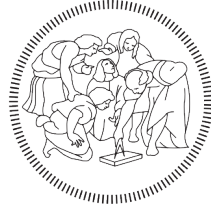# POLITECNICO DI MILANO

Scuola di Ingegneria Industriale e dell'Informazione

Corso di Laurea Magistrale in Electrical Engineering

POLITECNICO
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Q-GIS approach for rural electrification: The Puerto Carreno-Colombia case study

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Acknowledgement

" My mother said to me, If you are a soldier

You will become a general...

If you are a monk, you will become the Pope.

Instead, I was a painter, and became Picasso."

Pablo Picasso

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Abstract

During the last years, the electricity consumption have dramatically increased world wide. This force to the electric industry to search for alternative and strategies to overcome this problematic. Since provide electricity carry some costs related to the generation, transmission, distribution, and the civil labor, is necessary also narrowing solutions found attending to this economic view. Moreover, the problematic make harder and more complicated, considering those zones of hard access and remotely located in a country. Since is known that for security reasons many of these data is not at hand, also must be attached the lack of information of the currently systems that operates in that zones as a part of this bottleneck. And many another information related to geographical information, the coordinates of the substations location, the electrical information of lines, substations, and transformers.

Then, geographical information systems (GIS) have been used with more strength along many engineering solution. This kind of systems offer a wide variety of tools and features for many applications. GIS are computer based system, used by many services utilities and government institutions to store, read, edit and analyze data referenced by a spatial coordinate system. Given GIS consent a graphic representation of data and other stuffs, in rural electrification is really interesting the big quantity of possibilities that it offers. Hence, are really useful the solutions to the problematic above described by using GIS approach. However, it is important to precise and ultimate many design tools that employing these GIS solve electrification problems, specifically for those rural areas in which there aren't to much opportunities.

The authors rigorously review the majority of the approaches found in literature, with the purpose of classifying the models according to diverse methodologies; models are analyzed in terms of accuracy and computational effort.

Then, a GIS approach is proposed, descried and applied in a real case of study in the city of Puerto Carreño Colombia. The goal of this work is to accurately creating a model of the Colombian national transmission system using the GIS tools, and design an optimal distribution grid using kruskal algorithm for a city in Colombia with problem of rural electrification and not interconnected to the National transmission system. Finally, using minimum spanning tree algorithm connecting all the distribution substation defined for supply the load in this city, to create the most accurate and suitable distribution system.

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Introduction

At some point in time when the agricultural processes were identified as potential applications for electricity, and consequently, the lines began to be extended into the rural area. Here, the density of potential users and the intensity of electricity use was not as large as in the cities or the industrial centers. Therefore investments in grid extensions became hard to recover, so new institutional and financing mechanisms were developed to support the operation [30].

However, according to the bibliographic sources about an official rural electrification program, it is seen that these are punctually applied in developed countries. Mainly due to the high value of application installation. But the problem is really for those countries since of these initiative eventually trickled down to this ones. Thus, the process of rural electrification through grid extensions in many developing nations stalled to the point that the problem of rural electrification again became a major political issue around the world.

So it results mandatory to find alternatives that help to provide energy in developing countries. Hence, from many years have been rising different solutions like: off-grids networks and on-grids networks. In such way, the concept of using mini-grid or micro-grids that can interconnect multiple generation sources and loads to mobilize the combined resources of a community, has emerged as a potentially more effective and efficient community-based energy solution [42].

On the whole, is possible to identify many strategies in particular. Colombo, Masera, Bologna [6] have suggested a list of these strategies. These ones are sum up in below:

- **Grid extension**: Basically this action carry the expantion of the national existent and established grid is to sparsely populated area. Consequently, Cost of energy would be low, but investment costs as well as technical losses due to long distances could be very high.

- **Off-grid systems linked to established power grids:** Distributed genera-

tion, small scale electricity production could be an effective solution in remote areas, though requiring a high investment cost. Stand alone systems can range from home based systems relying on a single source to mini grids integrating more than one source of energy.

- **Integrated microgrids**: They can be defined as an aggregation of loads and micro-resources operating as single system providing both power and heat, integrated to national grid or not. They have their internal control and optimization scheme and could operate in connection with the main grid. The mentioned technology could be evidentiated in the figure 1
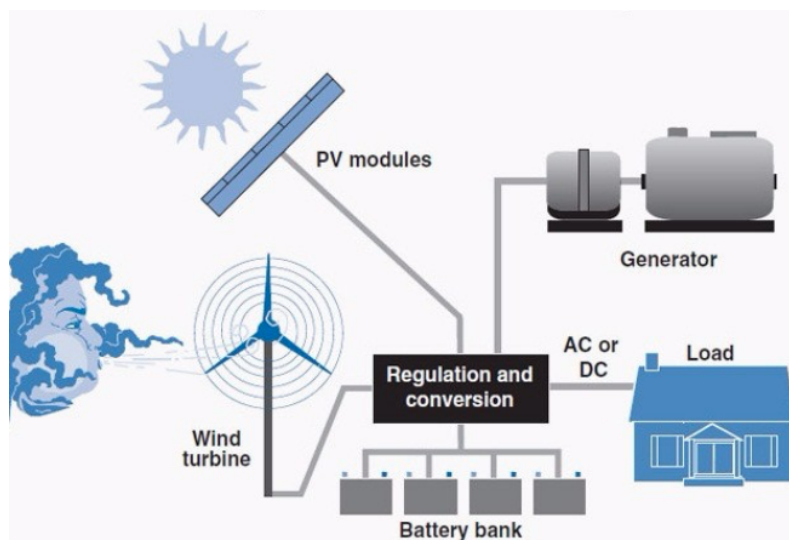
Figure 1: Microgrid representation with many renewable sources integrated among themselve [15]

On the other hand, according to the access to Energy Services through Renewable Sources in Latin America and the Caribbean, issued by the Alliance for Rural Electrification [10], is shown that electricity coverage in the Latin America region is at present about 97 %. However, the another 3 %, means that some 22 millions people (about six million households) are still lack of service. This open a space for evaluation of the factors limiting the access of these people to acquiare electricity. From these factors is possible to distinguish technology, environmental and social context, economic viability and a cost- benefit analysis.

Under normal conditions, more than 80 % of the energy generated in Colombia is produced with renewable resources, especially water, and some megawatts already come from wind and sun. In addition, there is thermal generation, generation, which allows for diverse energy matrix in wich the continuity of the service can be mantained. There are many meterological conditions conditions of low hydrological

contributions. In that case, the hydraulic generation is not capable to sustain the peak load.

The supply of electricity in Colombia is based on the National Interconnected System (SIN) and several isolated local systems in the Non-Interconnected Zones (ZNIs). SIN covers one third of the land, with 96 % of the population covered. The ZNI, which includes the remaining two third of the domestic land, provides only 4 % of the population. In Colombia, electricity coverage is 93 percent in urban areas and 55 percent in rural areas.

In Colombia there are three institutions dealing with the management and control of the electrical market activities:

1. UPME (Unit for Mining and Energy Planning), a specific compartment of the Ministry of Mine and Energy, which is in charge for the long term National Energy Plan and the Expansion Plan.

2. CREG (Regulatory Commission for Gas and Energy), public commission responsible for the efficiency of the energy supply and the market competition.

3. XM, the private company that acts as Market Operator; it manages the market closing and all the activities connected to the energy dispatch.

XM operates the SIN, complying with standards and technical agreements dictated by the Government and is monitored by several entities, which makes this operation reliable and safe for all users of the energy service.

In addition, the cost of the grid extension relay on the power system elements price, such as: the overhead transmission line, the mechanical structures, the isolators, and so on. Thus, could result really interesing for all countries, but specially for those developing countries with economic lacks, to find many alternatives to optimize the layout of new distribution grids connected to HV power grid.

Indeed, Friedl, Schmautzer, L. Fickert [16] support by stabilishing that the general requirements of electrical power supply are very high. In particular, the supply of the electricity must contain the following aspects:

- In sufficient quantity.

- With appropriate quality.

- Economical.

- Eco-friend.

- Socio-politically acceptable.

Therefore, for a region with a increasing electrical power demand, and considering the above specified requirements, there are two different solutions that could be employed

- A high voltage overhead transmission line to feed that demand.

- A new substation or a decentralized generation of power. [16]

Afterwards, to determine through an assessment process or by a methodology which solution (HV/MV grid extension , mini-grids or standalone systems-off grids) is best suited to a community, is a complex and multi-variable problem. Varied aspects have to be considered like: technical, economic, environmental and social factors.

Therefore, the described situation is an optimization problem. In that way, the utilization of optimization techniques or optimization algorithm potentially can help to minimize the overall installed generation and storage capacity, as well as the network cable lengths required of a mini-grid, hence minimizing the associated capital expenditure and optimizing system-operating efficiency.

This work is divided in the following chapters:

Chapter 1: An explanation of the power system elements which include a description of elements of power system. About the power flow method beginning for an exploration of the methods often used, and the method selected in this work. Then, a description about the mathematical model employed for the transformer and the transmission lines, and the approach used in this paper to model these elements of power system.

This phase constitute the cornerstone of this thesis since the basis of the power system are described.

Chapter 2: This section is intended to clarify the primary elements of the electrical scheme in Colombia. In that context, a particular overview of the Colombian electrical scheme is provided from a historical outline of that, moving on to the Colombian market structure and the overview of the interconnected Colombian scheme up to the FAZNI (in Spanish: Fondo de apoyo sur dos zonas no electrificadas or in English: Fund for Energizing Non-Interconnected Zones).

The information used in this chapter refers to a broad range of sources, starting from formal information released for many organizations related to the Republic of Colombia's Ministry of Mining and Energy, and from non-governmental organiza-

tions discovered by the world bank, emerging nations segment, and Latin America section.

Chapter 3: This chapter is devoted to explain about the proposed approach in this thesis work. Is described first of all about the creation and validation of transmission grid using GIS and the identification of rural areas. After that the Distribution grid planning trough clustering and k-means algorithm, for finally performing load flow of the transmission grid

Chapter 4: This chapter is devoted to discuss and analyze the results obtained after the implementation of proposed approach, and presenting the pictures of the results obtained.

Chapter 5: Finally, in this chapter are reported the main conclusion extracted from the results of the proposed approach.

Chapter 1

Elements of power system: Transmission system theory - model & Power flow computation.

1.1 Electrical power system

Electrical power systems are quite complex systems focused to served an electric demand under certain levels of reliability, flexibility or reliability. Thus, in a certain way to let this systems working properly, is necessary to model them for its studying, forecasting, analysis and estimation.

In that sense, for [1] all analysis in the engineering sciences starts with a formulation of appropriate models. In power system specifically we almost invariably means mathematical model, or a set of equations or relations, which appropriately describes the interactions between different quantities in time frame studied and with a desired accuracy of a physical or engineering component system.

Therefore, for each element of the power system, there is a diversity of models that can be applied for each element. In that sense, a model for transmission lines, and for transformers are taken in place for this case, which are also the harder elements to model. Section 1.3 and 1.4 are devoted to explain the different models in literature.
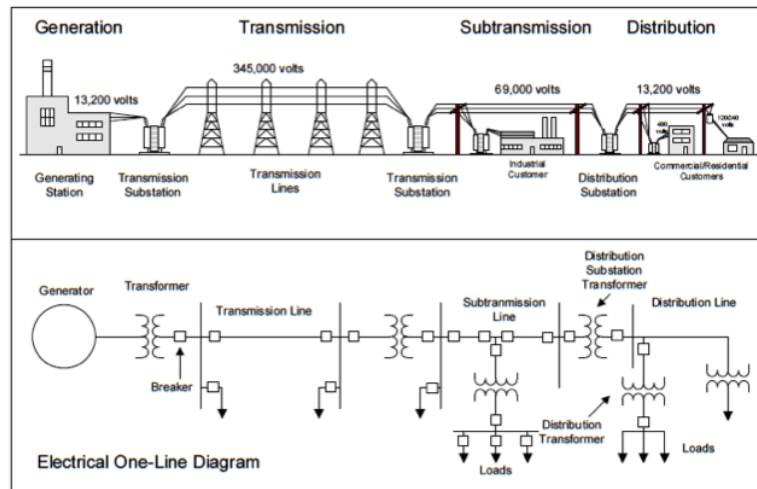
Figure 1.1: Power system according to the energy chain, and the one line diagram of this power system. Source: `https://www.researchgate.net/figure/Typical-electric-power-system-single-line-diagram_fig2_255212598`

1.2 Power flow

Power flow calculation is the most fundamental & critical numerical algorithm for power system analysis. Distribution systems require fast power flow solution with the development of smart grid that must be as efficient as possible in the future [3]. In our case, the study of power flow solution of distribution system attracts more the attention. However, the choice of an appropriate solution for practical cases like grid for rural electrification electric systems is frequently difficult. It requires a careful analysis of advantages and disadvantages among many available methods in such respects as storage, speed and convergence characteristics.

On the other hand, the power flow studies on transmission networks are well developed such as Gauss-Seidel, Newton- Raphson [27] and Fast Decoupled method [45]. Some features of distribution network such as radial/weakly meshed structure, higher R/X ratios of impedances than transmission network, the large number of branches and nodes. Thus, these features may cause failure in the distribution system applications by using of power flow algorithms for transmission networks [41]. All of these characteristics need to be considered to qualify for a good power flow method for distribution systems. In that sense, many power flow algorithms designed for distribution system have been proposed. Indeed, Forward/backward sweep method is one of the most popular solutions for solving distribution networks [11].

Relevantly, a work published in [18], where graph theory is used for building the Z-bus matrix, and it's still only for radial distribution systems. These forward/backward sweep algorithms are very creative and most commonly used for distribution networks, but it cannot be applied directly to weakly meshed structure.

Let's assuming a three-phase balanced system in steady state operation, to determine the voltage magnitude and phase angle in the buses that compose the network, the best possible solution is perform a power flow algorithm. Through this algorithm, 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 1.1 summarizes the input and output data to compute for each type of bus by means of a power flow algorithm.

Bus type	Input data	Output data
Slack bus	$V_i \ \delta_i$	$P_i \ Q_i$
Load bus (PQ bus)	$P_i \ Q_i$	$V_i \ \delta_i$
Voltage-controlled bus (PV bus)	$V_i \ P_i$	$\delta_i \ Q_i$

Table 1.1: Bus classification and input, output data requirement.

Now, let's try to deduce the real and the reactive power equations flowing from i-th to j-th bus. Let's considering the equation that relates the bus admittance matrix and assuming the bus j, the j-th equation is given by :

$$\bar{I}_j = \sum_{k=1}^{N} \bar{Y}_{jk} \bar{V}_k \tag{1.1}$$

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:

$$\bar{S}_j = S_j + jQ_j = \bar{V}_j \bar{I}_j^* = \bar{V}_j \left(\sum_{k=1}^{N} \bar{Y}_{jk} \bar{V}_k \right)^* \tag{1.2}$$

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

$$\bar{S}_j = \bar{V}_j \left(\sum_{k=1}^{N} \bar{Y}_{jk} \bar{V}_k \right)^* = V_j \left(\sum_{k=1}^{N} V_k Y_{jk} \right) e^{j(\delta_j - \delta_k - \theta_{jk})} \tag{1.3}$$

By Euler's identity, and separating the real and the imaginary parts, the real and
reactive power flowing from the j-th bus:

$$P_j = V_j \sum_{k=1}^{N} V_k Y_{jk} \cos(\delta_j - \delta_k - \theta_{jk}) = V_j \sum_{k=1}^{N} V_k [G_{jk} \cos(\delta_j - \delta_k) + B_{jk} \sin(\delta_j - \delta_k)] \tag{1.4}$$

$$Q_j = V_j \sum_{k=1}^{N} V_k Y_{jk} \sin(\delta_j - \delta_k - \theta_{jk}) = V_j \sum_{k=1}^{N} V_k [G_{jk} \sin(\delta_j - \delta_k) - B_{jk} \cos(\delta_j - \delta_k)] \tag{1.5}$$

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

1.2.1 Newton-Raphson power flow method

The Newton-Raphson method employs the bus admittance matrix in either first,
and second order expansion of Taylor series. Indeed, in general term this method
is well know for employing a sequential linearization. This numerical solution has
been evaluated as a best solution for the reliability and the rapid convergence, since
the convergence rate is quadratic.

The situation in 1.2 is a two buses power system, which is pretended to compute the
voltage at bus 2. Also, From 1.2 we see clearly two regions.The red region converges
to the high voltage solution, while the yellow region converges to the low voltage
solution.

Thus, to specify the Newton- Raphson solution is a preferred algorithm for nonlinear-
equations solved on workstation or personal computer systems. However, the use of
real arithmetic requires experimentally about twice as many memory references to
do the same amount of computation as with complex arithmetic.
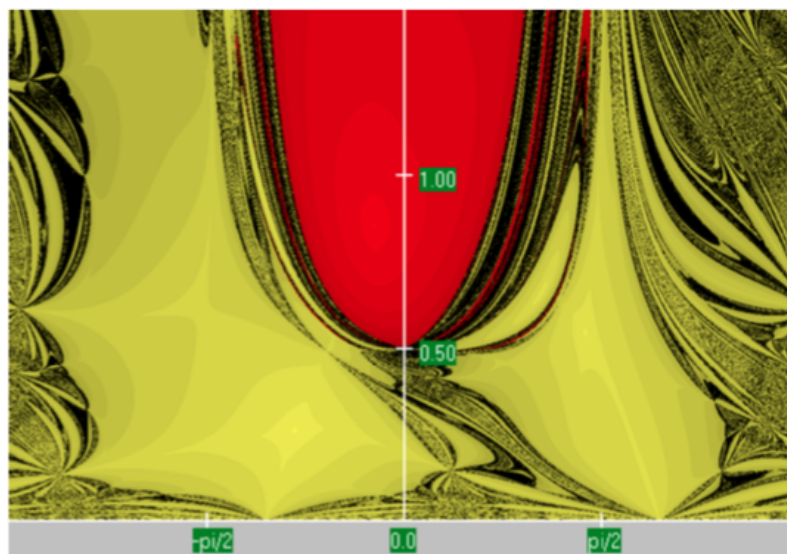
Figure 1.2: Fractal newton plot or converge region for different initial guesses for a two buses scheme.

Moreover, looking in a mathematical way, the standard power flow or *Load flow* involves solving for the set of voltages and flows in a network corresponding to a specified pattern of load and generation. Thus, a power flow program involves equation of the form:

$$g(x) = 0 \tag{1.6}$$

Thus, for each guess of x, x^k, define:

$$\Delta x^k = x - x^k \tag{1.7}$$

Representing $f(x)$ by a Taylor's series about x^k

$$f(x) = f(x^{(k)}) + \frac{df(x^{(k)})}{dx}\Delta x^{(k)} + \frac{1}{2}\frac{d^2 f(x^{(k)})}{dx^2}\left(\Delta x^{(k)}\right)^2 + highert - terms \tag{1.8}$$

Approximating $f(x)$ by neglecting all terms except the first two and find Δx^x such that:

$$f(x) \approx f(x^{(k)}) + \frac{df(x^{(k)})}{dx}\Delta x^{(k)} = 0 \tag{1.9}$$

Now, using this linear approximation to solve for Δx^k

$$\Delta x^{(k)} = -\left[\frac{df(x^{(k)})}{dx}\right]^{-1} f(x^{(k)}) \tag{1.10}$$

Computing a new estimate of x:

$$x^{(k+1)} = x^{(k)} + \Delta x^{(k)} \tag{1.11}$$

In this work it is adopted the Newton-Raphson method due to it's widely accepted and main usage in traditional power flow software such as MATPOWER. In the table 1.2 is described in many steps the procedure to perform iterations employing this method.

STEP	Description of procedure	Goal
1: Staring with the i- initial 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	Obtain the mismatches vector $\begin{bmatrix} \Delta P(i) \\ \Delta Q(i) \end{bmatrix} = \begin{bmatrix} P - P[x(i)] \\ Q - Q[x(i)] \end{bmatrix}$
2: Compute the Jacobian matrix, through the equations presented before.	$\begin{bmatrix} \frac{\partial f_1(x)}{\partial x_1} & \frac{\partial f_1(x)}{\partial x_2} & \cdots & \frac{\partial f_1(x)}{\partial x_n} \\ \frac{\partial f_2(x)}{\partial x_1} & \frac{\partial f_2(x)}{\partial x_2} & \cdots & \frac{\partial f_2(x)}{\partial x_n} \\ \vdots & \ddots & \ddots & \vdots \\ \frac{\partial f_n(x)}{\partial x_1} & \frac{\partial f_n(x)}{\partial x_2} & \cdots & \frac{\partial f_n(x)}{\partial x_n} \end{bmatrix}_{(k)}$	Updating the sensisity matrix of the system.
3: Computing the phase angle and voltage magnitude mismatches.	$\begin{bmatrix} \Delta\delta(i) \\ \Delta V(i) \end{bmatrix} = \begin{bmatrix} \Delta P(i) \\ \Delta Q(i) \end{bmatrix} \begin{bmatrix} J_1(i) & J_2(i) \\ J_3(i) & J_4(i) \end{bmatrix}^{-1}$	With the Jacobian matrix obtained in the previous step it is possible to find the state of variable for the electrical system.
4: Getting the values of the $x(i+1)$ value.	$\begin{bmatrix} \delta(i+1) \\ V(i+1) \end{bmatrix} = \begin{bmatrix} \delta(i) \\ V(i) \end{bmatrix} + \begin{bmatrix} \Delta\delta(i) \\ \Delta V(i) \end{bmatrix}$	Getting for the i-iteration the value of Voltage and Current.

Table 1.2: *General steps for the Newthon Raphson iterations for an electrical power system with n-nodes.*

1.3 Transmission lines systems

The transmission lines **(TL)** are the backbone of the power systems since through these conductors is transferred the power from generators to primary substations,

or from primary substation to secondary substations, or even to industries as is shown in figure 1.1. Therefore, it is necessary to propose distinct solutions, from traditional and high expense transmission lines to fresh options, perhaps using the accessible local natural resources. Transmission lines will always be a trustworthy and safe option, providing system stabilization and supply safety. Nevertheless, it requires to move through environmental barriers such as physical as indigenous forest or bureaucratic, such as licensing problems, more than the enormous cost of investment.

From it simplest definition according to Paul [35] (2006), the transmission of an analog signal between two points occurs over a pair of parallel conductor, which is referred to as *transmission line.* However, in a more sophisticated version, the transmission lines fundamentally are two ports networks with each port consisting of two terminals, one of the ports is the sending end, and the other is the receiving end [35].
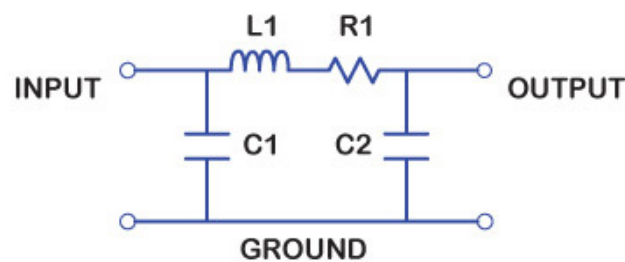
Figure 1.3: Pi model employed in the representation of componentes of a transmission line. Source: $http: // www. sigcon. com/ Pubs/ news/ 3\_ 18. htm$
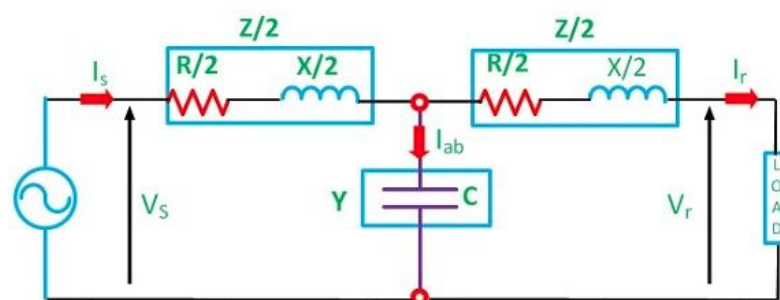
Figure 1.4: T-model for modelling a transmission line. Source: $https: // circuitglobe. com/ nominal-t-model-transmission-line. html$

In research field is always necessary to employ a mathematical model to support our studies. This mechanism improve the quality of the studied in course to describe and analyze the study phenomenon. In that way, for transmission lines, the literature

show us to main models, one is exhibit in figure 1.3 and the another one is exhibit in figure 1.4. The figure 1.3 shows the pi-model often used for modeling a transmission line. The figure 1.4 shows the T-model employed for modeling sometimes the transmission lines. The equivalent pi-model of a transmission line section was derived in the lectures of *in german: Elektrische Energiesysteme, 35-505.*

Pi-models comes from a set of formulations called the lumped-circuit line models [1]. Must be recalled that the general model given in the scientific literature for transmission lines come from the telegraph equation, that is a partial differential equation. Thus, assuming stationary sinusoidal conditions the long line equations and restricting the interest to the conditions at the ends of the lines, emerging the lumped circuit line models [34]. Since in this thesis work, has been used MAT-POWER matlab function for power flow computation [1], and this function employs the pi-models. Hence, this model is selected to mathematically model transmission lines.

Let's consider the figure 1.5. This figure exhibit the subsequent model of a transmission line, considering all the losses, and physical phenomenas due to the materials that constitutes these conductors. Thus, this model is characterized by the following elements which are seen in this picture.

- R' = Series resistance/km per phase (Ω/km).
- X' = Series reactance/km per phase (Ω/km).

and the shunt parameters,

- B' = Series resistance/km per phase (siemens/km).
- G' = Series reactance/km per phase (siemens/km).
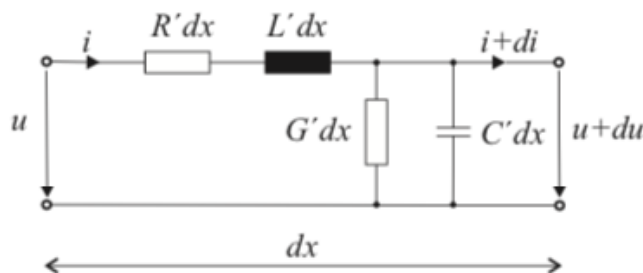
Figure 1.5: Equivalent circuit of a line element of length dx. [1]

Thus, the main important aspect from this (TL) representation are that these parameters above are specific for the line or cable configuration and are dependent on conductors and geometrical arrangements [45]. Indeed, from figure 1.5 are derived the telegraph equations [34] as seen in equation 1.12, and from this the lumped-

circuit model line model for symmetrical steady state conditions.

$$\frac{\partial^2 u}{\partial t^2} - c^2 \frac{\partial^2 u}{\partial s^2} + (\alpha + \beta)\frac{\partial u}{\partial t} + \alpha\beta u = 0 \tag{1.12}$$

This equation is satisfied by the intensity of the current in a conductor, considered as a function of time t and distance s from any fixed point of the conductor. C is the speed of light, α is a capacity coefficient and β is the induction coefficient. Moreover, from figure 1.6, is possible to appreciate the so called pi-model, but with other notation for the same variable.
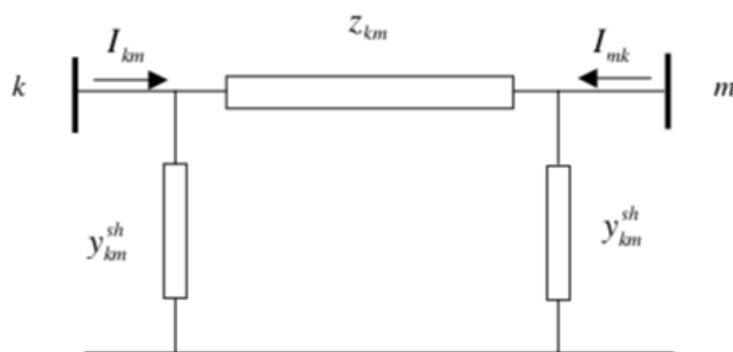
Figure 1.6: Lumped circuit model (pi-model) of a transmission line between node k and m.

This model is characterized with the following parameters:

- $Z_{km} = R_{km} + jX_{km}$ Series impedance (Ω)
- $Y_{km} = R_{km} + jX_{km}$ Series impedance (Siemens)

Note. In the following most analysis will be made in the p.u. system. For impedance and admittance, capital letters indicate that the quantity is expressed in ohms or Siemens, and lower case letters that they are expressed in p.u.

$$y_{km} = z_{km}^{-1} = g_{km} + jb_{km} \tag{1.13}$$

$$g_{km} = \frac{r_{km}}{r_{km}^2 + x_{km}^2} \tag{1.14}$$

$$b_{km} = -\frac{x_{km}}{r_{km}^2 + x_{km}^2} \tag{1.15}$$

For actual transmission lines the series reactance x_{km} and the series resistance r_{km} are both positive, and consequently g_{km} is positive and b_{km} is negative. Then, the shunt susceptance y_{km}^{sh}, and the shunt conductance g_{km}^{sh} are both positive for real line sections. In many cases, the value of g_{km}^{sh} is so small that it could be neglected [1].

The complex currents I_{km} and I_{mk} in figure 1.6 can be expressed as functions of the complex voltages at the branch terminal nodes k and m:

$$I_{km} = y_{km}(E_k - E_m) + y_{km}^{sh} \cdot E_k \tag{1.16}$$

$$I_{mk} = y_{km}(E_m - E_k) + y_{km}^{sh} \cdot E_m \tag{1.17}$$

Where the complex voltage are:

$$E_k = U_k e^{j\theta_k} \tag{1.18}$$

$$E_m = U_m e^{j\theta_m} \tag{1.19}$$

$$\begin{pmatrix} I_{km} \\ I_{mk} \end{pmatrix} = \begin{pmatrix} y_{km} + y_{km}^{sh} & -y_{km} \\ -y_{km} & y_{km} + y_{km}^{sh} \end{pmatrix} \begin{pmatrix} E_k \\ E_m \end{pmatrix} \tag{1.20}$$

As seen in the matrix, located on the right hand side of equation 1.20 is symmetric and the diagonal elements are equal. This reflects that the lines and cables are symmetrical elements.

