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Energization Strategies for Developing Countries

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Abstract

Nello scenario dei paesi in via di sviluppo, ci sono ancora vaste aree che non hanno il pieno dispiegamento di energia elettrica o, nel averlo, con bassa qualità del servizio. Per discutere e analizzare le migliori soluzioni per queste aree, è stata proposta la progettazione di modelli equivalenti dei sistemi di trasmissione nazionali del Brasile e della Colombia e la modellizzazione delle micro reti considerando diverse fonti di energia. Attraverso simulazioni che hanno valutato le aree propizie della rete nazionale e i diversi modelli per le micro reti, sono stati eseguiti approcci distinti come l'incremento del carico, l'espansione della rete di trasmissione e l'integrazione delle micro reti nella rete principale. Inoltre, è stato discusso un confronto dei costi basato sull'LCOE. I risultati hanno dimostrato prospettive rilevanti per entrambi i modelli, differenziando in base alle dimensioni della popolazione target, alla fonte rinnovabile disponibile, alla distanza dalla rete di trasmissione e alla capacità di investimento. È stata dimostrata la vulnerabilità su alcune aree periferiche della rete brasiliana e colombiana con la quantificazione dell'incremento del carico massimo dello 0,5% e del 4,18%, rispettivamente. L'inserimento della linea di trasmissione in un'area sovraccaricata ha migliorato la stabilità della zona studiata in tredici anni e l'integrazione della micro griglia nelle aree di instabilità tecnica ha dimostrato benefici reciproci come il miglioramento dei parametri tecnici della rete e nuove possibilità quali l'integrazione e la partecipazione delle rinnovabili ai servizi ancillari.

Abstract in English

In the scenario of developing countries, there are still vast areas that does not have the full deployment of electrical energy or, in having it, with low quality of service. In order to discuss and analyze the best solutions for those areas, it was proposed the design of equivalent models of the national transmission systems of Brazil and Colombia and the modelling of micro grids considering different sources of energy. Through simulations that assessed the propitious areas of the national network and the different models for micro grids, distinct approaches such as load increment, transmission network expansion and the integration of micro grids to the main network were performed. Moreover, a cost comparison based on the LCOE was discussed. The outcomes, demonstrated relevant perspectives for both models, differentiating according to the size of the targeted population, renewable source available, distance from the transmission network and capability of investment. It was demonstrated the vulnerability on some peripherical areas in the Brazilian and Colombian network with the quantification of the maximum load increment of 0.5% and 4.18%, respectively. The transmission line insertion in an overloaded area improved the stability of the studied zone in thirteen years and the micro grid integration in technical instability areas demonstrated mutual benefits such the improvement of technical parameters of the network and new possibilities such renewable's integration and participation on the ancillary services.

1. Introduction

The modern world is powered by the electrical energy, most of the spheres of the society are to this energy. Main social process as the learning, productive activities, family life, business, communications, are possible by the usage of electricity, and without it the social gap increases. The importance to bring the energy service is based on the equality principle, every person should have the same opportunities, and by these opportunities all the society could move forward faster and better. Almost the entire population of developed countries have access to electricity. While, developing countries have a good portion of the people without electric energy. Inside developing countries, and even in developed countries, the portion of the population whit lower access to the electric energy is the one living in rural areas. The energization of rural areas on developing countries presents a social, economic and technical challenge that must be faced as soon as possible.

Energization of rural areas represent a challenge since the geographical, environmental, security, and many other variables disadvantage the installation of the electrical systems used to energize the urban areas. The electrical systems nowadays are based on generation at big scale, and then the transport of this energy to the consumption locations. To bring paradigm of generation called centralized generation to rural areas of developing countries, has important issues such as the high investment cost due to the long distances to reach these areas, difficulties on the infrastructure installment, social problematics, and political issues.

It is important to mention on a large scale the political and social issues, because they are as important, or even more important than the technical ones. Developing countries have a dramatic problem, most of its population is poor. The middle class on developing countries is only a small group while most of the wealth belongs to few persons and the major part of society has low income, low quality of life, few opportunities in life, etc. This problem produces cultural phenomena that delay or prevent the development of projects such as the energization ones. Corruption, insecurity and low education level are some of the problems present on the societies of developing countries that could reduce by the energization projects on these countries.

Taking a step to the side of this situation, energizing rural zones on developing countries have technical issues. Developing countries concentrate the urban area in few locations over the country, leaving a vast terrain of rural zone. The distance is one problematic because the investment price increases with the distance, distance also increase the technical losses on the lines making more expensive the energy. But also, the geographical and weather conditions complicate the situation. It is necessary to make bigger investments given different kind of grounds, reliefs, hydrologic conditions, and extreme weather. Developing countries have low income compared with developed countries, and more necessities to solve than them. This fact is the reason why the budget must be executed carefully and the alternatives for energizing rural areas has to be evaluated in detail.

Nowadays a new generation paradigm appeared, distributed generation. This new paradigm appears with the renewable energies, these new generation technologies allow to generate energy from any location. Conventional energy generation optimizes the generation creating big power plants capable to supply the load at a competitive price. Currently, renewable energies' prices start to be competitive and the concept of micro grids, where the generation and transportation of the energy can be done at a lower scale, became a possibility to energize rural areas.

Micro grids can be competitive with the main network, because the high investment necessary to expand the main grid to rural areas could be higher, equal or lower of the micro grids depending the situation. The investment cost is one decision factor, nevertheless, the quality of the energy, the security on the service and the energy price are important factors to analyze. Because it is not only important to energize, but to provide a good quality of service that brings opportunities to those zones.

This thesis presents models and compares the two possibilities mentioned to energize the rural areas on developing countries. The expansion of the main transmission network until these areas or the installment of micro grids on those locations. A third option is about the connection of existent micro grids to main network, evaluating the mutual benefits that it could bring.

In order to achieve this objective, the present work presents a modeling process for both alternatives capable to evaluate the behavior of the main grid and the sizing of the micro grid, attached to the cost associated to both solutions. With the purpose to expose a complete and deep comparison, this work presents the study cases of Colombia and Brazil to evaluate real data and obtain applied solutions based on the models developed.

2. Electricity history and Energization process

The history about the uses that man has given to energy can be as long as human history. However, the history of electricity is recent and this is the subject the present text will expose. Hereby this text will consider some precedents about electricity; it is important to highlight how it has changed the use of this phenomenon and how human being has been benefited from these changes. In the first place, the first signs of the use of electricity are from a long time ago, before Christ (BC). Later, in the Renaissance the inventions such as the compass, encourage people to study magnetic fields and get into the world of energy and electricity. At the time of the Industrial Revolution, the study of lightning and the invention of the Steam Engine influence the social and economic dynamics of the world. Finally, the 20th century shows progress in electrification and demonstrates the influence of it on the man-environment relationship.

The present investigation will take into account the events that have impact the history of humanity in relation to energy and in addition, it will deepen in the specific case of the rural areas of Colombia and Brazil, this will be analyzed through the application of two forms of energization, which are: micro grids and expansion of the transmission network.

The first findings about electricity dates to 600 BC, when the philosopher Miletus seeks to understand the reason why when you rubbed an amber rod with wool, minimal jolts of electricity are obtained and if you continue rubbing, a spark arises. It is good to clarify that Thales did not come to understand electricity as having any load, however, he understood that it belonged to the object not to properties of amber or wool. Then, he experimented with minerals that have magnetic properties and he discovered from this that magnetite attracts iron.

It is important to mention that the finding of 1936, in Iraq, when we talk about the use of energy in antiquity; in this special case, a strange object was found in a tomb dating from 248 BC, that object was studied by the department of antiquities in Iraq and it was concluded that inside there was a copper cylinder that at the same time had an iron bar inside it. In 1940, an archaeologist cites that the object works in the same way as a modern battery and for this reason was given the name "Baghdad battery”. Perhaps this type of discovery is the proof of the use of electricity more than two thousand years ago and the confirmation of the uses of electricity in antiquity.

Another invention that impact the history, is the compass, which according to some academics, it was created in China in the sixth century, but others believe that it was created in Mesoamerica and was the natives who used the compass or something similar by 1000 BC. However, probably they did not know how or why it works, but the interaction with electromagnetic fields was there. The purpose of this device is to point to the magnetic south, which means, the geographic north. In China, they placed a needle with a tip magnetized magnetite stone, as previously mentioned, Thales used the same stone for their experiments. He put it on top of water and waited for it to point north. Although this accuracy could fail because there was high tide, so in the twelfth century in Europe, the Compass is modified as is known today; a needle with a magnetic tip, in equilibrium, on an axis in the center.

At first it was thought that the needle pointed in that direction because in the exact north of the planet there was a large magnetite rock that had a magnetic field so strong that it surrounded the entire planet, from these different myths emerged about what would happen if someone approached there, like ships destroyed by the attraction of the great rock among other stories. For the sixteenth century William Gilbert determined that the earth behaved like a magnet oriented and that the compass would point to the north, denying the theory of a large body with magnetic properties.

Later, in the seventeenth century, progress had been made in the theory, but not in the application of electricity, so William Gilbert published his article *De Magnete* which determines that there are two types of materials; electrical and non-electrical (today known as conductors and insulators). In addition, he studied the main basis of electrostatics and magnetism in order to improve the accuracy of compasses for navigation. For the eighteenth century with the Industrial Revolution also impacts the field of electric power, with all the implications that a revolution can bring to the advance of a physical phenomenon that began to take place within scientists, who increasingly knew manage more electricity at your disposal with the rules that it has.

In 1729 Stephen Gray determines that electricity can circulate through the conductor as long as it is not in contact with the earth, so the following inventors take this rule for apply it to their investigations.

The first of them was Pieter van Musschenbroek who carried out an experiment that today is the basis of electrical capacitors, the Leyden bottle**.** This and many other inventions culminated in the progress and uses given to electricity. One of them, the lightning conductor of Benjamin Franklin who focus his studies on natural electrical phenomena and also, included in its principle of electricity, the classification of two charges, positive and negative**.**

By 1800**,** Alessandro Volta manages to conduct continuous electric current from his battery. The first battery prototype with the operation of those currently known with the use of Zinc and Copper disks separated by sheets of cardboard wet by an electrolyte, the volt unit bears his name. In the same century, innumerable applications of electrical energy arise. In the present text, some that are relevant to the investigation will be taken into account. In 1819, Hans Christian Ørsted demonstrated the relationship between magnetism and electricity and he was the first person to suggest electromagnetism.

Three years later André-Marie Ampère who is recognized for his studies of electromagnetism supports Ørsted's thesis and creates the laws that determine the deflection of a magnetic needle according to the application of an electric current. In 1825 William Stur geon creates the first electromagnet; tool of 200 grams that could lift 4 Kg of iron, this could be regulated. However , not all Scientifics contributed with specific inventions, there are those who contributed with theories related to this phenomenon .Some of them are; Georg Simon Ohm who , in 1827 , obtained the formula for the relation between voltage V applied to a resistance R and the current intensity I. Johann Carl Friedrich Gauss brings in the study field electrostatic s s and of gravity where it relates the electric charge q covered by a volume V with the electric field flow E on the surface S that moderates the volume V.

Likewise, the contributions of Michael Faraday, who is known for the theory of electromagnetic induction that has been crucial in the creation of generators and electric motors, should be highlighted. In addition, he formulated two laws that dictate:

- The mass of substance released in an electrolysis is directly proportional to the amount of electricity that has passed through the electrolyte [mass = electrochemical equivalent, by intensity and by time (m = c I t)].
- The masses of different substance released s for the same amount of electricity are directly proportional to their equivalent weights. With his research, a fundamental step in the development of electricity was made by establishing that magnetism produces electricity through movement.

Samuel Morse, he made the first public demonstration of his new invention in 1833; the telegraph, a device capable of sending and receiving electrical signals for the purpose of transcribing coded texts. In addition, the alphabet used by the telegraph was created by him. In 1837 the innovative device won a contest that gave it a considerable amount of money to make the first line from Washington to Baltimore. On May 24, 1844 Samuel Morse send his first coded message saying "What has God brought us?"

At the beginning of the second half of the nineteenth century James Clerk Maxwell contributes to the studies of Faraday formulating the mathematical relationships between the electric and magnetic fields that we now call Maxwell's equations. These formulas represent the laws that frame the study of electricity and magnetism. His diverse investigations contributed to the creation of the wireless telegraph and the radio. The first three quarters of the nineteenth century are distinguished by the theoretical contributions of those who were responsible for preparing the framework for future engineers and technicians in electricity who found the applicability of theories in projects that give the importance to electricity, in the future social dynamics.

The Scottish-American Alexander Graham Bell, argued with other researchers the invention of phone and got the official patent in the United States in 1876 . Similar devices had previously been developed by other researchers, among whom he highlighted Antonio_Meucci (1871), who filed unsuccessful lawsuits with Bell until his death, and to whom the priority in the invention is currently recognized. Bell made a decisive contribution to the development of telecommunications through his commercial company (Bell_Telephone_Company , 1877, later AT&T). He also founded in the city of Washington the Volta Laboratory , where, together with its partners, he invented an apparatus that transmitted sounds by means of light rays (the photophone in 1880); also developed the first cylinder of wax to record (1886) which laid the foundations of the Gramophone .

On the other hand, Thomas Alva Edison. He has been considered the greatest inventor of all time. Although he is credited with the invention of Incandescent lamp, his intervention has rather the improvement of previous models (Heinrich_Göbel , German watchmaker, had manufactured functional lamps three decades earlier). Edison achieved, after many attempts, a filament that reached the incandescence without melting: it was not metal , but of bamboo carbonized. The October 21 of 1879 got his first light bulb to shine for 48 uninterrupted hours, with 1.7 lumens per watt.

The first Incandescent lamp with a carbonized cotton filament built by Edison was presented, very successfully, in the First Electricity Exhibition of Paris (1881) as a complete installation of electric DC lighting, a system that was immediately adopted in both Europe like in United States. In 1882, he developed and installed the first great power plant of the world, in New York. However, later, his use of direct current was displaced by the alternating current system developed by Nikola_Tesla and George Westinghouse.

The American inventor and industrialist, contemporary to those previously named, George Westinghouse (1846-1914), was initially interested in the railways (automatic air brake, railway signal system, crossing needle). Subsequently, with the help of Nikolas Tesla, he devoted his research to electricity, being the main responsible for the adoption of the alternating current (AC) for the supply of electric power in the United States.

Westinghouse bought the Croatian scientist Nikola Tesla the patent for the production and transport of alternating current, which he promoted and developed. Later he perfected the transformer , developed a alternator and adapted for its practical use the AC motor invented by Tesla. In 1886 founded the electric company Westinghouse Electric & Manufacturing Company , which in the first years had the decisive collaboration of Tesla, with whom it managed to develop the necessary technology to develop a AC supply system . Westinghouse also developed a system for transport natural gas , and throughout his life he obtained more than 400 patents, many of them from alternating current. Tesla is known for its immense contributions to electric power, so some of his discoveries with this are: theory rotating fields, base idea of the generators, first transmitter radius and propose alternating current in exchange for the continuous one proposed by Edison.

For the twentieth century electricity becomes a competition between nations, more specifically and with the growth of capitalism, companies play an important role as entities that constantly take energy to another level. In the case of electricity they began since the end of last century to sale a large scale of new equipment to society in developed countries bringing better life quality, demand produced increment in production, and this increases the cost efficiency making profitable to enhance the electric products.

The urbanism of the 20th century allowed the growth of megacities , with clear differences between neighborhoods of rich and poor, and with horizontal kilometric displacements and dozens of vertical plants (the skyscraper). Some examples of using electricity in mega works are reflected for example, in the London subway. For the twentieth century electricity was 'domesticated', homes began to be filled with appliances, light bulbs and cables that transport electricity and it is that you cannot deny its importance in any home. To conserve food and for heating in winter time, among other functions. The distribution of this service is at the head of each State and today there are great differences in access to electricity between rich and poor countries.

To this day, figures from the world economy claim that 88% of the world population has access to the electricity grid. However, its commercialization depends largely on private companies that propose high tariffs and hinder the supply in rural areas. In Colombia and according to DANE (National Department of Statistics) in the national survey of quality of life by 2017, 99.5% of Colombian households had access to electricity, there is a national electrification plan, which seeks to reach 100% of electrified homes, a plan that is supported by the world bank and that according to the mines and energy ministry. That is a universal priority to electricity access.

In Brazil, through the decree 4.873 in November 2003, it was instituted the National Program for Universalization of Access and Use of Energy. The main target was related to rural areas. In that period, the estimation was that around 2 millions of households were not served by any electrical energy service. The idea of the Program was promote the development and social inclusion in distant and poor areas.

Moreover, in terms of human rights, the UN, has recognized, cultural and social and economics rights as fundamental, as they depend upon life itself. However, they are not alone. Food, housing and education are, according to the Paraguayan newspaper ABC Color, electricity is "the support of basic rights such as adequate food, health, decent housing and education".

Supported on the above have been proposals in different countries for the recognition of an energy network as a human right, in 2015 the case was in Argentina, the ASADES (Argentine Association of Renewable Energy and Environment) released a statement in which sought to position to electricity as a human right, therefore you cannot exclude a part of the population, from it. ASADES cites: " Based on the application of non-parametric correlation tests (Kendall's tau-b and Spearman's rho), a very strong association was found between the indicators of exclusion of basic rights and energy exclusion at the Departments' level. Salta, exposing their connection as aspects of the same phenomenon and contributing elements to conceive energy planning from an inclusive framework. "(Meeting) in the case of Mexico, it was the CONUR (National Coordinator Users Resistance) which last October 10 searched for recognition of electric power as a right through the Chamber of Deputies. As stated above, there are several countries in Latin America that advocate giving electricity the recognition it needs to be vital to develop any activity that promotes the development of human capabilities.

2.1. Centralized Grid Management

The centralized grid management model is the most deployed after the consolidation of the power systems worldwide. The traditional power systems are composed by the generation, transmission and distribution working in synchronism according to the operation planned, permitted the consolidation of a reliable and solid model, which requires huge investments but provide the reliability and security necessary. The generation systems were established generally closer to the main primary sources or in a strategic location. The transmission systems have the role to transfer the energy produced in the generation centers to the main loads. The transmission lines reach the primary substations, in which the voltage is reduced. Finally, the consumers receive the energy through the distribution systems.

In order to transmit the energy with lower current and consequently lower power losses, particularly for long distances transmissions, step-up transformers are used to increase the voltage for generators connected to the transmission lines. On the other side, reaching the load hubs, the voltage is reduced through the step-down transformers.

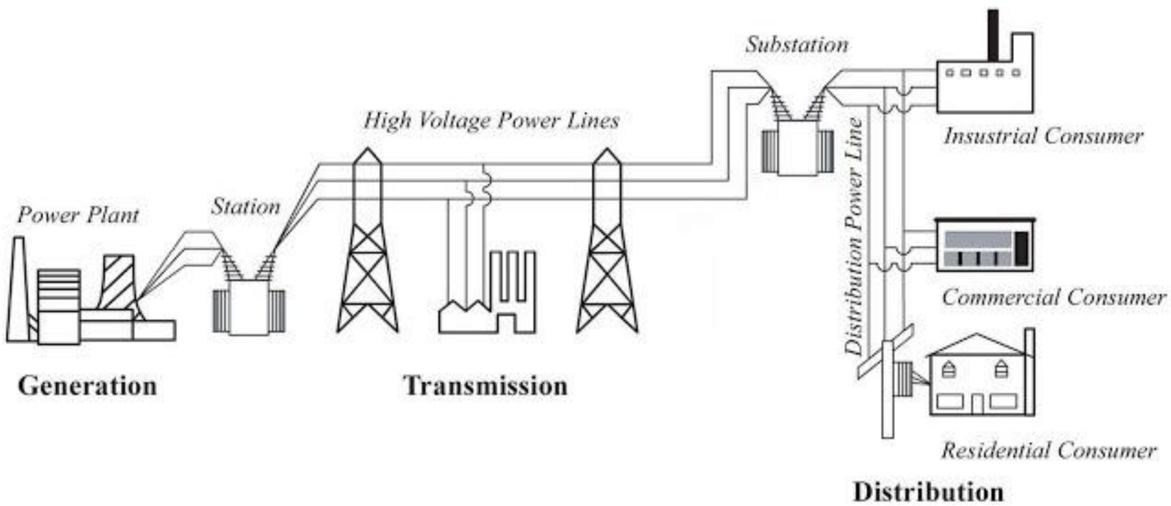


Figure. 1. Structure of the Electric Systems

The operation of these big systems requires different terms in planning procedures. Varying from very long-term planning, where considers projection of load for scenarios in the far horizon of 20 or 30 years, to short terms which the operation of the next week must be planned. This means that, further than just costs to build new assets in order to generate and transmit energy, it is necessary to invest on studies, researches, a consolidate transmission system operator (TSO) in order to coordinate and plan new infrastructure.

Another important characteristic of the centralized grid management is the possibility of building colossal projects in order to generate energy in places with high potential of production, a big hydro for instance, and transfer the energy produced directly to the center of the load. Projects that costs considerably, but as it is done for large scale, the final price of the energy reduces substantially comparing to projects of a decentralized dispatching.

Following this idea was the way that the centralized power system was developed. The main important points is the main location of the load and the locations of the generation. The more concentrated is the load, big cities for example, the easier to provide the energy than reach scattered loads, in terms of transmission costs.

2.1.1. Transmission Lines

The transmission lines are the backbone of the power systems. As it has been developed to transfer the power from the big production hubs to the main loads of the country, it is possible to infer about the transmission lines location of a country based on where is located the major part of its population.

In Figure 2 it is depicted the Brazilian and Colombian population concentration and the development of the transmission and distribution are mainly on those areas. At the same time, it is possible to see that still many people living outside these zones of concentrated load, but sometimes the amount of investment necessary to reach these remote areas is unpractical.

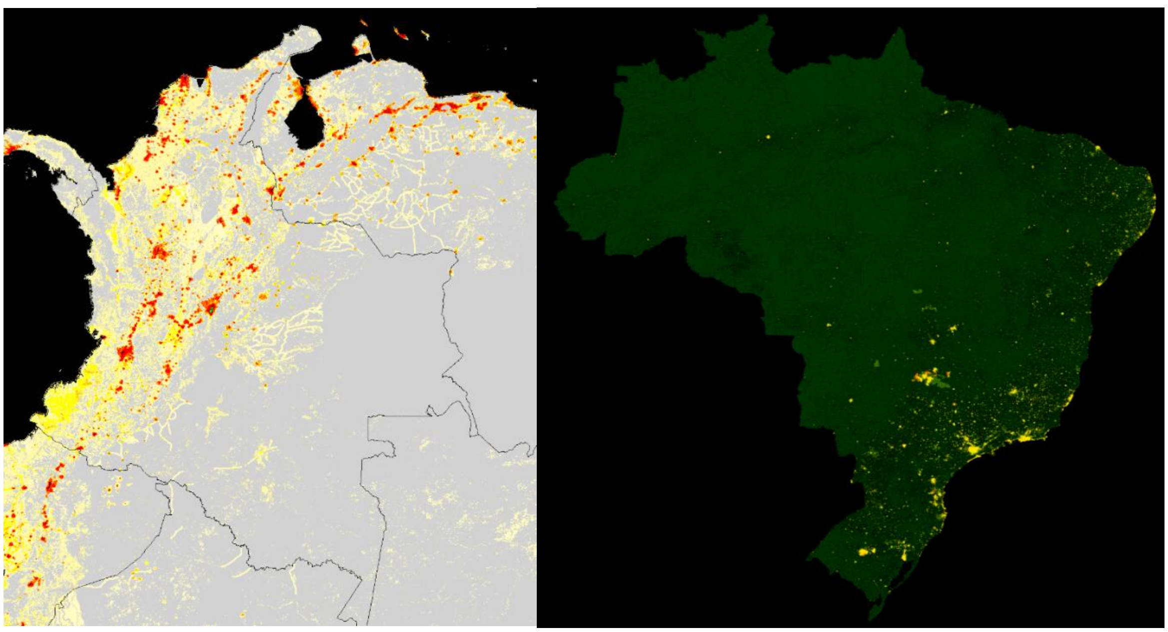


Figure. 2. Population density in Colombia and Brazil.

Therefore, different solutions must be proposed, from the traditional and high expenditure transmission lines to the new alternatives, perhaps using the local natural resources available. Transmission lines will always be a trustful and secure solution, bringing stability for the system and security of supply. Nevertheless, more than the huge costs of investments, it needs to pass through environmental obstacles such physical as native forest or bureaucratic, such as license issues.

2.2. Decentralized Grid Management

The decentralized dispatching paradigm was present at the beginning of the electrical systems when the energy generation was a privilege for the wealthy people. The generation was produced in the places where it was consumed, as the energy generation became a business, the energy power plant started to increase the size and to look for better efficiency. The centralized system is more robust and secure, but the decentralized system comes again to be the optimal option for zones where build the centralized infrastructure is too expensive or where the quality of the energy is not the one desired.

The micro grids are, as the name says, scaled versions of the main electrical grid. There are generation sources, transportation of the energy generated and finally the energy supply loads. The difference with the main grid is the size of the system. Micro grids are used to supply small loads, the advantage of them are the low losses and the low cost for disperse population. Since the generation is on place, the transportation losses are reduced and, the investment cost for communities or applications where the load does not justify the investment cost of transmission lines is comparatively speaking low. Local scale power systems come as a solution to energize zones where the main transmission grid is absent, and where it is too expensive or is not feasible to bring it.

Developing countries are using the micro grid to bring energy to those locations. The apparition of micro grids is associated with the implementation of renewable sources. Conventional energy source is too expensive when the row material, the transportation of it and the generation equipment is totalized. The renewable energy sources make possible to generate energy on the places without bringing there any raw material. With these new technologies even when the investment cost is higher than the conventional generators, the long-term cost of the micro grids powered by renewable energy sources is cheaper.

Renewable energy sources are those which generate electricity based on natural resources that are unlimited or can be regenerated in the medium term. Some examples of these technologies are the solar, the wind, the hydro, the biomass, the geothermal, etc. Those technologies use resources that most of the time are free, so the cost associated to them are related to the investment cost and the operation and management cost. Another advantage is that the contamination in modern world has reached dangerous levels, and renewable energies comes as an alternative to produce clean energy that allows the continuity of the modern life without deteriorating the environment more.

The renewable energy sources do not allow the micro grids to be economically feasible only. Renewable energy sources lead to the distributed generation paradigm. With small scale generators is possible to generate energy from any place where the natural resource is available. Sun and wind are resources available everywhere, so now it is possible to generate energy from the roof of any house or vacant lot. Distributed generation also reduces transmission and distribution losses since the energy is consumed where it is generated [34].

2.2.1. Micro grids

The micro grids are systems that implements generation, storage and consumption on place. They reduce the transmission losses and improve the efficiency in the energy use. They can be located in a not interconnected zone or can be connected to the main grid. When the micro grids are connected to the main grid, the management of its resources can provide improvements to the main electric system. The micro grids are compound by the following components:

- Low voltage distribution grid
- Local communication infrastructure
- Hierarchical control system
- Energy storage system
- Smart devices to know the state of the micro grid and control it

When a micro grid works isolated, the system should be able to manage the resources in order to supply the load. For example, PV systems can generate energy during the day only. During the night, the load must be supplied by the storage system with the energy generated in the day. The natural resources used in micro grids cannot be easily stored as gas, coal, etc. The energy production with renewable energies is performed when the resource is available. The availability of the resource and the need of the energy can be shifted in time, for this reason the presence of energy storage is necessary.

The investment cost of the micro grids is high and usually is used for low income communities. Because of this, the dimensioning of the micro grids must be as accurate as possible. In order to better dimension the micro grid, the forecast of the resources available plays an important role. The knowledge of the load profile also is very important. With the data of the generation and the load, it is possible to size better the storage system which is one of the most expensive components of the system [35].

3. Transmission Systems – Modelling

3.1. Transmission Systems

The transmission systems around the world work mainly on high-voltage or extra high-voltage, three-phase alternating current. Nowadays, with the development of the Power Electronics, high-voltage direct current (HVDC) is being deployed in strategic projects. Advantages such as the limitless distance for transmission, fast control regarding the power flow and consequently the stability improvement of the grid [2] bring the direct current role on the transmission systems to a higher baseline. Another important characteristic regards the installation of the transmission lines that can be overhead or underground installation. The underground installation promotes a better visual impact and lower maintenance costs, however with a considerable higher installation cost if compared to the overhead lines. The installation cost of an underground line can vary from 4 to 14 times of the overhead line costs [3] and therefore one determinant reason for the majority usage of overhead transmission lines, particularly on developing countries.

The voltage level deployed in the transmission system depends on studies that consider the distances covered, and possible losses. Each country determines its voltage levels for high-voltage (HV) and extra high-voltage (EHV) according to the geographical and topological aspects of the national grid. The characteristics of the topology of the transmission system is mainly a meshed structure. It is desirable in order to provide alternative paths for the power that is being transferred and have contingency in case of punctual problems in one of the transmission lines. It is essential to guarantee the reliability of the system. In the transmission planning studies, a principle called N-1 Criteria states that if a component of the transmission system fails in a network operating at the maximum forecast levels of transmission and supply, the network security must still be guaranteed [4]. Regarding this statement that is adopted worldwide in the transmission planning, the meshed transmission grid is indispensable for a reliable network. For the cases of sub transmission systems, which regards lower voltages and not essential transmission lines, the topology can have partially meshed structure. In the case of distribution system topologies is more related to a radial structure.

3.2. Transmission Line Parameters

The transmission line parameters are named as series resistance, series inductance, shunt capacitance and shunt conductance. Series resistance is related with the Joule effect and therefore the ohmic line losses. The series resistance and the inductive reactance are related to the series-voltage drops along the line and the shunt capacitance give rises to series-voltage drops along the line. Lastly, the shunt conductance is related with the line losses due to leakage currents among conductors or among conductors and the ground [5].

Considering the overhead transmission lines, the conductors are on the major part made of Aluminum material. It has some advantages if compared with the Copper conductors, such as the lower cost and the weight, considering that the density of the Aluminum (2.70 g/cm^3) is much lower than the Copper (8.96 g/cm^3). A conductor that is widely used [5] is the Aluminum Conductor Steel-Reinforced (ACSR), which is composed of a core of steel strands surrounded of Aluminum strands added in layers format as can be seen in the Figure 3. This stranded conductor form makes it easier to handle, providing a more flexible structure. Another important characteristic regards to the insulating. In order to allow the heat dissipation, these conductors have no insulating cover.

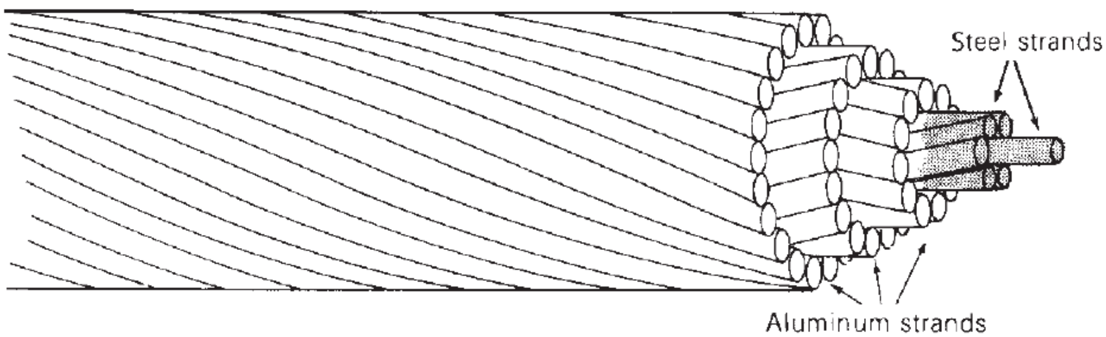


Figure. 3. Typical ACSR conductor [5].

Other components that take part of the transmission lines are the insulators, support structures and shield wires. The first is used in high voltage lines in order to sustain the lines. It is commonly a string of discs made of insulation material such as glass or porcelain, varying the design and material according to the voltage level. The second consists on the transmission towers that can vary according to the voltage and desired insulation level, height and width. The third is related to the lightning protection of the lines and consists of a wire that is placed above the conductors in order to flow the lightning eventually strikes to the ground, through the tower grounding considering the shield wires are grounded to the towers.

3.2.1. Resistance

There are some factors of the conductor that influences in the resistance value, among them: Dimension, temperature, frequency and current magnitude. Therefore, the resistance value varies between the dc and ac scenario. The dc resistance is given by:

$$R_{dc} = \frac{\rho_T l}{A}\ \Omega$$

Where, the ρ_T is the conductor resistivity at temperature T, l is the conductor length and A the conductor cross-sectional area.
Regarding the ac scenario, the resistance value can be given by:

$$R_{ac} = \frac{P_{loss}}{|I|^2}\ \Omega$$

Where, the P_{loss} is the conductor real power loss, $|I|^2$ is the square of the rms current that passes through the conductor.

3.2.2. Inductance

In order to determine the inductance of a conductor it is necessary to consider the internal, external and total inductance of it. Assuming a most practical scenario with a three-phase system, unequal space separating them and bundled conductors, which means more than one conductor per phase in order to reduce the series reactance and electric field strength, the inductance in one phase is given by

$$L_a = 2 \cdot 10^{-7} ln \frac{D_{eq}}{D_{SL}}\ H/m$$

Where,

$$D_{eq} = \sqrt[3]{D_{12} D_{23} D_{31}}\ m$$

D_{12}, D_{23} and D_{31} are the distances between positions of the conductors. D_{SL} is the geometric mean radius (GMR) of a specific conductor (value provided by the conductor manufacturer), but in case of bundled conductors it is replaced for an equivalent one. For instance, a two-conductor bundled can be given by:

$$D_{SL} = \sqrt{D_S d}\ m$$

Where, D_S is the GMR provided in the catalogue of the conductor and d is the bundle space between the conductors of the same phase.

3.2.3. Capacitance

In order to determine the capacitance of a conductor it is necessary to consider the electric field of a uniformly charged conductor and the voltage between two points outside the conductor [5]. Assuming again the most practical scenario with a three-phase system, unequal space separating them and bundled conductors, the capacitance in one phase is given by:

$$C_{an} = \frac{2\pi\varepsilon}{ln\left(\frac{D_{eq}}{D_{SC}}\right)} \quad F/m$$

Where,

$$D_{eq} = \sqrt[3]{D_{12}D_{23}D_{31}} \ m$$

D_{12}, D_{23} and D_{31} are the distances between positions of the conductors. D_{SC} is the outside radius (r) of a specific conductor (value provided by the manufacturer of the conductor), but in case of bundled conductors it is replaced for an equivalent one. For instance, a two-conductor bundled can be given by:

$$D_{SC} = \sqrt{rd} \ m$$

Where, *r* is the outside radius and d is the bundle space between the conductors of the same phase.

3.3. Transmission Line Representation

The transmission lines can be commonly represented as the π equivalent circuit, which consist in theoretical derivation of a two-port network, in which the electrical wave passes through it. This equivalent model can vary according to the length of the line, adopting the complete model in case of long lines (longer than 200 km) and a simplified model for medium and short lengths (from 40 up to 200 km) [7].

Adopting the simplified model for the π equivalent circuit, it is shown in the Figure 4 the representation of the ideal transformer and the transmission line.

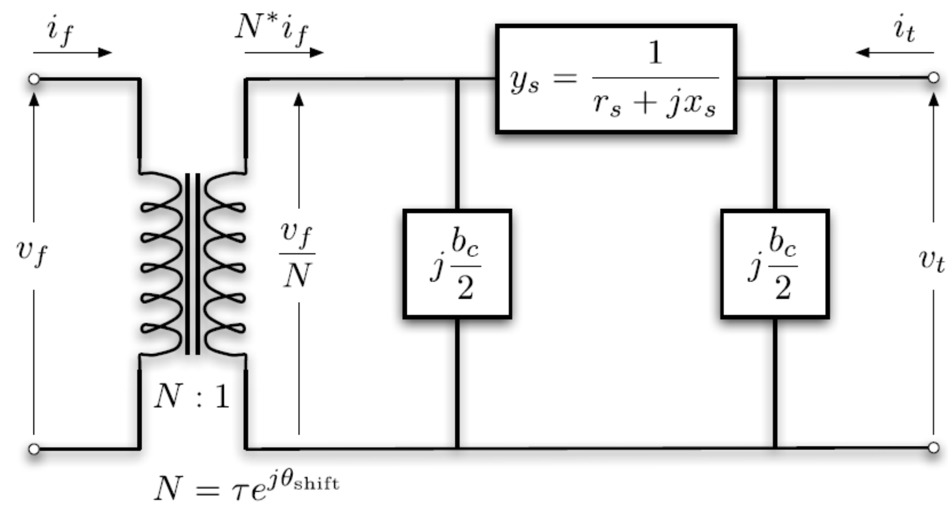


Figure. 4. Representation for transformer and transmission line [8].

The series admittance of the line is given by:

$$y_s = \frac{1}{r_s + jx_s} \ \ \text{S}$$

Where r_s is the series resistance and x_s the series reactance. The total charge susceptance is given by b_c. In the Figure 4, it is represented the transformer, whose tap ratio is given by τ and the phase shift angle given by θ_{shift}.

3.4. Bus Admittance Matrix

It is possible to represent the impedances referred to the lines that connect the buses in the grid through an admittance matrix, depicting the whole grid branches characteristics. Furthermore, with the bus admittance matrix (called Y_{bus}), it is possible to easily correlate it with the buses voltage and injected current that flows from one bus to another. The equation that relates it:

$$\bar{I} = \overline{Y_{bus}}\bar{V}$$

Where, Y_{bus} is the bus admittance matrix considering the size of NxN, V is the voltage column matrix with N bus voltages and I is related to the N current sources. The admittance matrix Y_{bus} is built considering the diagonal and non-diagonal elements. For the diagonal elements it is the sum of the admittances connected to the bus *i*, as it is given:

$$\overline{Y_{ii}} = \sum_{j=1}^{P} \overline{y_{ij}} + \sum \overline{y_j}$$

Considering P as the number of branches connected to the bus *i* and the y_j the admittance connected between the bus *i* and the ground.

For non-diagonal elements it is negative value of the sum of the admittances that are connected between the bus *i* and *j*.

$$\overline{Y_{ij}} = -\left(\sum \overline{y_{ij}}\right)$$

The bus admittance matrix Y_{bus} is a matrix composed of complex numbers and can be disjoined in the real part of the admittance, which is the conductance G and the imaginary part, which is the susceptance B.

$$\overline{Y_{bus}} = G + jB \text{ S}$$

3.5. Power Flow

Assuming a three-phase balanced system in steady state operation, in order to determine the voltage magnitude and phase angle in the buses that compose the network, it is performed a power flow algorithm. Through the algorithm, it is obtained the real and reactive power transferred between nodes and the losses in transmission lines and transformers as well.

The input data of the algorithm consists in the bus data, in which a classification of each bus is done according to the bus type. There are three types of bus: Slack bus, load bus and voltage-controlled bus. The first type is named slack bus, is a reference bus for which the voltage magnitude V_i is set to 1.0 per unit and the phase angle δ_i to zero degrees. The load bus has the input data the real P_i and reactive power Q_i, normally they represent load buses. The Voltage-controlled bus has the input data the bus real power and the bus voltage magnitude. The table I summarizes the input and output data that is obtained for each type of bus through the power flow algorithm.

Bus Type	Input data	Output data
Slack bus	V_i and δ_i	P_i and Q_i
Load bus (PQ bus)	P_i and Q_i	V_i and δ_i
Voltage-controlled bus (PV bus)	V_i and P_i	δ_i and Q_i

Table. I. Bus classification.

Considering the equation that relates the bus admittance matrix and assuming the bus j, the j-th equation is given by :

$$\overline{I_j} = \sum_{k=1}^{N} \overline{Y_{jk} V_k}$$

Where *I* represents the N vector of current injected in each bus. *V* represents the N voltages in each bus. The complex power delivered to the bus *j* is given by:

$$\overline{S_j} = S_j + jQ_j = \overline{V_j}\overline{I_j}^* = \overline{V_j}\left(\sum_{k=1}^{N} \overline{Y_{jk} V_k}\right)^*$$

Considering the bus admittance can be disjoined as already demonstrated and working with the phasor notation:

$$\overline{S_j} = \overline{V_j}\left(\sum_{k=1}^{N} \overline{Y_{jk} V_k}\right)^* = V_j\left(\sum_{k=1}^{N} V_k\, Y_{jk}\right) e^{j(\delta_j - \delta_k - \theta_{jk})}$$

Applying the identity of Euler and separating the real and the imaginary parts, the real and reactive power flowing from the j-th bus:

$$P_j = V_j \sum_{k=1}^{N} V_k\, Y_{jk} \cos(\delta_j - \delta_k - \theta_{jk}) = V_j \sum_{k=1}^{N} V_k \left[G_{jk} \cos(\delta_j - \delta_k) + B_{jk} \sin(\delta_j - \delta_k)\right]$$

$$Q_j = V_j \sum_{k=1}^{N} V_k\, Y_{jk} \sin(\delta_j - \delta_k - \theta_{jk}) = V_j \sum_{k=1}^{N} V_k \left[G_{jk} \sin(\delta_j - \delta_k) - B_{jk} \cos(\delta_j - \delta_k)\right]$$

For *j* = 1,…, N. Where δ_j is the phase angle of the bus *j* and δ_k is the phase angle of the bus *k.*

3.5.1. The Newton-Raphson method

In the power flow studies, in order to solve the non-linear system of equations there are several proposed methods, such as Gauss-Seidel and the Fast-Decoupled Power Flow method. In this work it is adopted the Newton-Raphson method due to its ample acceptance and main usage in traditional power flow software such as MATPOWER.

Furthermore, there are some technical advantages of using the Newton-Raphson method in computational programs, for instance the number of iterations required to reach the convergence is independent of the number of buses, which facilitates computational algorithms.

Defining the vector *x* composed of phase angles and voltage magnitudes of the buses, *y* composed of real and reactive power of the buses and *f(x)* the function that relate them, excepting the slack bus, which is already known.

$$x = \begin{pmatrix} \delta \\ V \end{pmatrix}$$

$$y = \begin{pmatrix} P \\ Q \end{pmatrix} \text{ and } f(x) = \begin{pmatrix} P(x) \\ Q(x) \end{pmatrix}$$

As the treated functions are non-linear, the iterative method to find x is based on Taylor series expansion of *f(x)* with a determined operating point *x*. Neglecting higher order terms, the Newton-Raphson method consists in the substitution in the function of the new obtained value of *x,* for instance *x(i),* in order to get the newest value *x(i+1)*. It is given by:

$$x(i+1) = x(i) + \boldsymbol{J}^{-1}(i)\{y - f[x(i)]\}$$

Where, the element $\mathbf{J}(i)$ is the Jacobian matrix, that is composed of partial derivatives.

Considering the real and reactive power equations obtained before, applied to the partial derivatives with respect to the phase angle and voltage magnitude in the buses, which consist in the Jacobian matrix that is given by the Figure 5:

$$\mathbf{J} = \left[\begin{array}{ccc|ccc} \multicolumn{3}{c|}{\mathbf{J1}} & \multicolumn{3}{c}{\mathbf{J2}} \\ \frac{\partial P_2}{\partial \delta_2} & \cdots & \frac{\partial P_2}{\partial \delta_N} & \frac{\partial P_2}{\partial V_2} & \cdots & \frac{\partial P_2}{\partial V_N} \\ \vdots & & & \vdots & & \\ \frac{\partial P_N}{\partial \delta_2} & \cdots & \frac{\partial P_N}{\partial \delta_N} & \frac{\partial P_N}{\partial V_2} & \cdots & \frac{\partial P_N}{\partial V_N} \\ \hline \frac{\partial Q_2}{\partial \delta_2} & \cdots & \frac{\partial Q_2}{\partial \delta_N} & \frac{\partial Q_2}{\partial V_2} & \cdots & \frac{\partial Q_2}{\partial V_N} \\ \vdots & & & \vdots & & \\ \frac{\partial Q_N}{\partial \delta_2} & \cdots & \frac{\partial Q_N}{\partial \delta_N} & \frac{\partial Q_N}{\partial V_2} & \cdots & \frac{\partial Q_N}{\partial V_N} \\ \multicolumn{3}{c|}{\mathbf{J3}} & \multicolumn{3}{c}{\mathbf{J4}} \end{array}\right]$$

Figure. 5. Jacobian Matrix form [5].

The Jacobian matrix is divided in four parts, relating real power and reactive power to phase angle and voltage magnitude. The outcome from the derivations applied to the power equations can be divided between the elements where $j \neq k$:

$$J1_{jk} = \frac{\partial P_j}{\partial \delta_k} = V_j Y_{jk} V_k \sin(\delta_j - \delta_k - \theta_{jk})$$

$$J2_{jk} = \frac{\partial P_j}{\partial V_k} = V_j\, Y_{jk} \cos(\delta_j - \delta_k - \theta_{jk})$$

$$J3_{jk} = \frac{\partial Q_j}{\partial \delta_k} = -V_j Y_{jk} V_k \cos(\delta_j - \delta_k - \theta_{jk})$$

$$J4_{jk} = \frac{\partial Q_j}{\partial V_k} = V_j\, Y_{jk} \sin(\delta_j - \delta_k - \theta_{jk})$$

And the elements where $j = k$:

$$J1_{jj} = \frac{\partial P_j}{\partial \delta_j} = -V_j \sum_{\substack{n=1 \\ n \neq j}}^{N} Y_{jk} V_k \sin(\delta_j - \delta_k - \theta_{jk})$$

$$J2_{jj} = \frac{\partial P_j}{\partial V_j} = V_j Y_{jj} cos\theta_{jj} + \sum_{n=1}^{N} Y_{jk} V_k \cos(\delta_j - \delta_k - \theta_{jk})$$

$$J3_{jj} = \frac{\partial Q_j}{\partial \delta_j} = V_j \sum_{\substack{n=1 \\ n \neq j}}^{N} Y_{jk} V_k \cos(\delta_j - \delta_k - \theta_{jk})$$

$$J4_{jj} = \frac{\partial Q_j}{\partial V_j} = -V_j Y_{jj} sin\theta_{jj} + \sum_{n=1}^{N} Y_{jk} V_k \sin(\delta_j - \delta_k - \theta_{jk})$$

For j, k = 2,…, N.

The iteration method can be divided in steps:

Step 1: Starting with the i-th iteration for the vector $x(i) = \begin{bmatrix} \delta(i) \\ V(i) \end{bmatrix}$, substitute $x(i)$ in the power equations and obtain the difference with the already known real and reactive power in order to get the power mismatches.

$$\begin{bmatrix} \Delta P(i) \\ \Delta Q(i) \end{bmatrix} = \begin{bmatrix} P - P[x(i)] \\ Q - Q[x(i)] \end{bmatrix}$$

Step 2: Compute the Jacobian matrix, through the equations presented before.

Step 3: With the Jacobian matrix obtained in the previous step it is possible to find the phase angle and voltage magnitude mismatches.

$$\begin{bmatrix} J1(i) & J2(i) \\ J3(i) & J4(i) \end{bmatrix} \begin{bmatrix} \Delta\delta(i) \\ \Delta V(i) \end{bmatrix} = \begin{bmatrix} \Delta P(i) \\ \Delta Q(i) \end{bmatrix}$$

Step 4: Finally, in order to get the values of $x(i+1)$:

$$x(i+1) = \begin{bmatrix} \delta(i+1) \\ V(i+1) \end{bmatrix} = \begin{bmatrix} \delta(i) \\ V(i) \end{bmatrix} + \begin{bmatrix} \Delta\delta(i) \\ \Delta V(i) \end{bmatrix}$$

The procedure is initiated with a start value for *x*, for instance *x(0).* It is repeated continuously until it reaches the convergence criterion or until a specified maximum number of iterations is reached.

4. Micro grid – Modeling

The tool used to perform the hybrid micro grid simulation is developed by energy4growing group in the University of Politecnico di Milano. This hybrid simulation is an extension of the existing software in order to add a secondary generation source to the PV-BESS systems dimensioned now. First it is going to be explained what was the state of the software before developing this approach and then, the implementation proposed for hybrid systems.

PoliNRG was developed to size a micro grid composed by photovoltaic energy as the generation source and batteries as the storage system PV-BESS. The tool is able to solve the problem using the fast space reduction algorithm and the imperialistic algorithm. This last one is the algorithm used to solve the hybrid system problem with a secondary generation source PV-BESS-SS.

4.1. Input chart and parameters

The algorithm works using eight structures of data. Each one of them contains variables with information relative to one scope to solve the optimization problem. Seven of them already existed for solving the PV-BESS, the eighth structure was created for the secondary source and four of the other seven were modified in order to have the information necessary to solve the PV-BESS-SS problem.

4.1.1. Battery

The battery model implemented has the characteristics shown in Figure. 6. The technology used is Lithium ion because it presents a good behavior on applications with high variability in the charging and discharging cycles. The efficiency is one of the highest in the market, it has a long lifetime, and it is possible to find them in the market on the study cases countries. The parameters as the efficiency, maximum of cycles, and power to energy ratio are normal values found in the batteries on the market.

Baterry (B)		
Tech	String	Li-ion
Model	String	Euristic
Model_Efficiency	String	Constant
Model_degradation	String	Not considered
CH_eff	Double	0,85
Dis_eff	Double	0,9
minSOC	Double	0,4
SOC_start	Double	1
Max_y_repl	Int	5
PE_ratio	Double	0,5
cost_coef_a	Double	200
cost_coef_b	Double	0
capcellAh	Double	Inf
nomV	Double	Inf
Cycle_max	Int	8000
SOH_min	Double	0,8

Figure. 6. Algorithm battery input.

I. Photovoltaics

The photovoltaic model implemented has the characteristics shown in Figure. 7. The balance of solar system includes the components that control the DC energy side; these components have an efficiency that reduces the energy generated by the PV panels to 15%. The array also can reduce the energy generated by the PV system. The cost has a commercial value offered in the market per kW installed.

Photovoltaic (PV)		
BOS	Double	0,85
Coeff_n_PV	Double	0,02
cost	Double	1200

Figure. 7. Algorithm photovoltaic input - Radiation.

The radiation model implemented has the characteristics shown in Figure. 8. The radiation an input necessary to calculate the energy generated by the PV array. The yearly profile is an array of n values of the radiance in the installation zone, where n is the number of point depending on the time step. For the simulation performed, the time step was “minutes” so the number of minutes in a year is 525.600. The name data points to the file with the radiation data, this data can be obtained from a mathematical model or real data measured in the zone. The profile_VU uses the yearly profile to generate the radiation for the number of years that last the simulation. This simulation evaluates 20 years.

Radiation (RAD)		
Yearly profile	Double array	t_step
NameData	String	solarProfile.mat
Profile_VU	Double matrix	t_step X years

Figure. 8. Algorithm radiation input.

II. Load curve

The load curve model has the characteristics shown in Figure. 9. The load curve is obtained with the program LoadProGen, where there are many possibilities to build realistic load curves and then import them into PoliNRG. The name data points to the importing file. The profile type gives the option of projecting a year in time with constant growth in the load, or to use a profile for the simulation time fully generated by LoadProGen.

Load Curve (LC)		
YearlyProfile	Double matrix	n_profiles X t_step
NameData	String	loadProfile.mat
ProfileType	String	Single Year

Figure. 9. Algorithm load curve input.

The inverter model has the characteristics shown in Figure. 10. For this class is only necessary to set the efficiency of the inverter and the cost per Kw installed.

Inverter (INV)		
eff	Double	0,9
cost	Double	300

Figure. 10. Algorithm inverter input.

4.2. Output description

The algorithm throws one structure with nine objects. The objects contain the global variables that concerns to the optimization of the problem. They are broken down below.

4.2.1. Results

The results object has information of the algorithm optimum points. For PV-BESS simulations the size of the results object is $Nx5$, where N is the number of iteration that the algorithm took to fulfill condition to stop. The variables are shown in Figure. 11 and the fields are the following:

- PV size: The nominal power of the photovoltaic array in the optimum point.

- Battery size: The nominal capacity of the battery storage system in the optimum point.
- Net Present Cost: The minimum NPC found in the simulation.
- Loss of load probability: The LLP in the optimum point.
- Levelized cost of energy: The LCoE is the price per kW, of the optimum point.

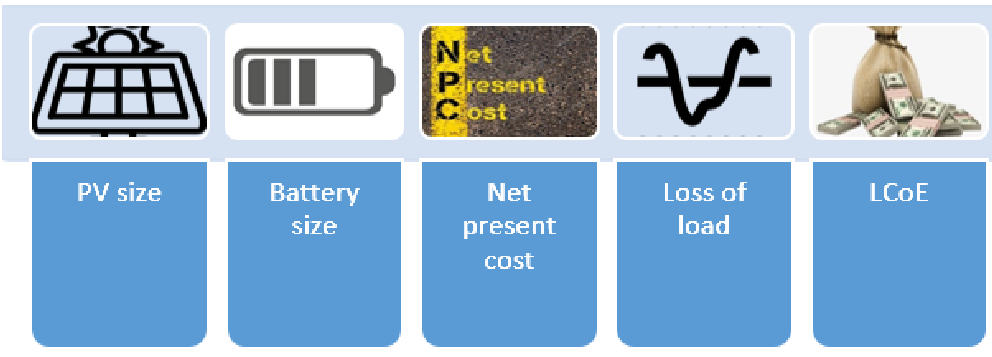


Figure. 11. Algorithm economic input.

4.2.2. NPC

The NPC matrix is a matrix of three dimensions where one of them is the PV research space, the second one is the BESS capacity research space, and the third one is the number of scenarios implemented and. Each point represents one PV-BESS combination, and the value stored in the matrix is the **NET PRESENT COST** for the combination that represents the point evaluated.

