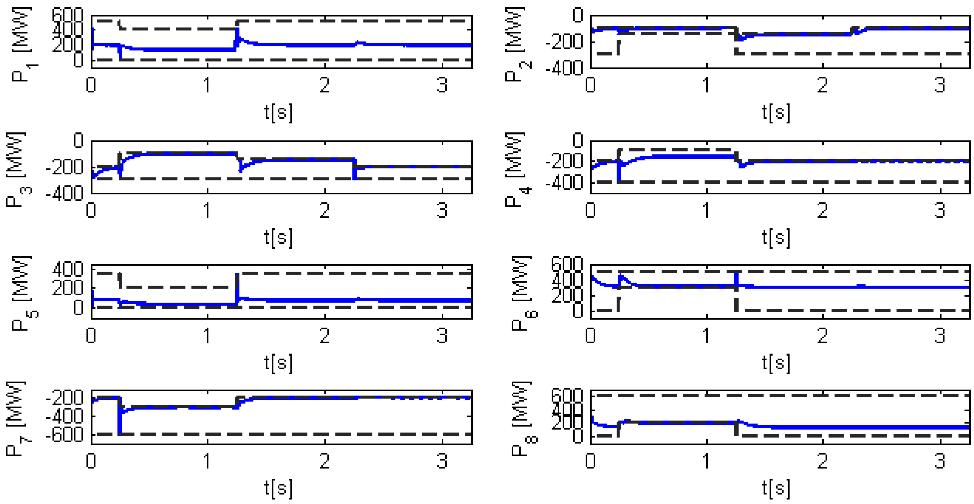

Figure 5.6: *Evolution of the generation and demanding power for each node along the simulation of all the programmed scenarios.*

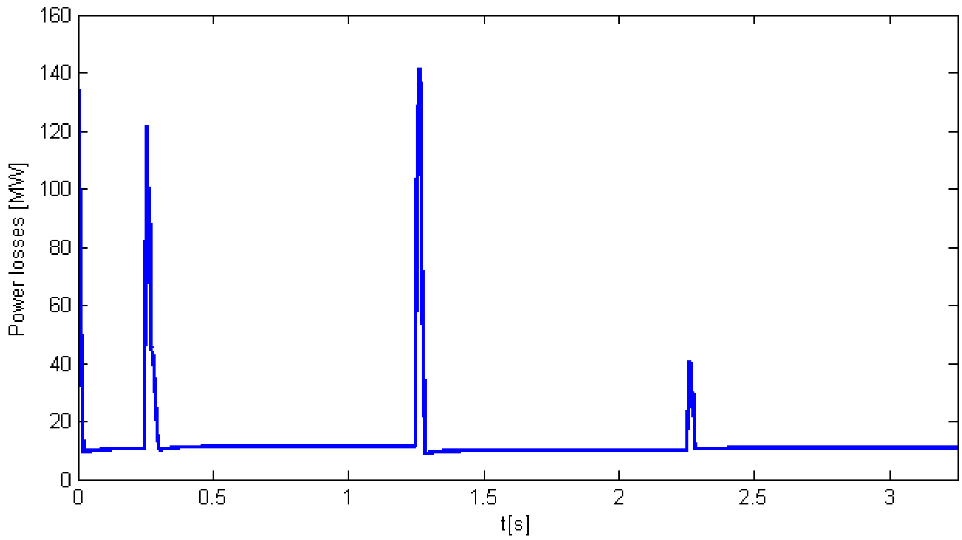

Figure 5.4: *Evolution of the power losses optimized results along the simulation of all the scenarios.*

Once the results presented in the previous five figures it is time to view and analyse the performance of the grid along the simulation of the specified scenarios. As the impositions were not restrictive enough the control of the network had much more freedom to operate it without any problem and any necessity of changing the operation levels constantly. In the first figure presented, Figure 5.2, there is shown the evolution of the working point for each node on each scenario simulated. This graphics are useful in order to interpret the performance that the control uses along a specific scenario. In this figure is possible to observe how the control carries the working point into the working area, as it happens at the start of the simulation, where the control elevates the voltage values from low values to values which are close to high limitation. When the point is into the working area, the control intends to maintain it into these bounds. It seems if the point goes out of the working area it owing to the start of a changing scenario. Meanwhile in a change of the operating situation the new determined operating values are stablished. There is a variation of voltage levels in some nodes, which is possible to be viewed in the figure 5.3. These variations are represented in the work point graphics whose network seems to have been operated out of the working area. The graphics show the complete path of the working point that the node has been working, but do not differ from the time the node has been operating at this point. That is why the figure 5.2 has to be complemented with the next one. In the figure 5.3 the evolution of the voltage level for each node along all the scenarios is represented. Here it is possible to observe that these variations commented were only instantaneous surges produced by the change of operating configuration. Moreover, in this figure there is represented how the control carries the nodes to work in the specified voltage levels which indicates the optimizing algorithm represented in the figure 5.3 with the green dotted line. Thereby, in this simulation, because all the proposed scenarios could be solved, the control has followed the indications of the optimizing algorithm.

In terms of current and power, which are represented on the figures 5.4 and 5.5, it seems that the power demand has been completely satisfied because the power line representation has always been between the maximum and minimum established bounds. In this case, not a single demanding node has demanded an exactly value of power, which would be represented by the superposition of the two black lines that indicates the delimitations. When it would occur, the unique form of accomplish this type of demand would be offering and cover this power levels, that would be represented with the superposition of the evolution line with the delimiting lines. In the current representation, it is possible to observe that the generation points are the nodes which inject current into the grid, establishing a positive fluctuation of current, and are the demanding nodes which have the negatives values of current, which indicates that are consuming this current injection made by the generation points. In terms of saturation, in this scenario the control have not to make any limitation because the current flow did not surpassed de delimitations established.

Finally, the last figure presented indicates the evolution of the power loss along the simulation in the transport of the energy from the generation points to the demanding nodes. Because the optimization had been 100%

successful, these results are the optimal that would be obtained. Once the network has been stabilized, there is no other operating configuration that could obtain a representation under the levels that are presented there. Otherwise, could be possible that other configuration would get lower instantaneous heavy increases of losses because of the scenario changing, but in the overall of all the scenarios, the result would be always worse than the obtained with the configuration determined by the optimizing algorithm.

5.2. Performance of the optimizing algorithm and the entire system in front an extreme scenario into the dynamic model

Having run and presented the look of the new model and which operating options it offers, it would be interesting to force the optimizing algorithm and the general control to intend to performance an extreme and complicated scenario and view which priorities will have each other and if the suggested model of the optimizing algorithm is respected in that case. To do it so, the same electrical grid which was used in the selective studio of the algorithm solver will be simulated, such scenarios of that analysis and others that will force complex situations. In this way, a restrictive scenario would make some power demands at a lower interval while anothers that would have a huge amount of demand or a decrease in the capacity of current fluctuation. With the imposition of the exact power demand of some node it is wanted to view the priority of the optimizing algorithm for intend to cover it, which was demonstrated in the solver selection that the SQP algorithm always prioritized the power demand cover in front other restrictions. Knowing that the scenario provably would not have a solution, it will be interesting which would be the performance of the general control once it have the purpose of the optimizing algorithm. On the other hand, with the current saturation, if the demand of power requires a higher current flow than the maximum permitted, it will be seen how the control delimits this current fluctuation and the demand will not probably be covered. After that, it will be simulated the previous network used with the dynamic model whose control would be much more difficult due to its size. For this reason force the grid to work in a specific value of any magnitude could entail in a non-stable situation. If it is wanted to establish an exact value, it would be necessary give the control more leeway for action in other magnitudes. For that reason, in the simulations of that grid a more restrictive scenario than was did first in this chapter will be simulated, but without fixing with an exact value any magnitude.

So firstly, it is going to be simulated the grid used in the non-dynamic model for made the optimizing algorithm selection solver process. Now, for extrapolate this grid into the dynamic model, it will have to be configured as well as was the first grid that was simulated in the dynamic model. Thereby, in order to implement the same topological configuration network and enter it into the dynamic model, the input table will look like the presented Table 5.7.

Table 5.7: *Topologic configuration of the five node network which was implemented in the non-dynamic model adapted for the dynamic simulation.*

N_s	N_a	R [Ohm]	L [mH]	iniL [KA]	Lenght [km]	rdc [Ohm/km]	ldc [mH/km]
1	2	30	2.865	0,3	150	0,2	19,1
1	5	20	1.910	0,5	100	0,2	19,1
2	5	60	5.730	-0,2	300	0,2	19,1
4	5	24	2.292	-0,4	120	0,2	19,1
3	4	14	1.337	-0,2	70	0,2	19,1

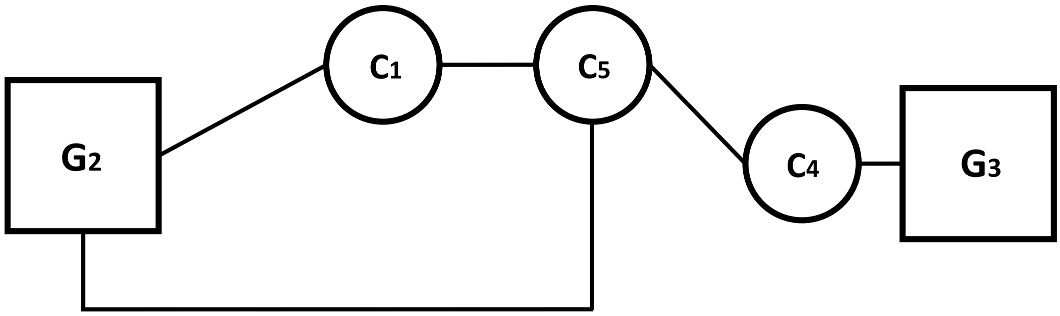

Figure 5.7: *Schematic representation of the topological constitution of the five node network that will be simulated.*

Table 5.8: *Definition of the nominal nodes delimitations, values of the constituent components and network control.*

N	P_{maxN} [MW]	P_{minN} [MW]	I_{maxN} [KA]	I_{minN} [KA]	E_{maxN} [KV]	E_{minN} [KV]	E_0 [KV]	C [μF]	iniC [KV]	k
1	-100	-300	1	-1	420	400	400	75	400	1
2	400	0	1	-1	420	400	417	75	400	1
3	400	0	1	-1	420	400	409	75	400	1
4	-100	-150	1	-1	420	400	405	75	400	1
5	-200	-400	1	-1	420	400	409	75	400	1

Table 5.9: *Definition of the limitations for the first changing scenario desired.*

N	P_{max} [MW]	P_{min} [MW]	I_{max} [kA]	I_{min} [kA]	E_{max} [kV]	E_{min} [kV]
1	-200	-300	1	-1	420	400
2	400	0	1	-1	420	400
3	400	0	1	-1	420	400
4	-150	-300	1	-1	420	400
5	-700	-800	1	-1	420	400

Table 5.10: *Definition of the limitations for the second changing scenario desired.*

N	P_{max} [MW]	P_{min} [MW]	I_{max} [kA]	I_{min} [kA]	E_{max} [kV]	E_{min} [kV]
1	-100	-300	1	-1	430	400
2	300	300	1	-1	430	400
3	400	0	1	-1	430	400
4	-150	-150	1	-1	430	400
5	-150	-300	1	-1	430	400

Table 5.11: *Definition of the limitations for the third changing scenario desired.*

N	P_{max} [MW]	P_{min} [MW]	I_{max} [kA]	I_{min} [kA]	E_{max} [kV]	E_{min} [kV]
1	-200	-500	1	-1	410	410
2	400	200	1,5	-1	430	410
3	300	200	1,5	-1	430	410
4	-100	-250	1	-1	410	410
5	-300	-500	1	-1	410	410

Table 5.12: *Instants of time defined for the end of the scenario and the change of operation configuration.*

Table of time			
t_0 [s]	t_1 [s]	t_2 [s]	t_3 [s]
0,25	1,25	4	5

Analysing all the proposed scenarios, in the Table 5.8 there is defined the nominal values of the grid, which will be the normal levels of work for each magnitude, and the grid would perform perfectly to ensure in these values. Straightaway, the first change would entail the grid into a situation of a massive power demand from the fifth point. Because the current limitations would remain at the same values, probably the current saturation would not permit that this demand would be satisfied. Therefore, in this scenario it could be viewed how the control would actuate in terms of delimiting the current flow.