1.4 Transformers

The transformers are the link between the generators, the power systems, the transmission lines and the different transmission lines voltage levels [24], see figure 1.7 & 1.8. From a physical point of view, is quite known that a transformer consist in two or more coils placed in such a way are linked by the same magnetic flux [24]. In a power transformer, the coils are placed in a ferromagnetic core such as in the figure 1.9, typically iron, with the purpose of confine the magnetic flux in such a way that whatever links a winding is also coupled to all other windings. In terms of winding connection, is possible to connect them in series or in parallel to constitute a winding. Each coils are stacked in a core from an alternative form which that one of other windings. In Power systems, transformer are characterized by many different voltage levels, ranging from 800 kV down to 240/120 V. The ability to inexpensively change voltage levels is a key advantage of ac over dc systems.

1.4.1 In-Phase transformers

We will begin with an standardized transformer model in which we ignore the magnetizing current and the loss of no-load. However, a shunt impedance often models
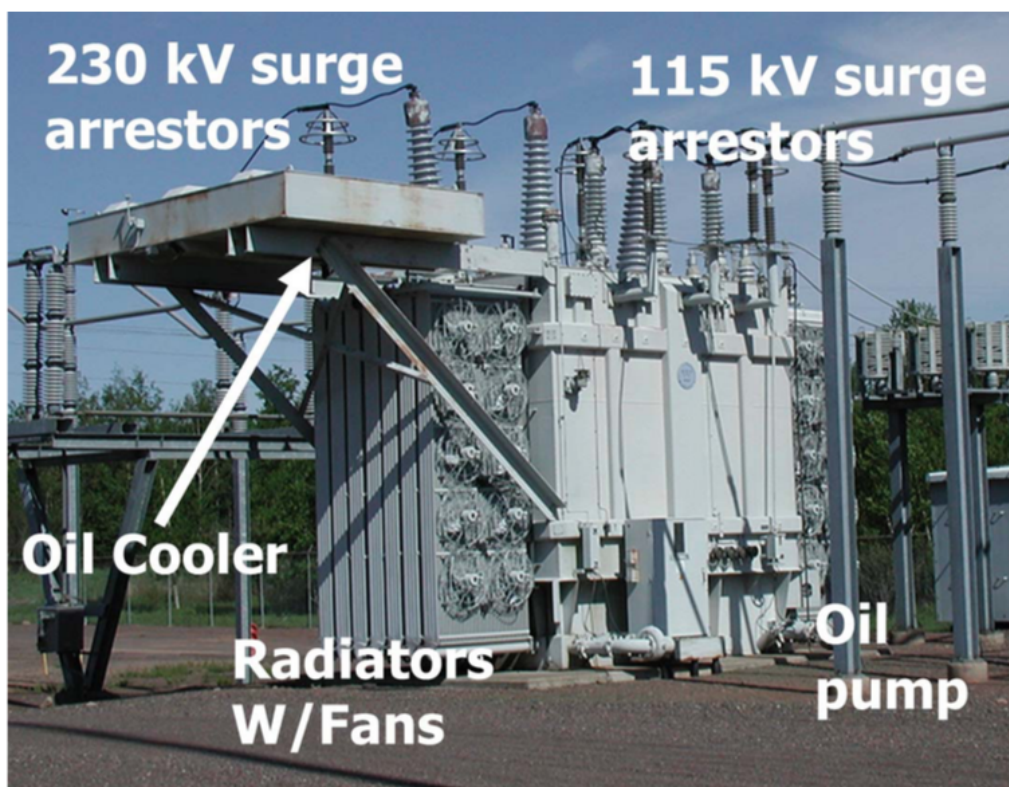
Figure 1.7: Power system transformer from 230kV-115kV described by its main components.

the magnetizing present and no-load failures, with much greater impedance than the impedance of leakage. The inductive portion of this impedance is then determined by the magnetizing present value and the non-load loss resistive part. In this case the transformer can be modelled by an ideal transformer with turns ratio t_{km} in series with a series z_{km} which represents resistive (load-dependent) losses and the leakage reactance, see figure 1.13. Thus, depending if the parameter t_{km} is real or non-real (complex value) the transformer is in-phase figure 1.10 or phase-shifting. Figure 1.10 shows an in phase transformer model indicating the voltage at the internal-non physical-node p. In this mode, the ideal voltage magnitude ratio (turns ratio) is:

$$\frac{U_p}{U_k} = a_{km} \tag{1.21}$$

Since $\theta_k = \theta_p$, this is also the ratio between the complex voltages at nodes k and p

$$\frac{E_p}{E_k} = \frac{U_p e^{j\theta_p}}{U_k e^{j\theta_k}} = a_{km} \tag{1.22}$$

There are no power losses (neither active nor reactive) in the ideal transformer (the
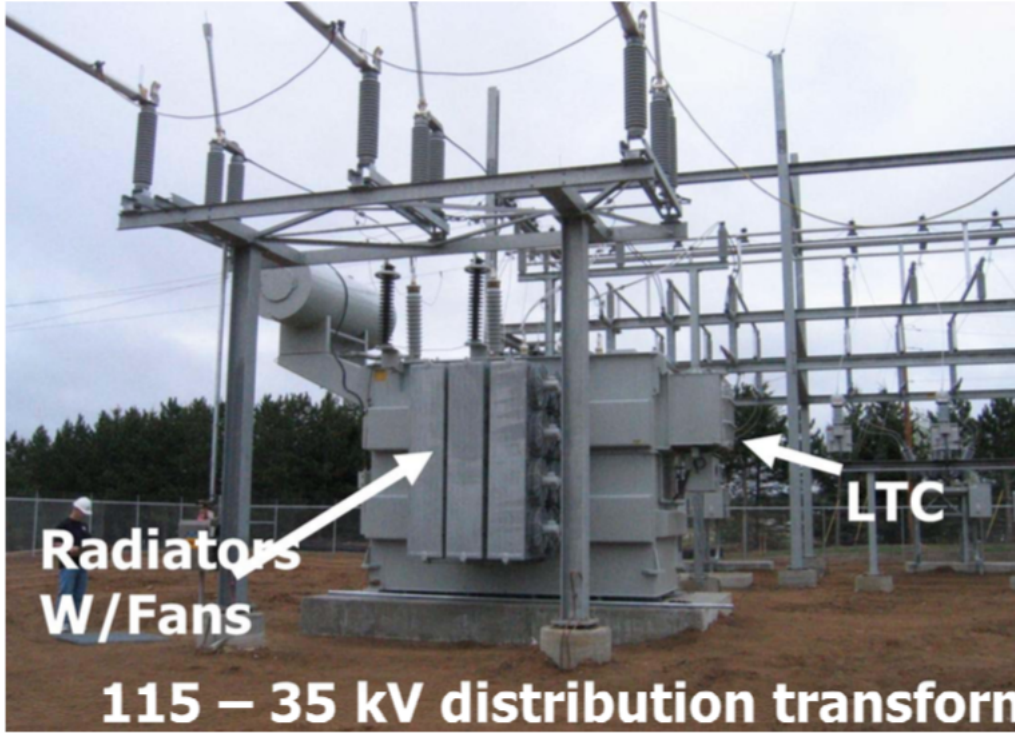
Figure 1.8: Power system transformer from 115kV-35kV described by some of its main components.

k-p part of the model), which yields.

$$E_K \times I^*_{km} + E_p \times I^*_{mk} = 0 \tag{1.23}$$

Thus, from the applying of equation 1.21 and 1.22 comes

$$\frac{I_{km}}{I_{mk}} = -\left|\frac{I_{km}}{I_{mk}}\right| = -a_{km} \tag{1.24}$$

This means that the complex currents I_{km} and I_{mk} are out of phase by 180° since $a_{km} \in \mathrm{R}$. Figure 1.11 represents the equivalent pi-model for the in-phase transformer in figure 1.10. Parameters A, B, and C of this model can be obtained by identifying the coefficients of the exppresions for the complex currents I_{km} and I_{mk} associated with the models of the figure 1.10 and figure 1.11. Thus, from figure 1.10, we obtain that:

$$I_{km} = -a_{km}y_{km}(E_m - E_p) = (a^2{}_{km}y_{km})E_k + (-a_{km}y_{km})E_m \tag{1.25}$$

$$I_{mk} = y_{km}(E_m - E_p) = (-a_{km}y_{km})E_k + y_{km}E_m \tag{1.26}$$
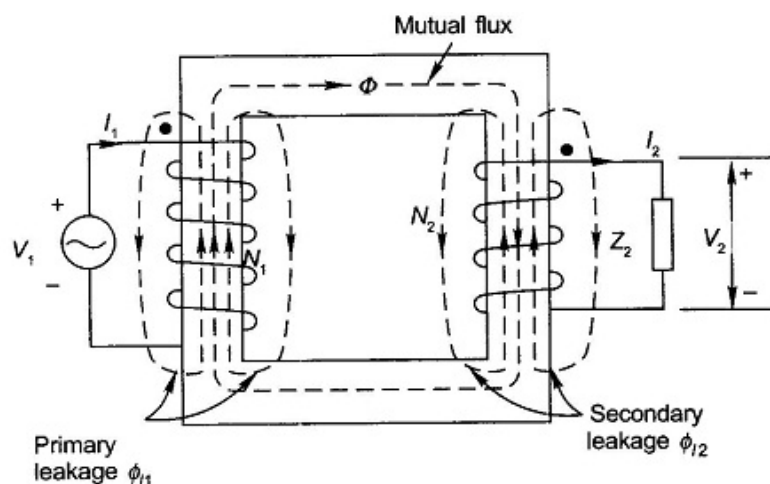
Figure 1.9: Transformer core of a transformer. Source: *https://shreejee.co/knowledge/types-of-magnetic-core-materials-for-transformers/*
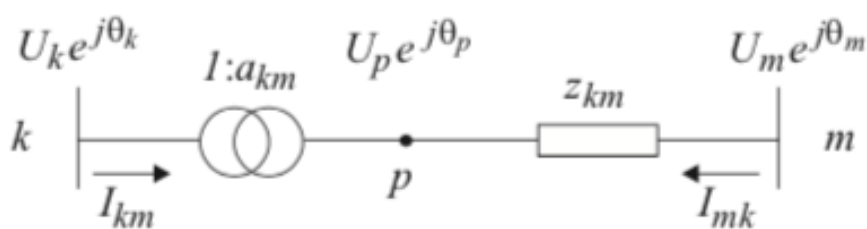
Figure 1.10: In-phase transformer model.

Which in matrix form is:

$$\begin{pmatrix} I_{km} \\ I_{mk} \end{pmatrix} = \begin{pmatrix} a^2_{km} y_{km} & -a_{km} y_{km} \\ -a_{km} y_{km} & y_{km} \end{pmatrix} \begin{pmatrix} E_k \\ E_m \end{pmatrix} \tag{1.27}$$

As seen the matrix on the right hand side of equation 1.27 is symmetric. However, the diagonal elements of these matrix are not equal. This is called **matrix non reciprocal**. In this case, It happens when $a^2 \neq 1$. From figure 1.11, we can approximate 1.27 to the following:

$$I_{km} = (A + B)E_k + (-A) \cdot E_m \quad I_{mk} = (-A)E_k + (A + C) \cdot E_m \tag{1.28}$$

$$\begin{pmatrix} I_{km} \\ I_{mk} \end{pmatrix} = \begin{pmatrix} A + B & -A \\ -A & A + C \end{pmatrix} \begin{pmatrix} E_k \\ E_m \end{pmatrix} \tag{1.29}$$
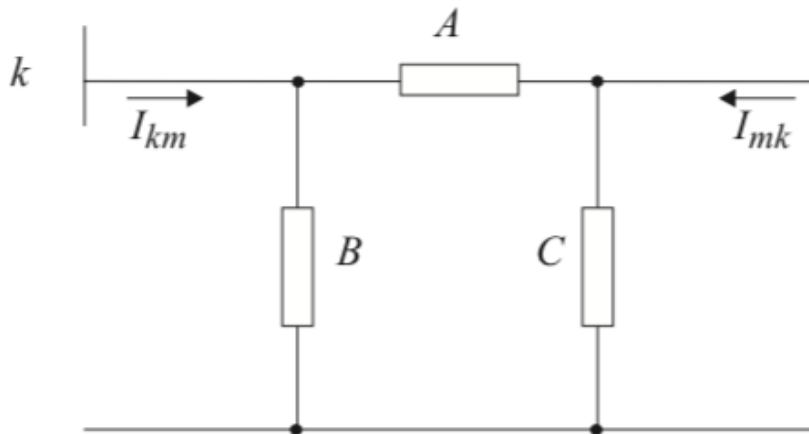
Figure 1.11: Most used equivalent pi-model of a transformer.

1.4.2 Phase shifting transformers

Phase-shifting transformers, such as the one represented in figure 1.13, the control variable is the phase angle and the controlled quantity may be the active power flow in the branch where the shifter is located, among other possibilities. In the figure 1.12 the physical design of phase-shifting transformer is described.
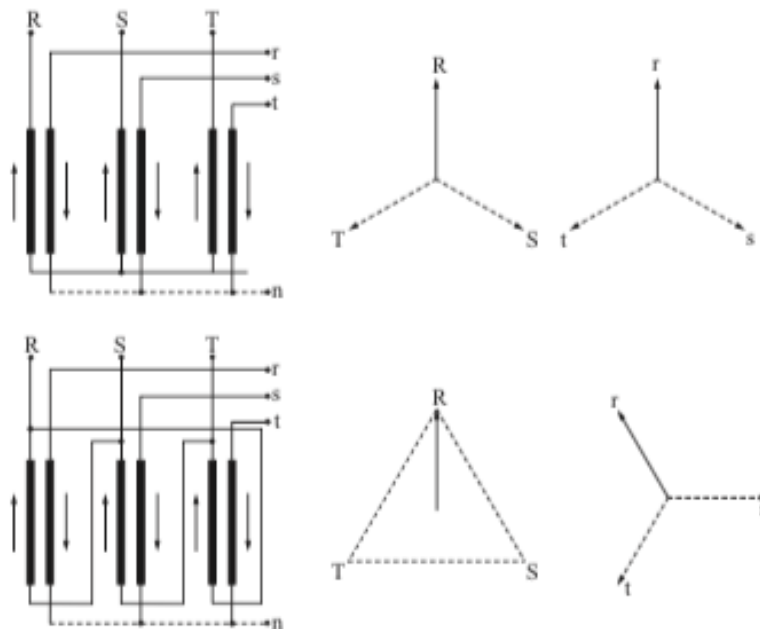
Figure 1.12: Two different configurations three winding transformer.

A phase-shifting transformer affects as both the phase and magnitude of the complex voltages E_k and E_p, without changing their ratio, i.e,

$$\frac{E_p}{E_k} = t_{km} = a_{km} e^{j\varphi_{km}} \qquad (1.30)$$
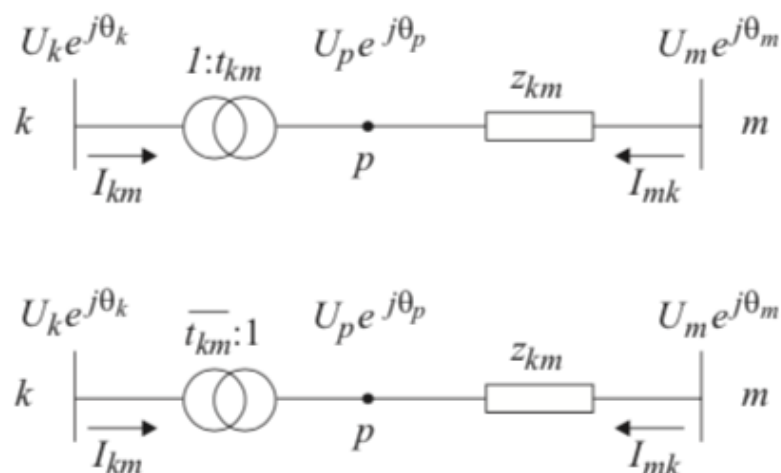
Figure 1.13: a) Transformer model with complex ratio $t_{km} = a_{km}e^{j\phi_{km}}$ [1]

Thus, $U_p = a_{km}U_k$ and $\theta_P = \theta_k + \varphi_{km}$, using equations 1.23 and 1.30,

$$\frac{I_{km}}{I_{mk}} = -t^*_{km} = -a_{km}e^{-j\varphi_{km}} \tag{1.31}$$

As with in-phase transformers, the complex currents I_{km} and I_{mk} can be expressed in terms of complex voltages at the phase-shifting transformer terminals:

$$I_{km} = -t^*{}_{km}y_{km}(E_m - E_p) = (a^2{}_{km}y_{km})E_k + (-t^*{}_{km}y_{km})E_m \tag{1.32}$$

$$I_{mk} = y_{km}(E_m - E_p) = (-t_{km}y_{km})E_k + y_{km}E_m \tag{1.33}$$

or in matrix form:

$$\begin{pmatrix} I_{km} \\ I_{mk} \end{pmatrix} = \begin{pmatrix} a^2{}_{km}y_{km} & -t^*{}_{km}y_{km} \\ -t^*{}_{km}y_{km} & y_{km} \end{pmatrix} \begin{pmatrix} E_k \\ E_m \end{pmatrix} \tag{1.34}$$

Thus, from equation 1.34, this matrix is not symmetric if t_{km} is non-real, and the diagonal matrix elements are not equal if $a^2 \neq 1$. There is no way to determine parameters A, B, and C of the equivalent pi-model from these equations due to the coefficient $-t^*_{km}y_{km}$ of E_m in equation 1.32 differs from $-t_{km}y_{km}$ in equation 1.33, as long as there is nonzero phase shift, i.e $t_{km} \notin$ R. In that sense, can be concluded that a phase shifting transformer can not be represented by pi model.

Chapter 2

Study Case: Colombian Context & Puerto Carreño-Vichada, Colombia

This chapter is aimed to explain the main aspects regarding the Colombian electric system. In that sense, is presented a general description of the Colombian electric system from an historical description of that, passing for Colombian market structure and the description of the Colombian interconnected system until the FAZNI (in spanish: Fondo de apoyo para las zonas no electrificadas-in english: Fund for the energization of the non interconnected zones.) The data used in this chapter belongs to a wide variety of sources, parting from official data issued for many institutions linked to the Ministry of mines and energy of the Republic of Colombia, and non governmental institutions the world bank found, section developing countries, and section Latin America.

This data were collected aiming to explain at the best how is composed the Colombian electric power system at its main features quantitatively.

2.1 Historical description of the Colombian electric system

First of all, the structure to supply the electricity was the result of a long process of state intervention, which began in **1928** with the issuance of Law 113 which declared the utilization of the hydraulic force to be of public utility. Since then it has functioned centrally until the law reforms carried out in **1994** during the government of Mr. Samper Pizano. During the old regulation, state vertically integrated maintained the power monopoly over a given area, and vertically integrated, providing generation, transmission and distribution services. This type of monopoly on

a specific area obey to the regional development of the country.

Later, the Colombian electrical system was finally created and interconnected, and ISA-Interconexión Eléctrica S.A. E.S.P was left under the control of the national interconnected system, allowing the exchange of energy between regional systems, in order to achieve the best use of the energy capacity of the whole system. Since then ISA, was responsible for the coordination of the electricity supply, following optimization processes, where the costs of the system were minimized, planning of the expansion of the generation and transmission system and, if necessary, for construction and operation of the new generation plants. During the **1980s**, the Colombian electricity sector went into a crisis, as well as in most Latin American countries. This situation was mainly due to tariff subsidies and the politicization of state enterprises, which led to a deterioration in the performance of the sector. At the same time, they developed large generation projects, with significant cost overruns and delays, eventually making the sector a major burden for the State.

On the other hand, throughout the world, the effectiveness of State monopolies in the provision of public services began to be questioned, with major reforms being undertaken in some countries such as the United Kingdom, Norway and Chile. The change was radical: Introducing competition in the electricity sector. Allowing private investment, reaching the point of privatizing state companies. Eliminate vertical integration, separating the business of transmission, distribution and generation. Leave to the state only the role of supervisor and regulator.

At the beginning of the **1990s** it was necessary in Colombia to modernize the electricity sector, opening it up to private participation, and following a similar scheme to the pioneer countries in this development, especially the United Kingdom. This restructuring was carried out with the laws 142 (Public Services Act) and 143 (Electrical Act) of **1994**, which defining the regulatory framework to establish the conditions for its development, it was determined under healthy competition. These laws created the Wholesale Electricity Market. The regulation of this market was developed by the Energy and Gas Regulation Commission - CREG. For this purpose, the national commission consulted and international consultants, and with the support of companies in the same sector, has promulgated the basic regulations and launched the new scheme from 20 July **1995**.

2.1.1   Legal mark

The political Colombian constitution of 1991 establish as an obligation of the Colombian state the achievement of the efficiency in the public service provision. For that purposes created the free competition in that activities, admits the concurrency of

thrid parties in this economy sector, and accenting the regulator role of the Colombian state.

2.1.2 Constitutional mark

For establishing the new structured mark due to the constitution, is issued the home public services law (law 142 emitted in 1994.), and the "electric law" (law 143 emitted in 1994.), by means of are defined the generals criterion and the politics that must be followed for the home public service provision in the country. Additionally, are defined the procedure and the mechanism for its regulation, control an vigilance.

2.2 Description of the Colombian interconnected system

At the end of the 60's, the National government decided to connect and integrate all the regional electrical systems of the country and what we know today as the *National Interconnected System, SIN*, was created. It is made up of all the power transmission lines and substations in the country, means through which energy is transported from the power plants to the towns and cities where it is consumed. As the entire energy production chain is integrated into this system (generators, transmitters, distributors and marketers), also it is guaranteed that all regions of the country receive energy service 24 hours a day, all year round.

The SIN is made up of more than 30 energy companies among power generation, transmission and distribution companies in Colombia along with 209 generation plants (hydraulic, thermal, solar, wind, co-generators and auto-generators) and approximately 26,333 kilometers of energy networks. These networks make up the National Transmission System (STN), which are network systems that operate at voltages greater than 220 kV, and the Regional Transmission System, (STR), which operate at voltages between 110 kV and 220 kV. Some international interconnections (Ecuador and Venezuela) are also part of the SIN. In table 2.1 is sum up the total line belonging to the Colombian interconnected system with its line length in km and the percentage of line corresponding each line portion between the total length of lines.

In other hand, SIN is operated and managed by the company XM - Company of Market Experts, which is a subsidiary company of ISA and operates the SIN through the National Dispatch Center (CND). However, XM is not alone nor has absolute control since the SIN has a very important institutional structure that is integrated with the different entities of the National Government.

The direction is in charge of the Presidency of the Republic, through the Ministry of

	Longitud (km)	Longitud (%)
TOTAL LÍNEAS DE TRANSMISIÓN STR	26,630.39	
TRANSMISIÓN 110 kV	3,583.90	
ELECTRIFICADORA DEL CARIBE S.A. E.S.P	1,487.23	41.5
EMPRESA COLOMBIANA DE PETROLEOS	6.7	0.19
EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	19.9	0.56
EMPRESA DISTRIBUIDORA DEL PACIFICO S.A. E.S.P.	98.07	2.74
EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	1,652.22	46.1
INTERNATIONAL COLOMBIA RESOURCES CORPORATION	304	8.48
TRANSELCA S.A. E.S.P.	12.58	0.35
ZONA FRANCA CELSIA S.A E.S.P.	3.2	0.09
TRANSMISIÓN 115 kV	7,490.57	
CELSIA TOLIMA S.A. E.S.P.	538.42	7.19
CENTRAL HIDROELECTRICA DE CALDAS S.A. E.S.P.	495.68	6.62
CENTRALES ELECTRICAS DE NARIÑO S.A. E.S.P.	693.91	9.26
CENTRALES ELECTRICAS DEL NORTE DE SANTANDER S.A. E.S.P.	382.76	5.11
CODENSA S.A. E.S.P.	1,203.92	16.07
COMPA?A ENERGETICA DE OCCIDENTE S.A.S. ESP	338.7	4.52
ELECTRIFICADORA DE SANTANDER S.A. E.S.P.	539.61	7.2
ELECTRIFICADORA DEL CAQUETA S.A. E.S.P.	111.5	1.49
ELECTRIFICADORA DEL HUILA S.A. E.S.P.	332.27	4.44
ELECTRIFICADORA DEL META S.A. E.S.P.	376.3	5.02
EMPRESA DE ENER? DE ARAUCA E.S.P.	60	0.8
EMPRESA DE ENERGIA DE BOYACA S.A. E.S.P.	512.21	6.84
EMPRESA DE ENERGIA DE CASANARE S.A. E.S.P.	426	5.69
EMPRESA DE ENERGIA DE PEREIRA S.A. E.S.P.	7.8	0.1
EMPRESA DE ENERGIA DEL BAJO PUTUMAYO S.A. E.S.P.	92	1.23
EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	959.05	12.8
EMPRESA DE ENERGIA DEL QUINDIO S.A. E.S.P.	17	0.23
EMPRESA DE ENERGIA ELECTRICA DEL DEPARTAMENTO DEL GUAVIARE S.A. E.S.P.	187	2.5
EMPRESA DISTRIBUIDORA DEL PACIFICO S.A. E.S.P.	206.79	2.76
EMPRESAS MUNICIPALES DE CALI E.I.C.E. E.S.P.	3.4	0.05
Ingenio Mayaguez S.A.	2.85	0.04
INTERCOLOMBIA S.A. E.S.P.	3.4	0.05
TRANSMISIÓN 138 kV	15.49	
INTERCOLOMBIA S.A. E.S.P.	15.49	100

Table 2.1: Table of the total lines belonging to STR in the Colombian interconnected system. Description of the line length in km and in percentage. Source: XM colombian sytem operator paratec web system. [44]

Mines and Energy, the planning is done by the Energy Mining Planning Unit, UPME ,the regulation corresponds to the Energy and Gas Regulation Commission, CREG, and the Ministry of Mines, the Treasury and the National Planning Department also participate there, superservices and the Superintendence of Industry and Commerce exercise control and surveillance, agree on the technical aspects to ensure that the operation of the SIN is safe, reliable and economical is the responsibility of the National Operating Council, who is also the executor of the Operating Regulations, the Advisory Commission for the Monitoring of the Energy Situation CACSSE, makes the sector coordination and monitoring, and the aforementioned XM, does the operation and settlement.

XM operates the SIN, complying with standards and technical agreements dictated by the Government and is monitored by several entities, which makes this operation reliable and safe for all users of the energy service. The National Dispatch Center, is in charge of planning, programming, coordination, supervision and control of the integrated operation of the generation and transmission resources of the National Interconnected System. The approach of the operation is made under the following principles: reliability, safety and sufficiency, also complying with articles 33 and 34 of Law 143 of 1994, with the operating regulations issued by the Energy and Gas Regulation Commission, CREG, and the technical agreements approved by the National Operating Council, CNO. Indeed, the energy generated by all hydroelectric, solar and wind power plants in Colombia is delivered to the National Interconnected System (SIN), an entity that is responsible for distributing that energy and meeting the demand of the entire country. This means that the generation plants do not meet the energy demand of the municipality or region where it is located, since the energy goes directly to the SIN.

The SIN has an installed capacity of 17,326 MW and an annual maximum demand of approximately 10,700 MW. In 2018, a total of 68,944 GWh of energy was generated through the SIN. Under normal conditions, more than 80% of the energy generated in Colombia is produced with renewable resources, especially water, and some megawatts already come from wind and sun. In addition, there is thermal generation, which allows for a diverse energy matrix in which the continuity of the service can be maintained. There are many meteorological conditions of low hydrological contributions such as an the "boy" phenomenon. This phenomenon according to [19] is a natural phenomenon of variability climatic (Not the climatic change). This phenomenon is developed in the pacific tropical ocean. This phenomenon is characterized by an increase in the pacific tropical ocean temperature. Also the alisiso winds are weakened. Therefore, there is a declining in rainfall, related with

the normal rain indicator in the country. In that case the hydraulic generation is not capable to sustain the peak load There, the contribution of national natural gas, imported natural gas (liquefied natural gas regasification plant in Cartagena) and coal stand out.

However, let's see the other face of the moon. For example, In 2018, from the figure 2.1 the generation was 82.16% of hydraulic energy, 16% from fossil fuels and 1.14% was generated by biomass, wind and solar. This huge hydrualical generation obey to the "girl phenomenon" or in spanish: fenomeno de la niña.
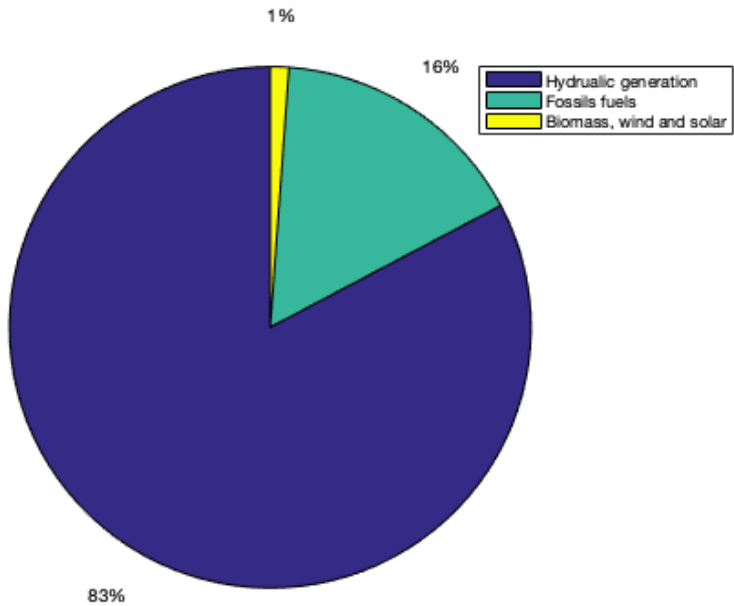
Figure 2.1: Generation profiles in percentage of the total energy generated in the girl or niña phenomenon of 2018, sorted by the fuel used for the generator in mention.