4.2.3. LLP

The LLP matrix is a matrix of three dimensions where one of them is the PV research space, the second one is the BESS capacity research space, and the third one is the number of scenarios implemented. Each point represents one PV-BESS combination, and the value stored in the matrix is the **LOSS OF LOAD PROBABILITY** for the combination that represents the point evaluated.

4.2.4. LCoE

The NPC matrix is a matrix of three dimensions where one of them is the PV research space, the second one is the BESS capacity research space, and the third one is the number of scenarios implemented and. Each point represents one PV-BESS combination, and the value stored in the matrix is the **LEVELIZED COST OF ENERGY** for the combination that represents the point evaluated.

4.2.5. Skyscraper

The skyscraper is a matrix of the same dimension and the same representation of the last three matrixes mentioned and the objective of this one is to have an identifier of which combinations have been already tested. For this reason, all the fields start in zero and the code sum one unity each time to the point. The code uses this to search around the point that has been already simulated.

4.2.6. Additional outputs

There are other matrixes output such as the Warnings where are displayed the advertisings in the code. The evaluation time that took the code to perform the simulation. The convergence array shows the algorithm convergence that displays 1 of the algorithm has converge and 0 if the convergence criteria is not enough.

4.3. Imperialistic algorithm for hybrid system

For the simulation, the flow of the information is shown in the Figure. 12. There is shown the input data presented above, the algorithm iteration performed over the generation profile feeding the loads, and the BESS as storage or supplier depending the situation. Then there is a convergence criteria that decides if the evaluation performed by the algorithm is good enough or if it is necessary to iterate another time. The algorithm will be explained in detail with the hybrid problem modifications so the flux of the information is well explained. Here is the presentation of the algorithm used for both designs (PV-BESS and PV-BESS-SS) in general.

It is important to mention that there are two important changes from this flow chart to the one presented for hybrid algorithms. One is that the generation profile involves a secondary source, so before comparing the PV generation with the load, there must be added the generation of the PV array with the secondary source generation. The second is that the algorithm convergence criteria for PV-BESS is set with the change in the size of photovoltaic generation and storage size. For hybrid systems, the variation of the axes is big as it will be shown in the next chapter. Because of this, there is necessary to stablish a new convergence criteria based on the net present cost, which is the objective of the optimization problem.

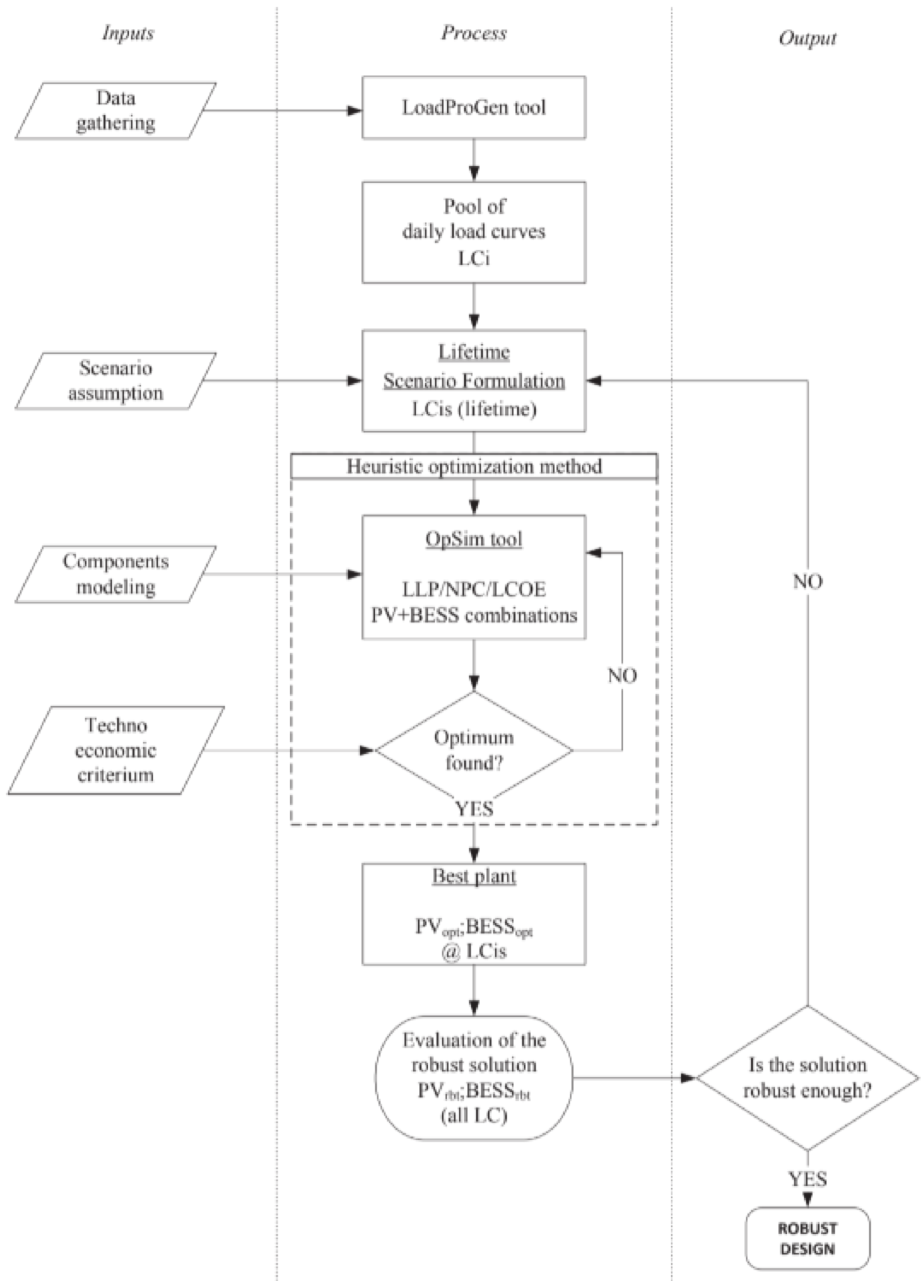


Figure. 12. Flowchart of the imperialist algorithm for PV-BESS micro grid [37].

5. Optimal micro grid design for hybrid systems in PoliNRG

The approach proposed for micro grids in developing countries includes two generation sources. The problem increases the research space proposed previously by the tool PoliNRG in one more dimension. This three-dimensional problem is complex to solve since there are many variables involved and the computational time to find the optimum is not appropriate for design purposes. For this reason, the micro grid design is done with an iterative algorithm capable to find the size of the system with a net present value close to the global minimum.

In order to test the algorithm, there are going to be used two generation sources available in many development countries, wind and hydro generation. These generation sources are commonly used in nowadays systems and the generation resource is available in all the territory of the study cases that will be presented. The parameters, changes in the algorithm, validation of the algorithm and the presentation of the two generation models are presented on this chapter.

5.1. Input parameters for hybrid systems

The hybrid system involves a new structure of data and some modifications on the existing input structures. The input parameters added for the hybrid simulation are presented below.

I. Secondary source

The secondary source model has the characteristics shown in Figure. 13. The secondary source is supposed to handle the information of any source available on the zone where the micro grid is going to be implemented. Nevertheless, given the variability of the different possible sources it is necessary to identify the generation source in order to implement different procedures inside the code, as it will be explained more in detail forward. For this reason, the source field implements a character that identifies the different sources.

The profile of the secondary source is a matrix used to calculate the energy generated by the source each minute of the 20 years of simulation given a nominal value for the source generator. This profile can be a multiplier factor as in wind energy source or the generation capacity of the river where the hydro generator is going to be installed. The structure and the use of the secondary source profile is going to be explained on the next section. The cost is the price per kW in the literature or the market.

Secondary Source (SS)		
Profile_SS	Double matrix	t_step X years
Source	String	h,w
cost	Double	3500

Figure. 13. Algorithm secondary source input.

II. Simulation parameters

The parameters model has the characteristics shown in Figure. 14, it is an existing class with modifications for the hybrid system. This has the information to build the research space of the PV, BESS and the SS inputs. Furthermore, here goes the flag “SS” used to activate the code that simulates the hybrid system, the value must be one. There are parameters to limit the simulation as the maximum number of profiles, the time step, the Rs parameter that limits the combinations for generation and the number of scenarios.

Parameters (PAR)		
min_PV	Int	0
n_PV	Int	3000
step_PV	Int	1
min_B	Int	0
n_B	Int	3000
step_B	Int	1
min_SS	Int	0
n_SS	Int	30
step_SS	Int	15,25,50,100
SS	Int	1
num_max_prof	Int	200
Validation_Std	Double	0,005
t_s	Int	60
n_scen	Int	1
Rs	Int	1000
method	Struct{STRING}	'Imperialist Competitive Algorithm'

Figure. 14. Algorithm parameters input. Inverter

III. Economic parameters

The economic parameters model has the characteristics shown in Figure. 15, this structure also exists for the PV-BESS design but has been modified for the hybrid system design. This model has the parameters needed to calculate the cost of the system once the algorithm has calculated the energy simulations for the nominal values. Also, on this model are the loss of load probability target and variation used to limit the optimization problem.

Economic (ECON)		
VU	int	20
r_int	Double	0,06
OeM	Double	20
coeffBOSel	Double	0,2
LLP_targ	Double	0,12
LLP_var	Double	0
OeMSS	Double	35

Figure. 15. Algorithm economic input.

5.1.2. Results

For hybrid simulations the size of the results object is $Nx6$, where N is the number of iteration that the algorithm took to fulfill condition to stop. The variables are shown in Figure. 16, the only difference with the previous output structure is that there is a new column where the size of the secondary source is saved. The output values presented are the same than in the PV-BESS design but the size of the matrixes changes as follows:

- Secondary source: The nominal power of the secondary source generator in the optimum point.

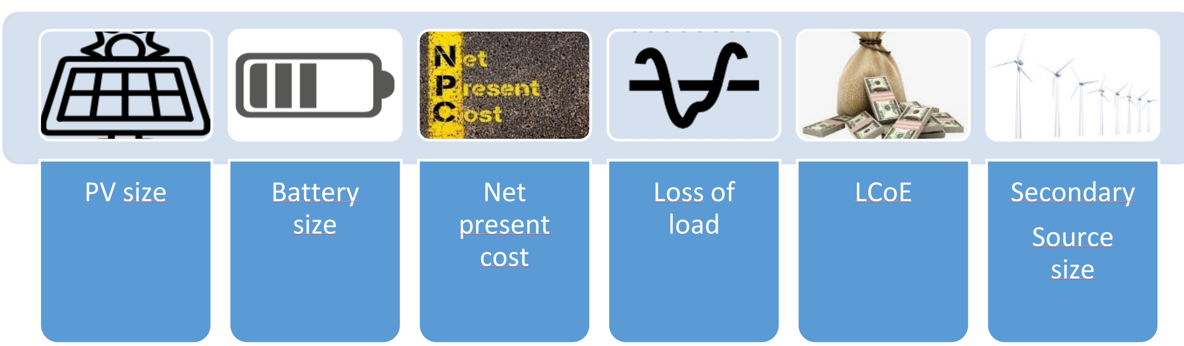


Figure. 16. Algorithm economic input.

5.1.3. NPC

The NPC matrix is a matrix of four dimensions where one of them is the PV research space, the second one is the BESS capacity research space, the third one is the number of scenarios implemented and, the fourth one is the SS research space.

5.1.4. LLP

The LLP matrix is a matrix of four dimensions where one of them is the PV research space, the second one is the BESS capacity research space, the third one is the number of scenarios implemented and, the fourth one is the SS research space.

5.1.5. LCoE

The NPC matrix is a matrix of four dimensions where one of them is the PV research space, the second one is the BESS capacity research space, the third one is the number of scenarios implemented and, the fourth one is the SS research space.

5.2. Imperialistic algorithm for hybrid system

For the simulation, the flow of the information is shown in the Figure. 17. The main supposition on the hybrid simulation is that the energy generated by the PV array and the secondary source can be added without any constrain for each simulation step. Once the energy generated is added, the load consumes what it needs and the remaining energy is stored in the BESS. In case the energy generated is not enough for the load is supplied by the storage system.

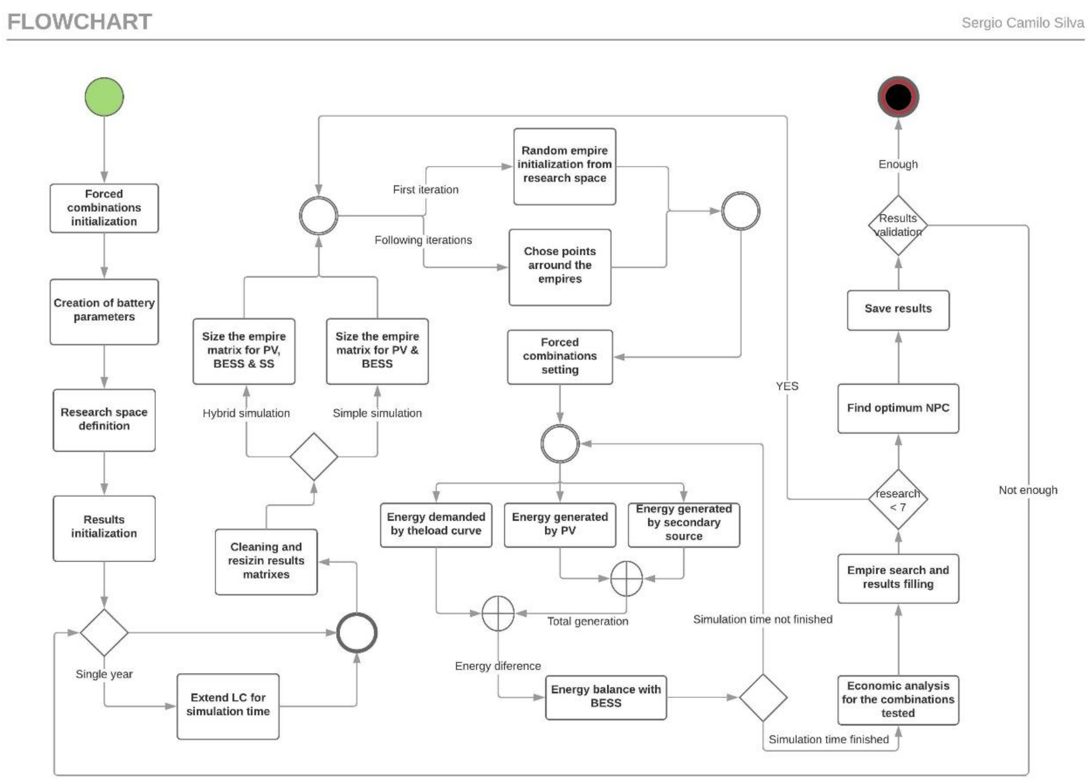


Figure. 17. Flowchart of the imperialist algorithm for hybrid micro grid.

5.2.1. Initialization

Some characteristics need to be initialized before start iterating with the algorithm. The battery model has implementation parameters that need to be set up. The research space has to be defined with the input parameters and the results matrixes are defined with it. There are also forced combinations that can be added to the code in order to fix initialization points in the algorithm. This is in case there are PV-BESS-SS combinations that could be close to the minimum. On the other hand, force combinations that want to be tested such as only PV-BESS or only SS-BESS.

5.2.2. Preparation of environment for iteration

The preparation of the environment for the iteration cleans and prepares the input variables to start the iteration from a neutral start. In this part of the algorithm is set up the load curve for the simulation time. One possible input is to have the complete load curve for all the years of the simulation, in such case the code only organize the dat. The other possible combination is to have one-year load curve, and the code projects the growth of the load with a constant.

When the algorithm results do not fulfill the convergence criteria the algorithm starts over and the results, the load curve and, the empire matrixes need to be initialized. This in order to start a complete new simulation searching the optimum. This step of the simulation prepares all the variables for the iteration step.

5.2.3. Iteration

The iteration step is the part of the algorithm where the optimization problem is solved. The objective is to find the combination of photovoltaics, battery energy storage system and secondary source with the lowest net present cost, with the constrain of loss of load probability. The loss of load probability constrain ensures that the system will supply energy for an amount of time enough or bigger than the time we want to have energy. This parameter is set up by the user and can change depending on the application of the micro grid. For example, illumination systems only need to supply energy in the night, offices, factories or many productive applications only need to supply energy during the day, etc.

The PV-BESS-SS points of the research space are evaluated searching the best combination that fulfills the LLP parameter with the lowest NPC value. In order to find the optimum this step could be sub divided into three big processes: The selection of the combinations for the simulation, the technical evaluation of the selected combinations on the time and, the economic evaluation of the combinations.

I. Selection of the PV-BESS-SS combination

The selection of the combination process takes a number of points in the research space to evaluate them technically and economically. It is necessary to evaluate only some points because the computational effort to evaluate all the possibilities is too big, and the program would take a great amount of time to evaluate all the possible combinations of the research space if it is too big. In case the research space is reduced, it is possible to lose the optimum values and the optimum found by the program could be oversized or undersized. The research space must be big enough to contain the global minimum, and in this case, the computational time will be too high. For this reason, the algorithm only takes some points and start iterating over them looking for the best solution.

The optimization problem is too complex with many variables that converts the mathematical solution in a difficult problem to be solved. For this reason, the iterative algorithms reduce complexity to the problem evaluating some points and then using the available information to get closer to the minimum. This way to solve the problem lose accuracy in the optimum but it accelerates the computational time.

$$Empire = \min(NPC)$$

During the first iteration, the points chosen are random points (except for those, which have been set up in "forced combinations"). After the first iteration, the algorithm fills a matrix called "Empire" with the minimum_NPC values obtained (eight empires). Around this empires there are selected the colonies, again the first iteration is selected randomly from the evaluated points.

From the second iteration and ahead, the colonies are set in the proximity of the empires. Then, after the technical and economical evaluation, the "power" of the colonies is evaluated using the next function with the values simulated. The lower the NPC the lower the power function, also the lower the LLP, the lower the power function. With this function is possible to compare with the empires if there is a colony with a better NPC-LLP relation and swipe the empire with it in case it is true.

$$ColonyPower = NPC_{colony} * LLP_{colony}$$

II. Technical evaluation

The technical evaluation performs the energy balance of the generators, the storage and the load. The load curve is given as an input for the program, so the calculus done in this process of the algorithm regard to the energy generation and the storage of it. Then, the missing energy or the over produced energy is supplied or stored in the batteries, on this part the BESS constrains has to be verified.

The first step of the technical evaluation is to know for every time step how much energy the load demands. The assumption on this point is that for every time step the load is constant in such a way that the energy demanded is the power value of every time step multiplied by the time step factor. For these specific simulations, the time step is minutes (60 minutes for each hour) and the power unit is Kw. For this reason, the energy demanded unit is kWh.

$$Energy\ demanded_{t\_step}\ [kWh] = P_{load,t\_step}[kW]\ *\ timeFactor\left[\frac{h}{min}\right]$$

The second step of the technical evaluation is to calculate the energy generated by the PV generator. The nominal power is the one chosen from the research space. The PV profile is related to the radiation and how it makes the PV array produce different quantities of energy for every moment of the day depending on the amount of radiation received The PV BOS is the total efficiency of the DC part in the photovoltaic generation [36].

$$PV_{generated,t\_step}[kWh] = P_{nom}[kW] * PV_{profile,t\_step}[h] * PV_{BOS}$$

The third step of the technical evaluation is to calculate the energy generated by the secondary source generator. This part of the code has been modified to identify the kind of secondary source implemented because every generation source may have specific conditions. It is going to be explained in deep on the following pages that explains the models of the hydro and wind. In summary, on this step there are performed the necessary operations with the nominal value chosen from the research space, and the profile input related to the second source in order to have the energy generated for each time step in kWh.

The fourth step of the technical evaluation is to make the energy balance. For this part, the assumption is that the energy generated by both generation sources can be added. Once the energy production is one the algorithm calculates the difference between the load and the generation. Depending on the result of this difference, the battery storage system is asked to supply the missing energy or store the remaining production. On this part, parameters such as the state of charge and the state of health of the BESS are checked to know if it is possible to supply/store the energy, in case it is not possible to supply the energy the amount not provided would increase the loss of load probability. Furthermore, the use of the battery can make shorter the lifetime of the BESS, so the state of health is verified in order to check when is necessary to change the system.

$$Energy\ balance_{t\_step} = PV_{generated,t\_step} + SS_{generated,t\_step} - \frac{Energy\ demanded_{t_{tep}}}{Inv_{eff}}$$

$$Loss\ of\ load_{t\_step} = Energy\ balance_{t\_step} - Energy\ available_{t\_step}$$

This procedure is repeated for every minute during 20 years the simulation. At the end of this iteration, the output value is the loss of load probability for each one of the combinations selected from the research space.

III. Economic analysis

The economic analysis has the objective of calculating the cost of the system with the combination selected. In order to calculate the cost there are different elements that compound the system:

The first one is the inverter; the inverter has to be sized for the peak power load, since the inverter has an associated efficiency, the power lost on the conversion should be added to the nominal value of the inverter. Then, it is multiplied by the cost per kilowatt in the inverter input parameters.

$$Inv_{cost} = \frac{P_{max}}{Inv_{eff}} * Inv_{cost\ per\ kW}$$

The second one is the BOS system, this system is calculated as a factor of the sum of the components on the system with DC management. The following expression shows the BOS cost formula used in case the secondary source has DC components, when it does not has this term in the formula must be removed [37].

$$BOS_{cost} = BOS_{coef} + (Battery_{cost} + Inv_{cost} + PV_{cost} + SS_{cost})$$

$$PV_{cost} = PV_{power}[kW] * PV_{coef}\left[\frac{\$}{kW}\right]$$

$$SS_{cost} = SS_{power}[kW] * SS_{coef}\left[\frac{\$}{kW}\right]$$

$$Battery_{cost} = Coef_a * BESS_{capacity}[Ah] + Coef_b$$

The investment cost is calculated adding all the previous costs presented above. The cost of the inverter, the PV system, the BESS system, the SS generator and the BOS costs.

$$IC = Battery_{cost} + Inv_{cost} + PV_{cost} + SS_{cost} + BOS_{cost}$$

Then it is necessary to calculate the costs related to the operation and management. The operation of the generation is related to each generation source. For this reason, the input should be a constant that gives the O&M value per kW per year. In such way, that the O&M cost is calculated with the expression below.

$$O\&M_{cost} = PV_{power}[kW] * PV_{O\&Mcoef} + SS_{power}[kW] * SS_{O\&Mcoef}$$

These costs are transferred to the present using the present value formula for the years of the simulation, where r is the rate.

$$PV = \sum_{years} \frac{O\&M_{cost,year}}{(1+r)^{year}}$$

Then, these costs are added with the costs related to the replacement of the batteries due to the lifetime of them. Finally, the net present cost (NPC) is found adding the investment cost and the yearly costs.

$$NPC = IC + YC$$

5.2.4. Optimum search and convergence validation

The optimum search objective is, again, to find the minimum (non-zero) NPC value of the research space that fulfills the condition of loss of load probability. This process is very simple; In the NPC matrix are all the values from the selected combinations of the research space. With those values is possible to compare with the LLP matrix and set the NPC of the combinations that does not fulfill the LLP condition to infinite and then from the remaining points calculated find the optimum.

From the optimum NPC value, is possible to find in the matrixes LLP and LCoE are obtained the loss of load probability and the levelized cost of energy of the optimum combination, and the PV-BESS-SS size also. This result is saved on the results object and then the convergence validation is checked.

I. Convergence criteria

The convergence criteria of the algorithm deals with the NPC mean and the standard variation. The objective is to check if the NPC through the iterations is stable or the difference between the values is too big. This convergence criterion has been adopted since the amount of variables lead to many different combinations of PV-BESS-SS where the NPC value is very close to the global minimum.

For this reason, the validation code calculates the mean and the standard variation of the results. These two variables are calculated for the previous iteration and the actual iteration. Then, there is an absolute comparison between the two values and this result is validated with the input parameter stablished for this convergence criterion as follows.

$$\overline{NPC} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

$$\sigma_{NPC} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{NPC})^2}$$

$$Mean_{validation} = \frac{(\overline{NPC_{iteration-1}} - \overline{NPC_{iteration}})}{\overline{NPC_{iteration-1}}}$$

$$\sigma_{validation} = \frac{\sigma_{NPC,iteration-1} - \sigma_{NPC,iteration}}{\sigma_{NPC,iteration-1}}$$

If the Mean validation and the standard deviation are lower than the validation parameters the simulation stops, otherwise the iteration starts over the life load curve initialization to look for another optimum that leads to a stable minimum.

5.3. Algorithm validation

The algorithm has a random start over the research space and then it starts looking for the best points (The lowest NPC) that fulfills the loss of load probability constrain. The number of iterations and the starting point leads to the algorithm to bring out many "optimum" outputs with different PV-BESS-SS combinations. The validation consists to prove that the algorithm gives an output close to the global optimum point in all the cases or at least with a high probability.

The way to validate if the algorithm work is to check if the net present cost of the PV-BESS-SS point that throws the algorithm is close to the best point on the research space. The method used to try to prove this condition is to perform a set of simulations where the first one, has evaluated all the possible points of the research space. The other simulations are standard ones where the output should be close to the optimum.

Practically, the simulation was done with a PV array between 0-3000 kW, the BESS capacity between 0-3000 kWh and, the wind generator between 0-450 kW. The radiation, the wind profile, the economic and simulation parameters were the same for all the simulations so the only changing variable were the random configurations at the beginning of the algorithm. For each simulation was extracted from all the evaluated points that fulfills the LPP condition, the minimum NPC configuration (Optimum), the maximum NPC configuration, and the average. Then, for each simulation was extracted a graph where the points in the PV-BESS.SS matrix where categorized for the closeness to the optimum point to see where are located the best points in the research space.

The results are summarized in the Table. V, where:

- The first column shows the number of the simulation
- The second column is the PV size of the optimum point
- The third column is the size of the BESS of the optimum point
- The fourth is the optimum value of the NPC for the simulation
- The fifth is the loss off load probability of the optimum point
- The sixth column is the levelized cost of energy of the optimum point
- The seventh column is the SS size of the optimum point
- The eighth column is the difference between the NPC of the optimum point and the global NPC optimum

SUMARY VALIDATION

SIM	PV [kW]	BESS [kWh]	NPC [€]	LLP [%]	LCoE [€/kWh]	SS [kW]	Optimum difference[€]	Error [%]
Complete Simulation	142	125	$ 1.546.500	0,1170%	0,1571	225	$ -	0%
Simulation 1	26	246	$ 1.551.600	0,0944%	0,1598	218	$ 5.100	0,33%
Simulation 2	150	143	$ 1.546.900	0,1074%	0,1595	225	$ 400	0,03%
Simulation 3	4	237	$ 1.583.600	0,0851%	0,1611	270	$ 37.100	2,40%
Simulation 4	155	212	$ 1.576.000	0,0528%	0,1601	240	$ 29.500	1,91%
Simulation 5	68	307	$ 1.579.900	0,0908%	0,1609	242	$ 33.400	2,16%
Simulation 6	127	127	$ 1.585.300	0,0998%	0,1631	240	$ 38.800	2,51%
Simulation 7	133	402	$ 1.590.800	0,1136%	0,1639	210	$ 44.300	2,86%
Simulation 8	155	115	$ 1.579.100	0,0918%	0,1603	220	$ 32.600	2,11%
Simulation 9	130	143	$ 1.596.500	0,1063%	0,1661	228	$ 50.000	3,23%
Simulation 10	146	112	$ 1.596.400	0,1002%	0,1654	250	$ 49.900	3,23%

Table. I. Summary data for algorithm validation.

This table shows the optimum results of ten random simulations (in the practice there were performed other simulations but the table shows one sample of the simulations performed), and the optimum of the simulation when all the combinations of the research space were tested. The error between the simulations performed and the global optimum is lower than 3.5%. With a good number of samples is possible to ensure that the algorithm flows to a NPC value close to the minimum.

It is possible to make an observation of the LLP. The closer the LLP to the threshold the lower the NPC, it means that if we want to have a lower LLP the price will increase. Even when the combinations of the PV-BESS-SS system are quite different, the mixed costs of all of them throws not only a close NPC, but also a close LLP and LCoE.

Using the "complete simulation" is possible to calculate the points closer to the global optimum and then, validate the other simulations with the values obtained in the first one. The point, is to see where are located the PV-BESS-SS points where the NPC is closer to the global minimum that the others. In order to see extract more information from the graphs there were selected five regions:

- Green: The green region is the one where the NPC is the optimum or 1.2 times the global optimum. This means 20% bigger than the optimum.
- Cyan: The cyan region is the one where the NPC is bigger than 1.2 times the global optimum and lower than 1.5 times the global minimum.
- Blue: The blue region is the one where the NPC is bigger than 1.5 times the global minimum and lower than the mean of the NPC values.
- Yellow: The yellow region is the one where the NPC is bigger than the mean of the NPC values and halfway the maximum$\left(\frac{NPC_{max}-NPC_{mean}}{2}\right)$.
- Red: The red region has the values between halfway the maximum and the maximum value of NPC.

The following examples show the comparison of a couple simulation with the values obtained with the complete simulation. They show that the local optimums are close to the global maximum in the PV-BESS-SS configuration. It is possible to identify zones where the NPC is lower and where it is higher. This zones show that if the simulations gives points in green the local optimum value will have a 20% of error at maximum. In fact, what Table V shows in the eighth column is that the optimum NPC error is lower than 3.5%.

The graphs showed in the examples filtrate all the points that fulfill the LLP condition and the plot them with the colors given in the five regions above. There are two examples to illustrate that the results are not the same but there can be identified some regions were the values are closer to the global minimum than others are.

5.3.1. Example 1

The 3D graph of the first simulation is shown in the Figure. 18. This figure show how are distributed all the evaluated point in a simulation on the research space (PV-BESS-SS). The combination tested are colored by the zones previously described. The dispersion of the data does not allow observing clearly the relation between the variables and the NPC. For this reason, there are the following figures with 2D plots.

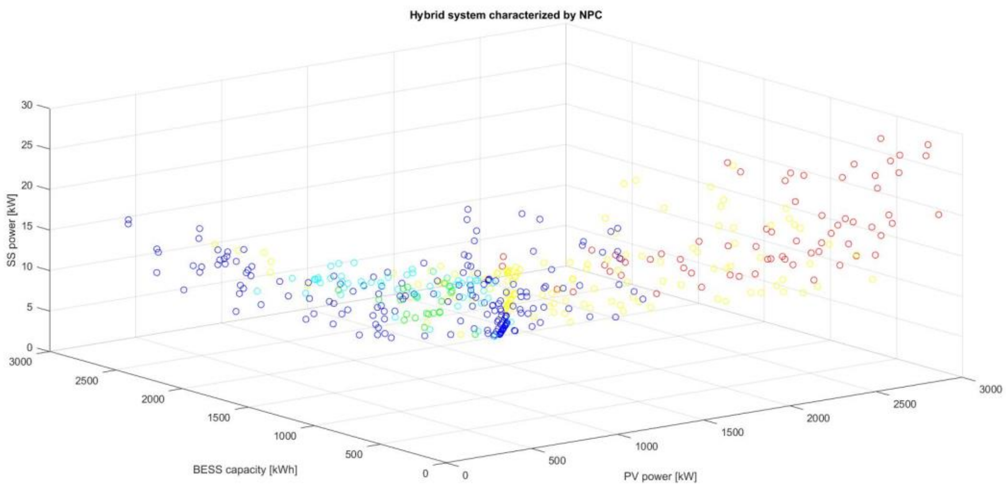


Figure. 18. 3D plot for simulation 1 with the NPC characterization.

Figure. 19 shows the BESS-PV plane. It is possible to observe the five regions previously mentioned, where the values closer to the global optimum are located in a zone and, the further from this zone the bigger the NPC. There are some points crossing the borders but since it is a 2D projection of a 3D space, the envelope region is a solid, not a curve. Still, the regions mentioned can be identified showing a relation of PV-BESS with the NPC.

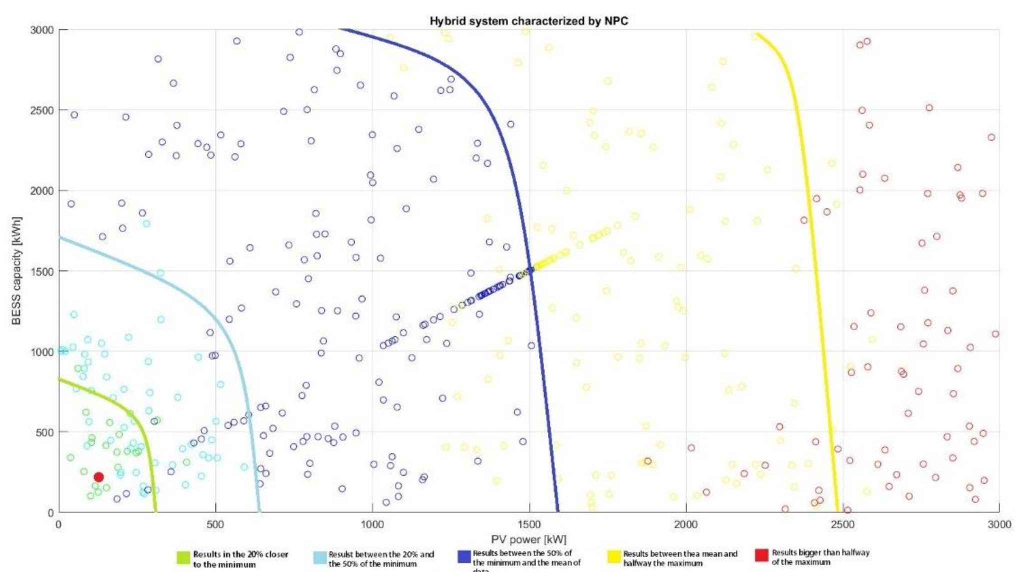


Figure. 19. 2D plot for simulation 1 for BESS-PV axes with NPC characterization.

Figure. 20 shows the SS-PV plane. Again, it is possible to observe the five regions identified where most of the point between the values are located. One more time, the values closer to the global optimum present a lower NPC in relation to the values further to it. In this case, the regions shape are quite different from the ones showed in the Figure. 17.

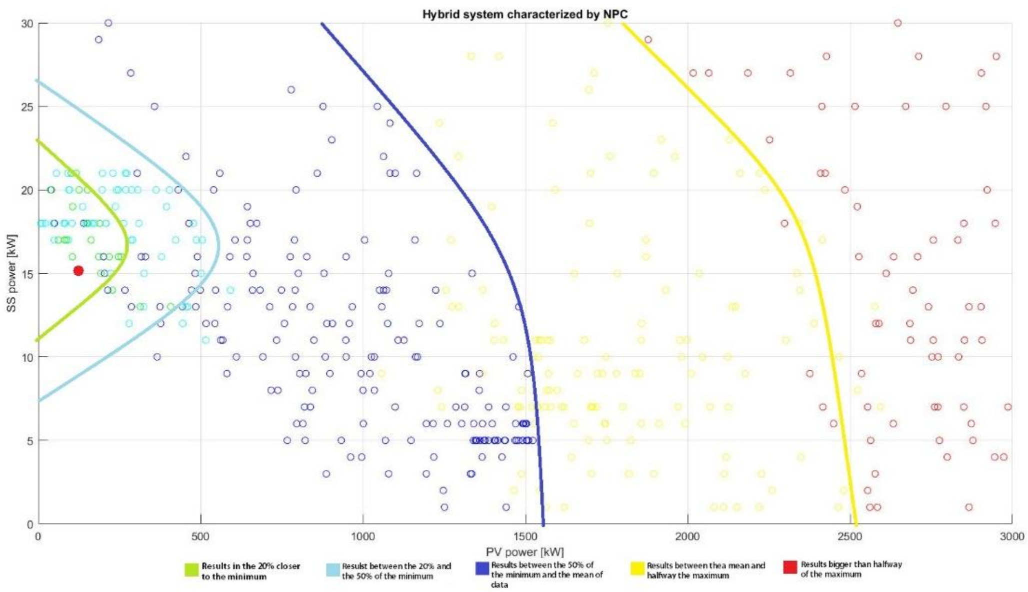


Figure. 20. 2D plot for simulation 1 for SS-PV axes with NPC characterization.

Figure. 21 shows the SS-BESS plane. On this plane is difficult to identify the regions where the PV-BESS-SS combinations are located. This result point that the variable that affects more the NPC value is the PV. Since for close values of BESS and SS the NPC value changes radically with the PV size. Beyond this, the green points and the cyan ones are again located in a region close to the global minimum. There are not points of these two colors dispersed all over the research space. Enforcing the theory that the local minimums are close to the global minimum only.

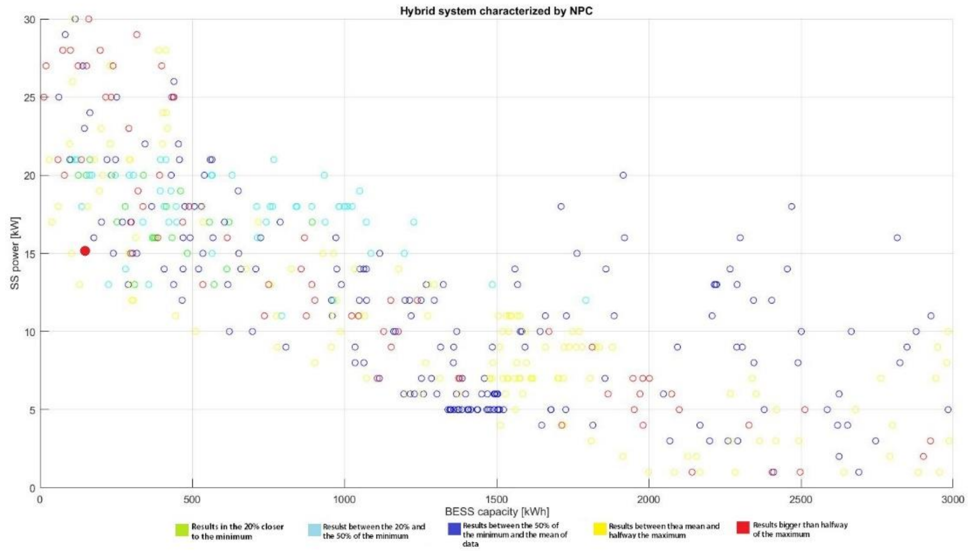


Figure. 21. 2D plot for simulation 1 for SS-BESS axes with NPC characterization.

5.3.2. Example 2

Figure. 22 shows a different set of data from another simulation with the three dimensions and the distribution seems to be very similar but it is going to be a two-dimension analysis to check the behaviors of the combinations.

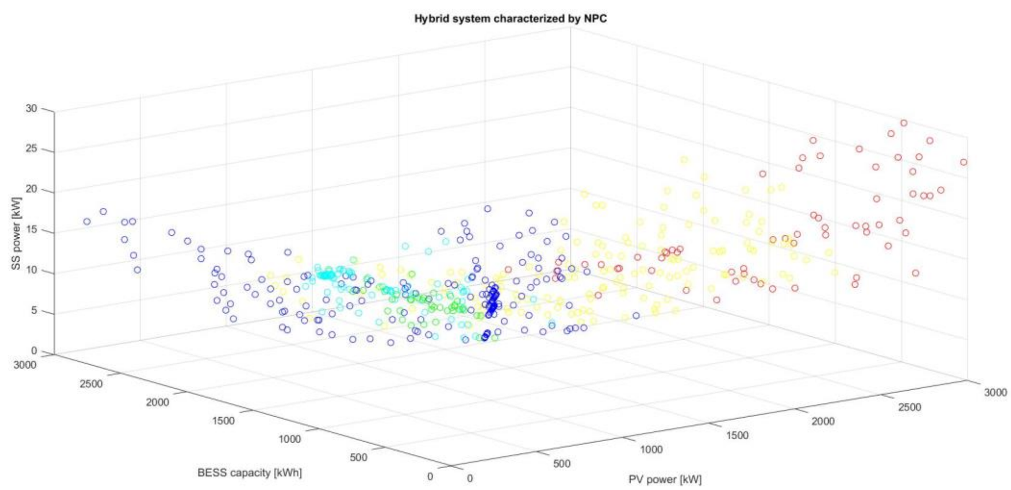


Figure. 22. 3D plot for simulation 2 with the NPC characterization.

Figure. 23 shows the BESS-PV plane of the second simulation. In the previous simulation for BESS-PV the regions where located in the same zones of the plane. For these simulations, the sampled points with the lower NPC value are again close to the global minimum and the further the bigger the NPC.

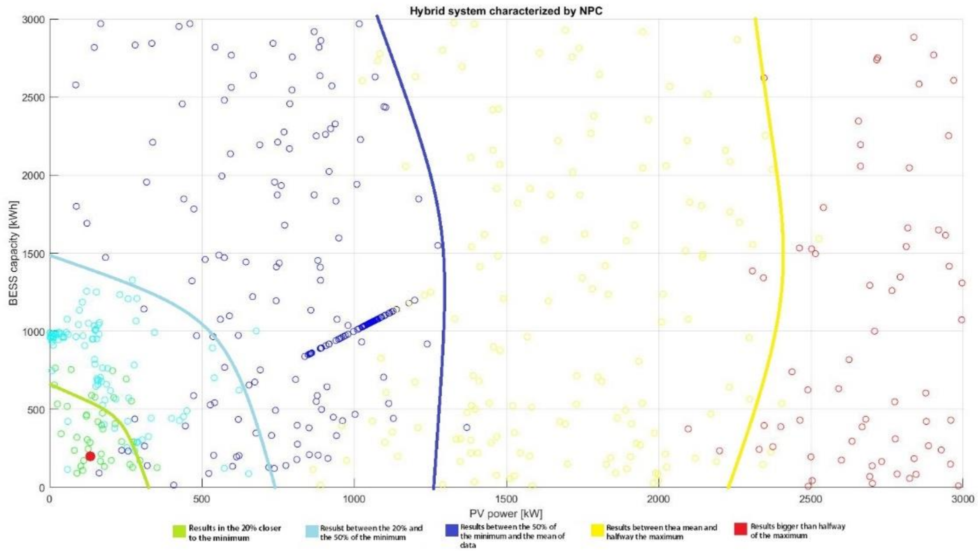


Figure. 23. 2D plot for simulation 2 for BESS-PV axes with NPC characterization.

Figure. 24 shows the SS-PV plane of the second simulation. One more time, the regions are located in the same zone and with a similar shape than the first simulation.

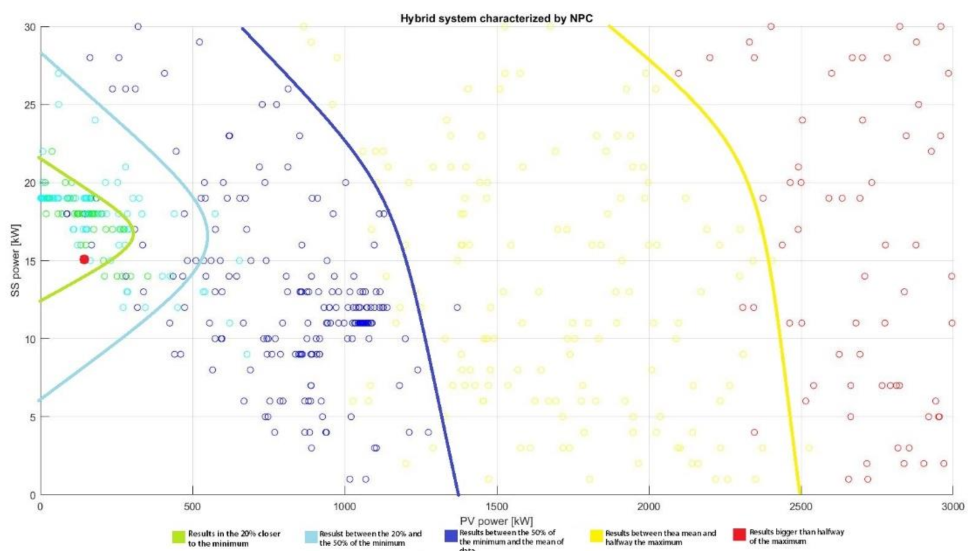


Figure. 24. 2D plot for simulation 2 for SS-PV axes with NPC characterization.

Figure. 25 shows the SS-BESS plane of the second simulation. The behavior is the same; the green and cyan points are clustered around the global maximum, the NPC values are dispersed over all the plane pointing that PV variable is the one that changes the NPC cost radically and, the points that fulfill the LLP are distributed in the same zone.

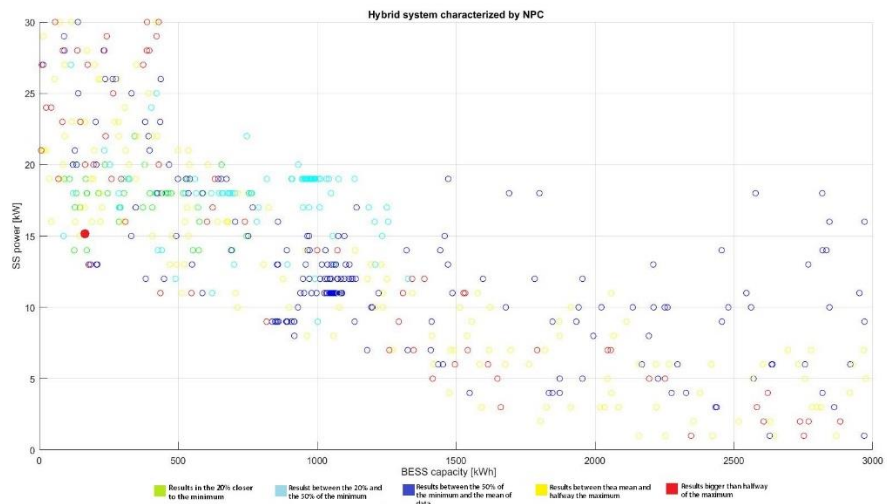


Figure. 25. 2D plot for simulation 2 for SS-BESS axes with NPC characterization.

5.3.3. Validation summary

From the set of simulations performed with the same inputs all the NPC values obtained in the optimum are close to the global minimum. The maximum error obtained in the simulations performed is 3.5%, which can be acceptable for this iterative algorithm. The size of the systems differs between them, nevertheless the optimization function tries to minimize the NPC value. For this reason, is not a problem that the PV-BESS-SS configuration differs if the final NPC is close to the global optimum. There can be many configurations close to the global minimum given the freedom degrees.

There can be identified regions where the points are located in function of the proximity to the global minimum. These regions are observed in the PV-BESS and SS-PV planes. On the SS-BESS plane, the dispersion of the points does not allow to recognize the regions clearly pointing out that PV variable is the one that changes the NPC in a major way.

The points where filtered at the beginning using the LLP condition. Once the filtering is finished, the combination points are located in the same zones of the research space even if they are not the exactly the same values.

5.4. Generation models implemented

5.4.1. Wind generation

The wind flow is produced by the temperature difference between zones on the earth. The temperature difference is caused by the energy received from the sun, so the wind energy is an energy derivate from the solar one. The temperature difference prints kinetic energy to the particles of the air. The wind can be used as a fluid that can be turbinated in order to transform this energy into electrical energy.

Figure. 26 shows the schema of a wind power system. The wind turbine catches the flow and moves producing mechanical energy. The speed of the turbine is not enough to generate electrical energy in an efficient way, for this reason there is a gearbox to increase the rotational speed for the asynchronous generator. Then, the speed of the wind is not constant so it is necessary to control the energy produced by the generator in order to supply energy with good quality. This means a constant frequency at stable voltage values. For this task there are used an ac-dc converter followed by a dc-ac one, this configuration allows to control the wind power system properly [38].

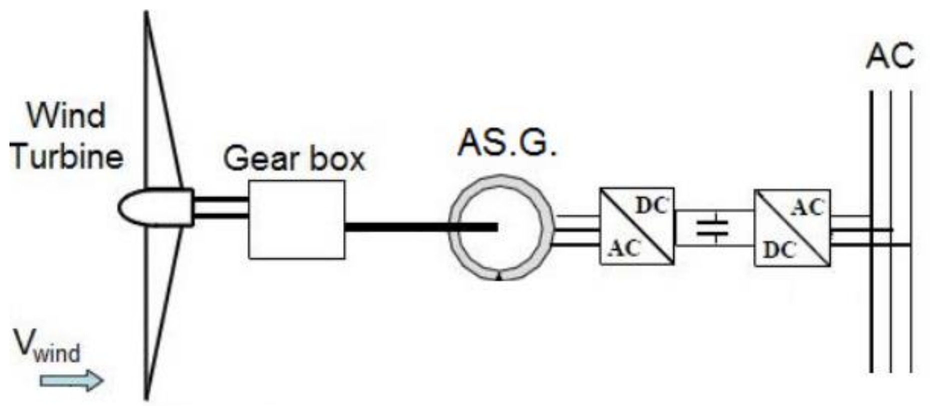


Figure. 26. Wind power system schema [38].

From the speed of the turbine is possible to create the response curve for the output power of the generator. With this curve and the wind speed for each time step is possible to determine the energy generated by a wind farm with a specific turbine on time. This section explains how the wind model has been implemented to calculate the generation for a wind power system in a micro grid.

I. Input parameters

There is a set of parameters needed to set the profile for the wind generation. The energy generated by a wind turbine depends on the wind flow and the response of the turbine to the flow. For this reason, there are two input parameters necessary to calculate the energy generated for a micro grid in one zone. The response curve is the first input; the wind profile is the second one.

II. Response curve of the turbine

The response curve of the turbine gives the output power generated by the selected wind turbine. For these simulations, the turbine used is the VESTAS V90-3.0 MW. The objective is to know which is the power generated with the wind available in the zone. It is possible to choose different turbine models but if the size of the PV is smaller than the turbine nominal power the real price will not be coherent with the simulation because it will be oversized. In case the size of wind given by the algorithm is bigger, it is possible to find a bigger and cheaper turbine or to install a wind farm with many turbines selected [39].

The selected model is a wind turbine medium and high wind speed with high turbulence. Figure. 27 shows the power output response of the turbine, before 4m/s there is no energy generated, and then it follows $\sim v^3$ approximately until it reaches the maximum. When the wind is bigger than 25 m/s it does not work for security reasons.

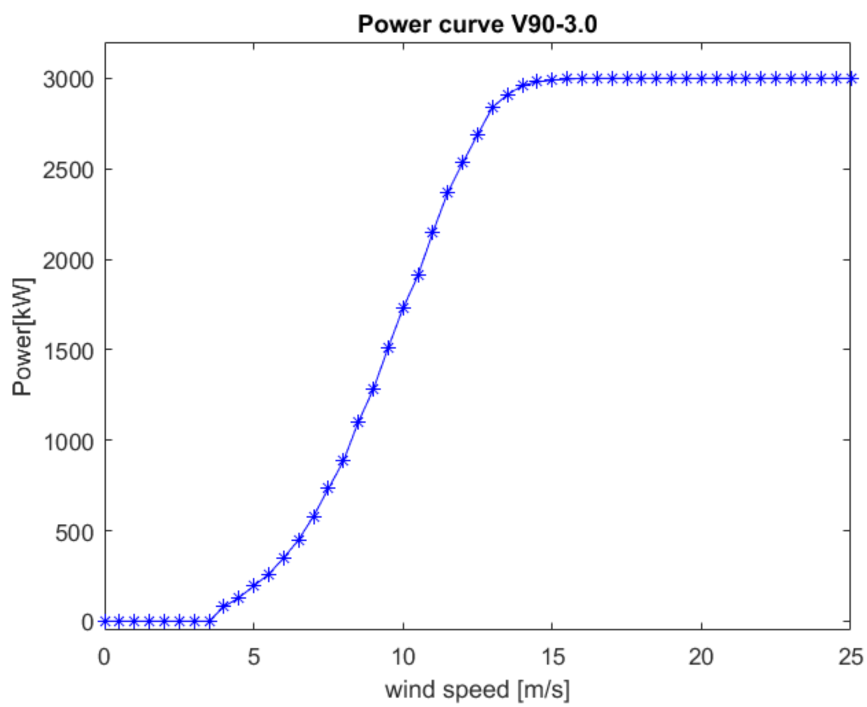


Figure. 27. Characteristic power curve of the wind turbine V90-3.0.

Figure. 28 shows the wind intervals in which the turbine control works. The red line shows the cut in speed where the turbine starts working, the brown line shows the cut out speed where the turbine stops working and the yellow line shows the rated speed where the turbine reaches its maximum output power. In addition, there can be seen three operational zones; the first is when the turbine follows the power of the wind with an increase of power proportional to v^3. The second zone starts in the green line, which is an inflection point where the shape of the function changes in order to arrive to the rated speed in an exponential way. The third zone starts in the rated speed and finish in the cut out speed, and it is characterized for a constant power output independent from the wind speed.

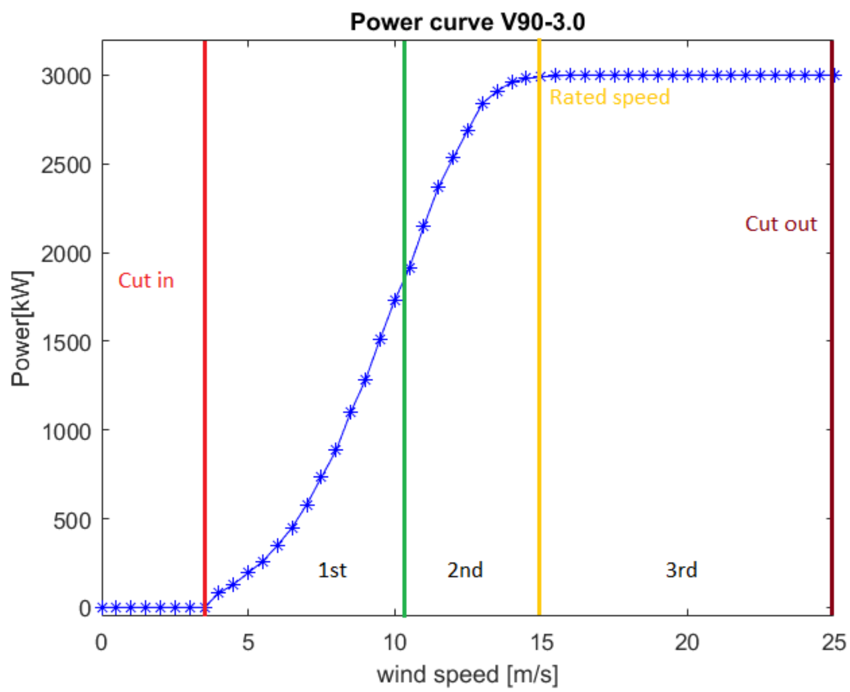


Figure. 28. Operation intervals in wind turbine.