In the next scenario an exactly generation power level one generation node and one demanding node will be fixed. Fixing these two points it would entail a more restrictive situation and a lower operating margin, which could result in a non-stable situation. In order to prevent that the system could enter in an unstable operation were increased the maximum voltage permitted, establishing a margin of 30 V between the maximum and minimum levels.

Finally, the last scenario is the same *Case 6* studied in the evaluation algorithm process. This scenario obligates the generation nodes to produce a minimum amount of energy meanwhile it fixes the operation voltage levels for the demanding nodes, which only permitting the control and the optimizing algorithm to manage the generation points.

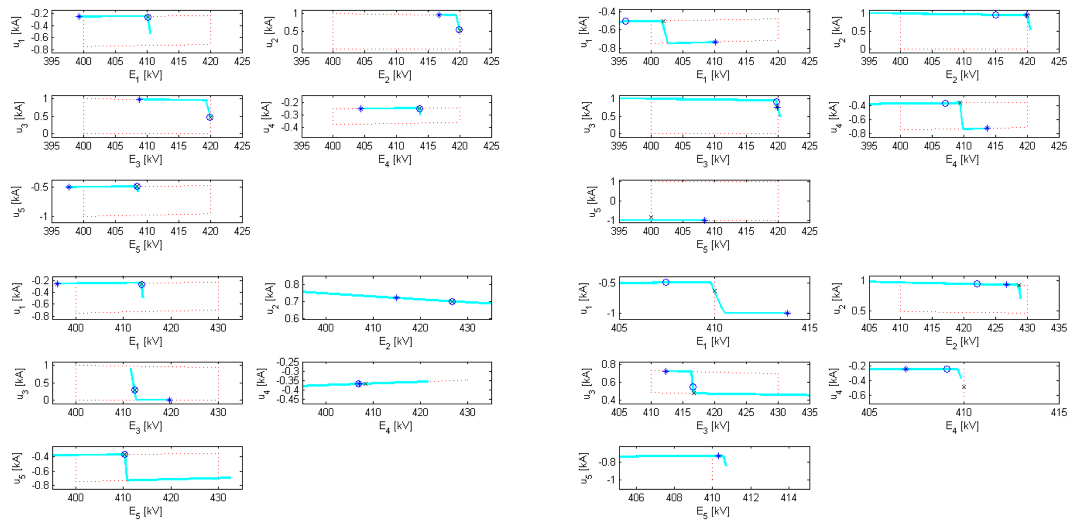

Figure 5.8: *Evolution of the workpoint along the simulation period for each node in all the scenarios. The start point is indicated by a diamond mark, meanwhile the final point is marked by a circle. The cross mark indicated the desired point of work defined by the optimizing algorithm. Order: 1st Scenario: Top Left; 2nd Scenario: Top Right; 3rd Scenario: Bottom Left; 4th Scenario: Bottom Right.*

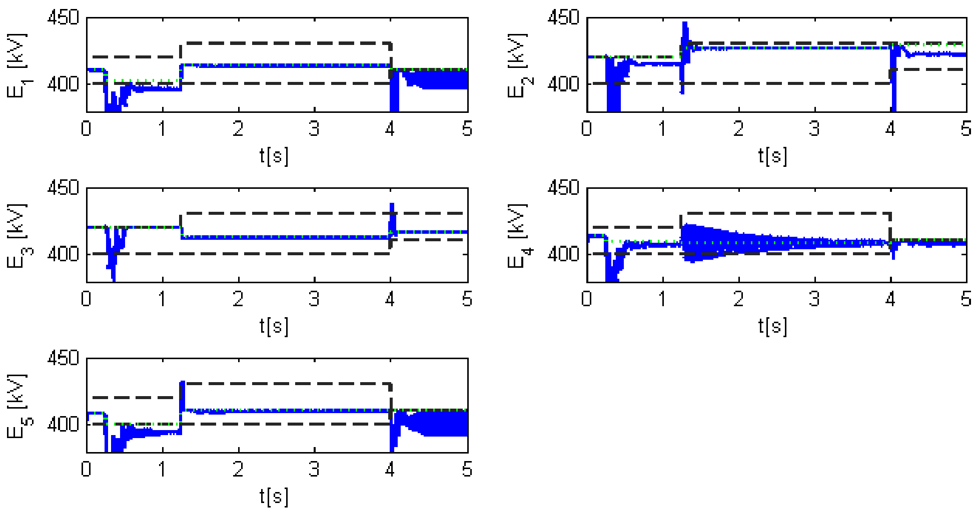

Figure 5.9: *Evolution of the voltage levels for each node along the simulation of all the programmed scenarios.*

After having presented the work point graphic and the voltage evolution graphic, it would be interesting to extract the first conclusions. Starting from the first defined change seems that the non-accomplishment of the power demand had become a problem. The high demand required a high voltage difference which took the control to decrease the voltage level of the fifth node. Seems that at the end of the scenario, all the voltage levels had get to be stabilized, and only the first and fifth nodes had operated out of bounds, but really close that the minimum and marked voltage desired value. Referring to the second scenario, the second node which was forced to generate a 300 MW of power seems that had not had problems with the stabilization of his voltage level, as well as the other generation point and the more freedom demanding nodes. Otherwise, the node which was forced to demand an exact value of 150 MW had more troubles for reaching the desired voltage level and presented some oscillation, but at the end seems that the point was stabilized. Is for that reason that the simulation time of that scenario was increased in order to claim that the point addressing his voltage level to a stablish value. Moreover than addressing its voltage level to a stablish level, the node seems to establish itself in the desired voltage determined by the optimizing algorithm. Finally, the defined as the *Case 6* was the scenario which had made incur the system into a non-stablish situation. Of the three values where the voltage level were fixed, only in the fourth node the voltage was able to address its value to a stablish levels, and were not perfectly. The only perfectly voltage levels established in the scenario were the voltage determined freely by the optimizing algorithm. On the first and fifth nodes, where the voltage value were fixed as on the fourth demanding point, the operating voltage incurred into a permanent oscillation that would make the grid uncontrollable and useless.

It looks like that as a result of the EXITFLAG success of the optimizing algorithm, the network is capable to stablish itself into the limitations, how it could not be otherwise. In the first and last change, the result of the optimizing algorithm for these two scenarios was -2 for both of them. On these scenarios almost one of the voltage levels of a determined node was out of the delimitations instead the optimizing algorithm assigned a value into the delimitations. This fact is a consequence that the optimizing algorithm was not able to obtain a resolution for the problem because it would not exist. Having no solution implicates that the power demand will not be possible to be covered, which carries the grid to intend to cover it creating a high voltage differential between the generation nodes and the specific demand. In spite of these non-covering demand problems, the control was able to stabilize the network and make it operable. On the other hand, in the last scenario the imposition of the 60% of the voltages and the power demand associated to these nodes made firstly the grid unable to provide all these amount of energy to the demanding nodes, and besides, enforced an oscillation situation that would entail with the non-operability of the network, in contrast to the viability of the operation in the first changing scenario.

In conclusion, it seems that it would be possible operate a grid despite the desired scenario would have no solution, on the condition that the operability of it would be flexible and the voltage values stabilized would be close with the maximum or minimum bounds. Obviously, is for sure which the operation of one of these scenarios would implicate the non-coverage of some demanding powers of any node.

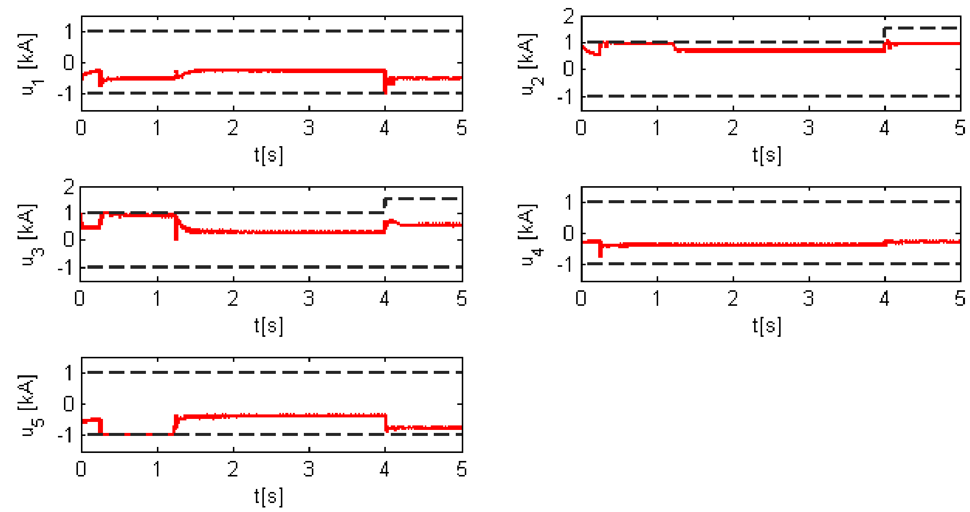

Figure 5.10: *Evolution of the current levels for each node along the simulation of all the programmed scenarios.*

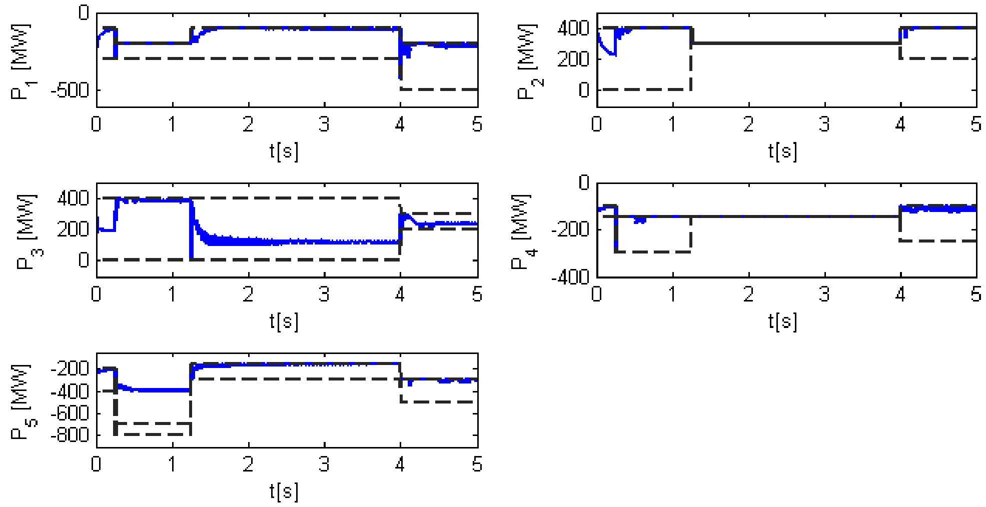

Figure 5.11: *Evolution of the generation and demanding power for each node along the simulation of all the programmed scenarios.*