Contrary to the "Boy phenomenon", the " Girl phenomenon" inside the climatic variability scales, there are cold and hot phases. In that sense, the cold phase about climatic variability is what is called "girl phenomenon". These two are determinants in the climatic pattern of the areas in the terrestrial surface. Thus, the "girl phenomenon" is characterize by a decrease in the pacific tropical ocean temperature. Indeed, the sea surface temperature across the equatorial Eastern Central Pacific Ocean [19] will be lower than normal by 3 to 5°C (5.4 to 9°F). An appearance of La Niña persists for at least five months. It has extensive effects on the weather across the globe. However, each country and island nation has a different threshold for what constitutes a La Niña event, which is tailored to their specific interests. La

Niña causes higher rainfall than normal rainfall in the central Andes [14] as is seen in figure 2.2.

On the oher hand, one of the great advantages of having an interconnected system has to do with having the energy resources of all regions of the country integrated, connected and complying with the same regulatory standards. In this way, the energy produced in Boyacá can reach the Valle del Cauca or Nariño, or the deficiency that could be registered, for example, in the plants of the Atlantic Coast can be taken care of by a transporter that makes it arrive from any other region.

All companies that are part of the SIN must comply with an investment plan for maintenance and updating of the electricity networks as established by the regulations of the Colombian electricity sector, which is issued by the Energy and Gas Regulation Commission (CREG). These investments must be reflected in the improvement of the quality of the service, the reduction of the losses of the system and in general in the provision of the service to the users. Indeed, during 2018, Celsia made investments in its electrical infrastructure worth $80,237 million that contemplated improvements in substations ($17,862 million), reinforcement of the grounding of high voltage lines ($1,700 million), medium and low voltage networks, new Transformers and Technological Modernization ($60,675 million). They are also working to strengthen the electricity network of three departments of the Coast: Córdoba, Sucre and Bolívar. Celsia won the Upme tender to advance the construction of the 220 kV Toluviejo substation and the assembly of 160 km of new networks at that same voltage level.

Between 2022 and 2023, 23 new power generation plants will enter the SIN: 12 thermal, 3 hydraulic, 6 wind and 2 solar, which cover the demand defined by CREG for these years. These projects are located in the municipalities of Bolívar, Córdoba, Antioquia, Caldas, Valle del Cauca, Cesar, Guajira, Casanare and Meta. These works will strengthen the National Transmission System (STN) in that area of the country for and also the SIN to provide greater reliability to the system.

2.3 Description of the Colombian non interconnected system

The supply of electricity in Colombia is based on the **National Interconnected System (SIN)** and several isolated local systems in the **Non-Interconnected Zones (ZNIs)**. SIN covers one third of the land, with 96 % of the population covered. However, exists another 4% which is not supplied by (SIN). The ZNI includes the remaining two third of the domestic land, provides only 4 % of the
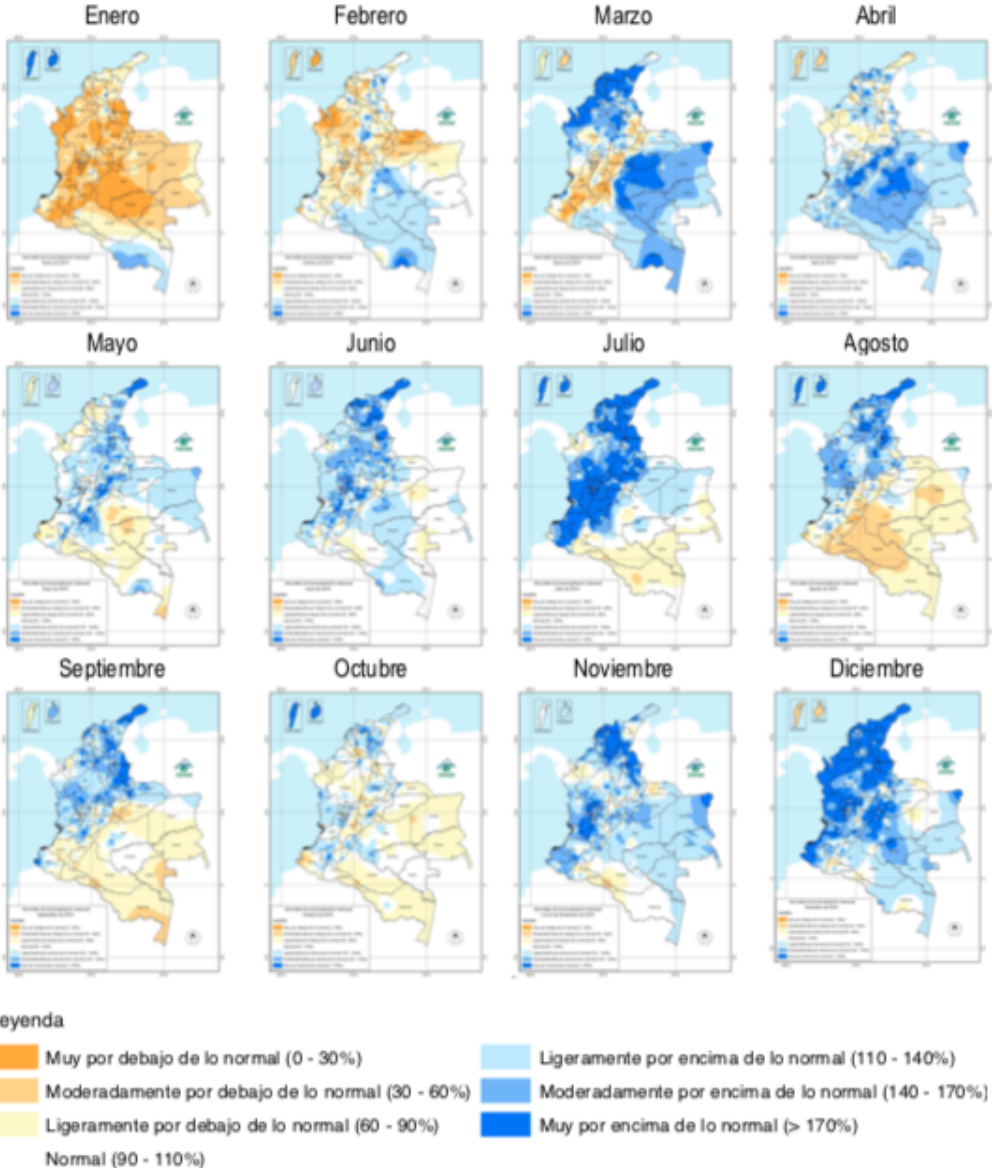
Figure 2.2: Alteration rainfall map in January and December month of the niña phenomenon in 2018.

population [5]. Looking a reason for that 4% of the Coolombian population not covered of electricity, is found in figure 2.3 the perfect answer. As seen, there is a lot of scattered nature of several areas in Colombia, and a a lot of green extension and dense jungles. Clearly, the consequence about this fact electrically speaking, is about the local generation to feed those communities, instead of employing a connection to the national transmission system. Therefore, the topic about rural electrification is a problematic in the Colombian power system. Consequently, must been generated also opportunities for looking many strategies and approaches to solve the rural electrification problem. However, there are not a lot of strategies in literature to overcome many barriers well known as the lacking of geographical information in these zones, also an electric consumption estimated, and other important data useful for design and structuring an electrical MV distribution network.

Thus, from rural electrification we see a motivation fro through this master of science thesis, perform an methodology aimed to solve these lacking of information. In that sense, in chapter 3 is described an approach for that problems of electrification in rural areas employing GIS tools. Additionally, to validate this model proposed, has been applied the proposed approach in the city of Puerto Carreño, Colombia. This city is in the boundary with Venezuela, and is inside the ZNI of Colombia.

Figure 2.3: Colombian main natural reserve. Map from QGIS google map layer.

These ZNI are mostly served by small diesel generators, many of which are not in good working conditions [5]. In Colombia, electricity coverage is 93 percent in urban areas and 55 percent in rural areas. About 2.3 million people do not have access to electricity yet [40]. From figure 2.4 we can appreciate those zones highlighted in green which do not belongs to the National Interconnected system (SIN).

These zones are under the control of the Institute for the planning and promotion of Energy solutions for the non-interconnected areas **(IPSE)**. This Institute (IPSE) covers the energy requirements of individuals who do not have this service. Also, identifies, implements and monitors sustainable energy alternatives with requirements of efficiency and effectiveness in those Non-Interconnected Areas. So IPSE finally look for improving the living circumstances of their residents builds and its security from enhancing the electric flow service. The non interconnected zones. These zones are present in 18 departments, including 5 departmental capitals covering indeed 95 municipalities across the extension of Colombia. There are located 209.204 users with electric flow provision, provided by 94 provider entities. In electrical terms, there is 227.439 kW of operative capacity which represent the equivalent range of power that is possible to feed. Respectively the installed power for non conventional renewable energies, the amount dedicated for (ZNI) is 6.787kW.

IPSE is an institution entailed from the Minister of mines and energy of the Republic of Colombia with total control of (ZNI). As each institution with a public duty, exist a list of functions and objectives which are described in below:

1. Structure, promote, execute and supervise sustainable energy initiatives in order to contribute to access and enhance the performance and continuity of NIZ energy services.

2. Promote the use of non-conventional energy sources in NZs as an energy alternative under the requirements of energy efficiency leadership.

3. Monitoring and controling the delivery of energy services in NZs through the exchange of appropriate technical data.

4. Improve the perception of the products and services provided by the Institute by IPSE stakeholders (customers, distributors, contractors, groups, representatives and control bodies).

5. Improve the effectiveness, efficiency and effectiveness of procedures by stopping and alleviating environmental, security and health hazards at job with a extremely skilled human crew.

6. Promote the health and safety of IPSE public servants and stakeholders, prevent and control hazard and hazard factors associated with job through the operations scheduled and established in the Institute's Health and Safety Management System.

7. Prevent and decrease pollution by controlling the important financial elements of IPSE for the security of the ecosystem.
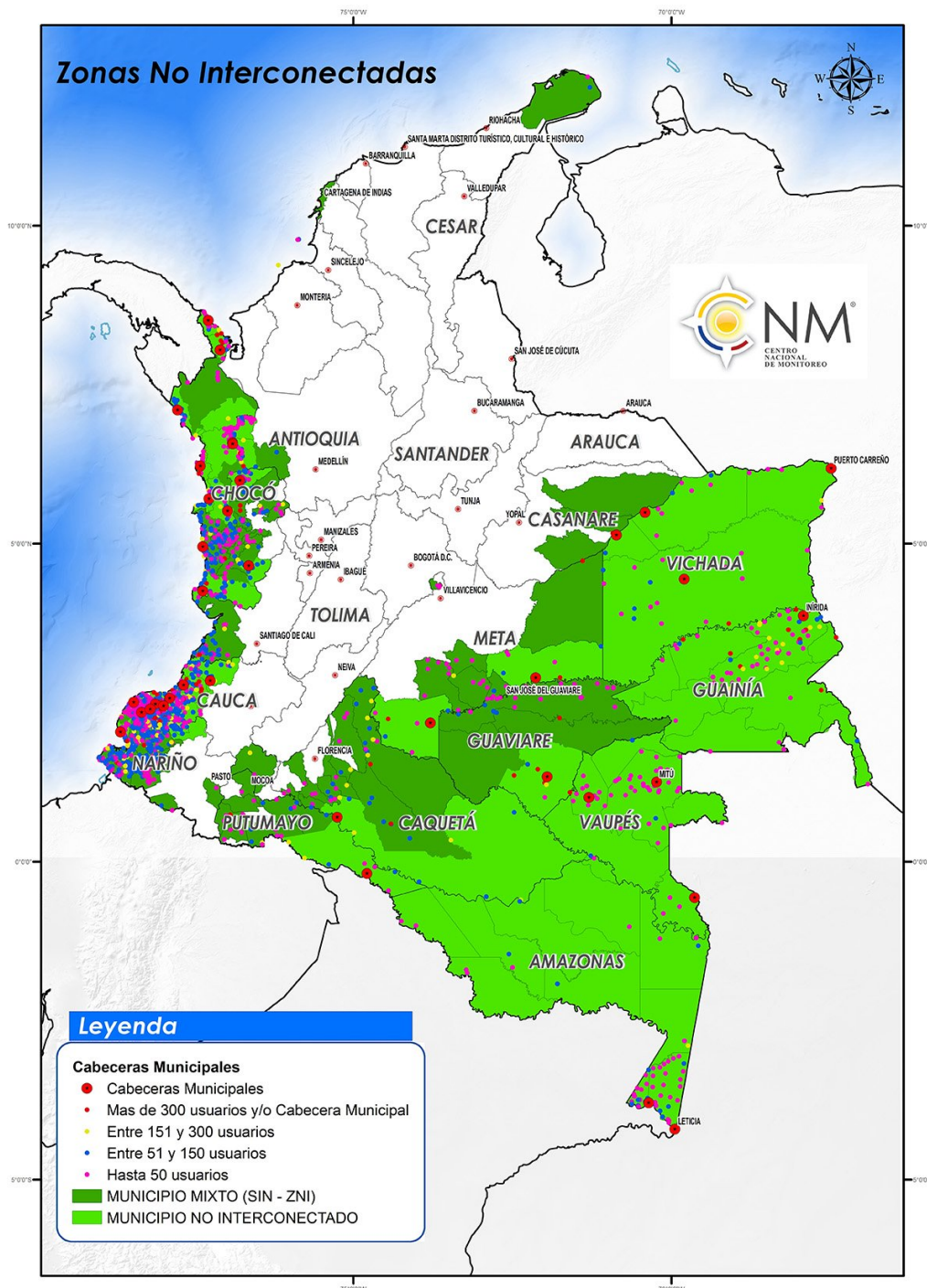
Figure 2.4: Non interconnected zones in Colombia. These zones are highlighted in green.
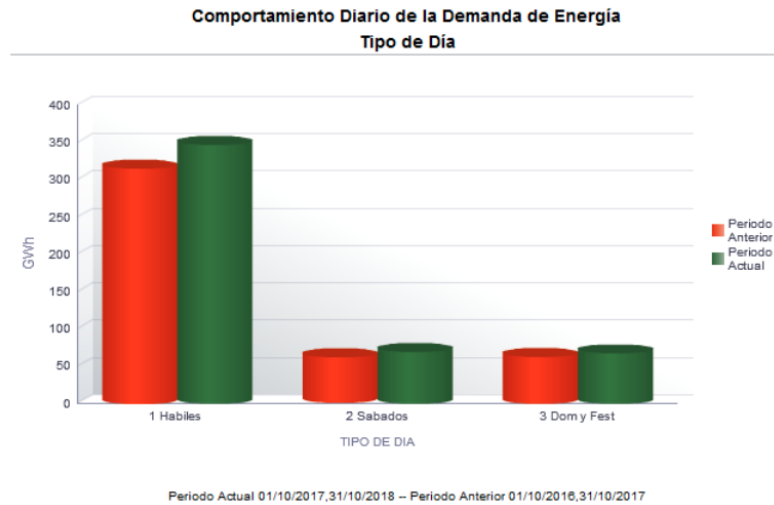
Figure 2.5: Demand daily behaviour in the non interconnected zones (ZNI spanish sigle)

2.4 Description of Puerto Carreño in generalities: Demographical data & electric information

The town of Puerto carreño has 16.000 habitants according to monthly telemetry report from IPSE [22]. However, in figure 2.7 can be appreciated the population layer (from QGIS 3.4) converted in vectorial point type. Then, summing all the points appreciated in the figure 2.7, can be concluded that the total population are 10986 habitants. In addition, belong to this municipality the village of Casuarito , and the Police inspection of Garcitas, La Venturosa y Puerto Murillo.

Moreover, from the DANE geoportal is possible to see the total extension of the total Puerto Carreño's city. Puerto Carreño's has a total extension about 12241 km^2.Also, from the QGIS layers the county seat has an extesion of 7.23 km^2. For further information about this municipality, the url of Puerto Carreño's city is: `http://www.puertocarreno-vichada.gov.co/MiMunicipio/Paginas/Informacion-del-Municipio.aspx`

Although this number, is not completely near to the population number reported in [22], is worth to mention the following aspects to validate the population data from the layer selected:

- From the 16000 habitants, 13480 correspond to the county seat according again to [22], page 471. While 2520 correspond to the rurals areas. In that sense is nearer our QGIS population data to the real data (county seat).

- For economical reason, would be thought that designing a MV substation for less people, would result in a cheaper budget for its construction. Also, according to [22] in page 471, the number of users which consuming energy from
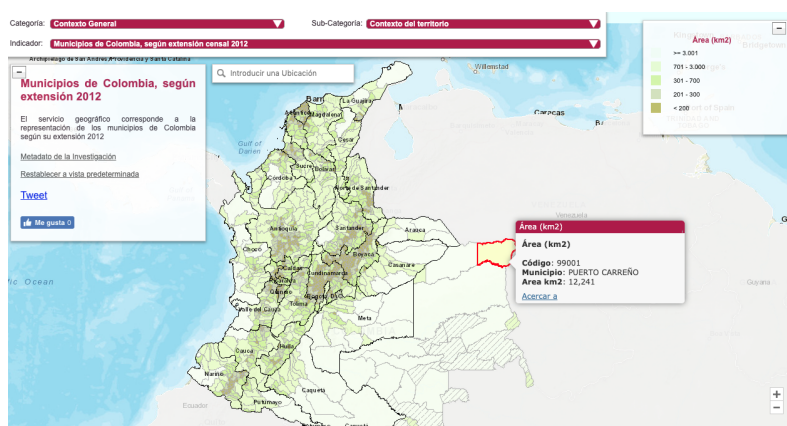
Figure 2.6: Area extesion of Puerto Carreño Vichada, Colombia. Image extracted from DANE geoportal [8].

the Puerto Carreño's circuits are 4533.

Thus, setting the habitational input data according to the estimated from QGIS is a good middle ground, since of we can see combined the potential numbers of users with the demand growing conditions. In table 2.2 is summarized the main data for the MV substation characterization.

Data	Value
County seat number of habitants	13480
Electricy users declared on IPSE telemetry report	4533
QGIS population layer data (habitants numbers)	10986
Total area extension Puerto carreño's city	12241 km^2
County seat extension	7.3 km^2
Altitude of county seat	51 msnm
Peak value of load curve	3500kW

Table 2.2: Main data for the MV substations characterization

Figure 2.8 exhibit the one line diagram of the local electric system of Puerto carreño-Vichada.

2.5 Colombian market structure

In Colombia there are three institutions dealing with the management and control of the market activities:

1. UPME (Unit for Mining and Energy Planning), a specific compartment of the Ministry of Mine and Energy, which is in charge for the long term National Energy Plan and the Expansion Plan.

2. CREG (Regulatory Commission for Gas and Energy), public commission re-
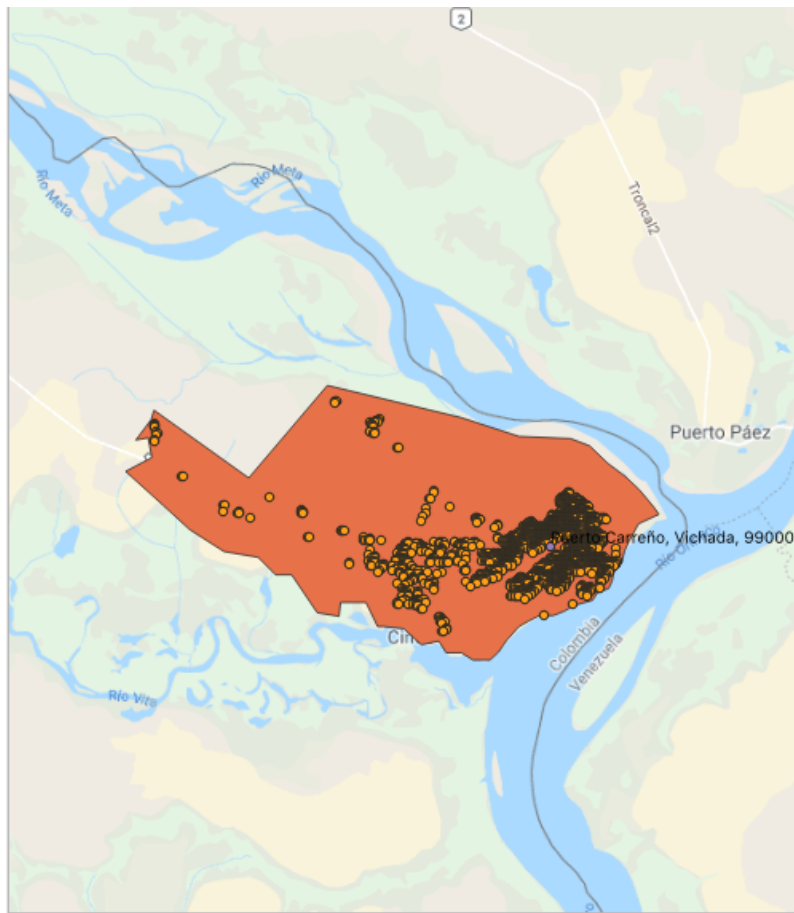
Figure 2.7: Population (pop-2018-10-01) layer clipped with the polygon shape of Puerto Carreño, Vichada-Colombia.

sponsible for the efficiency of the energy supply and the market competition.

3. XM, the private company that acts as Market Operator; it manages the market closing and all the activities connected to the energy dispatch.

Also, the figure 2.9 shows a hierarchical scheme of the market institutions. Those compose administrative and technically the Colombian electrical market. Also, specify the official name of each of this market participant, and their role inside the electric energy sector [44].

In other hand, Colombia has a liberalized energy market since 1995 when Generation, Transmission, Distribution and Commercialization were unbounded from the chain of electricity. However, transmission part is the only activity in which there is not competition among the market participants. Colombia's electricity industry was the exception to the rule of a gradual approach to private sector involvement in Colombia's infrastructure. It has finished a major program of privatization over the period 1993/01 together with the gas industry. This resulted in US$ 1.8 billion in asset revenues (mainly in the electricity industry) and an additional US$ 3.1 billion
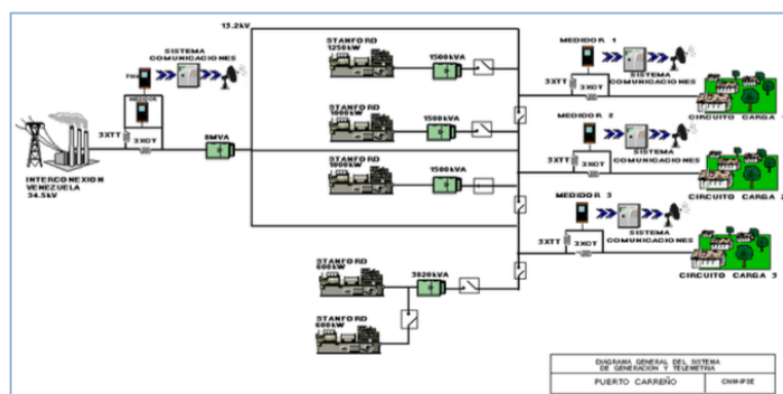
Figure 2.8: One line diagram of Puerto Carreño's city. Here also can be appreciated the interconnection agreement between Colombia and Venezuela.Source: http: //www.dane.gov.co/EstimacionesdePoblacion1985-2005yProyeccionesDePoblacio? n2005-2020-DANE-Fechadeactualizacio?ndelaserie-2016.

in capitalization (mainly in the production industry), including some revenues to staff and trade unions as authorized by Law 226/95. While these transactions were not always straightforward, more than one bidder attracted several of them, and several of them attracted only one bidder, but nevertheless brought about significant structural changes in the industry, as well as significant fresh fiscal and capital assets. As a result, approximately 45% of installed generation capacity and 50% of distribution assets are controlled by private investors. [40]. To summarize the private participation in electricity sector in Colombia, the table 2.3 organize the information suitably by year of market entrant, mobility, value (US$m).

2.5.1 Colombian generation portfolio

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 2.11 and figure 2.10 is really useful for further information about the "non common" generation technologies.
Private generators perceive that laws are subject to significant regulatory uncertainty and regulations actions that govern the electricity wholesale market. Since the wholesale market was established, on average, the Regulatory Commission (CREG) has released more than eighty fresh laws each year. These regulations often require basic adjustments in market rules, including how different costs are calculated, how electricity supplies are regulated, and whether price cap constraints are imposed, with significant impact on economic results of companies. Private investors are also worried about the Regulatory Commission's absence of autonomy (CREG), which

	Year	Modality	Value (US$m)
Generation			
	1993/97	BOT	-
7 IPP's	1993/99	Merchant plant	-
4 IPP's	1996	Privatization	506
Betania	1996	Privatization	641
Chivor	1996	Privatization	18
Termotasajero	1996	Privatization	16
Termocartagena	1997	Capitalization	951
EMGESA			
Transmission Isa	2000	Capitalization	135
Distribution EPSA	1996	Privatization	622
CODENSA	1997	Capitalization	1226
Electrocosta and Electrocaribe	1997/98	Capitalization	1035
Total			5150

Table 2.3: Private participation of private electricity companies in Colombia. Source: [Chahin, & Rojas, 2004 REDI electricity report.]

Figure 2.9: Market institutions which compose the Colombian electricity market.

Generation technology	Percentage of the total installed capacity (%)	Installed capacity (MW)
Hydraulic	69.17	12.258
Thermal	30.71	5443.5
Natural gas	20.97	3716.5
Coal	9.74	1727
Wind	0.2	19.5

Table 2.4: Summary of the percentage of the total installed capacity (%) and its equivalent installed capacity in MW.

leads to a tendency to still see electricity tariffs as a tool for social policy, preventing them from being based on business factors. According to [44] the 17,721 MW in June 2018, Colombia had an effective installed generation capacity around 17,721 MW. In that sense, the generation technologies in Colombia most used have the following participation (in percentage) which is equivalent in MW a certain capacity.

Digging deeper from table 2.5 is possible to analyze many aspects in the generation capacity of the Colombian generation market. First of all, the 2016 year presented a really interesting reduction in terms of the electricity generation in GWh. First of all, the 2016 year presented a really interesting reduction in terms of the annual growth rate (%). As principal consequence, has been found the crude "Boy phenomenon", characterized for a rain absence. Indeed, according to IDEAM(2016) during these month the temperature is increased in 2.5 Celsius degrees, causing a reduction of

	Year	2014	2015	2016	2017	2018
Generation technology						
Hydro		10,920	11,501	11,606	11,726	12,258
Coal		1,172	1,348	1,356	1,369	1,727
Gas and others		3,581	3,635	3,635	3,742	3,736
Total		15,673	16,484	16,597	16,837	17,721
Annual growth rate (%)		7.7	5.2	0.7	1.4	5.3

Table 2.5: Growth in installed electricity capacity (MW) in Colombia. **Source:***[44], and Unidad de Planeación Minero Energetica (UPME); Expertos en Mercados (XM); Sistema de Información Electrico Colombiano (SIEL or Colombian Electric Information System); Global Transmission Research*

the 40% in the stored capacity of the water reservoir. As the main part of the generation in Colombia is due to Hydraulic sources, this dramatically reduction broke every contingency scheme. Thus, to overcome this big problem and supply the peak load, the thermal plants were employed at its nominal capacity which cause an important increase diesel consumption.
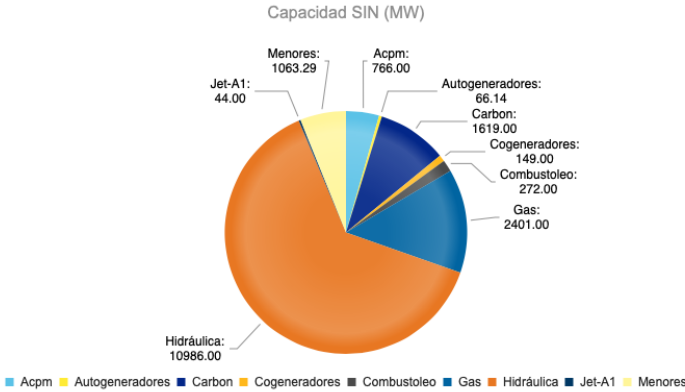
Figure 2.10: Description about the total generation technologies belonging to the electric Colombian power system.

The figure 2.11 exhibits that the main natural resource used in Colombia for the electric generation is the hydraulic. Indeed, figure 2.12 detail the contribution for each member per Colombian zone of the SIN (National interconnected system) where the hydraulic reserves is around 70% of the total installed capacity. A number equivalent to 11,985.89 GWh. Thus, according that is possible analyze the cleanliness of the Colombian energetic matrix. The country has a great number of rivers, lakes, and other hydraulic resources plus a geography with many mountains ranges and natural reservoirs that allows the creation of big hydraulic power plant with relative

low investment cost.