III. Wind profile

The wind profile is the speed of the wind for each time step of the simulation period. For this profile there are two possibilities; the first one is to generate a theoretical profile with a model of the wind and the second one is to search for real data measured in a weather station and combine or duplicate the fields in case they are too many or too few for the simulation time step.

Solving the first option. The Weibull velocity characterizes the speed of the wind with a probabilistic function. This model is the most basic and repeated one for preliminary analysis of wind farms. The expression of the probability of a wind speed is given by the following equation.

$$f(v) = k * \left(\frac{v^{k-1}}{c^k}\right) e^{-\left(\frac{v}{c}\right)^k}$$

Where k and c are constant that can be calculated using the mean of the wind and the standard deviation of it in a set of measures.

$$k = \left[\frac{\sigma}{v_m}\right]^{-1.086}$$

$$c = \frac{v_m}{\Gamma\left(1 + \frac{1}{k}\right)}$$

Where Γ is the gamma function $\Gamma(x) = \int_0^a t^{x-1}\, e^{-t} dt$.

The ideal energy produced by wind can be found with the derivation the kinetic energy produced by its speed. The expression in function of the speed is $P_w = \frac{1}{2}\rho S v^3$. But then, Betz has stablish a theorem which limits the ideal power that can be extracted from the wind assuming that S is the rotor surface, the velocity of the wind flowing is normal to the rotor plane, incompressible air, stationary flow, and no shears at the control surfaces. After these assumptions, the possible extracted power is limited by 60% as the expression following shows $P^* = \frac{1}{2}\rho S \frac{16}{27}\, v^3$. Figure. 29 shows the curves of ideal power produced by wind, the ideal power including the Betz limit, and the real power of the turbine-selected output.

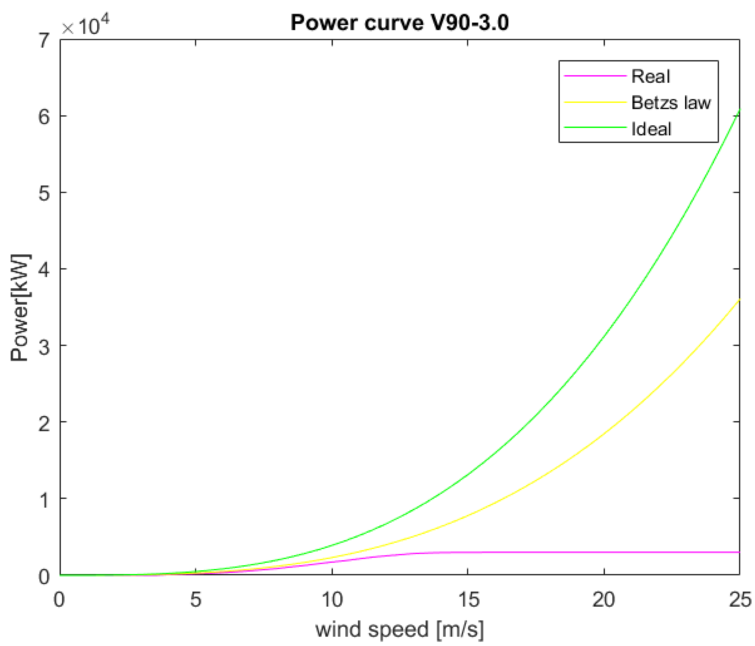


Figure. 29. Ideal, Betz and real power output produced by wind.

IV. Power factor profile generation

The function implemented in Matlab to generate the power profile factor for the wind follows the next expression. Where “w” is the characteristic power curve of the wind turbine matrix (one column has the wind vector and the other the power output). The input samples is the number of samples per year needed in the simulation, “years” is the number of years that last the simulation and, c and k are the values described to characterize the Weibull distribution (These parameters can be estimated, researched on the literature, or calculated from a set of data).

```
function [profile] = windProfile(w, samples, years, c, k)
```

The output “profile” is a vector of “samples” rows and “years” columns where the values are the relative value that the turbine generates. To calculate the relative values is necessary to compare the random wind velocity values with the output power curve of the turbine and then, the output power must be divided by the nominal power of the turbine. In this way. The values of the output vector are zero when the wind speed is in the cut in zone. The values are one when the wind speed is in the cut out zone. Finally, the values are between zero and one when the wind speed is between the cut in and the cut out zone.

The power generated by the turbine with a wind profile is calculated getting the output power from the Figure. 27 with the closest value of the wind value generated with the Weibull distribution. Figure. 30 shows the code used to generate random values that fits the distribution function. It is use an interpolation using the cumulative distribution function of f (v) over the wind velocity vector of a random values vector.

```
x=linspace(0,max(w(:,1)),length(w));
f1=k.*(x.^(k-1)./(c^k)).*exp(-((x./c).^k))/2;
%GENERATION OF A VECTOR THAT FITS THE WEIBULL FUNCTION
xq = x;          % x
cdf = cumsum(f1);         % P(x)
% remove non-unique elements
[cdf, mask] = unique(cdf);
xq = xq(mask);
% create an array of "samples" random numbers
randomValues = rand(samples,1);
% inverse interpolation to achieve P(x) -> x projection of the random values
projection = interp1(cdf, xq, randomValues);
```

Figure. 30. Code that generates the wind random points according a probabilistic distribution.

Figure. 31 shows the probabilistic wind velocity distribution given the parameters c=5 and k=11. This figure shows the probability for each speed. Then, Figure. 32 shows the histogram of the values generated by the previous code. It is seen that the shape of the histogram fits with the generation

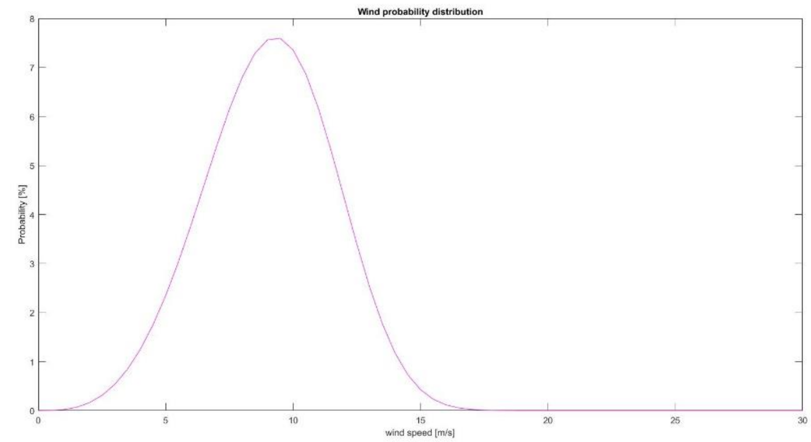


Figure. 31. Probabilistic wind velocity distribution for c=5 and k=11.

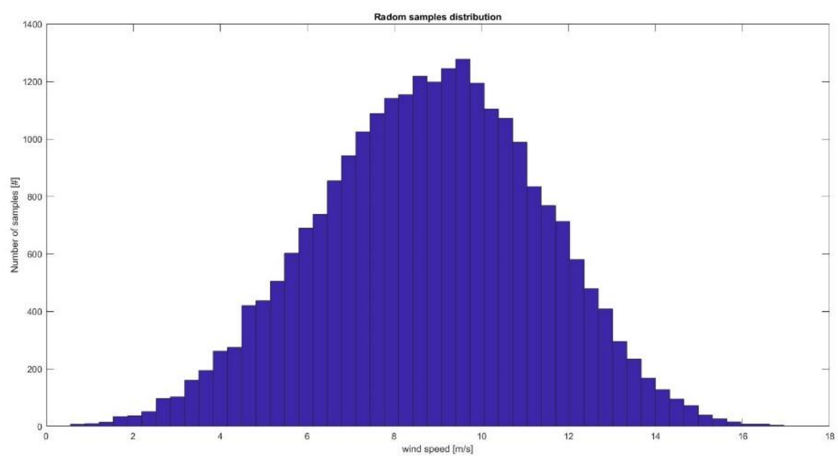


Figure. 32. Histogram of the wind profile vector.

The same code can be used to generate the power profile factors using real values of wind data instead of the Weibull distribution. In order to perform the simulation the number of wind speed samples must fit with the number of steps of the simulation for the 20 years. This kind of simulation is suggested when the histogram of the data does not behave like the Weibull distribution, otherwise the c and k parameters can be calculated with any set of data and then be used as input of the wind profile generation function.

V. Secondary source profile use

This “profile” will be used in the code as a multiplier factor for the different power values chosen in the simulation from the research space. Since the algorithm does not cares the nominal value of the turbine and selects the nominal power of the wind turbine randomly, the amount of energy generated for many wind turbines of the same reference is the addition of the generated energy of each one of them. That is why the generation factor of one turbine can be used as the generator factor of any nominal power chosen from the research space.

5.4.2. Hydro generation

The hydraulic energy is the type of energy generated by a mass of a liquid, due to its elevation, speed and pressure associated. Thus, the electrical hydraulic energy generated is a transformation from three types of energy in the mass of liquid. The potential energy associated with the elevation respect to a reference level of the water. The kinetic energy associated to the movement of the water and the pressure energy, which is the internal energy of a liquid [36].

$$Hydraulic\ energy = \frac{v^2}{2g}[kinetik] + \frac{P}{\gamma}[pressure] + Z[potential]$$

The origin of the hydraulic energy is the one absorbed from the sun, which produces in the earth planet by different conditions to transform the water generating the cycle of water. On this way, the hydraulic energy is a manifestation of the solar energy.

The process to transform the energy from a liquid mass into electrical energy needs a turbine and a generator. There is a pipeline where the water comes in and moves the turbine. The generator transforms the rotation of the flow turbine into electrical energy. The hydro generators can generate many MW whit the correct infrastructure. The small hydro generators are those, which has a nominal power lower than 5MW. These generators take advantage of the flow and /or the fall of water to generate energy.

I. Power production

The production of the small hydro generator is proportional to the caudal of the source and the jump height for each instant. The expression used to calculate the power produced by the generator is shown below. The gamma factor is the specific weight of the water and the total efficiency η can be considered 0.8 for modern generators [36].

$$P[kW] = \gamma * Q_{t_{step}} * H_n * \eta_{tot}$$

Since the power is function of the caudal on each instant, the energy generated is calculated in periods of time where the caudal can be considered constant. Since the simulation is performed with a time step of minutes, the caudal is practically constant over this time window. The height for this kind of generators is considered constant because there is no dam involved. In case the generator has a variable height, the variable should be considered for each time step as the caudal is.

II. Caudal

The energy generated by the hydro generator depends on the caudal. For this reason, it is very important to determine how will behave the caudal in time. The measure of the rivers caudal is done in the gauging station, there the instantaneous caudal are registered in the point where is located the station. Based on these measurements is possible to determine the maximum and minimum caudal per day and, time series of the forecasted cauda. At the end of the hydrologic study, regardless if the data is theoretical or real data, there will be enough data to build a sadistic distribution. This distribution is shown in the Figure. 33 that typifies the years in function of the contribution registered.

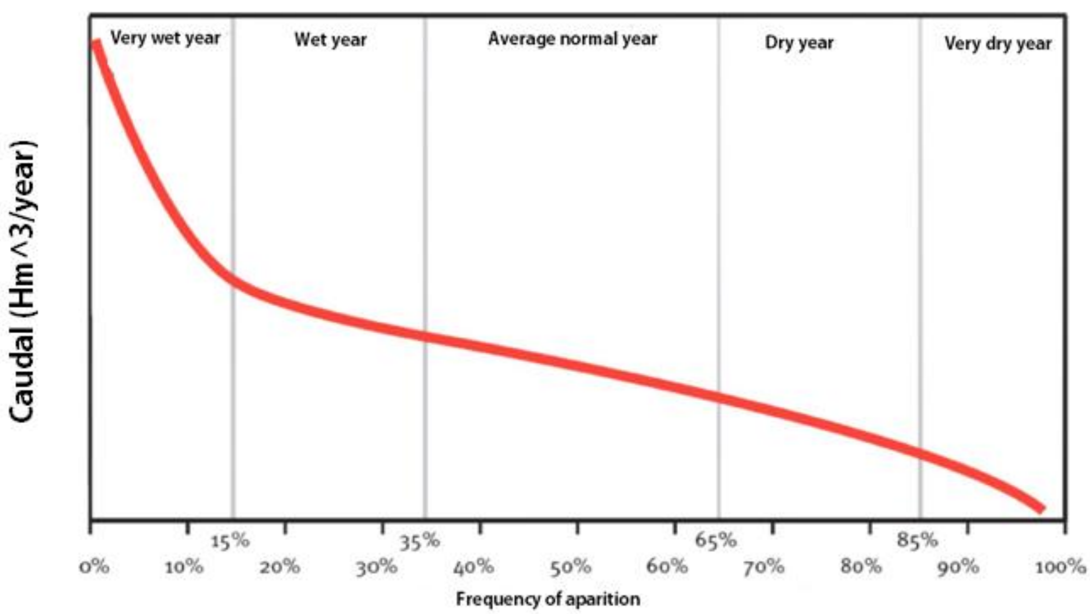


Figure. 33. Caudal frequency per years [40].

Once obtained the previous distribution, it will be taken a representative year and the classified caudal curve is built with this data. This curve, will throw the caudal in function of the time. It characterizes properly the hydrologic regime of a river. The classified caudal curve, shown in Figure. 34, gives important information about the water volumes.

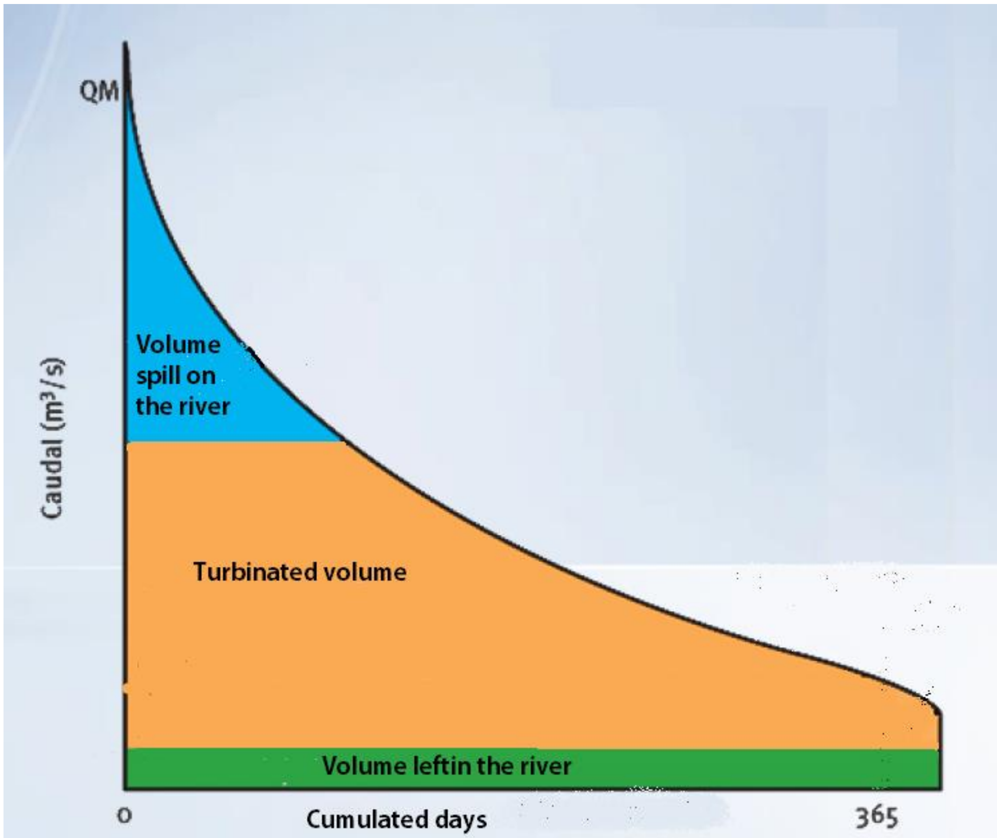


Figure. 34. Classified caudal in function of the cumulated days [40].

III. Power profile generation

When a hydro generator is going to be installed is necessary to perform a hydraulic study that determines the precious information. Nevertheless, even when there is real or theoretical data for the caudal of a river, it is possible that the step used in the study does not fulfill the time step parameter of the simulation. For this reason, it is necessary to generate a code where the caudal data is used to generate the data for the caudal.

The following function implemented on Matlab generates the profile used by the code using data from the caudal “q”, the number of years of the simulation “years”, the height of the fall of the water “h”, the efficiency of the turbine “eff” and the probabilistic data “std”.

```
function [profile] = pchProfile(q, years, h, eff, std)
```

Having any amount of data is possible to characterize it as a probabilistic function. The code calls this function and generated random caudal using the values of “q” for the mean of the distribution and “std” as the standard deviation of this one. The mean and the standard deviation of the caudal can be found with real data or theoretical one.

Once the caudal random points are generated, the code calculates the amount of power that the river can generate with the caudal and height given for each instant of time. Since the energy generated by the turbine depends on the nominal power of the turbine selected there will be implemented a function inside the lifetime simulation that calculates the power generated by a hydro generator of any nominal power with the caudal of the river.

The profile output is a matrix of dimension t_step x years where each value is the maximum power that the river cad generates with the amount of caudal available to be turbinated. On this case, the value is not between zero and one, on this case, the values depend on the caudal, the height of the river and the efficiency used.

$$P_{available}[kW] = \gamma * Q_{t_{step}} * H_n * \eta_{tot}$$

The hydro generator selected in the simulation will produce an amount of power equal to the nominal power if the available power on the river is higher than the power of the turbine. Moreover, it will be a fraction in the case when the available power on the river is lower than the generator’s nominal power. This selection process and calculation is shown in the following expressions. Once again, it is important to remember that the time step is minutes and that is why the factor to obtain energy is $\frac{1}{60}$.

$$Hydro\ power_i\ [kW] = \begin{cases} Nominal\ power[kW] & if\ P_{available} > P_{nominal} \\ \left[\frac{Profile_i}{P_{nominal}}\right] * P_{nominal}\ [kW] & if\ P_{available} \leq P_{nominal} \end{cases}$$

$$Hydro\ generation_i\ [kWh] = \frac{Hydro\ power_i\ [kW]}{60\left[\frac{1}{h}\right]}$$

6. Approach Proposed

In order to evaluate the best solutions for providing electrical energy to remote areas it is necessary first appoint how and why the adopted approach is chosen. The possibility of measuring and therefore evaluate the performance of the different solutions is indispensable to provide the trustworthiness of the work. Hence, mathematical models associated with the characteristics of the transmission network or micro grids studied, give possibilities to elaborate hypothesis and validate it.

One proposition is to model the transmission systems of the studied countries (Brazil and Colombia), obtaining as far as possible the amount of information necessary to full describe it, at least closely to a realistic approach. The evaluation of the transmission networks will be based also on the grid code regarding each country. Moreover, it is necessary a trustful power flow program to ensure the reliability of the results, therefore was chosen the MATPOWER program, described in more details in the Annex of this work.

The same idea for the micro grids design, in which the data referred to the location where the micro grid will be set is crucial for the most reasonable results.

With the two approach it is possible to hypothesize innumerous solutions and working on the program, to model the changes and evaluate the results of the simulations. Possibilities such as insert a new transmission line or a micro grid in the main network are performed and the outcomes compared.

The idea of load increment in selected regions of the transmission network aims to quantify and forecast the impacts on those areas. As the focus is related to some specific areas, in which the transmission systems do not reach or reach partially, it is specified the propitious areas of micro grids development in Brazil and Colombia. The presented maps regards the models of the transmission system that will be presented in the next chapter.

6.1. Load Increment – Methodology

In order to assess the network on these selected areas it was proposed the performance of load progressive increment.

The proposition was to consider, based on the total load of the respective scenario, implement progressive load increment focused on the selected buses. The incremental amount is based on a percentage of the total demand. Thus, the behavior of the network considering the steady-state parameters are evaluated in each simulation until it reaches the technical constraints or even the power flow does not converge anymore. The progression starts from small percentages such as 0.1% of the total load, growing to 0.5%, 1% and so on. As each simulation is performed per time, it is possible to evaluate how the growth impacted the network and ponder about the percentage quantity that would be more adequate in order to a better evaluation of the system. Therefore, if the behavior of the system changes abruptly in terms of steady-state parameters such as voltage magnitude or line loading, the next simulation will consider an adequate load increment amount. The flowchart is presented in the Figure 35 with the methodology.

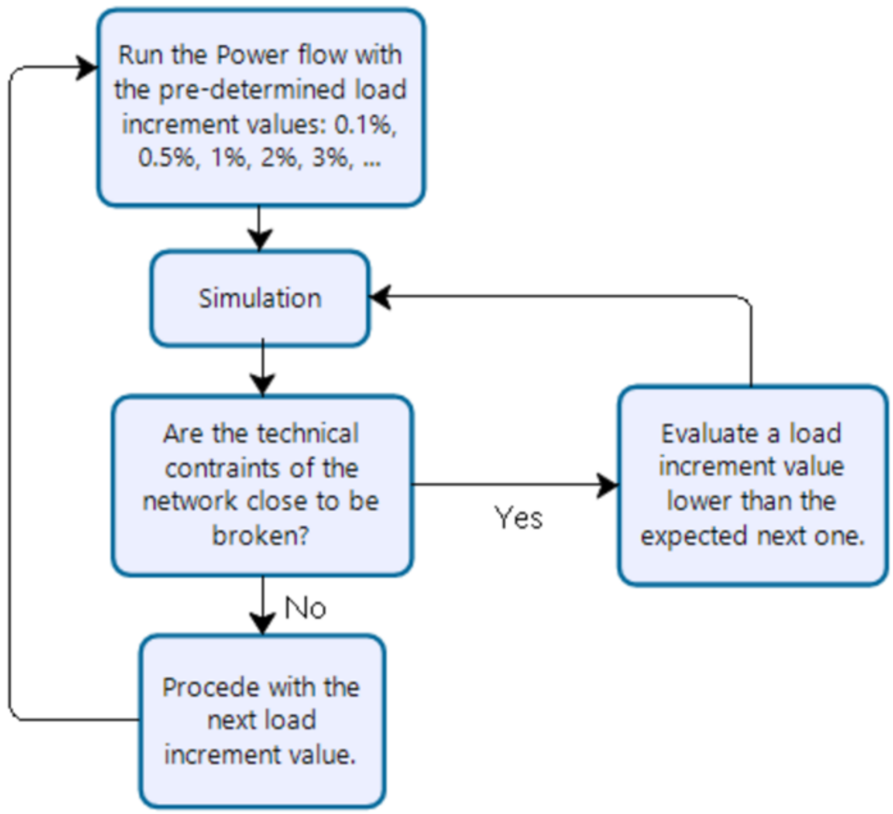


Figure. 35. Flowchart with the load increment methodology.

It is important to mention that the progression considers the percentage of the total load and it is distributed between the selected buses considering the population number of each department considered. The population of all the departments that the buses were selected are summed and the load increment will be divided proportionally to the state's population and number of buses.

6.1.1. Load Increment based on the Regional Growth.

Another proposal for evaluating the network with respect to the load increment is referred to the consideration of the regional energy growth in order to perform a more realistic scenario. In this case, it is necessary the information regarding the energy consumption in the interested state or department in the last years. It would be also interesting if the used growth factor is referred to a high growth year rate, allowing a more conservative analysis that could be classified as the worst load forecast in terms of planning.

In this case the procedure does not anymore change the load increment value due to eventual broken constraints after each simulation, but consider when (number of years), maintained the determined demand growth each year the system will not be able to operate following the steady-state constraints.

6.2. Transmission Lines Insertion

The load increment aims to analyze the impacts caused in the grid and to discuss and compare possible solutions for the presented problem. One way could be the integration of micro grids to the main system, allowing in one hand, the mutual benefit for the micro grids, which will have the security and reliability of the Interconnected Network and on the other hand, the benefit for the main system, which could postpone investments in such areas due to the micro grids power capabilities.

As an alternative in way to compare the results of the load increment in micro grids insertion context, it is proposed the analysis of transmission line insertion. The main idea consists in providing more stability and energy transfer capacity to such peripheral branches that are mainly radial and as resultant quantify the load increment with this new connection.

The insertion of the new transmission line does not intend to be the best technical solution among all the connection points in the studied area, but just to connect the furthest bus in the analyzed branch to a more stable bus, creating a sort of ring topology.

Furthermore, in order to have a more realistic comparison, the calculation of the Levelized Cost of Energy (LCOE) is performed both for the transmission line and micro grids solution in order to compare.

6.3. LCOE calculation

The Levelized Cost of Energy (LCOE) can be defined as a method to compare different generation projects based on the values capital costs, capital recovery factor, operation and maintenance costs, fuel expenditures and the yearly electricity production. The resultant unit is the adopted currency by the energy produced, being a good parameter that allows practical comparisons.

The formulation of the LCOE is given by:

$$LCOE = \frac{Total\ annual\ costs\ \left[\frac{€}{y}\right]}{Yearly\ electricity\ production\ \left[\frac{MWh}{y}\right]} \left[\frac{€}{MWh}\right]$$

In which the Total annual cost can be open in:

$$Total\ annual\ costs\ \left[\frac{€}{y}\right] = CCC\ \left[\frac{\%}{y}\right] * Cinv, total[€] + \ yearly\ fuel\ costs\ [\frac{€}{y}] + yearly\ O\&M\ costs\ [\frac{€}{y}]$$

Where, *CCC* is the Company Cost of Capital which is the yearly return capital to the company make an investment worthwhile. It is composed of the cost of debt and cost of equity and is a parameter used to analyze if the investment is or not a good option. $Cinv, total$ is the total investment cost of the enterprise. The $Yearly\ fuel\ costs$ and *Yearly O&M costs* is a variable cost that considers the fuel and the *Operation and Maintenance costs (O&M)* expenditures, respectively.

All the costs were based on the Bank of Prices 2018 provided by the energy Brazilian Authority (ANEEL) [27]. Considering the difficulties of native forest area, a factor of 1.5 was considered for higher towers. Similar methodology applied for factors was adopted in concerning to assessment reports published by the Energy Research Office in Brazil (EPE) [28].

The Bank of Prices works with the Brazilian currency (Brazilian *real*). The exchange rate was based on quote on 14th of November of 2018. The value of one euro was equivalent to 4.2987 *reais*.

6.4. Propitious Areas for Micro grids Development

6.4.1. Propitious Areas in Brazil

In Brazil, based on the analysis of the reach of the National Interconnected System (SIN), it is possible to evaluate prone areas to the development of Microgrids. Considering that the greatest part of the loads is connected to the main system, it still around 0.7% of the total demand that is not yet connected, due to technical or economic reasons [23].

The major part of the isolated systems is located on the north part of the country, specifically on the Amazonian region. The energy matrix of the isolated system is composed predominantly of Diesel and a small percentage of gas, biomass and small hydro. The size of the isolated systems varies tremendously, from small villages scattered in the Amazonian region with maximum demand of 4 MW, to a capital of a state that is not connected to the main system yet, with the maximum demand around of 233 MW.

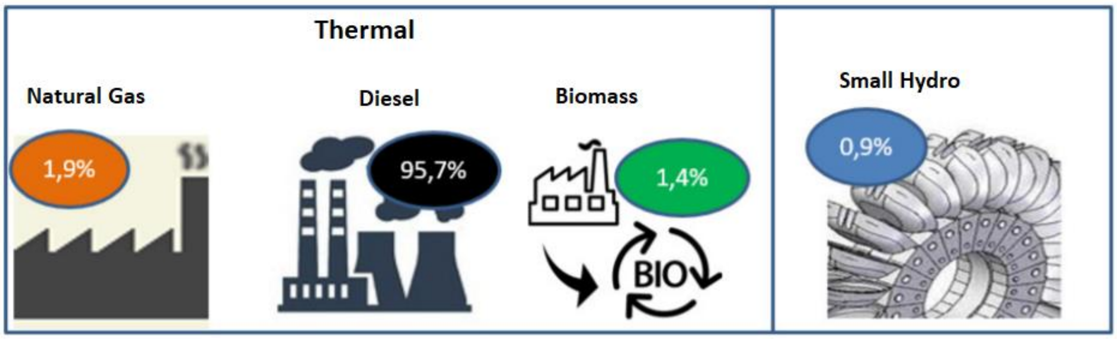


Figure. 36. Energy matrix of the isolated systems in Brazil [23].

As shown in Figure 36, almost the totality of the isolated systems uses thermal sources, which creates logistical problem considering the huge distances that must be travelled to deliver the fuel, planning problems in order to estimate continuously and accurately the demand, hours of use and all the costs that are implicit.

The development of micro grids that could use the abundant resources available on those areas, such as the high sun irradiation all the year, the vastness of rivers that could be used for small hydro power plants, good sites for wind energy in the coast, and so on.

In order to assess the capacity and possibility of load growth, focusing on the more isolated areas that the National System reaches, it is proposed to perform a progressive load increment evaluating the behavior of the system with respect to the technical constraints. Presumably, the network on those areas has a more radial topology characteristic, working with less reliability, and lower level of voltage due to the reduced transferred power to those areas.

Considering the Brazilian equivalent model, which will be presented in more details next chapter, it contains only one part of the National Interconnected System (SIN). It was chosen the closest area to the Amazonian region, which encompasses the state of Mato Grosso. Actually, it is an important rural area of the Brazilian agribusiness, however, it still has native forest and the inherent difficulties.

In the Brazilian model map of the grid, the buses considered in order to perform the load increment are highlighted with the arrows, depicted in Figure 37.

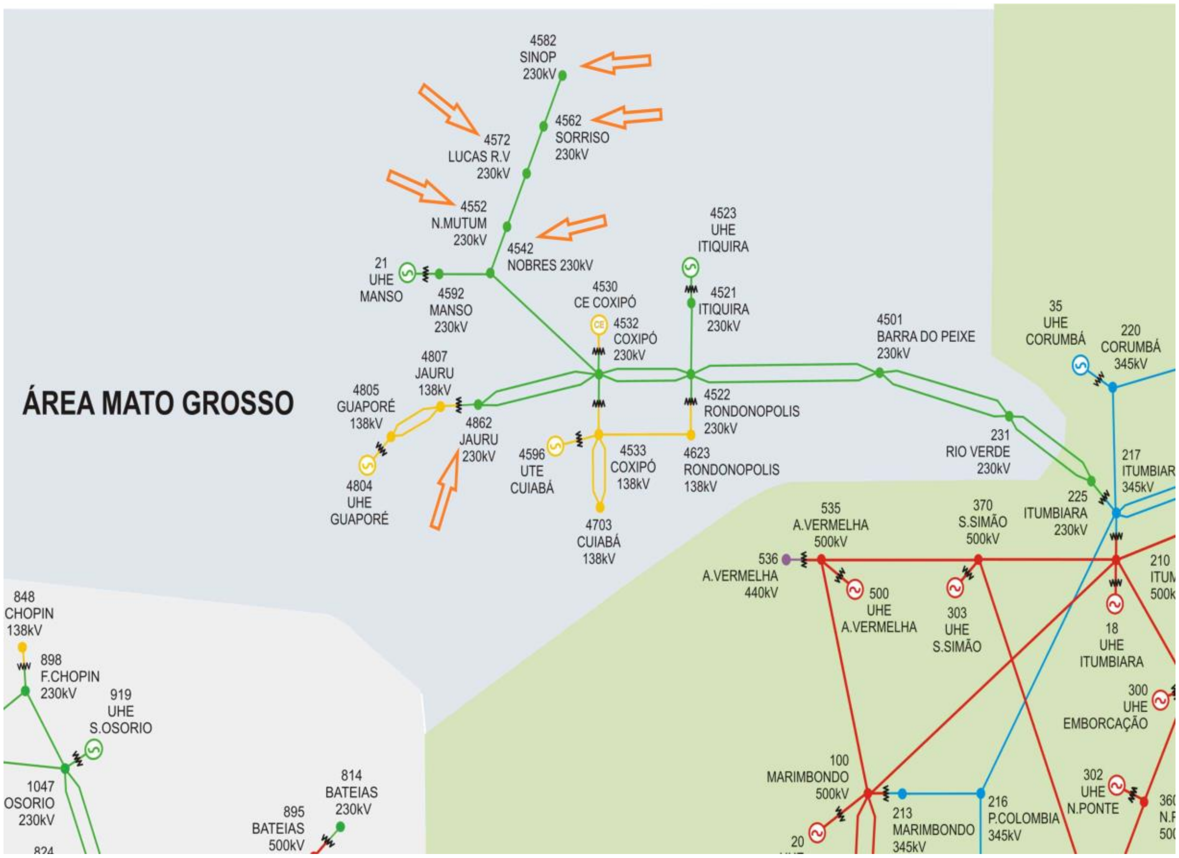


Figure. 37. Buses considered in the Mato Grosso area to perform the load increment in Mato Grosso Area.

As mentioned, Mato Grosso is a state of relevant importance for the agriculture of the country and the demand in part of the state is substantially related to it. The state has the population estimated in 3 441 998 for an area of 903 357 km^2 [24], therefore a small density.

The energy consumption in the state in the last two years is given in the Table III [25], where is possible to notice a growth of 6.81% comparing the two years, it is significantly high, considering Brazil has just passed for moment of economic crisis.

Year	January	February	March	April	May	June	July	August	September	October	November	December	Total [MWh]
2017	628,327	657,465	706,312	698,378	709,430	713,467	693,316	727,634	814,280	778,714	735,574	712,264	8,575,161
2016	623,158	656,234	692,601	708,787	661,121	650,785	659,836	702,379	688,823	686,056	667,997	630,231	8,028,008

Table. II. Electrical Energy Consumption in the state of Mato Grosso, 2016 and 2017.

6.4.2. Propitious Areas in Colombia

For the Colombian situation, as it was modelled the whole National Transmission System, gives the possibility of considering more areas, taking into account more than one department in order to assess prone areas for the development of Micro grids. The full model will be presented in details next chapter.

It was proposed consider the departments located in the eastern part of the country, in which are departments with a smaller population density, native forest and with precarious or non-connected to the main grid.

There are in Colombia a designation for the systems that are not connected to the main grid, it is called Non-Interconnected Zones (ZNI). The major part of the country, around 52% [26], is part of the ZNI. It encompasses the eastern part of country and also areas in the coast. Around 90 counties, 5 capital of departments and villages of indigenous are in the ZNI.

Considering the eastern part of the country, and electing the most prone departments to Microgrids development, based on the geographical location, non-connection to the main network and feasibility of connection, it is possible to see the chosen departments, displayed in the table IV. More than considering the population and area of these departments, the connection with the main grid was taken into account. Despite the fact that the grid of 110 kV is not part of the National Transmission System, the existence allows the possibility of reaching those more isolated areas and open the possibility for simulations. Lastly, considering the Colombian model it was checked the location of the buses and listed referring it to the respective department. The Figure 38 shows the Colombian network, the departments and the chosen buses pointed by the arrows.

Eligible Areas					
Departament	Population	Area [km2]	Pop Density [hab/km2]	Connection with the main grid	Bus number
Arauca	267992	23818	11.252	230/110 kV	43, 44
Casanare	368989	44640	8.266	230/110 kV	92
Vichada	75468	100242	0.753	230 kV	95
Guaviare	114207	53460	2.136	110 kV	none
Guainía	42777	72238	0.592	No connection	none
Vaupés	44500	54135	0.822	No connection	none
Caquetá	490056	88965	5.508	110 kV	none
Amazonas	77948	109665	0.711	No connection	none
Meta	998162	85635	11.656	230/110 kV	93, 94, 105
Total Population	1710611				

Table. III. Information regarding the Eligible Areas in Colombia.

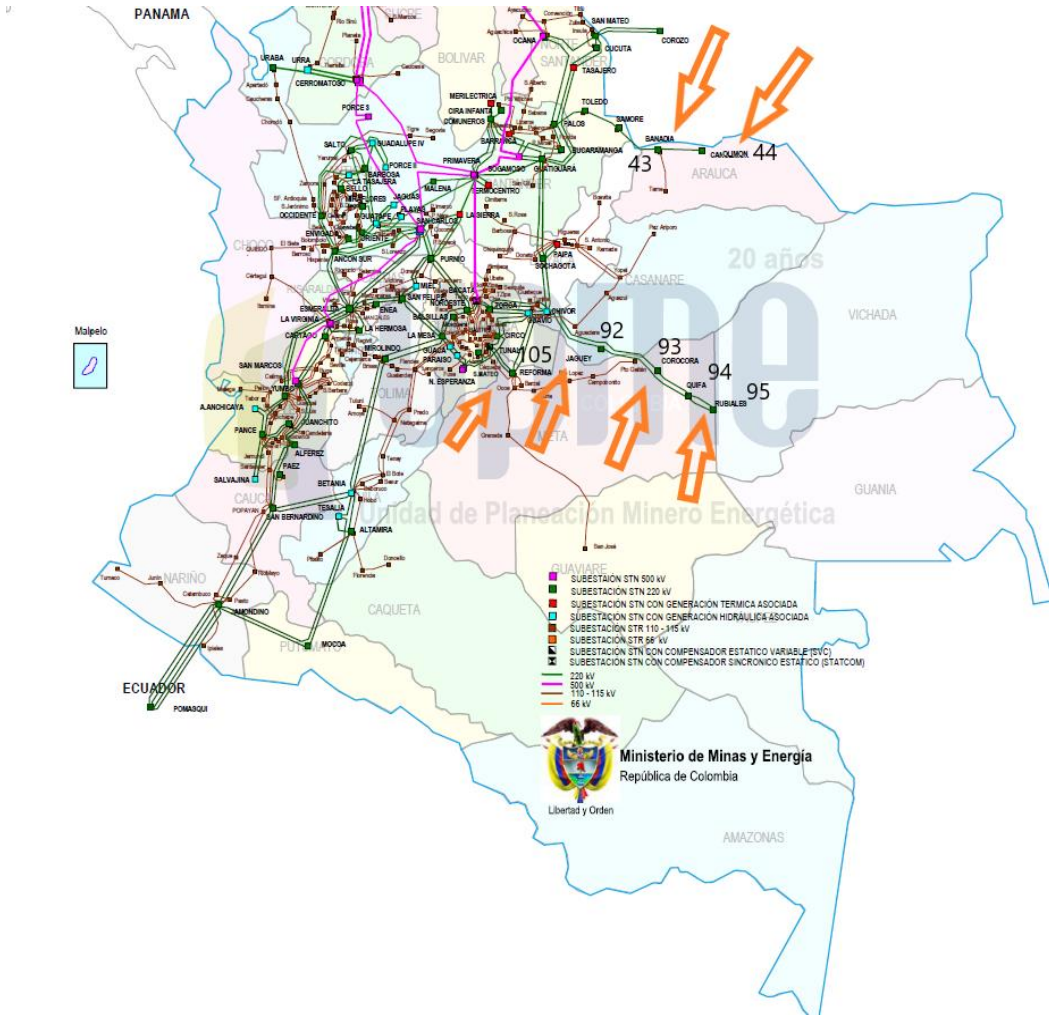


Figure. 38. Buses selected in the Colombian grid to perform the load increment.

6.5. Micro grids Insertion Proposition

Considering the assessment of the insertion of micro grids on the main system, with the target to assist the main network, it was proposed the insertion of clusters of micro grids of different sizes, in the areas more affected by the load increment drawbacks. As mentioned before, the load increment was performed in the propitious areas of the country for micro grids development.

Assuming the Colombian network model and considering the buses that the load increment was performed, it was focused on the more distant branches, in which the micro grids would have more possibility to be connected on. In the Figure 39, it is shown the two selected peripheral buses: 44 (CañoLimón) and 95 (Rubiales), in which the clusters will be connected. In order to evaluate the effects more clearly, the simulation regarding each bus will be performed separately.

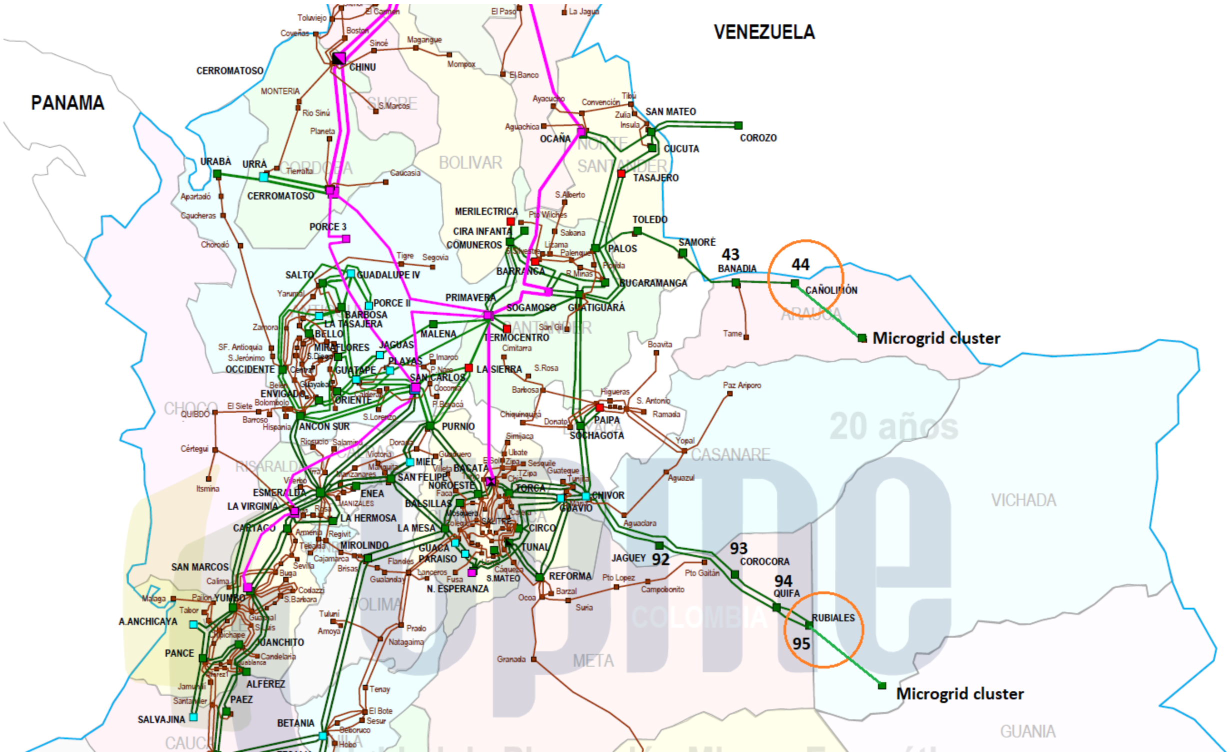


Figure. 39. Selected buses for the micro grids insertion.

Assuming that the micro grids have a unique model of 0.5 MW of maximum generation capacity and the maximum registered demand of 0.228 MW. Considering also, an optimistic scenario that the micro grids work with maximum producing capacity, perhaps with the support of the BESS. Regarding the demand, the most pessimistic scenario with the full possible demand, then, an overproduction of 0.272 MW is available to assist the main grid. As the legislations of Brazil and Colombia accepts clusters of small production units, clusters of different sizes were proposed in order to evaluate the impact on the interconnected network of Colombia. The transmission line that connects the elected bus to the bus that represents the micro grids is characterized with similar parameters of the transmission lines of the nearby radial branches. The length of the line is around 75 km.

The chosen scenario, which will be presented, for this simulation was the Peak Summer case with 4% of total grid load increment. The idea is to analyze the insertion of the micro grids in problematic scenarios in order to see the collaboration possible to perform. Furthermore, it opens new possibilities such as the ancillary services that the micro grids could implement helping the network and suggestions for strategical paid services that could foster the micro grids development.

7. Study cases - Brazilian and Colombian context

7.1. Brazilian Energy Scenario

The Brazilian Network has intrinsic characteristics that make it a singular network if compared to other systems worldwide. Starting from the geographical particularities such as the size of the country and the inherent difficulties in terms of transferring energy from high potential producing areas, located sometimes in the distant center-north of the country, to the load centers mainly in the coast. Another important point is related with the natural obstacles of electrifying remote areas, in which the main grid (National Interconnected System - SIN) does not reach, and the solution established is the deployment of isolated systems. The Brazilian Transmission System Operator, called ONS, manages and operates a total installed capacity of 174 254 MW [9]. Traditionally, due to the high potential of the hydro resources, the Brazilian energy matrix has been founded based on hydro power plants. According to recent studies [10], the total hydro potential in Brazil that could be technically explored is around 260 GW, in which only 105 GW is actually being explored. The major part of the unexplored potential is referred to the Amazon basin, where 87 GW is still available, however, only 5% of the Brazilian population live on this area [10]. The actual installed capacity is detailed on the table V, referring to the year 2017.

Source of Electricity	**Installed Capacity [MW]**	**Percentage of the total [%]**
Hydro	105 406	67.8
Thermal - Gas	12 597	8.1
Thermal - Oil	4 732	3
Thermal - Coal	3 138	2
Biomass	13 623	8.8
Wind	12 309	7.9
Nuclear	1 990	1.3
Solar	952	0.6
Other	779	0.5
Total	155 526	

Table. IV. Brazilian Installed Capacity in 2017 [10].

In order to better operate the system considering the particularities of each region, a connected grid was developed. Assuming the predominance of hydro power plants in the energy matrix, the interconnection of hydro basins with distinct characteristics can provide more security and reliability to the system. Different solutions were adopted, and a wide range of voltage levels selected according to the distance, technical analysis and operational aspects. The voltage levels actually used on the Brazilian system vary from 230 kV up to 800 kV. There are alternating current (AC) and direct current (DC) technology employed. In the Figure 40 there is a better description of the transmission lines panorama.

Figure. 40. Length of the Brazilian Transmission Network in 2017 [10].

Considering the huge distances between generation and load, solutions as the extra-high voltage in DC are being employed more frequently. One recent example are the lines of 800 kV that connect a recent built hydro power plant (Belo Monte) located on the Amazon basin to the loads in the south-east region. The center and northern regions have been focused on the last years as the new frontiers to become part of the main grid. The high variable cost of the thermal generators and the difficulties to reach these off-grid systems promote new projects for the network expansion. The Figure 41 depicts the Brazilian National Interconnected System (SIN). Projects of high complexity involving work on native forest and also legal complications are now set as priority projects due to the vulnerability of relevant cities that are fed by off-grid systems. Nevertheless, the main part of the small cities and communities in the Amazon region are supplied by off-grid systems due to of the impracticability of the full connection to the main grid.

The National Interconnected System (SIN) has connections with the Argentinian, Uruguayan and Paraguayan networks. Furthermore, there is a connection between the Venezuelan grid and the capital of the Roraima state, northern region of Brazil.

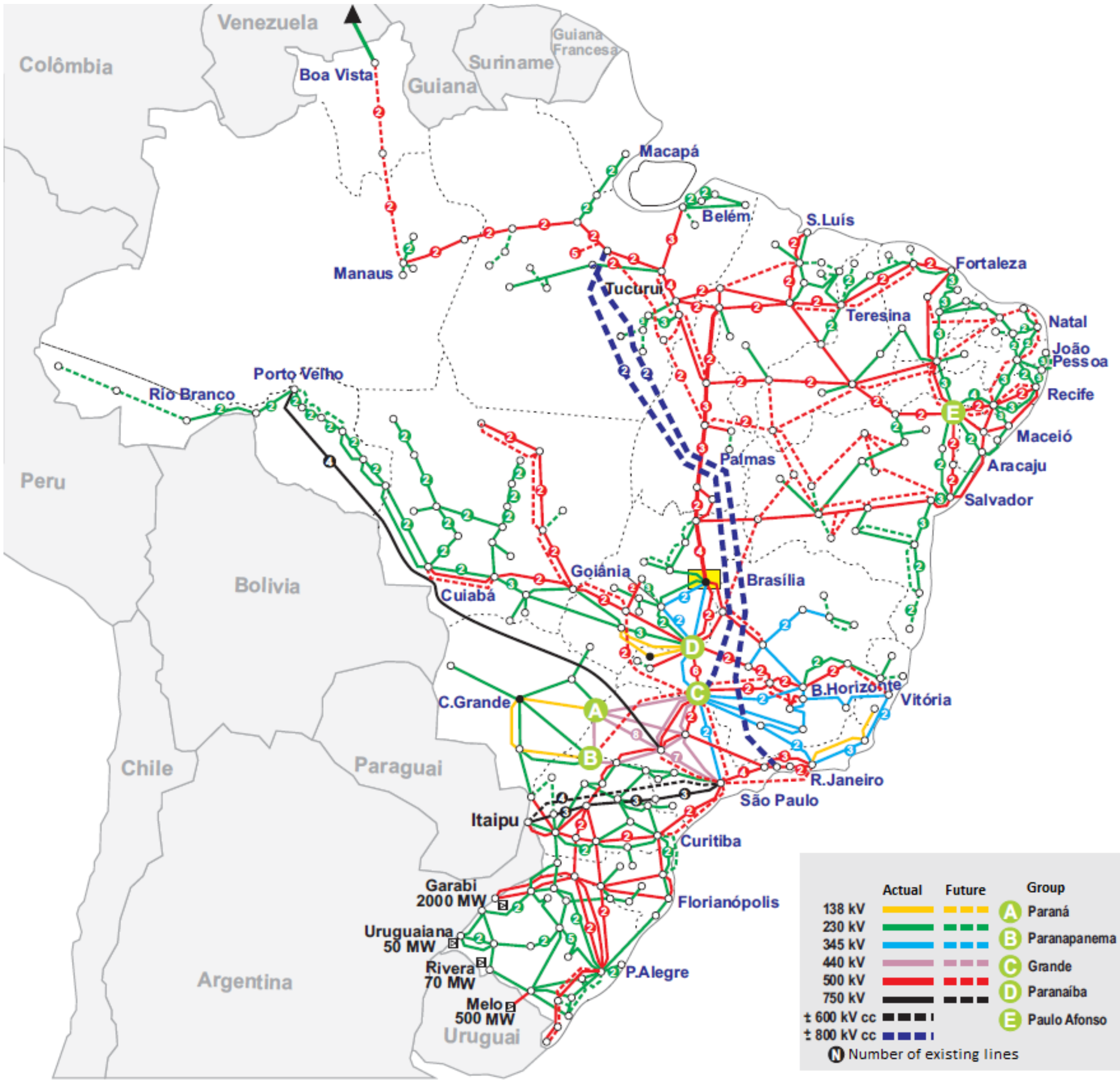


Figure. 41. National Interconnected System in 2017 [10].

7.2. Colombian Energy Scenario

The Colombian market nowadays is a liberalized pool market. The liberalization started on 1994 when the laws 142 and 143 were released. The law 142 of 1994 covers the public services as the cleaning, energy, gas, telephony, aqueduct and sewage. It defines the juridical nature of the public service companies, and the regulatory framework of the commissions which oversight these companies. Furthermore, defines the customers' rights and duties included the contribution or subsidy policy based on the social stratum. The stratums are six from 1 to 6, where the lower the number the lower the income of the population which uses the public services. The objective is to charge less to the population with the lowest income and make the one with the highest income to contribute for the subsidies. The stratums 1-3 receive subsidies and the stratums 4-6 gives contributions.

In the 90's Colombia started an opening process privatizing its economy in view of break free the public budget. The law 143 of 1994 is focused on the electrical sector, its purpose is to bring competitive prices, to enhance the service, to rise the quality of service and to extend the coverage. With this law Colombia was one of the first countries opening a wholesaler energy market.

7.2.1. Market structure

The Colombian market trades with big blocks of energy and power freely by demand and supply. The structure of this market is given in the Figure. 42 following a vertical separation. There are four big agents in the structure of the market, generation, transmission, distribution and commercialization. Some of them operates in competence and others are natural monopolies as it is seen bellow [41].

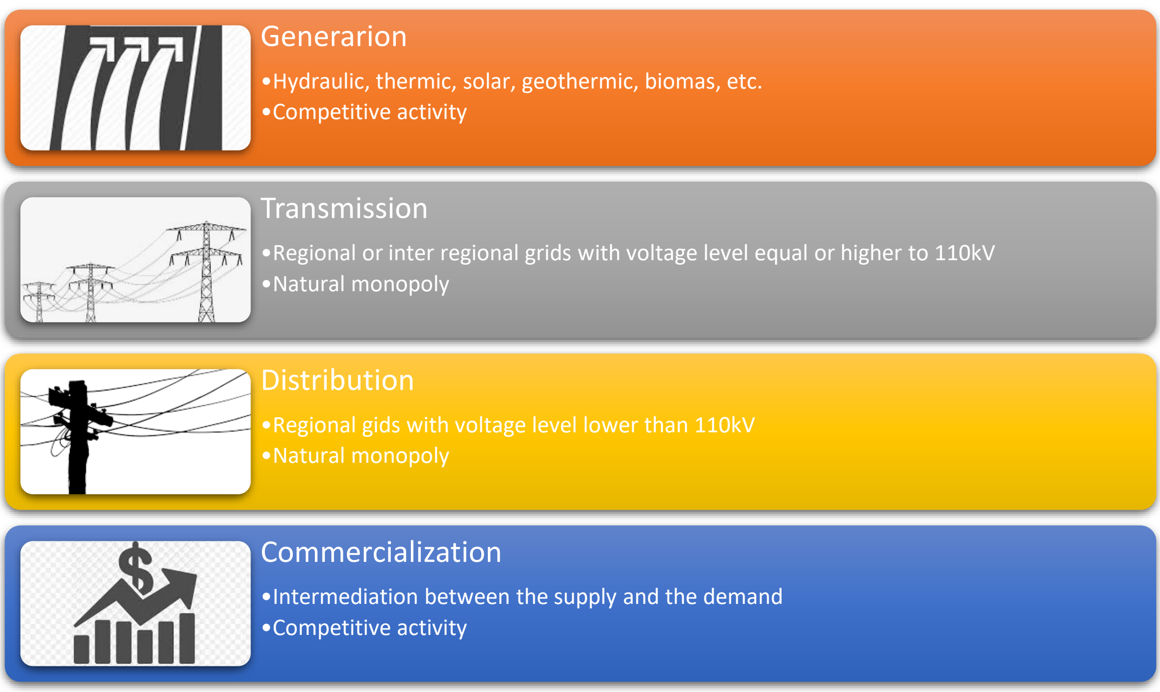


Figure. 42. Colombian market structure.