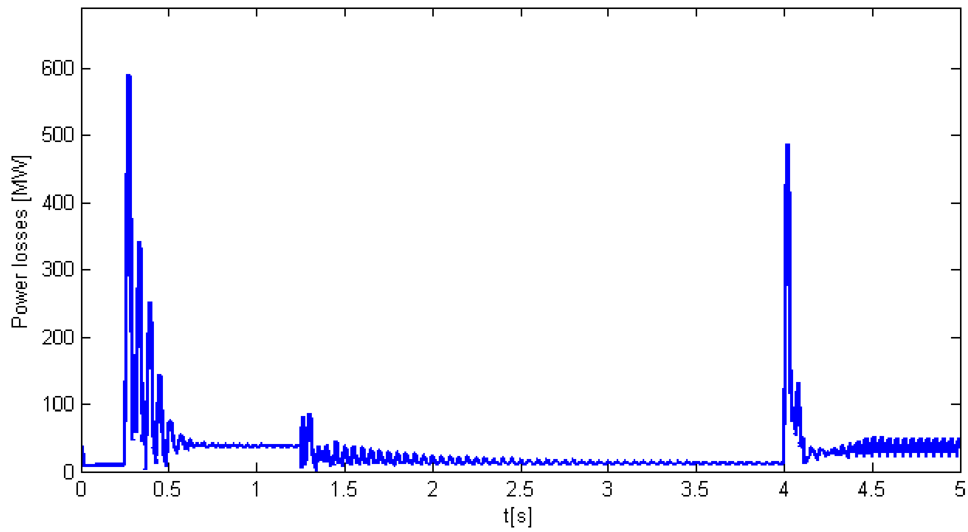

Figure 5.12: *Evolution of the power losses optimized results along the simulation of all the scenarios.*

Seeing the above results which the simulation had obtained, now it is possible to view the consequences of the non-complete compliance of the scenarios purposed. Starting with the first changing scenario, the power results show that both generation nodes were offering to the grid the maximum power which were able to made, meanwhile the nodes one and four consume the minimum power that were assigned to them. That was because the demand of the fifth node was determined at a much higher value than the nominal, establishing a huge power demand. This huge demand is visible in the power graphics, were the limitations were moved since the interval [-200, -400] to the interval [-600, -800]. In order to cover this demand, the power evolution graphic representation would have to be into this area delimited by the two black dotted lines, which demarcate the demanding power zone. As is shown in the power graphic of the fifth node, the power received in that point of the grid is not enough for accomplish the minimum demand. This is because the current saturation imposed by the control. This saturation is shown in the current graphics on the fifth node representation, where is viewed how the current fluctuation is delimited exactly at the defined point in the input data. Finally, according to the power losses in the network for this scenario, in the last presented figure is shown that the first oscillations of the voltages levels of some nodes produced a huge amount of wasted energy. Once the network started to establish itself, the total power losses of the grid decreased until reach to become a constant value.

On the next scenario, in terms of current and power, all the demand and the limitations were covered and tolerate. There is nothing interesting in the current graphics than the compliment of the delimitations. On the other hand, in the power graphics is shown how the system was able to stablish correctly the exactly generation on the second node and the exactly demand on the fourth node. Besides that, seems that the third node suffered the consequences of the oscillation on the voltage establishment of fourth node, which took a while until be constant, because its power generation seems to have a little curly after been completely constant at the end of the scenario. Concerning the power losses, these were not so huge as the other scenarios at the beginning and despite the oscillations of some nodes were stabilized quickly and in a low total value.

At last, the scenario presented most instability was the simulation of the *Case 6* proposed due to the solver evaluation process. This scenario presented a tremendous oscillation on the voltage magnitudes in the first and fifth nodes. In consequence was determined that the grid could not be operated at these conditions. Looking at the power losses results for this scenario, the graphic shows that because these oscillations the power losses oscillate too and could not remain constant. Comparing the dynamic results obtained on the dynamic simulation and the theoretical results of the calculations on the optimizing algorithm, it is observed because the continuous oscillation of some nodes, the grid was able to accomplish all the demands of power, meanwhile in the theoretical results in this case was impossible to cover the demand of the fifth node implementing the voltage levels designed by the solver.

Table 5.13: *Theoretical power results for the sixth case obtained by the optimizing algorithm.*

P results [MW]	P_{max} [MW]	P_{min} [MW]
-255,07	-200	-500
400,02	400	200
200,20	300	200
-196,97	-100	-250
-127,54	-300	-500

As shown in the Table 5.13, implementing the voltage results defined by the optimizing algorithm, the only node that the grid will be not able to cover the power demand will be the fifth. If it is observed de dynamic simulation, in the representation of the evolution of the power in the fifth node, it is viewed that the minimum demand for the fifth node is covered and guaranteed and more or less in a constant value. This is only possible because average constant value of the oscillation voltage level for the node fifth is lower than the voltage designed by the optimizing algorithm. These median values are out of bounds and are lower than the minimum voltages permitted by the input data, which are not a good solution. Even so, because this value establishes a higher voltage difference between this node and a generation point, the current flow established to the fifth node is higher too, making it possible to cover the demand because the current not surpass the current limitations and is possible to generate sufficient energy. However, this solution still keeps the voltage levels under the permitted levels, which is a non-allowed situation and the system should not be operate like this. It should be noted that in these points the voltage is imposed, that is why a lower value not so far of the nominal minimum values could not produce any problem to the grid, and an increase of the permitted voltage range would be a solution in order to accomplish the demands and operate the grid correctly.

Once finished the simulation of the five node network and obtained a results with non-solution scenarios in order to view the performance of the control and the optimizing algorithm, it is going to be intended make a similar studio with the eight node grid, but intending to accomplish all the scenario, introducing some new aspects into the model which probably give more options to the optimizing algorithm and the control to find a possible solution or in case falls through, a stable situation without oscillations and the maximum covered demands. Establishing the new nominal values of the grid and defining the scenarios that should derivate the performance of the network.

Table 5.14: *Definition of the nominal nodes delimitations, values of the constituent components and network control*

N	P_{maxN} [MW]	P_{minN} [MW]	I_{maxN} [KA]	I_{minN} [KA]	E_{maxN} [KV]	E_{minN} [KV]	E_0 [KV]	C [µF]	iniC [KV]	k
1	500	0	1	0	420	400	400	75	400	1
2	250	-400	1,5	-1,5	420	400	417	75	400	1
3	-200	-300	1,3	-1,3	420	400	409	75	400	1
4	-200	-400	1,5	-1,5	420	400	413	75	400	1
5	350	0	1,2	0	420	400	400	75	400	1
6	600	-300	1,4	-1,4	420	400	405	75	400	1
7	-200	-500	1,5	-1,5	420	400	400	75	400	1
8	500	0	1	0	420	400	410	75	400	1

Table 5.15: *Definition of the limitations for the first changing scenario desired.*

N	P_{max} [MW]	P_{min} [MW]	I_{max} [kA]	I_{min} [kA]	E_{max} [kV]	E_{min} [kV]
1	400	0	1	0	420	400
2	-100	-150	1,5	-1,5	420	400
3	-200	-300	1,3	-1,3	420	400
4	-300	-400	1,5	-1,5	420	400
5	350	0	1,2	0	430	400
6	0	0	0	0	420	400
7	-300	-600	1,5	-1,5	420	400
8	600	0	1	0	420	400

Table 5.16: *Definition of the limitations for the second changing scenario desired.*

N	P_{max} [MW]	P_{min} [MW]	I_{max} [kA]	I_{min} [kA]	E_{max} [kV]	E_{min} [kV]
1	500	0	1	0	440	400
2	-450	-550	1,5	-1,5	440	400
3	-200	-500	1,3	-1,3	440	400
4	-300	-350	1,5	-1,5	440	400
5	300	0	1,2	0	440	400
6	400	0	1,4	0	440	400
7	-400	-500	1,5	-1,5	440	400
8	600	0	1	0	440	400

Table 5.17: *Definition of the limitations for the third changing scenario desired.*

N	P_{max} [MW]	P_{min} [MW]	I_{max} [kA]	I_{min} [kA]	E_{max} [kV]	E_{min} [kV]
1	500	0	1	0	430	400
2	250	-400	1,5	-1,5	430	410
3	-200	-300	1,3	-1,3	430	400
4	-200	-400	1,5	-1,5	430	400
5	0	0	0	0	430	400
6	600	-300	1,1	-1,1	430	405
7	-100	-300	1,5	-1,5	430	415
8	500	0	1	0	430	400

Table 5.18: *Instants of time defined for the end of the scenario and the change of operation configuration.*

Table of time			
t_0 [s]	t_1 [s]	t_2 [s]	t_3 [s]
0,25	1,25	2,25	3,25

Having presented the scenarios that will be intended to be simulated, it is possible to view two concepts that already have not been tried to be introduced in the simulations. The first new idea that is going to be implemented in the simulation is the option of a certain node to actuate as a power generator in some scenarios and like a demanding point in others situations. This would be the case of an interconnection between different countries or regions, that in some moments would need to demand energy because they do not produce the amount that they need, and on the other hand, if they have an overproduction of energy, be able to provide other grids with this surplus of energy generated. Otherwise, the other new idea is the disconnection of a node from generating or demanding power, being cause if it is necessary to disconnect a power plant or if a certain demand will rest disconnected for a while, or in another way, because is wanted to configure the grid with a middle node which would connect more than two points but that it would not generate or demand power. In this simulation, since it is going to be used the primary stablished grid, it will not been configured a middle point, but for a specific scenario it is going to be configured like one an existent node. Moreover, it is going to be simulated a disconnection of a generating plant too.

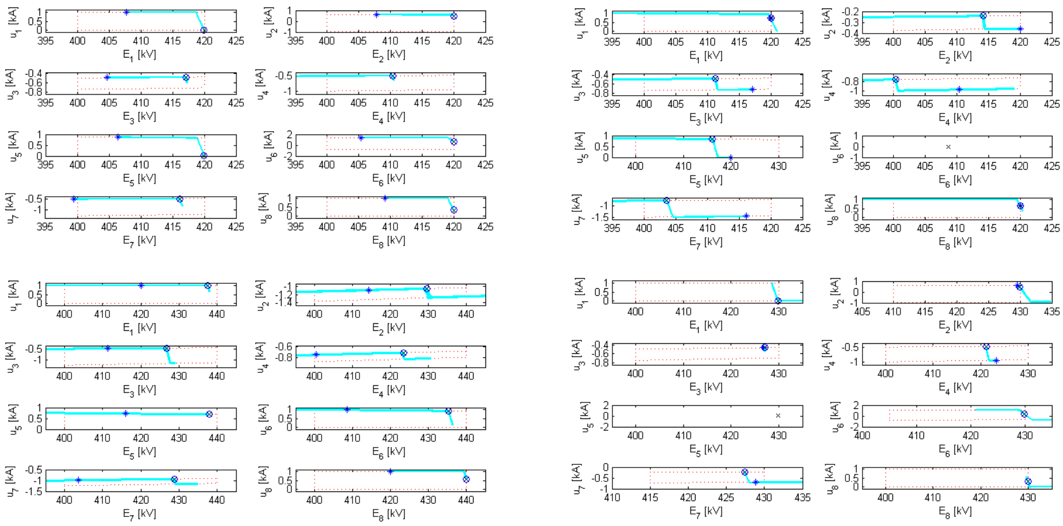

Figure 5.13: *Evolution of the workpoint along the simulation period for each node in all the scenarios. The start point is indicated by a diamond mark, meanwhile the final point is marked by a circle. The cross mark indicated the desired point of work defined by the optimizing algorithm. Order: 1st Scenario: Top Left; 2nd Scenario: Top Right; 3rd Scenario: Bottom Left; 4th Scenario: Bottom Right.*

Once all the changes had been simulated, looking at the voltage graphics and the working point representations, it is deductible which much probable despite the scenarios were stable and at the end the network has remind stable until the next change, these huge oscillations at the start of the scenarios would complicate the correct running of the grid, making an entirely possible dangerous situation because the enormous changing of the voltage levels. However, it is interesting to view how the control system was able to redirect the situation and establish the voltages that the optimizing algorithm was determined. According to the optimizing algorithm, all the scenarios defined in the input data were possible to operate and be solved without problem, and only the last scenario did not get an EXITFLAG equal to 1.