Finally, exits a classification in the form dispatching and productive activity is done. If the generation plan is bigger than **20MW** is considered a "Centrally dispatched" plant, otherwise it is considered "Not centrally dispatched". Moreover, if the plant produced thermal and electric energy as part of productive processes, where the main activity is not related to electric generation is called "Co-generation". If electricity generation is concentrated on local production and the only surplus sold to the National Interconnected System (SIN) is called "auto generation" Otherwise if the primary activity is electrical generation, its called "generation".
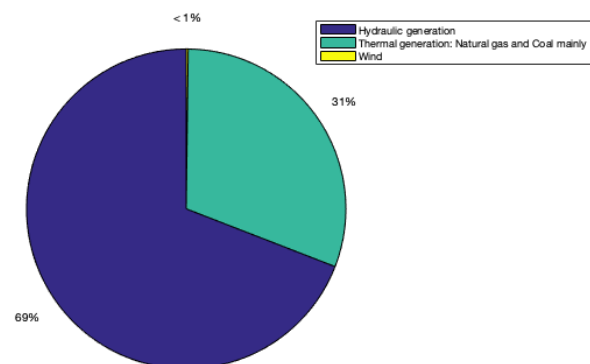
Figure 2.11: *Generation percentage by technology of power generation. List of the main generation technologies employed in the Colombian electric power system.*

Figure 2.12: *National interconnected system aggregate of the hydraulic consumption*

2.5.2 Colombian transmission system

Colombia's integrated national power grid serves more than one third of the country's territory, covering the 96% of the population. [40]. The transmission network

is generally in good condition, but suffers from frequent terrorist attacks until 2014 where the armed conflict between the Colombian government with the antique Guerrilla of FARC has ceased. The SIN transmission grid comprises **26,630.39** kilometers with 118 substations organized in 13 areas [12]. It is divided in two groups. One operates at 220 kV or above, which is called the national transmission system or (STN initial in Spanish). The another group is the regional transmission system or (STR) which operates from 66kV to 220kV. This is really strong transmission system compared with other countries in the region, even in the world. As evidence of it, looking the Technical standards used for maintenance labors, and maneuver of operation are quite good. Additionally, evaluating the state of their assets is possible to conclude they are well maintained [40]. The main problem faced by the grid are terrorist attacks, which destroyed 483 transmission towers in 2002, during 127 separate attacks [25]. The amount of towers attacked, however, decreased in 2003 to 326. The transmission network's radial topology amplifies the disturbance created by such assaults, which may be considerably reduced by some strategic reinforcements in network design. Furthermore, some regional links are weak, leading to issues of stability and regulation of electrical frequencies.

From macroeconomic point of view, the transmission system in Colombia is a natural monopoly, attending even to a technological definition of natural monopolies. It is managed by public and private companies. The National interconnected system, at national transmission system layer, has electrical tension levels equal or higher than 220 kV. In the Table 2.6 is shown the length of the transmission grid owned by different system system operators, sorted by voltage levels of STR and STN. Many companies manage the transmission system since of before the conformation of the national interconnected system, each region was owner of its own networks, including transmission and distribution. 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.

2.5.3 Colombian distribution system

The distribution system is a zonally operated natural monopoly. That signifies in the same city, and so on. There may be more than one system operator for distribution. By bidding, the operators are chosen. In the distribution system, the voltage rates are below 110kV. The primary circuits mainly operate at voltages of 13.2, 11.4 and 7.62 kV, while the secondary circuits mainly operates at 120/208 & 120/240

	Longitud (km)	Longitud (%)
TOTAL LÍNEAS DE TRANSMISIÓN SIN	26,630.39	
TRANSMISIÓN 110 kV	3,583.90	
ELECTRIFICADORA DEL CARIBE S.A. E.S.P	1,487.23	41.5
EMPRESA COLOMBIANA DE PETROLEOS	6.7	0.19
EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	19.9	0.56
EMPRESA DISTRIBUIDORA DEL PACIFICO S.A. E.S.P.	98.07	2.74
EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	1,652.22	46.1
INTERNATIONAL COLOMBIA RESOURCES CORPORATION	304	8.48
TRANSELCA S.A. E.S.P.	12.58	0.35
ZONA FRANCA CELSIA S.A E.S.P.	3.2	0.09
TRANSMISIÓN 115 kV	7,490.57	
CELSIA TOLIMA S.A. E.S.P.	538.42	7.19
CENTRAL HIDROELECTRICA DE CALDAS S.A. E.S.P.	495.68	6.62
CENTRALES ELECTRICAS DE NARI? S.A. E.S.P.	693.91	9.26
CENTRALES ELECTRICAS DEL NORTE DE SANTANDER S.A. E.S.P.	382.76	5.11
CODENSA S.A. E.S.P.	1,203.92	16.07
COMPAÑIA ENERGETICA DE OCCIDENTE S.A.S. ESP	338.7	4.52
ELECTRIFICADORA DE SANTANDER S.A. E.S.P.	539.61	7.2
ELECTRIFICADORA DEL CAQUETA S.A. E.S.P.	111.5	1.49
ELECTRIFICADORA DEL HUILA S.A. E.S.P.	332.27	4.44
ELECTRIFICADORA DEL META S.A. E.S.P.	376.3	5.02
EMPRESA DE ENERGIA DE ARAUCA E.S.P.	60	0.8
EMPRESA DE ENERGIA DE BOYACA S.A. E.S.P.	512.21	6.84
EMPRESA DE ENERGIA DE CASANARE S.A. E.S.P.	426	5.69
EMPRESA DE ENERGIA DE PEREIRA S.A. E.S.P.	7.8	0.1
EMPRESA DE ENERGIA DEL BAJO PUTUMAYO S.A. E.S.P.	92	1.23
EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	959.05	12.8
EMPRESA DE ENERGIA DEL QUINDIO S.A. E.S.P.	17	0.23
EMPRESA DE ENERGIA ELECTRICA DEL DEPARTAMENTO DEL GUAVIARE S.A. E.S.P.	187	2.5
EMPRESA DISTRIBUIDORA DEL PACIFICO S.A. E.S.P.	206.79	2.76
EMPRESAS MUNICIPALES DE CALI E.I.C.E. E.S.P.	3.4	0.05
Ingenio Mayaguez S.A.	2.85	0.04
INTERCOLOMBIA S.A. E.S.P.	3.4	0.05
TRANSMISIÓN 138 kV	15.49	
INTERCOLOMBIA S.A. E.S.P.	15.49	100
TRANSMISIÓN 220 kV	2,675.23	
EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	842.95	31.51
GRUPO ENERGIA BOGOTA SA ESP	20	0.75
INTERCOLOMBIA S.A. E.S.P.	177.64	6.64
TRANSELCA S.A. E.S.P.	1,634.64	61.1
TRANSMISIÓN 230 kV	10,329.81	
CENTRALES ELECTRICAS DEL NORTE DE SANTANDER S.A. E.S.P.	9.2	0.09
DISTASA S.A. E.S.P.	18.75	0.18
ELECTRIFICADORA DE SANTANDER S.A. E.S.P.	120.41	1.17
EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	272.33	2.64
EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	149.12	1.44
GRUPO ENERGIA BOGOTA SA ESP	1,617.32	15.66
INTERCOLOMBIA S.A. E.S.P.	8,142.68	78.83
TRANSMISIÓN 500 kV	2,535.39	
EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	45.9	1.81
INTERCOLOMBIA S.A. E.S.P.	2,489.49	98.19

Table 2.6: Table of transmission lines length per operator agent and voltage level of operation. [44]

Nombre	Sigla	Ciudad	URL	Inicio Oper.
Electrificadora Del Caribe S.A. E.S.P.	ELECTRICARIBE S.A. E.S.P.	Barranquilla (Atlantico)		22/08/1998
Empresa De Energía Del Putumayo S.A E.S.P.	EEPSAESP	Mocoa (Putumayo)	http://www.energiaputumayo.com	06/07/1997
Compañía Energética Del Tolima S.A. E.S.P.	ENERTOLIMA S.A. E.S.P.	Ibague (Tolima)	http://www.enertolima.com	03/09/2003
Empresa De Energía De Casanare S.A. E.S.P.	ENERCA S.A. E.S.P.	Yopal (Casanare)	http://www.enerca.com.co	22/11/2004
Empresa De Energía Del Bajo Putumayo S.A. E.S.P.	BAJO PUTUMAYO	Puerto Asis (Putumayo)	http://www.eebpsa.com	03/02/1999
Empresa De Energía Del Quindio S.A. E.S.P.	EDEQ S.A. E.S.P	Armenia (Quindio)	http://www.edeq.com.co	01/01/1996
Ruitoque E.S.P.	RUITOQUE E.S.P.	Floridablanca (Santander)		01/01/1996
Empresas Municipales De Cartago S.A. E.S.P.	EMCARTAGO S.A. E.S.P.	Cartago (Valle)	http://www.emcartago.com.co	30/09/1998
Empresa De Energía De Arauca E.S.P	ENELAR E.S.P.	Arauca (Arauca)	http://www.enelar.com.co	01/01/1996
Electrificadora Del Caquetá S.A. Esp.	ELECTROCAQUETA S.A. E.S.P.	Florencia (Caqueta)	http://www.electrocaqueta.com	01/01/1996
Codensa S.A. E.S.P.	CODENSA S.A. E.S.P.	Santafe De Bogota D.C. (Bogota)	http://www.codensa.com.co	23/10/1997
Empresa De Energía Del Valle De Sibundoy S.A. E.S.P.	EMEVASI S.A. E.S.P.	Sibundoy (Putumayo)		01/02/1997
Empresa De Energía Eléctrica Del Departamento Del Vichada S.A. E.S.P.	ELECTROVICHADA S.A ESP	Puerto Carreno (Vichada)		24/06/2002
Compañía Energética De Occidente S.A.S. Esp.		Popayan (Cauca)		29/06/2010
Expertos De Energía Esp Sas		Bogota		01/04/2018
Empresa Distribuidora Del Pacifico S.A. E.S.P	DISPAC S.A. E.S.P.	Quibdo (Choco)		01/08/2002

Table 2.7: List of the main distribution companies in Colombia. This companies plays a role in the market as distributors and trading company. Source: CREG information portal

\textbf{Nombre}	\textbf{Sigla}	\textbf{Ciudad}	\textbf{URL}	\textbf{S.I.}	\textbf{Inicio Oper.}
Empresa Municipal De Energía Eléctrica S.A-E.S.P		Popayan (Cauca)		Si	01/01/1996
Electrificadora Del Huila S.A. E.S.P.	ELECTROHUILA	Neiva (Huila)	http://www.electrohuila.com	Si	01/01/1996
Electrificadora Del Meta S.A. Esp.	EMSA	Villavicencio (Meta)	http://www.emsa-esp.com.co	Si	01/01/1996
Empresa De Energía Eléctrica Del Departamento Del Guaviare S.A. E.S.P	ENERGUAVIARE S.A E.S.P	San Jose Del Guaviare (Guaviare)		Si	10/09/2001
Empresa De Energía De Pereira S.A. E.S.P.	EEP	Pereira (Risaralda)	http://www.eep.com.co	Si	16/05/1997
Centrales Electricas De Narino S.A. E.S.P.	CEDENAR	Pasto (Narino)	http://www.cedenar.com.co	Si	01/01/1996
Compañia De Electricidad De Tulua S.A.	CETSA	Tulua (Valle)	http://www.cetsa.com.co	Si	01/01/1996
Empresas Municipales De Cali Eice	EMCALI	Cali (Valle)		Si	01/01/1994

Table 2.8: Table about the companies which develop the role of distributors of energy in Colombia, but also develop the business of generation and trading company.

V and generally at voltages below 600 V. Table 2.7 exhibits the main companies which plays a role in the Colombian market structure as distributors and trading companies. These companies have the denomination of distributor and trading companies in the Colombian market structure. However, along this subsection is possible to appreciate many other typologies for companies which run this business. Table 2.8 exhibits the main companies which plays a role in the Colombian market structure as distributions, generation and trading companies. Also, there are companies developing as well as the distribution business in Colombia, and the generation business. It's necessary to remember that in some zones in Colombia there is only local generation, since there is not a connection through a transmission line or a group of transmissions lines with the national interconnected system (SIN). Therefore, for feeding that zones with electric energy, a local, and almost dedicated generation company is necessary. Thus, These companies of 2.8 serves the zones in its boundaries with electric flow and providing through their distribution networks facilities for transporting the power until low voltage or domestic voltage levels.

2.6 CREG Technical rules indicators (AT, MT), quality indexes

The national regulation commission for energy and gas (**CREG** sigles in Spanish), is the Colombian institution entailed to regulate the electricity and gas public services. The **CREG** was born from the law act 142, and the law act 143 of 1994. It was created for the National Colombian government with the purpose of control the public service activities. Thus, intuitively the **CREG** mission is regulating the public services of electric energy and combustible gas in a technical way, independently, transparently, promoving the development in that sectors. Therefore, **CREG** acts in Colombia as the regulator entity in the Colombian sector entailed to legislate monopolies where is not possible competition for the market. In that sense, **(CREG)** issues periodically many resolutions aimed to promote the quality indexes for an efficient public service.

2.6.1 Primary frequency regulation

First of all, the **CREG** 025 from 1995, is a public document issued for controlling the primary regulation restoring action in which this resolution state that: Automatic variation, while the speed governor, the delivered power for the generation unit as the response in front of frequency changes in the system. The characteristic time of response are between 0 and 10 seconds. Then, are described a list of action automatically performed for each generation unit.

Additionally to the **CREG** 025 from 1995, the **CREG** 023 from 2001 state in complementariety *"All generation plants, and generation units centrally dispatched are in the obligation of allowing the primary regulation in frequency, equivalent to the 3% of the programmed hourly generation."*.

Consequently, are defined the following aspects:

- **Article 1st:** Characteristic time constant from 0-10 seconds.

- **Available capacity:** plants or generating units necessary for the regulation service provision.

- **Article 2nd:Obligatory nature of the service in the Primary frequency regulation.** All plants and/or centrally dispatched generation units are in the obligation of offering a primary frequency regulation service. Therefore, the frequency is stabilize in a different nominal value. *This service is not profitable.*

- **Article 4th: Rolling reserve, and dead band, and statism.** Every plant and/or generation units centrally dispatched must keeping, as minimum, a 3%

primary frequency regulation reserve of its programmed hourly generation. To give compliance with previous, the plants and/or generating units must be authorized to increase or decrease the generation, even when units are dispatched with the maximum availability declared, until the margin an in the defined actuation times.

- **Article 5th: Service evaluation of primary frequency regulation.** In base with the information obtained from the CND, the operation of plants and/or units of SIN, and/or units of SIN, and/or obtained from the field effectuated to the same ones, CND will determine the effective service provision of the regulation service of the primary frequency.

2.6.2   Secondary frequency regulation

The gas and energy regulation commission, by the **CREG-198 regulation of 1997.** are established transitory rules applicable to the service provision of the secondary frequency regulation (Automatic generation control-AGC).

Secondary regulation are control action in which is diminished or is injected additional power to the system with the goal of reaching the value of the nominal frequency after an event of load imbalance or generation imbalance. Characteristic response time from 40sec to 10 minutes.

The automatic generation control (AGC) plays a very important role in power system as its main role is to maintain the system frequency and tie line flow at their scheduled values during normal period and also when the system is subjected to small step load perturbations. Thus, beginning that load has dynamic behaviors. In that sense, if power generation is higher than power load, the generator speed and frequency will rise. Otherwise, If power generation is lower than power load, the generator speed and frequency will drop. Control signals can be obtained from speed and frequency.

2.6.3   Voltage control

The voltage control is one of the most important limits to be respected in a power system analysis. Voltage is supposed to be constant which is obviously. So we have to control it in such a way that it remains constant. Because off, most of the devices, apparatus, electrical machines, consumer appliances etc. are all designed to work at a specified voltage. Wide variations of voltage may cause errors in operation, malfunctioning or performance deterioration. The voltage control in transmission and distribution systems is usually obtained by using tap changing transformers. In this method, the voltage in the line is adjusted by changing the secondary **EMF** of

the transformer by varying the number of secondary turns. Secondary voltage of a transformer is directly proportional to the number of secondary turns. In Colombia, the regulation act that describes as a general criteria the planning of the electric operation of high voltage system, regarding to the (National transmission system) and (Regional transmission system) is the **CREG regulation 025 of 1995.**

Thus, in this administrative regulation act are considered the following considerations:

- **Article 2nd:** "In steady state the voltage in the busbars of 115kV,110kV, 220kV and 230kV can't be lower than 90% neither higher than 110% about the nominal value."
- **Article 3rd:** Are described the following steps in order to control the voltage when the voltage is higher the threshold for its equivalent nominal voltage level:

    Connection of Overhead transmission lines or distribution in hours of low load.

    Reactors disconnection.

    Capacitor connection.

    TAPS's transformers change of position.

    Capacitor disconnection.

    Reactors connection.

    Objective Voltage adjustment in generators.
- **Article 4th:** Are described the following steps in order to control the voltage when the voltage is lower the threshold for its equivalent nominal voltage level:

    Objective Voltage adjustment in generators.

    TAPS's transformers change of position.

    Capacitor disconnection.

    Reactors connection.

    Connection of Overhead transmission lines or distribution in hours of low load.

2.6.4 Acceptable frequency range in the electric system

First of all, the frequency stability is the ability of the power system of maintain the frequency inside of a range after an strict disruption, resulting in a significant imbalance between generation and load. In that sense, the creg resolution 070 of 1998 state that:

- **Article 1st:** The nominal frequency value is 60Hz.
- **Article 2nd:** The acceptable frequency range in Colombian is 59.8 and 60.2

Frequency	Demand preventive disconnection [%]	
[**Time**]	Con mantenimiento sin riesgo de disparo o sin mantenimiento	En mantenimiento con riesgo de disparo
0	10	20
1	20	20
≥ 2	30	30

Table 2.9: Demand preventive disconnection action chart according to CREG resolution 070 of 1998 [7]

Hz.

In this topic, also is important to stand out about the preventive demand disconnection, in case of maintenance without shot risk and without maintenance. In maintenance with shot risk. In that sense, the CREG resolution number 224 of 2016 say that:

Reliability criteria in presence of contingency: Where exist delays in the implementation of the expansion or replacement of the STN or STR networks, and in the electrical planning analyses of the SIN operation, it is detected that, without such expansion or replacement, the transport or generation resources available in the system are not sufficient to cover a simple contingency, maintaining a safe and reliable operation, the CND (Dispatched national center) will order preventive demand disconnections, provided that the following conditions are met: a) The possible occurrence of a simple contingency would generate an affectation greater than 20% of the total demand of at least one operational sub-area where the demand affectation was presented. b) Preventive demand disconnection compared to corrective demand disconnection represents a percentage

2.7 FAZNI

There are three distinct grants and programs that promote rural electrification in Colombia, each set up at distinct times for distinct reasons and all administered by the Ministry of Mines and Energy. At the end of 2006, the Ministry of Mines and Energy approved a total of US$ 23.3 million of rural electrification funds from these three funds and programs to benefit 14,965 families [20].

The Non-Interconnected Zone Electrification Fund **(FAZNI)** was set up in 2000 by the law 633 of this year to help remote areas outside the interconnected scheme. It considered both the development of current networks and the introduction of stand-alone solutions [21]. This law has three pillar which are the article 81, 82, and 83.

A continuation, these three articles are exhibited to understand the "roots" of this

founds, the goal for collecting that fund, and how is used.

ARTICLE 81: *"For each kilowatt hour dispatched on the Wholesale Energy Exchange Market, the administrator of the Commercial Exchange System (ASIC) will collect a weight ($1.00) m/cte, for the Financial Support Fund for the energization of unconnected areas. This value* **shall be paid** *by the energy generating agents and shall be valid until 31 December 2007 and shall be indexed annually with the producer price index (PPI) calculated by the Bank of the Republic. The Energy and Gas Regulatory Commission (CREG) will make the necessary adjustments to the current regulation to enforce this article."* [36]

Now, in the article 82 is possible to understand the nature of that financial support fund, aimed to serve the energization of the non interconnected zones.

ARTICLE 82: *"The Financial Support Fund for the Energy of interconnected Areas is a special fund for the management of public and private resources, without legal personality subject to the rules and procedures established in the Political Constitution of Colombia, the Organic Statute of the General Budget of the Nation and the other legal norms applicable thereto. Resources from the national budget and those channeled by the national Government from different public and private sources, national and international, may also be channeled into this fund."* [36]

Finally in article 83, is clear how another additional resources are added to the enhance the funds to finance the energization of uninterconnected areas.

ARTICLE 83: *"All resources of the Financial Support Fund for the Energization of Uninterconnected Areas shall be used to finance plans, investment programmes and projects aimed at the construction and installation of the electrical infrastructure that will allow the extension of the coverage and satisfaction of the demand of energy in the Noninterconnected Areas."*[36]

However, the CREG 005 resolution from 2001, are adopted the adjustments required to the law 633 of 2000 to the compliance of article 81 of law 633 of 2000. This basically is worth to review it since of explain the settlement, invoicing, an collection of the fund.

ARTICLE 2: *"In accordance with Article 81 of Law 633 of 2000 and for its effective compliance, the Administrator of the System of Commercial Exchanges (ASIC), will liquidate, invoice and collect from the energy generating agents, the tax provided for in this provision, in accordance with the procedure and terms laid down in Annex B to Resolution CREG-024 of 1995 and Resolution CREG-047 of 2000 or the rules replacing or modifying them and applying the indexation formula provided for in Article 3o. of this resolution."*

On the other hand, there is an article in this resolution 005 from 2001 that describe

through a formula the fiscal burden destined to the FAZNI in ($/MWh) valid for year t.

ARTICLE 3: *"PRICE OFFERS ON THE ENERGY BAG. For the purposes of the price of the offers referred to in Article 6o. In addition to the EEC, the following amount shall be included as a variable generator cost in Resolution CREG-055 of 1994."*

$$FAZNI_{I_t} = 100 \times \left[\frac{IPP_{(t-1)}}{IPP_{(0)}} \right] \qquad (2.1)$$

Where,

1. $FAZNI_{I_t}$ Financial burden to the Financial Support Fund for the Energy of Noninterconnected Areas ($/MWh) in force for year t.

2. $IPP_{(t-1)}$ Total National Producer Price Index for the month of December of year t-1, reported by the Bank of the Republic.

3. $IPP_{(0)}$ Total National Producer Price Index of December 2000, reported by Banco de la República.

However, this article also detail that: *"In no case shall the Stock Exchange Price be lower than the EEC plus the FAZNI. When the Offer Price of a Generator is lower than the EEC plus the FAZNI, it will be assumed as the Offer Price, the corresponding to the highest Offer Price reported for the respective hour plus 1 $/MWh."*

Additionally in 2003, the interconnected scheme create an unique fund known as the Rural Electrification Fund (FAER), with comparable features to the **FAZNI** to support investment in rural regions concurring to the article 83 of law 633 from 2000. The fund was intended to obtain a surcharge of US$ 0.40 per MWh of electricity delivered to the wholesale sector that would produce about US$ 18 million annually. Projects are submitted by local authorities to the FAER. They must be part of the local development plan and the savings strategy of the respective transport utility in order to be qualified and must also move through the national project testing and assessment scheme. Electrification initiatives are also supported by the National Development Plan (DNP sigles in spanish) Network Normalization Program (PRONE)[5]. The Institute for Energy Solutions Research and Application (IPSE) promotes the Ministry of Mines and Energy in its attempts to encourage rural electrification.

Chapter 3

Proposed approach

Project planners in rural areas have always been involved in developing communities which a rapidly changing economic conditions, no registration of useful information, and no control in the developing rate in that case, in electrical consumption terms. This have further complicated the process of enhancing the infrastructure in all scenarios of this rural areas. To date, local governments have been rightsized and downsized and have had budgets drastically cut while trying to maintain service levels. Information technology, especially GIS, has proven crucial in helping local governments cope in this environment.

In this chapter, will be explained an approach using GIS tools to overcome problems related with the rural electrification as the creation and validation of transmission grid, the lack of information regarding to geographical an also electrical information about rural areas, and the optimal design of distribution grids (MV) to feed rural areas with electrical energy. In that sense, first of all is described how was created the Colombian transmission grid by the information technology proposed, QGIS. And which was the mechanism implemented to validate this data obtained. Act followed, a load flow was performed to validate electrically speaking the electric limits of the created or modeled Colombian (SIN), and concluding whether according to that model is feeded the load.

On the other hand, is presented how using GIS features, is possible to identify rural areas, and even planning and desing optimal distribution grids which satisfy in electrical terms, the consumption curve of a selected rural area.

3.1 Creation and validation of transmission grid using GIS tools

Some time ago, for drawing transmission lines was necessary to employ CAD software to support this task, specially for esthetic reasons. But, at the same time it requires to use a GPS with a tracking option, to record the points composing the line path. Employing this device generated more costs since employing this device, intrinsically requires a walk over the terrains which it is a human labor. Additionally the time employed to recreate the transmission line at scale is higher, since as is seen, is not possible to trace the lines at the same time the points have been located. On the other hand, geographical information systems **(GIS)** are computer based system, used by many service utilities and government institutions to store, read, edit and analyze data referenced by an spatial coordinate system [4]. Moreover, GIS consent a graphic representation of data. For example: power utilities use GIS to store characteristics and attributes of utility assets such as electric poles, lines transformers and final customer electric meters, all of them geo-referenced by a coordinate system that allows to find their exact location [38]. Then, it seems like a great solution for improving transmission line tracing. In that sense, GIS tools could be useful both for the transmission grid planning and control, and as will be seen, it also supports the distribution grid planning and control. These features make GIS the main aspect to consider by proposing GIS tools as the base for the proposed approach in this chapter.

In that sense, one of the most popular open source tools for geographical systems is *quantum GIS (QGIS)*, under the GNU-GPL license. This software reads and analyzes [*.shp] files (compatible with commercial software) of GIS layers which contain information of object classes, example layer of HV, MV lines, layer of HV/MV/LV transformers, etc [38]. Hence, our approach consists in exploiting these QGIS features to model the Colombian transmission grid of Colombia. In the following subsection of this chapter is quite clear how were composed the substation layer [*.shp] and lines layer [*.shp]

For validating the different layers modeled (substations, and lines) of the Colombian interconnected system, was employed only for **educational purposes** a document launched in NEPLAN containing many data of the Colombian electric power system, issued from [43]. This will take a place quantitatively in chapter 4.2.

This validation take place since, as in science validating an approach proposed and also defining until it's applicable, becomes mandatory. Moreover, must be cleared that the information of the Colombian data in [43] is not the most updated data since

is a document prepared with the power system information until 2015. However, by looking in [12] the next grid expansion will take place in 2021, and considering also from this document that this grid expansion will not change dramatically the stability, generation profile, and load profile of the Colombian power system. In that sense, using this file is a good option for the purposed described.

3.1.1 Substation layer's construction

QGIS offers many options useful to locate some places in the world, just by typing its name. It means that by typing the city, department or country name **QGIS** find the place. However, to find the substations was necessary to include the Google earth files in [*.kml,*.kmz] format, since was not possible by just typing the name of the substation finding its location on a map.

Google earth files are possible of load them since **QGIS** support these format, and is possible to obtain google earth as a raster layer by means of a plug-in downloaded. Thus, giving the intrinsic engine search of google earth is possible by typing the substation name locate it spatially speaking, what allow us to obtain the coordinates of it. To construct the Colombian, HV grid including the substations and lines, was employed the Annexes XIII of the UPME [12] seen in the figure 3.1. Although, in some cases the geo-referenced name of the substation, doesn't correspond to the official name issued by the national planning mine energetic unit **(UPME)** of the Colombian government. For those cases, must be required an independent research on many useful internet pages until is found the equivalent name of the substation in google earth to the official **UPME** name. As can be inferred, must have been necessary to one by one find the substation manually.

After located all substations, even those foreign substation which Colombia has a connection, were merged all these substations sorting them by voltage levels. For example, a group of substations devoted for these at 230kV voltage level, and a group of substations devoted for these at 500kV voltage level. Finally in figure 3.2 are reported all substations of the Colombian interconnected system. From the figure 3.1 is seen that for each substations is defined an identification number which was randomly given for each substation, beginning from 1 to 118.

3.1.2 Lines layer's construction

Once the substations have been located and splitted regarding to the voltage level, using the **QGIS** features which for joining substations through lines, the mechanism used by QGIS through a plug-in rely on considering a "hub" point and a "spoke" point. In the table E.4 is possible to appreciate the list of buses with their iden-

SISTEMA DE TRANSMISIÓN NACIONAL ACTUAL 2016

Figure 3.1: HV transmssion Colombian grid from UPME updated to 2016.
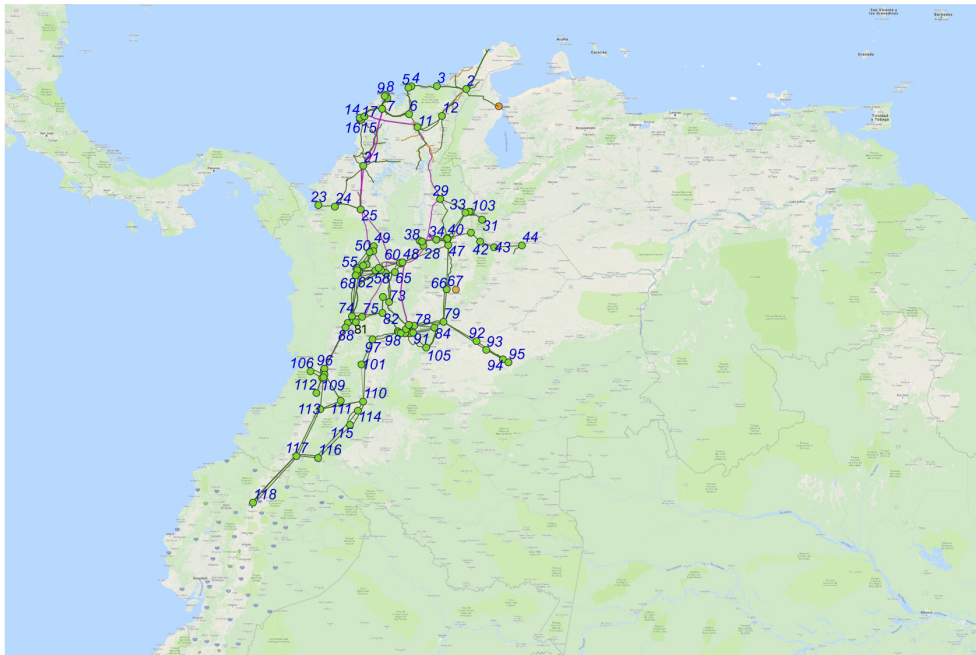
Figure 3.2: Colombian national transmission system (SIN) modelled through the approeach proposed using GIS files in a GIS software,

tification number as was described before, and the substation names. Then, once selected the hub and spoke point, the plug-in used in **QGIS** by using the "draw order" parameter of the vectors layers (points) associated to these substations. After, automatically comes traced a straight line that connect these substations.