I. Generation

The Colombian generation sector is a competitive market where many actors and technologies are involved, bidding energy blocks in the wholesale market. The most used generation resources in Colombia are shown in the Figure. 43.

- Hydraulic (67%)
- Natural gas (27.5%)
- Coil (5.2&)
- Wind (0.1%)
- Others (0.1%)

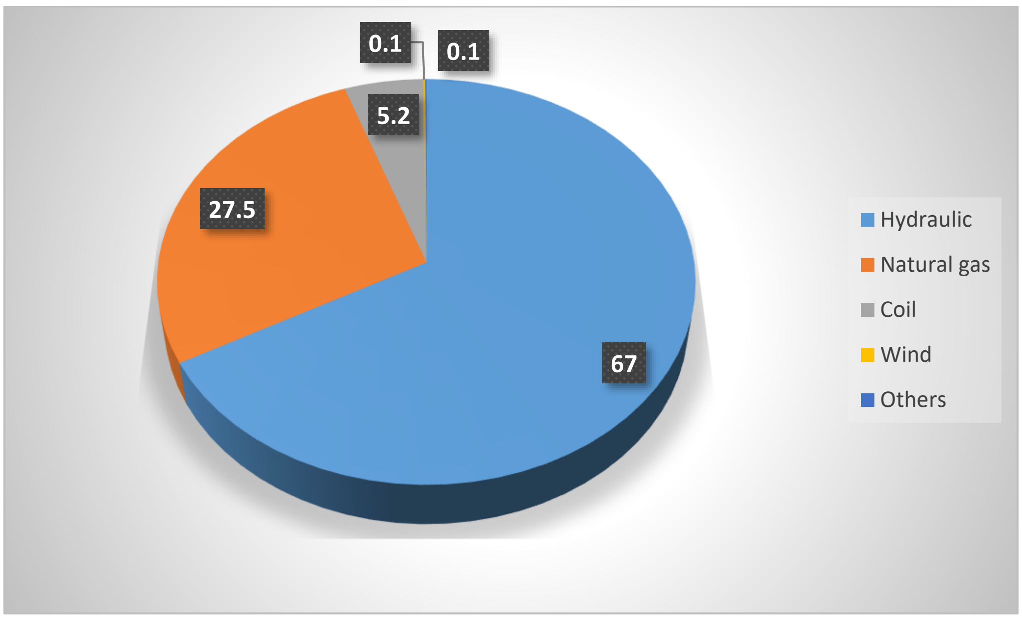


Figure. 43. Natural resources associated with the electric generation.

The main natural resource used in Colombia for the electric generation is the hydraulic. The country has a great number of rivers, lakes, and other hydraulic resources plus a geography with many mountain ranges and natural reservoirs that allows the creation of big hydraulic power plant with relative low investment cost.

The energy generation is be classified by the dispatching mode and the productive activity. If the generation plan is bigger than 20MW is considered a **“Centrally dispatched”** plant, otherwise it is considered **“Not centrally dispatched”**. If the plant produced thermic and electric energy as part of productive processes, where the main activity is not related to electric generation is called **“Cogeneration”**. If the electric generation is focused on the local supply and the only the surplus is sold to the National Interconnected System (SIN) is called **“auto generation”**. Else if the electric generation is the main activity is called **“generation”.**

II. Transmission

The transmission system in Colombia is a natural monopoly managed by public and private companies. The National interconnected system has tension levels equal or higher than 110 kV. In the Table. VI is shown the length own by the transmission system operators different ordered by the tension levels.

Many companies manage the transmission system because in the beginning each region was owner of its own transmission network. Each region managed their infrastructure before the law 143 of 1994, and sometimes the operator was a public agent and some other it was a private company. In the moment of the unification, there were identified interfaces in the SIN. The management of the transmission grid was divided between the agents based on these interfaces.

TOTAL TRANSMISSION LINES	Lenght (km)	Longitud (%)
TRANSMISSION 110 kV	**3,477.33**	
ELECTRIFICADORA DEL CARIBE S.A. E.S.P	1,454.81	41.84
EMPRESA COLOMBIANA DE PETROLEOS	6.70	0.19
EMPRESA DISTRIBUIDORA DEL PACIFICO S.A. E.S.P.	98.07	2.82
EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	1,597.97	45.95
INTERNATIONAL COLOMBIA RESOURCES CORPORATION	304.00	8.74
TRANSELCA S.A. E.S.P.	12.58	0.36
ZONA FRANCA CELSIA S.A E.S.P.	3.20	0.09
TRANSMISSION 115 kV	**7,249.71**	
CENTRAL HIDROELECTRICA DE CALDAS S.A. E.S.P.	509.22	7.02
CENTRALES ELECTRICAS DE NARIÑO S.A. E.S.P.	476.50	6.57
CENTRALES ELECTRICAS DEL NORTE DE SANTANDER S.A. E.S.P.	339.53	4.68
CODENSA S.A. E.S.P.	1,210.25	16.69
COMPAÑIA ENERGETICA DE OCCIDENTE S.A.S. ESP	338.70	4.67
COMPAÑIA ENERGETICA DEL TOLIMA S.A. E.S.P.	538.42	7.43
ELECTRIFICADORA DE SANTANDER S.A. E.S.P.	539.61	7.44
ELECTRIFICADORA DEL CAQUETA S.A. E.S.P.	111.50	1.54
ELECTRIFICADORA DEL HUILA S.A. E.S.P.	332.27	4.58
ELECTRIFICADORA DEL META S.A. E.S.P.	376.30	5.19
EMPRESA DE ENERGÍA DE ARAUCA E.S.P.	60.00	0.83
EMPRESA DE ENERGIA DE BOYACA S.A. E.S.P.	512.22	7.07
EMPRESA DE ENERGIA DE CASANARE S.A. E.S.P.	426.00	5.88
EMPRESA DE ENERGIA DE PEREIRA S.A. E.S.P.	7.80	0.11
EMPRESA DE ENERGIA DEL BAJO PUTUMAYO S.A. E.S.P.	92.00	1.27
EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	958.95	13.23
EMPRESA DE ENERGIA DEL QUINDIO S.A. E.S.P.	17.00	0.23
EMPRESA DE ENERGIA ELECTRICA DEL DEPARTAMENTO DEL GUAVIARE S.A. E.S.P.	187.00	2.58
EMPRESA DISTRIBUIDORA DEL PACIFICO S.A. E.S.P.	206.79	2.85
EMPRESAS MUNICIPALES DE CALI E.I.C.E. E.S.P.	3.40	0.05
Ingenio Mayaguez S.A.	2.85	0.04
INTERCOLOMBIA S.A. E.S.P.	3.40	0.05
TRANSMISSION 138 kV	**15.49**	
INTERCOLOMBIA S.A. E.S.P.	15.49	100.00
TRANSMISSION 220 kV	**2,675.23**	
EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	842.95	31.51
GRUPO ENERGIA BOGOTA SA ESP	20.00	0.75
INTERCOLOMBIA S.A. E.S.P.	177.64	6.64
TRANSELCA S.A. E.S.P.	1,634.64	61.10
TRANSMISSION 230 kV	**10,033.28**	
CENTRALES ELECTRICAS DEL NORTE DE SANTANDER S.A. E.S.P.	8.53	0.09
DISTASA S.A. E.S.P.	18.75	0.19
ELECTRIFICADORA DE SANTANDER S.A. E.S.P.	120.41	1.20
EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	272.33	2.71
EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	149.12	1.49
GRUPO ENERGIA BOGOTA SA ESP	1,513.58	15.09
INTERCOLOMBIA S.A. E.S.P.	7,950.56	79.24
TRANSMISSION 500 kV	**2,535.37**	
EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	45.90	1.81
INTERCOLOMBIA S.A. E.S.P.	2,489.47	98.19

Table. V. Transmission lines in Colombia.

III. Distribution

The distribution system is a natural monopoly operated by zones. This means that in the same city, town, etc. There can be more than one distribution system operator. The operators are selected by bidding.

The voltage levels in the distribution system are those below 110Kv. The primary circuits operate mainly at the voltages 13.2, 11.4 and 7.62 kV, while the secondary circuits operates mainly at 120/208 – 120/240 V and generally at voltages below 600 V.

IV. Commercialization

The energy commercialization is the economical process where the different agents, companies, persons interact in order to buy and sell energy. The purpose of the commercialization is to bring the service to the final user in such way that the price paid for it is the best possible price. The competence between the resellers reduce the price paid by the users bringing a fair profit to all the agents involved (generator, transmission, distribution and resellers).

V. Clients

The clients are the final users which use the energy. They participate in the wholesale market through the commercial intermediary, and they are free to choose the one they prefer. There are also two kind of clients, the regulated and the non-regulated ones.

7.3. Technical Rules – Indicators for Electrical Energy Quality in Transmission Lines

The transmission system operator (TSO) in the case of Brazil and the Regulation Committee in the case of Colombia, determine the performance indicators in the interest of more than maintain the reliability and security of the transmission lines, evaluate the electrical energy quality in both global and individual aspects. There are many different technical parameters that are used. The main aspects encompassed by these sorts of rules are: Continuity of the service, Frequency indicators and Voltage indicators. Each country has its own specificities, however, in general the rules are similar due to the international experiences and common practices in the area.

7.3.1. Brazilian Indicators

In Brazil the TSO (ONS) is responsible for the planning and scheduling the dispatch regarding the generators that taken part on the National Interconnected System (SIN). Another important role regards the proposition of rules for the operation of the SIN. Among the extensive sort of technical rules, there are the requirements of electrical energy quality in the SIN [15].

I. Continuity of Service Indicators

It is considered interruption of the service in the control point (frontier between transmission installations and the generation or distribution installations) when the voltage remains null for a period equal or higher than 1 (one) minute.

The following indicators are used for the evaluation of service continuity:

a) Interruption Duration in the Control Point – DIPC: The sum of the service interruption duration in the control point in the considered period.
b) Frequency Interruption in the Control Point – FIPC: Number of times in which occurred the service interruption in the control point in the considered period.
c) Maximum Interruption Duration in the Control Point – DMIPC: The longest service interruption duration in the control point in the considered period.

The TSO is responsible for the assessment of the indicators based on established values of performance. It is possible to have distinct values for different buses according to influence factors such as the historical data of a specific bus.

II. Frequency Indicators

The assessment of frequency is performed in the steady-state regime and in transient periods. It this work it was considered only the steady-state regime. The indicator DFP – Frequency Performance in Steady-state is given by:

$$DFP = \left(1 - \left(\frac{n}{1440}\right)\right).100(\%)$$

Where, *n* is the number of times that an integral of the module of the frequency deviation (*A*), calculated for intervals of one minute, was higher than 0.1 *Hz.min*, considering the total of 1440 daily intervals.

Integral of the module of the frequency deviation (*A*):

$$A = \int |\Delta f(t)| dt \; (Hz.min)$$

Where, Δf = Frequency deviation $f - f_0$;
f = Frequency measurement (Hz);
f_0 = Nominal frequency: 60.00 Hz
t = Time (minutes)

Assuming normal conditions in the steady-state regime, the instantaneous frequency deviations, comparing with the nominal value, cannot exceed more or less than 0.1 Hz.

III. Voltage Indicators

The assessment of voltage is composed of many indicators that encompasses: Voltage in the steady-state regime, voltage fluctuations, voltage unbalances, harmonic distortions of voltage and rapid voltage change. As mentioned before, only the steady-state regime will be contemplated.

The evaluation of the performance of the steady-state regime voltage will be done considering the values from the measurement systems supervised by the TSO, regarding the busbar under the responsibility of the transmission dealership.

The performance of the steady-state voltage regime can be quantified considering, in monthly base, the measured voltage (TL) in relation with the contracted voltage (TC), and can be classified as: Adequate, Precarious or Critical. The measured voltage (TL) is obtained by the value of the Root Mean Square (RMS) phase-neutral from each phase, considering time intervals of 10 (ten) minutes. The relative duration for the Precarious (DRP) and Critical (DRC) voltage is given by:

a) Relative Duration of the Violation of the Precarious Voltage – DRP

$$DFP_{Phase}(\%) = \left(\frac{nlp_{Phase}}{n_{Phase}}\right).100$$

b) Relative Duration of the Violation of the Critical Voltage – DRC

$$DRC_{Phase}(\%) = \left(\frac{nlc_{Phase}}{n_{Phase}}\right).100$$

Where:

nlp_{Phase}= number of measurements of the phase with precarious voltage, in a monthly base.

nlc_{Phase}= number of measurements of the phase with critical voltage, in a monthly base.

n_{Phase}= number of measurements of the phase, in a monthly base.

The Table VII and the Figure 44 summarize the voltage limits according to the technical rules. It is possible to infer that for higher voltage levels the requirements are stricter. As the National Interconnected System (SIN) is composed of transmission lines with voltage levels equal or higher than 230 kV, the adequate operation consists of being between 0.95 and 1.05 p.u.

Nominal Voltage (TN) of the observation [kV]	Classification of the Voltage in the Steady-state regime		
	Adequate	Precarious	Critical
TN ≥ 230	0.95 TC ≤ TL ≤ 1.05 TC	0.93 TC ≤ TL < 0.95 TC or 1.05 TC < TL ≤ 1.07 TC	TL < 0.93 TC or TL > 1.07 TC
69 ≤ TN ≤ 230	0.95 TC ≤ TL ≤ 1.05 TC	0.90 TC ≤ TL < 0.95 TC or 1.05 TC < TL ≤ 1.07 TC	TL < 0.90 TC or TL > 1.07 TC
1 < TN < 69	0.93 TC ≤ TL ≤ 1.05 TC	0.90 TC ≤ TL < 0.93 TC	TL < 0.90 TC or TL > 1.05 TC

Table. VI. Classification of the Voltage in the Steady-state regime.

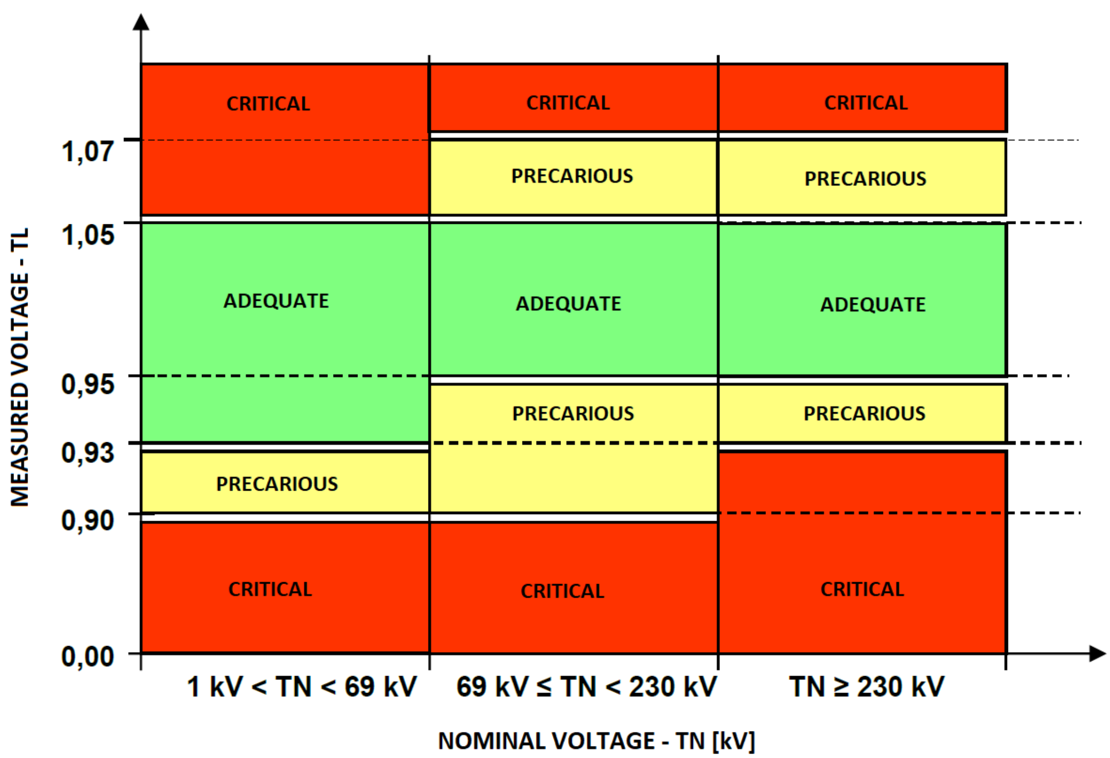


Figure. 44. Classification of the Voltage in the Steady-state regime [15].

The evaluation of performance is done comparing the obtained values for DRP and DRC with the following reference values:

a) Relative Duration of the Maximum Transgression of the Precarious Voltage – DRPM: Established as 3%;

b) Relative Duration of the Maximum Transgression of the Critical Voltage – DRCM: Established as 0.5%.

It must be classified as Critical the performance that present, simultaneously, considering the period of monthly observation, values for the indicators DRP and DRC greater than the reference values DRPM and DRCM, respectively.

7.3.2. Colombian Indicators

In the Colombian framework, the Energy and Gas Regulation Committee (CREG) is the responsible for the performance indicators based on the General Resolution of Energy [16]. This resolution encompasses definitions of the electrical sector, the structure of the Colombian system, the regulation for the operations, planning, supervision and control, methodologies for tariffs and so on.

I. Frequency Indicators

The target frequency of the interconnected network is 60.00 Hz and its range of operation variation is between 59.80 and 60.20 Hz, except in states of emergency, failures, energy deficit and rest periods.

II. Voltage Indicators

It is determined by Resolution that in steady-state regime the voltages in the buses of 115 kV, 110 kV and 220 kV, 230 kV must not be lower than 90% nor higher than 110% of the nominal value, as presented in Table VIII. For the 500 kV network the minimum permissible voltage is 90% and the maximum is 105% of the nominal value. In the main buses of the transmission system the transient voltage must not be below 0.8 (p.u.) for more than 500 ms.

Nominal Voltage of the observation [kV]	Classification of the Voltage in the Steady-state regime	
	Adequate	Critical
500	0.90 TN ≤ TL ≤ 1.05 TN	TL < 0.90 TN or TL > 1.05 TN
110, 115 and 220, 230	0.90 TN ≤ TL ≤ 1.1 TN	TL < 0.90 TN or TL > 1.1 TN

Table. VII. Classification of the Voltage in the Steady-state regime.

7.4. Brazilian Electricity Market

The Brazilian Power System is characterized by a huge network that must supply different kinds of demand through a continental country. It implies in a sophisticated institutional organization in order to guarantee the reliability and security of the grid.

7.4.1. Main Entities of the Brazilian Power Sector

Ministry of Mines and Energy – MME: It can be described as an entity linked to the Brazilian Presidency that is in charge of implementing the energy sector policies in compliance with the guidelines determined by the Energy Council (CNPE). The MME has the Grantor Authority role for the Brazilian power sector, determining the guidelines for the energy auctions, execution of concession agreements and issuing the authorization acts.

National Electricity Agency - ANEEL: It regulates and oversee the generation, transmission, distribution and trading activities, analyzing whether it complies with the policies and guidelines of the energy sector. Activities related to the tariff adjustment, establishing fines and arbitrage are examples of the numerous roles performed by the ANEEL.

National Power System Operator - ONS: It performs the activities required to coordinate the Brazilian Power System. The main functions are related to planning and schedule the centralized dispatch and operations in the generation segment, supervising and coordinating the power system, contracting and managing transmission services, also the ancillary services. Also, there is an important role related to propose upgrades to the existing system.

Energy Research Office – EPE: It is a specialized office composed by technical groups in order to promote planning studies regarding the Brazilian energy sector. Among the vast sort of activities, it is important to mention the identification and quantification of potential energy sources, studies for the best potential sites for hydro-based projects, generation and transmission expansion plans and feasibility studies.

Electric Energy Commercialization Chamber - CCEE: It is responsible for running auctions, maintaining the registration of the Power Purchase Agreements in the Regulated Trading Environment (CCEAR), register the amount of power and energy transacted through the agreements in the Free Trading Environment (ACL) and calculating the Imbalances Settlement Prices (PLD). The agents that are obligated to participate in the CCEE: Generation agents with generation capacity of at least 50 MW, Authorized agents to import or export electricity with exchanges of at least 50 MW, Concessionaries, permit holders or

Authorizes representing distribution companies whose sales reach at least 500 GWh/year and Free and special consumers.

7.4.2. System Planning and Operation in the Brazilian Power Sector

Brazil energy matrix is largely dependent on the hydro-based power plants. The second most important generation base is the thermal. Due to this scenario, the planning of the operation involves the particularities of the two source types. The hydro systems are substantially dependent on the time. Considering the seasons of the year and their effect on the water storage, a decision of dispatching a hydropower plant must encompass the long-term analysis and the costs in order to balance the hydro and the thermal power plants usage in an optimum way.

The Process of the Operation Planning aims to minimize the expected value of the total cost, considering the uncertainties, which is solved through calculation models. In this process it is comprised the Medium-term horizon (5 years), the short-term horizon (1 year), daily schedule horizon (2 weeks) and the Despatch horizon (1 day).

Some programs and models are used by the Operator in order to plan the operation. The *Newave* model is used in the medium-term horizon in order to minimize the total operation cost considering in the calculation hydrological and historical series and the results feed the short-term horizon model called *Decomp*, which has a smaller timeframe up to twelve months. In the *Decomp* model, the power plants that compose the Brazilian system are represented individually and consider a more accurate time description. The outcomes of the *Decomp* model are the generation goals for each plant and the energy exchange between the subsystems considering the available information such as limits between transmission line subsystems and flow rate in hydro basins.

The energy studies models are performed considering the Annual Energy Planning (PEN) and the Monthly Operation Program (PMO). The PEN consider the available information from a vast energy agents and authorities and through optimization mathematical models perform simulations in order to find out operation strategies and evaluating the supply conditions. In the case of the PMO, monthly meetings define the energetic guidelines in the short-term framework in order to optimize the generation and transmission infrastructure comparing to the load forecast and the scheduled new assets.

Finally, there is the *Dessem-Pat* model, where the dispatch is calculated to a timeframe of up to two weeks considering thirty-minute intervals.

7.4.3. Market Mechanisms in the Brazilian Power Sector

I. Physical Guarantee

Each power plant that composes the Brazilian Power System is related with a quantity of energy based on technical criteria and with the reliability for supplying the system. This quantity is defined by the grantor Authority (MME) when issuing the operating license. This is called Physical Guarantee of the plant**.** Each generator may trade its energy by the Power Purchase Agreements up to the limit of its Physical Guarantee. In the case of the Hydro Power plants, the Physical Guarantee defines also the quota of participation in the Energy Reallocation Mechanism (MRE). All the Power Purchase Agreements that accorded must be attached with a specific Physical Guarantee for a given plant, this is called Backing, which is the base for the energy commercialization. The calculation of the Physical Guarantee is performed for the Hydro and Thermal power plants that are centrally dispatched by the TSO. The Physical Guarantee is a function of a contribution considering the maximum possibly energy quantity to be supplied. In the case of Wind and Solar power plants, the Physical Guarantee is calculated based on the production data, certified by independent entities.

For cases of power plants with not centralized dispatching, the Physical Guarantee of the Hydro (small hydro) is calculated according to the technical characteristics of the power plant. For the other power plants, the calculations consider the monthly availability of the energy [21].

II. Imbalances Settlement Prices

Imbalances Settlement Price (PLD) is the marginal cost to produce 1 MWh more that is expected to the next operative week. This price is defined as the generation cost of the most expensive thermal power plant that is producing energy at this moment. The PLD reflects the Marginal Operation Cost, which is calculated through the *Newave* and *Decomp* models.

The PLD is the base value for the energy prices in the short-term market. The short-term market is where the highest and lowest differences in relation with the contracts are negotiated. For a consumer with an amount of contracted energy and that consumes more than this predetermined amount, the difference will be arranged with contracts that considers prices based on the PLD with the addition of Spread to sell or purchase of energy (considering that the Energy Reallocation Mechanism is not sufficient to cover the imbalances).

The PLD is calculated on a weekly basis for each load level and for each sub-market by the National Electricity Agency. In Brazil it is possible to divide the market in four submarkets (South, North, Northeast and Southeast/Center-West). However, it does not consider the transmission constraints within sub-markets.

III. Energy Reallocation Mechanism

Considering that the output of the Hydro plants varies substantially due to the hydrological cycles, the Power Purchase Agreements can become impracticable due to high and frequent commercial risks related to the consideration of the Imbalances Settlement Price (PLD) that rule the differences between generation output and contracted amount.

Even considering that the Imbalance Settlement Prices (PLD) have ceilings and regulatory thresholds, it can varies largely also considering that it is based on the Marginal Operation Cost. Then, in order to avoid this condition of extreme risk to the producers it was created the Energy Reallocation Mechanism (MRE).

The Energy Reallocation Mechanism can be described as a financial instrument that shares the hydrological risk between all the participants. The goal is to achieve financially, for each participant power plant, the Physical Guarantee, independently of the real levels of generation, since the total amount of the MRE generation is greater than its total Physical Guarantee. The Mechanism reduces the Hydrological Risk by way of transferring surpluses from units generating more than their Physical Guarantee to those generating less. Considering this, the revenues of the generation companies come from the Physical Guarantee of each plant and no more of the energy effectively produced by their plants. The participation on this Mechanism is mandatory for Hydro power plants with a capacity more than 30 MW and optional for the small ones. Those are hydro power plants that are centrally dispatched.

There are three situations for the Energy Reallocation Mechanism (MRE): Surplus, Deficit and Even balance.

Surplus and Even Balance scenarios

In the Even balance situation, the total output under the Energy Reallocation Mechanism is equal to the sum of the Physical Energy Guarantee. This means that the MRE reaches an even balance. In the example, one plant outputs exceeds its Physical Guarantee and sells its electricity surplus at the Energy Optimization Tariff (TEO). The plants in which the output was below the Physical Guarantee purchase at the same price (TEO). This tariff, given in R$/MWh, is established by the National Electricity Agency (ANEEL) and aims to compensate financially the producers that contribute with the MRE individually. It is paid by the participants of the MRE that receive energy to cover the Physical Guarantee deficits and/or Secondary Energy allocation.

In the Surplus situation (more usual), the Hydro plants generate more than is required for its physical guarantees, and the Energy Reallocation Mechanism (MRE) operates with surpluses. For example, the surplus of one plant, exceeds the shortfall of the other two plants. All the plants purchase a portion of the surplus given the proportion of their respective Physical Guarantee. If there is any leftover quantity above the total Physical Guarantee, it is related to the Secondary Energy allocation. The Secondary Energy allocation is performed to all the participants' power plants proportionally to each Physical Guarantee. Considering the participants power plants that have their production below their Physical Guarantee, they will receive the MRE supplementary contribution and also a proportional part referred to the Secondary Energy. Moreover, the allocation of the Secondary Energy is performed preferentially within the submarket in which it was produced, then being available to other submarkets. The Secondary Energy remains accounting referred to the submarket in which it was generated, and it is attached with the Energy Optimization Tariff (TEO).

It is possible to define mathematically the Physical Guarantee and its relation with the total generated and the Secondary Energy. The Physical Guarantee is given by [22]:

$$GFIS\_MRE_{r,w} = \sum_{p \in PMRE} GFIS\_2_{p,r,w}$$

Where, $GFIS\_MRE_{r,w}$ is the MRE Physical Guarantee in the baseline *r* and week *w*;

$GFIS\_2_{p,r,w}$ is the Physical Guarantee adjusted considering the losses factor in the Interconnected grid and the availability factor of the power plant *p*, the baseline *r* and week *w*;

PMRE is the group of portions of power plants *p*, which integrates the MRE.

All the units given in MWh.

The total generation that composes the MRE is given by:

$$GTA\_MRE_{r,w} = \sum_{j \in RW} GMRE_j$$

Where,

$GTA\_MRE_{r,w}$ is the total aggregated generation in the baseline *r* and week *w*;

$GMRE_j$ is the total generation of the MRE participant power plants by the commercialization period *j*;

RW is the group of commercialization periods *j*, in the baseline *r* and week *w*.

All the units given in MWh.

The MRE adjustment represents the relation between the total aggregated generation, $GTA\_MRE_{r,w}$, and the total Physical Guarantee, $GFIS\_MRE_{r,w}$, both referred to the MRE in the baseline *r* and week *w*.

$$AJUSTE\_MRE_{r,w} = \frac{GTA\_MRE_{r,w}}{GFIS\_MRE_{r,w}}$$

If the value of $AJUSTE\_MRE_{r,w}$ is above one, it means the existence of the Secondary Energy for the considered period. The amount of Secondary Energy can be given by the difference of $GTA\_MRE_{r,w}$ and the Physical Guarantee $GFIS\_MRE_{r,w}$. Differently, for a value below one, means the Adjustment Factor that must be applied to the Physical Guarantee of the MRE participants power plants in order to enable the generation coverage.

In the Deficit situation (less probable), the total output generated under the Energy Reallocation Mechanism (MRE) does not reach the total Physical Guarantee. Considering a submarket, where a power plant is in a deficit position, the Physical Guarantee coverage for this power plant is defined based on the power plant's deficit, in the proportion of the available Physical guarantee coverage and total deficit. In the case where this deficit cannot be entirely supplied by the available Physical Guarantee of its own submarket, the difference can be complemented by the surplus from other submarket.

$$COBGFIS\_P_{p,s*,r,w} = \left(DEFICIT\_G\_MRE_{p,r,w} - COBGFIS\_PS_{p,r,w}\right)\frac{EXCED\_S\_MRE_{s*,r,w}}{T\_EXCED\_MRE_{r,w}}$$

Where,

$COBGFIS\_P_{p,s*,r,w}$ is the allocated quantity of other submarkets to the Physical Guarantee coverage for the power plant p, in the submarket s, baseline *r* and week *w*;

$DEFICIT\_G\_MRE_{p,r,w}$ is MRE power plant generation deficit in the baseline *r* and week *w*;

$COBGFIS\_PS_{p,r,w}$ is the allocated quantity of its own submarket to the Physical Guarantee coverage for the power plant p, in the submarket s, baseline *r* and week *w*;

$EXCED\_S\_MRE_{s*,r,w}$ is the surplus of the MRE for the submarket *s,* baseline *r* and week *w*;

$T\_EXCED\_MRE_{r,w}$ is the total surplus of the MRE in the baseline *r* and week *w*.

All the units given in MWh.

In the case of the Secondary Energy, it follows the same procedure considering the priority. The allocation of the Secondary Energy occurs firstly in its own submarket, considering the right for Secondary Energy of each power plant, and formerly to other submarkets. A submarket with an available Secondary Energy surplus greater than its total right to Secondary Energy in the same submarket, will equalize it in its own submarket and hence cover other submarkets.

The energy flow for each submarket can be calculated for each participant power plant. It consists in the difference between the allocated energy for the power plant, for the Physical Guarantee coverage or Secondary Energy right (both referring to the submarket where the power plant is located), and its generation surplus transferred to the MRE.

The financial generation compensation related to the MRE aims to refund the generation costs of the power plant that allocated a part of its production in order to cover a part of the Physical Guarantee or the Secondary Energy referred to other power plants that participates of the MRE. These costs are paid by the indebted power plants. The financial value is calculated by the product of the allocated energy by the Energy Optimization Tariff (TEO), considering the specific month and the contribution of each power plant. The Figure 45 depicts the financial and energy relation in the MRE.

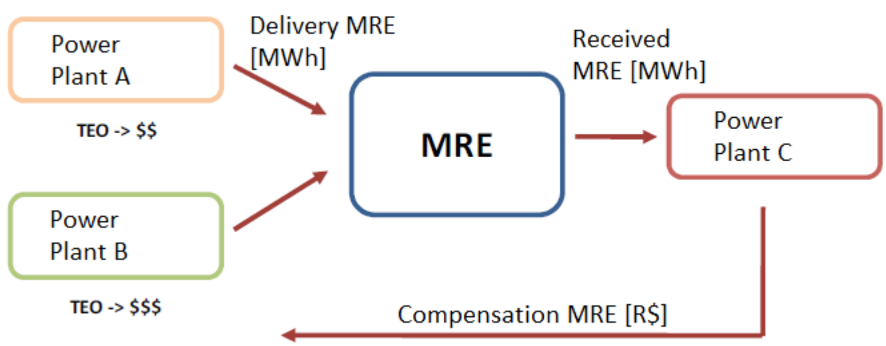


Figure. 45. Compensation system in the MRE [22].

IV. Energy Balance

The Commercialization Chamber (CCEE) is in charge of accounting the differences between the amount that was produced or consumed and the contracted energy through the Power Purchase Agreements and the measurements registered. The eventual differences referred to each agent (producers, traders and distributors) are priced according to the Imbalance Settlement Prices (PLD), which is determined weekly, considering the load baseline (peak, medium and off-peak) and the submarket. Based on the difference of the contracted energy volumes and the measured energy volumes it is possible to account the energy traded in the Short-term Market.

The composition of the Measured Energy is composed by the generation or consumption of each agent and by the eventual reallocated energy if the agent has a power plant that integrates the Energy Reallocation Mechanism (MRE). The Contracted Energy is referred to the net contractual position, which considers the difference between the total selling contracts and the total purchasing contracts.

The Energy Balance formula is given by:

$NET_{a,s,r,w} = \left(TGG_{a,s,r,w} + MRE_{a,s,r,w} - TGGC_{a,s,r,w}\right) - \left(TRC_{a,s,r,w}\right) - \left(PCL_{a,s,r,w}\right)$, where:

Factor	Description	Possible values
$\boldsymbol{TGG_{a,s,r,w}}$	Total agent generation obtained in the accounting measurement.	Positive or zero.
$\boldsymbol{MRE_{a,s,r,w}}$	Results consolidation of the MRE.	Positive, negative or zero.
$\boldsymbol{TGGC_{a,s,r,w}}$	Total generation consumption of the agent obtained in the accounting measurement.	Positive or zero.
$\boldsymbol{TRC_{a,s,r,w}}$	Total agent consumption obtained in the accounting measurement.	Positive or zero.
$\boldsymbol{PCL_{a,s,r,w}}$	Net contractual position, which is the difference between the selling and the purchasing contracts for the agent. The PCL is calculated for each submarket. Positive PCL means a selling position, while negative PCL means a purchasing position.	Positive, negative or zero.

Table. VIII. Energy Balance Formula.

a stands for agent profile (producer, trader or purchaser);
s is the referred submarket;
r is the referred baseline;
w is the referred week.
The values of all the factors are given in MWh unit.

V. Free and Regulated Trading Environments

The Free Trading Environment (ACL) is the market segment in which the energy purchase and sale transactions are conducted through bilateral contracts and allows free negotiation among traders, agents and free consumers.

The producers are the same in the Regulated Trading Environment (ACR) and in the ACL. Part of the production is purchased in the ACR through official Auctions, generally in the long-term, and other part is purchased through bilateral contracts. The producer, then produces for both types of the market.

The ACR works with compulsory contracts in which the consumer acquires the energy direct from the distribution company. The tariffs are determined by the Authority (ANEEL) and cannot be negotiated. Actually, all the residential consumers are in this kind of market (known also as Captive Market). It is shown in the Figure 46 the energy trading environment in Brazil.

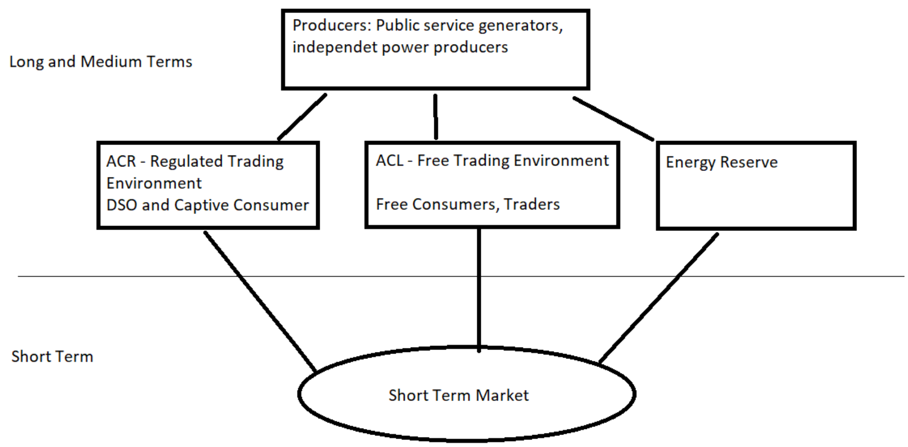


Figure. 46. Energy trading environment [21].

There are two types of consumers in the ACL:

Free Consumers: Must have at least 3.000 kW of contracted demand and can purchase energy from any kind of source. For customers that were connected in the electrical system before 7 of July of 1995, must be connected with voltage higher than 69 kV.

Special Consumers: Must have contracted demand equal or higher than 500 kW and lower than 3.000 kW, independently from the voltage level. They can purchase energy only from renewable sources (wind, solar, small hydro and biomass) or from hydro source with power lower or equal than 50 MW. A summarization is shown on the Table X.

	Contracted Demand	Connection date	Connection Voltage	Energy Source
Free Consumer	≥ 3000 kW	Connection after 08/07/1995	Any Voltage	Any Source
	≥ 3000 kW	Connection before 08/07/1995	Higher than 69 kV	Any Source
Special Consumer	≥ 500 kW and < 3000 kW	Any date	Higher than 2.3 kV	Renewable Sources

Table. IX. Consumer specifications in the Free Trading Environment.

Regarding the producers, it is possible to classify them in Conventional, which: Hydro and Thermal power plants are the most common and incentivized. The Incentivized: The consumers that purchase from renewable sources (wind, solar, biomass, hydro or cogeneration with power lower or equal than 30 MW), receive a reduction that ranges between 50 to 100 % in the wire service tariffs: Distribution Use of the System Tariff (TUSD) and Transmission Use of the System Tariff (TUST). The discount percentage depends on the date of the approval of the grant or of the register by the Authority and the type of the energy source.

VI. Energy Reserve Trading

In order to enhance the supply security of the Brazilian Power System the energy reserve trading is a solution implemented by the CCEE. It has a supplementary energy role, contracted in addition to the procured in the regular energy auctions. It is generated exclusively from plants contracted for this purpose, and it does not have any relation with commercial backing for sales to consumption agents.

It requires auctions in order to trade this energy. The Authority (ANEEL) performs it either directly or indirectly with the amount of energy reserve defined by the Ministry of Mines and Energy (MME) based on studies conducted by the Energy Research Office (EPE). This kind of trading is performed through the Energy Reserve Agreements (CER) signed by the seller agents at the Auctions and the Electric Energy Commercialization Chamber (CCEE) who represents the consumption agents (including Distributors, Free Consumers, Special consumers and self-producers). The allowed sources that compose the Energy Reserve Auctions encompasses solar, wind, biomass and Small hydro power plants (known as PCH). Each type of source has a different procedure and tolerance limits for the difference between the generated energy and the contracted. Regarding these limits it is performed the accounting of the revenues or the repayments by the producers or agents. For the energy generated above or below the contracted quantity defined in the Energy Reserve Agreements the revenues or repayments regarding the difference is computed by the CCEE. The amount of revenues or repayments by the producer varies according to the source and can be summarized in the Table XI.

Energy Production	Biomass and Small Hydro	Wind	Solar
Above the contracted amount of energy	Non-Applicable	Based on the Imbalances Settlement Price (PLD)	Actualized Sales Price (Auction based)
Below the contracted amount of energy	Average Price Value (Auction based)	Actualized Sales Price (Auction based)	Actualized Sales Price (Auction based)

Table. X. Imbalances between energy produced and contracted in the CER [22].

The CCEE maintains the account receiving the Energy Reserve Charge (EER) and manages the agreements, overseen by the Authority (ANEEL). In the periods that it is produced energy by the Power plants that are committed with the CER, the energy generated will be settled on the Short-term market. It pays the seller agents according to the Energy Reserve Agreements (CER), referred to the Auction price and receives the amounts related to energy reserve settled on the Short-term market.

The Energy Reserve Agreements (CER) and Use of Energy Reserve Agreements (CONUER) are not registered with the CCEE as it is with other agreements. However, the obligations are treated by the Trading Rules. The Energy Reserve is dealt on the Short-term market, at Imbalances Settlement Prices (PLD) for the submarket where the project is located. Revenues brought are used to reduce the costs associated with the trading. Figure 47 depicts the accounting of the energy reserve trading.

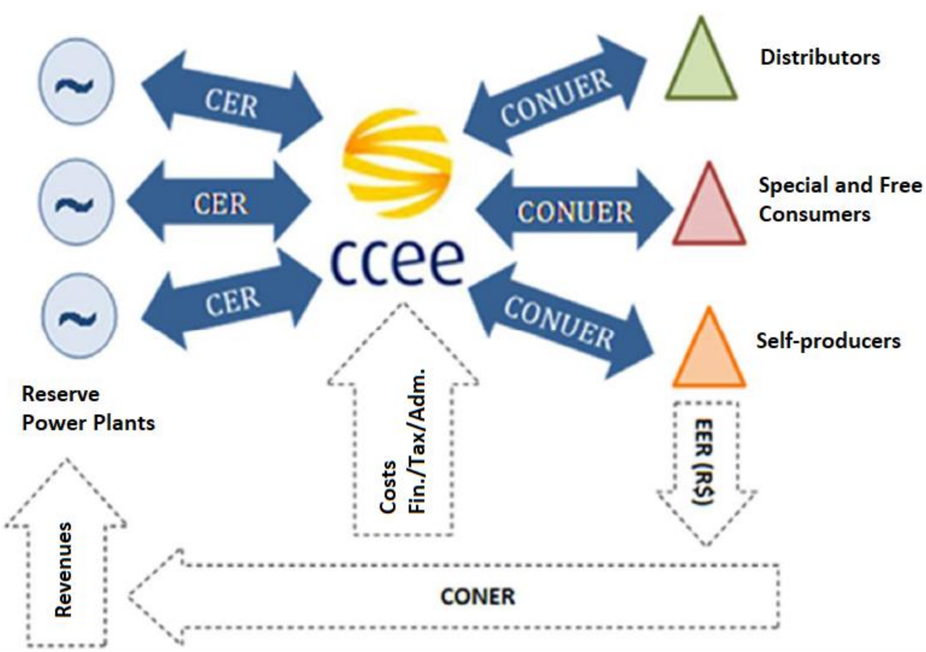


Figure. 47. Accounting and Settlement of the Energy Reserve Trading [22].

7.5. Colombian Electricity Market

7.5.1. Market agents

The market has agents mentioned previously as the generators, the transmission system operators, the distribution system operators, the resellers and the final users. In addition to these agents, there are state agents, and each one has a roll inside the energy sector. The Figure. 48 shows a hierarchical scheme of the market agents with their names and their roll inside the electric energy sector [41].

Figure. 48. Market agents in Colombian electrical market.

I. Management

The management agent called "Ministerio de minas y energía" is a government entity in charge of the administration of the natural nonrenewable resources of the country. Some of the objectives of this entity is to formulate, adopt, lead and coordinate the politics in the electric energy generation, transmission, distribution and commercialization matters. Furthermore, to ensure and organize the energy efficiency and renewable energies programs.

II. Planning

The planning agent called unity of planning miner energy "UPME" is a special administrative unit attached to the Mines and energy ministry. Its function is to advise the government in the formulation of politics that lead the sustainable development in the mines and energy sector. It brings all the necessary information to take decisions. At the same time, UPME formulates the project that ensure the right use of the resources.

III. Regulation

The regulation agent called Regulation commission of energy and gas "CREG" is entity in charge of regulating the public services of energy, natural gas, liquid gas and oil. Its objective is to bring these services to the biggest amount of people possible, at the lowest cost for the users and the adequate profit for the companies, making possible the quality, coverage and expansion.

IV. Operation and market management

The operator and manager of the market called "XM" is a company that operates the National transmission system and manages the wholesale market. Additionally, it forecast the demand of more than 42 million of habitants, receiving the generators' bids, and dispatching them.

7.5.2. Wholesale market operation

The dispatching is the process where is programmed the generation which covers the forecasted demand in such way that for every hour the dispatched resources are those which the lower market price. The dispatching process also takes into account the reserve, the restrictions and the inflexibilities. The most relevant variables and restrictions are the ones showed below:

- **Price offer:** The generation companies inform the national dispatch center (CND) before 8:00 hours, a unique price offer for 24 hours (expressed in $/kWh) for each generation resource.
- **Starting and stopping price:** The generation companies with thermic plants in the last days of December, March, June and September of every year the starting and stopping price to the CND. This price is expressed in American dollars ($USD) for each generation resource.
- **Generator availability:** The generation companies must inform daily to the CND before the 8:00 hours the maximum power available (expressed in MW) that a generator can supply to the system for each time interval.
- **Ramp configuration:** At the same time when the wholesale market price offer is done, the generation companies must inform the fuel and the configuration to be considered for each generation resource.
- **Mandatory minimum declaration:** The generation resources authorized to declare mandatory minimum generation, for technical limitations or environmental obligations, should send the offer within the timelines stablished for this.

- **AGC availability:** The generation plant eligible, could freely offer their availability to offer the frequency regulation second reserve service for each day and time interval.

7.5.3. Ancillary services

The ancillary services are those associated to the electric energy generation, transportation and distribution that allows stablishing a minimum level of security, quality and efficiency in the supply. These services are the blackout start, voltage regulation and frequency regulation. On 26 April of 2007 was the total disconnection of the National interconnected system (SIN), it was classified as the worst in Colombia. It lasted 4 hours and a half, including fault isolation and system restauration. Motivated on this disconnection the regulatory agent and the SIN operator started a coordinated process to improve the system security and reliability [42].

Keeping the electrical system safety and reliability is a hard task in all the economies in the world, the success on this task could be based on keeping the voltage and frequency on within the limits. In Colombia is more complex because the system must be prepared to respond to terrorist attacks, multiannual climatic phenomenon, and high ceraunic level also.

I. Blackout start

The SIN is a dynamic system stable the most of the time, but when it is exposed to operative problems like the forced generation plant stop, output of transmission lines, big demand blocks disconnection, etc. The severity of these operative problems can produce voltage and/or frequency collapse and end up in a blackout. Most of the blackouts occurs for the combination of multiple circumstances. The following figure shows the main causes of blackouts from 1991.

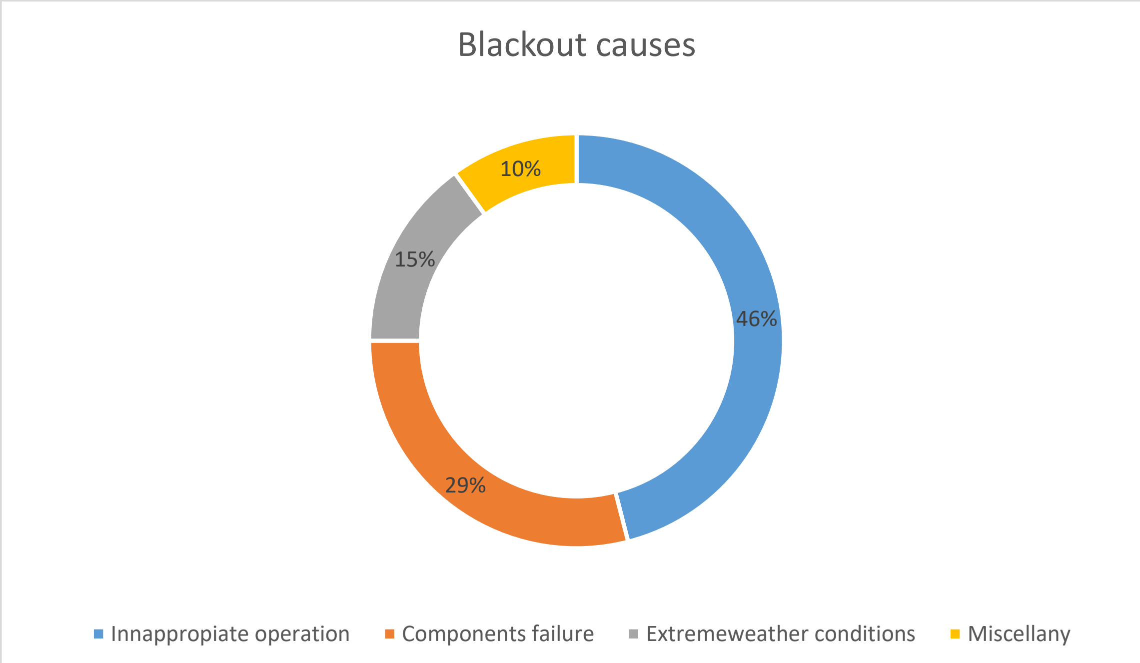


Figure. 49. Blackout causes from 1991.

The technical requirements for blackout restart are the following:

- Capability to restart one or more generators of the plant without using external energy supply.
- Capability to energize portion of the transmission grid, absorbing the reactive power necessary for one hour after the event. The generator must support the connection of one load or generator defined previously.
- Capability to work in isolated mode with demand supply established in blocks of 10-50MW. The generator must control the frequency (±2%Hz) and the voltage (±10%Vn).
- Capability to start at least three times in the two hours after the event. This, for controlling the recidivisms.
- Having reserves for four hours of autonomy operation.
- Communication system with redundancy. The grid operator perform trials over this communication system.

II. Voltage and reactive energy regulation

The reactive energy and voltage regulation consist in the use of the generation and transmission resources to keep the voltage in between the mandatory limits. This regulation allows the system to release apparent power making itself more secure because the active power reserve increases preparing the system for an overcharge and reduce the probability of disconnection. Furthermore, the better are the voltage profiles are, the lower the losses for the Joule effect are.

There are three levels of control. The primary or local control uses fixed capacitors or reactors controlled by switches. Secondary control acts on the branch of the transmission system and changes the configuration of the equipment over it and the taps on the transformers. The tertiary control acts over the full network and tries to optimize the voltage profile for the whole network.

The remuneration price of the reactive regulation is considered as a part of the active power generation. This means that reactive control is an obligation “not paid” for the generators, since the price of the energy does not change if the reactive control is or not needed. In the cases when is necessary to have generators acting like synchronic capacitor, the energy produced by the generator would be paid at the clearing price of the market.

III. Frequency control

The frequency cannot variate more than 1% of the nominal value in Hz. In order to control the frequency there are three types of reserve. The primary reserve is a margin of 3% the nominal capacity of the conventional generators, then the secondary and tertiary reserve is proportioned by generators that sells the energy necessary to the network when the frequency variation is higher than 1% and 2% respectively [43].

7.5.4. Regulation for micro grids connected to the transmission system

The resolution CREG 030 is a resolution, which looks forward to regulate the operative and commercial settings to allow the auto generation at small scale, and the distributed generation connected with the SIN. This resolution has validity until the total amount of energy exported by DGs is greater than 4% of the commercial national demand. At this point, the CREG is able to review and modify the conditions for the connection and remuneration established on this resolution [44].

I. Technical standards and availability for the connection

Before any natural DG connects to the grid, it must check on the web page of the grid operator the availability for connection on the circuit desired. Then, the user must comply with the following parameters:

- All the injections of power from the DGs shall be equal or lower than 15% of the nominal power of the circuit where the connection is requested. The nominal capacity of the circuit is given by the transformer capacity.

- The energy injected to the grid, by DGs different to solar with storage capacity, in one hour shall be lower than 50% of the annual average in the hours of minimum demand registered in the previous year of the request date.
- The energy injected to the grid, by DGs different to solar with storage capacity, shall be lower than 50% of the annual average in the frame of 6am - 6pm registered in the previous year of the request date.

II. Generators covered by the resolution

There are three classifications for the generators which can apply to the advantages proposed in the CREG030. This classification is based on the nominal power of the generators.

- Distributed generators: Juridical person with a generators with a nominal capacity equal or below 0.1MW. The energy produced is injected into the grid.
- Small scale auto generators: Generator with a nominal capacity equal or below 1MW but, bigger than 0.1 MW.
- Big scale auto generator: Generator with a nominal capacity equal or below 5MW but, bigger than 1MW.

III. Connection schemes:

There are also three connection schemes in order to request the connection of the generators above mentioned to the grid. The classification is not only based on the nominal capacity of the generator but, in the injection of the energy to the grid.

- Process 1:

  The process 1 is applied to auto generators with nominal capacity below or equal to 0.1MW without the capacity to inject energy in the grid. In order to access to this kind of connection is necessary to fill the form with the estimated connection date which shall be not sooner than 5 days from the request. The request must have attached the design and electrical drawings.

  The answer has a maximum delay of 5 days and, in case it is approved it contains the date of trial. Otherwise, it contains the reasons why the connection has been declined. The system will be allowed to work once the trial is performed correctly.
- Process 2:

  The process 2 is applied to auto generators with nominal capacity below or equal to 0.1MW with the capacity to inject energy in the grid. With the account number or the distribution center number is needed to check the availability of the grid. If the grid has capacity available the request form shall be delivered with a connection date not sooner than 5 day from the request date, with the design and the electrical drawings (If the grid has no capacity the user must follow the steps of the process 3).