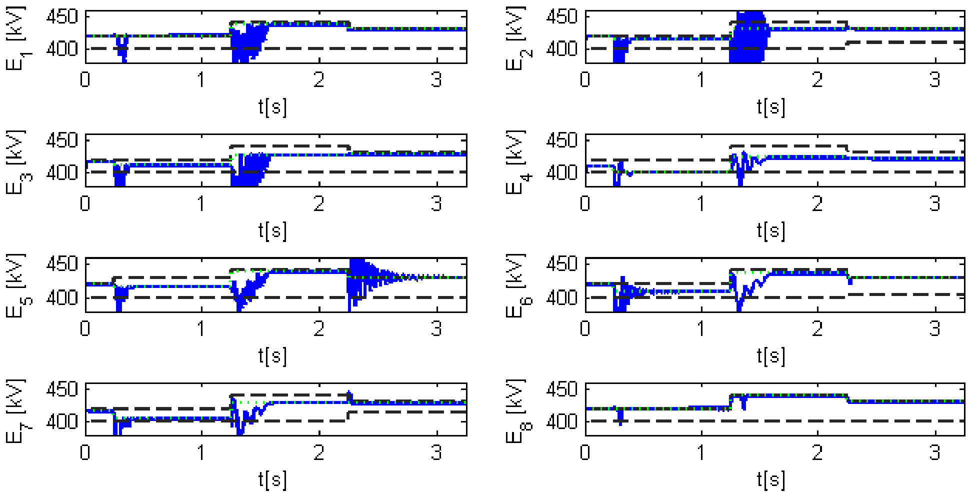

***Figure 5.16:** Evolution of the voltage levels for each node along the simulation of all the programmed scenarios.*

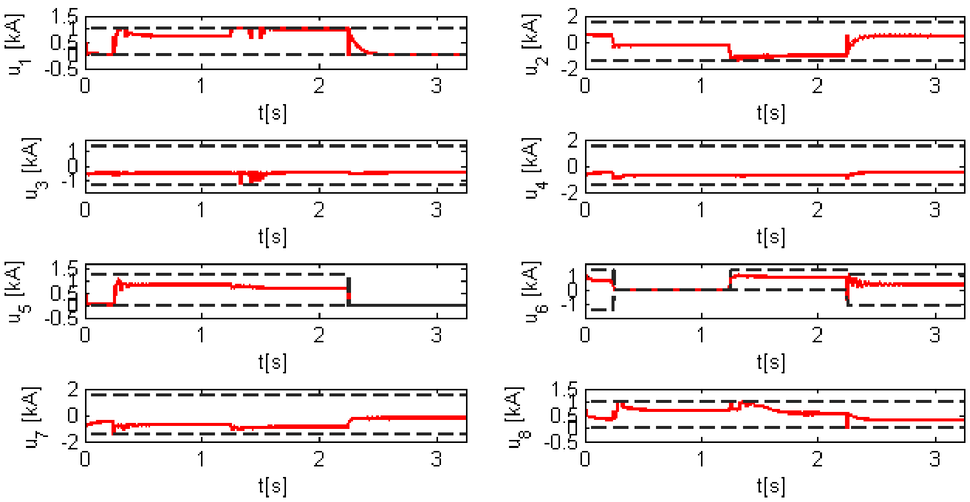

***Figure 5.15:** Evolution of the current levels for each node along the simulation of all the programmed scenarios.*

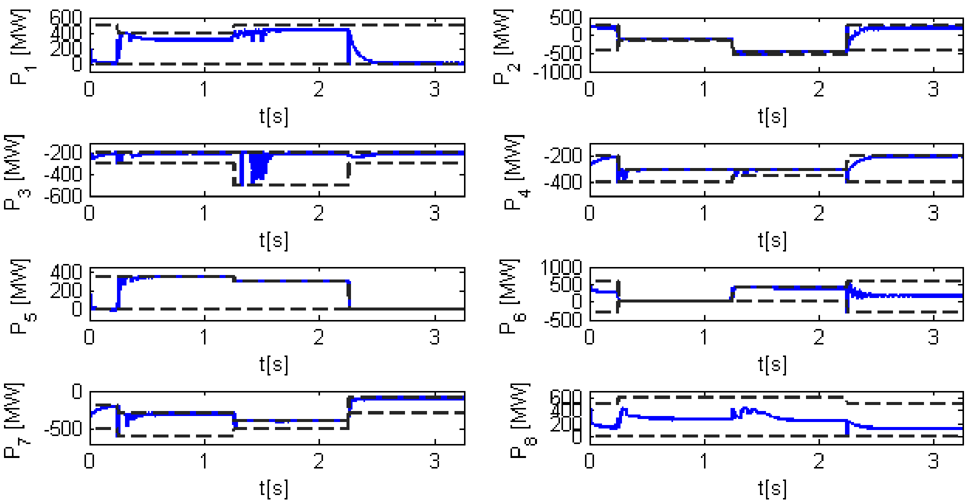

***Figure 5.14:** Evolution of the generation and demanding power for each node along the simulation of all the programmed scenarios.*

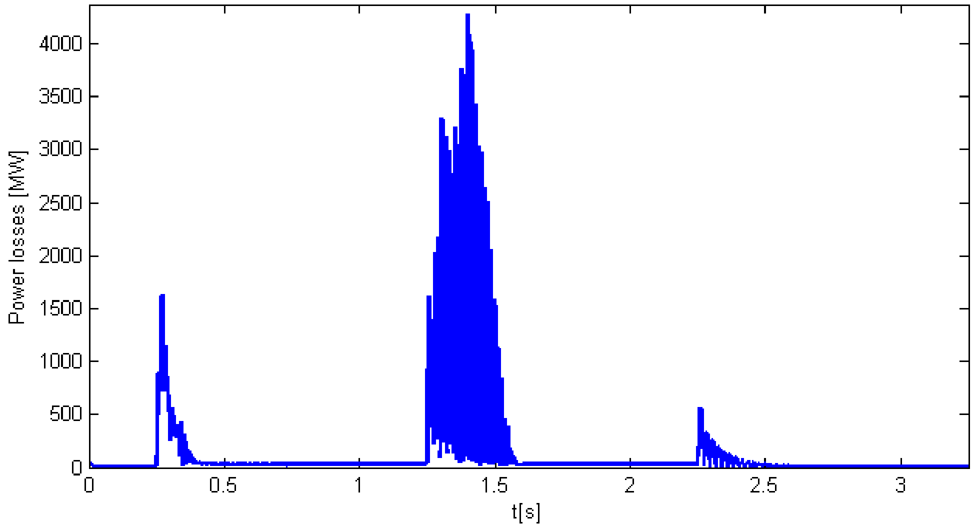

Figure 5.17: *Evolution of the power losses optimized results along the simulation of all the scenarios.*

Entering into the scenario per scenario analysis, in the first case was configured an intermediate non-power interconnection point in the sixth node instead a generation source or a demanding load. This configuration of the node has produced a short oscillation period in the grid that caused a little increase of the power losses and had an effect on the other nodes making them oscillate too for a while. However, at the same time that the sixth node was stabilizing itself, the rest of the grid reached the desired voltage levels and stabilized the grid. Therefore, probably the configuration of an interconnection node would implicate a starting oscillation of the network. Regarding the second scenario, was configured a situation with much restrictive demand than the previous one was configured, however, the sixth node was configured this time as a generation source and the system had not problems in order to cover the demand. Moreover, was increased the voltage management range for secure that the scenario had solution. Once ended, looking at the voltage results is viewed that in the second node a huge oscillation until the control was able to stabilize completely the network had occurred. Probably, due to this oscillations the other nodes had been affected and some of them presented oscillations too. These oscillations would probably implicate the non-possibility of operating the scenario starting with type of node performances, because these voltage drops would entail more than likely some damages in any equipment connected to these nodes. In addition, on account of these voltage drops and the non-brief instauration of a stable performance, the power losses of the grid reached high values and had been oscillating in a continue way, caused by the voltage drops established in the network. Finally, the last scenario simulates a breakdown of the generation point configured in the fifth node. These failure simulation is defined like the configuration of the interconnection point in the first scenario was defined, but in this case, the node only is connected with two other points, which when the voltage will be assigned, because this node is not able to consume or produce current, will be managed at the same voltage as one of these two nodes, making it the same electrical point. This situation is what the optimizing algorithm had determined and the control did. The fifth and the sixth nodes were at the same voltage level when the network was stabilized. How occurred in the first changing scenario, the non-power node started oscillating for after a while, and after having an exponential decrease stabilized its value to the defined by the optimizing algorithm. In this case, not a single node has suffered oscillations caused by the breakdown of the fifth node, and only the sixth node, which was induced to be in the same voltage value, had a smallish voltage drop.

5.3. Comparing the optimizing algorithm results with any other stable configuration possible

Once the complete model and the performance of the optimizing algorithm into the dynamic model has been shown, it is time to verify whether the results obtained by this algorithm are the best which should manage the grid. In order to do that a parallel model was programmed, which instead of find the best voltage configuration for reduce the power losses, makes it first a random voltage assignation and after looks for the stable voltage values closest to these random values for each node, establishing one of the other possible configuration for the scenario. With this simulation a stable situation is obtained. This operation configuration should run correctly the grid. Depending on the scenarios purposed in the input data, the network would have much or less possible voltage assignments that could operate the network. The idea of obtain the optimum configuration of all these possible voltage assignments is to operate and manage the grid in the best way that the scenarios offer. It is the aim of implementing the optimizing algorithm. So as to prove that this algorithm works correctly, it will be compared with any other possible configuration that could fit with the purposed scenarios, and for sure, the energy wasted in the operation of the grid with the optimizing algorithm assignment will be lower than any other result obtained with any other possible configuration for this situation. Obviously, depending on the margin the scenario simulated will offer, the possible configurations would be lower or higher, and depending on that, the new assignment algorithm will have much or less success. With that, it is going to be simulated some non-extreme cases on both two grids in order to view the success of the optimizing algorithm when the control establishes the levels that it determined.