However an "straight line" is not a good solution since in reality lines often are not with that shape. Thus, to make the lines in a more realistic way, was employed the Altitude layer, the google streets maps, and the google satellite. This first file is a raster layer devoted to represent graphically the mountain extension, and the topography of the terrain. The second one which is also introduced and launched by another plug-in to QGIS, to accommodate the line trace as near as possible to any streets. In practice to build an overhead line, a squad of workers must be displaced to that zone. Thus, is really useful an easy access zones to put the structure of the line. Finally, the third was employed to better suit the line trace to the mountains boundary, avoiding to put it in the middle of them which in practice is almost non feasible. Then, these three QGIS layer serve as input data to another plug-in which is downloaded metadata from open street maps, specially. To find the correct line's shape was necessary to additionally to these layers, employ two parameters called "Key" and "Value". In our case, since we're looking for transmission lines the "Key" parameter is filled with the command power, meanwhile for "Value" is filled with

the command line. Thus, employing this combination, QGIS is following the path of (overhead) power cables. This QGIS features is so useful. Indeed, for minor power lines with poles and not towers, you may want to use $power = minor_line$. Useful combinations: $voltage = *$, $cables = *$ and $wires = *$. Please see the respective feature pages for details. Also, this will help to find many others stuffs just by selecting correctly the "Key" and the parameter "Value". In [17] there is wide list of stuffs which can be found, equivalently with the "Key" and "Value". Hence, with this, thanks to this QGIS plug-in, the real path of the overhead transmission line is adjusted.

After that, the lines belonging to 230kV were merged in one layer which contains other lines of 230kV. Also, the same procedure for those 500kV overhead transmission lines was done. These action is performed since in order to sort easily the lines according to its voltage level, is easier through

Finally, once the lines are traced suitably, QGIS layer's has a property table which allow us to compute the length of the segment. It's computed initially by default in meters, which becomes necessary its conversion to kilometers.

3.1.3   Kilometric impedance computation of the modeled lines

This action is necessary to computing the kilometric impedance of each HV transmission line and comparing them among themself, in order to identify at a determinate voltage level, these conductors have the same value. This proof that for a certain voltage level, is used the same type of conductor. Since of we have saved separately the transmission lines according to its voltage level in a layer, is possible thanks to the compatibility of QGIS with some external programs, download these two vector layers of transmission lines in a **(*.csv)** file. Thus, in this file is possible to have at a hand the information regarding to the **(x,y)** pair of cartesian coordinates, and the line length, and the type of conductor employed for the transmission line. Thus, with this information is possible to easily compute the kilometric impedance.

For this purpose, the procedure implemented was basically summed up in the chart below:

Thus, the formulation in specific employed was the following one:

For computing the base impedance.

$$Z_{base} = \frac{\left|\hat{V}_{base}\right|^2}{S_{base}}$$

Where,

Z_{base} = The base impedance for the zone in which the line is placed. V_{base} = The

base voltage. S_{base} = The base power for the entire system.

For 230 kV The $Z_{base} = 5.29 X 10^2 \Omega$
For 500kV The $Z_{base} = 2.5 X 10^3 \Omega$

And the **norm** of the **line impedance** was computed employing the following formulation:

$$\left| \hat{Z} \right| = \sqrt{R^2 + X_L{}^2} \textbf{in p.u} \tag{3.1}$$

Therefore, once is obtained those values, applying the logic of the flow gram above, we obtain the real value of the [p.u] impedance value with the following formula:

$$Z^{real-\Omega} = S_{base} \cdot \left| \hat{Z} \right|^{p.u} \tag{3.2}$$

$$Z^{real-\Omega/km} = \frac{Z^{real-\Omega}}{length} \tag{3.3}$$

$$B = 2 \cdot \pi f \cdot C \cdot 1000 \cdot Lg[\Omega] \tag{3.4}$$

Where,

- Lg = Line Length in km.
- R = Resistance of the line length in Ω
- X = Reactance of the line length in Ω
- B = Susceptance of the line length in Ω

However, result easy to analyze that, X and B depends on the physical value of the Inductance and capacitance. The following formulas correspond to the ones used to compute these parameters.

$$L = 2 \cdot (10^{-7}) \cdot \ln \frac{GMD}{Geometric mean radius}[H] \tag{3.5}$$

$$C = \frac{2 \cdot PI \cdot (8.854 \cdot 10^{(-12)})}{LN \left(\frac{GMD}{r0(outer radius-conductor)} \right)}[F] \tag{3.6}$$

Finally, to compute the [**p.u**] values was just necessary to divide between the line length.

$$r = \frac{R}{Line length} \quad (3.7) \qquad x = \frac{X}{Line length} \quad (3.8) \qquad b = \frac{B}{Line length} \quad (3.9)$$

3.2 Performing load flow of the transmission grid

Once created the Colombian interconnected system (SIN) modeled in QGIS, is required to compose three matrices for running a Power flow (bus, branch, gen). This task is supported by MATPOWER function [46], which is run in MATLAB. This tool run a load flow employing the power flow method explained in the chapter 1 that correspond to the Newthon Raphson method. This matrices have some variables. These ones are seen in figure C.1, C.2, and C.3.

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.)

[†] Included in OPF output, typically not included (or ignored) in input matrix. Here we assume the objective function has units u.

Figure 3.3: Bus format in MATPOWER.

Then, summarizing the steps in before,

1. Merging of all substations from the Colombian interconnected system (SIN): This task was completed through the merging tool in vector tools QGIS tab.

2. Once all substations were merged in these two vector files (*.shp type), the geometry information about the substations was computed. Remember that, the geometry information provide us the geographical Cartesian coordinates (x,y).

3. After that, is possible to complete the downloaded excel file **(*.xlsx)** with the information regarded to generated power, demanded power as both as in peak load condition and off-peak load condition.

4. To enhance as much as possible, the QGIS model, this new EXCEL file with all the power information was imported in QGIS layers.

To perform the load flow of the modeled Colombian interconnected system, was necessary to obtain the most updated demand or load value supported by the (SIN). To do it, XM information regarding to the users of the National interconnected sys-

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, $\begin{array}{l} > 0 = \text{machine in-service} \\ \leq 0 = \text{machine out-of-service} \end{array}$
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 minute reserves (MW)
RAMP_30*	19	ramp rate for 30 minute reserves (MW)
RAMP_Q*	20	ramp rate for reactive power (2 sec timescale) (MVAr/min)
APF*	21	area participation factor
MU_PMAX†	22	Kuhn-Tucker multiplier on upper P_g limit (u/MW)
MU_PMIN†	23	Kuhn-Tucker multiplier on lower P_g limit (u/MW)
MU_QMAX†	24	Kuhn-Tucker multiplier on upper Q_g limit (u/MVAr)
MU_QMIN†	25	Kuhn-Tucker multiplier on lower Q_g limit (u/MVAr)

* Not included in version 1 case format.
† Included in OPF output, typically not included (or ignored) in input matrix. Here we assume the objective function has units u.
‡ Used to determine voltage setpoint for optimal power flow only if opf.use_vg option is non-zero (0 by default). Otherwise generator voltage range is determined by limits set for corresponding bus in bus matrix.

Figure 3.4: Gen matrix format MATPOWER.

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, if non-zero (taps at "from" bus, impedance at "to" bus, i.e. if $r = x = b = 0$, $tap = \frac{|V_f|}{|V_t|}$; $tap = 0$ used to indicate transmission line rather than transformer, i.e. mathematically equivalent to transformer with $tap = 1$)
SHIFT	10	transformer phase shift angle (degrees), positive $\Rightarrow$ delay
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)
MU_SF‡	18	Kuhn-Tucker multiplier on MVA limit at "from" bus (u/MVA)
MU_ST‡	19	Kuhn-Tucker multiplier on MVA limit at "to" bus (u/MVA)
MU_ANGMIN‡	20	Kuhn-Tucker multiplier lower angle difference limit (u/degree)
MU_ANGMAX‡	21	Kuhn-Tucker multiplier upper angle difference limit (u/degree)

* Not included in version 1 case format. The voltage angle difference is taken to be unbounded below if ANGMIN ≤ -360 and unbounded above if ANGMAX ≥ 360. If both parameters are zero, the voltage angle difference is unconstrained.
† Included in power flow and OPF output, ignored on input.
‡ Included in OPF output, typically not included (or ignored) in input matrix. Here we assume the objective function has units u.

Figure 3.5: Branch format MATPOWER.

tem [44] provides us the consumption in GWh per each Colombian electrical region. Additionally, the generated power as both as in peak generation and in off-peak generation was required to be updated for the same purposes. In that sense, is obtained the information about Region Centro, Antioquia, Costa Atlántica, Valle, Oriente, THC (Tolima, Huila y Caquetá), CQR (Caldas, Quindío y Risaralda), Sur, Chocó, Guaviare. May is necessary to be clarified that these regions don't correspond to the geograhical Colombian region which are region Pacífica, Orinoquía, Insular, Caribe, Andina y Amazonia. However, as might be clear the **(SIN)** doesn't serve with electric flow to all the Colombian territory. According to [37] is important to mention that this demand updates are computed by XM using the average pondered of the different growth by some week days as commercial days, saturday, sunday, and holidays.

Thus, once the demand participation in percentage is known and the demand in GWh is also known, is computed for each Colombian department belonging to the above mentioned regions the equivalent power consumption. This allow us to estimate the power demanded for each substation, since of in each region exist many substations which are clearly identified thanks to QGIS features. In other words, **QGIS** allow us from a layer of the Colombian department division, select and highlight each department. This graphically speaking, help us to identify the substations inside each zone.

Let's consider $i = 1 : 118$, where i is the counter variable representing the Colombian substations of the **SIN**. Then to summarize the mathematical expression to compute the demand action power and the demand reactive power can be computed as:

$$Pd_i = \frac{P_{demand}}{NS} \tag{3.10}$$

Where,

- Qd_i is the active power demanded at node i.
- $Q_d emand$ is the consumed power or the participation demand for each department of the Colombian regions above from the file [44] file.

$$Qd_i = \frac{P_{demand}}{NS} \tag{3.11}$$

Where,

- Qd_i is the active power demanded at node i.
- $Q_d emand$ is the consumed power or the participation demand for each department of the Colombian regions above from the file [44] file.

For the generated power, the task was simpler. In the same UPME 2018 [33] report was found the updated value of power (MW) for each generation node, in the

Interconnected HV Colombian system. The interconnected Colombian system as mentioned before count with 30 generation nodes. Thus, for these nodes are well known power generated and additionally the reactive power generated.

Moreover, XM web portal (PORTAL BI) offers public data. One of the public data offered, is regarding to the generation power monthly, and yearly. To access to that information, there are some system requirement needed as the Microsoft Silverlight. May is needed to remember that Microsoft Silverlight is not still developed for some web browser. Therefore, is better employing internet explorer for that purposes. Additionally, it also get useful for sakes of co-validating UPME information contained in [33] from another national authority in these fields, the (`http://informacioninteligente10.xm.com.co/Pages/default.aspx`)

Finally, tu run the power flow is necessary to employ the MATPOWER function, as have been mentioned in before. This MATLAB function employ three main matrices as have been mentioned before. One useful to summarize all the branches information. Another one to summarize all the bus information, and another one to summarize the generation information of the system. Once matrices have been loaded, MATPOWER runs the power flow immediately offering the result of the state variable (Electrically speaking) per each node, i.e the complex voltage in rectangular coordinates. Also, the current is computed specifically the current regarded to the bus $i - th$ to the $j - th$.

3.3 Identification of rural areas

From the chapter 2 is seen among others aspects, a description of the non interconnected zones. **IPSE** as the devoted institute from the Ministry of mines and energy in Colombia for the non-interconnected zones, has plenty identified all the zones with lacking of electricity and without interconnection to the **SIN**. IPSE count with an institute committed to the monitoring of these zones. This is the (**Monitoring national center**) **CNM** which is filial area of the **IPSE** that carries out fundamental activities for the monitoring of the provision about the electricity service in the Noninterconnected Areas - ZNI, and assisting the responsible entities to ensure the provision and quality of service to users in those areas. It also provides timely information on electrical parameters for planning, decision making and development of structural energy solutions.

From the webpage of this institute, is possible to appreciate a GIS map which represent in the political Colombian map, the location of each non electrified node. CMN also **CMN** is based on pillars as verifying the conditions of provision of the electric

power service in the ZNI, and managing and disseminate baseline information on ZNI.

In figure 3.6 is exhibited a georeferenciated image of the Colombian map, including some dots classified in different colors. Red dots means those nodes not interconnected to the Colombian national system and without energy provision. Green dots means those nods not interconnected to the Colombian national system and with energy provision. Additionally, the following figure 3.7 show us the convention used for their groups of nodes.

Figure 3.6: Georeferenciation image of Colombian Map. Red dots means the non interconnected zones without services, and green dots means the non interconnected nodes with service.

Since green dots contain more information regarding to electrical info, from these nodes stand out the city of Puerto Carreño, placed in the department of Vichada. From figure 3.8 we can appreciate the main information of the municipality of Puerto Carreño which include demographical data, and the electric data. From this picture is possible to appreciate the following points which make really interesting this City among other cities under the green group. In that sense, the city of Puerto Carreño is the largest city in consumption terms, as both as in active power, and reactive power. Also, has a connection devoted in its substation with Venezuela. The Central substation of Puerto Carreño has an interconnection of 34,5kV with Puerto Páez and Puerto Nuevo Venezuela (Agreement signed between CADAFE (CORPOELEC) Venezuela and IPSE Colombia). This substation has a bay at 34,5kV, where is installed a transformer of 8 MVA and three bays of 13,2kV. It has a measure that totals the energy delivered by the interconnection. Again, by looking

Figure 3.7: Convention used and proportion or users provided with service of electric energy.Green users means with electrical energy and telemetry service. Red user means those user without service, and yellow users means those users without of telemetry.

in the figure 3.9 is clear that Puerto Carreño has many highway which make easier the access for a determinated building. Hence, based on the reasons above, Puerto Carreño was the most attractive city from those belonging to the green one group. Consequently, after defining the rural zone, the next step will be applying GIS tools to design the optimal distribution grid. In that sense, are defining the number of substations required to feed the electric demand of Puerto Carreño's based in the peak demand of it. And consequently, for locating the MV substation in the Puerto Carreño's map using the coordinates extracted from the kruskal algorithm implemented. This algorithm will be presented and explained in next sections. In that way from now is possible to introduce its usage.

3.4 Distribution grid creation employing data clustering and k-means algorithm

There are many data minning algorithms divided in methods of clustering. The method we're employing is the partitioning method, and the code is the k-means,
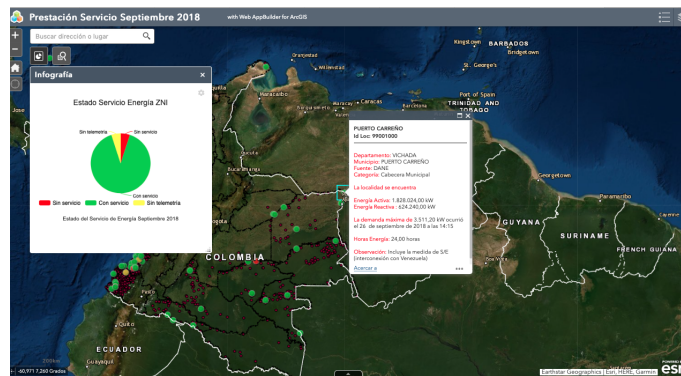
Figure 3.8: Puerto carreño main information from CMN webpage.

Figure 3.9: Picture employing the google sattellite layer of Puerto Carreño main streets.

which is also known as the Lloyd algorithm. Consequently from the documentation of *k-means* algorithm, the matrix of data are the coordinates of each point, where each point represent the pixel's centroid of the population layer used.

Then, cluster analysis or simply clustering is the process of partitioning a set of data objects (or observations) into subsets [23]. Also, data clustering can be identified as a learning method which grouping a set of data in such a way that the data in the same group, show higher similarity in certain properties when considering with data in other groups [2]. These groups are commonly referred to as clusters in data mining [23].

Each subset is a cluster, such that objects in a cluster are similar to one another, yet dissimilar to objects in other clusters. The set of clusters resulting from a cluster analysis can be referred to as a clustering. In this context, different clustering methods may generate different clusterings on the same data set.

In that sense, clustering becomes a relevant aspect to consider since to planning a

distribution network, is useful hypothesize the position of the secondary substations. Hence, is a must be implemented task to identify the populated zones that represent electrical clients or electrical users. Consequently, have been decided following with the workflow of this proposed approach, using this clustering technique.

3.4.1 K-means algorithm: Literature review

K-means clustering, or Lloyd's algorithm [28], is an iterative, data-partitioning algorithm that assigns n observations to exactly one of k clusters defined by centroids, where k is chosen before the algorithm starts.

The k-means algorithm uses an heuristic to find centroid seeds for k-means clustering. According to Arthur and Vassilvitskii [2], k-means improves the running time of Lloyd?s algorithm, and the quality of the final solution.

Graphically, looking over an ocean of unlabeled data, waving in front of us is a really mess. It is true that the lack of labels can sometimes freak us out, leaving us wondering how to group the data together. But luckily, k-means clustering algorithm is one of the simplest but powerful algorithms for unsupervised clustering (dealing with data without defined categories). Assigning data points into k-clusters based on the minimum distance, *k-means* clustering is simple, helpful, and effective for finding the latent structure in the data.

Finally, *k-means* clustering algorithm is an unsupervised machine learning algorithm for determining which group a certain object really belongs to. What it means by "being unsupervised" is that there are no prescribed labels in the data denoting its structure. The main idea is to assign each observation into the cluster with the nearest mean (centroid), serving as a prototype of the cluster.

Thus, the algorithm proceeds as follows:

1. Choose k initial cluster centers (centroid). For example, choose k observations at random. A good strategy is simply visualizing n data points and decide the number of clusters (k).

2. Choose k random points on the graph as the centroids of each cluster. For this example, we would like to divide the data into 4 clusters, so we pick 4 random centroids.

3. Compute point-to-cluster-centroid distances of all observations to each centroid. The strategy is calculating the Euclidean distance between each data point and chosen clusters? centroids. A point is considered to be in a particular cluster if it is closer to that cluster?s centroid than any other ones.

4. Compute the sum of squares point ot cluster centroid distances.

Total distances:

$$\sum_{j=1}^{k}\sum_{i=1}^{n}\left\|x_i^{(j)} - c_j\right\|^2 \tag{3.12}$$

Where: k: the number of clusters.

n: the number of points belonging to cluster j.

cj: the centroid of cluster j.

5. Finally, Compute the average of the observations in each cluster to obtain k new centroid locations. The strategy adopted is after assigning all observations to the clusters, calculate the clustering score, by summing up all the Euclidean distances between each data point and the corresponding centroid.

$$\frac{\sum_{i=1}^{n} x_i}{n} \tag{3.13}$$

6. Repeat steps 2 through 4 until cluster assignments do not change, or the maximum number of iterations is reached. This means, until the positions of the centroids no longer move and the assignments stay the same.

3.4.2 Elbow method

How to determine the optimal value of k is indeed a good challenging question. Note that before determining the number of clusters to assign the data into variable *(k)*, should have been developed an *overview* of the data, and on what basis you want to group them. Indeed, even is possible to apply an hierarchical clustering on the data first to briefly understand the structure of the data before choosing k by *hand*. Hence, a well known method to validate the number of clusters is the **Elbow method**. The Elbow method is a heuristic method of interpretation and consistency validation within cluster analysis intended to assist find a suitable number of clusters in a dataset. However, according [26] It is often vague and not very safe, and therefore it is preferable to use other methods to determine the amount of clusters like the Silhouette technique .

Practically speaking *k-means* clustering several times for a range of values of k (usually from 2 to 10) and pick out the value of k that causes sudden drop in the sum of squared distances. More specifically, for each value of k, we calculate the sum of squared distances (between each point and the corresponding centroid), and graphing the results on a line chart. This, choose the value where the sum of squares drops, giving an angle in the graph (an elbow) that is the optimal value of k. [31] Thus, employing in Pyhton that method, the figure 3.10 represent the linear relationship between different values of k and the distortion. Distortion means when K

increases, the centroids are closer to the clusters centroids. The improvements will decline, at some point rapidly, creating the elbow shape. That point is the optimal value for K. the distortion on the Y axis (the values calculated with the cost function). In the image above, **K=4**. Although, 4 substations is a really low number for sake of the MV network, since of in the good practice manual of [29] for rural electrification is recommend only pole mounted transformer, and for the Colombian legislation the maximum power in [kVA] is 250kVA.
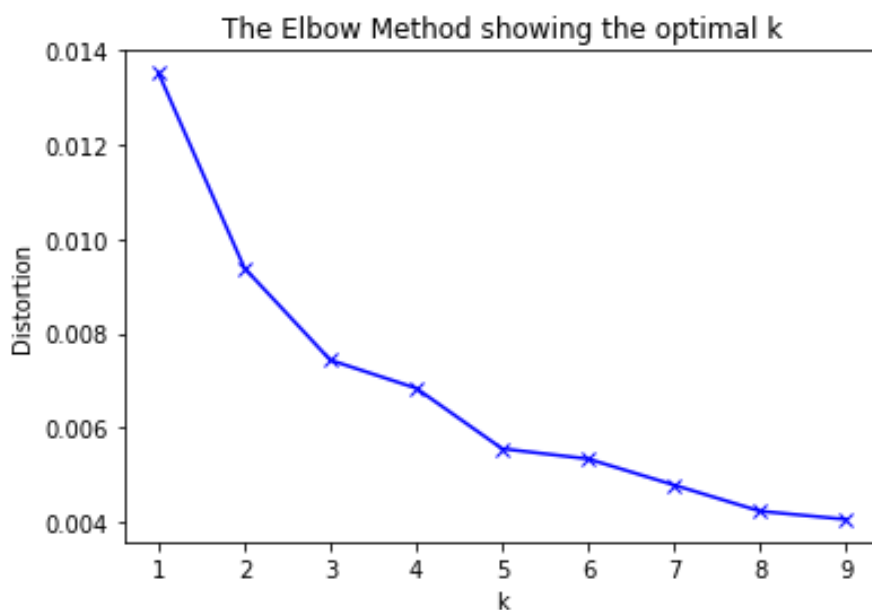
Figure 3.10: Linear relationship between the distortion and a set of K (number of centroids) values. Outcome picture from the Elbow method

3.4.3   Distribution line design and cost

Economically, conductors represent between 20 to 40% of the total cost of a line. Consequently, their selection is of prime importance. In earlier days of electrical power transmission, copper was mainly used as the material of overhead line conductors, however with the expansion of electricity networks, several factors, such as price, weight, availability and conductivity have virtually compelled Designers to concentrate on aluminium based conductors as listed below. [13]

- AAC = All Aluminium Conductor.
- ACSR = All Aluminium Conductor Steel Reinforcement.
- AAAC = All Aluminium Alloy Conductor.

Steel conductors are still widely used as overhead earth wires and also as phase conductors on rural distribution lines as listed below.

- SC/GZ = Galvanised Steel Conductor
- SC/AC = Aluminium Clad Steel Conductor

Phase conductors fulfill an electromechanical function; hence both the electrical and mechanical aspects are to be considered.

The most important parameter affecting the choice of conductor is its resistance, because it influences voltage regulation, power loss and current rating.

For AC lines, the diameter of a conductor affects the inductance and the capacities. Up to a voltage of 132kV, the above considerations are generally adequate, however at higher voltages, the above gradient on the conductor surface may require the selection of a conductor on the basis of its diameter, thus leading to the use of bundled conductor (i.e. 2, 3 or 4 phase).

As already indicated aluminum based conductors represent the highest proportion of conductor usage. The advantageous mechanical properties of aluminum alloys have also been recognized for a long time, but AAAC has always been more expensive than ACSR, for equivalent conductivity. However there are cases where initial cost is not the governing factor. One of these is the corrosion performance, since being mono metallic, the risk of bimetallic corrosion between the aluminium and the zinc on the steel core are non-existent. Consequently AAAC conductors are used on lines in coastal areas.

After determining the length of the proposed system and calculating the demand of potential loads in existing lines and those proposed for the project, the engineer must determine the number of phases required in the proposed lines of the project. As indicated at the start, the RUS integrated design system assumes that rural lines should be single-phase, for economic reasons, i.e. phase and neutral [29]. However, some situations require consideration of the extension of two- phase lines (two phases and neutral) or three- phase lines, for the following reasons:

- There are three-phase loads in the project area that are large enough to make a conversion into single-phase impossible. Generally, motors of over **10HP** are three-phase, though the technology exists to overcome this limitation.[29]
- The nature of the loads to be covered by the project rules out the use of single-phase systems. For example, a project to develop an extensive irrigation system with electric pumps of over **10HP** each should be designed from the beginning with three- phase lines.[29]

According to [22] and `http://www.puertocarreno-vichada.gov.co/MiMunicipio/Paginas/Informacion-del-Municipio.aspx`, this municipality is well known by its airport. Although this is a minor airport according ot its traffic and duty operation, serves the zone with connectivity with the Colombian capital,

and so on. Thus, typically airport are characterized by three phase loads. In that sense, the two reasons according to [29] result convenient employing a three phase system (two hot wires plus a neutral conductor)

Thus, assuming three phase line with a primary voltage of 13.2 kV, which feed secondary transformers of 225kV, the elements required typically are exhibited in figure 3.11. In that sense, following the equation 4 of [29], is possible to compute the total annual cost of a line. The total annual cost of a line means:

The **total annual cost of a line**, according to the manual of distribution line design means the range of costs that determines the range of loads for which each conductor is optimal, thus identifying the conductor with the minimum annual cost. Thus,

$$C_A = K_A * (Cons) + K_L * (Cons) \tag{3.14}$$

Where:

- CA = Total annual cost of one kilometer line
- KA = Fixed charge rate for investment costs, typically = 0.15
- Const = Construction cost of one kilometer line with a specific conductor cross-section
- K_L= Acquisition cost of one kWh energy at the beginning of the project
- Loss = Annual loss in kWh of one kilometer line with the specific conductor cross- section for a specific peak demand and load factor.
- I = Phase current in amps for the specific load
- n = 3.0 if the line is three-phase, 2.0 if the line is single-phase
- R = resistance in ohms of one kilometer of the specific conductor

And the loss is computed as:

$$LLF \cdot n \cdot I^2 R \cdot 8.76 \tag{3.15}$$

And LLF is computed thanks to,

$$Load factor of losses = (Load factor)2 \cdot 0.84 + (Load factor) \cdot 0.16 \tag{3.16}$$

3.4.4 Adjacency matrix

First, let's consider a graph is a set of points (called vertices, or nodes) and a set of lines called edges connecting some pairs of vertices. Two vertices connected by an edge are said to be adjacent. Consider the graph in figure 3.12. So notice that two vertices may be connected by more than one edge (A and B are connected by
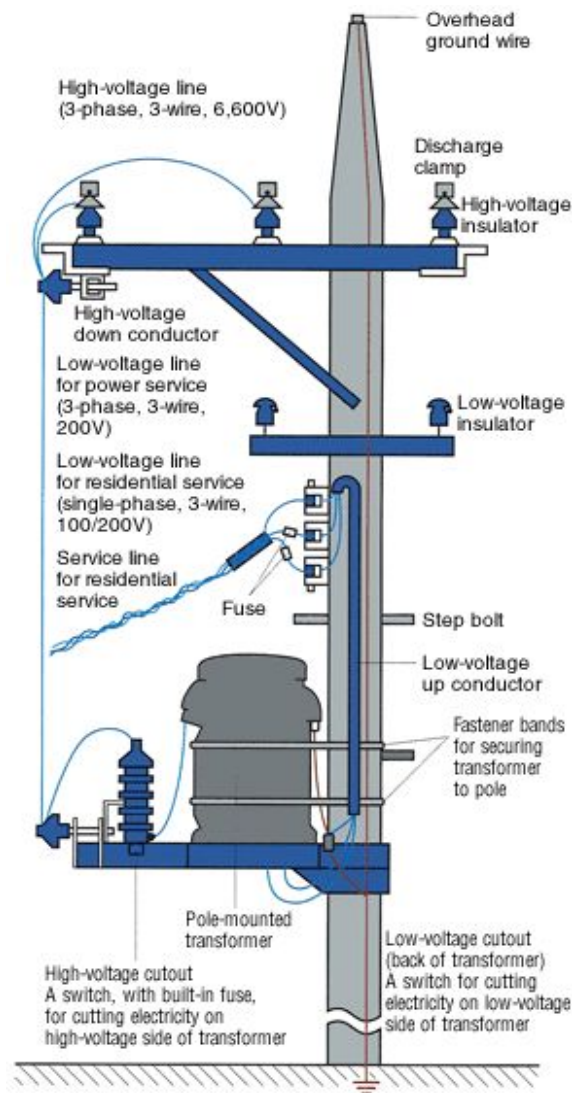
Figure 3.11: Three phase pole, with power system elements, including a pole mounted transformer. A look of the possible pole used for this computation.

2 distinct edges), that a vertex need not be connected to any other vertex (D), and that a vertex may be connected to itself (F).