The answer has a maximum delay of 5 days and, in case it is approved it contains the date of trial. Otherwise, it contains the reasons why the connection has been declined. Once the trial has been performed correctly will be programed the connection date or, in the best case, the system will be operative from that day.

- Process 3:

  The process 2 is applied to auto generators with nominal capacity over 0.1MW but, below or equal to 5MW with or without the capacity to inject energy in the grid. This request process also apply to generator below 0.1MW without the availability of the grid. On this case, is possible to ask to the distribution network operator the "connection study" according to the numeral a. of the paragraph 11 in CREG030.

  Then, it is necessary to send the connection form filled with all the attachments. The distribution network operator has 7 days to reply the request with the viability of the connection and the contract for this one to be signed. The contract shall be signed before 5 days from the delivery of the distributor network operator's answer. The contract must be sent with the signature and the date when the system will be read in order to make the technical visit to verify the parameters and perform the trial. If the system complies with the regulatory framework and succeeds on the trial, it can be connected to the grid.

The forms to be filled and the information about this connection request can be found in the web page https://www.codensa.com.co/resolucion-creg-030. Also, there is possible to contact the distribution network operator CODENSA. CODENSA is one of the main distributor's operators in Colombia and it is part of ENEL group.

IV. Energy commercialization

The commercialization scheme in Colombia has been established with the main purpose of increasing and incentivize the auto consume of the users. The CREG030 explains the commercialization alternatives and pricing rules for the surplus of a non-conventional renewable source.

a. Pricing for DG

The pricing rules are described in the article 15. The first option for distributed generators is to sell the energy according to the resolution CREG 086 of 1996. The second option is to sell the energy directly to the reseller integrated with the network operator. In this case the reseller is obliged to buy the energy to the distributed generator and the price is given by the expression:

$$PVgd_{h,m,n,i,j} = PB_{h,m} + benefits$$
$$benefits = 0{,}5 * P_{n,m-1,i,j}$$

Where,

- $PVgd_{h,m,n,i,j}$ Selling price of the energy in the hour h, month m, level of voltage n, to the reseller i in the commercialization market j in $/kWh.
- $PB_{h,m}$ Price in the pool market in the hour h of the month m in $/kWh. This price should not exceed the weighted price of shortage. In the case this price is higher this parameter will be equal to the weighted price of shortage defined in the resolution CREG140 of 2017.
- $P_{n,m-1,i,j}$ is equal to the technical losses in the system of the network operator j, accumulated in the level of voltage n, $P_{n,m-1,i,j} = \frac{G_{m-1,j,i} * PRTe_{n,j,t}}{1-PRTe_{n,j,t}}$.
- $G_{m-1,j,i}$ Cost of buying the energy ($/kWh) for the month m, of the reseller I in the market j.
- $Benefits$ are the economic incentive for the technical benefits that the distributed generator contributes to the grid.

V. Commercialization alternatives for auto generators

The commercialization alternatives are described in the article 16. There are two options depending on the use or not of non-conventional renewable sources [45].

1) If the generator classifies as an auto generator of small scale not using renewable technologies:
   a) It is possible to sell the energy to any marketer which attends the regulated market. There shall not be any relationship between the generator and the reseller. In this case the price is the pool price for each corresponding hour.
   b) It is possible to sell the energy to unregulated users, in this case the price can be any accorded with the user through bilateral contracts.
   c) It is possible to sell the energy to the reseller integrated with the network operator who is obliged to receive the surplus. On this case, the price is the pool price.
2) If the generator classifies as an auto generator of small scale using renewable technologies:
   a) It is possible to sell the energy to any marketer which attends the regulated market. There shall not be any relationship between the generator and the reseller. In this case the price is defined by the next section.
   b) It is possible to sell the energy to unregulated users, in this case the price can be any accorded with the user through bilateral contracts.
   c) It is possible to sell the energy to the reseller integrated with the network operator who is obliged to receive the surplus. On this case, the price is defined by the next section.

a. Pricing of auto generators' surplus

At the end of each billing period, the energy surplus will be recognized as energy credits according to the following rules:

Auto generators with installed capacity equal or below 0.1 MW

a) The surplus injected below the importations will be permuted for the importation during the billing period. For this surplus the auto generator will pay the commercialization cost which is the parameter $Cv_{m,i,j}$ in the resolution 119 of 2007.
b) The surplus injected above the importations on the billing period. This surplus will be paid at the corresponding pool price.

Auto generators with installed capacity above 0.1 MW

a) The surplus injected below the importations will be permuted for the importation during the billing period. For this surplus the auto generator will pay the commercialization cost which is the parameter $Cv_{m,i,j}$ plus the system service represented with the summation of the parameters $T_m, D_{n,m}, PR_{n,m,i,j}$ and $R_{m,i}$ defined in the resolution 119 of 2007. Between unregulated users these parameters are accorded between the parts.
b) The surplus injected above the importations on the billing period. This surplus will be paid at the corresponding pool price.

b. Information to the auto generator's user

It is responsibility of the marketer the liquidation and billing, including detailed information about the energy consumption, exportations, among others, according the article 18 of the CREG030. This information depends on the installed capacity as follows:

1) For the auto generator using non-conventional renewable energies with an installed capacity equal or below 0.1MW

$$VE_{i,j,n,f} = \left(Exp1_{i,j,n,f-1} - Imp_{i,j,n,f-1}\right) * CUv_{n,m,i,j} - \left[Exp1_{i,j,n,f-1} * Cv_{m,i,j}\right] + \sum_{h=hx,hx+1,\ldots,H} Exp2_{h,i,j,n,f-1} * PB_{h,f-1}$$

2) For the auto generator using non-conventional renewable energies with an installed capacity above 0.1MW

$$VE_{i,j,n,f} = \left(Exp1_{i,j,n,f-1} - Imp_{i,j,n,f-1}\right) * CUv_{n,m,i,j} - \left[Exp1_{i,j,n,f-1} * Cv_{m,i,j}\right] - [Exp1_{i,j,n,f-1} * \left(T_m + D_{n,m} + PR_{n,m,i,j} + R_{m,i}\right)] + \sum_{h=hx,hx+1,\ldots,H} Exp2_{h,i,j,n,f-1} * PB_{h,f-1}$$

3) For the auto generator not using non-conventional renewable energies

$$VE_{i,j,n,f} = \sum_{h \in f-1} ExpT_{h,i,j,n,f-1} * PB_{h,f-1}$$

Where,

i Marketer i

j Marketer market j

n Level of voltage n

h Hour h

m Month m

f Billing period f

hx Is the hour when the surplus exceeds the electrical imports in the billing period f-1. H is the total hours of the billing period.

$VE_{i,j,n,f}$ Surplus value in $ for the period f. This represents income when is bigger than zero.

$Exp1_{i,j,n,f-1}$ Summation of all the exportations in the period f-1 in kW. This parameter can get values between 0 and $Imp_{i,j,n,f-1}$.

$Imp_{i,j,n,f-1}$ Summation of the energy imports from the auto generators for each hour of the period f-1.

$CU_{m,i,j}$ Unitary cost for the service delivery in $/kWh according to the resolution CREG 119 of 2007. In case there are non-regulated users this parameter should be an agreement between the parts.

$Cv_{mi,j}$ Commercialization margin in $/kWh according to the resolution CREG 119 of 2007. In case there are non-regulated users this parameter should be an agreement between the parts.

$Exp2_{h,i,j,n,f-1}$ Exportation delivered by the auto generator during each hour of the period f-1 in kWh, this parameter get over $Imp_{i,j,n,f-1}$.

$PB_{h,f-1}$ Pool hourly price on the period f-1, if this does not get over the shortage price. If this parameter gets over, the value shall be the shortage price.

$Rr_{m-1,i}$ Restriction cost of the system defined by the resolution CREG 119 of 2007.

$P_{n,m,-1,i,j}$ This parameter is equal to the variable $PR_{n,m-1,i,j} - CPROG$ defined in the resolution CREG 119 of 2007.

T_m Cost for using the transmission system in $/kWh according the resolution CREG119 of 2007.

$D_{n,m}$ Cost for using the distribution system in $/kWh according the resolution CREG119 of 2007.

$PR_{n,m,i,j}$ Buying, transport and reduction of losses cost in $/kWh.

$R_{m,i}$ Cost of restrictions and services associated with the generation in $/kWh.

$ExpT_{h,i,j,n,f-1}$ Hourly exports of the auto generator on the period f-1 in kWh. This parameter is equal to the summation of $Exp1 + Exp2$.

c. Commercialization summary

The commercialization rules established incentivize the auto consume since the price paid for the energy generated is approximately 90% of the imported energy cost if the energy generated is equal or below the energy imported. The extra 10% corresponds to the cost of commercialization. Once the energy exported is bigger than the energy imported the system treats the operator as any generator paying it at the pool market. The pool market price rounds the 40% of the energy cost of the user.

This measure tries to incentivize the auto consume giving a high sell price when the energy exported is equal or lower than the energy imported and then reducing drastically the price for the surplus. Also, this measures does not take away the marketers business since they are still receiving the commercialization price. Finally, the system operator shall observe an improvement in the energy transport.

8. Models Set-up

8.1. Modelling the Brazilian Network

In order to propose solutions considering the main network and micro grids, the evaluation of the Brazilian network is necessary. Considering the size and detailing of the National Interconnected System, to model the entire system proved to be impractical.

The data of the system can be obtained on the Transmission System Operator (TSO) website [9]. A software called ANAREDE [11], developed by *Cepel* – (Electrical Energy Research Center), and is the most used by the Brazilian entities in order to analyze power systems in the steady-state regime. Through the files destined to the ANAREDE, the TSO makes available the data referred to the National Interconnected System (SIN). As the ANAREDE is a commercial software used by energy entities and companies, the expectance remains on the academic license, which is not reasonable due to the limitations of number of buses. Therefore, the solution proposed is use an open program as MATPOWER, presented in the Annex of this work. However, there is the incompatibility between the input data of each program. An alternative for converting, at least partially, one input file in another, was proposed [12]. A computational tool developed in Excel using the Visual Basic for Applications (VBA) was deployed in order to facilitate the conversion of the files and consequently the analysis of the Brazilian main grid in open programs such as MATPOWER.

The full data regarding the entire Brazilian Grid (SIN) obtained in ANAREDE format file was composed of 6604 buses, 9731 branches and 700 generators. The conversion to the MATPOWER file (*.m* or *.mat*) was performed but the size of the represented grid and the unfeasibility of evaluating in detail the whole system turned it impossible to analyze all the reasons for the non-convergence of the power flows. Because of this, alternatives were sought in order to have a more reliable and trustful model of the National Interconnected System.

One relevant thesis work [13] designed four different equivalent models (with 16, 33, 65 and 107 buses) created from extracted data of the Brazilian network, considering its topologies and complete relation with its electric parameters. The model that most suits our proposal would be the 107 buses model, depicted in the Figure 50, encompassing many important circuits of the south, south-east and center areas of the Brazilian grid.

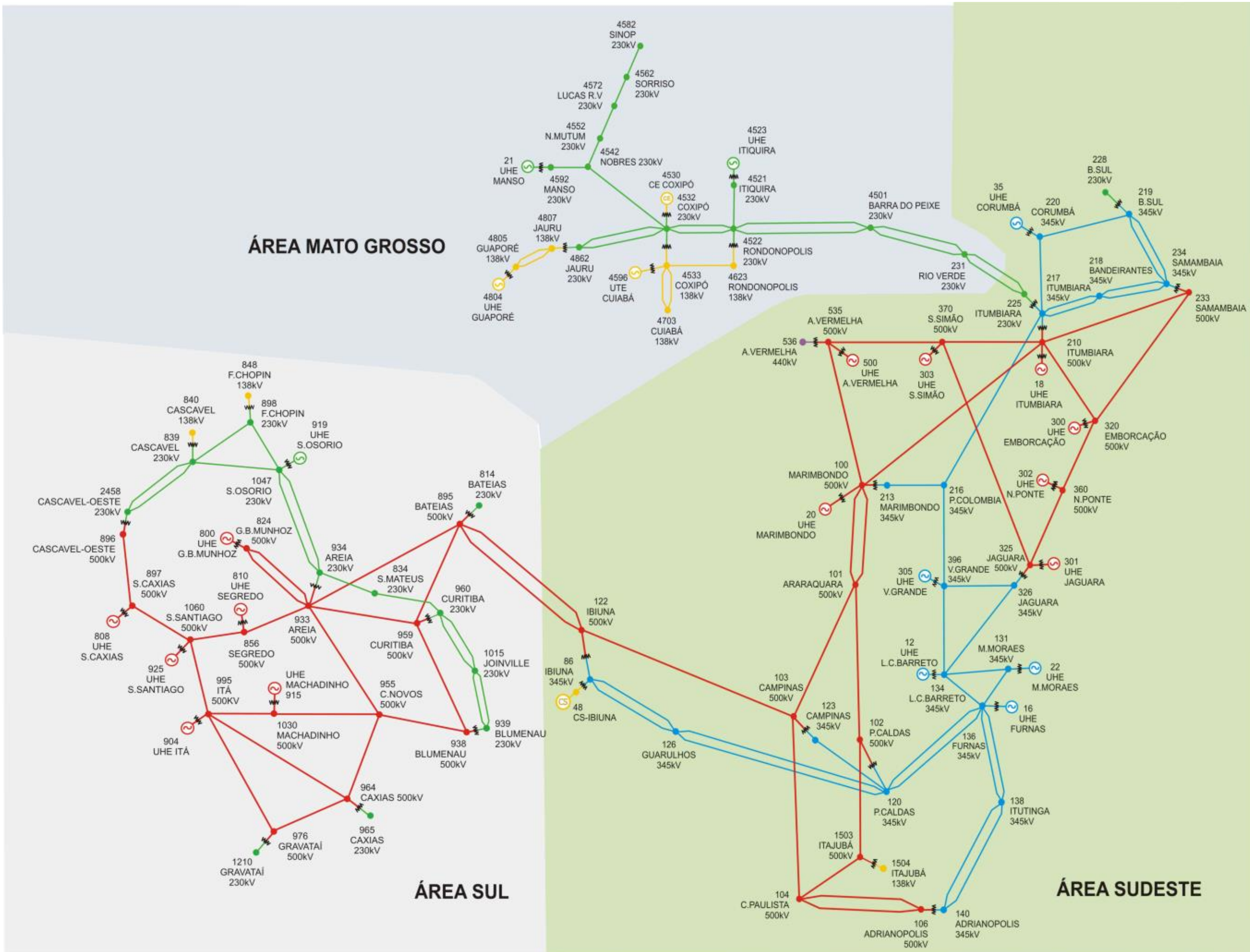


Figure. 50. Equivalent system with 107 buses [13].

8.1.1. Relation between input data

The data used to design the model were obtained from the TSO and compiled together in the appendices of the thesis work [13], named STB107. The elemental correspondence between the presented data similar to ANAREDE’s file format and the MATPOWER input data, was performed following the previous work [12]. The correspondence for each field is given in the Tables XII, XIII and XIV.

Bus Data

Name	Column	Description	Correspondent
BUS_I	1	Bus number (positive integer)	Set according to the bus identification numbers in the section A-5.1, column 1 from the data report STB107.
BUS_TYPE	2	Bus type (1 = PQ, 2 = PV, 3 = ref, 4 = isolated)	Set according to bus classification from ANAREDE format extracted from the section A-5.1, column 3 from the data report STB107.
PD	3	Real power demand (MW)	Set according to the section A-5.5, column 4 from the data report STB107.
QD	4	Reactive power demand (MVAr)	Set according to the section A-5.5, column 5 from the data report STB107.
GS	5	Shunt conductance (MW demanded at V = 1.0 p.u.)	Set according to the section “Relatório de Barras”, column 12 from the data report STB107.
BS	6	Shunt susceptance (MVAr injected at V = 1.0 p.u.)	Set as zero.
BUS_AREA	7	Area number (positive integer)	Set according to the section A-5.1, column 7 from the data report STB107.
VM	8	Voltage magnitude (p.u.)	Set according to the section “Relatório de Barras”, column 5 from the data report STB107.
VA	9	Voltage angle (degrees)	Set according to the section “Relatório de Barras”, column 6 from the data report STB107.
BASE_KV	10	Base voltage (kV)	Set according to the section A-5.1, column 4 from the data report STB107.
ZONE	11	Loss zone (positive integer)	Set as one.
VMAX	12	Maximum voltage magnitude (p.u.)	Set according to the section A-5.1, column 5 from the data report STB107.
VMIN	13	Minimum voltage magnitude (p.u.)	Set according to the section A-5.1, column 6 from the data report STB107.
LAM_P	14	Lagrange multiplier on real power mismatch (u/MW)	Set as zero.
LAM_Q	15	Lagrange multiplier on reactive power mismatch (u/MVAr)	Set as zero.
MU_VMAX	16	Kuhn-Tucker multiplier on upper voltage limit (u/p.u.)	Set as zero.
MU_VMIN	17	Kuhn-Tucker multiplier on lower voltage limit (u/p.u.)	Set as zero.

Table. XI. Bus Data correspondence with STB107.

Generator Data

Name	Column	Description	Correspondent
GEN_BUS	1	Bus number	Set according to the section A-5.7 “Geração de Potência Ativa”, column 1 from the data report STB107.
PG	2	Real power output (MW)	Set according to the section “Relatório de Barras”, column 7 from the data report STB107.
QG	3	Reactive power output (MVAr)	Set according to the section “Relatório de Barras”, column 8 from the data report STB107.
QMAX	4	Maximum reactive power output (MVAr)	Set according to the section A-5.7 “Geração de Potência Reativa”, column 7 from the data report STB107.
QMIN	5	Minimum reactive power output (MVAr)	Set as negative value according to the section A-5.7 “Geração de Potência Reativa”, column 5 from the data report STB107.
VG	6	Voltage magnitude setpoint (p.u.)	Set according to the section “Relatório de Barras”, column 5 from the data report STB107.
MBASE	7	Total MVA base of machine, defaults to baseMVA	Set as the Power Base of the system (100 MVA).
GEN_STATUS	8	Machine status: > 0 = machine in-service ≤ 0 = machine out-of-service	Set as one (1) for machine in-service and zero (0) for machine out-of-service.
PMAX	9	Maximum real power output (MW)	Set according to the section A-5.7 “Geração de Potência Ativa”, column 5 from the data report STB107.
PMIN	10	Minimum real power output (MW)	Set as zero.
PC1	11	Lower real power output of PQ capability curve (MW)	Set as zero.
PC2	12	Upper real power output of PQ capability curve (MW)	Set as zero.
QC1MIN	13	Minimum reactive power output at PC1 (MVAr)	Set as zero.
QC1MAX	14	Maximum reactive power output at PC1 (MVAr)	Set as zero.
QC2MIN	15	Minimum reactive power output at PC2 (MVAr)	Set as zero.
QC2MAX	16	Maximum reactive power output at PC2 (MVAr)	Set as zero.
RAMP_AGC	17	Ramp rate for load following/AGC (MW/min)	Set as zero.
RAMP_10	18	Ramp rate for 10 minutes reserves (MW)	Set as zero.
RAMP_30	19	Ramp rate for 30 minutes reserves (MW)	Set as zero.
RAMP_Q	20	Ramp rate for reactive power (2 sec timescale) (MVAr/min)	Set as zero.
APF	21	Area participation factor	Set as zero.

Table. XII. Generator Data correspondence with STB107.

Branch Data

Name	**Column**	**Description**	**Correspondent**
F_BUS	1	"from" bus number	Set according to the "from" bus identification number in the section A-5.2, column 1 from the data report STB107.
T_BUS	2	"to" bus number	Set according to the "to" bus identification number in the section A-5.2, column 2 from the data report STB107.
BR_R	3	Resistance (p.u.)	Set according to the section A-5.2, column 6 from the data report STB107, transformed from percentage to p.u.
BR_X	4	Reactance (p.u.)	Set according to the section A-5.2, column 7 from the data report STB107, transformed from percentage to p.u.
BR_B	5	Total line charging susceptance (p.u.)	Set according to the section A-5.2, column 8 from the data report STB107, considering the power base.
RATE_A	6	MVA rating A (long term rating), set to 0 for unlimited	Set according to the section A-5.2, column 9 from the data report STB107, considering the normal condition.
RATE_B	7	MVA rating B (short term rating), set to 0 for unlimited	Set as zero (unlimited).
RATE_C	8	MVA rating C (emergency rating), set to 0 for unlimited	Set according to the section A-5.2, column 10 from the data report STB107, considering the emergency condition.
TAP	9	transformer off_ nominal turns ratio, (taps at "from" bus, impedance at "to" bus)	Set as zero to transmission lines. For the remaining cases it is set according to the section "Relatório de Linhas", column 4 from the data report STB107.
SHIFT	10	transformer phase shift angle (degrees)	Set as zero.
BR_STATUS	11	initial branch status, 1 = in-service, 0 = out-of-service	Set as one.
ANGMIN	12	minimum angle difference, $\theta_f - \theta_t$ (degrees)	Set as -360°.
ANGMAX	13	maximum angle difference, $\theta_f - \theta_t$ (degrees)	Set as 360°.
PF	14	Real power injected at "from" bus end (MW)	Set as zero.
QF	15	Reactive power injected at "from" bus end (MVAr)	Set as zero.
PT	16	Real power injected at "to" bus end (MW)	Set as zero.
QT	17	Reactive power injected at "to" bus end (MVAr)	Set as zero.

Table. XIII. Branch Data correspondence with STB107.

8.2. Modelling the Colombian Network

With the objective of a consistent and reliable model of the Colombian electrical network, it was searched through many theses works for an already designed model. However, in the major part of the works the technical data was not available or only partially shared, by the reason of confidentiality that the candidates agreed with the Colombian electrical entities.

Some entities of the Colombian electrical sector, among them the XM - Company of Experts in Markets in Colombia's electricity market and the UMPE - Energy Mining Planning Unit, provide relevant information, in which it is possible to have a general panorama of the Colombian system. The map of the National Transmission System is provided by the UMPE [17] and shows the topology and electrical network organization of the country. It is given in the Figure 51 and it is possible to see that the main loads are located in the central area and how the production zones are connected.

Figure. 51. Colombian National Transmission System in 2016 [17].

The national transmission system in Colombia is composed of lines of 220 kV, which constitute the major part of the system and 500 kV, which consists in a ring topology connecting the northern and the central areas. The main important generation sources in Colombia are the Hydro power plants, around 70%, and the Thermal Power plants from Gas, around 10% and Coal, around 7.5% [17].

Considering the partial data that is available by the Colombian electrical entities and the academic experience for modelling systems without all the parameters availability, it is possible to design the Colombian network performing some assumptions and estimations.

Based on the works in the area of Synthetic Networks [18, 19], some parameters were estimated following the methodologies adopted.

Firstly, assuming the line diagram of the Colombian Transmission System provided by UPME [17], the numbering of the buses was performed. It is a system composed of 118 buses, 240 branches in which 16 are of 500 kV and 30 generators. In the Figure 52 it is shown the line diagram.

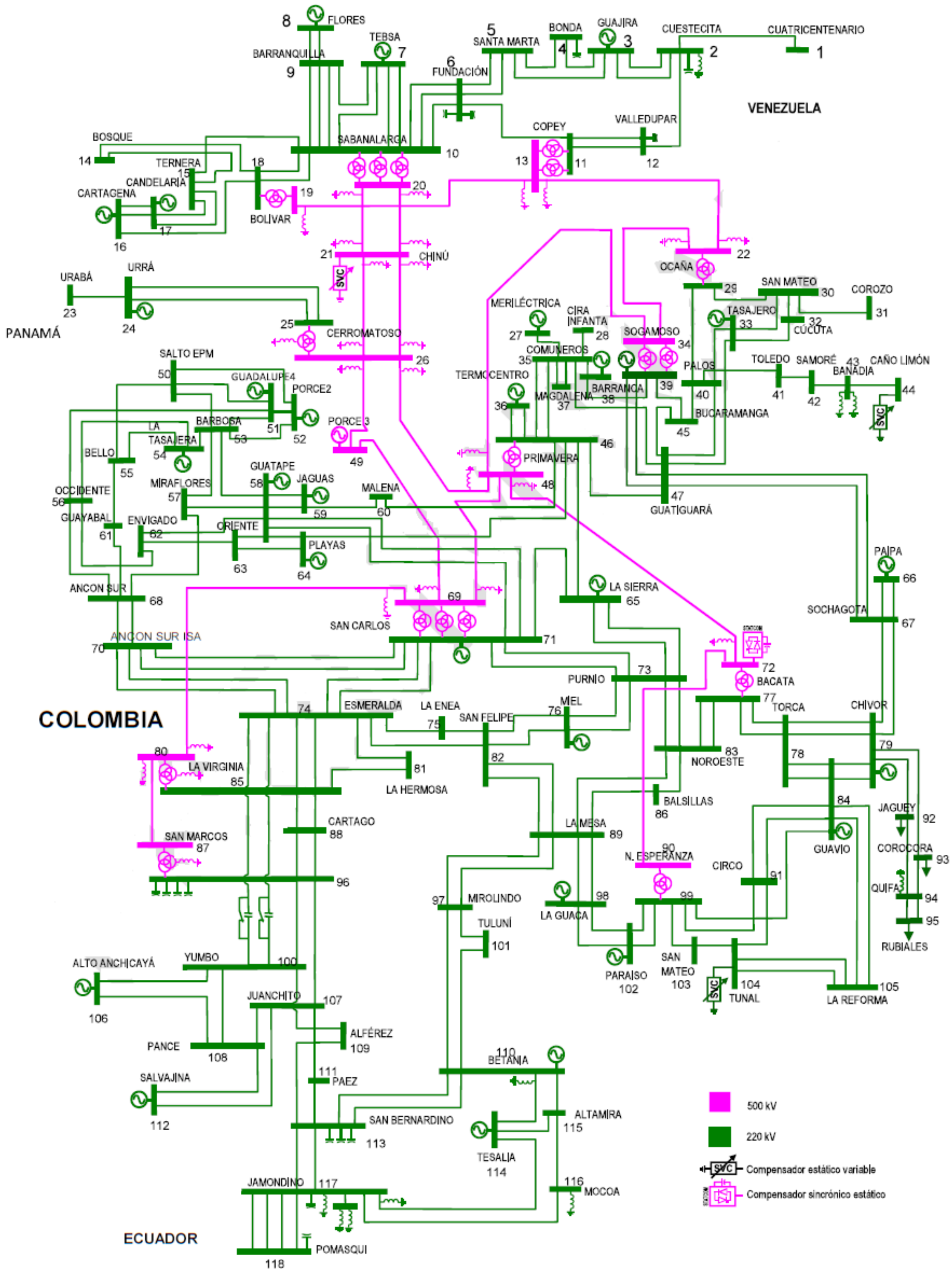


Figure. 52. Line diagram of the Colombian Transmission System [17].

As the model is design to be run in the MATPOWER format file, the bus, branch and generator data field need to be detailed.

The bus field, as described before, is composed of information regarding each bus of the system and this data was not available due to confidentiality. A methodology is proposed in order to estimate the demand in each bus.

According to the data from the Colombian's electricity market [20], it is possible to know the participation of each Colombian macro-region in the total demand for a specific year. For the year 2017 the participation in the main populated macro-regions of Colombia is given by the Table XV highlighting the regions of *Centro* and *Costa Atlantica* that together corresponds to more than the half of the country's demand.

Region	**Participation [%]**	**Demand Participation [MW]**
Centro	26.14	256962.381
Antioquia	14.57	143206.4913
Costa Atlantica	25.05	246232.957
Valle	11.03	108448.8293
Oriente	11.05	108562.5743
CQR	4.24	41633.77995
THC	4.39	43162.32554
Sur	3.06	30028.67542
Chocó	0.39	3789.421888
Guaviare	0.09	872.5642505

Table. XIV. Demand participation for each department [20].

Each macro-region is controlled by one network operator and can be divided in states known as departments in Colombia. In order to perform a more accurate division of the load, it was computed the population of each department that composes the macro-region. Then, considering the demand of a macro-region and the total population of the department that is inside this macro-region, it is possible to divide proportionally the demand for each department. Based on a map in Figure 53 that depicts the network and the divisions in departments, the partition of the total load for each department by the number of buses that are inside it is performed. All the buses that are inside the department have the same amount of load demand except the generation buses that eventually are inside the department. In the case of reactive demand, the value was based on the Synthetic network works [18, 19], based on the average reactive demand per capita employed and set proportionally to the Colombian demand per capita. The limits of voltage were set according to the Colombian General Resolution of Energy [16].

Figure. 53. Colombian Transmission System and departments [17].

The Branch data is even more sensitive than the Bus data in the context of security of the grid. In order to estimate the transmission line parameters (resistance, reactance and charging susceptance) it was adopted the methodology presented on [18]. The length of the transmission lines was estimated considering the map and the respective scale. The transmission line types were chosen based on the technical catalogue [5] and are displayed in the Table XVI.

Characteristics	TL of 230 kV - Aluminum cable ACSR	TL of 500 kV - Aluminum cable ACSR
Code Word	Starling	Thrasher
Circular Mils [kcmil]	715	2312
Resistance 50o, 60Hz [ohm/km]	0.089601726	0.029950091
Reactance, at 1 feet spacing [ohm/km]	0.251655333	0.212508948
Shunt capacitance Reactance [Mohm/km]	0.057663247	0.04765917
r0 (outer radius - conductor) [m]	0.013345	0.022885
Geometric mean radius [m]	0.01082	0.01813
I MAX [A]	840	1380

Table. XV. Transmission lines characteristics [5].

Other important data to estimate the transmission lines parameters refers to the frequency of the system (60 Hz), Permittivity of free space ($8.85418782 \times 10^{-12}$ m^{-3} kg^{-1} s^4 A^2), geometric mean distance *GMD* (12.6 m), Bundling distance (0.4 m), clearance phase-to-phase (10 m) and geometric mean radius *GMR* for bundled conductors (D_{SL}=0.085158675 and D_{SC}=0.095676538).

The resistance of each transmission line is given by:

$$R = \frac{r \cdot l}{b} \ \Omega$$

Where, *r* is the resistance per km, *l* is the distance in km and *b* is the number of conductors per bundle (1 for conductors of 230 kV and 2 for conductors of 500 kV). In the case of reactance for each transmission line, it is given by:

$$X = 2\pi f \cdot L \cdot l \cdot 1000 \ \Omega$$

Where, *f* is the frequency of the system, *L* is the inductance in *H/m* and *l* is the distance in km.

Lastly, the charging susceptance of the transmission lines is given by:

$$B = 2\pi f \cdot C \cdot l \cdot 1000 \ \mathrm{S}$$

Where, *f* is the frequency of the system, *C* is the Capacitance in *F/m* and *l* is the distance in km. Then, the parameters are converted to per unit based on the base impedances, where $Z_{B1} = 529\,\Omega$ for the lines of 230 kV and $Z_{B2} = 2500\,\Omega$ for the transmission lines of 500 kV. The transmission lines capacity is given by:

$$MVA_{MAX} = \sqrt{3} \cdot V_{line} \cdot I_{max} \cdot b$$

Where, I_{max} is the maximum current carrying capacity, V_{line} the voltage on the line and *b* is the number of conductors per bundle. For the cases of transformers, a commercial model of 672 MVA was selected, based on the Brazilian equivalent grid equipment.

In relation to the Generator data, some information was available in the reports presented by the XM Company of Experts in Markets in Colombia's electricity market [14]. The main generators connected to the National Transmission System had their hourly production presented in the mentioned reports. Based on this, the power generated could be estimated. The installed capacity of the majority of power plants was also available in the reports and the minimum power production, when unknown, was set to zero as suggested in the works of synthetic network [18]. The generator reactive power curve was based on the power factor of 0.9 both for overexcited and under-excited scenarios. The proportion related to the real power was 0.48432.

8.3. Scenarios

There are many factors, which determine the characteristics of the demand of a country. For instance, economic growth, day of the week, number of daylight hours, demographic parameters, weather conditions and so on. In order to better evaluate the electrical aspects of the networks in Brazil and Colombia, it was obtained the demand historical values in the interest of creating different scenarios according to the maximum and minimum demand in the summer and winter. According to these values, it was built four case scenarios for each country – Summer Peak, Summer Off-peak, Winter Peak and Winter Off-peak.

Analyzing the demand historical data, considering the summer and winter periods of each country, it was possible to search for the maximal and minimum values in each year. Thus, the average of the values is considered in order to build the scenarios. The chosen reference scenario was the Summer Peak case, and the resultant other scenarios were obtained from the multiplication by the scaling factor according to the average values. An example of the load curves considered is showed on the Figure 54, which refers to the Brazilian Interconnected System (SIN) in the summer of 2016. It is possible to identify the peak value of 81.999 GWh/h on 17th February 2016 at 3:00 PM and the off-peak value of 45.916 GWh/h on 1st January 2016 at 7:00 PM.

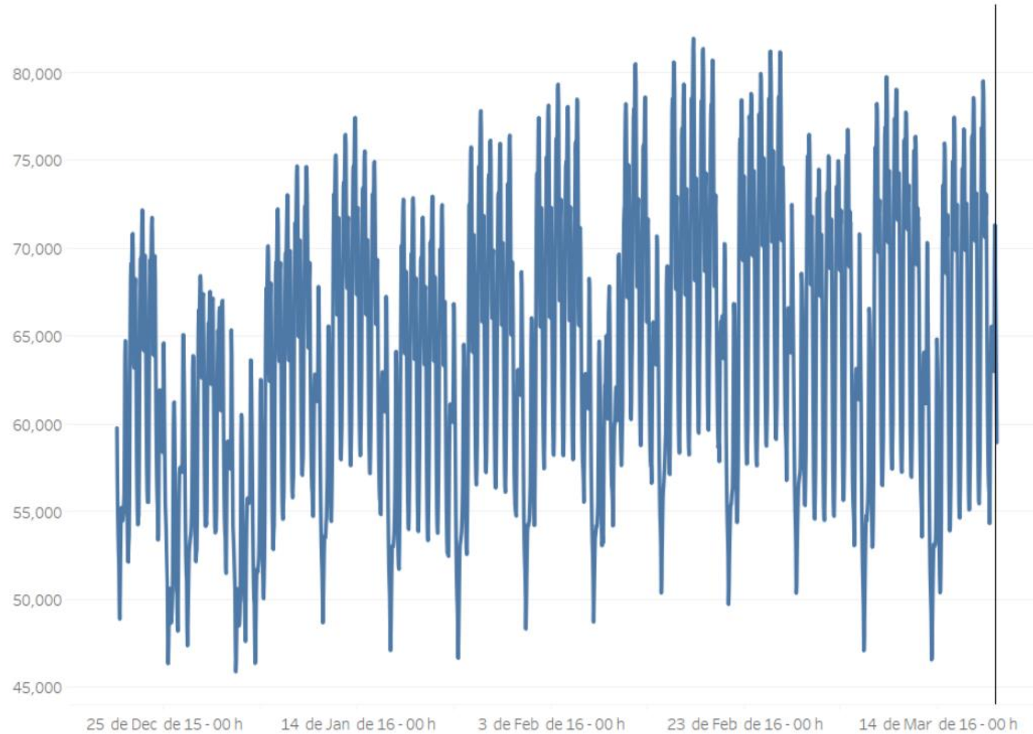


Figure. 54. Brazilian Load Curve – summer of 2016 [9].

8.3.1. Brazilian Scenarios

Brazil, as a continental country, has different economic conditions and weather characteristics that varies according to the region. Nonetheless, it is possible to consider general main features at least in the two extremal seasons, summer and winter. As a tropical country, even in the winter season the temperatures do not fall considerably in the major part of the regions. In the summer, there is a predominance of the high temperatures even in the most southern parts. Temperatures normally around 40 degrees Celsius impose great effort on the electrical system, in order to generate and dispatch the necessary amount of energy. Further than the normal demand, these high temperatures cause an overload mainly due to acclimatization appliances.

The data is based on the historical demand available on the Brazilian TSO website [9]. Considering the interval of years from 2011 to 2016, a growth of consumption occurred but the proportionality among the four scenarios maintained practically the same in all the years analyzed.

It is presented by the Table XVII, the data referred to the maximum and minimum demand considering the periods of summer and winter, month and year registered and the ratio in comparison with the reference scenario (Peak summer). The average values of the yearly comparison from Peak summer case is obtained (0.5128 – Off-peak summer, 0.9189 – Peak winter, 0.4955 Off-peak winter) and therefore used to build the four scenarios referred to the Brazilian network.

Brazil - Scenarios												
	Peak Summer		Off-Peak Summer			Peak Winter			Off-Peak Winter			
Year	Maximum demand [Gwh/h]	Month/ Year	Minimum demand [Gwh/h]	Month/ Year	Comparing to Peak Summer	Maximum demand [Gwh/h]	Month/ Year	Comparing to Peak Summer	Minimum demand [Gwh/h]	Month/ Year	Comparing to Peak Summer	
2016	81.999	Feb-16	45.916	Dec-15	0.5600	73.367	Sep-16	0.8947	40.626	Aug-16	0.4954	
2015	84.525	Jan-15	41.501	Dec-14	0.4910	75.343	Sep-15	0.8914	38.611	Jul-15	0.4568	
2014	84.92	Feb-14	42.553	Dec-13	0.5011	73.34	Sep-14	0.8636	39.867	Jul-14	0.4695	
2013	77.605	Mar-13	40.839	Jan-13	0.5262	72.991	Sep-13	0.9405	39.801	Jun-13	0.5129	
2012	76.044	Feb-12	37.027	Dec-11	0.4869	72.482	Sep-12	0.9532	38.783	Aug-12	0.5100	
2011	70.661	Feb-11	36.141	Dec-10	0.5115	68.542	Aug-11	0.9700	37.333	Jul-11	0.5283	
Average					0.5128			0.9189			0.4955	

Table. XVI. Brazilian Scenarios and comparison with the Peak summer case.

8.3.2. Colombian Scenarios

In Colombia as the major part of the country is located on the northern hemisphere, makes the summer in the period from June to September and winter from December to March. As the country is located entirely in the central part of the tropical zone, the weather seasons do not distinguish substantially, therefore similarities between the Peak summer and Peak winter, and between Off-peak Summer and Off-peak Winter scenarios are expected.

The data used to build the Colombian scenarios was collected based on the reports presented by the XM Company of Experts in Markets in Colombia's electricity market [14]. The period considered was the interval from 2015 to 2017 and the data was the assemble of the hourly production of each generator in order to produce the day curve and formerly evaluate the behavior in each season. In this case it was used generation data instead of demand by reason of confidentiality in some parts of the source's website. In the way that the target in the two cases (Brazilian and Colombian) is analyze and compare the differences between the scenarios, generation or demand will provide the same proportionality.

In Table XVIII it is shown the data referred to maximum and minimum generation considering the periods of summer and winter, period of the year and the ratio related to the comparison with the Peak summer scenario. The average values of the yearly comparison from Peak summer case is obtained (0.5473 – Off-peak summer, 0.9875 – Peak winter, 0.4808 Off-peak winter) and therefore used to build the four scenarios referred to the Colombian network.

Colombia - Scenarios												
	Peak Summer		Off-Peak Summer			Peak Winter			Off-Peak Winter			
Year	Maximum generation [Gwh/h]	Month/ Year	Minimum generation [Gwh/h]	Month/ Year	Comparison to Peak Summer	Maximum generation [Gwh/h]	Month/ Year	Comparison to Peak Summer	Minimum generation [Gwh/h]	Month/ Year	Comparison to Peak Summer
2017	9.841	Sep-17	5.488	Jul-17	0.5577	9.843	Dec-16	1.0002	4.567	Jan-17	0.4641
2016	9.877	Aug-16	5.33	Jul-16	0.5396	9.931	Mar-16	1.0055	4.958	Jan-16	0.5020
2015	10.006	Sep-15	5.449	Jul-15	0.5446	9.575	Feb-15	0.9569	4.766	Jan-15	0.4763
Average					0.5473			0.9875			0.4808

Table. XVII. Colombian Scenarios and comparison with the Peak summer case.

8.4. Network Models and Adjustments

The network models of the Brazilian and Colombian systems were developed in order to simulate the insertion of micro grids in the national systems. Therefore, it is necessary to have a voltage profile of the whole system that follows the steady-state technical rules in conformity with the grid code of each country. Considering the voltage profile presented, it was necessary to add in the models some shunt capacitors and shunt reactors in order to obtain a more flat and stable voltage profile. Additionally, tap changes were performed in order to intervene in critical areas of the system, where the transformers were located.

8.4.1. Brazilian Network Models

The first scenario considered was the Brazilian Summer Peak due to the highest load demand, making it the worst case among the Brazilian scenarios. In the initial simulation, which the voltage profile is depicted in Figure 55, the voltage values in many buses were clearly above the Adequate (voltage between 0.95 and 1.05 p.u.) and Precarious (voltage between 0.93 up to 1.07 p.u.) classification. It is possible to highlight the three greatest values, which were bus 4501 with 1.283 p.u., bus 231 with 1.255 p.u. and bus 106 with 1.254 p.u.

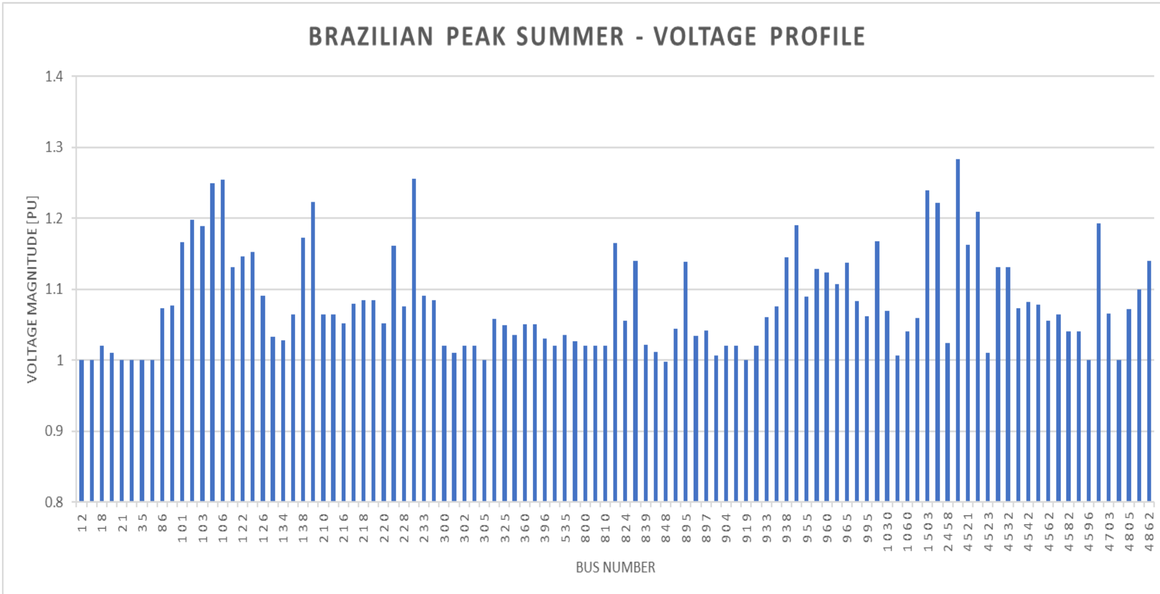


Figure. 55. Initial voltage profile of the Brazilian Peak Summer scenario.

In order to understand deeply how the grid was performing it was also executed the analysis of the system's power flow. For this reason, the analysis considered the directions of the power flow and the specially the amount of reactive power in order to better place the shunt reactors. In the Figure 56 it is possible to see the flow and the quantity of power. There are many branches with a critical transfer of reactive power, for instance it is being injected around 882 Mvar through the branch between the buses 122 and 86. Another case is related to the transfer of 984 Mvar through the branch between the buses 101 and 100. Similar cases were throughout some parts of the grid but on a smaller scale.

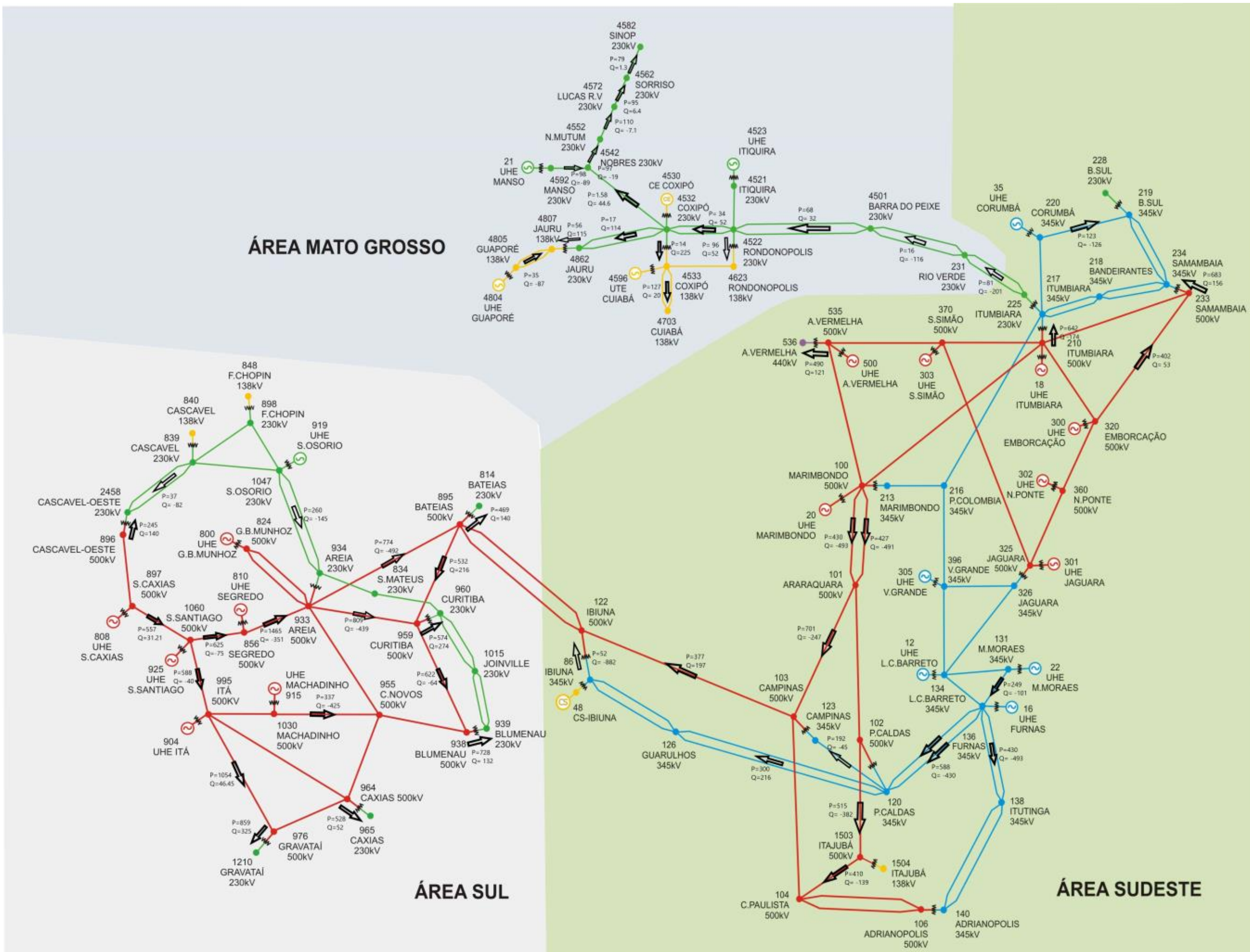


Figure. 56. Power flowing on the Brazilian network.

As the problem in general is related to the overvoltage profile, it is necessary to absorb reactive power in order to reduce the voltage magnitude. For this reason, the insertion of shunt reactors is suggested. In order to find out the nominal value of the shunt reactance that could be deployed, it is inserted an initial experimental value and from the resultant behavior it is progressively increased or reduced aiming to get a flatter profile for the bus and the surrounding buses.

For example, in the case of the branch between the buses 122 and 86, is depicted in more details in the Table XIX.

Branch number	From Bus	To Bus	From Bus Injection		To Bus Injection		Loss (I^2 * Z)	
			P [MW]	Q [MVAr]	P [MW]	Q [MVAr]	P [MW]	Q [MVAr]
203	122	86	-26.18	441.72	26.18	-413.22	0	28.5
204	122	86	-26.18	441.72	26.18	-413.22	0	28.5

Table. XVIII. Detailed result of the power flow, between buses 122 and 86.

The insertion of the shunt reactance and the consequently reduction in the reactive power flowing in the branch is shown in Figure 57, where initially the reactive power flow in the branch with no shunt inserted. Then, the insertion in the bus 122 and the progressive increase in the nominal value varying from 0 to -605 Mvar and the consequent absorption of the reactive power that was flowing from the bus 122 to the bus 86. The outcome is a reduction in the voltage magnitude from 1.13 to around 1.07 in the bus 122, just in the first intervention. Moreover, the surrounding buses (buses 86, 103 and 895) that were connected to the bus 122 suffered also a reduction in the voltage magnitude. The Figure 57 and 58 depicts the shunt reactance insertion.

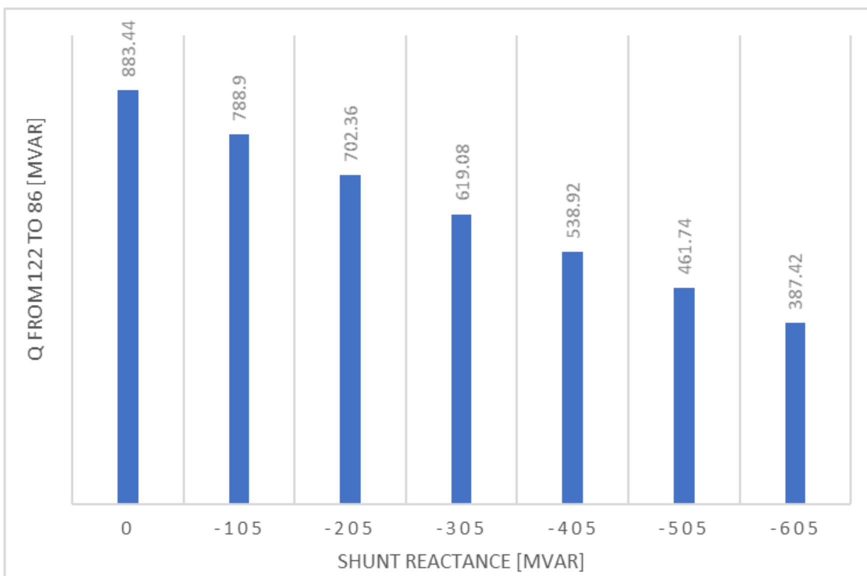


Figure. 57. Reactive Power flow from bus 122 to bus 86 with shunt reactance increment.

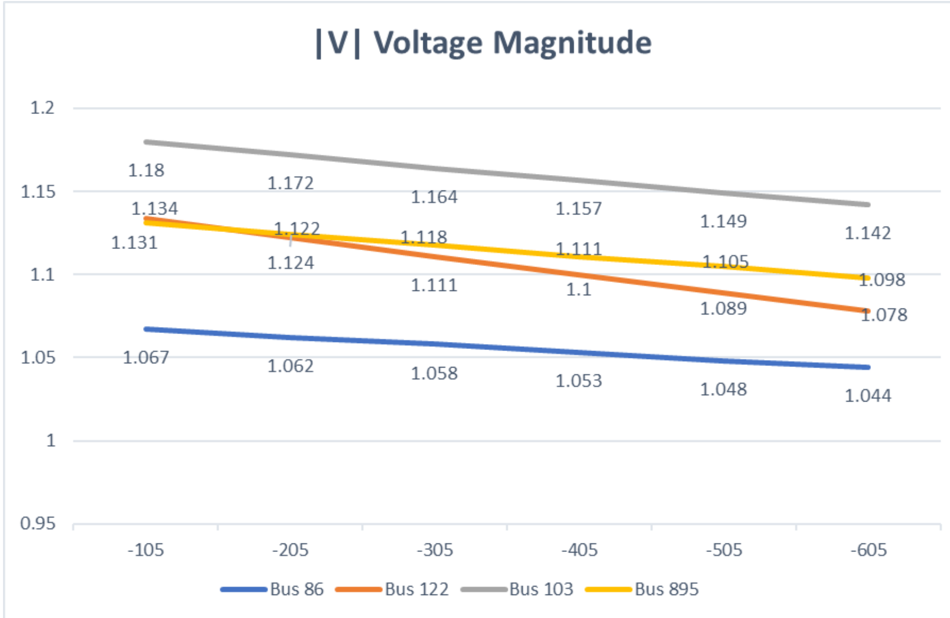


Figure. 58. Voltage Magnitude in the buses 86, 103, 122 and 895 with shunt reactance increment.

Another focus of high reactive power flow and high voltage profile is in the bus 104 and nearby buses (103, 106 and 1503) detailed in Table XX.

Bus 122 with Bs = -605 Mvar and bus 104 with Bs= 0								
Branch number	From Bus	To Bus	From Bus Injection		To Bus Injection		Loss (I^2 * Z)	
			P [MW]	Q [MVAr]	P [MW]	Q [MVAr]	P [MW]	Q [MVAr]
8	103	104	199.8	-432.78	-198.18	91.62	1.617	25.58
9	104	1503	-410.69	103.47	411.35	-193.62	0.657	10.77
84	106	104	14.07	-118.71	-14.06	-179.65	0.012	0.19
85	106	104	14.07	-119	-14.06	-179.94	0.012	0.19

Table. XIX. Detailed result of the power flow, nearby bus 104.