Table 5.19: *Instants of time defined for the end of the scenario and the change of operation configuration.*

Table of time			
t_0 [s]	t_1 [s]	t_2 [s]	t_3 [s]
0,25	1,25	2,25	3,25

Table 5.20: *Definition of the nominal nodes delimitations, values of the constituent components and network control*

N	P_{maxN} [MW]	P_{minN} [MW]	I_{maxN} [KA]	I_{minN} [KA]	E_{maxN} [KV]	E_{minN} [KV]	E_0 [KV]	C [μF]	iniC [KV]	k
1	-100	-300	1	-1	420	400	400	75	400	1
2	400	0	1	-1	420	400	417	75	400	1
3	400	0	1	-1	420	400	409	75	400	1
4	-100	-150	1	-1	420	400	405	75	400	1
5	-200	-400	1	-1	420	400	409	75	400	1

Table 5.21: *Definition of the limitations for the first changing scenario desired.*

N	P_{max} [MW]	P_{min} [MW]	I_{max} [kA]	I_{min} [kA]	E_{max} [kV]	E_{min} [kV]
1	-150	-300	1	-1	420	400
2	300	0	1	0	418	400
3	300	0	1	0	420	400
4	-100	-150	1	-1	420	400
5	-200	-400	1	-1	420	400

Table 5.22: *Definition of the limitations for the second changing scenario desired.*

N	P_{max} [MW]	P_{min} [MW]	I_{max} [kA]	I_{min} [kA]	E_{max} [kV]	E_{min} [kV]
1	-100	-300	1	-1	420	403
2	250	0	0,8	0	420	400
3	450	0	1,5	0	420	400
4	-100	-150	1	-1	420	408
5	-200	-400	1	-1	420	405

Table 5.23: *Definition of the limitations for the third changing scenario desired.*

N	P_{max} [MW]	P_{min} [MW]	I_{max} [kA]	I_{min} [kA]	E_{max} [kV]	E_{min} [kV]
1	-100	-300	1	-1	420	407
2	400	0	1	-1	425	400
3	300	0	1	-1	415	400
4	-150	-250	1	-1	420	404
5	-300	-500	1	-1	420	400

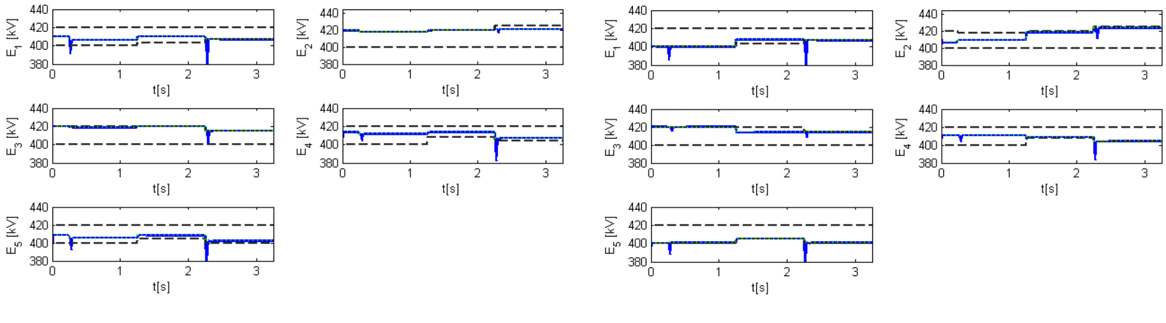

Figure 5.18: *Comparison of the voltage evolution and the desired voltage assignment on the two simulations made. On the left are presented the results of the model with the optimizing algorithm implemented and on the right are presented the results of the model without the optimizing algorithm.*

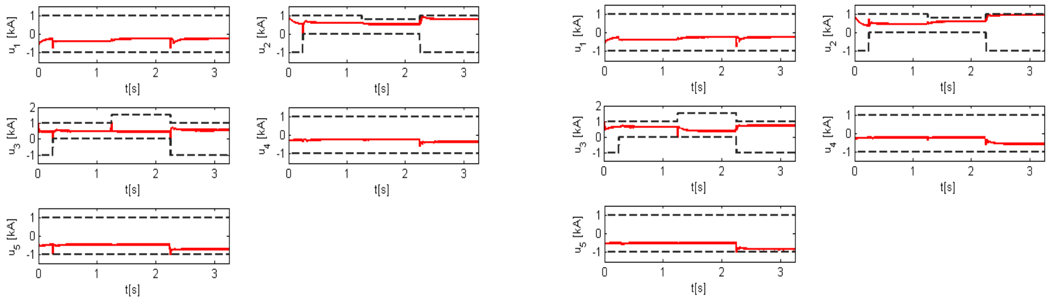

Figure 5.19: *Comparison of the current evolution on the two simulations made. On the left are presented the results of the model with the optimizing algorithm implemented and on the right are presented the results of the model without the optimizing algorithm.*

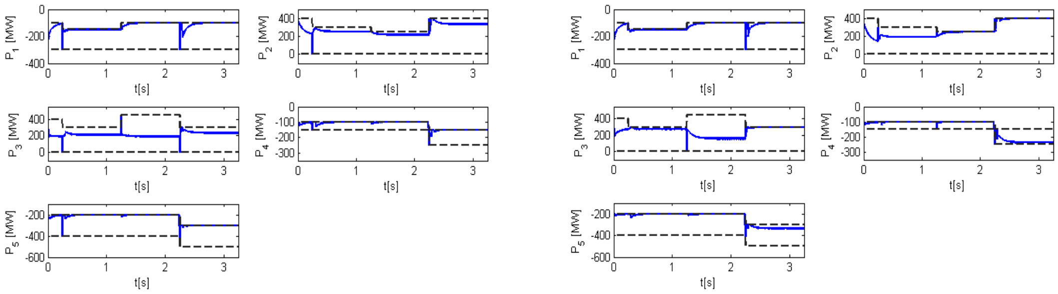

Figure 5.20: *Comparison of the power evolution on the two simulations made. On the left are presented the results of the model with the optimizing algorithm implemented and on the right are presented the results of the model without the optimizing algorithm.*

After obtaining the results on both simulation processes, it could be viewed that the management of the different situations are quite similar. In spite of this equality, observing the optimized results it is viewed that this process has elevated the generation voltage levels close to the maximum level for all the scenarios, which is logical because working in much higher voltage values would entail less power losses. In the other case, these values are subjected to the random assignation, and in some scenarios this criteria is not followed. Nevertheless, in the majority of the cases the random process a high value for the voltage of the generation points. On the other magnitudes, the performance of the grid is almost identical, which is logical too because the simulated situation is the same and the behaviour of the network could not vary to a large extent.

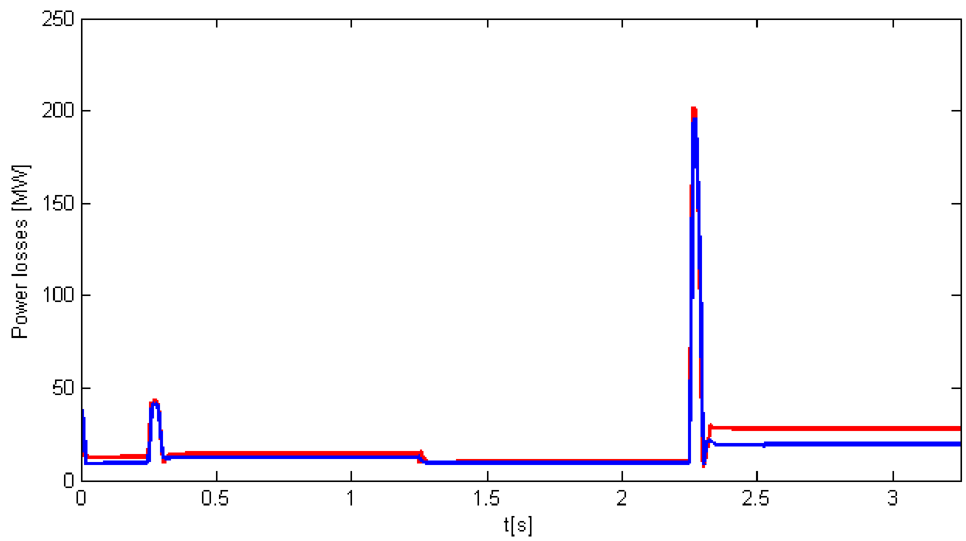

Figure 5.21: *Comparison of the power losses evolution on the two simulations made in the same graphic. The blue representation belongs to the model with the optimizing algorithm implemented meanwhile the red representation belongs to the non-optimized model.*

Observing the last figure, the solution offered by the optimizing algorithm is listed as the best of both. The two voltages configurations have produced the same behaviour in the grid. However, like was commented previously, for each scenario the optimizing algorithm has found the best possible configuration for reduce the power transmission losses. With the proper functioning and these graphic results, the improvement on the management of the network with the optimizing algorithm installed is confirmed. Now, if the random algorithm ran again, it would show either a higher loss of power or in the best results an equal power losses level. Nevertheless, the random assignation is never going to get a lower power losses level than the Secondary control configuration. Finishing the study of this case and for corroborate the argued results, programming a numeric integration code in order to calculate the area under the two graphical representation is possible to get the total energy lost in the transporting process. In this way, using the Trapezoidal rule as the numerical integration process and implementing it like:

$$\int_a^b f(x)dx \approx (b-a)\cdot\left[\frac{f(a)+f(b)}{2}\right] = (a-b)\cdot f(a) + (a-b)\cdot\left|\frac{f(b)-f(a)}{2}\right| \qquad (5.\ 1)$$

```
for i=1:length(vectOPF)-1
   Int = (vectOPF(i+1) - vectOPF(i)) * PlossesOPF(i) + ((vectOPF(i+1) - vectOPF(i)) * abs(PlossesOPF(i+1)-PlossesOPF(i)))/2;
   EnergyLossesOPF = EnergyLossesOPF + Int;
end

for i=1:length(vectNotOPF)-1
   Int = (vectNotOPF(i+1) - vectNotOPF(i)) * PlossesNotOPF(i) + ((vectNotOPF(i+1) - vectNotOPF(i)) * abs(PlossesNotOPF(i+1)-PlossesNotOPF(i)))/2;
   EnergyLossesNotOPF = EnergyLossesNotOPF + Int;
end
```

Using this numerical method, a total of 60,688 MJ in transmission power losses for the random process has been obtained, meanwhile the optimized solution has got a final result of 49,717 MJ.

In order to conclude this power losses comparison study and step forward to the final simulation, an eight node grid simulation would be made to demonstrate once again the success of the implementation of the optimizing results in the network management. Thereby, the following scenarios will be suggested to the model for implement and simulate them.