The adjacency matrix for a graph with n vertices is an nxn matrix whose (i,j) entry is 1 if the $i-th$ vertex and $j-th$ vertex are connected, and 0 if they are not. If in Figure 3.12 A is vertex 1, B is vertex 2, etc.

Adjacency matrix, is specified as a full or sparse, numeric matrix. The entries in A specify the network of connections (edges) between the nodes of the graph. The location of each nonzero entry in A specifies an edge between two nodes. The value of that entry provides the edge weight. A logical adjacency matrix results in an unweighted graph. For computing this matrix, was necessary to respect many aspects. First, Adjacency matrix must be symmetric unless the type input is specified. Thus,

is recommended to confirm symmetry of the matrix. Also for triangular adjacency matrices, is recommended to specify type to use only the upper or lower triangle.
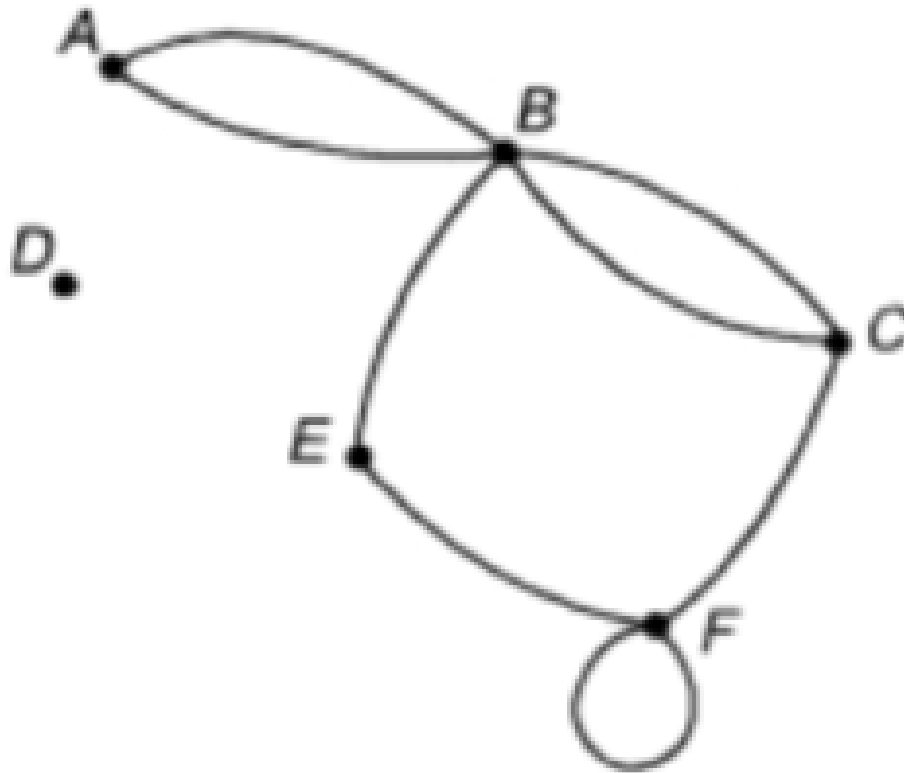
Figure 3.12: Graph picture used to make a graphical idea about the adjacency matrix.

So after the theoretical description, let's identify the use of the adjacency matrix to obtain a *graph*. So, since the adjacency matrix allow us to include the distance between vertex, adjacency matrix is devoted to construct a matrix in which the vertex are the nodes or the substations of the distribution network pretended.

3.4.5   Minimum spanning tree algorithm MST

To explain about a minimum spanning tree, may is necessary beginning by a spanning tree is a subset of Graph G, which has all the vertices covered with minimum possible number of edges. Hence, a spanning tree does not have cycles and it cannot be disconnected. By this definition, is drawn a conclusion that every connected and in directed Graph G has at least one spanning tree. A disconnected graph does not have any spanning tree, as it cannot be spanned to all its vertices. From figure 3.13 is found three spanning trees off one complete graph. A complete directed graph can have maximum n^{n-2} number of spanning trees, where n is the number of nodes. In the above addressed example, n is 3, hence $3^{3-2} = 3$ spanning trees are possible.

Then, an Spanning Tree has many properties. Is known that one graph can have more than one spanning tree. Following are a few properties of the spanning tree connected to graph G. A connected graph G can have more than one spanning tree. All possible spanning trees of graph G, have the same number of edges and vertices. The spanning tree does not have any cycle (loops). Removing one edge from the spanning tree will make the graph disconnected, i.e. the spanning tree is minimally connected. Adding one edge to the spanning tree will create a circuit or loop, i.e. the spanning tree is maximally a cyclic.
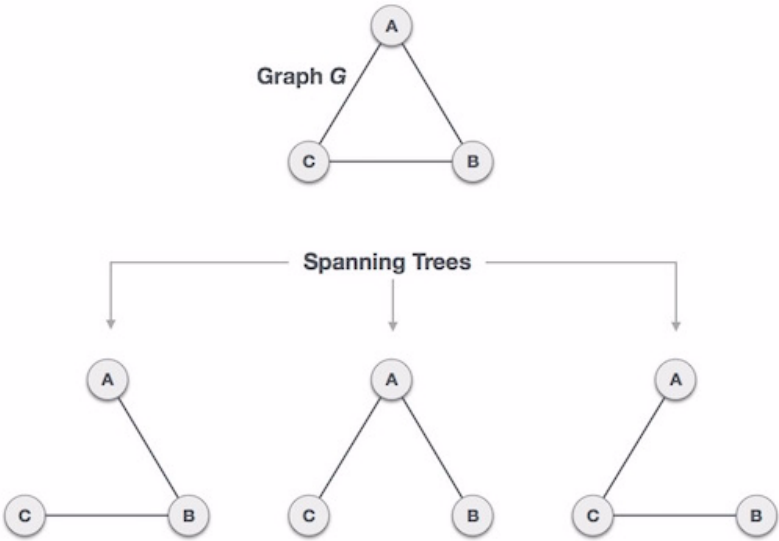
Figure 3.13: An ilustrative graph for explaining the minimum the spanning tree graphically speaking.

From the Mathematical point of view, Spanning tree has many properties. Spanning tree has n-1 edges, where n is the number of nodes (vertices). From a complete graph, by removing maximum e - n + 1 edges, we can construct a spanning tree. A complete graph can have maximum n^{n-2} number of spanning trees. Thus, we can conclude that spanning trees are a subset of connected Graph G and disconnected graphs do not have spanning tree. Then, is seen that the Spanning tree is basically used to find a minimum path to connect all nodes in a graph.

Consequently, Minimum Spanning Tree, In a weighted graph, a minimum spanning tree is a spanning tree that has minimum weight than all other spanning trees of the same graph. In real-world situations, this weight can be measured as distance, congestion, traffic load or any arbitrary value denoted to the edges.

Finally, all above mentioned is useful for arguing that to connect in that case substations, must be identified a minimum cost grid. Again, this substations points indicated comes after the implementation of the KRUSKAL algorithm once have been used the coordinates pair (x,y) of the population layer used in so called GIS

tools. Therefore, from this minimum cost grid has the lowest length, is possible looking to connect all the transformers allocated in the poles (poles mounted substation) applying the minimum spanning tree.

Chapter 4

Results & discussion

4.1 Modeled transmission grid load flow.

Once all substations were merged in one only vector file (.shp type), the geometry information about the substations was computed using GIS tools. Remember that, the geometry information provide us the geographical cartesian coordinates (x,y). Followed, is filled each substation of the model Colombian transmission system with the information regarded to generated power, demanded power as both as in peak load condition and off-peak load condition.

In that sense, since we would obtain the most realistic and updated case for the Colombian interconnected system, is necessary to update the demand consumption for each Colombian department as both as in peak load and off-peak load. Additionally, the generated power as both as in peak generation and in off peak generation was required to be updated for the same purposes.

To solve it, an exploration in literature was necessary. From this seeking comes out, the UPME 2018 [33] yearly report for the energetic affairs was employed. This document is strongly reliable since is issued from the national authority in the energetic mining affairs (UPME). Thus, this provides us the value measured and stated for the maximum demand condition. Thus, once the delta or increment of load is known, was computed finally the peak load and off-peak load.

In addition, from the same UPME 2018 report was found the updated value of power (MW) for each generation node, in the Interconnected HV Colombian system. Thus, for these data, was necessary copying and pasting the information. Indeed, for sakes of co validating from another national authority in these fields, the XM POR-TAL BI (`http://informacioninteligente10.xm.com.co/Pages/default.aspx`) was used.

To continuation are presented the results of the power flow from the electrical data

estimated for the modeled Colombian interconnected system:

4.1.1   Load flow voltage results
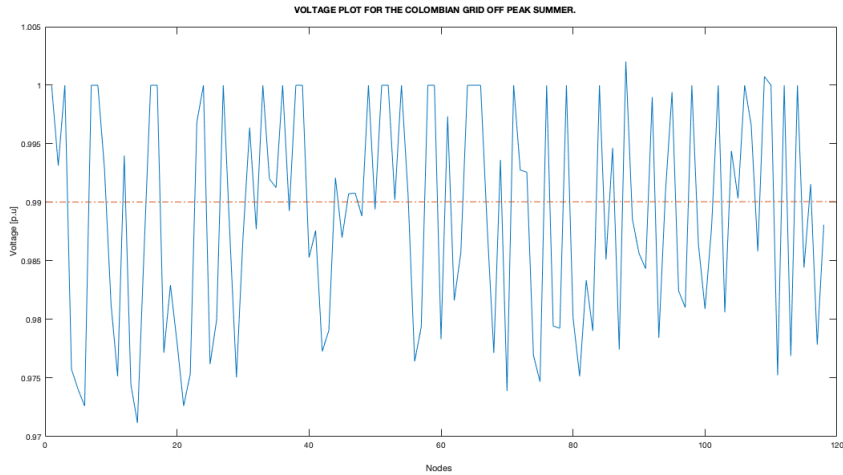
Figure 4.1: Voltage profile from the Load flow in the Colombian grid OFFPEAK summer scenario.
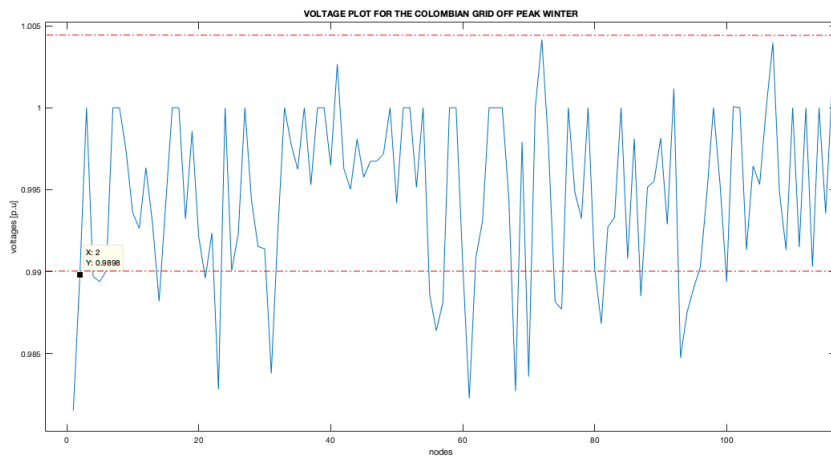
Figure 4.2: Voltage profile from the Load flow in the Colombian grid OFFPEAK winter scenario.

To analyze this images, to decide if the voltage is inside the internationals benchmark, must be verify that voltages are inside 1.1 V in [p.u] and higher than 0.9 V in [p.u]. Then, as we could appreciate this voltages are inside these limits considering all load scenarios. Having all the nodes of the Colombian interconnected system inside the voltage limits, is a good indicator since substations do not leads to over-voltages or under-voltages issues, which are a sufficient aspect to conclude about possibles stability problems. In this case the voltage stability, and voltage limits violations are validated.
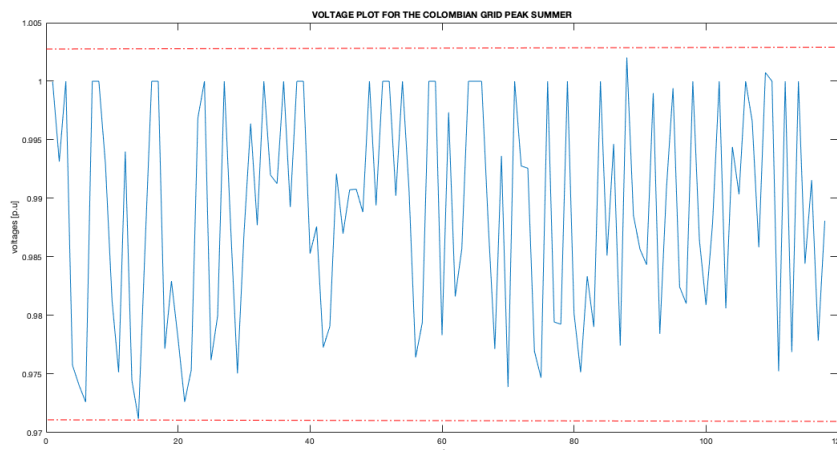
Figure 4.3: Voltage profile from the Load flow in the Colombian grid PEAK summer scenario.
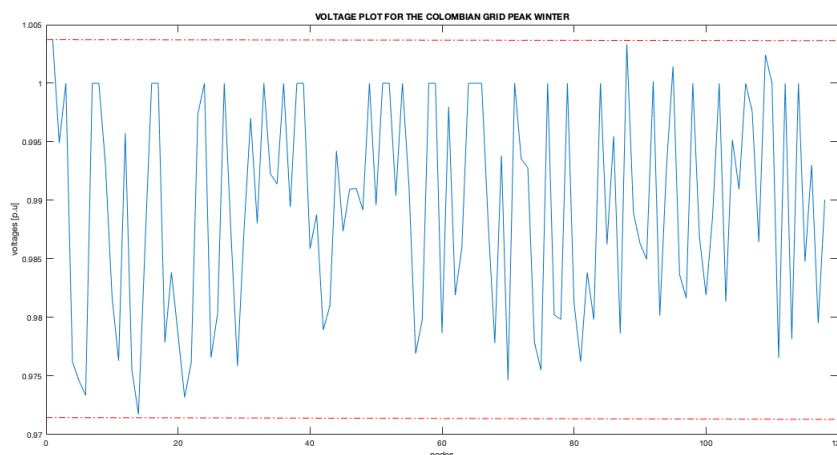
Figure 4.4: Voltage profile from the Load flow in the Colombian grid PEAK winter scenario.

4.1.2 Load flow results for current.

As we see, to analyze in term of the current the results of the power flow, the maximum current of a branch is not related to its length, it?s related to the type and section of the conductor. Thus, the maximum current of a line is not related to its length but to the technology (material and section) of the conductor and of the technical rules in place.

Maximum current is a thermal problem, i.e. increasing the current you are increasing the temperature of the conductors: these will suffer a thermal dilatation getting closer and closer to the ground. Maximum current is related to the minimum distance from the ground you have to guarantee.

As a benchmark, In Italy are some standard cable, described in the following:
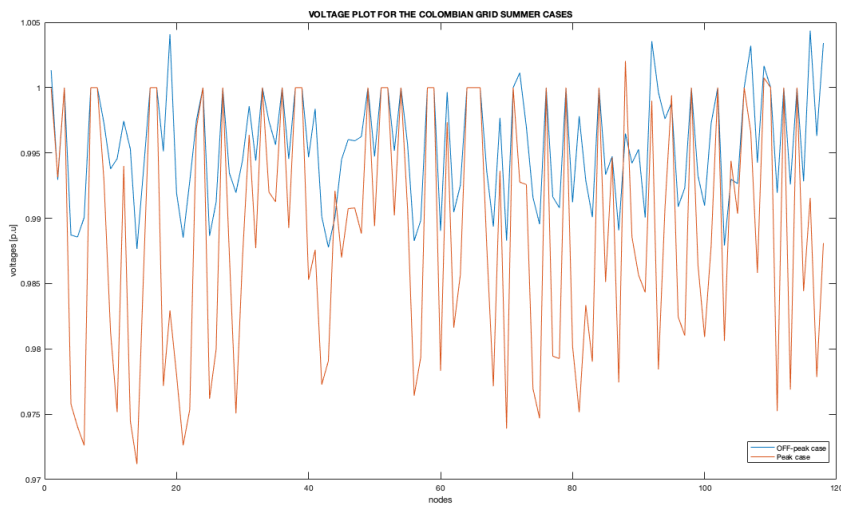
Figure 4.5: Voltage profile from the Load flow comparing the two scenarios in the summer in the Colombian grid.
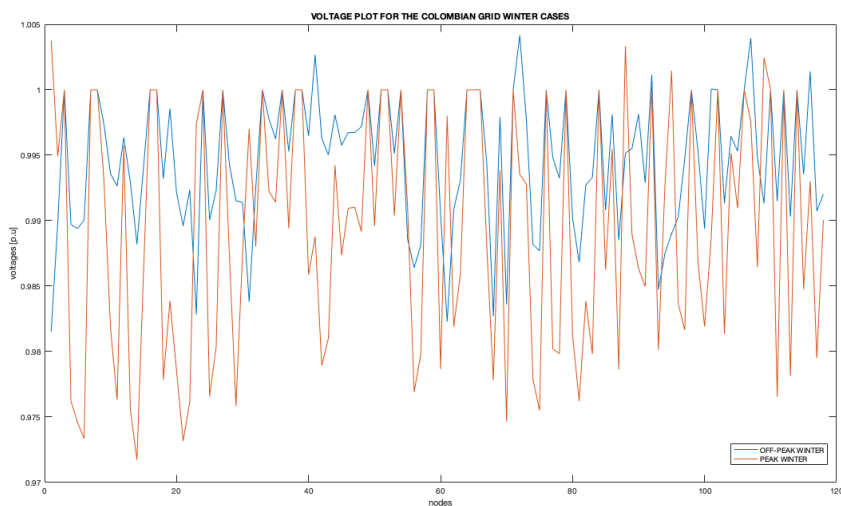
Figure 4.6: Voltage profile from the Load flow comparing the two scenarios in the winter in the Colombian grid.

A (Overhead lines) 1 (one conductor for each phase) 2 (two conductors for each phase, etc) AA (Aluminium Steel technology) - CU (Copper wires) XXX, eg. 585 (section of the conductor: 585 mm^2)

Then for each line could have different current limit: the maximum one (highest value, relevant just for theoretical working condition), the nominal one (the theoretical maximum current the line could manage), the security one (the one the TSO should respect in order to guarantee security criteria).

So in Colombian were seek the most adopted technologies in Colombia for each
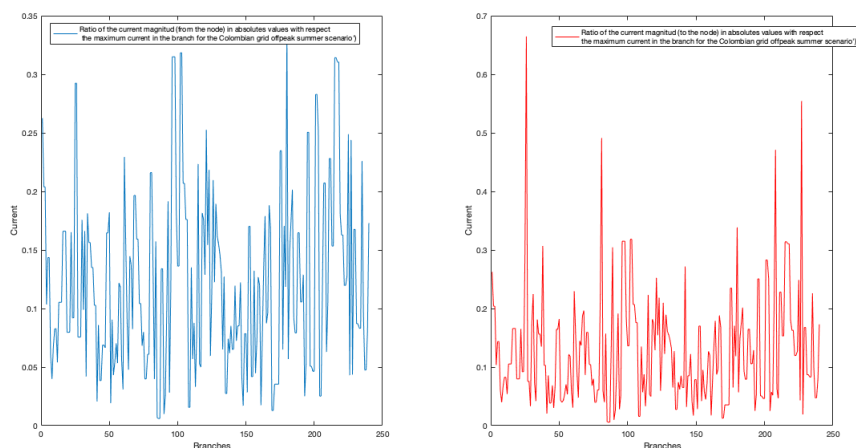
Figure 4.7: Ratio of the current magnitud with the maximum current in the branch from the Load flow in the Colombian grid OFFPEAK summer scenario.
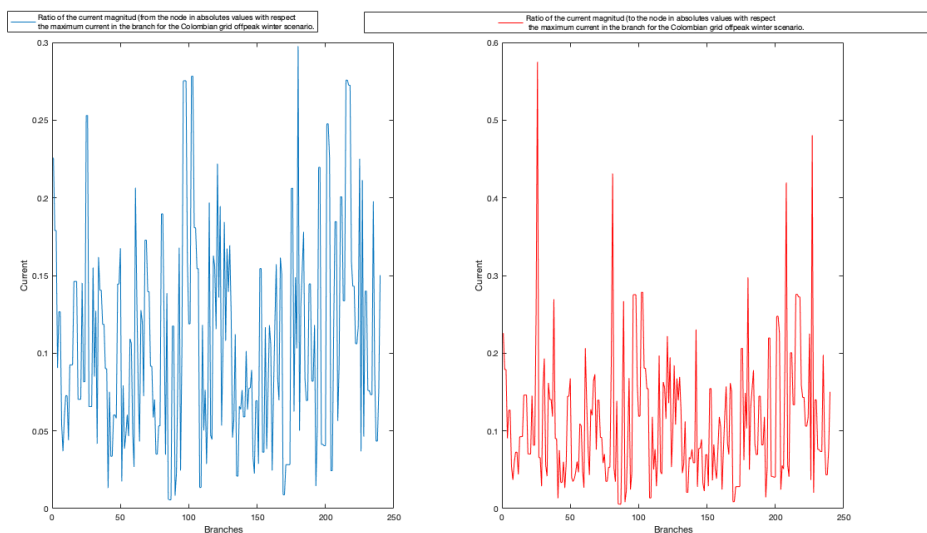
Figure 4.8: Ratio of the current magnitud with the maximum current in the branch from the Load flow in the Colombian grid OFFPEAK winter scenario.

nominal voltage (Remember that different lines, i.e. lines designed with different nominal voltages, would have different conductors) and was tried to cross-compare the limit set in the Neplan model [43] you have in order to find out a reasonable criteria for the I_max parameter. In that way, the result of the current obtained from the load flow over this maximum current has been employed to analyze the load flow results.

To analyze this images, to decide if the voltage is inside the internationals benchmark, must be verify that currents have to be inside 1 [p.u]. Then, as we could appreciate this currents are inside these limits considering all load scenarios. Hav-
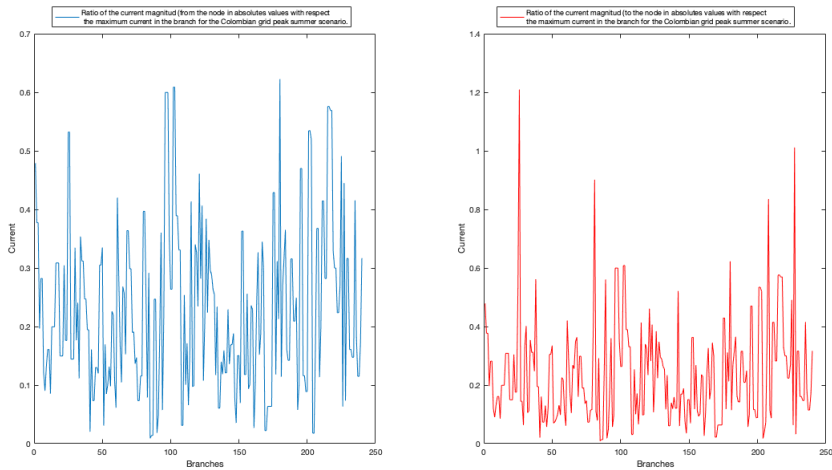
Figure 4.9: Ratio of the current magnitud with the maximum current in the branch from the Load flow in the Colombian grid PEAK summer scenario.
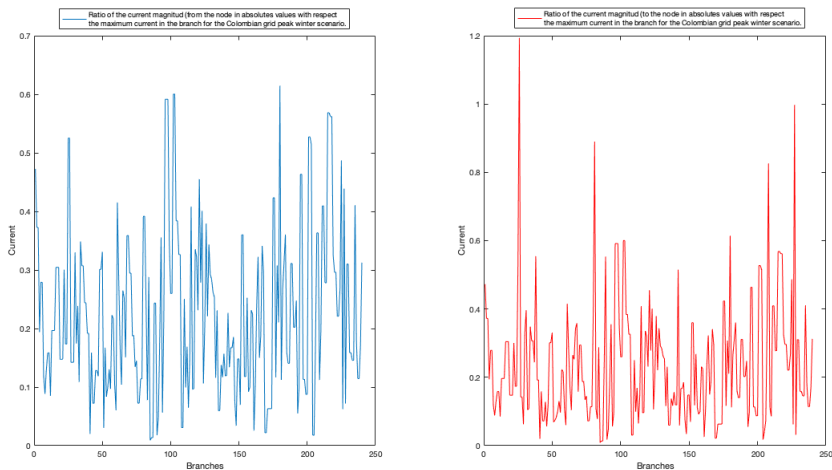
Figure 4.10: Ratio of the current magnitud with the maximum current in the branch from the Load flow in the Colombian grid PEAK winter scenario.

ing all the nodes of the Colombian interconnected system inside the currents limits, is a good indicator since substations do not lead to short circuits phenomenon or over-load issues, which are a sufficient aspect to conclude about possibles power system stability problems. In this case the load power system stability, and currents limits violations are validated.

4.2   Line length comparison

The table E.4 exhibit the length of the lines constituting the Interconnected transmission system of Colombia. In the column named "Length[km]" is summarized the
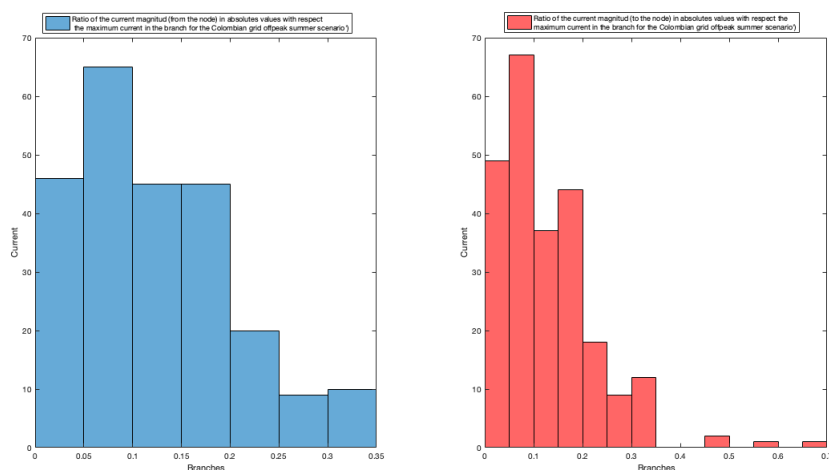
Figure 4.11: Histogram of the current magnitud with the maximum current in the branch from the Load flow in the Colombian grid OFFPEAK summer scenario.
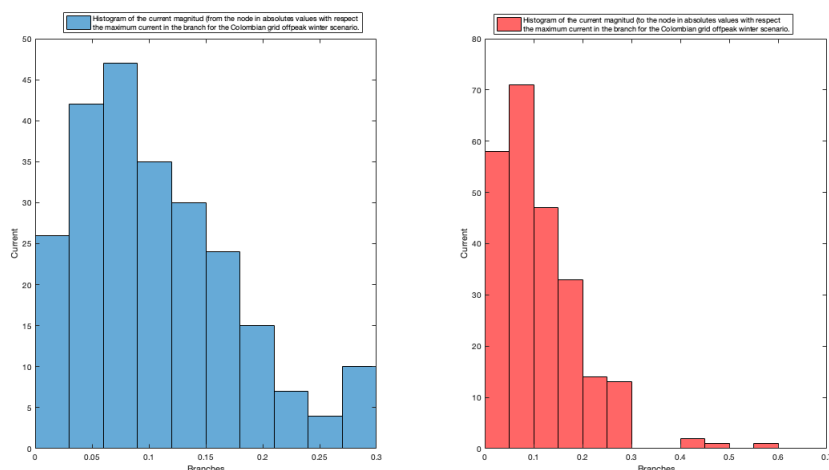
Figure 4.12: Histogram of the current magnitud with the maximum current in the branch from the Load flow in the Colombian grid OFFPEAK winter scenario.

lines modeled using the GIS approach, and are immediately compared to the line "length [km] Neplan" obtained from an official non updated NEPLAN file that contain many data about the electrical information of the National Colombian transmission system. This file is done by the UPME [43], and contain all about the electrical information regarding to lines, substations and another power system elements. This file was shared only for **educational** purposes thus do not contain all the electrical parameters for security reasons. However, according to the information in the file is useful. UPME has employed to compute the line length of the lines composing the **SIN** by means on the traditional method, that in another words is a territorial walk. Indeed, one data of the information contained in this file, is the line length
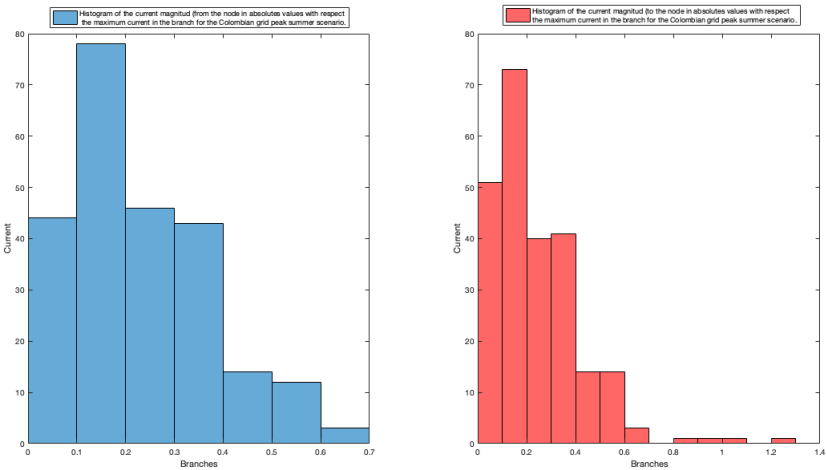
Figure 4.13: Histogram of the current magnitud with the maximum current in the branch from the Load flow in the Colombian grid PEAK summer scenario.
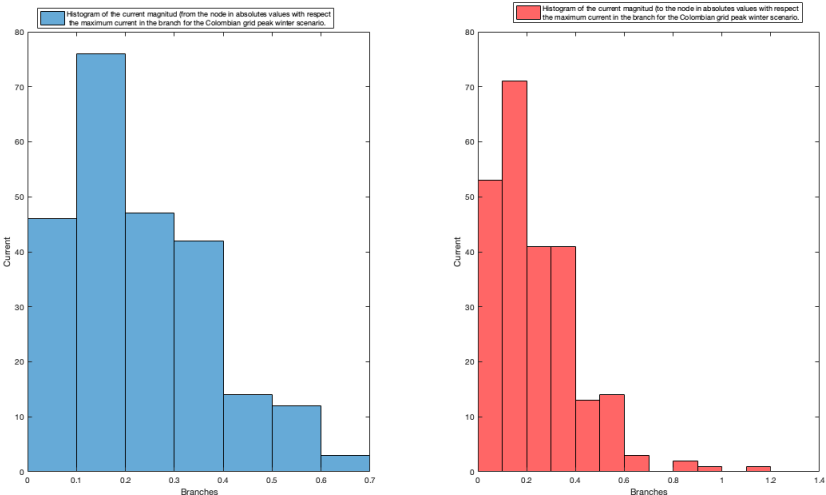
Figure 4.14: Histogram of the current magnitud with the maximum current in the branch from the Load flow in the Colombian grid PEAK winter scenario.

of the transmission lines that compose the SIN, and UPME is the official entity in Colombia for planning purposes. Hence, this information rejoice of feasibility and validity since it's is an official document.