The progressive insertion of the shunt reactance in the bus 104 varying from 0 to -400 Mvar, reduced substantially the voltage magnitude. For instance, the bus 106 that had a voltage magnitude of 1.21 p.u. decreased to 1.1 p.u.

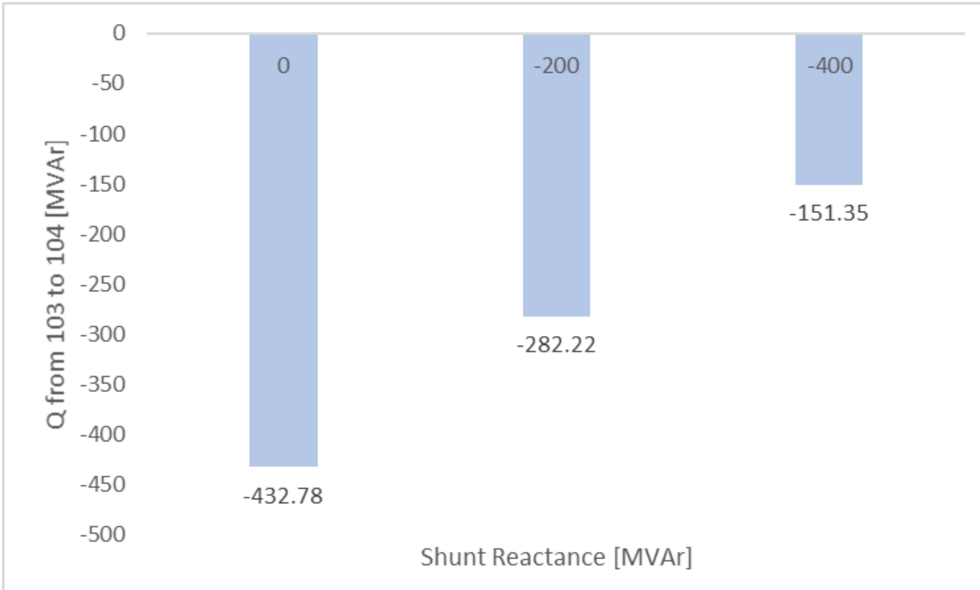
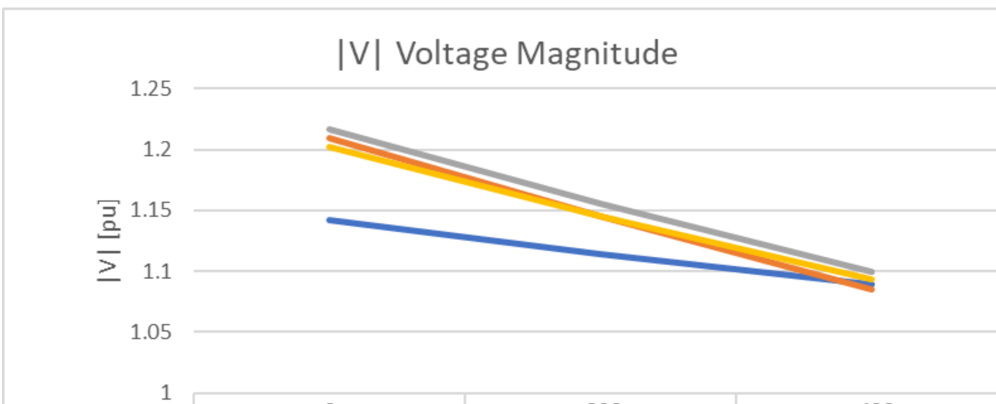


Figure. 59. Reactive Power flow from bus 103 to bus 104 with shunt reactance increment.



	0	-200	-400
Bus 103	1.142	1.114	1.089
Bus 104	1.21	1.145	1.085
Bus 106	1.217	1.156	1.1
Bus 1503	1.202	1.145	1.093

Figure. 60. Voltage Magnitude in the buses 103, 104, 106 and 1503 with shunt reactance increment.

Another procedure deployed in order to improve the voltage profile is referred to tap changes. It is not as efficient as the shunt reactance insertion, but it has satisfactory results considering that it does not incur any costs to implement in real grids. For that reason, it was performed in the Transformer between buses 964 and 965. The information related to the transformer characteristics, as the number and the values of the taps, were available in the Brazilian model STB107 [13]. The tap variation was from 0.9717 to 1.0333. It is necessary to increase the tap in order to reduce the voltage in the lower voltage side (bus 965). It is shown in the Figure 61 the reduction in the voltage caused by the tap change in the transformer located between the buses 964 and 965. Clearly, the bus 965 voltage magnitude had a strong decrease from 1.12 to 1.05 p.u., however, the reduction in the nearby buses was insignificant.

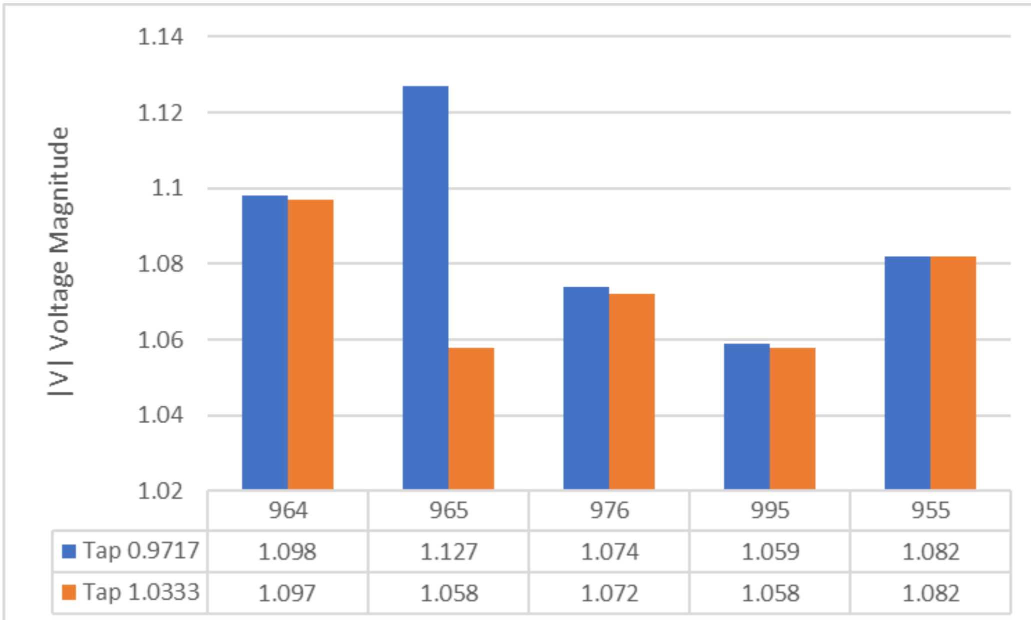


Figure. 61. Comparison of the voltage magnitude in the buses 955, 964, 965, 976 and 995 with tap change.

Another case was performed with the transformer located between the buses 938 and 939. Again the rise in the tap change, from 0.9586 to 1, in order to reduce the voltage magnitude in the lower voltage side. The outcome is a reduction in the voltage magnitude in the bus 939 and 1015, but a slight rise in the bus 938 as shown in the Figure 62.

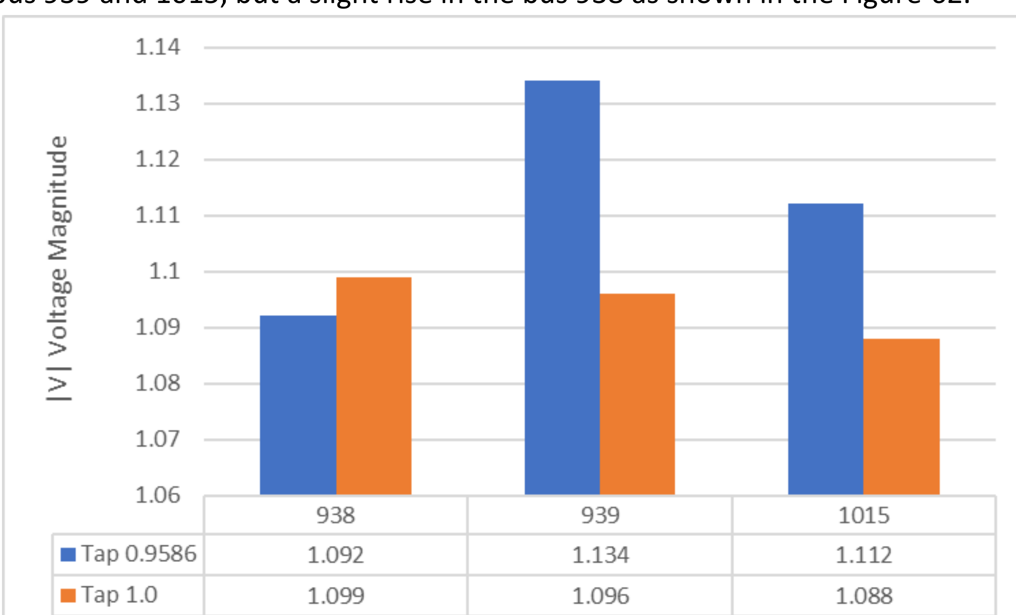


Figure. 62. Comparison of the voltage magnitude in the buses 938, 939 and 1015 with tap change.

Successive similar interventions were performed with the same procedure in order to obtain flatter voltage profile in the other three scenarios as well.

The final voltage profile for the four scenarios are depicted in: Figure 63 depicts the Brazilian Peak Summer voltage profile, Figure 64 depicts the Brazilian Off-peak Summer voltage profile, Figure 65 depicts the Brazilian Peak Winter voltage profile and Figure 66 depicts the Brazilian Off-peak Winter voltage profile. The main target of the voltage improvement was attend the technical rules of the Brazilian grid code, determined by the TSO, in conformity with the voltage levels of the transmission lines modelled. All the buses in the four scenarios remains between the thresholds of 0.95 p.u. and 1.05 p.u., which is called in the classification as adequate operation.

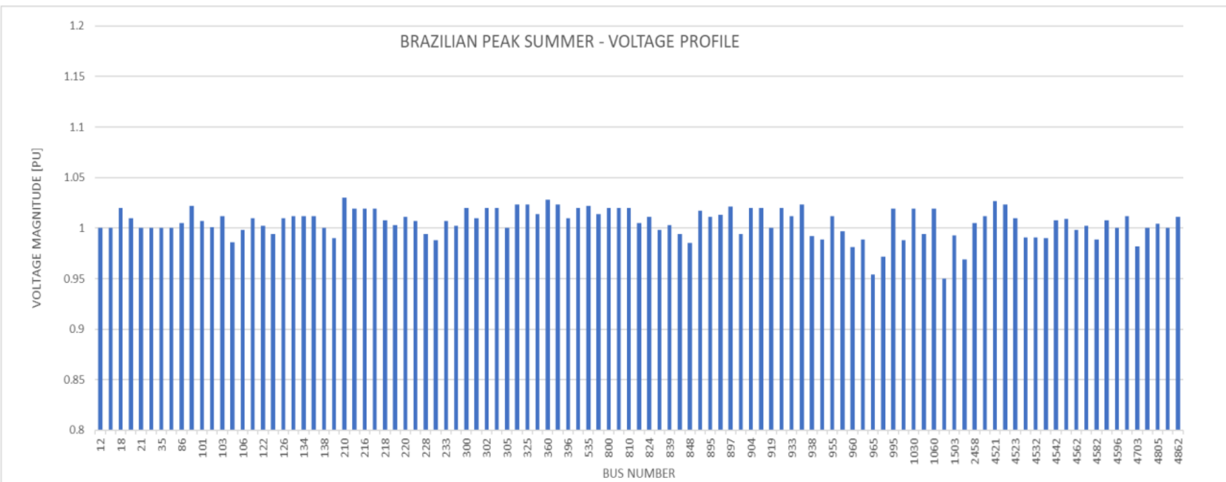


Figure. 63. Voltage profile of the Brazilian Peak Summer scenario after the solutions proposed.

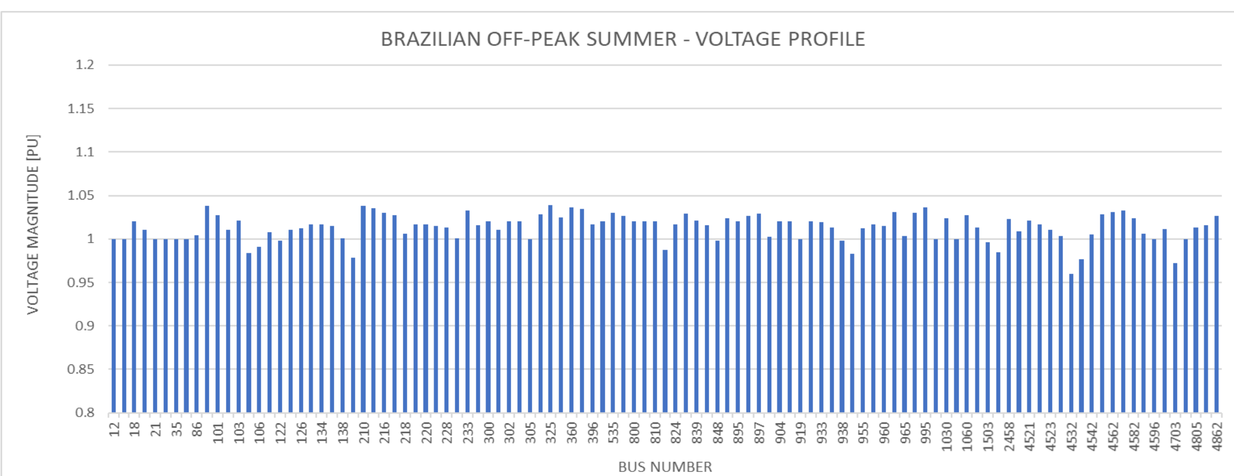


Figure. 64. Voltage profile of the Brazilian Off-peak Summer scenario after the solutions proposed.

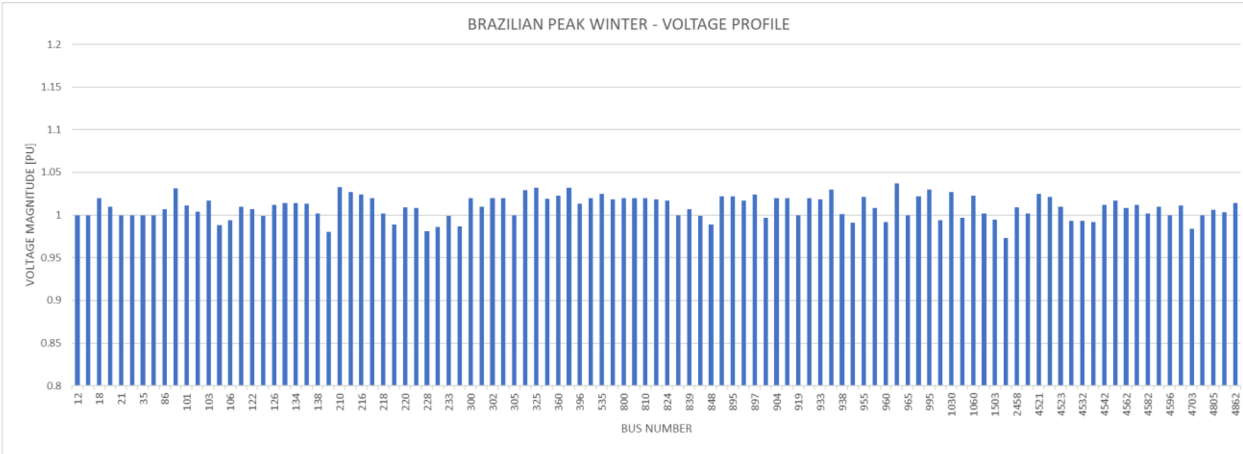


Figure. 65. Voltage profile of the Brazilian Peak Winter scenario after the solutions proposed.

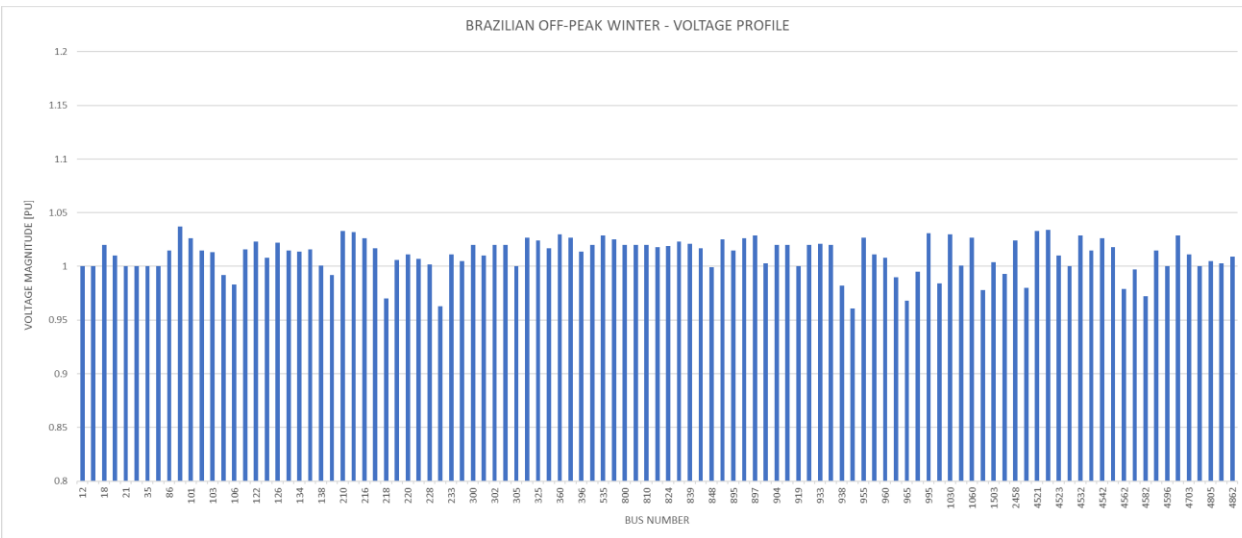


Figure. 66. Voltage profile of the Brazilian Off-peak Winter scenario after the solutions proposed.

8.4.2. Colombian Network Models

In the Colombian case, the resultant non-flat voltage profile, after the modelling procedure, shown voltages below the bottom critical values, which according to the Colombian technical rules is 0.9 p.u. In contrast to the Brazilian cases, the problems in the modelled Colombian scenarios are in general related to under voltage situation. In order to solve this problem, it is necessary to insert shunt capacitors for the sake of injecting reactive power, therefore, increasing the voltage magnitude on certain buses. Furthermore, tap changes were also used.

Considering the first model of the Colombian Peak Summer scenario, which the voltage profile is depicted in Figure 67. It is shown some critical buses such as bus 1 with

0.78 p.u. and bus 44 with 0.86 p.u. The method for the assessment and insertion of shunt capacitors was similar performed in the Brazilian cases. Running the power flow and resulting in the voltage profile, it is possible to evaluate the critical buses, applying the solutions of insertion and tap changes.

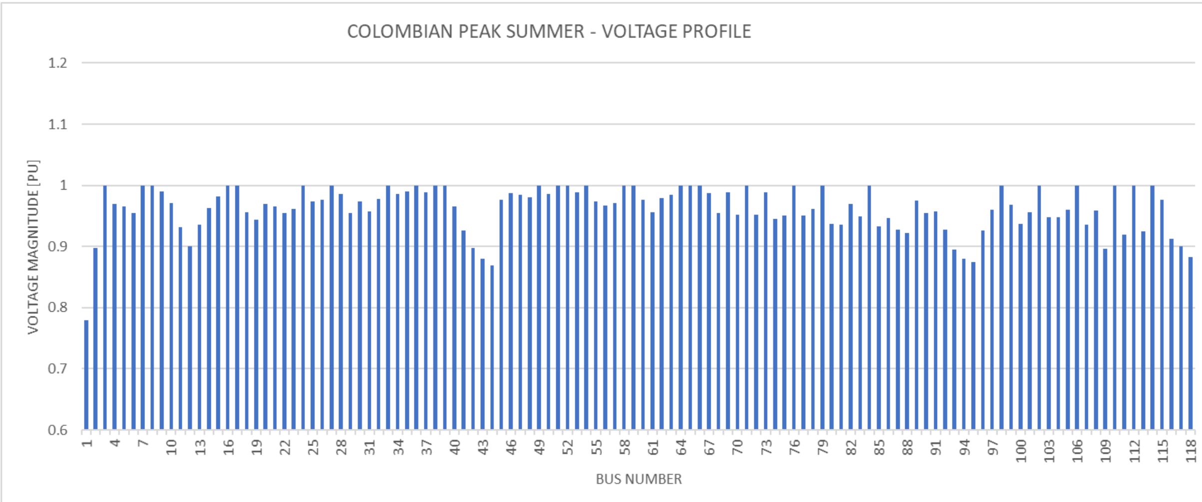


Figure. 67. Initial voltage profile of the Colombian Peak Summer scenario.

The voltage profile regarding the four scenarios of the Colombian model are presented in: Figure 68 shows the Colombian Peak Summer voltage profile that varies from 0.971 p.u. (bus 14) up to 1.002 p.u. (bus 88), Figure 69 shows the Colombian Off-peak Summer voltage profile that varies from 0.988 p.u. (bus 14) up to 1.004 p.u. (bus 116), Figure 70 shows the Colombian Peak Winter voltage profile that varies from 0.972 p.u. (bus 14) up to 1.004 p.u. (bus 1) and Figure 71 shows the Colombian Off-peak Winter voltage profile that varies from 0.982 p.u. (bus 1) up to 1.004 p.u. (bus 72). All the scenarios are in conformity with the technical rules of steady-state voltage magnitude contained in the Colombian Resolution. Comparing the parameters of voltage magnitude in the Brazilian and Colombian grid code it is clear that the Colombian allows a more flexible voltage profile (from 0.9 to 1.1). Nevertheless, the four scenarios of each country are within the limits for the both technical rules.

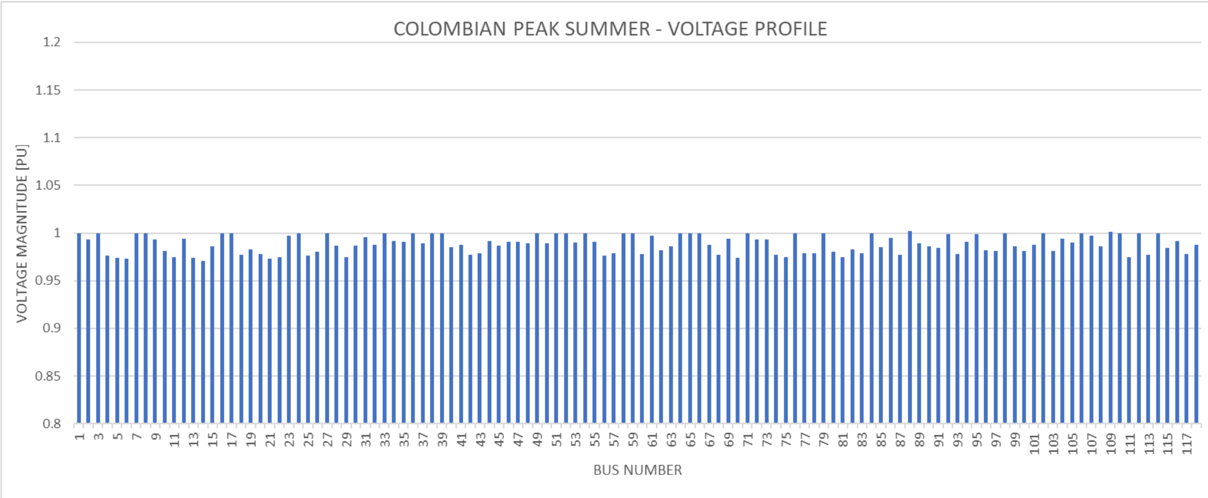


Figure. 68. Voltage profile of the Colombian Peak Summer scenario after the solutions proposed.

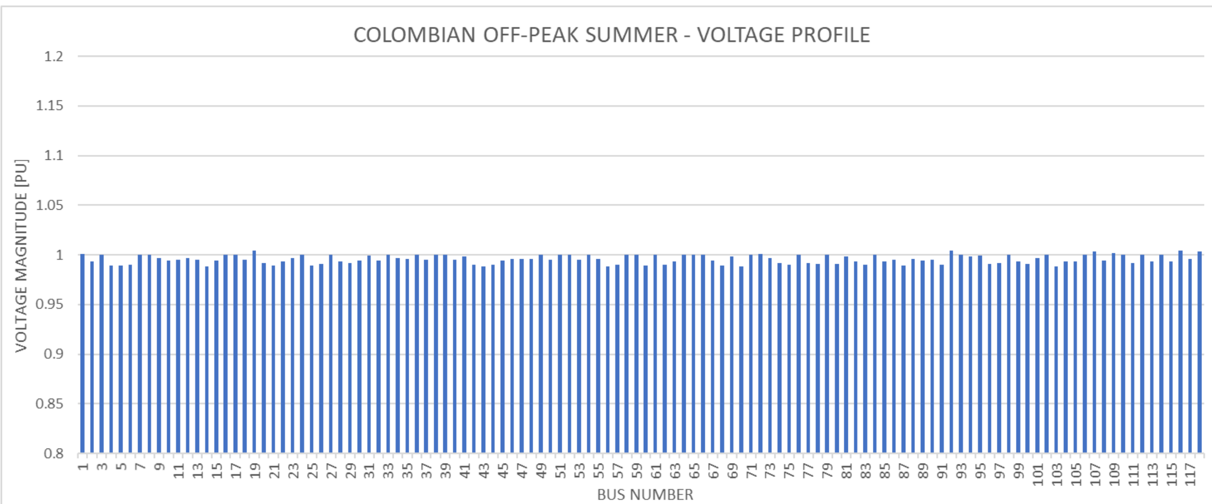


Figure. 69. Voltage profile of the Colombian Off-peak Summer scenario after the solutions proposed.

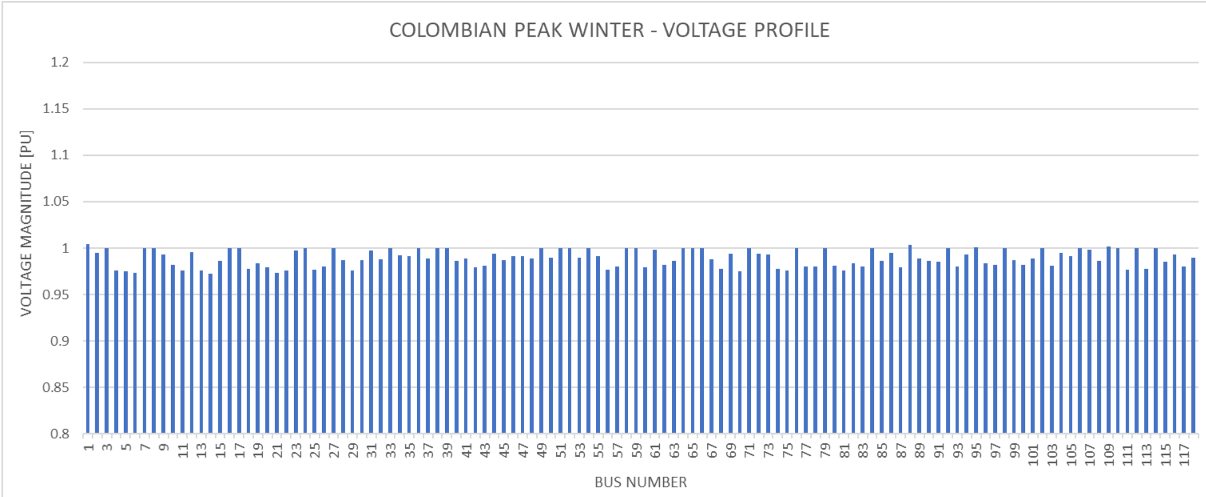


Figure. 70. Voltage profile of the Colombian Peak Winter scenario after the solutions proposed.

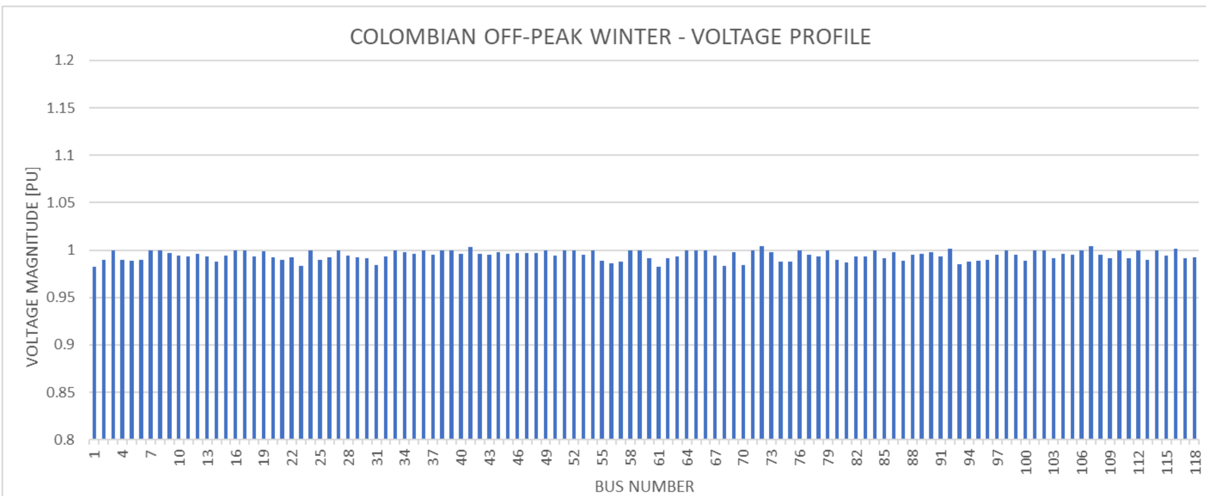


Figure. 71. Voltage profile of the Colombian Off-peak Winter scenario after the solutions proposed.

9. Results

9.1. Transmission lines results

9.1.1. Brazilian Network – Load Increment

I. Results from Progressive Load Increment based on Total Load

In order to analyze the Brazilian system within the load increment scenario it is presented in the Table XXI the total load amount for the four scenarios, regarding the total load.

Brazilian Scenarios	Total load [MW]	Total load [Mvar]
Peak Summer	8877.19	2518.25
Off-peak Summer	4552.05	1291.31
Peak Winter	8157.34	2314.05
Off-peak Winter	4398.56	1247.77

Table. XX. Total load regarding the Brazilian scenarios.

It is considered for the simulation, the most determinant scenario, which is the Peak Summer, by the reason of being the most loaded case it constraints all the other scenarios and, in a sense, determine the whole system load increment.

As it was stated previously in the methodology, after the first simulation, the evaluation of the results will define the next values of the load increment. For instance, whether the voltage profile did not change substantially after the first load increment it is possible to go to the next simulation with the defined value. However, if the changes were significant, it is more prudent to choose smaller values in order to understand better the behavior of the network. Therefore, after analyzing the first simulation results regarding those areas in the Brazilian network it was decided to perform the load increment with smaller values. The Table XXII, displays the selected buses and their respective load for each increment, increasing by 0.1% of the total load.

Peak Summer											
Division of Load	Bus	0.1 % of Total Load [MW]	0.1 % of Total Load [MVAr]	0.2 % of Total Load [MW]	0.2 % of Total Load [MVAr]	0.3 % of Total Load [MW]	0.3 % of Total Load [MVAr]	0.4 % of Total Load [MW]	0.4 % of Total Load [MVAr]	0.5 % of Total Load [MW]	0.5 % of Total Load [MVAr]
Sinop	4582	3.47	0.98	6.94	1.97	10.41	2.95	13.88	3.94	17.35	4.92
Sorriso	4562	2.18	0.62	4.36	1.24	6.53	1.85	8.71	2.47	10.89	3.09
L. Rio Verde	4572	1.57	0.45	3.15	0.89	4.72	1.34	6.29	1.78	7.86	2.23
Nova Mutum	4552	1.06	0.30	2.11	0.60	3.17	0.90	4.23	1.20	5.28	1.50
Nobres	4542	0.38	0.11	0.76	0.22	1.14	0.32	1.53	0.43	1.91	0.54
Jauru	4862	0.22	0.06	0.44	0.12	0.65	0.19	0.87	0.25	1.09	0.31

Table. XXI. Load increment values considered in the Brazilian Peak Summer.

Thus, the simulations were performed with the values considered for the buses of the area of Mato Grosso. The Figure 72 depicts the voltage profile of the whole system with different Increment percentages, all the voltage profiles were normalized by the voltage values of the non-increment case. It is possible to notice that the area of Mato Grosso in general was strongly affected, in terms of voltage magnitude fall. It is possible also to highlight that two buses 4582 (Sinop county) and 4562 (Sorriso county) presented the worst results, with 0.751 p.u. and 0.775 p.u, respectively.

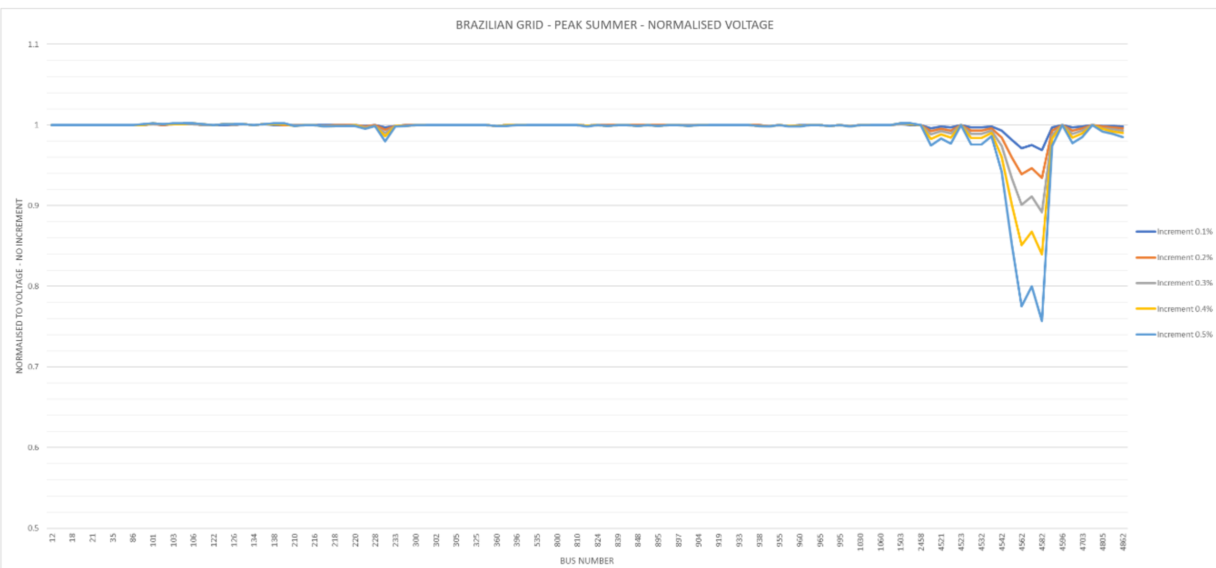
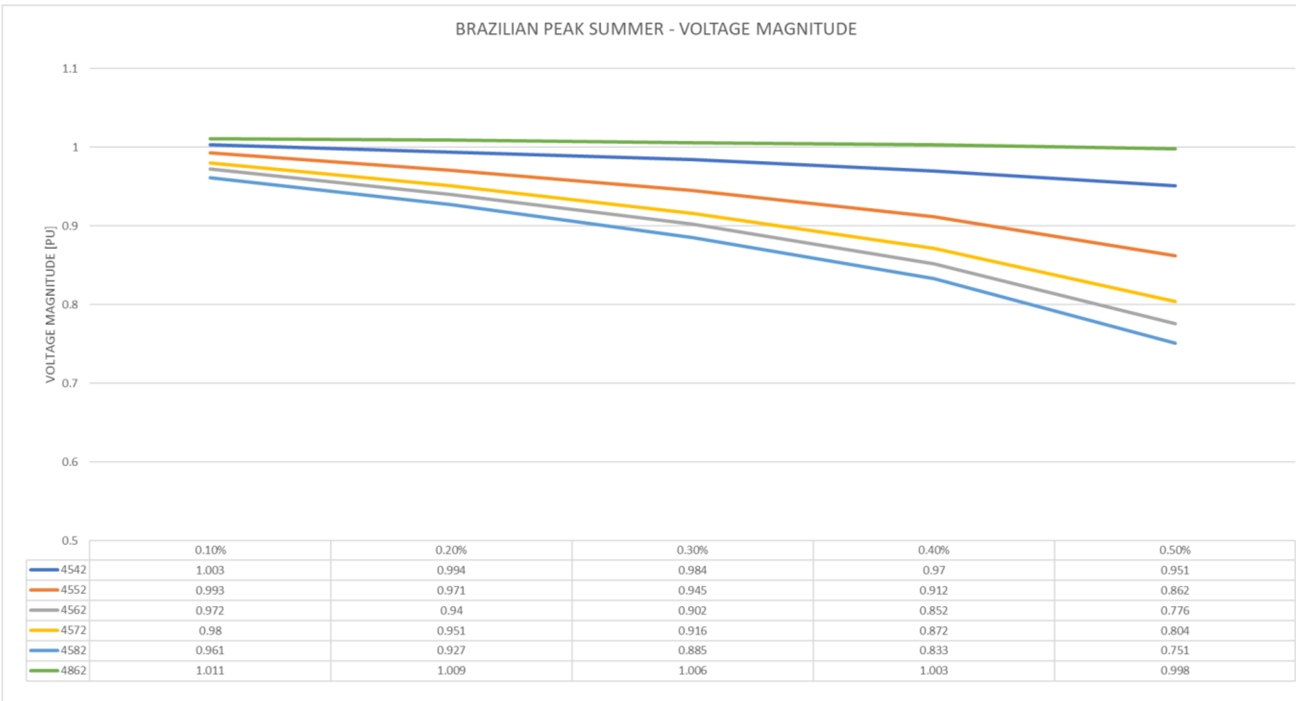


Figure. 72. Comparison of the voltage profile normalised in different load increments.

Focusing on the voltage magnitude in the selected buses, and analysing the results presented in the Figure 73, it is possible to notice that the most affected bus is the 4582 (Sinop), since the first simulation. Moreover, with 0.2% of load increment the bus 4582 is on Critical operation state with 0.927 p.u. and 4562 is in precarious operation state with 0.94 p.u., therefore it is possible to declare that technically after 0.2% of load increment there are some buses breaking the technical constraints. For further load increments, reaching the final value of 0.5%, all the selected buses operate out of the Adequate operation condition, with the exception of the bus 4862 that remains practically flat and bus 4542 that fell to 0.951 p.u. which is in the limit to be considered in an Adequate condition.

Another important point is that the worst voltage situation regards the bus 4582, which is the last bus of a radial transmission line. This reinforces the conception of the lack of stability and security regarding radial structures.



	0.10%	0.20%	0.30%	0.40%	0.50%
4542	1.003	0.994	0.984	0.97	0.951
4552	0.993	0.971	0.945	0.912	0.862
4562	0.972	0.94	0.902	0.852	0.776
4572	0.98	0.951	0.916	0.872	0.804
4582	0.961	0.927	0.885	0.833	0.751
4862	1.011	1.009	1.006	1.003	0.998

Figure. 73. Voltage magnitude of the selected buses throughout the simulations.

Analyzing the line loading with different load increment applied in the Figure 74, it is noticed that in general the loading in the branches does not change considerably with the load increment. The exceptions are the branch 93, which alter from 0.675 to dangerous 0.972 and branch 94, changing from 0.7166 to 0.920.

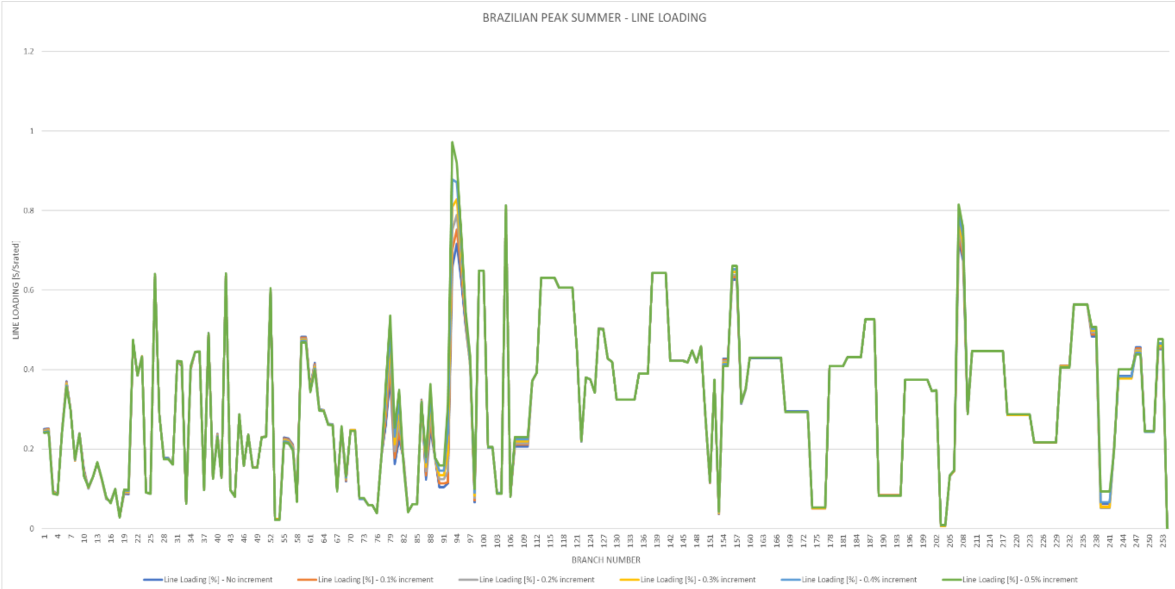


Figure. 74. Line loading according to the increment.

Figure 75 depicts the most loaded branches cited. Located in the beginning of the radial transmission line, it is an important impediment for the load growth on the regions and counties fed by this transmission line.

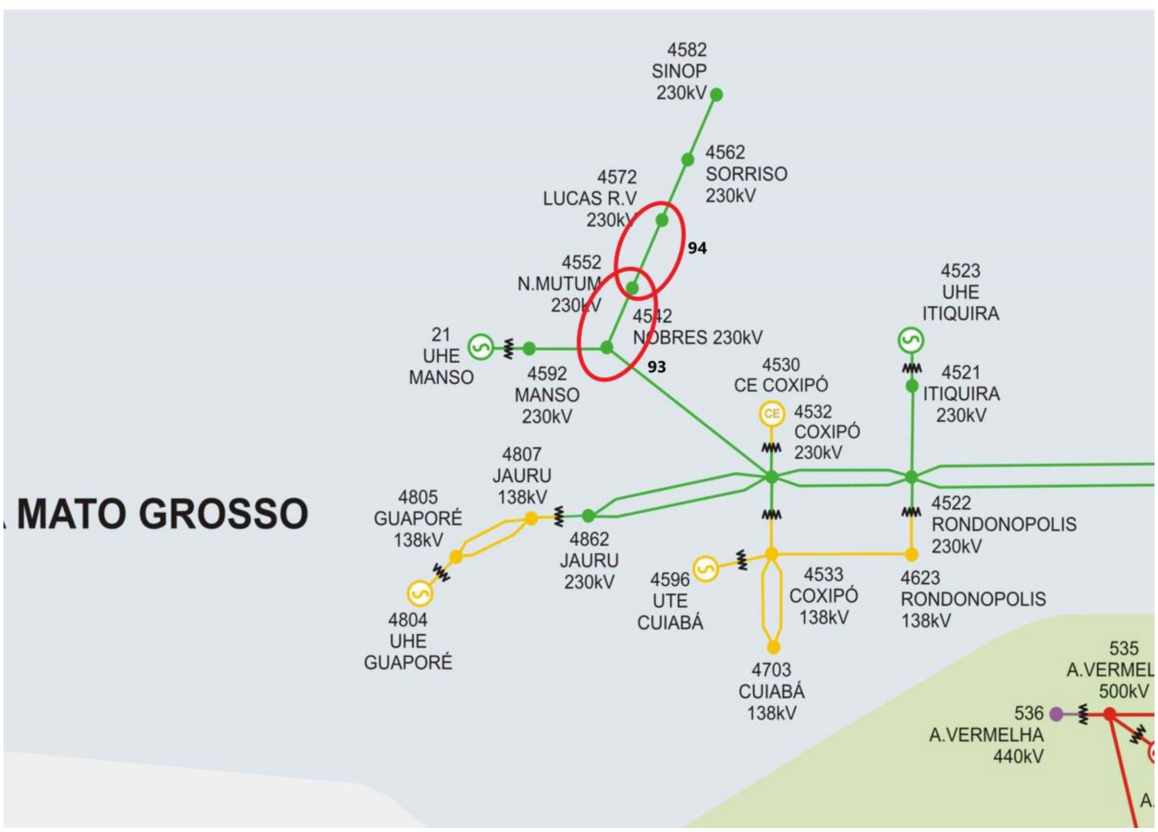


Figure. 75. Most loaded Branches in Brazilian network.

II. Results from Progressive Load Increment based on the Regional Growth

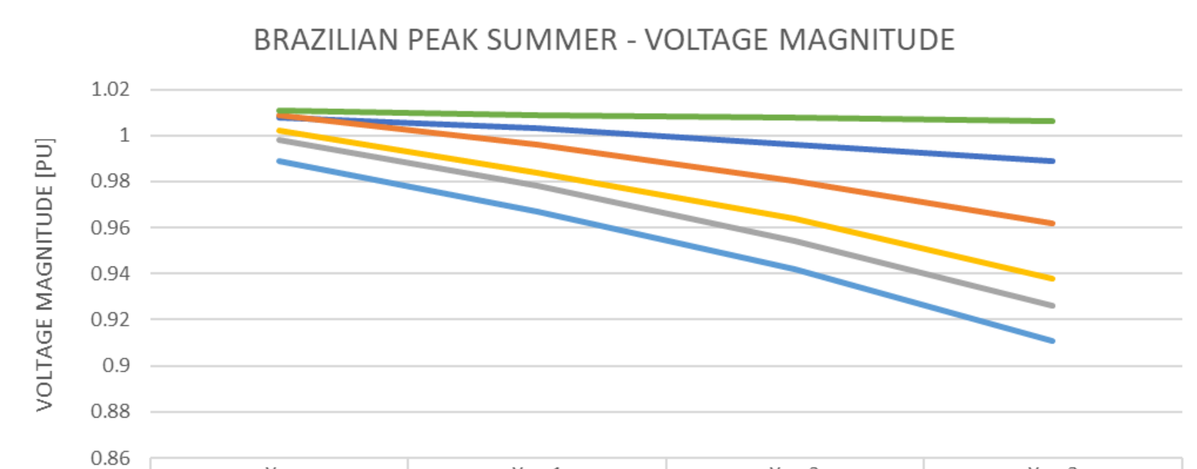
In order to evaluate the regions scenario with a realistic approach, it was assumed the regional growth of the region in the last years. In Mato Grosso state, considering the last year’s energy consumption growth, the increase of 6.81% from 2016 to 2017 is an unusual value if compared with the previous years. However, use this value improves the analysis with the adoption of the worst scenario.

In the Table XXIII, it is presented the data regarding the values for each bus in the original scenario of the summer peak and the respective projection of each year based on the growth of 6.81%.

Peak Summer													
Division of Load	Bus	Original Load [MW]	Original Load [MVAr]	Year n+1 [MW]	Year n+1 [MVAr]	Year n+2 [MW]	Year n+2 [MVAr]	Year n+3 [MW]	Year n+3 [MVAr]	Year n+4 [MW]	Year n+4 [MVAr]	Year n+5 [MW]	Year n+5 [MVAr]
Sinop	4582	45.85	11.69	48.97	12.49	52.31	13.34	55.88	14.25	59.69	15.22	63.75	16.25
Sorriso	4562	16.66	5.18	17.80	5.53	19.01	5.91	20.30	6.31	21.69	6.74	23.17	7.20
L. Rio Verde	4572	12.60	4.48	13.46	4.79	14.38	5.11	15.36	5.46	16.40	5.83	17.52	6.23
Nova Mutum	4552	8.82	0.84	9.42	0.90	10.06	0.96	10.75	1.02	11.48	1.09	12.26	1.17
Nobres	4542	2.92	0.91	3.12	0.97	3.33	1.04	3.56	1.11	3.80	1.18	4.06	1.26
Jauru	4862	1.66	0.52	1.78	0.55	1.90	0.59	2.03	0.63	2.17	0.67	2.32	0.72
Total		88.51	23.62	94.55	25.22	100.99	26.94	107.87	28.78	115.23	30.74	123.08	32.84

Table. XXII. Load increment values considered in the Brazilian Peak Summer.

Thus, it was performed the simulations in order to evaluate network with the mentioned yearly growth projection. It was evaluated the technical constraints that eventually were broken and the estimation of time that whether the growth happens, the network on these areas will suffer with operational problems. In the Figure 76 it is shown the voltages magnitude behavior in different years. After the Year n+2, with this rate of growth, the limit is reached due to the voltages that are below the precarious operation. The bus 4562 and 4582 with 0.926 and 0.911 p.u. respectively, alert for the soon scenario of precarity in the operation, only 3 years of distance in the pessimistic forecast.



	Y n	Y n+1	Y n+2	Y n+3
4542	1.008	1.003	0.996	0.989
4552	1.009	0.996	0.98	0.962
4562	0.998	0.978	0.954	0.926
4572	1.002	0.984	0.964	0.938
4582	0.989	0.967	0.942	0.911
4862	1.011	1.009	1.008	1.006

Figure. 76. Voltage magnitude of the selected buses throughout the simulations.

III. Results from Insertion of Transmission Line on Critical Areas

Evaluating the results of load increment based on the regional growth and considering the behavior of the buses located on this radial part of the network, motivated the assessment of alternatives to reinforce the grid and also provide the possibility for a medium and long-term growth of the load on those areas.

The alternative proposal is to insert a transmission line connecting the critical area a more stable part of the grid in order to quantify the possible increment of load with the stability. Then, in order to enter in the economic analyses, evaluate the LCOE based on the length of this new transmission line.

One elected option is to insert a transmission line from the bus 4521 (Itiquira), assessed as a more stable bus to the bus 4582 (Sinop), which is one of the most problematic in terms of technical constraints. The outcome is a sort of ring topology approach. The new transmission line will be a 230 kV, with the similar parameters of the lines that are located in that area. The Figure 77 depicts the location of the two buses.

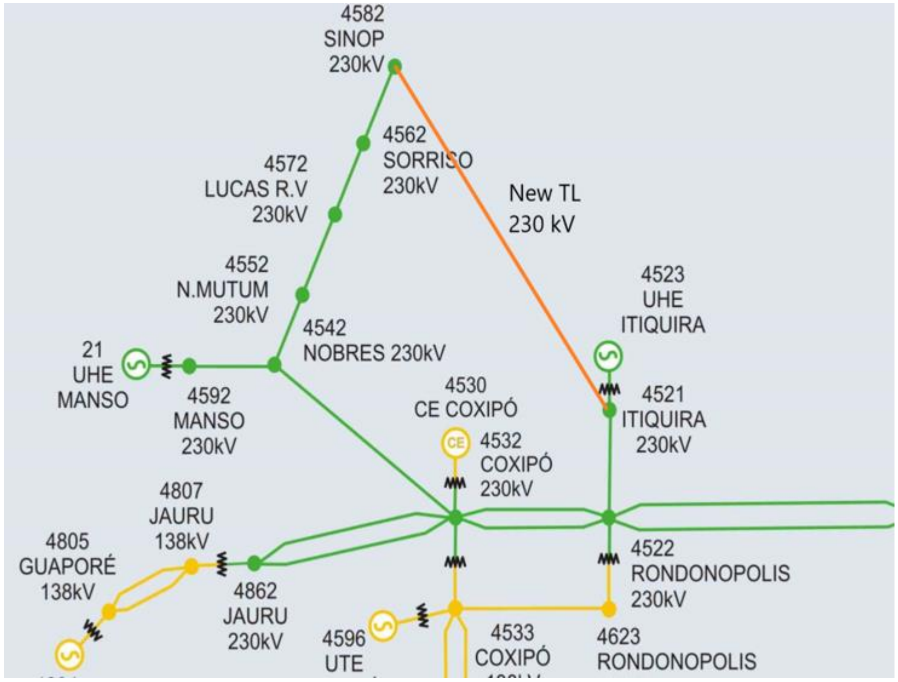


Figure. 77. Transmission line insertion in the area of Mato Grosso.

Thus, with the new transmission line it is performed the simulations with load increment based on the regional yearly energy growth of 6.81%. The idea is evaluate for how many years, with this continuing high growth, the network on this area will maintain the technical constraints.

In Figure 78 depicts the voltage profile from the bus 4501 to 4862, all located in the Mato Grosso area. The first thing noticed is that the voltages in the initial Year n raised automatically with the transmission line insertion. The highest value of the voltage is in the bus 4562 (Sorriso) which reached 1.068 p.u., staying on the Precarious operation condition. On the other hand, it has an advantage of the suddenly rise of the voltages, that is a higher capacity for enduring the strong load increment projected to the next years. The voltage magnitude in general, simulated over the years, decays each year, reaching a flatter profile on the year n+10. From this period, the voltage starts to fall more abruptly. In the year n+13, the bus 4582 reaches 0.939 p.u. and bus 4562 reaches 0.947 p.u., values on the Precarious condition. For the year n+14, the two buses enter in the Critical condition, as bus 4582 reaches 0.912 p.u. and bus 4562 reaches 0.922 p.u.