Table 5.24: *Definition of the nominal nodes delimitations, values of the constituent components and network control*

N	P_{maxN} [MW]	P_{minN} [MW]	I_{maxN} [KA]	I_{minN} [KA]	E_{maxN} [KV]	E_{minN} [KV]	E_0 [KV]	C [μF]	iniC [KV]	k
1	500	0	1	0	420	400	400	75	400	1
2	250	-400	1,5	-1,5	420	400	417	75	400	1
3	-200	-300	1,3	-1,3	420	400	409	75	400	1
4	-200	-400	1,5	-1,5	420	400	413	75	400	1
5	350	0	1,2	0	420	400	400	75	400	1
6	600	-300	1,4	-1,4	420	400	405	75	400	1
7	-200	-500	1,5	-1,5	420	400	400	75	400	1
8	500	0	1	0	420	400	410	75	400	1

Table 5.25: *Definition of the limitations for the first changing scenario desired.*

N	P_{max} [MW]	P_{min} [MW]	I_{max} [kA]	I_{min} [kA]	E_{max} [kV]	E_{min} [kV]
1	400	200	1	0	420	400
2	250	-400	1,5	-1,5	440	410
3	-200	-300	1,3	-1,3	420	400
4	-200	-400	1,5	-1,5	420	405
5	100	0	1,2	0	420	400
6	600	-300	1,4	-1,4	415	403
7	-400	-500	1,5	-1,5	420	400
8	300	100	1	0	425	410

Table 5.26: *Definition of the limitations for the second changing scenario desired.*

N	P_{max} [MW]	P_{min} [MW]	I_{max} [kA]	I_{min} [kA]	E_{max} [kV]	E_{min} [kV]
1	0	0	0	0	420	400
2	250	-400	1,5	-1,5	420	400
3	-300	-400	1,3	-1,3	410	407
4	-200	-400	1,5	-1,5	418	400
5	350	0	1,2	0	415	400
6	600	-300	1,4	-1,4	430	400
7	-200	-500	1,5	-1,5	420	400
8	500	100	1	0	420	400

Table 5.27: *Definition of the limitations for the third changing scenario desired.*

N	P_{max} [MW]	P_{min} [MW]	I_{max} [kA]	I_{min} [kA]	E_{max} [kV]	E_{min} [kV]
1	350	50	1	0	420	400
2	250	-400	1,5	-1,5	420	400
3	-350	-400	1,3	-1,3	420	400
4	-200	-400	1,5	-1,5	420	400
5	350	0	1,2	0	420	400
6	600	-300	1,4	-1,4	420	400
7	-300	-500	1,5	-1,5	420	400
8	500	0	1	0	420	400

Table 5.28: *Instants of time defined for the end of the scenario and the change of operation configuration.*

Table of time			
t_0 [s]	t_1 [s]	t_2 [s]	t_3 [s]
0,25	1,25	2,25	3,25

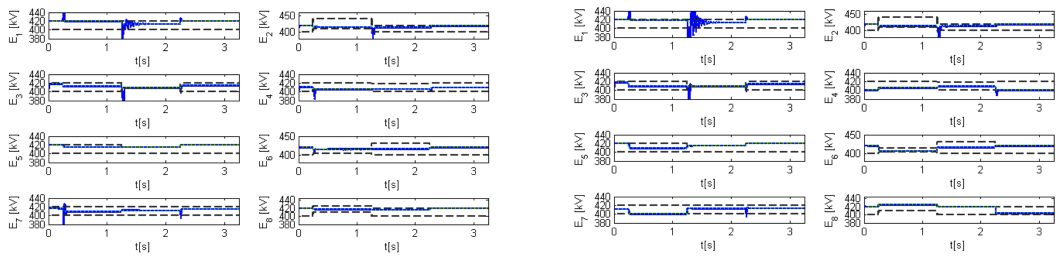

Figure 5.24: *Comparison of the voltage evolution and the desired voltage assignment on the two simulations made. On the left are presented the results of the model with the optimizing algorithm implemented and on the right are presented the results of the model without the optimizing algorithm.*

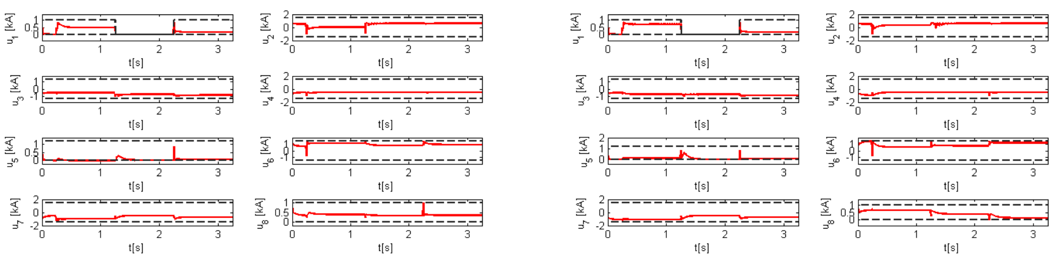

Figure 5.23: *Comparison of the current evolution on the two simulations made. On the left are presented the results of the model with the optimizing algorithm implemented and on the right are presented the results of the model without the optimizing algorithm.*

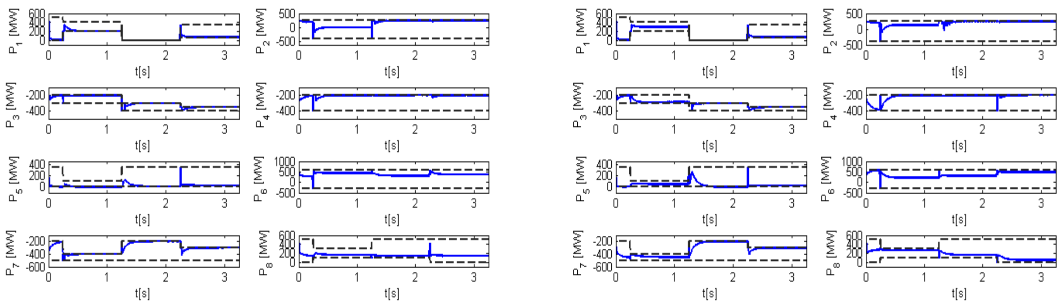

Figure 5.22: *Comparison of the power evolution on the two simulations made. On the left are presented the results of the model with the optimizing algorithm implemented and on the right are presented the results of the model without the optimizing algorithm.*

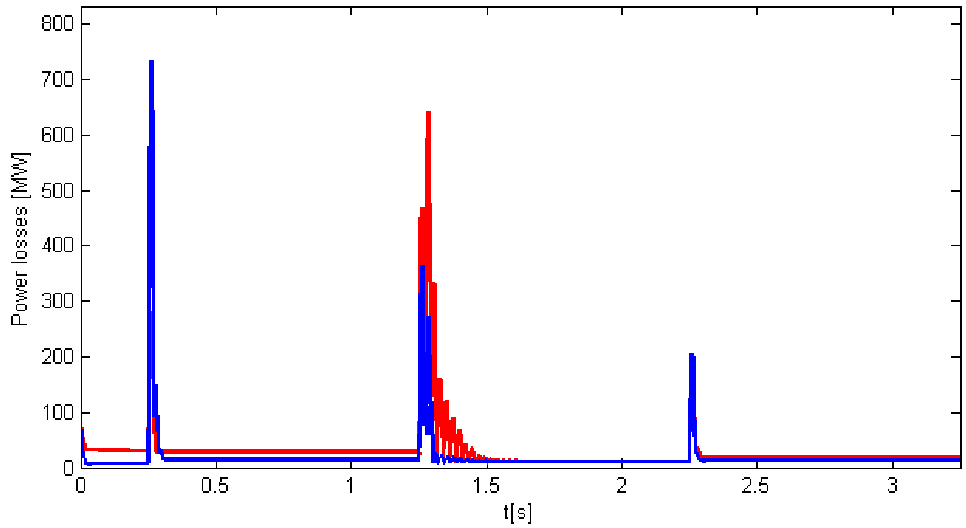

Figure 5.25: *Comparison of the power losses evolution on the two simulations made in the same graphic. The blue representation belongs to the model with the optimizing algorithm implemented meanwhile the red representation belongs to the non-optimized model.*

Once the simulation results for the eight-node grid were obtained, it is obviously to view the power losses comparison graphic that the simulation with the optimizing process obtained a much better results than the other possible configuration. In this case, the transmission power losses for the random assignation were on the order of 93,378 MJ against the 60,767 MJ reached on the optimized simulation. Having a look at the same time as at voltage evolution representation, in the second changes there has occurred a huge oscillation in the first node as consequence of the disconnection of the power generation plant configured on this node. It seems that with the optimizing algorithm implanted on the model, the oscillation of a disconnection of a node is controlled better than without it. Otherwise, looking at the current flow graphic and the power evolution, it seems that in this case the two different voltage configurations have signified a diverse form of cover the demand, making it generate much more in some generation nodes than the other simulating process just has used. This small detail would be for sure the cause of the big differential between the two power losses results.

Therefore it is not possible to do any extreme case comparison because it is not sure that the current flow and the power provided to the grid would be managed at the same conditions. In extreme cases the optimizing algorithm depending on if the purposed problem has solution or not, it could establish a work point out of bounds defined in the input data. In this situation, reach the assignation made by the optimizing algorithm would result impossible. The control will start to carry the system to the desired work point. However, once reached the limitations, the system will not be able to stablish itself in the assigned point and it could remain until the change of scenario in a worse work point than the random assignation. Furthermore, it is known that if the system intends to work in a work point assignation established out of the defined node bounds, this situation could entail into a node oscillation.

As a result, these oscillations would produce a large amount of power losses making it a worse situation. Other possibility is that normally in an extreme case the power demand is not covered, which implicates that the current transported through the power lines would be different depending on the voltage configuration. On the normal cases, the total energy established on the network is subjected to a certain constraints and the energy transported depends on the voltage configuration defined. This voltage levels definition would entail different demand and generation situations but will be always subjected to the same regulations. Is for that reason that in a normal case the configuration reached by the optimizing algorithm always would be the best one. However, in an extreme case, these limitations would not be respected and the establishment of a specific scenario is not subjected to any common and equal regulations. The non accomplishment of the system restrictions establish a non-equal condition situation for the comparison of both simulations. As a result, it could be possible that for the optimizing algorithm process the voltage configuration defined would intent to cover the maximum demand in order to minimize the deficiency of power and on the other hand, the random voltage assignation could be not careful with this ideal and instead of do it assigns any other option. Due to this to assignations independently of which criteria would used, the different systems are not restricted to common limitations because the impossibility of accomplish them. As consequence of it the scenarios implemented would not be attempting to operate the same situation, making the comparison a non-sense analysis.

CHAPTER 6: Conclusions

Ended the presentation of the obtained results in the simulations made and having interpreted it, it is time to extract final conclusions about the improvements of the implementation of the Secondary control created and the other changes to the main model. Comparing the results with the primary model presented, it is obvious that the new model offers a much more realistic simulation. The old model was configured in order to view the performance of the primary model ahead a specified voltage configuration. Despite being an important part of an MTDC control system, the simulations which could be done were not realistic at all. In the former model it was supposed that the primary model was working with the optimal voltage configuration. The necessity to determine manually the voltage level for each change limits the realistic scenario configuration. In this way, once the correct running of the primary model was confirmed, a restructure of the model to a more realistic simulation was needed. Thanks to having the Primary control already designed, it was possible to configure a system which represents the changing situation given in real life as well as to define a feedback mechanism with the determination of each scenario demands. All these could be done owning to the implantation of the Secondary control created. Thereby, the implantation of the Secondary control in the model has permitted to obtain a model much more close to the realistic scenarios. Now, the simulations are planned defining the power demand and generation of the network nodes instead of assigning randomly the voltage levels. The power demand forecast is done in real life daily. It is for this reason that determining the scenarios through the change of the power demand implies a better way to define the simulated situations.

Otherwise, besides the improvement on the scenario configuration there has been demonstrated the importance of the optimization process for any system. Viewing that many countries would like to add to their main grids renewable generation optimization becomes an important fact. The MTDC is defined itself as an ideal method to implement the renewable energies and make it a stable way to provide electricity. Renewable energies is the way to reduce the electric generation through traditional ways. Unfortunately, the generation with renewable methods does not produce the same high amount of energy as the classical plants. That is why it is so important to make the most of the produced energy with renewable sources. As proved in the last simulations in the fourth chapter, the implementation to the control system of the Secondary control has ensured the best performance configuration as long as the scenario would have a possible solution. Once demonstrated, it is possible to confirm that the main aim of this research has been reached. Otherwise, it was viewed during the simulations that if the scenarios have not had any possible solution, the Secondary control could not ensure the best performance of the grid. This is because the point assigned by the optimizing algorithm is out of bounds of the working area of the node. In this case, it is much probable that the configured working area does not offer the possibility to determine a stable working point. For this situation, the Secondary control assigns a working point that is unreachable for the primary control due to its saturation limitations.