Consequently this information is used to firstly validate the GIS approach outcome (line length of the modeled transmission lines), and to compare the numbers to determine which is the most adjusted and accurate value. As we see, the line length obtained using the GIS approach is lower than the one with respect to the obtained using the NEPLAN file.

4.3 Characterization of MV substations

4.3.1 MV substations Colombian Law requirement: Voltage parameters.

According to RETIE [9], chapter 7, is found the guidelines and requirements for the distribution process. From this chapter in the page 156, is possible to extract the following aspects:

- Are considered as distribution electrical instalation, any group of devices, circuits associated for the transport, and transformation with tensions higher than 120V and lower than 57.5kV.
- Distribution transformers with nominal values higher than 3kV. These, can be installed in poles, sites at ground level, or in vaults in the vicinity of consumers.

Thesee according to CREG resolution 097 - 2008, CREG resolution 025-1995, CREG resolution 070-1998 the common levels of voltage for designning the distriution networks, are the following ones: 13.8, 34.5, 57.5, 66kV. However, for sake of simplicity, the suited level for the distribution cabines is 34.5 kV considering the following aspects.

- According to [9], (Art, 14.4), no need to perform electromagnetic computations for the output substations lines.
- The cost of the power element such as trafos, switches, circuit breakers and other, is lower.

According to figure 4.15, the total energetic demand of September is equal to 1.931.669 kVA/h . However, for definning the nominal power for the future substations, is selected the peak power value in MW of figure 4.16, during the month of september. This value is 3500kW.

According to [32] exist three types of Distribution substations in masonry. Then, the most appropiated is the distribution substations with MV metering called specific substations. And clearly a transformer HV/MV with a rated power **S≥630 KVA** or several transformers with this power rated.

In that sense, the procedure to compute the rated power of the transformer for the HV/MV is the following:

1. Get the maximum peak value in MW.
2. From the 2.2 take the values of electricity users declared on IPSE telemetry report, and the total Puerto Carreño's habitants from the IPSE anual telemetry inform.

With the data above, let's compute the rated power of the HV/MV transformer for the main substation. Shall be reminded that its goal is for feeding the MV network

PUERTO CARREÑO (PUERTO CARREÑO - VICHADA)				
Fecha	Energía Activa (kWh)	Energía Reactiva (kVARh)	Energía Aparente (kVAh)	Factor de Potencia (p.u)
Septiembre 1, Sábado	60.875	21.115	64.433,19	0,94
Septiembre 2, Domingo	60.451	20.703	63.897,71	0,95
Septiembre 3, Lunes	62.858	21.640	66.479,18	0,95
Septiembre 4, Martes	56.312	19.078	59.455,54	0,95
Septiembre 5, Miércoles	55.261	19.032	58.446,58	0,95
Septiembre 6, Jueves	55.494	18.710	58.563,42	0,95
Septiembre 7, Viernes	53.553	18.424	56.633,23	0,95
Septiembre 8, Sábado	55.965	19.452	59.249,55	0,94
Septiembre 9, Domingo	57.030	20.191	60.498,38	0,94
Septiembre 10, Lunes	64.780	21.483	68.249,12	0,95
Septiembre 11, Martes	62.030	20.680	65.386,65	0,95
Septiembre 12, Miércoles	62.093	20.336	65.338,09	0,95
Septiembre 13, Jueves	64.326	20.840	67.617,05	0,95
Septiembre 14, Viernes	61.690	20.843	65.116,42	0,95
Septiembre 15, Sábado	59.652	20.554	63.094,25	0,95
Septiembre 16, Domingo	57.939	20.490	61.455,78	0,94
Septiembre 17, Lunes	60.163	20.040	63.413,02	0,95
Septiembre 18, Martes	64.183	21.672	67.743,01	0,95
Septiembre 19, Miércoles	63.975	21.426	67.467,63	0,95
Septiembre 20, Jueves	63.658	21.682	67.249,01	0,95
Septiembre 21, Viernes	65.515	21.854	69.063,43	0,95
Septiembre 22, Sábado	55.752	20.390	59.363,86	0,94
Septiembre 23, Domingo	57.082	20.653	60.703,16	0,94
Septiembre 24, Lunes	59.188	20.128	62.517,05	0,95
Septiembre 25, Martes	63.750	21.021	67.126,32	0,95
Septiembre 26, Miércoles	68.405	23.157	72.217,83	0,95
Septiembre 27, Jueves	63.170	21.482	66.722,99	0,95
Septiembre 28, Viernes	65.005	22.153	68.676,49	0,95
Septiembre 29, Sábado	63.973	22.269	67.738,41	0,94
Septiembre 30, Domingo	63.895	22.742	67.821,30	0,94
TOTAL	1.828.024	624.240	1.931.669,11	0,95

Figure 4.15: Table extracted from the IPSE telemetry report from Septembre 2018.
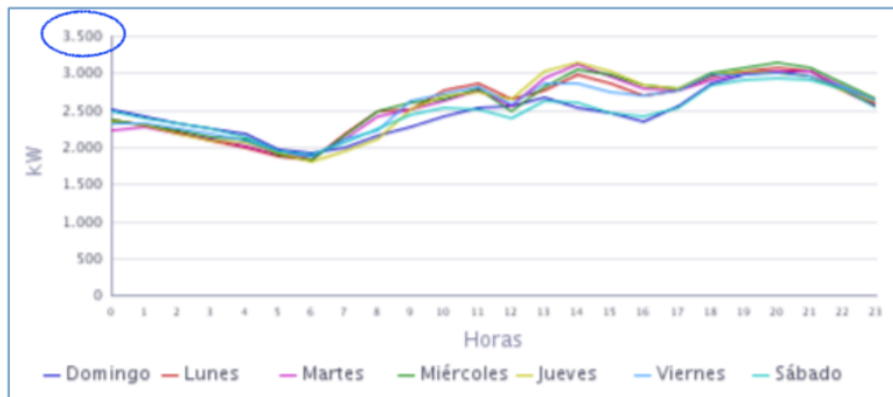
Figure 4.16: Average Load Curve per day from telemetry report from IPSE 2018.

intended to be designed in the city of Puerto Carreño.

$$\frac{3500kW}{4533} \cdot 16000 = 12MVA \tag{4.1}$$

So taking a 12 MVA transformer from scheneider OIL Immersed transformers brochure [39], consequently the design is one HV/MV substations, provided with a 12 MVA trafo. In that sense, this *main* substation will feed the other MV substations, allocated throughout the geography of Puerto Carreño. The process of locating these substations is according to the identified approach for clustering the load, and processing the coordinates of the pixel centroids of population layer, getting many cluster centroids. This approach will be explained and detailed in section 3.4.1.

Thus, the next step consist in the calculation of the required number of poles to cover the energetic demand of total habitants of Puerto carreño (see table 2.2). It is done by dividing the rated power of the HV/MV transformer with the rated power of the MV transformer placed in poles. This result times the total habitants, also considering the rural area from Puerto Carreño, Colombia.

$$\frac{12000}{kVA\,trafo - dist}\frac{kW}{kW} \tag{4.2}$$

From computation above, the number of poles necessary to cover that energetic demand are 107 poles with a transformer rated capacity of 112.5 kW.

4.4 HV/MV - substation siting

To choose the place for positioning the main HV/MV substation, the simplest solution rely on the barycenter of all the coordinates data of figure 2.7. From the figures 4.17 and 4.18, the **blue** point correspond to the location of the HV/MV main substation.

The coordinates of this one is the following one:

Coordinates of HV/MV substation.	
6.1872	-67.488

NOTE: Would result more accurate if are considered all monthly report from IPSE for 2018, and selecting the highest demand about all of them.

Moreover, in figure 4.17 and 4.18 is located the generation station, marked as a green dot. Its location was achieved through the QGIS plug-in QuickOSM (QOSM), explained before. Thus, to employ this plug-in the procedure was the following one: Indeed, for sake of simplicity, and for computational time, the extention declared to run the query in QOSM was the county seat polygon extesion of Puerto Carreño. This polygon is the orange shape of figure 2.7.

Additionally, is worth to mention that for finding the correct parameters, the webpage wiki.openstreetmap.org is an useful tool for that purposes. On that webpage, simply by looking the **Key parameter** and the **value parameter** based on categories. Once inside the page, we can appreciate many categories. For our purposes, we're looking for the Power category.
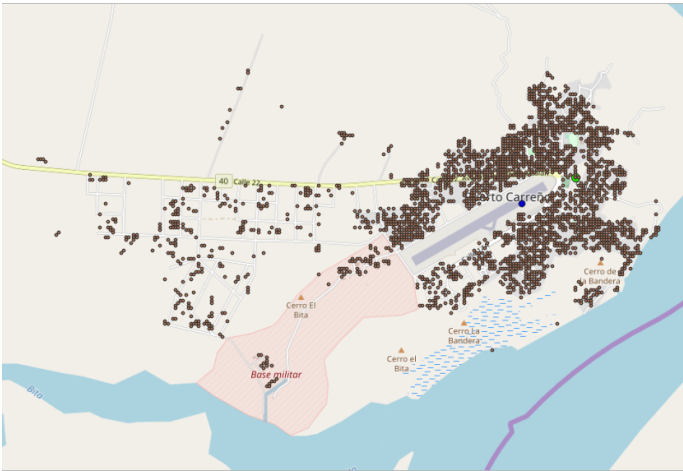
Figure 4.17: Physical distribution of HV/MV substation for Puerto Carreño, Vichada, Colombia. Image using the google maps layer. The blue dot correspond to that substation.

Figure 4.18: Physical distribution of HV/MV substation for Puerto Carreño, Vichada, Colombia. Image using the google satellite layer. The blue dot correspond to that substation
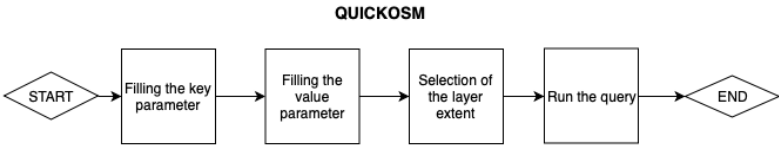
Figure 4.19: Flowgram for using QuickOSM plug in.

4.5 Distribution substations in Puerto Carreño: Centroids of the cluster using Kruskal

According to the peak value of power, which is in the table 2.2, was possible to compute the rated power of the HV/MV transformer. Consequently, with this value, we are able to compute the number of transformers raised in pole.

According to [9] in the chapter 24, section 3 *Spanish: Subestaciones tipo poste. English: Pole mounted substations.*, in urban areas of public concurrency, is possible to install a transforme in a pole with a maximum weight of 800kgf, and 250kVA. Or a transformer with a power rated of 112.5 kVA and a weight of 600kgf.

From the last law scenarios is a little bit clear that we have two options for designing the grid. One is for a trafo about 250kVA, and for a trafo about 112.5kVA. So, intuitively the numbers of poles resulting for selecting a transformer about 250kVA, instead of a trafo of 112.5kVA are lower.

Performing some mathematics, in table 4.5 and according to equation 4.3.1 we're going to sum up the numbers of poles resulting with the correspondent transformer.

Relation between the rated power for a trafo, and the numbers of poles.	
112.5 kVA	107
225 kVA	54

Table 4.1: Table of the relation between the rated power for a trafo and the number of poles required to raise this power elements.

From computation above, if the number of poles necessary to cover that energetic demand are 107 poles with a transformer rated capacity of 112.5 kW. For the 107 poles, the figure 4.21 show us the cluster centroids.
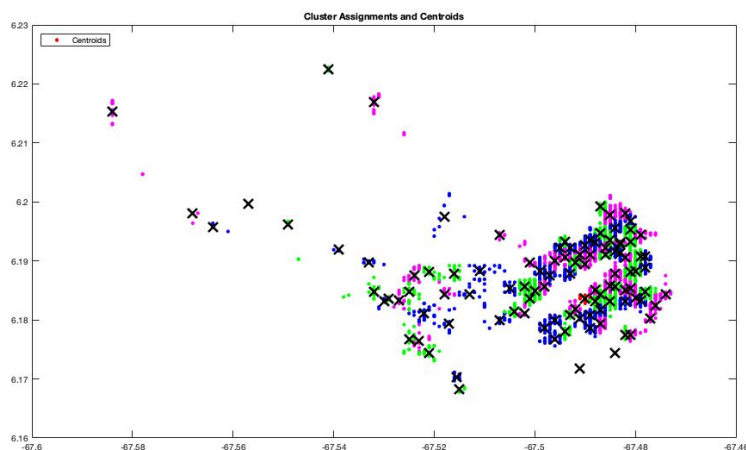
Figure 4.20: Cluster's centroids for a k= 107 clusters, employing the k-means algorithm.

However, if we select a transformer of 225kVA number of poles necessary to cover that energetic demand are 54 poles.

In the figure 4.22 we can appreciate the cluster distribution, and cluster centroids assingment for the cluster number input. Also in figure 4.23 we can appreciate the distribution of the centroids after selecting a k=54 poles.
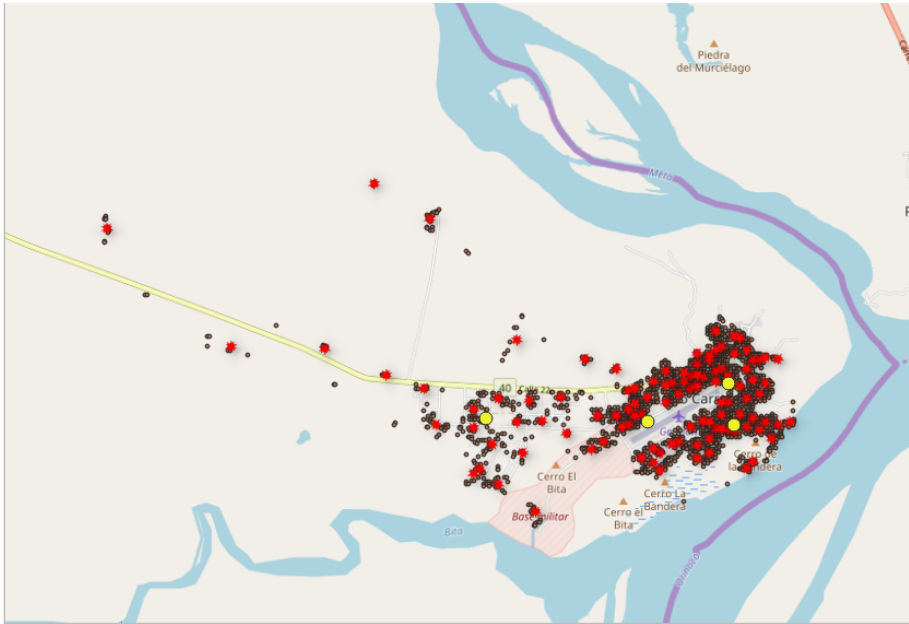
Figure 4.21: Cluster centroids for 107 numbers of cluster according to the ratio of power rated for HV/MV transfomer with respect the rated power for a supposed transformer of 112.5kVA
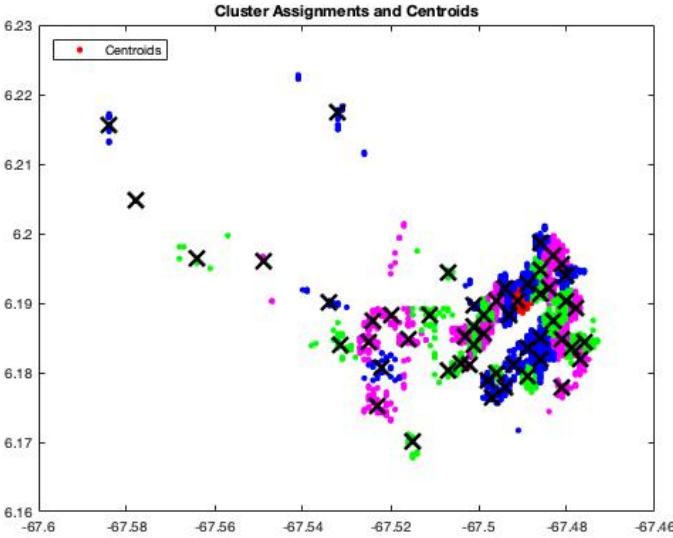
Figure 4.22: cluster distribution, and cluster centroids assingment for the cluster number input of 54 clusters

Thus, the kruskal algorithm provide as outcome us the centroids of this clusters. Then, Obtaining centroids for us means that the cartesian coordinates of this centroids, are equivalent to the substation coordinates of the distribution network substations. Thus, thanks to the last fact, is possible to locate each substation in Puerto Carreño's geographical map by means of QGIS features. Additionally, is possible to compute also using QGIS features the distance between a node i to each other.
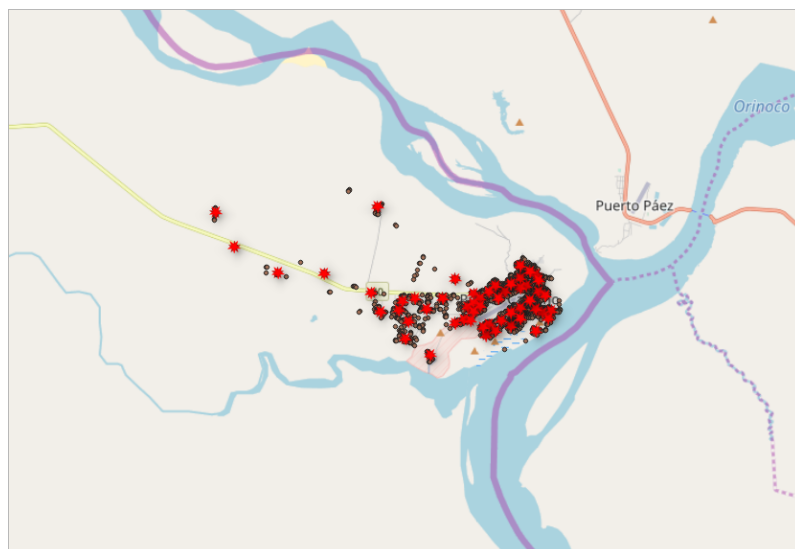
Figure 4.23: Figure of the cluster centroid on a google map about the number of cluster selected initially of k=54.

These distances are summarized in the table E.2. Thus, from this distance table is built the adjacency matrix. This matrix has been used as input data for the minimum spanning tree algorithm, since for using the minimum spanning tree algorithm is necessary an adjacency matrix.

Indeed, Lets suppose our adjacency matrix is called A. this is really useful to create the graph which is required to launch the minimum spanning tree algorithm. Thus, from an square, symmetric adjacency matrix necessary creates a weighted graph. The location of each nonzero entry in A specifies an edge for the graph, and the weight of the edge is equal to the value of the entry. For example, if A(2,1) = 10, then the graph contains an edge between node 2 and node 1 with a weight of 10 which correspond to the distance between the node 2 and the 1. Then, the concept of using this kind of adjacency matrix is relate the weights with the distance between nodes.

4.6 Distribution grid employing Minimum spanning tree algorithm MST algorithm.

First to launch the Minimum spanning tree algorithm, the computation of an adjacency matrix of the distance between centroids was obligatory as is mentioned before. Let's suppose i as the substations of the MV distribution network. It was a matrix of 54x54 (equivalent to the substation numbers) where at each point of the matrix we find the distance between the two points, that is, between each pair of

coordinates. Again, the adjacency matrix was made initially built from the distance of table E.2 in EXCEL. Then through the a code ($*.m$) is possible to import the information from this EXCEL into MATLAB. Hence, the graphs shown as output: plot of the graph created by Adjacency matrix vector plot [T], which corresponds to the minimum spanning tree of this graph.

So the figures 4.24 and 4.25 exhibit result of this technique graphically speaking. In that sense, from the picture 4.25 which represent the adjacency matrix of the system comes the figure 4.24 which basically is the minimum spanning tree of the graph previously created.
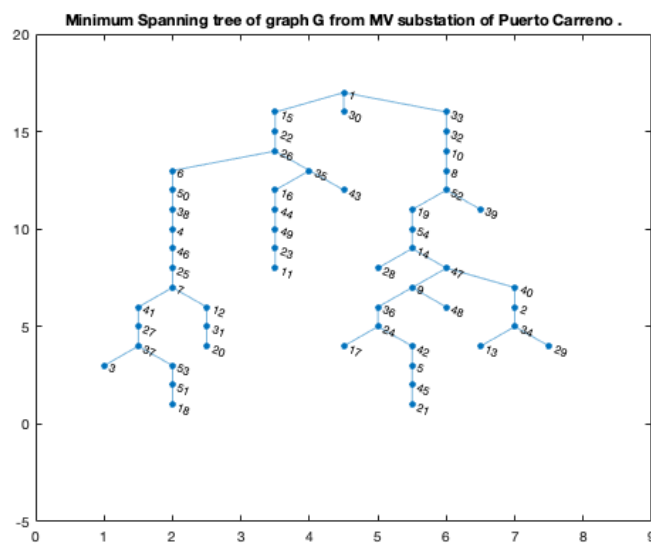
Figure 4.24: Mininum spanning tree outcome from the adjacency marix of the power system.

Finally, by using figure 4.24 is possible to connect all the points described there in QGIS. Then through that representation is evidenced the model of the distribution grid in Puerto Carreño. Hence in the figure 4.26 is seen the MV network modeled for the Puerto Carreño's city. Automatically stand out that MV lines do not cross the airport trail. This is obey to the high weight given to the possibles line between the nodes in the boundary of adjacency matrix. The boundary nodes near to this airport trail are the following nodes: **44, 43, 30, 11, 33, 32, 10, 45, 5, 24, 36, 9, 47.**.

Thus, notice how from a simple adjacency matrix is possible to accurately feed an heuristic route as the minimum spanning tree. Indeed, in a weighted graph, a minimum spanning tree is a spanning tree that has minimum weight than all other spanning trees of the same graph algorithm. Then, from this are traced the lines of a distribution networks. The purpose of using of the adjacency matrix rely on the
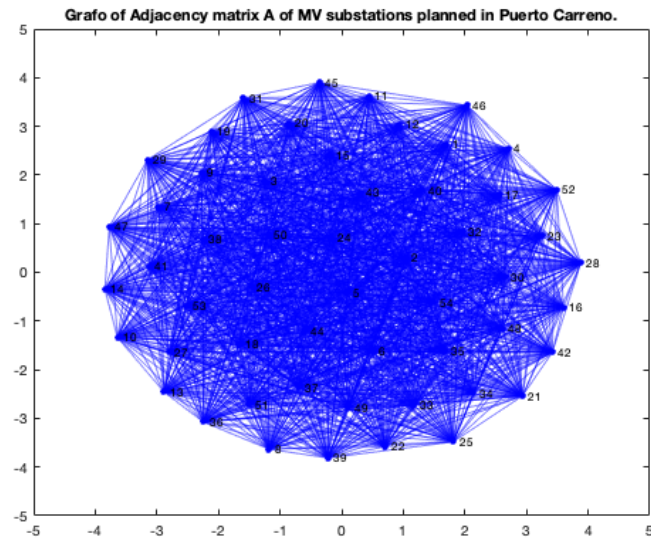
Figure 4.25: Graph created from the adjacency matrix.

definition of an adjacency matrix. May is necessary to remember that an adjacency matrix is a square matrix used to represent a finite graph. The adjacency matrix may be used as a data structure for the representation of graphs in computer programs for manipulating graphs.
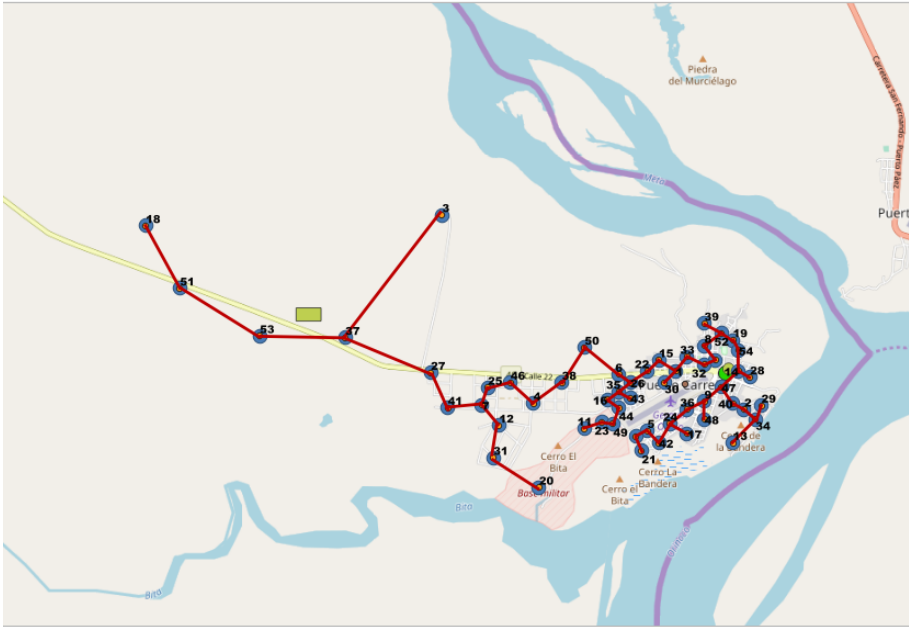
Figure 4.26: Distribution network for the city of Puerto Carreño Colombian, modeled through the Minimum spanning tree algorithm for a centroids numbers (k) of 54.

Chapter 5

Conclusion

Geographic information systems are computer-based systems that are used by many service utilities and government agencies to store, read, edit and evaluate data referenced by a spatial coordinate system. In addition, GIS consents to a data graphic representation. For example: power utilities use GIS to store characteristics and attributes of utility assets such as electric poles, lines transformers and final customer electric meters, all of them geo-referenced by a coordinate system that allows to find their exact location. From all the described approach, is possible to appreciate that all tools that GIS information technology are quite useful for planning and control distribution and transmission grids. Notice that, this system allow us from practically speaking no information, to design electrical grids.

Thus, any application which is satisfying the Business needs or solving challenges are considered to be important. Exact goes on with the progress of GIS applications it solves the business challenges by offering inexpensive and far more accurate effects. Transversely, GIS is really useful for Cost efficient and time saving since GIS application developments have now built mapping pretty quick and cost-effective for anyone such as transportation market, for instance. And Controlling Geography at a Region stage, due to at a larger stage, GIS applications progress could assistance the governments in evaluating what the current problem in their respective geographical boundaries. Governments officers can use GIS applications to communicate by visuals and maps. It could assistance in preserving land acquisitions, Criminal offense Rate, Safety and security scenarios, Flood managements, methods allocations and so on.

The elbow method is a good method to estimate the optimal number of cluster. Although elbow method have suggested a number not really accurate to the currently case, since of four substations to feed all the population of Puerto Carreño's city is a really low number. This mainly obey to the Colombian technical regulation given

the maximum rated power that a pole can withstand is 225 [kVA], and since of in the good practice manual of [29] for rural electrification is recommend only pole mounted transformer. Therefore result quite complicated to design a MV network with only four 4 substations and considering this violation. Hence, can be concluded that elbow method for estimating the optimal cluster number is not a Unequivocal method. Require a revision in terms of the good practice of the engineering.

On the other hand, to validate the Minimum spanning tree algorithm (MST) is quite important to notice that none of the line pass over the landing trail. Intuitively, this was one of the main constraint since it results unfeasible that a line overpass the trail. In that sense, consequently are respected the security distance given the RETIE (Reglamento tecnico de instalaciones eléctricas). As another conclusion for the usage of the (MST) in real-world situations, using a graph based on adjacency matrix which contain "Weight" between each nodes among themselve this weight can be measured as distance, congestion, traffic load or any arbitrary value denoted to the edges.