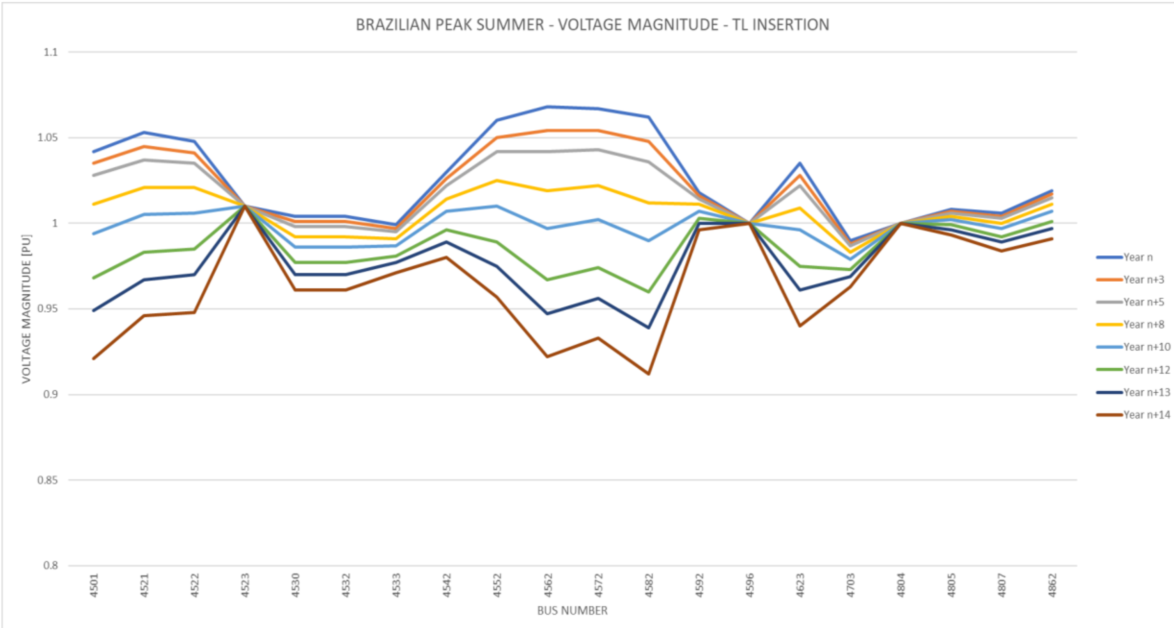


Figure. 78. Voltage profile with the Transmission line insertion considering the different years.

Also, the line loading was evaluated. Figure 79 depicts the line loading concerning to all the branches of the system. It is possible to highlight the branch 255 which is the new transmission line added with 0.920 of loading. Another important loaded line is the 207 with 0.952, this line is a transmission line with a transformer that connects Mato Grosso's region to the southeast network.

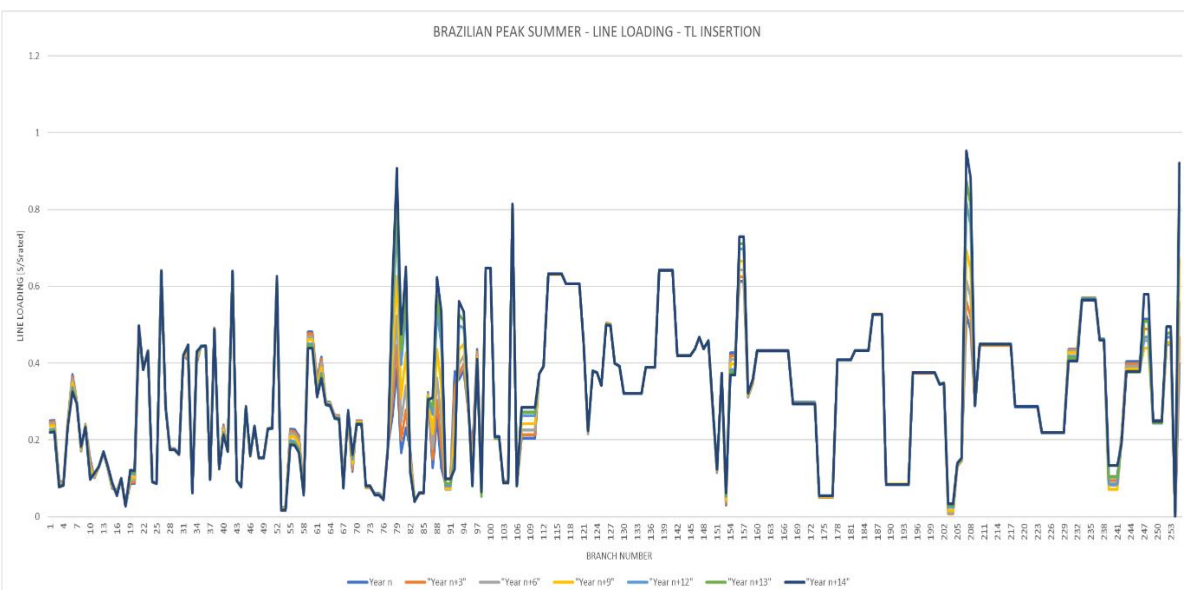


Figure. 79. Line loading according to the increment.

The incremental demand gained after the insertion of the transmission line is 120.06 MW. It is shown in the Table XXIV, where the original and the year n+13 load are compared.

Peak Summer					
Division of Load	Bus	Original Load [MW]	Original Load [MVAr]	Year n+13 [MW]	Year n+13 [MVAr]
Sinop	4582	45.85	11.69	108.04	27.55
Sorriso	4562	16.66	5.18	39.26	12.21
L. Rio Verde	4572	12.60	4.48	29.69	10.56
Nova Mutur	4552	8.82	0.84	20.78	1.98
Nobres	4542	2.92	0.91	6.88	2.14
Jauru	4862	1.66	0.52	3.92	1.22
Total		88.51	23.62	208.57	55.65

Table. XXIII. Original and year n+13 load increment comparison.

IV. Calculation of the LCOE with the Results of the Transmission Line Insertion

Based on the quantity of load increment that the new Transmission Line brought to the area, and the costs of adding a new transmission line it is possible to estimate the LCOE.

Considering the distance of the two counties were the buses are located, it is possible to estimate the total cost. The direct length from bus 4521, located on the county of Itiquira, to the bus 4582, located on the county of Sinop, reaches 613.89 km as shown in the Figure 80.

Figure. 80. Measured distance of the hypothetical transmission line.

The costs referred to the new transmission line are shown in the Table XXV. The components are related to modules that contains all the material, the construction and/or installation and other costs embedded as insurance, profit and licenses. For instance, the module of Simple circuit covers cables, structure, lightning protection, and so on; line entrance convers equipment, isolators, protection system, construction costs and so on, MIM and MIG are referred to maneuver and general infra-structure module, accounting for other costs like the land acquisition.

Transmission Line - From Bus 4521 to Bus 4582					
Description	Quantity	Factor	Unit Cost [€]	Unit Cost x Factor	Total Cost [€]
Simple Circuit 230 kV, 1 x 795 MCM (DRAKE) [km]	306.945	1	103814.6163	103814.6163	31865377.39
Simple Circuit 230 kV, 1 x 795 MCM (DRAKE) - HIGH TOWERS [km]	306.945	1.5	103814.6163	155721.9244	71697099.14
LE - Line Entrance - 230 kV - BD4 Arrengement	1	1	1143791.068	1143791.068	1143791.068
LE - Line Entrance - 230 kV - BD4 Arrengement	1	1	1143791.068	1143791.068	1143791.068
MIM - 230 kV - one side	1	1	83787.48661	83787.48661	83787.48661
MIG-A - Rural Land	1	1	440839.5488	440839.5488	440839.5488

Table. XXIV. Cost table referred to the transmission line.

To calculate the LCOE, some assumptions were considered, such as: The Capital Recovery Factor (*CCC*) was based on the Brazilian typical that is 8%. The transmission lines could stay for 15 years without deep maintenance, then the O&M costs were set to zero, because the period considered is 13 years. The demand increment with the TL was 120.06 MW based on the simulation. The energy possible to be transmitted with the new transmission line in the period of one year will be: 1,051,729.9 MWh.

The total investment: 106,374,685.7 €. Then, based on the formula already mentioned:

$$LCOE = \frac{total\ annual\ costs\ \left[\frac{€}{y}\right]}{yearly\ electricity\ production\ \left[\frac{MWh}{y}\right]} \left[\frac{€}{MWh}\right]$$

Then, the $LCOE$= 8.09141 $\left[\frac{€}{MWh}\right]$

9.1.2. Colombian Network – Load Increment

I. Results from Progressive Load Increment based on Total Load

Firstly, in order to perform the progressive load increment, the total load of the Colombian scenarios was considered, the amount is in the Table XXVI regarding the real and reactive demand in the PQ buses of the elected areas.

Colombian Scenarios	Total load [MW]	Total load [Mvar]
Peak Summer	9619.68	2741.61
Off-peak Summer	5264.75	1500.45
Peak Winter	9499.72	2707.42
Off-peak Winter	4625.05	1318.14

Table. XXV. Total load regarding the Colombian scenarios.

The first scenario considered is the Peak Summer scenario, understood as the most determinant scenario for the analysis. The limitations presented by this scenario with the load increment, will consequently constraint the other scenarios and determine the whole system load increment limitation on those areas.

Then, the progressive percentages considering the Peak Summer scenario is given by the Table XXVII, displaying the for the selected buses amounts of 0.1%, 0.5%, 1% and 2%, however, the simulations were performed with further values.

Peak Summer									
Division of Load	Bus	0.1 % of Total Load [MW]	0.1 % of Total Load [Mvar]	0.5 % of Total Load [MW]	0.5 % of Total Load [Mvar]	1 % of Total Load [MW]	1 % of Total Load [Mvar]	2 % of Total Load [MW]	2 % of Total Load [Mvar]
Arauca	43	0.75	0.21	3.77	1.07	7.54	2.15	15.07	4.30
	44	0.75	0.21	3.77	1.07	7.54	2.15	15.07	4.30
Casanare	92	2.08	0.59	10.38	2.96	20.75	5.91	41.50	11.83
Vichada	95	0.42	0.12	2.12	0.60	4.24	1.21	8.49	2.42
Meta	93	1.87	0.53	9.36	2.67	18.71	5.33	37.42	10.67
	94	1.87	0.53	9.36	2.67	18.71	5.33	37.42	10.67
	105	1.87	0.53	9.36	2.67	18.71	5.33	37.42	10.67

Table. XXVI. Load increment values considered in the Colombian Peak Summer.

Initially, considering the buses selected, which are located in the Colombian departments of Arauca, Casanare, Vichada and Meta, using the populational criteria of distribution of the load increment, it is possible to see the distributed increment per bus in each simulation.

In the first simulation it was performed the load increment in progressive steps, beginning from 0.1% of the total load and advancing until the power flow performance reaches the non-convergence state, in the 4.18%. The voltage profile resultant of each simulation was normalized with relation to the voltage profile without increment in order to analyze the behavior of the buses.

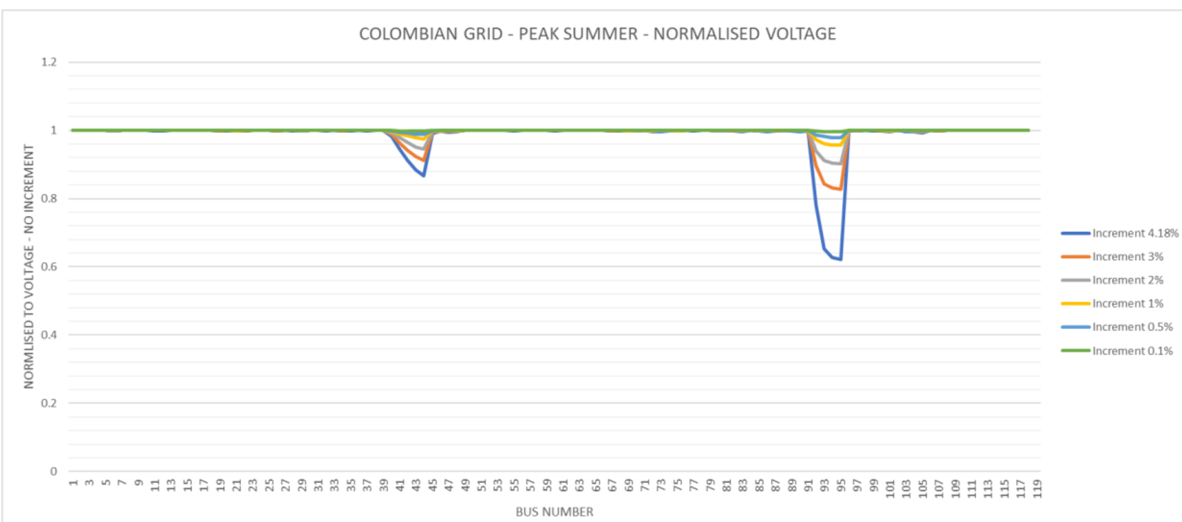
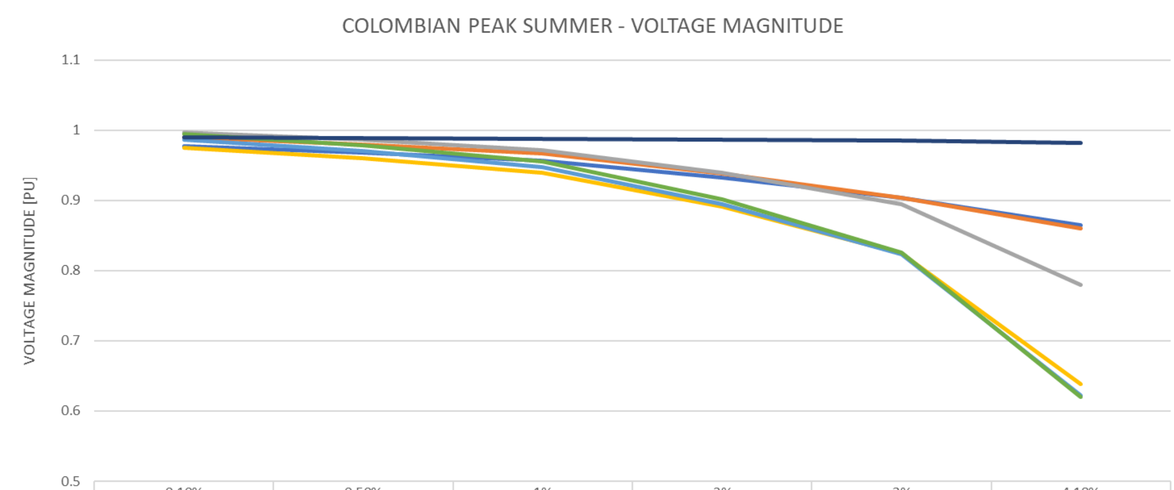


Figure. 81. Comparison of the voltage profile normalised in different load increments.

Analyzing the break of technical constraints referred to voltage magnitude, it is noticed that some buses of the system stays under the limit determined by the Colombian grid Resolution (0.9 p.u.), in the load increment of 2%. For the case of 1% of load increment, the most critical bus is the number 93 (Meta department) with 0.939 p.u. In the next simulation (2%), the value fell for 0.891. It is possible to see the behavior in the six buses in the six increments simulation in the Figure 82.



	0.10%	0.50%	1%	2%	3%	4.18%
43	0.977	0.968	0.957	0.932	0.904	0.865
44	0.99	0.98	0.967	0.938	0.904	0.86
92	0.997	0.986	0.972	0.939	0.895	0.78
93	0.975	0.96	0.939	0.891	0.824	0.638
94	0.987	0.97	0.948	0.895	0.823	0.622
95	0.995	0.978	0.955	0.901	0.826	0.62
105	0.99	0.989	0.988	0.987	0.985	0.982

Figure. 82. Voltage magnitude of the selected buses throughout the simulations.

Regarding the loading of the branches in the Colombian System, it was evaluated all the branches in progressive increments. In the Figure 83 it is depicted the branches and it is possible to notice that all of the branches stays below the line loading limit of 100% loaded. At 4.18% the higher loading are in the branches: 235 (1.06), 240 (0.82), 102 and 103 (0.78) and their location is presented in Figure 84 highlighted in the yellow circles.

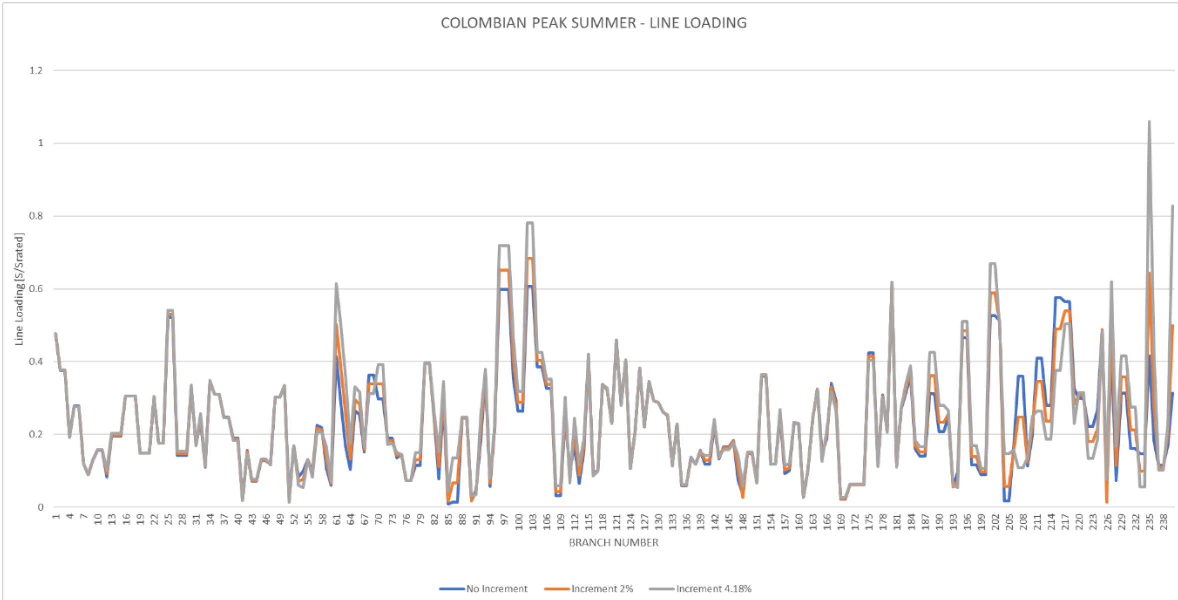


Figure. 83. Line loading according to the increment.

Figure. 84. Most loaded Branches in Colombian network.

For the reason of comparison, it was also performed the analysis of the line loading normalised with relation to the line loading case without increment. In this kind of analysis is possible to see the most sensible branches to the load increment. It is highlighted the buses and the respective growth at 4.18% of increment: 85 (4.94), 86 and 87 (9.76), 204 and 205 (8.35).

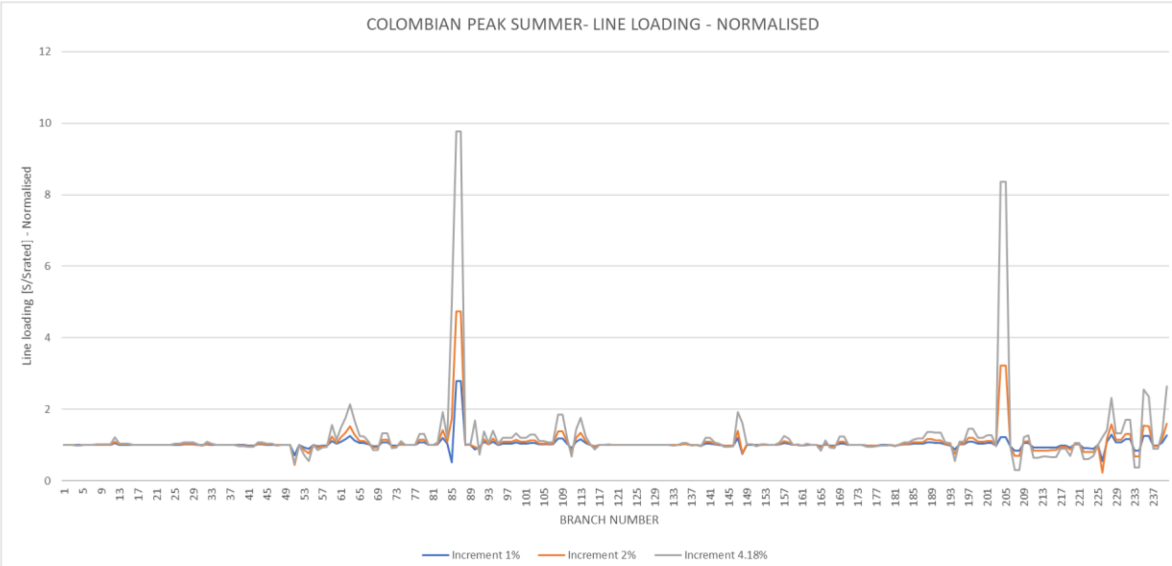


Figure. 85. Line loading according to the increment.

II. Results from Continued Load Increment based on Total Load

Now, as the load limits increment were found out by the simulations performed considering the most influent scenario, the idea is assume the Off-peak Summer scenario and evaluate how it behaves if the load increment is performed above the 4.18% limit of the summer peak scenario.

To perform this, it was used the MATPOWER routine *runcpf*, which is known as a continuation power flow. In this manner, the simulations were run initially with zero *Pd* and *Qd* for the analyzed buses: 43, 44, 92, 93, 94, 95 and 105. Then, it was performed the continuation power flow that gradually increases the loading on these buses and the results are displayed on the Table XXVIII.

The result is based on the maximum capacity of the network of converging the power flow, therefore the results are out of the technical limits based on the Grid Code. Even though it is an Off-peak summer case and out of the technical limits, the maximum load capacity in certain buses such as the 92 with 103 MW (even with 40.77 MW already in place), is a relevant information.

Bus Number	Max loading increment [%]	Total Load capacity [MW]
43	9.08	37.436
44	9.08	37.436
92	9.08	103.090
93	7.32	74.936
94	7.32	74.936
95	32.26	74.937
105	7.32	74.936

Table. XXVII. Maximum loading increment in percentage and real power.

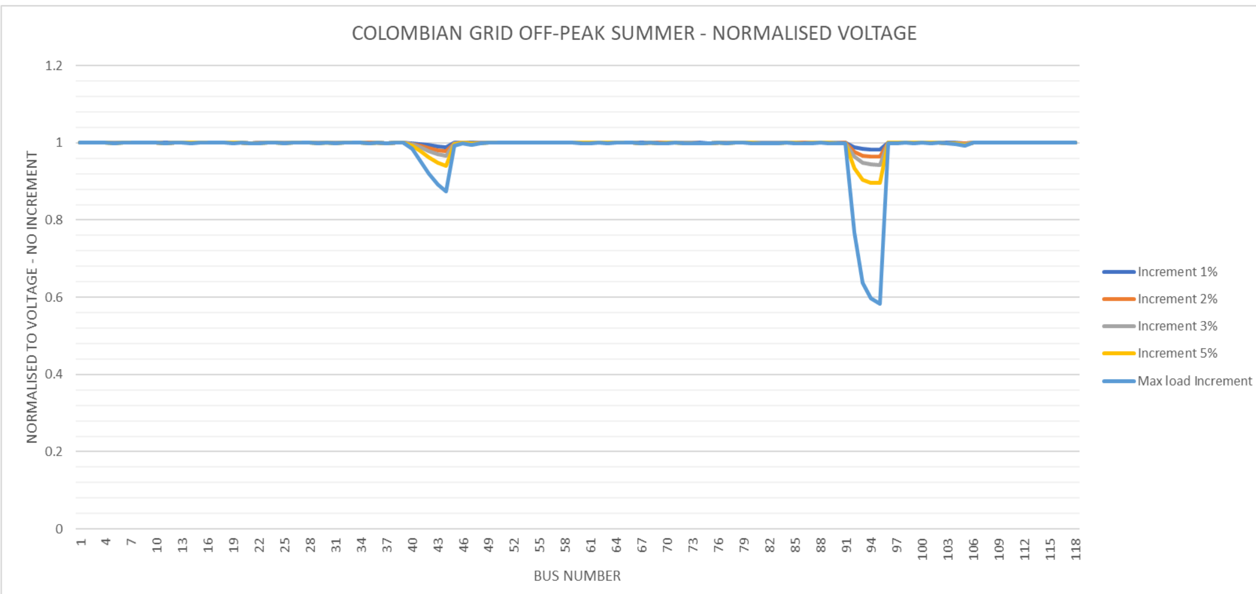


Figure. 86. Comparison of the voltage profile with different load increments.

In Figure 86 is given the voltage profile normalised with the non-incremental voltage case and it is possible to how deep the voltages fell in the maximum load increment scenario. A highlight is the bus 95 that reached the voltage magnitude of 0.582 p.u. Analyzing the loading behavior in the branches during the maximum load increment based on Figure 87, it is possible to notice that the loading in the branches remained perfectly under the limits even in the case of 5% of increment. In the situation of maximum loading increment, the only branch that stays above the limit is the branch 235 with 1.02 of loading. This branch connects the bus 79 to the 92, what is coherent considering that the 92 is the bus with the highest load capacity found out by the simulation and there is only one line connecting them.

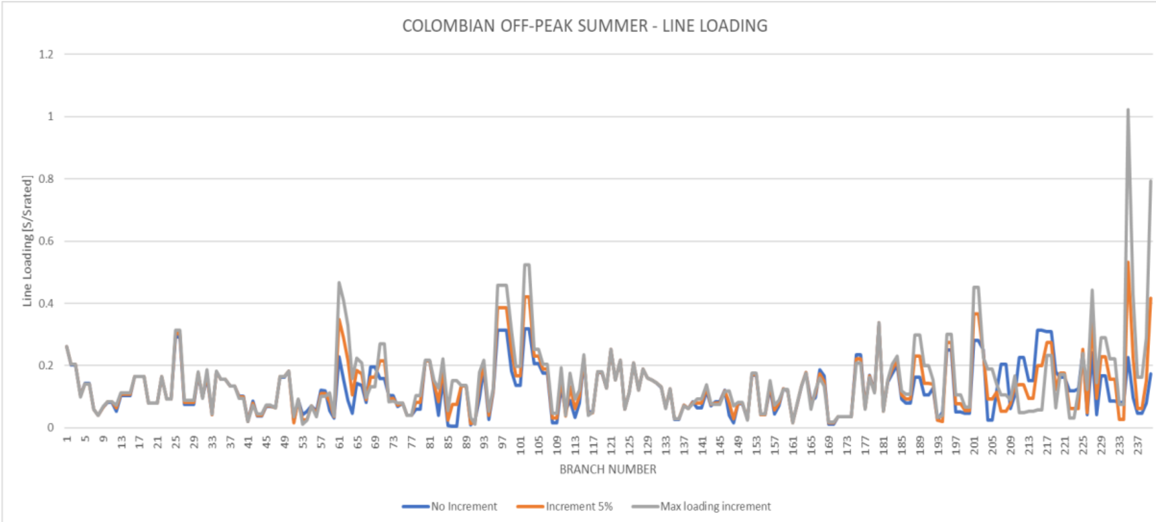


Figure. 87. Line loading according to the increment.

It is possible to see, both in the Brazilian and Colombian increment load cases that the network on those areas more distant of the main demand are not adapted to the load increment. In some cases, with tiny percentages of load increment it is enough to cause disturbs in the technical constraints of the systems. Solutions as transmission lines are not viable in many cases, due to the high costs involved on building on remote areas and also does not justify if the target load is not great enough.

Considering this kind of situation, a possible solution would be the deployment of micro grids on these remote areas. In some cases, if the micro grids are on a reasonable distance of the transmission line, the connection could bring advantages for both sides. The micro grid could assist the main grid, especially those radial transmission lines that suffer with small rise in the demand, providing power in certain hours of the day and benefit itself from the security and capability of a centralized system. Moreover, if the country has some instruments regarding ancillary services that permits micro grids to participate in the electricity market, it is possible to encourage more than technically but economically as well.

9.2. Micro grids design

9.2.1. Problem analysis

The simulation has the inputs described on previous chapter, in the input chart and parameters. The user who performs the simulation defines those inputs. On this simulation, most of the parameters are assumed as average or regular values from the market. Specifically, the data used to generate de secondary source power profile is extracted from real databases. On this section is going to be explained the values of the parameters used.

I. Assumptions

Most of the parameters are assumed with values obtained from the market or regular values used in the micro grids systems. Table. XXIX shows all the parameters assumed from the "input chart and parameters" section divided by each model with the value assumed and the unit. Below is the explanation for the values of each model.

Technical and economic assumptions

PoliNRG model	Parameter	Note	Value	Unit
batery	Charging efficiency	ηch	85,00	%
	Discharging efficiency	ηdish	90,00	%
	Minimum state of charge	SOC_MIN	40	%
	Maximum cycles	Cycle_max	8000	cycles
solar	BOS efficiency	DC	85	%
	PV cost per kW	Monocrystalline	1100	e/kWp
ss	SS cost per kW	Depending	0	e/kWp
Econ	Discount rate	r	7-8	%
	OeM	PV	20	e/kWp
	BOS fraction cost	coeffBOSel	0,2	%
	Loss of load target	LLP_targ	3	%
	Loss of load variation	LLP_var	0	%
	OeMSS	Depending	0	e/kWp
Inverter	Inverter efficiency	eff	90,0	%
	Inverter cost	Inv_cost	450	e/kWp
Parameters	Minimum PV	min_PV	0	kW
	Number PV	n_PV	3000	#
	Step PV	step_PV	1	kW
	Minimum Battery	min_B	0	kW
	Number Battery	n_B	3000	#
	Step Battery	step_B	1	kW
	Minimum SS	min_SS	0	kW
	Number SS	n_SS	30	#
	Step SS	step_SS	15	kW
	SS	SS	1	#

Table. XXVIII. Imperialistic algorithm input assumptions.

a. Battery

Even if the lithium batteries are the ones with the highest efficiency in the market with an affordable price. The process to store and supply energy involves reactions where energy is lost. The process is not uniform and that is why there are two parameters for this process. The charging efficiency is lower than the charging efficiency by 5% because the reaction used to store the energy requires a bigger amount of energy than the reaction to set free the energy. The values of 85% and 90% are usual values found in lithium batteries.

The state of charge of the lithium batteries again is one of the best. These batteries allow reaching a high level of discharge without deteriorating the cells in such way that the battery cannot recover. When the battery reach a level, where it is not possible to continue the chemical cycle to store and supply energy is called deep discharge. One value for the minimum state of charge in lithium batteries is 40%. This kind of battery are expensive but when the micro grids are going to be installed in a not interconnected zone is important to use robust equipment that supports difficult conditions and last in time. This because is not easy the transportation of the equipment to those zones and in the final cost would be more expensive to bring another kind of batteries than these ones.

The maximum cycles are the number of charge and discharge cycles that the battery can reach in the lifetime. This number depends on the use given to the battery, but manufacturers give an average number. The maximum number of cycles for the lithium battery can reach the 8000 cycles. This value is 4 times the lead-acid, three times the Ni-Cd and, two times the NaS technologies lifetime. This enforce the reason why is used lithium for the micro grids applications in not interconnected zones, the lifetime of these batteries is longer.

b. Photovoltaic

The BOS is the “balance of solar system” equipment. This equipment is compound by the elements that moves the energy on the DC part. The components include the conductors, the DC-DC converter, bars, etc… In addition, all those components have an efficiency associated to it. The converter usually has an efficiency of 90% and there is a loss of energy of 5% on the other components so the total BOS efficiency used is 85%.

The PV panels are sold in the monocrystalline form with a maximum peak value of 340-400 Wp. The PV panel cost more or less 0.5-1.3 €/Wp after the importing costs. For that reason, the cost used is 1100 €/kWp.

c. Secondary source

There are two-generation sources used on this simulation. The wind generation differs on the price mainly based on the structure that handles the turbine. The hydro generation has been used for a longer time so the prices are more stable than the wind ones. The cost per kW used on this simulation will be justified based on the location of the micro grids.

The locations selected to install the micro grids are zones that fulfills three conditions. The conditions are the absence of the transmission grid, the need of the energy and the feasibility of the installation. The first one, the absence of the transmission grid condition is because the main power plants on both countries produce energy at a very low cost, and the micro grids using technologies that are more expensive cannot compete with the price of the big generators. The absence of the main transmission grid make that the cost of the micro grid, compared with the building of the infrastructure necessary to bring the transmission network to the non-interconnected zones, cheaper for the short and medium term. The second one, the need of the energy is the population in need of the energy. As it is mentioned, the energy service is seen as a right and the states looks for the energization for all the population. The dispersion of the population and the geographical conditions of the zones makes very difficult to bring the energy to some places, there is where micro grids can provide a solution with a reasonable investment cost to fulfill the energization growth proponed by the governments. The third one is the feasibility of the project, if the micro grid for the conditions of the zone has no natural resources (low wind flow, no rivers or low radiation) the feasibility of the micro grid is compromised. Thus, there can be other problems not related to the technical or economic issues. Some of these problems are zones with environmental protection, zones with security problems, zones where the indigenous population refuse to receive the micro grids, etc.

The places selected in Colombia and Brazil to receive the micro grids comply on the three requirements previously mentioned. The place in Colombia selected is Orinoquia, a region where there is a lot of population available to receive energy. The region selected in Brazil is Mato Grosso, which is not an industrialized zone, and because of this, the micro grids can bring solutions to the energization goals in Brazil. Both regions comply with the three requirements stablished to install the micro grid.

The geographical zones selected to install the micro grid have good hydraulic and wind resources. The wind farm installed will be on shore, and the cost for the on-shore wind turbines, with specific plant cost is in the interval of 1500 to 2000 €/kWp. For new renewable technologies PV and wind on shore are the less expensive.

For hydropower plat there is a study analysis performed where many turbines in the market are the sample to build a graph show in Figure. 88. On this graph is shown a regression that can be used to calculate the price for any power selected. The price decrease while the power increase. For the range of power used in the simulation a good value per kilowatt is 3500 €/kW.

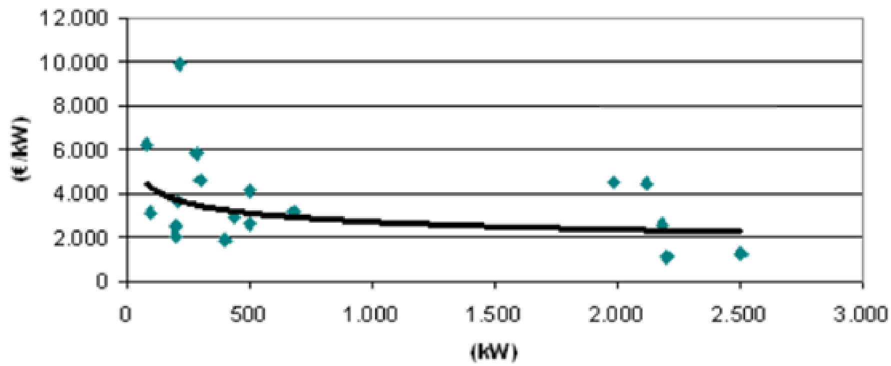


Figure. 88. Hydropower plant price versus power.

d. Economic parameters

There are other economic parameters associated with the cost in the generation and BESS models. However, this model groups all the other economic variables. The discount rate has been chosen as 7% for Colombia and 8% for Brazil, which is a value close to the discount rates of both countries on the las 8 years. The operation and management cost of the PV consist on the maintenance of the equipment and has been assumed as 20€/kW/y. The cost associated to the BOS is a 20% of the total PV system. The target of the loss of load has been set as a 3%, which is a good value for micro grids with residential or productive zones.

The operation and maintenance costs are related to the insurances, the maintenance of the equipment, reparation and replacement of some part of the system, and the administration of the systems. Hydro and wind power plants cannot be operated as independent as the PV systems. Is important to perform regular maintenance and to administrate the operation of the plants. For this reason, the operation and management value for both technologies are higher than PV value.

For on shore wind power plants the O&M cost is 30 €/kWp and for micro hydro power plant the cost is 22€/kWp. The cost can vary depending on the zone, the local conditions but this is a good forecast for the maintenance of wind and hydro power plants.

e. Inverter

The inverter cost has been selected as the average value per kWp of a group of inverters from the marks Proinso, Victron and Acacia, which are three of the main sellers on both countries. The average price is 450€/kW. The efficiency of most of the inverters is 90%, some of them have a higher efficiency but the usual value is 90% so the parameter has been set to this value.

f. Parameters

The research space is completely defined by the user of the software. The values of the research space such as the minimum, the number of intervals and the step of the intervals is selected based on the simulations performed to validate the algorithm. These values must be changed depending on the amount of energy needed to supply the load. The values of PV and BESS have a smaller step because it is easier to configure them than find in the market any value for wind or hydro generation.

The PV system will be evaluated from 0-3000 kW. The optimum point is below 1000 kW according to the validation. The battery energy storage system is in the interval 0-3000kWh of capacity. The optimum again is lower than the PV-BESS simulation, and below 1000kWh of capacity. The secondary source power is in the interval 0-500kW for wind and from zero to the maximum capacity of the river in hydro generation. The optimum point is around 225 kW, so all the research spaces are big enough to find a point close to the optimum.

g. Input load curve

The input load curve has been generated with the tool LoadProGen. With this program is possible to determine in a stochastic way, the behavior of loads for residential use. With this program is possible to simulate from a small environment with few equipment, until a whole community. Figure. 87 shows the average load profile for each day of the first year of simulation. The following years have a growth scaled by a constant factor of 0.2.

The input power profile has 1440 values for each day (time step of minutes). It is assumed that in the interval of one minute the load will not change. For this reason, the energy consumed is calculated as the value of power for each step divided by 60. With this energy calculated for each minute is calculated the average energy consumed shown in Figure. 87. The maximum power consumed is 228kW and the minimum is 52.54kW.

The micro grid is designed for a residential use. Figure. 89 also shows the daily profile, where is seen that the power consumed is changing on time. The consumption is low during early morning hours, increases with the sunrise, and then there is a peak on the night. This profile is typical of residential users. Since the micro grid is dimensioned for many residential users, the shape of the input curve is adequate for the purpose of the simulation.

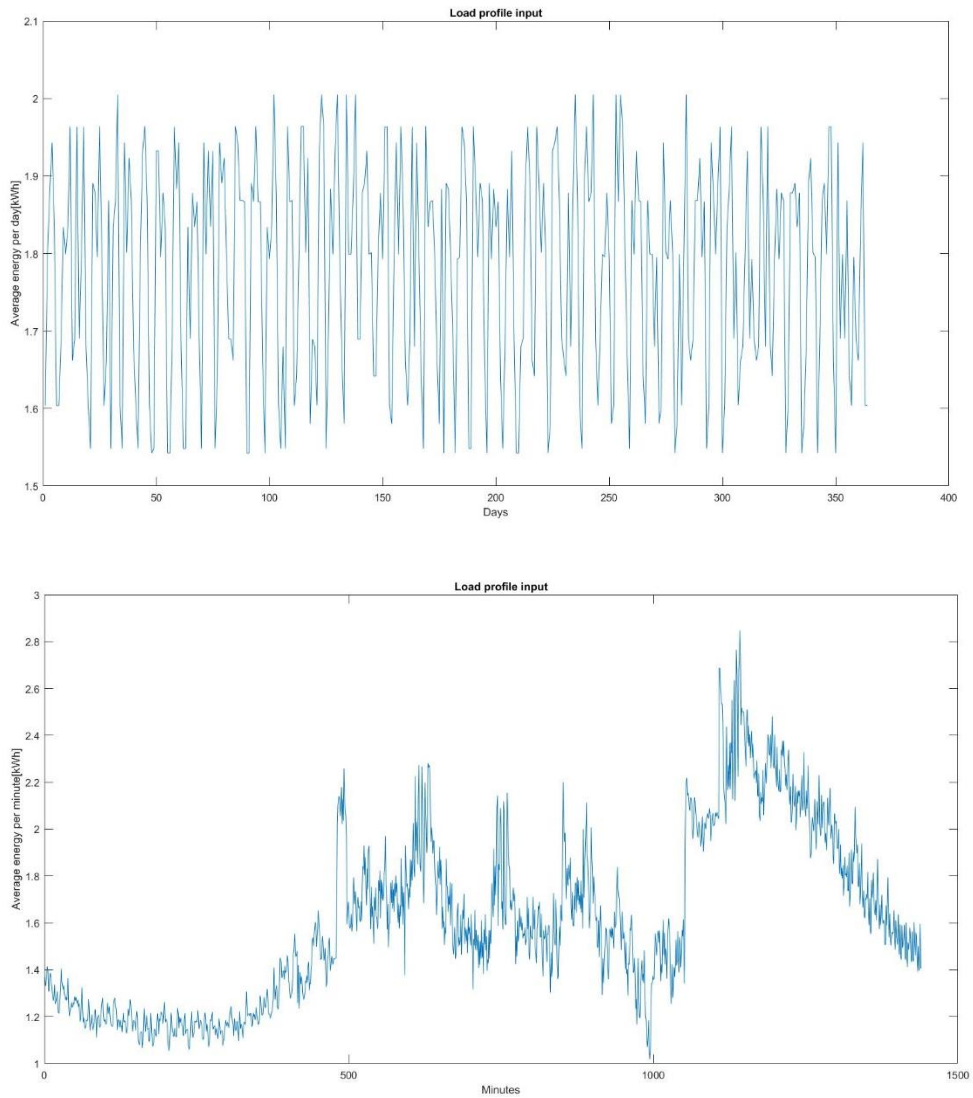


Figure. 89. Average energy consumption for the micro grid design on one day and year.

II. Data sources

The simulations were performed with four sets of data. Two for the wind flow and two for the rivers in the regions of Orinoquia and Mato Grosso. The data origin and validation is important because it is not easy to find valid data in order to perform better simulations. Because of this, the validation of the data is a critical task in order to have results that are more accurate.

a. Wind profile in Colombia

The wind flows data from the "Orinoquia region" has been extracted from [46]. In this thesis work, is performed a deep analysis of the weather stations' data sets of the region. As the thesis is focused on the specific model used for this research, the parameters calculated on that thesis can be used as the input parameters of the code.

The thesis previously mentioned take the data measurements of weather stations at a height of 30m. The region is big, but the geographical zone is characterized for being planes. Ate the end of the study the research thesis concludes that there is the same flow wind current in most of the stations, but the parameters "K" and "c" of the model are affected by the proximity of the "Andes" mountain range. For this reason, depending on the specific location it would be right to search on this thesis for the exact parameter.

For the simulations performed on this job, the values have been selected for most of the territory of the region with a c parameter equal to 5 and a k parameter equal to 11. This region has a great amount of wind flow coming from the Venezuelan gulf in Caribbean Sea. Figure. 90 shows the wind distribution profile of the samples generated for one year with the parameters mentioned above.

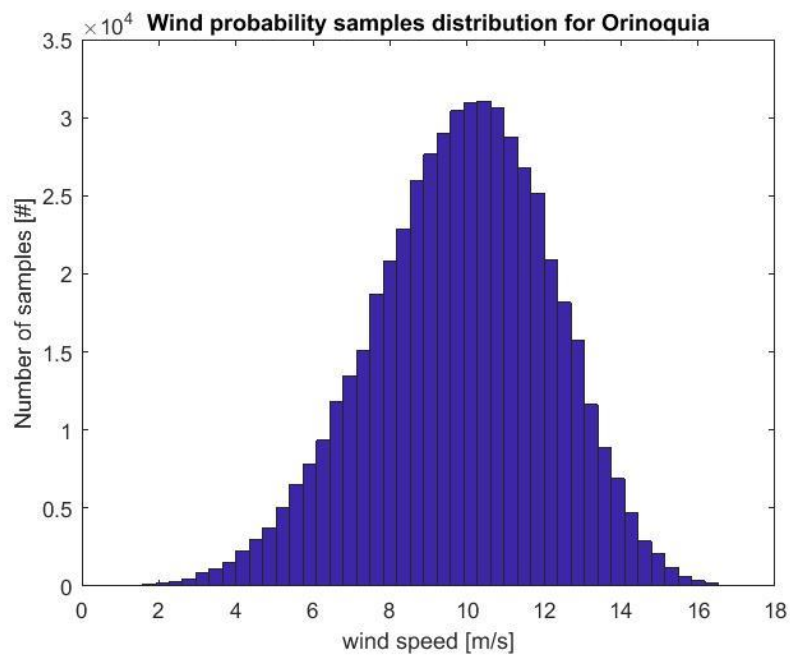


Figure. 90. Wind data profile distribution of 1 year in Orinoquia.

b. Wind profile in Brazil

The institution "Kaggle" provides on their page the dataset of the measurements done in the weather stations of the country per year, with a time step of hours also divided by regions since Brazil is a very big country and the data of all the country would result in a not manageable dataset. The data set selected for Mato Grosso is named "sudeste.csv". On this file, the 27th column gives the hourly speed of the wind in meters per second. This database and many others can be found in the web address https://www.kaggle.com/PROPPG-PPG/hourly-weather-surface-brazil-southeast-region [47].

The amount of wind available on this region is lower than the one available in Orinoquia region. Nevertheless, the amount is enough to run a wind farm with a competitive price for the micro grid as it will be seen in the next sections. Figure. 91 shows the representation of the wind measurements of one weather station on the region for the time window from the 19 of December of 2012 at 0:00, until 15 of September of 2015 at 14:00.

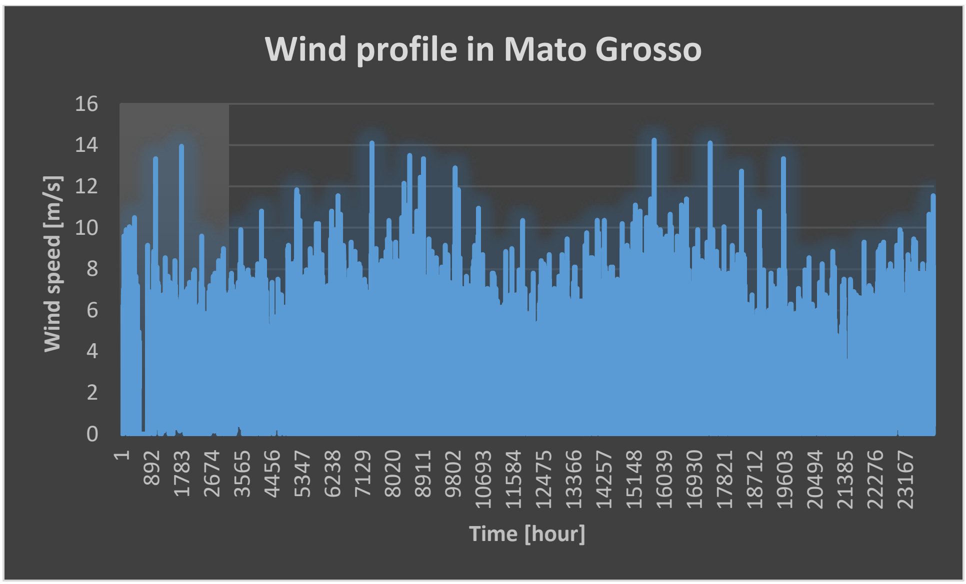


Figure. 91. Wind data profile of Mato Grosso.

c. Hydro profile in Colombia

For the hydro profile in Colombia there is a foundation dedicated to perform hydrological studies named "SIMA". This foundation has a big amount of databases related to the rivers in Colombia. In the official page can be found data about the caudal of the rivers measured in different point of the river, also if there is any kind of micro hydro installed there are data sets of the caudal turbinated from 1991 until now, there are flood flow data, overflow rates, and much more data. All this information can be found in the web address http://www.sima-magdalena.co/search/type/dataset?query=caudal&sort_by=changed&sort_order=DES.

Figure. 92 shows the average caudal from the river in Orinoquia per each month, from January 2004 until September 2014. This was the sample used to generate the missing samples needed to calculate the caudal per each minute in the code using the existing values as the mean and the standard deviation in the values of the moth.

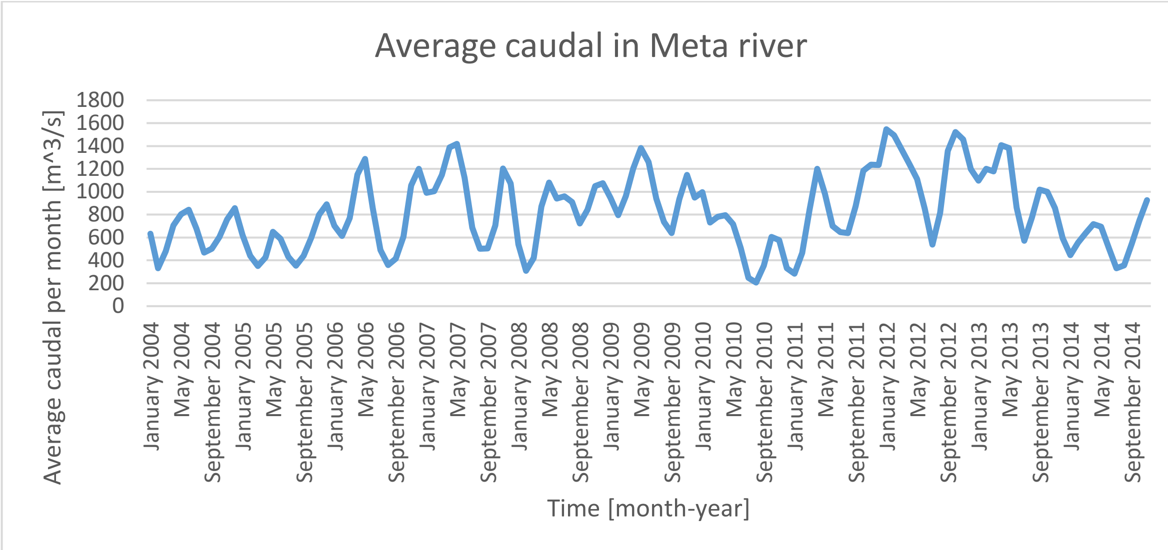


Figure. 92. Hydro data profile of Orinoquia River.

d. Hydro profile in Brazil

For the caudal data in the region of Mato Grosso there is a tool in the web page datahub, called "Brazil open data" which the government of Brazil use in order to show public data and to interact with social agents. With this tool is possible to access to hydrologic resources data sets and there is a list of rivers with measurement stations.

In that list is the Taquari River, this river belongs to the region of Mato Grosso and lies to the Parana region. The data has an hourly measurement and the average per month is shown on the Figure. 93.

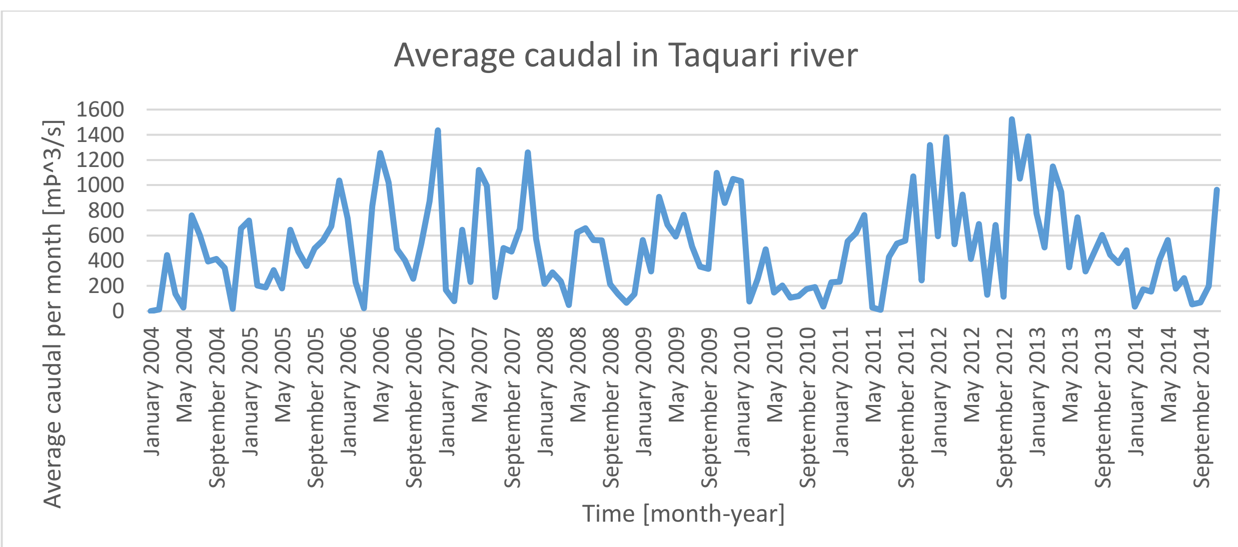


Figure. 93. Hydro data profile of Taquari River.

9.2.2. Optimum search

Before showing the result obtained with the software, it is important to show the behavior how the algorithm finds the optimum. The following figures show the behavior of the empires (8 empires per each simulation). In order to perform the analysis, the plots are divided in 2D-plots where is possible to make an analysis of the samples evaluated by the algorithm.

It is appropiate to mention again that the empires evaluate the LLP restriction before selecting a PV-BESS-SS combination. Once the empires are selected the colonies are evaluated in order to find if a colony is better than the empire, in that case, the empire is replaced. Once the empire is stable, the colonies start looking for a better combination in the surrounding space of the empire.

I. Wind simulation

The wind simulation throw the following empires at the end of the simulation. Figure. 94 shows the BESS-PV plane of the empires. It shows that six of the eight empires lies to the zone where the optimum is located. There are two empires that diverge on the search, but that is why there are multiple empires contemplated. In addition, it is possible to see that the values of the empires has a linear movement before arriving to the "stabilization point". The so-called stabilization point is the value where the algorithm stops moving around the research space and starts looking and spreading around a good combination.