To conclude, further research based on this model should pay attention on the study of the performance of the grid when the Secondary control is not able to determine a working point among the magnitude limitations. It was viewed that depending on where the desired point of work was determined, the grid performance becomes uncontrollable. Moreover, the non-saturation of the voltage levels as well as the impossibility to simulate some grid configurations are facts that could be considered to study in further projects in order to improve the control system and the simulations respectively.

On the other hand, a student of EUETIB (Nil Falgueras Farrerons) is actually working on the implementation of realistic inputs such as the meteorological conditions for wind farm generation nodes. With this work the realism of the model should be higher as long as the secondary control created in this research would be implemented.

CHAPTER 7:
Bibliografía

Aragüés-Peñalba, Mònica, Agustí Egea-Àlvarez, Oriol Gomis-Bellmunt, and Andreas. Sumper. “Optimum voltage control for loss minimization in HVDC multi-terminal transmission systems for large offshore wind farms.” *Electric Power Systems Research*, no. 89 (2012): 54-63.

Benedito, Ernest, Dunstano del Puerto-Flores, Arnau Dòria-Cerezo, Olivier Van der Feltz, and Jacquelien .M.A. Scherpen. “Strictly convex losses functions for port-Hamiltonian based optimal algorithm for MTDC networks.” *55th IEEE Conference on Decision and control.* 2016.

Dòria-Cerezo, Arnau, Josep M. Olm, and Jacqueline M.A. Scherpen. “Passivity based control of multi-terminal HVDC systems under control saturation constraints.” *5th IFAC Workshop on Lagrangian and Hamiltonian Methods for Non Linear Control.* Lyon, 2015. 135-140.

Doria-Cerezo, Arnau, Josep M. Olm, Mario di Bernardo, and Emmanuel. Nuno. “Modelling and control for bounded synchronization in multi-terminal VSC-HVDC transmission networks.” *IEEE Transactions on Circuits and Systems I: Regular Papers.* 2016.

Egea-Alvarez, A., J. Beerten, D. Van Hertem, and O. Gomis-Bellmunt. “UPCommons.” *Primary and Secondary Control of Multiterminal HVDC Grids.* Edited by Universitat Politècnica de Catalunya and ELECTA, Electrical Engineering Department Departament d'Enginyeria Elèctrica. Barcelona; Leuven, 2010.

Frau, Joan Ignasi, and Jordi Gutiérrez. “Transporte de energía eléctrica en corriente continua: HVDC.” *Automática e Instrumentación, nº 361* (CETISA - Boixareu Editores), 2005: 72-84.

Jiménez Carrizosa, Miguel, Fernando Dorado Navas, Gilney Dammc, and Françoise. Lamnabhi-Lagarrigue. "Optimal power flow in multi-terminal HVDC grids with offshore wind farms and storage devices." *Electrical Power and Energy Systems*, no. 65 (2015): 291–298.

Paredes Hernández, Silvestre. "Optimización No Lineal. Chapter 2 of the subject Optimización y Control Óptimo." Universidad Politécnica de Cartagena. 2007. http://filemon.upct.es/~paredes/am_ti/apuntes/guia_onl.pdf.

Pons Perelló, Joan-Bartomeu. *Modeling And Simulation Of An Hvdc Network For Offshore Wind Farms.* Master Thesis Energy Engineering., Universitat Politecnica de Catalunya., 2015.

Red Eléctrica Española (Bola Merino, D. Juan). "Operación de Sistemas HVDC. Particularidades." *Third Workshop GESTE.* Madrid: Electrical Engineering Department from Universidad Carlos III, 2012.

Teixeira Pinto, Rodrigo. *Multi-Terminal DC Networks: System Integration, Dynamics and Control.* TU Delf, Delf University of Technology: PhD Thesis, 2014.

Van der Feltz, Olivier. "Control of multi-terminal HVDC transmission systems." Master Thesis Industrial Engineering and Management. University of Groningen, Universitat Politècnica de Catalunya , 2016.

Appendix:
MATLAB Code

General Code

```
clear all
close all
clc

%% Simulation parameters
tstart=0;
tiniC=1;
minstepsize=1e-5;
maxstepsize=1e-1;

     file='MTDC1';

     %% Parameters
     global A R iC iL On Odn In AiRA n
     disp('----------------')
     disp('Loading data ...')
     disp('----------------')

     lines=xlsread(file,'Lines');     % Sheet which contains the topology characteristics of the MTDC Network
     vertex=xlsread(file,'Vertex');   % Sheet which contains maximum and minimum nominal levels of all nodes of the MTDC Network

     disp('----------------------------')
     disp('Generating Network data ...')
     disp('----------------------------')

     %Network parameters
     Rvec=lines(:,3);          % Array of resistances parameters for all lines of the MTDC Network
     Lvec=1e-3*lines(:,4);     % Array of inductances parameters for all lines of the MTDC Network
     Cvec=1e-6*vertex(:,9);    % Array of capacitances parameters for all lines of the MTDC Network

     d=size(lines,1);    % Size of the matrix where are the values for line's resistances
     n=size(vertex,1);   % Size of the matriz where are the number of vertex

     n3=lines(:,1:2);    % Matrix of beginning node and final node for all the network lines
     n4=vertex(:,1);     % Array of the number of nodes of the MTDC Network
     n5=unique(n3);      % Array of the number of nodes of the MTDC Network

     Av=zeros(n,d);      % Initialization of the network topology variable

```

```
    i=1;
    while i<=d                    % Creation of the matrix in order to stock the information of the lines
        away=lines(i,1);          % Array which stock the nodes which are the beginning of a line
        toward=lines(i,2);        % Array which stock the nodes which are the end of a line
        Avec(away,i)=1;           % Designation with a 1 all the nodes which begins a line
        Avec(toward,i)=-1;        % Designation with a -1 all the nodes which ends a line
        i=i+1;
    end
    Av=Avec(1:n,1:d);             % Result asignation of the Avec vector to a global matrix

    R=diag(Rvec);         % Diagonal matrix with the resitance parameters
    L=diag(Lvec);         % Diagonal matrix with the inductance parameters
    iL=inv(L);            % Inverse matriz of the diagonal matrix with the inductance parameters
    C=diag(Cvec);         % Diagonal matrix with the capacitance parameters
    iC=inv(C);            % Inverse matriz of the diagonal matrix with the capacitance parameters
    A=Av;                 % Asignation of the Av matrix to a global parameter
    On=zeros(n);          % nxn null matrix used in the dynamics of the grid
    Odn=zeros(d,n);       % dxn null matrix used in the dynamics of the grid
    In=eye(n);            % nxn identity matrix
    AiRA=A*inv(R)*A';     % Calculation of the conductance matrix G

    % Control parameters
    global Imax Imin Pmax Pmin Emax Emin E0 Eo K
    Pmax=1e6*vertex(:,2);          % Array of the maximus nominal power bounds for all the nodes of the network
    Pmin=1e6*vertex(:,3);          % Array of the minimum nominal power bounds for all the nodes of the network
    Imax=1e3*vertex(:,4);          % Array of the maximus nominal current bounds for all the nodes of the network
    Imin=1e3*vertex(:,5);          % Array of the minimum nominal current bounds for all the nodes of the network
    Emax=1e3*vertex(:,6);          % Array of the maximus nominal voltage bounds for all the nodes of the network
    Emin=1e3*vertex(:,7);          % Array of the minimum nominal voltage bounds for all the nodes of the network
    K=0.75*diag(vertex(:,11));     % Array of the constant k of the control sistem
```

```matlab
    t0=vertex(1,12);                % Initial time for the beginning of the simulation
    E0=1e3*vertex(:,8);             % Array of the initial voltage of all the nodes of the network

    %% Simulations
    disp('----------------------')
    disp('Initial conditions ...')
    disp('----------------------')

    Eo=E0;    % Assignation of the initial voltage array to the desired voltage array

    tic
    iniC=1e3*vertex(:,10);  % Initial conditions of current for the inductance elements of the network
    iniL=1e3*lines(:,5);     % Initial conditions of voltage for the capacitance elements of the network
    x0 = [iniC;iniL];         % Matrix of the initial conditions for the simulation
    options = odeset('RelTol',1e-5,'AbsTol',1e-5,'MaxStep',maxstepsize);  % Options and specifications for the simulation process
    [t,X] = ode45(@mhvdc_v01,[0 tiniC],x0,options);  % Simulation function
    toc

    for i=1:n+d     % Assignation of the final conditions of the network after the simulation to the initial conditions variable
        x0=X(end,:);
    end

    %% Simulations
    [type,sheetname] = xlsfinfo('MTDC1.xlsx');  % Information of the Excel file
    m=size(sheetname,2);  % Number of sheets of the Excel file
    options1 = optimoptions('fmincon','Algorithm','sqp');  % Options and specifications for the optimization process
    options2 = odeset('RelTol',1e-5,'AbsTol',1e-5,'MaxStep',maxstepsize);  %Options and specifications for the simulation process

    cellsims = cell(1, m);  % Initialization of the cell sims
    cellsimsV = cell(1, m); % Initialization of the voltage cell
    cellt = cell(1, m);      % Initialization of the time cell
    cellu = cell(1, m);      % Initialization of the current cell
    vect = [];       % Initialization of the time array
    vecsimsV = [];  % Initialization of the voltage array
```

```
    vecu = [];       % Initialization of the current array
    Emaxvec = [];    % Initialization of the simulation progress array for the maximum voltage level
    Eminvec = [];    % Initialization of the simulation progress array for the minimum voltage level
    Umaxvec = [];    % Initialization of the simulation progress array for the maximum current level
    Uminvec = [];    % Initialization of the simulation progress array for the minimum current level
    Pmaxvec = [];    % Initialization of the simulation progress array for the maximum power level
    Pminvec = [];    % Initialization of the simulation progress array for the minimum power level
    Eovec = [];      % Initialization of the simulation progress array for the desired voltage
    Plosses = [];    % Initialization of the simulation progress array for the network power losses


    for(k=2:1:m); % Simulations for all expected scenarios

        disp('----------------------')
        disp('Starting the optimization ...')
        disp('----------------------')

        Sheet = char(sheetname(1,k)) ;        % Determination of which sheet has the algorithm to read
        matrix = xlsread('MTDC1', Sheet);  % Creation of a matrix which contains all the information of the condition change

        Pmax = matrix(:,2)*1e6;    % Array of the maximus power bounds for all the nodes of the network in a specific scenario
        Pmin = matrix(:,3)*1e6;    % Array of the minimus power bounds for all the nodes of the network in a specific scenario
        Imax = matrix(:,4)*1e3;    % Array of the maximus current bounds for all the nodes of the network in a specific scenario
        Imin = matrix(:,5)*1e3;    % Array of the minimus current bounds for all the nodes of the network in a specific scenario
        Emax = matrix(:,6)*1e3;    % Array of the maximus voltage bounds for all the nodes of the network in a specific scenario
        Emin = matrix(:,7)*1e3;    % Array of the minimus voltage bounds for all the nodes of the network in a specific scenario
        tc = matrix(1,12);         % Final time of the simulating scenario

        numS = ['SCENARIO ',num2str(k-1)];

```

```
        disp('-----------------------')
        disp(numS)
        disp('-----------------------')
        lb=[Emin];    % Lower bounds for the optimizing algorithm
        ub=[Emax];    % Upper bounds for the optimizing algorithm
        tic
        [V,FVAL,EXITFLAG,OUTPUT] = fmincon(@OPFof,E0,[],[],[],[],lb,ub,'OPFnlc',options1);   % Optimizing algorithm function
        toc
        EXITFLAG   % Indication parameter of the success of the optimization process
        disp('-----------------------')
        disp('Running simulation ...')
        disp('-----------------------')
        Eo=V   % Assignation of the results of the optimization process to the desired voltage variable
        tic
        [t,X] = ode45(@mhvdc_v01,[tstart tc],x0,options2); % Simulation function
        toc    %ode15s
        cellsims{k} = X;          % Stock of all the results of the simulation in a cell
        celllt{k} = t;            % Stock of all the time points of the cimulaion in a cell
        vect = [vect;celllt{k}];  % Creation of the time vector
        disp('----------------------')
        disp('Post computations ...')
        disp('----------------------')
        for i=1:n        % Creation an only voltage matrix
            simsV(:,i)=X(:,i);
        end
        for i=n+1:n+d    % Creation an only current matrix
            simsI(:,i-n)=X(:,i);
        end
        cellsimsV{k} = simsV;                     % Stock of all the voltage results of the simulation in a cell
        vecsimsV = [vecsimsV;cellsimsV{k}];    % Creation of the voltage vector
```

```
        for i=1:size(t)   % Calculation of the specific current "u" in all nodes
            udi=AiRA*Eo-K*(simsV(i,:)'-Eo);
            usatP=min(Pmax, max(Pmin, simsV(i,:)'.*udi))./simsV(i,:)';  % Power saturation
            u(:,i)= min(Imax, max(Imin, usatP));     % Current saturation
        end

        cellu{k} = u';             % Stock of all the current results of the simulation in a cell
        vecu = [vecu;cellu{k}];    % Creation of the current vector

        for i=1:n+d     % Assignation of the final conditions of the network after the simulation to the initial conditions variable
        x0=X(end,:);
        end

        E0 = simsV(end,:)';    % Assignation of the final voltages of the network after the simulation to the initial voltages variable

        for i=1:size(t)   % Creation of all the progressing arrays of the upper/lower levels for the subsequent graphics
            Eovec = [Eovec, Eo];
            Emaxvec = [Emaxvec, Emax];
            Eminvec = [Eminvec, Emin];
            Umaxvec = [Umaxvec, Imax];
            Uminvec = [Uminvec, Imin];
            Pmaxvec = [Pmaxvec, Pmax];
            Pminvec = [Pminvec, Pmin];
        end

        tstart = tc;   % Assignation of the final time of the simulation to the initial time variable for the next scenario

    % Power losser results for all nodes
        for i=1:size(simsV)
          Ploss = simsV(i,:)*AiRA*simsV(i,:)';
          Plosses = [Plosses, Ploss];
        end


    %Work point plots
    I = AiRA * Eo;   % Calculus of the current value related with the desired voltage assigned
    figure
    for i=1:n
```

```
    subplot(ceil(n/2),2,i)
    Vvec=Emin(i):1*1e3:Emax(i);    % Array of possible voltage values in the simulation for each node
    IPmax=Pmax(i)./Vvec;    % Maximum current level array for each node according to the maximum power level
    IPmin=Pmin(i)./Vvec;    % Minimum current level array for each node according to the minimum power level
    Imaxvec=Imax(i).*Vvec./Vvec;    % Maximum current level conditions array for each node
    Iminvec=Imin(i).*Vvec./Vvec;    % Minimum current level conditions array for each node
    MatsegE = cellsimsV{k};    % Data of the voltage progression
    MatsegU = cellu{k};    % Data of the current progression
    if (max(IPmax) > Imin(i)) && (min(IPmin) < Imax(i))
        plot(Vvec*1e-3,max(Iminvec,IPmin)*1e-3,':r')   % Graphic of the current lower bounds of the work point for each node
        hold on
        plot(Vvec*1e-3,min(Imaxvec,IPmax)*1e-3,':r')   % Graphic of the current upper bounds of the work point for each node
        plot([Emax(i) Emax(i)]*1e-3,[min(Imaxvec(end),IPmax(end)) max(Iminvec(end),IPmin(end))]*1e-3,':r')    % Graphic of the voltage upper bounds of the work point for each node
        plot([Emin(i) Emin(i)]*1e-3,[min(Imaxvec(1),IPmax(1)) max(Iminvec(1),IPmin(1))]*1e-3,':r')    % Graphic of the voltage lower bounds of the work point for each node
        MaxU = max(min(Imaxvec,IPmax));
        MinU = min(max(Iminvec,IPmin));
    elseif max(IPmax) < Imin(i)   % Graphic the real work area for a specific case
        plot(Vvec*1e-3,Imaxvec*1e-3,':r')
        hold on
        plot(Vvec*1e-3,max(Iminvec,IPmin)*1e-3,':r')
        plot([Emax(i) Emax(i)]*1e-3,[Imaxvec(end) max(Iminvec(end),IPmin(end))]*1e-3,':r')
        plot([Emin(i) Emin(i)]*1e-3,[Imaxvec(1) max(Iminvec(1),IPmin(1))]*1e-3,':r')
        MaxU = max(Imaxvec);
        MinU = min(max(Iminvec,IPmin));
    elseif min(IPmin) > Imax(i)   % Graphic the real work area for a specific case
        plot(Vvec*1e-3,Iminvec*1e-3,':r')
        hold on
        plot(Vvec*1e-3,min(Imaxvec,IPmax)*1e-3,':r')
        plot([Emax(i) Emax(i)]*1e-3,[min(Imaxvec(end),IPmax(end)) Iminvec(end)]*1e-3,':r')
        plot([Emin(i) Emin(i)]*1e-3,[min(Imaxvec(1),IPmax(1)) Iminvec(1)]*1e-3,':r')
        MaxU = max(min(Imaxvec,IPmax));
```

```
                MinU = min(Iminvec);
            end
            plot(MatsegE(:,i)*1e-3,MatsegU(:,i)*1e-3,'-c','Linewidth',2)    % Graphic of the progression of the work point during the simulation for each node
            plot(MatsegE(end,i)*1e-3,MatsegU(end,i)*1e-3,'ob') % Graphic of the final work point for each node
            plot(MatsegE(1,i)*1e-3,MatsegU(1,i)*1e-3,'*b')    % Graphic of the first work point for each node
            plot(Eo(i)*1e-3,(I(i))*1e-3,'xk')  % Graphic of the desired work point selected by the optimizing algorithm for each node
            xlabel(['E_{' num2str(i) '} [kV]'])
            ylabel(['u_{' num2str(i) '} [kA]'])
            axis([((Emin(i)*1e-3)-5) ((Emax(i)*1e-3)+5) (MinU-100)*1e-3 (MaxU+100)*1e-3])

        end

        clear simsV   % Reset of the variable simsV
        clear simsI   % Reset of the variable simsI
        clear u       % Reset of the variable u
    end

    %% Plots

    disp('------------------------------')
    disp('Ploting simulation results ...')
    disp('------------------------------')

    for i=1:n     % Calculations for the correct assigment of the axis
        if max(Emaxvec(i,:)) > 0
            Emaxaxes(i) = (max(Emaxvec(i,:))*1e-3)+20;
        else
            Emaxaxes(i) = (max(Emaxvec(i,:))*1e-3)+20;
        end

        if max(Eminvec(i,:)) > 0
            Eminaxes(i) = (min(Eminvec(i,:))*1e-3)-20;
        else
            Eminaxes(i) = (min(Eminvec(i,:))*1e-3)-20;
        end

        if max(Umaxvec(i,:)) > 0
            Umaxaxes(i) = (max(Umaxvec(i,:))*1e-3)+0.5;
        else
            Umaxaxes(i) = (max(Umaxvec(i,:))*1e-3)+0.5;
        end

        if max(Uminvec(i,:)) > 0
            Uminaxes(i) = (min(Uminvec(i,:))*1e-3)-0.5;
```

```
        else
            Uminaxes(i) = (min(Uminvec(i,:))*1e-3)-0.5;
        end

        if max(Pmaxvec(i,:)) > 0
            Pmaxaxes(i) = (max(Pmaxvec(i,:))*1e-6)+100;
        else
            Pmaxaxes(i) = (max(Pmaxvec(i,:))*1e-6)+100;
        end

        if max(Pminvec(i,:)) > 0
            Pminaxes(i) = (min(Pminvec(i,:))*1e-6)-100;
        else
            Pminaxes(i) = (min(Pminvec(i,:))*1e-6)-100;
        end
    end

    %Voltage plots
    figure
     for i=1:n
         subplot(ceil(n/2),2,i)
         plot(vect,vecsimsV(:,i)*1e-3,'b','Linewidth',2)   % Graphic of the progress voltage array
         hold on
         plot(vect,Emaxvec(i,:)*1e-3','--','Linewidth',2,'color',0.15*[1,1,1])   % Graphic of the maximum levels for each scenario
         plot(vect,Eminvec(i,:)*1e-3','--','Linewidth',2,'color',0.15*[1,1,1])   % Graphic of the minimum levels for each scenario
         plot(vect,Eovec(i,:)*1e-3',':g','Linewidth',2)   % Graphic of the desired voltage level for each scenario
         xlabel(['t[s]'])
         ylabel(['E_{' num2str(i) '} [kV]'])
         axis([0 t(end) (Eminaxes(i)) (Emaxaxes(i))])
     end

     %Current plots
     figure
     for i=1:n
         subplot(ceil(n/2),2,i)
         plot(vect,vecu(:,i)*1e-3,'r','Linewidth',2)   % Graphic of the progress current array
         hold on
         plot(vect,Umaxvec(i,:)*1e-3','--','Linewidth',2,'color',0.15*[1,1,1])   % Graphic of the maximum levels for each scenario
         plot(vect,Uminvec(i,:)*1e-3','--','Linewidth',2,'color',0.15*[1,1,1])   % Graphic of the minimum levels for each scenario
         xlabel(['t[s]'])
         ylabel(['u_{' num2str(i) '} [kA]'])
         axis([0 t(end) (Uminaxes(i)) (Umaxaxes(i))])
```

```
    end

   %Power plots
   vecp = vecsimsV.*vecu;   % Calculation of the power vector for all nodes
   figure
    for i=1:n
        subplot(ceil(n/2),2,i)
        plot(vect,vecp(:,i)*1e-6,'b','Linewidth',2)   % Graphic of the progress power array
        hold on
        plot(vect,Pmaxvec(i,:)*1e-6','--','Linewidth',2,'color',0.15*[1,1,1])   % Graphic of the maximum levels for each scenario
        plot(vect,Pminvec(i,:)*1e-6','--','Linewidth',2,'color',0.15*[1,1,1])   % Graphic of the minimum levels for each scenario
        xlabel(['t[s]'])
        ylabel(['P_{' num2str(i) '} [MW]'])
        axis([0 t(end) (Pminaxes(i)) (Pmaxaxes(i))])
    end

    % Power losses plot
    figure
    plot(vect,Plosses(1,:)*1e-6,'b','Linewidth',2)
    xlabel(['t[s]'])
    ylabel(['Power losses [MW]'])
    axis([0 t(end) 0 max(Plosses(1,:)*1e-6)+100])
    save('PlossesOPF','Plosses','vect')
```

MTDC dynamics and Primary control code

```
function dxdt=mhvdc_v01(t,x)
global A R iC iL On Odn In Eo

Ed=Eo;
E=[In Odn']*x;
u=PBC(E,Ed);
dxdt=[On -iC*A;iL*A' -iL*R]*x+[iC*In;Odn]*u;

function y=PBC(E,Ed)
global AiRA Imax Imin K Pmax Pmin

alpha=AiRA*Ed;
     udi=alpha-K*(E-Ed);                 % PBC algorithm
     usatP=min(Pmax, max(Pmin, E.*udi))./E;  % Power
saturation
```