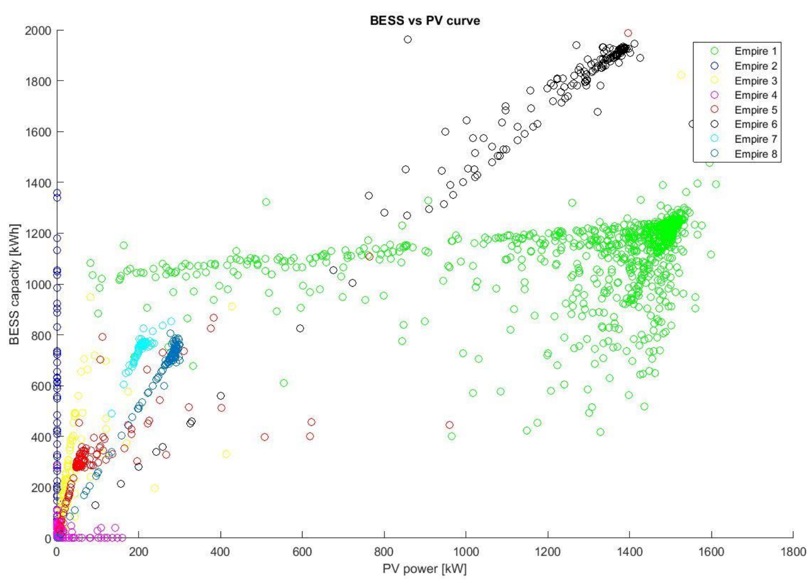


Figure. 94. Empire behavior for wind simulation BESS-PV plane.

Figure. 95 shows the SS-BESS plane. From this plane is possible to observe that the search starts on the 0,0,0 point, which has been forced by the initialization settings, and moves linearly (each empire in one direction), again when the search finds a good combination it stops moving and tarts searching in the space close to this point. From this graph is possible to see that empire 1 searches PV-SS combinations without BESS, and PV-BESS combinations without SS.

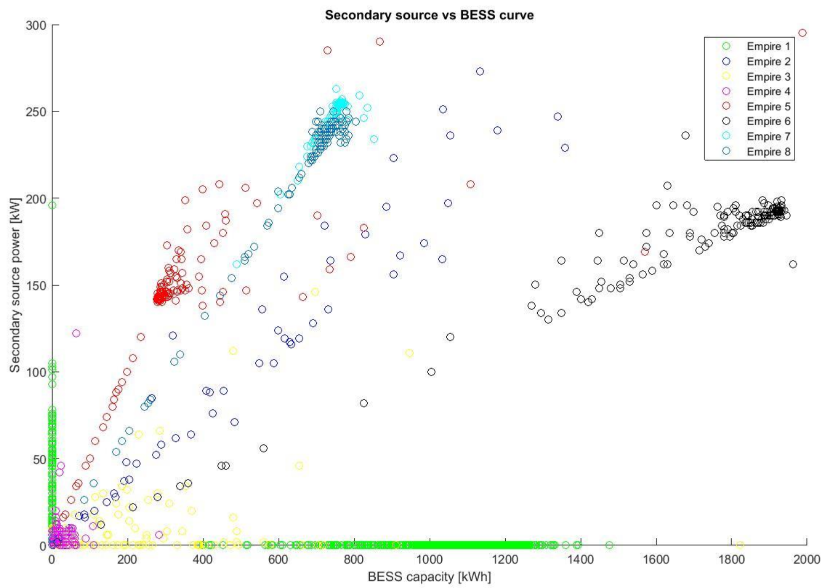


Figure. 95. Empire behavior for wind simulation SS-BESS plane.

Figure. 96 shows the SS-PV plane of the empires. This figure corroborate the linear movement of the combinations selected and the searching around optimum points found on this linear path. Here is possible to see the premise exposed in the previous plot, the search of PV-SS and PV-BESS.

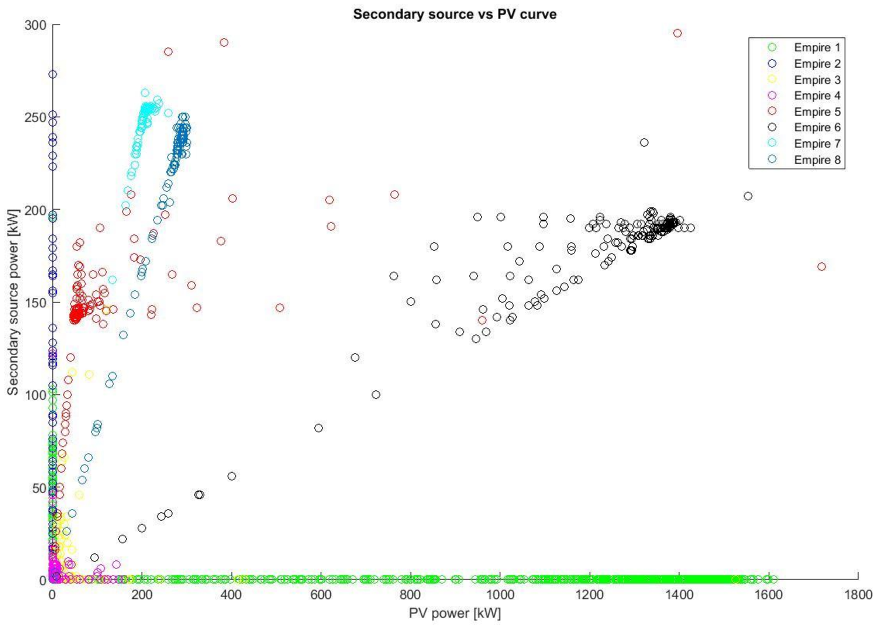


Figure. 96. Empire behavior for wind simulation SS-PV plane.

Figure. 97 shows a dissagregated plot of each empire for the three planes where is possible to see more in detailed the situations mentioned above. Empire two looks only SS-BESS combinations, Empire one looks for PV-SS and PV-BESS combinations and all the others have a 3D-search. Six out of eight empires find “stable points” in the closeness of the optimum point.

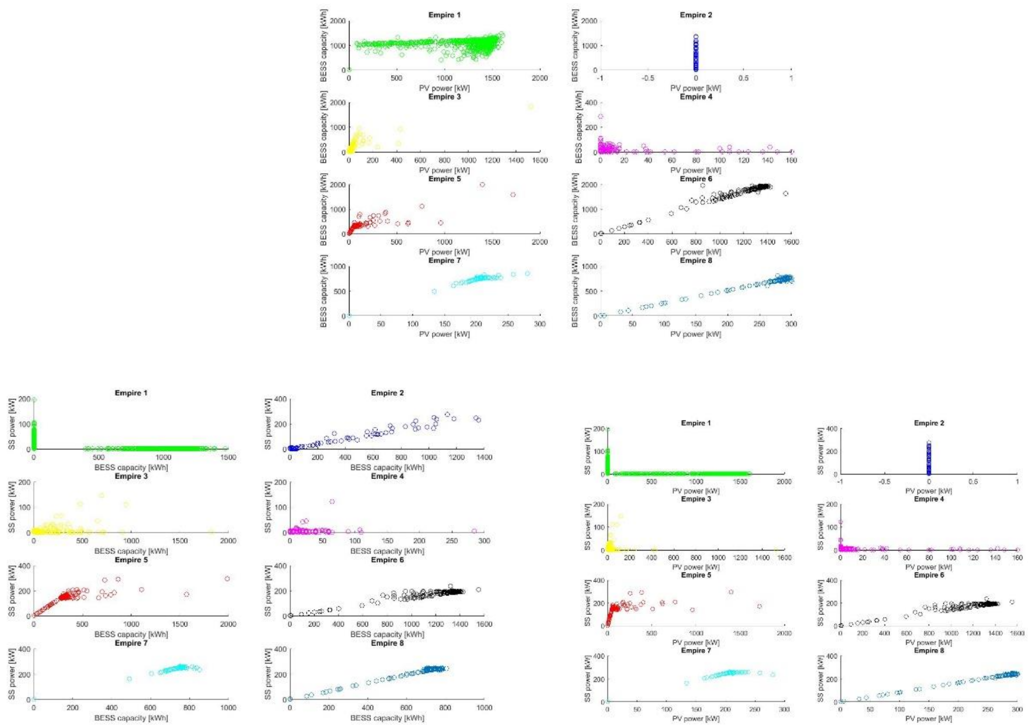


Figure. 97. Empire behavior for wind simulation disaggregated.

II. Hydro simulation

The hydro simulation has a big difference on the research space of the secondary source. Figure. 98 shows the BESS-PV plane for the hydro simulation. Since the research space on the SS axe is bigger, the distribution of the points are more grouped on the PV-BESS plane. On this case, a scenario that could not be seen in the wind simulation is observed, the empire one reached the stable point very fast and that is why there is no “path” to the cluster. On the other empires is still possible to distinguish the path. Empire two shows a divergence of the empire example. The empire two did not reach any stable point and there were many combinations with a diminution of the NPC and that is why the combination point start to move on many directions. All the other empires focused a region where stable points with low NPC were found.

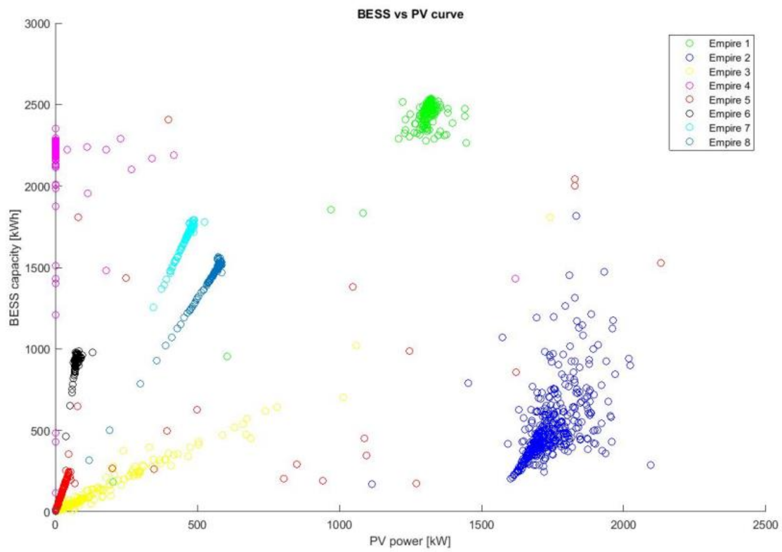


Figure. 98. Empire behavior for hydro simulation BESS-PV plane.

Figure. 99 shows the SS-BESS plane where it is seen that most of the samples are located at low values of the SS power, this is because on this scenario the mximum power of the secondary source was the maximum power available on the river. Since the load does not need that big amount of energy the best points are located at a very low value in the SS axe. It is notice also, that when the secondary source power goes really up this source supply all the load, this does not need any BESS but the price is too high.

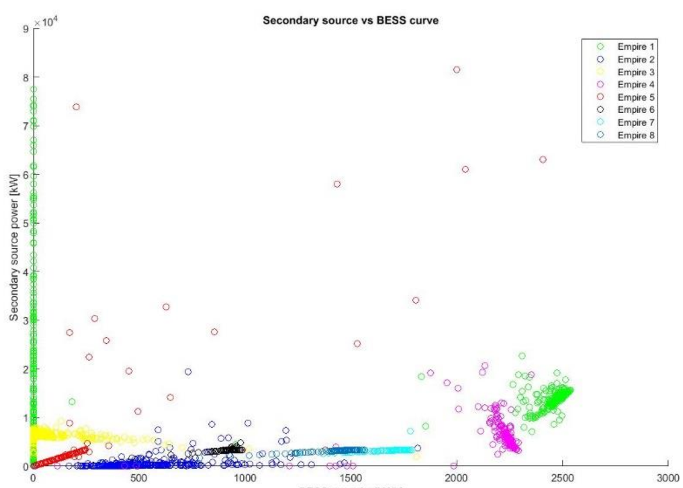


Figure. 99. Empire behavior for hydro simulation SS-BESS plane.

Figure. 100 shows the SS-PV plane of the hydro simulation. Once again, when the power of the secondary source is too big there is no need of PV, so mixing the result of the previous graph and this one, Empire one has researched only on the SS axe and has been able to find that the river can cover the demand but the price is too high for being competitive with PV at this scale of power. Hydro power plants are weight more competitive at high power rates, that explains the existence of PV on this simulation results. Empire two, different from empire one reached very low levels of the hydro generation and searched on the high values of PV-BESS plane.

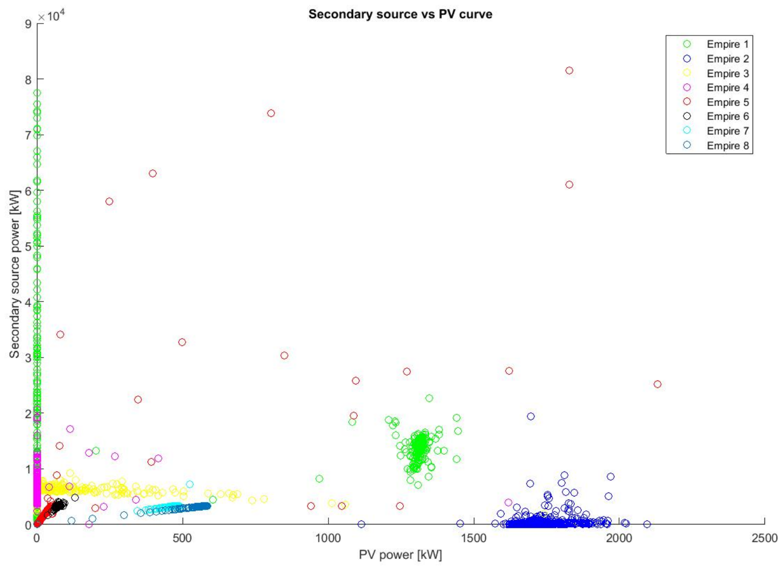


Figure. 100. Empire behavior for hydro simulation SS-PV plane.

Figure. 101 shows the disagregation of the previous graphs per empire. This disagregation allows to better observe in colors the search for each one of the empires. There can be some linear searches over all the planes, divergent empires, fast converging empires, etc.

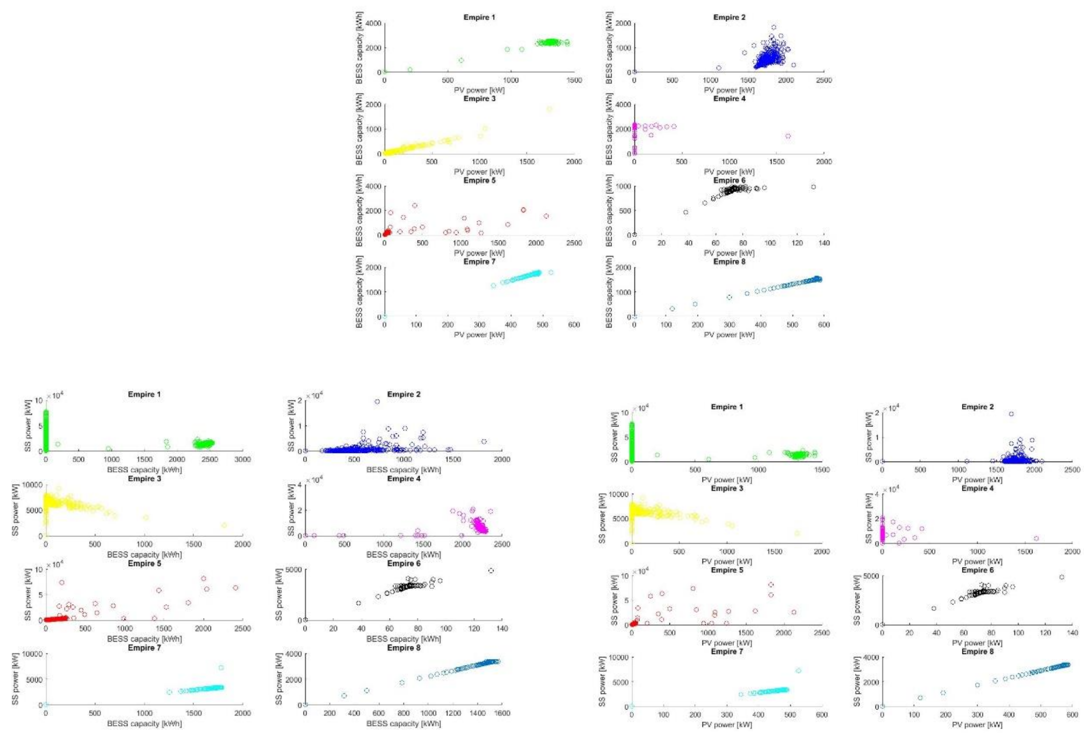


Figure. 101. Empire behavior for hydro simulation disaggregated.

9.2.3. Micro grid dimension

The result of the software as it has been mentioned before is a matrix with the optimum results (Table XXX). These results have been obtain from a set of 6-10 simulations load evolutions per each scenario. Then, the best performance has been selected to represent the closes point to the minimum NPC found to supply the load.

Result summary

Scenario	Secondary source	Best scenario					
		PV [kW]	BESS [kWh]	SS [kW]	NPC [€]	LLP [%]	LCoE [€/kWh]
Colombia	Wind	142	125	225	$ 1.546.500	0,1170%	0,1571
Colombia	Hydro	225	48	125	$ 1.015.872	0,0814%	0,1002
Brazil	Wind	150	121	227	$ 1.549.900	0,1106%	0,1615
Brazil	Hydro	249	54	100	$ 1.022.474	0,06155	0,1015

Table. XXIX. Micro grids sizing results.

The first result that is important to analyze is the objective function and the restriction of the algorithm. The net present cost (NPC) is 52% lower when the hydro technology is used. Still in both simulation the PV is presents, this is because the cost of the

PV is lower at this scale, but the energy is only produced during the day, the hydro plant basically reduces the capacity needed for the storage system which cost is very high. Reducing the storage system even when the PV is increased, the NPC is reduced in a big value. The loss of load probability parameter was set up at 3%. All the optimum values obtained with these simulations fulfill the restriction. So, it is possible to tell that the simulation throw the lowest value of NPC found fulfilling the LLP condition, and this optimum configuration is close to the global minimum since the convergence is measured with the variation in the net present cost.

Analyzing the combinations obtained for the micro grids is possible to see two trending. The first one is that the wind profile of the locations is not the best for wind generation, for this reason there is necessary to have a bigger amount of power generating wind power. The wind profile in Mato Grosso variates more than the wind profile in Orinoquia, which is why the wind power plant is bigger in Brazil's simulation and also the BESS. Mato Grosso is also close to the tropics where there are times of the year when the radiation is low, while the radiation in the Orinoquia (Ecuador line) is very good all the time. This also increases the size of the PV. All the factors previously mentioned increase the cost of the micro grid.

From the hydro simulation the battery energy storage system is lower than the wind simulation. This is because the caudal of the river over the time is capable to manage the complete load. The system is not pure hydro because the price of hydro is more expensive than the price of PV, so during the day is cheaper to generate with solar energy and during the night generate using the river, this reduces the size of the hydro generator at the same time that reduces the energy storage system. The storage system is more expensive than the hydro generator, for this reason it is better to supply using the river than batteries. The existing BESS is because the rivers also have variability and there are dry seasons when the river cannot supply all the load. Because of this there is necessary the presence of storage systems that supply the load in extreme conditions. Still the size of the storage is low compared with the wind simulation and the net present cost of the complete system is lower than PV-BESS-WIND system.

The PV power has increased, this is because the price of hydro compared with the price of photovoltaic energy is more than twice. For this reason, is cheaper to generate energy with PV. Once again, the system is not fully PV because the sun is only available during the day and the storage system to supply the load is more expensive. The combination shown in the results table is the equilibrium where some energy is generated with PV and for the peaks or the night hours there is a hydro generator capable to supply the load. This configuration says that more hydro would be more expensive because it is the most expensive generation source on the simulations. In addition, more storage system would increase the cost because it would be oversized for most of the time.

An analysis than cannot be seen on the results table is that PV-BESS makes the storage system to work all the days charging during the day and discharging during the night. The configuration with an alternative generation reduces the BESS effort because during the night there is a generator that supports the load. This can increase the lifetime of the BESS but it is also important to stablish a control that keeps working the storage system even in the time intervals where the load can be supplied by the PV-HYDRO generators all the time. If the BESS stops working for a long time, it can stop functioning, especially given the weather conditions where the micro grids would be installed (High temperature and humidity).

The levelized cost of energy is lower in the hydro simulations. This is because the variability of the wind is higher than the caudal of the river, for this reason the size of the battery energy storage system is higher and, it increases the cost making the energy more expensive. The hydro configuration reduces the storage, since the energy load is the same for all the scenarios, the storage only shift the energy consumption (even increases the losses). If the storage system is reduced it means that the energy is being consumed when it is generated and it is not necessary to shift the energy consumption. This reduces the losses produced by the charging and discharging process and reduce the final cost of the system.

Figure. 102 shows the levelized cost of energy of different technologies and then the LCoE of the micro grids designed with the tool. The levelized cost of energy of the technologies exposed are for interconnected applications, this means that the energy generated is supplied in that moment. The LCoE of the micro grids designed is very good taking into account that the system is designed for isolated systems. Off course is more expensive than the energy on the market but the cost is still on the same scale than the other technologies.
PV-BESS-H systems provide not only a lower investment cost but also a better LCoE value. The LCoE for micro grids with hydro technologies with these caudal conditions competes with the cost of the coal and nuclear.

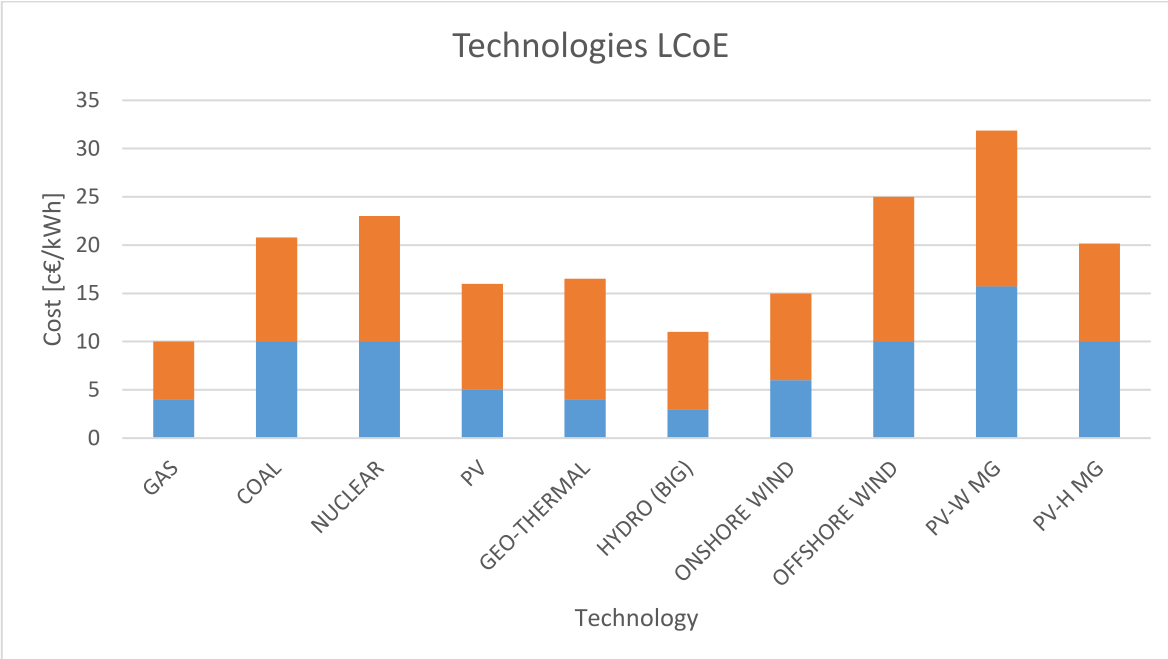


Figure. 102. Levelized cost of energy comparison.

9.3. Results comparison

9.3.1. LCOE Comparison

In order to evaluate the different alternatives to provide energy to remote areas of a country, there are innumerous factors that could be taken into account in order to elect the best alternative. One of the most important is the economic factor, especially because these kinds of responsibilities are managed by the public sector that develop studies in order to promote the best mutual economic and technical choice.
In this work it was performed the design of micro grids, in which it was also contemplated the calculation of the LCOE varying according to the location, source and design configuration.

At the same time, it was performed the load increment in the most distant regions that the Interconnected Systems cover, analyzing the effect and impact of different increment sizes in the technical constraints of the main systems. As an alternative solution for the poor performance of certain buses located on peripheral parts of the grid, especially on radial topology transmission lines, a transmission line was inserted with the target to bring more stability to the problematic buses. Assuming the incremental load capacity brought with the insertion of the transmission line, it was then proposed the calculation of a sort of LCOE, which is based on the total investment regarding a transmission line construction and the energy that is possible to transfer.

For an effect of simple and straightforward comparison, the LCOE for the four Micro grids scenarios (2 in Brazil and 2 in Colombia), varies from the cheapest one of 100.20 €/MWh (Colombia-Hydro) to the most expensive 161.50 € /MWh (Brazil-Wind). In the case of the transmission line insertion, the total of the investment of the case presented was 106,374,685.70 € and the Company Cost of Capital (WACC) of 8%. Considering the total of yearly transferred energy without breaking any technical constraint, is 1,051,729.9 MWh, providing the LCOE equal to 8.09 € /MWh.

The enormous difference is related to the different proposals that each kind of project has as the target. Theoretically, big projects as transmission lines are planned to feed continuously big demands and to cover big areas, considering the ramification with the distribution systems. Therefore, normally the projects has a high initial investment cost. On the other side, there are scattered communities throughout isolated regions, in which considering the small demand and the large distances that should be covered, does not values the huge investment. Therefore, the micro grids are the best solution. Even, with a higher LCOE it compensates when it is compared the total investment and size of the demand that will be covered. The transmission line solution will only be feasible, among other factors, if a certain demand is reached in order to justify the amount invested.

9.3.2. Investment cost

The investment cost of transmission line is much more expensive than the investment cost of a micro grid. The net present cost for a transmission line of 613 km is 106,374,685€, this transmission line brings an extra capacity of at least 120MW of energy constantly, without any technical intervention that could bring more capacity. The net present cost of the micro grids dimensioned is between 1 and 1.5 million euros. The power supplied by the micro grid is around 400kW. The scale of the micro grid and the scale of the transmission line are completely different. The investment cost is an important variable even when the levelized cost of energy of transmission lines is cheaper than the one for micro grids.

The transmission lines are built to transport high amounts of energy, while the micro grid is dimensioned to supply the necessary energy for a community or facility. The energy demanded by the not interconnected zones is not concentrated geographically. For this reason, building a line for disperse population need a very high investment, and bring energy to not many people. The building of a transmission line for few people would rise the LCoE of the line because even if is capable to transport high amounts of energy, the use given to it would be very low. These situations when the population is dispersed the low investment cost of micro grids, comparatively speaking with the investment of transmission lines, makes feasible the construction of these kind of system with a higher LCoE.

When the population is grouped in a geographical zone, and the zone is close to the existing infrastructure it is possible to build transmission lines. The transmission lines cost depends on the length of it, so if the target community is close to the existing infrastructure the investment cost would be reasonable and the energy price would be lower than the energy price of micro grids. The transmission lines come with many advantages, like more stability, the quality of the energy is regulated and the investment cost is paid when the energy is consumed as a portion of the tariff. The micro grids stability is very sensitive, the quality of the energy regulation is incomplete, and the payment of the investment cost is done at the beginning since the natural resources are free, this payment for some communities is a big shock. That is why the governments comes to incentivize or subsidize the renewable energies and the micro grids.

Some communities argue that if they receive the micro grid they are not going to be beneficiaries of the transmission projects so they prefer not to accept the micro grids. Once the micro grids are built, the connection of transmission lines to those micro grids can benefit not only the community bringing them energy at a lower cost, but also the main grid can benefit.

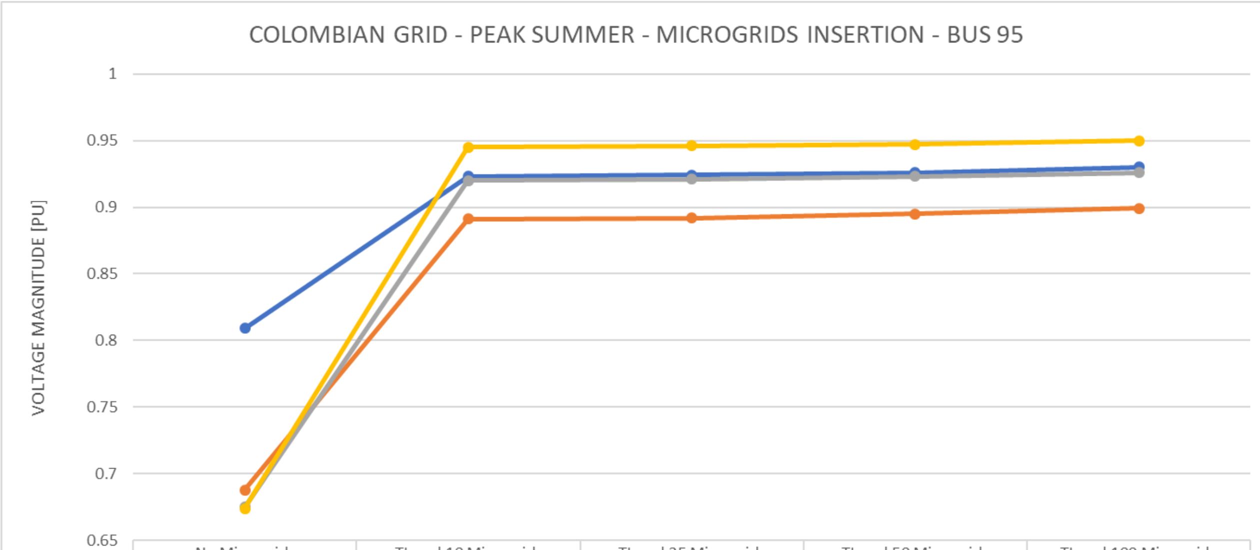
The micro grids are located in the periphery of the main electrical network, so the buses that would be connected are the further buses. Connecting them to micro grids would convert those systems in dispersed generators. Those generators can support the voltage profile, can reduce losses, reactive energy support and all the benefits of dispersed generators. Thus, building lines between the existing system and micro grids benefits the main grid, reducing other possible reinforcement investments such as new lines, bank of capacitors, storage systems, etc.

9.3.3. Micro grids Insertion

I. Colombian Network – Cluster of Micro grids – Insertion on the bus 95

The idea was perform progressive increments on the size of the clusters, and evaluate the results in the main grid. The clusters sizes were 10, 25, 50 and 100 micro grids. The technical constraints considered were the voltage magnitude in the steady-state regime and the line loading.

In the first simulation, the bus 95 (Rubiales) was connected to the bus representing the cluster of micro grids. Even a cluster of micro grids does not cause big impact on the main grid, in this way it was evaluated only the buses that the micro grids were connected and the nearby buses that had the load increment in the previous simulation. In Figure 103, it is possible to see the voltage profile of the buses 92, 93, 94 and 95. The first simulation is related to the absence of micro grids and the load increment of 4% in the Colombian Peak Summer scenario, which shows the considerable poor voltage performance due to the demand rise. Connecting the bus that represents the cluster of micro grids rises automatically the voltage to reasonable values. The most problematic bus is the bus 95 that step up from 0.674 p.u. to 0.945 p.u. with the connection with cluster of 10 micro grids. The other buses considered had similar behavior, however, in smaller amplitude.



	No Microgrids	TL and 10 Microgrids	TL and 25 Microgrids	TL and 50 Microgrids	TL and 100 Microgrids
Bus 92	0.809	0.923	0.924	0.926	0.93
Bus 93	0.688	0.891	0.892	0.895	0.899
Bus 94	0.675	0.92	0.921	0.923	0.926
Bus 95	0.674	0.945	0.946	0.947	0.95

Figure. 103. Voltage profile with the insertion of micro grids clusters.

Considering more properly the micro grid insertion, it is possible to note that the voltage rises only slightly with the progressive increment of the number of micro grids in the cluster. In Figure 104 is shown in more details the rise of the voltages due to the cluster size growth. Nevertheless, even being 100 micro grids in the last case, the maximum power available is around 27 MW, which is few considering the main network size.

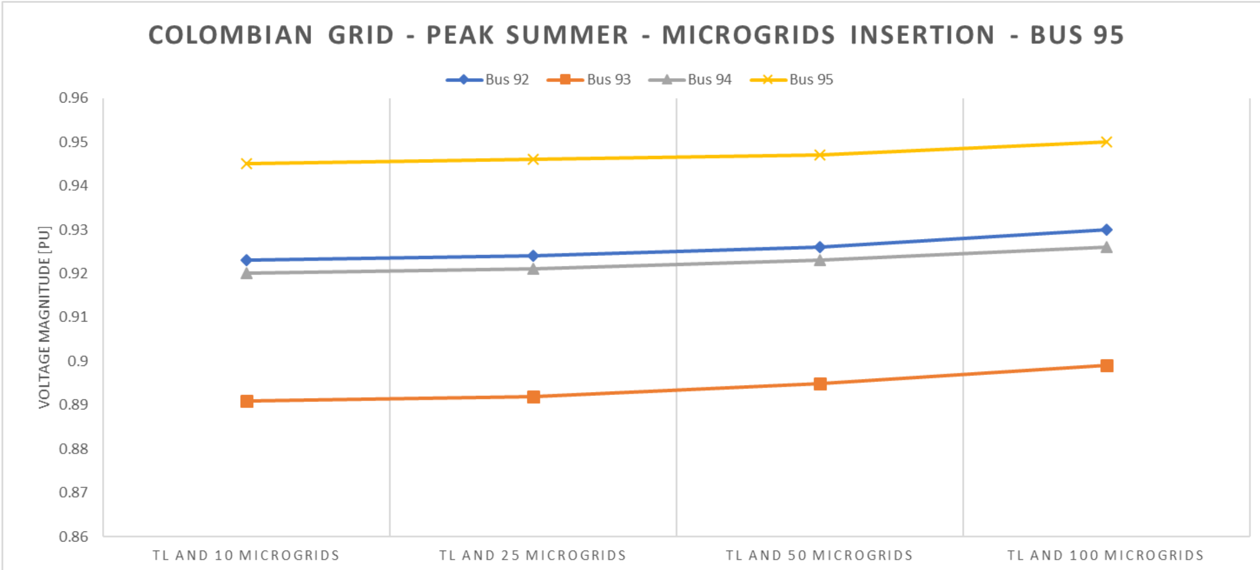


Figure. 104. Detailed voltage profile with the insertion of micro grids clusters.

For the line loading analysis, it was considered the case with no micro grid inserted ad then with the progressive increment of micro grids. As seen in the Figure 105, the profile of line loading did not variate considerably, with the exception of the branch 235 (from bus 79 to bus 92) that the value fell with the insertion of the micro grids.

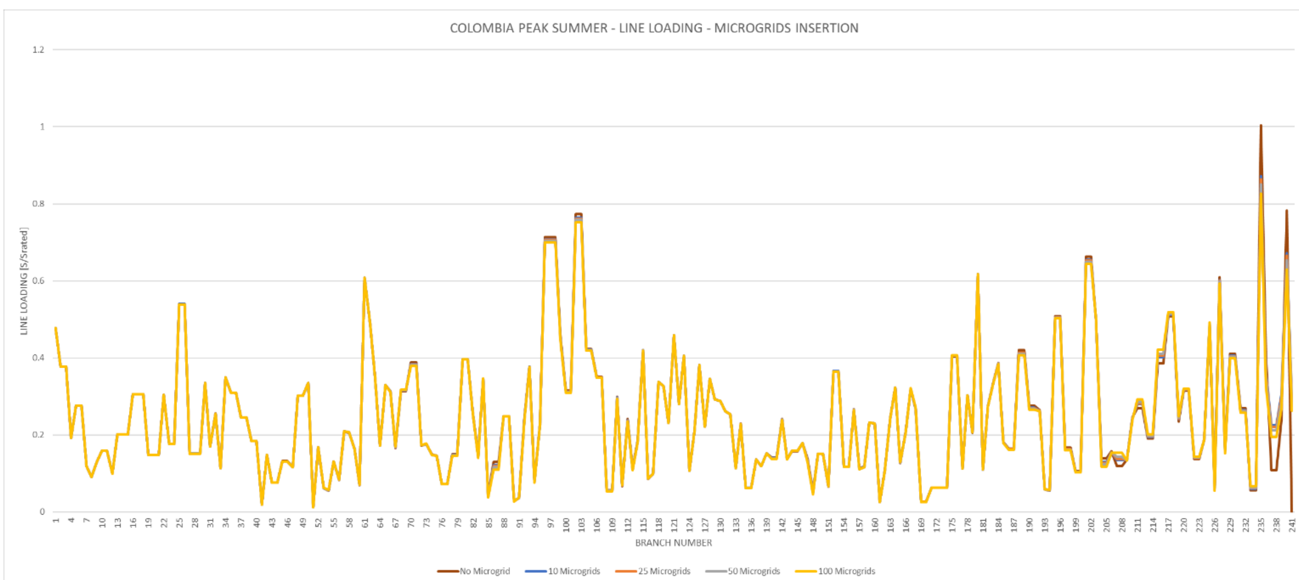
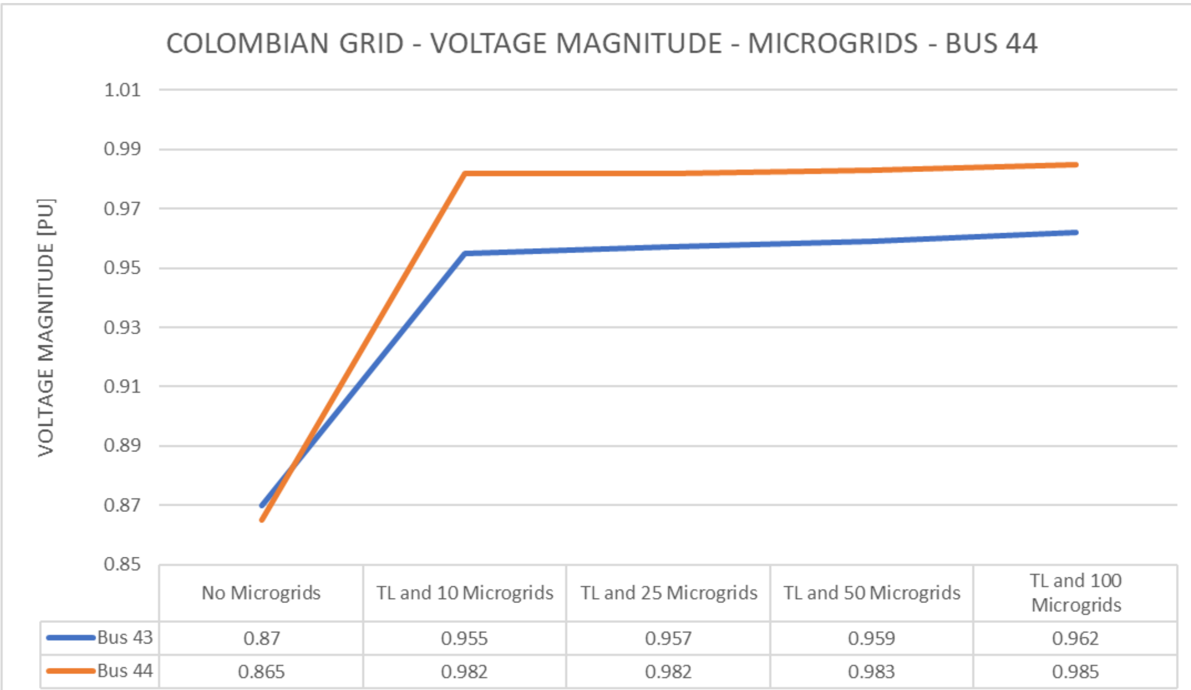


Figure. 105. Line loading with micro grids insertion.

II. Colombian Network – Cluster of Micro grids – Insertion on the bus 44

The same simulations were performed in the bus 44 which is another radial branch of the Colombian Grid. In the Figure 106 it is available the voltage profile of the buses 43

(Banadia) and 44 (Cañolimón). The same result was obtained, with the poor voltage scenario changing substantially due to the sudden insertion of the cluster of micro grids. Again, the increment of the number of micro grids affected marginally the growth of the voltage in the two buses. The rise of 24 MW in power capability (from 10 to 100 micro grids) caused a direct increment of 0.003 p.u. to bus 44 and 0.007 p.u. to bus 43.



	No Microgrids	TL and 10 Microgrids	TL and 25 Microgrids	TL and 50 Microgrids	TL and 100 Microgrids
Bus 43	0.87	0.955	0.957	0.959	0.962
Bus 44	0.865	0.982	0.982	0.983	0.985

Figure. 106. Voltage profile with the insertion of micro grids clusters.

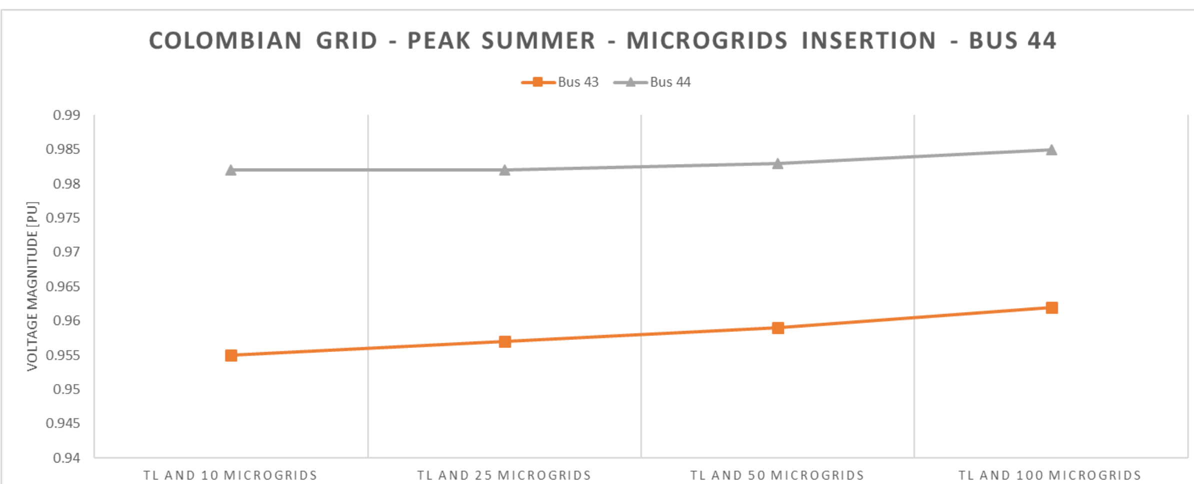


Figure. 107. Detailed voltage profile with the insertion of micro grids clusters.

Regarding the obtained results, it appears at the first glance that the insertion of microgrids does not promote many benefits to the main network. However, further than the first good results on the voltage profile by the interconnection with the cluster of micro grids, it has other advantages that the integration can provide. The possibility of small but important regulations on the main system using only the micro grids could be a solution for some temporary problems on the grid.

The future possibility of using the micro grids to provide the ancillary services, transforming it in a financially sustainable mode, considering also the incentives that are in practice in Brazil and Colombia. Furthermore, for the micro grids being connected to the main system makes it more interesting in the reliability and security aspects.

10. Conclusion

The energy access for many regions of the world is still problematic even nowadays. Different challenges are in place and in many cases the most classical model of centralized dispatch systems is not applicable.

With the development of this work was possible to analyze deeply the main transmission system from Brazil and Colombia, understanding better how it is organized, planned and operated. Moreover, the electricity market, technical constraints of the grid, topology, main load and generation areas were better comprehended in order to model it and perform the simulations proposed. The Brazilian model, as an equivalent model available for this sort of studies, proved to work properly even being just a part of the main transmission grid. In the case of the Colombian model, it was built from scratch but with synthetic network theoretical methodologies, proved to be a reliable and it is available for further studies and usage in other works.

When the load increment simulations were performed considering the propitious zones of the two countries investigated, the main idea was analyze how the network, specially the buses located on the most remote areas of the grid, behave. The behavior, especially on the technical constraints sense, quantified the possibilities of growth for the load on those areas with the actual infrastructure. Both for Brazil and Colombia, 0.5% of increment based on the total Brazilian scenario and around 4% of the total Colombian scenario, the load increment caused problems regarding the voltage profile that has fallen out of the determined limits. The difference of topology contributed for the difference, as the Colombian system is characterized by a meshed topology and the Brazilian part considered in this work is a more radial one.

Another important result regarding the load increment analysis is related with the regional growth. Using official data about the last year's growth, it was forecasted that after three years in Mato Grosso's region in Brazil, the system will operate in poor technical conditions. As an alternative for this consumption growth on this vulnerable area is to connect a transmission line from the more peripherical bus to a stable area in the grid. The outcome performance improved, and the area earned at least more thirteen years of stability with the constant strong growth of demand. As a way to quantify this solution proposed, the LCOE was calculated based on the estimated investment costs and by the additional energy that the transmission line will bring to the selected buses. With the obtained value is possible to compare with the LCOE calculated to the microgrids models and evaluate in which situation it is better to deploy microgrids or expand the transmission systems.

The analysis of the most affected buses with the load increment and also the maximum capability was performed for the Colombian selected buses. This is useful for planning studies and better usage of the network. Additionally, it was performed for the Colombian model the analysis of the integration of microgrids in the main transmission system. The target was evaluating how the main grid affected by a strong load would react to integration of microgrids. The outcome was valuable, although the fact of the small power produced even by a cluster of microgrids. Therefore, for slight improvements in remote parts of the main system it can perform a relevant role and provide stability for the micro grids as well.

The dimension of the micro grid provides a competitive cost and the capacity to provide energy to the communities with low loss of load probability. The tool PoliNRG has been improved to look forward into a robust tool that designs micro grids with the specific conditions of each place. The algorithm seems to find a combination close to the global minimum always. This is a good solution for a very complex problem with many variables, most of the researches done in order to solve this problems use the genetic algorithm, this software provide a different solution.

Another important point is the integration of small renewables on the main system, promoting the clean energy usage and more smart practices taking advantage of the most productive hours of some sources and injecting it on the national network. Considering the possibility of connecting some clusters to the same substation, provides the possibility of a bigger importance and therefore more relevant they become.

For future works it is suggested a deeper analysis of the electricity market in Brazil and Colombia and how the mechanisms already in place, such as the incentives for renewables and microgrids, could improve this analysis. Another interesting point would be the modelling of the Brazilian and Colombian networks in a program that performs the analysis in the transient regime, considering the constraints determined by the Brazilian and Colombian grid code. The design of micro grids can be improved with new generation sources such as biomass since many developing countries have economies based on agriculture and the residuals can be used to power a biomass generator.

Two different strategies for energizing rural areas on developing countries have been explored. Furthermore, a new possibility mixing micro grids and transmission networks have been explored. The solutions seem to have different ranges of action depending on the conditions, but with the methodology proposed on this work shows a path to compare which strategy could solve better the energization problematic on each location of developing countries.

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12. Annex

MATPOWER

The MATPOWER is a package developed to the MATLAB® environment that allow the performance of power flow simulations [8]. The data files are known as M-file or MAT-file, where the struct is available to be edited. In the struct are basically four fields: *BaseMVA* that is a scalar and *bus*, *branch* and *gen* that are matrices. The first field *BaseMVA* is the power base of the treated network. The *bus* field contains all the information referred to the network buses, such as voltage magnitude, phase angle and bus type. The *branch* field comprise the transmission line and transformer data. Lastly, the *gen* field includes the information about the generators, such as the maximum real power output. The main functionality of the MATPOWER is solving power flow and optimal power flow problems. On this thesis only the power flow routines were mainly used.

Based on the data contained in the mentioned fields, the inputs can be prepared to the simulation through the routine *loadcase* that loads the data from the case file into a struct. In order to run the simulation of AC power flow, the routine *runpf* must be invoked, generating by default the results of the simulation. There are many routines and possibilities available, which makes MATPOWER a powerful platform for running power flow simulations.

12.1.1. MATPOWER case format

The fields of the struct that MATPOWER works can be deeper described in order to comprehend the models that are used in this work. The *bus* field elements are characterized in the table III. All the parameters described are mandatory for the power flow simulation, with the exception of the parameters LAM_P, LAM_Q, MU_VMAX and MU_VMIN, which are related to simulations of optimization specification and therefore used on optimal power flow routine.

The slack bus is named by the program as the reference bus. The parameters *PD*, *QD*, *GS* and *BS* are extremely important in order to describe the grid, particularly to the load buses (PQ). In relation to *VM* and *VA,* are the initial guesses of the power flow that will be performed. The model of the load adopted by the MATPOWER is the constant real and reactive power consumed by the bus. Exist the possibility of modelling the load as constant impedance adopting shunt elements to design it.

Bus Data		
Name	**Column**	**Description**
BUS_I	1	Bus number (positive integer)
BUS_TYPE	2	Bus type (1 = PQ, 2 = PV, 3 = ref, 4 = isolated)
PD	3	Real power demand (MW)
QD	4	Reactive power demand (MVAr)
GS	5	Shunt conductance (MW demanded at V = 1.0 p.u.)
BS	6	Shunt susceptance (MVAr injected at V = 1.0 p.u.)
BUS_AREA	7	Area number (positive integer)
VM	8	Voltage magnitude (p.u.)
VA	9	Voltage angle (degrees)
BASE_KV	10	Base voltage (kV)
ZONE	11	Loss zone (positive integer)
VMAX	12	Maximum voltage magnitude (p.u.)
VMIN	13	Minimum voltage magnitude (p.u.)
LAM_P	14	Lagrange multiplier on real power mismatch (u/MW)
LAM_Q	15	Lagrange multiplier on reactive power mismatch (u/MVAr)
MU_VMAX	16	Kuhn-Tucker multiplier on upper voltage limit (u/p.u.)
MU_VMIN	17	Kuhn-Tucker multiplier on lower voltage limit (u/p.u.)

Table. XXX. Bus Data [8].

The *generator* field elements are characterized in the table IV. Parameters such as PC1, PC2, QC1MIN, QC1MAX, QC2MIN, QC2MAX, RAMP_AGC, RAMP_10, RAMP_30, RAMP_Q and APF are not mandatory in order to run the power flow. However, give the possibility of a more precise and accurate description of the behavior of the generators. The generator model approached on MATPOWER is related to a complex power injection at specified buses.

Generator Data		
Name	**Column**	**Description**
GEN_BUS	1	Bus number
PG	2	Real power output (MW)
QG	3	Reactive power output (MVAr)
QMAX	4	Maximum reactive power output (MVAr)
QMIN	5	Minimum reactive power output (MVAr)
VG	6	Voltage magnitude setpoint (p.u.)
MBASE	7	Total MVA base of machine, defaults to baseMVA
GEN_STATUS	8	Machine status: > 0 = machine in-service ≤ 0 = machine out-of-service
PMAX	9	Maximum real power output (MW)
PMIN	10	Minimum real power output (MW)
PC1	11	Lower real power output of PQ capability curve (MW)
PC2	12	Upper real power output of PQ capability curve (MW)
QC1MIN	13	Minimum reactive power output at PC1 (MVAr)
QC1MAX	14	Maximum reactive power output at PC1 (MVAr)
QC2MIN	15	Minimum reactive power output at PC2 (MVAr)
QC2MAX	16	Maximum reactive power output at PC2 (MVAr)
RAMP_AGC	17	Ramp rate for load following/AGC (MW/min)
RAMP_10	18	Ramp rate for 10 minutes reserves (MW)
RAMP_30	19	Ramp rate for 30 minutes reserves (MW)
RAMP_Q	20	Ramp rate for reactive power (2 sec timescale) (MVAr/min)
APF	21	Area participation factor

Table. XXXI. Generator Data [8].

The *branch* field elements are characterized in the table V. From the arrangement of the branch data and the connection among the buses, it is constructed the network. The data referred to the line parameters: *BR_R*, *BR_X* and *BR_B* are of a substantial importance defining how the network will behave in what regards real and reactive losses, sensitivity and so on. The transmission lines and transformers follow the π equivalent circuit, in which the simplifications of the medium and short lines were already mentioned.

Branch Data

Name	Column	Description
F_BUS	1	“from" bus number
T_BUS	2	“to" bus number
BR_R	3	Resistance (p.u.)
BR_X	4	Reactance (p.u.)
BR_B	5	Total line charging susceptance (p.u.)
RATE_A	6	MVA rating A (long term rating), set to 0 for unlimited
RATE_B	7	MVA rating B (short term rating), set to 0 for unlimited
RATE_C	8	MVA rating C (emergency rating), set to 0 for unlimited
TAP	9	transformer off_ nominal turns ratio, (taps at “from” bus, impedance at “to” bus)
SHIFT	10	transformer phase shift angle (degrees)
BR_STATUS	11	initial branch status, 1 = in-service, 0 = out-of-service
ANGMIN	12	minimum angle difference, $\theta_f - \theta_t$ (degrees)
ANGMAX	13	maximum angle difference, $\theta_f - \theta_t$ (degrees)
PF	14	Real power injected at “from” bus end (MW)
QF	15	Reactive power injected at “from” bus end (MVAr)
PT	16	Real power injected at “to” bus end (MW)
QT	17	Reactive power injected at “to” bus end (MVAr)

Table. XXXII. Branch Data [8].

12.1.1. MATPOWER results

In the MATPOWER the routine *runpf* performs the AC power flow using the Newton-Raphson method by default. This command provides the outcome of this power flow in a struct called *results*. In this struct is stored relevant data from the simulation, such as voltage magnitude and phase angle of all the buses, real and reactive power injections from the generators, real and reactive power injected into “to” end of branch and “from” end of branch. Moreover, there are data related to the simulation performance itself, such as computation time and the number of necessary iterations to reach the final solution.

In the system summary it is described the number of generators, loads, shunts, branches, transformers, total generating capacity, load, shunt injections and losses. Furthermore, the minimum and maximum voltage magnitude and phase angle is provided and the maximum real and reactive losses is displayed as well.