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Appendix A

APPENDIX A: FWtool

Overview

FWTools is a set of Open Source GIS binaries for Windows (win32) and Linux (x86 32bit) systems produced by Frank Warmerdam (ie. FW). The kits are intended to be easy for end users to install and get going with. No fudzing with building from source, or having to collect lots of interrelated packages. FWTools includes OpenEV, GDAL, MapServer, PROJ.4 and OGDI as well as some supporting components. The FWTools kits also aims to track the latest development versions of the packages included as opposed to official releases. While this may mean the packages are less stable, it is intended to give folks a chance to use the latest and greatest. FWTools releases also are a means by which I make recent development version bug fixes available to a wider audience than would be prepared to build them from the source. With FWTools releases, I also endeavor to build in as many optional components as possible. Thus, I include support for ECW, JPEG2000, HDF and other file formats that require extra libraries.

Linux FWTools releases are intended to be distribution and packaging system agnostic. They should install on pretty much any x86 style Linux system released within the last few years.

Codes for running the tool

For completeness, here is what needs to be done, within the FWTools shell. Extract the metadata:

```
C:\> listgeo -no_norm original.tif > metadata.geo
```

Once edited, copy the metadata to the edited tiff file:

```
C:\> geotifcp -g metadata.geo edited.tif output.tif
```

Download

Current Release: FWTools 2.0.6 (Linux x86 32bit), FWTools 2.4.7 (Windows 32bit)
All downloads: Primary Site, Mirror Site

Subpackages

OpenEV: A high performance raster/vector desktop data viewer and analysis tool.
MapServer: A web mapping package. GDAL/OGR: A library and set of commandline utility applications for reading and writing a variety of geospatial raster (GDAL) and vector (OGR) formats. PROJ.4: A cartographic projections library with commandline utilities. OGDI: a multi-format raster and vector reading techology noteworthy for inclusion of support for various military formats including VPF (ie. VMAP, VITD), RPF (ie. CADRG, CIB), and ADRG. Python: a scripting language. Details of the subcomponents and version built in are contained on the platform specific and release specific pages.

Platform Installation and Packaging Details

FWTools on Linux FWTools on Windows
Experimental FWTools3 on Linux

User Help Mailing List

Requests for assistance, discussion of how to do things with FWTools, or suggestions on how to improve it can be directed to the FWTools Mailing List. In depth help on individual packages would be best directed to the individual project web page. Some auxiliary information is also available on FWTools within the GDAL Wiki.

Appendix B

APPENDIX B: MATLAB script for set up the QGIS environment within Matlab

In the following code, we're setting the QGIS functions to be used in MATLAB.

```
1   QGISTOOLS_DIR='C:\Program Files\QGIS 2.18';
2   setenv('QGISTOOLS_DIR', QGISTOOLS_DIR);
3   setenv('PATH', [QGISTOOLS_DIR '\bin;' getenv('PATH')]);
```

After setting up the QGIS environment (in the script above), we can now call the QGIS functions from within Matlab. We may also want to pass user input to the QGIS functions. In order to convert the user input into a Matlab expression that is passed to QGIS, we can use the eval function of MATLAB.

Here, the user input for layer, input and output is passed onto the QGis $gdal_{rasterize}$ function. The code is below:

```
1   % [img, R, info] = rasterise(layer, input, output)
2   %
3   % This function takes a layer and shape file as input
4   %
5   % It outputs a GeoTiff file using the GET attribute set in
        the shape file
6   % The GET attribute is specified in the scenario
        specification work flow
7   % document
8   %
9   % The function also optionally reads the image data into img
```

```matlab
        , the spatial
10 % referencing object into R, and the geotiff info into info
11
12 function [img, R, info] = rasteriseShp(layer, input, output)
13
14 Call the QGis Tools Environment setup script for this
       session
15 QGisToolsSetup
16
17 eval(['!gdal_rasterize -a GET -tr 1.0 1.0 -l ' layer ' "'
       input '" "' output '"']);
18
19 [img, R] = geotiffread(output);
20 info = geotiffinfo(output);
21
22 end
```

Appendix C

Appendix C: MATPOWER

The MATPOWER is a package developed to the MATLAB® environment that allow the performance of power flow simulations [46]. The data files are known as M-file or MAT- file, where the struct is available to be edited. In the structure 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.

C.1 Matpower 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.

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.)

[†] Included in OPF output, typically not included (or ignored) in input matrix. Here we assume the objective function has units u.

Figure C.1: Bus case format in MATPOWER.

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. 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.

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 ? equivalent circuit, in which the simplifications of the medium and short lines were already mentioned.

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, $\begin{array}{l}> 0 = \text{machine in-service} \\ \leq 0 = \text{machine out-of-service}\end{array}$
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 minute reserves (MW)
RAMP_30*	19	ramp rate for 30 minute reserves (MW)
RAMP_Q*	20	ramp rate for reactive power (2 sec timescale) (MVAr/min)
APF*	21	area participation factor
MU_PMAX†	22	Kuhn-Tucker multiplier on upper P_g limit (u/MW)
MU_PMIN†	23	Kuhn-Tucker multiplier on lower P_g limit (u/MW)
MU_QMAX†	24	Kuhn-Tucker multiplier on upper Q_g limit (u/MVAr)
MU_QMIN†	25	Kuhn-Tucker multiplier on lower Q_g limit (u/MVAr)

* Not included in version 1 case format.
† Included in OPF output, typically not included (or ignored) in input matrix. Here we assume the objective function has units u.
‡ Used to determine voltage setpoint for optimal power flow only if opf.use_vg option is non-zero (0 by default). Otherwise generator voltage range is determined by limits set for corresponding bus in bus matrix.

Figure C.2: Gen matrix case format MATPOWER.

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, if non-zero (taps at "from" bus, impedance at "to" bus, i.e. if $r = x = b = 0$, $tap = \frac{\|V_f\|}{\|V_t\|}$; $tap = 0$ used to indicate transmission line rather than transformer, i.e. mathematically equivalent to transformer with $tap = 1$)
SHIFT	10	transformer phase shift angle (degrees), positive $\Rightarrow$ delay
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)
MU_SF‡	18	Kuhn-Tucker multiplier on MVA limit at "from" bus (u/MVA)
MU_ST‡	19	Kuhn-Tucker multiplier on MVA limit at "to" bus (u/MVA)
MU_ANGMIN‡	20	Kuhn-Tucker multiplier lower angle difference limit (u/degree)
MU_ANGMAX‡	21	Kuhn-Tucker multiplier upper angle difference limit (u/degree)

* Not included in version 1 case format. The voltage angle difference is taken to be unbounded below if ANGMIN ≤ -360 and unbounded above if ANGMAX ≥ 360. If both parameters are zero, the voltage angle difference is unconstrained.
† Included in power flow and OPF output, ignored on input.
‡ Included in OPF output, typically not included (or ignored) in input matrix. Here we assume the objective function has units u.

Figure C.3: Bus case format MATPOWER.

Appendix D

Appendix D

Automatic procedure interface - graphical user interface codes.

D.1   Branch matrix button

```matlab
function pb_branchmatrix_Callback(hObject, eventdata,
    handles)
% hObject      handle to pb_branchmatrix (see GCBO)
% eventdata    reserved - to be defined in a future version of
    MATLAB
% handles      structure with handles and user data (see
    GUIDATA)
all_Col_branch = zeros(1,13);\\

CB_fbus = get(handles.CB_fbus,'value');
CB_tbus = get(handles.CB_tbus,'value');
CB_r = get(handles.CB_r,'value');
CB_x = get(handles.CB_x,'value');
CB_b = get(handles.CB_b,'value');
CB_rateA = get(handles.CB_rateA,'value');
CB_rateB = get(handles.CB_rateB,'value');
CB_rateC = get(handles.CB_rateC,'value');
CB_ratio = get(handles.CB_ratio,'value');
CB_angle = get(handles.CB_angle,'value');
CB_status = get(handles.CB_stat,'value');
CB_angmax = get(handles.CB_angmax,'value');
CB_angmin = get(handles.CB_angmin,'value');
```

```matlab
20
21  while (CB_fbus==1) && (CB_tbus==1) && (CB_r==1) && (CB_x==1)
22  && (CB_b==1) && (CB_rateA==1) && (CB_rateB==1) && (CB_rateC
       ==1)
23  && (CB_ratio==1) && (CB_angle==1) && (CB_status==1) && (
       CB_angmax==1)
24  && (CB_angmin==1)
25  all_Col_branch(1) = 1;
26  all_Col_branch(2) = 3;
27  all_Col_branch(3)= 5;
28  all_Col_branch(4) = 6;
29  all_Col_branch(5) = 7;
30  all_Col_branch(6) = 18;
31  all_Col_branch(7) = 19;
32  all_Col_branch(8) = 20;
33  all_Col_branch(9) = 21;
34  all_Col_branch(10) = 22;
35  all_Col_branch(11) = 23;
36  all_Col_branch(12) = 24;
37  all_Col_branch(13) = 25;
38  break
39  end
40  all_Col_branch;
41  %For EXPORTING INTO WORKSPACE
42  assignin('base','all_Col_branch',all_Col_branch)
43  %For IMPORTING FROM WORKSPACE
44  A = evalin('base','A');
45  %Equaling the generator branch to A{1,1} (Validation line
       length,
46  sheet usefull for branch matrix)
47  generator_branch = A{1,1};
48  branch = zeros(241,13);
49  %FOR PASSING INTO WORKSPACE
50  assignin('base','generator_branch',generator_branch)
51  vref_branch = zeros(241,1);
52  %For filling the Branch matrix.
53  for i=2:241
```

```matlab
54  branch(i,1) = generator_branch{i,all_Col_branch(1)};
55  branch(i,2) = generator_branch{i,all_Col_branch(2)};
56  branch(i,3) = generator_branch{i,all_Col_branch(3)};
57  branch(i,4) = generator_branch{i,all_Col_branch(4)};
58  branch(i,5) = generator_branch{i,all_Col_branch(5)};
59  branch(i,6) = generator_branch{i,all_Col_branch(6)};
60  branch(i,7) = generator_branch{i,all_Col_branch(7)};
61  branch(i,8) = generator_branch{i,all_Col_branch(8)};
62  branch(i,9) = generator_branch{i,all_Col_branch(9)};
63  branch(i,10) = generator_branch{i,all_Col_branch(10)};
64  branch(i,11) = generator_branch{i,all_Col_branch(11)};
65  branch(i,12) = generator_branch{i,all_Col_branch(12)};
66  branch(i,13) = generator_branch{i,all_Col_branch(13)};
67  vref_branch(i,1) = generator_branch{i,17};
68  end
69
70  vref_branch([1,1]) = [];
71  assignin('base','vref_branch',vref_branch)
72  filename = 'vref_branch.mat';
73  save(filename,'vref_branch')
74  %Exporting in the workspace.
75  assignin('base','branch',branch)
76  %Save the matrix like a matlab file. Thanks that is able to
        load the branch
77  %matrix in the Loadflow (MATPOWER) like a .m file, and
        avoiding to load
78  %it like a
79  %Saving the branch matrix in the current folder.
80  filename ='branch.mat';
81  save(filename,'branch');
```

D.2   Bus matrix button

```matlab
1  % ——— Executes on button press in PB_busmatrix.
2  function PB_busmatrix_Callback(hObject, eventdata, handles)
3  % hObject      handle to PB_busmatrix (see GCBO)
4  % eventdata    reserved – to be defined in a future version of
        MATLAB
```

```matlab
5   % handles    structure  with  handles  and  user  data  (see
        GUIDATA)
6   all_Col_bus = zeros(1,13);
7   CB_busi = get(handles.CB_busi,'value');
8   CB_type = get(handles.CB_type,'value');
9   CB_pd = get(handles.CB_pd,'value');
10  CB_qd = get(handles.CB_qd,'value');
11  CB_gs = get(handles.CB_gs,'value');
12  CB_bs = get(handles.CB_bs,'value');
13  CB_area = get(handles.CB_area,'value');
14  CB_vm = get(handles.CB_vm,'value');
15  CB_va = get(handles.CB_va,'value');
16  CB_basekv = get(handles.CB_basekv,'value');
17  CB_zone = get(handles.CB_zone,'value');
18  CB_vmax = get(handles.CB_vmax,'value');
19  CB_vmin = get(handles.CB_vmin,'value');
20
21  while (CB_busi==1 & CB_type==1 & CB_pd==1 & CB_qd==1 & CB_gs
        ==1
22  & CB_bs==1 & CB_area==1 & CB_vm==1 & CB_va==1 & CB_basekv==1
23  & CB_zone==1 & CB_vmax==1 & CB_vmin==1)
24  all_Col_bus(1) = 1;
25  all_Col_bus(2) = 3;
26  all_Col_bus(3)= 8;
27  all_Col_bus(4) = 9;
28  all_Col_bus(5) = 23;
29  all_Col_bus(6) = 24;
30  all_Col_bus(7) = 25;
31  all_Col_bus(8) = 26;
32  all_Col_bus(9) = 27;
33  all_Col_bus(10) = 28;
34  all_Col_bus(11) = 29;
35  all_Col_bus(12) = 30;
36  all_Col_bus(13) = 31;
37  break
38  end
39  all_Col_bus;
```

```
40  %For EXPORTING INTO WORKSPACE
41  assignin('base','all_Col_bus',all_Col_bus)
42  %For IMPORTING FROM WORKSPACE
43  A = evalin('base','A');
44  %Bus MATRIX
45  generator_bus = A{1,2};
46  %FOR PASSING INTO WORKSPACE
47  bus = zeros(118,13);
48  assignin('base','generator_bus',generator_bus)
49  %Input in vector form
50  %All_Col_bus = input('Enter the numbers of the columns
        equivalents
51  to the bus_i type Pd Qd Gs Bs area Vm Va baseKV zone Vmax
        Vmin
52  RESPECTIVELY FROM YOUR EXCEL FILE validation sheet:')
53
54  for i=2:118 %Here, by beginning in 2 we're avoding typing
        the
55  header of the matrix.
56  bus(i,1) = generator_bus{i,all_Col_bus(1)};
57  bus(i,2) = generator_bus{i,all_Col_bus(2)};
58  bus(i,3) = generator_bus{i,all_Col_bus(3)};
59  bus(i,4) = generator_bus{i,all_Col_bus(4)};
60  bus(i,5) = generator_bus{i,all_Col_bus(5)};
61  bus(i,6) = generator_bus{i,all_Col_bus(6)};
62  bus(i,7) = generator_bus{i,all_Col_bus(7)};
63  bus(i,8) = generator_bus{i,all_Col_bus(8)};
64  bus(i,9) = generator_bus{i,all_Col_bus(9)};
65  bus(i,10) = generator_bus{i,all_Col_bus(10)};
66  bus(i,11) = generator_bus{i,all_Col_bus(11)};
67  bus(i,12) = generator_bus{i,all_Col_bus(12)};
68  bus(i,13) = generator_bus{i,all_Col_bus(13)};
69  end
70  bus;
71  %Exporting in the workspace.
72  assignin('base','bus',bus)
73  %Save the matrix like a matlab file. Thanks that is able to
```

```
74  load the branch
75  %matrix in the Loadflow (MATPOWER) like a .m file, and
        avoiding to load
76  %it like a
77  %Saving the branch matrix in the current folder.
78  filename ='bus.mat';
79  save(filename,'bus');
```

D.3 Generation matrix button

```
1   % ——— Executes on button press in pushbutton6.
2   function pushbutton6_Callback(hObject, eventdata, handles)
3   % hObject       handle to pushbutton6 (see GCBO)
4   % eventdata    reserved − to be defined in a future version of
        MATLAB
5   % handles       structure with handles and user data (see
        GUIDATA)
6   all_Col_gen = zeros(1,10);
7   CB_bus = get(handles.CB_bus,'value');
8   CB_pg= get(handles.CB_pg,'value');
9   CB_qg = get(handles.CB_qg,'value');
10  CB_qmax = get(handles.CB_qmax,'value');
11  CB_qmin = get(handles.CB_qmin,'value');
12  CB_vg = get(handles.CB_vg,'value');
13  CB_mbase = get(handles.CB_mbase,'value');
14  CB_status = get(handles.CB_status,'value');
15  CB_pmax = get(handles.CB_pmax,'value');
16  CB_pmin = get(handles.CB_pmin,'value');
17
18
19  while (CB_bus==1 & CB_pg==1 & CB_qg==1 & CB_qmax==1
20  & CB_qmin==1 & CB_vg==1 & CB_mbase==1 & CB_status==1
21  & CB_pmax==1 & CB_pmin==1)
22  all_Col_gen(1) = 1;
23  all_Col_gen(2) = 11;
24  all_Col_gen(3)= 12;
25  all_Col_gen(4) = 32;
26  all_Col_gen(5) = 33;
```

```matlab
27  all_Col_gen(6) = 34;
28  all_Col_gen(7) = 35;
29  all_Col_gen(8) = 36;
30  all_Col_gen(9) = 37;
31  all_Col_gen(10) = 38;
32  break
33  end
34  all_Col_gen;
35  %For EXPORTING INTO WORKSPACE
36  assignin('base','all_Col_gen',all_Col_gen)
37  %For IMPORTING FROM WORKSPACE
38  A = evalin('base','A');
39  %Copying the sheet 2 of loaded excel file
40  generator_gen = A{1,2};
41  %FOR PASSING INTO WORKSPACE
42  assignin('base','generator_gen',generator_gen)
43  %Input in vector form
44  %All_Col_bus = input('Enter the numbers of the columns
45  equivalents to the
46  %bus_i type Pd Qd Gs Bs area Vm Va baseKV zone Vmax Vmin
47  RESPECTIVELY FROM YOUR EXCEL FILE validation sheet:')
48  for i=2:119 %Here, by beginning in 2 were avoding typing the
        header
49  of the matrix.
50  %Aqui extraes todos los nodos y en la segunda columna
        indicas el
51  %tipo de nodo.
52  Nodes(i,1) = generator_gen{i,1};
53  Nodes(i,2) = generator_gen{i,3};
54  end
55  assignin('base','Nodes',Nodes)
56  %Row column give us the
57  [row,col] = find(Nodes(:,2)==2);
58  l=length(row);
59  assignin('base','row',row)
60  %Prelocating the matrix nodes_pv
61  nodes_pv = zeros(1,l);
```

```
62  for i=1:l
63  nodes_pv(i) = Nodes(row(i))
64  end
65  nodes_pv = transpose(nodes_pv);
66  %Assingning the vector nodes_pv
67  assignin('base','nodes_pv',nodes_pv)
68  %Length of the vector nodes_pv
69  lgth_gen = length(nodes_pv);
70  gen = zeros(lgth_gen,21);
71  for i=1:lgth_gen
72  gen(i,1) = generator_gen{row(i),all_Col_gen(1)};
73  gen(i,2) = generator_gen{row(i),all_Col_gen(2)};
74  gen(i,3) = generator_gen{row(i),all_Col_gen(3)};
75  gen(i,4) = generator_gen{row(i),all_Col_gen(4)};
76  gen(i,5) = generator_gen{row(i),all_Col_gen(5)};
77  gen(i,6) = generator_gen{row(i),all_Col_gen(6)};
78  gen(i,7) = generator_gen{row(i),all_Col_gen(7)};
79  gen(i,8) = generator_gen{row(i),all_Col_gen(8)};
80  gen(i,9) = generator_gen{row(i),all_Col_gen(9)};
81  gen(i,10) = generator_gen{row(i),all_Col_gen(10)};
82  end
83  gen;
84  Nodes;
85  %Exporting in the workspace.
86  assignin('base','gen',gen)
87  %Save the matrix like a matlab file. Thanks that is able to
88  load the branch
89  %matrix in the Loadflow (MATPOWER) like a .m file, and
        avoiding to load
90  %it like a
91  %Saving the branch matrix in the current folder.
92  filename ='gen.mat';
93  save(filename,'gen');
```

D.4 Incidence matrix button

```
1  function pushbutton5_Callback(hObject, eventdata, handles)
2  % hObject    handle to pushbutton5 (see GCBO)
```

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```matlab
3   % eventdata    reserved − to be defined in a future version of
        MATLAB
4   % handles      structure with handles and user data (see
        GUIDATA)
5   %Once the branch matrix is created or is loaded in the
        workspace.
6   branch = evalin('base','branch');
7   f_bus=branch(:,1);
8   t_bus=branch(:,2);
9   f_bus(1) = [];
10  t_bus(1) = [];
11  for i=1:length(f_bus)
12  ft(i,1) = f_bus(i,1);
13  ft(i,2) = t_bus(i,1);
14  end
15  ft = unique(ft,'rows');
16  assignin('base','ft',ft)
17  G = graph(ft(:,1),ft(:,2));
18  assignin('base','G',G)
19  inc_matrix = incidence(G);
20  assignin('base','inc_matrix',inc_matrix)
```

Appendix E

Appendix E

E.1 Distance between one substation to each other

Table of the distance between a substation to each other substation in the proximity. This table was used to built the adjacency matrix A, described in 4.5. This basically sum up these distance and using them as a weight to relate the substation points.

Substation Input i	Substation output i	Distance [m]
1	2	1520.809885
1	3	5444.028684
1	4	2835.35093
1	5	1276.31684
1	6	1108.739036
1	7	3819.122017
1	8	736.8767286
1	9	806.0752381
1	10	802.7121987
1	11	2087.764097
1	12	3588.203437
1	13	1770.819782
1	14	1217.426315
1	15	392.9240911
1	16	1438.613986
1	17	1225.559604
1	18	10666.04225
1	19	1257.577543
1	20	3477.841142

Table E.1 continued from previous page

1	21	1674.472052
1	22	553.3755977
1	23	1743.221074
1	24	1023.40757
1	25	3666.342214
1	26	912.6095766
1	27	4759.14712
1	28	1443.911383
1	29	1787.824916
1	30	312.9130076
1	31	3915.582384
1	32	566.5878112
1	33	354.1620671
1	34	1806.587786
1	35	1176.181205
1	36	773.2940033
1	37	6451.087529
1	38	2224.529096
1	39	1071.782576
1	40	1268.239569
1	41	4483.250142
1	42	1421.660701
1	43	1026.690715
1	44	1313.711408
1	45	1479.7204
1	46	3217.196156
1	47	937.9867353
1	48	1081.272593
1	49	1586.589526
1	50	1827.920954
1	51	9759.403979
1	52	1147.45243
1	53	8107.351005
1	54	1280.863993
2	1	1520.809885

Table E.1 continued from previous page

2	3	6961.355002
2	4	4096.833164
2	5	1925.485091
2	6	2526.589076
2	7	5091.884411
2	8	1451.55533
2	9	790.0529637
2	10	1100.331374
2	11	3120.365957
2	12	4769.16528
2	13	678.5289171
2	14	749.1569966
2	15	1913.255773
2	16	2662.876715
2	17	1200.278678
2	18	12147.56873
2	19	1356.293925
2	20	4258.811136
2	21	2145.415185
2	22	2022.124496
2	23	2777.594198
2	24	1465.119397
2	25	4998.12283
2	26	2273.72491
2	27	6128.179425
2	28	629.1022403
2	29	340.9339767
2	30	1634.316908
2	31	4957.612448
2	32	1159.420449
2	33	1503.336933
2	34	290.4150007
2	35	2458.891747
2	36	1106.765132
2	37	7869.624516

Table E.1 continued from previous page

2	38	3579.569078
2	39	1830.808785
2	40	252.5764889
2	41	5755.272688
2	42	1779.75397
2	43	2224.548548
2	44	2435.108615
2	45	2166.145157
2	46	4567.387396
2	47	618.0610974
2	48	797.220615
2	49	2560.535132
2	50	3321.100794
2	51	11202.46755
2	52	1535.994634
2	53	9513.290397
2	54	1144.416123
3	1	5444.028684
3	2	6961.355002
3	4	4036.424969
3	5	5758.812654
3	6	4606.758472
3	7	3741.533131
3	8	5681.087201
3	9	6231.798583
3	10	6004.012652
3	11	4957.741489
3	12	4206.757447
3	13	7150.782969
3	14	6493.651907
3	15	5051.199922
3	16	4793.863056
3	17	6356.123653
3	18	5758.656069
3	19	6137.560872

Table E.1 continued from previous page

3	20	5579.693109
3	21	5971.852086
3	22	4992.177058
3	23	5053.774073
3	24	5983.432316
3	25	3444.424245
3	26	4875.035721
3	27	3049.204098
3	28	6746.173606
3	29	7203.55818
3	30	5390.480721
3	31	4782.726668
3	32	5852.213806
3	33	5487.100544
3	34	7249.219857
3	35	4834.486162
3	36	6058.20887
3	37	3023.311946
3	38	3978.568786
3	39	5503.240685
3	40	6709.353244
3	41	3717.391586
3	42	6079.639578
3	43	5077.751525
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3	45	5690.434326
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3	47	6357.288252
3	48	6435.624145
3	49	5217.994401
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3	51	5283.986893
3	52	5881.980776
3	53	4241.099227
3	54	6319.077306

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4	10	3637.438712
4	11	1108.585474
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4	15	2572.248831
4	16	1440.320061
4	17	3045.211711
4	18	8265.237726
4	19	4060.146732
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4	27	2076.594302
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4	30	2576.489822
4	31	1305.35242
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4	33	3119.606484
4	34	4327.478718
4	35	1674.809558
4	36	2990.737735

Table E.1 continued from previous page

4	37	3863.741269
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4	41	1662.501152
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4	53	5467.69965
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5	4	2276.293085
5	6	1216.865718
5	7	3247.97767
5	8	1975.774599
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5	10	1901.078314
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5	15	1378.119686
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5	23	900.8217843
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5	27	4351.485709
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5	29	2266.386761
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5	32	1685.907774
5	33	1623.372381
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5	35	933.6645512
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5	40	1742.949767
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5	51	9480.676933
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5	53	7743.982276

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6	11	1233.523441
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6	24	1377.202771
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6	26	270.1225681
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6	32	1670.736949
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6	35	331.7626798

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6	36	1489.611124
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6	50	843.2749137
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7	14	5022.964908
7	15	3537.712492
7	16	2436.910909
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7	18	7385.252152
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7	21	3222.771122
7	22	3275.243629
7	23	2347.768682
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7	28	5228.778789
7	29	5423.152781
7	30	3567.794311
7	31	1041.206639
7	32	4385.216147
7	33	4091.173845
7	34	5319.666175
7	35	2668.376715
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7	37	2954.577184
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Table E.1 continued from previous page

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8	32	364.9390143
8	33	392.9227821
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Table E.1 continued from previous page

8	35	1881.146433
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8	38	2855.959405
8	39	431.2916208
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8	41	5121.595802
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8	44	2045.114415
8	45	2194.738195
8	46	3828.927297
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8	49	2323.30713
8	50	2324.395704
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8	54	669.9131825
9	1	806.0752381
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9	3	6231.798583
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9	14	885.7185981
9	15	1190.765629
9	16	1881.787721

Table E.1 continued from previous page

9	17	702.6838136
9	18	11361.60725
9	19	1306.289626
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9	23	2031.568797
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9	25	4214.053312
9	26	1484.347264
9	27	5341.132091
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9	43	1440.31925
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9	47	432.0619849
9	48	342.8213747
9	49	1822.590777
9	50	2546.060014
9	51	10412.48286

Table E.1 continued from previous page

9	52	1357.230921
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10	4	3637.438712
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10	7	4618.954761
10	8	354.1615881
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10	23	2515.177662
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10	28	742.3134028
10	29	1243.86123
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10	31	4708.027131
10	32	238.3749219
10	33	557.3371317

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10	34	1377.550906
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10	36	1100.331374
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10	40	893.39638
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10	44	2093.438196
10	45	2136.384411
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10	47	531.4142313
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10	49	2339.98601
10	50	2557.113552
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10	52	531.4141174
10	53	8866.117291
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11	2	3120.365957
11	3	4957.741489
11	4	1108.585474
11	5	1218.253004
11	6	1233.523441
11	7	2043.127115
11	8	2817.408279
11	9	2381.618853
11	10	2865.596755
11	12	1661.077769
11	13	2890.864391
11	14	3186.320189
11	15	1949.857451

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11	16	708.3285428
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11	18	9373.437225
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11	20	1442.711805
11	21	1187.840652
11	22	1644.723461
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11	24	1662.51236
11	25	2038.758447
11	26	1251.657798
11	27	3174.95896
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11	29	3459.378467
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11	31	1858.488402
11	32	2628.440839
11	33	2424.789107
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11	37	4965.921296
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11	47	2773.006691
11	48	2330.943082
11	49	560.4128346
11	50	1559.284545

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11	51	8308.286746
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11	53	6554.942498
11	54	3345.385407
12	1	3588.203437
12	2	4769.16528
12	3	4206.757447
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12	7	518.4010877
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12	11	1661.077769
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12	14	4765.638692
12	15	3345.549108
12	16	2160.937877
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12	19	4827.607364
12	20	1423.619988
12	21	2809.397696
12	22	3063.361174
12	23	1993.291267
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12	25	762.7048241
12	26	2677.268545
12	27	1673.021144
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12	29	5105.821553
12	30	3315.046286
12	31	629.1023553
12	32	4153.197563

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12	33	3885.920793
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12	35	2414.05191
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12	37	3434.006275
12	38	1473.117155
12	39	4444.046133
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12	42	3116.675361
12	43	2600.318158
12	44	2349.359274
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12	47	4379.51132
12	48	3986.227863
12	49	2213.789888
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13	1	1770.819782
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13	5	1676.326961
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13	7	4924.182234
13	8	1949.134977
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13	10	1626.706497
13	11	2890.864391
13	12	4549.885316
13	14	1386.767821

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13	15	2146.171055
13	16	2572.278643
13	17	902.9269587
13	18	12141.68361
13	19	1979.517215
13	20	3860.666276
13	21	1777.600894
13	22	2160.315123
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13	45	1885.447583
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13	48	715.4132834
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Table E.1 continued from previous page

13	50	3413.273055
13	51	11140.0057
13	52	2123.78898
13	53	9413.56505
13	54	1783.896136
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14	2	749.1569966
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14	7	5022.964908
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14	12	4765.638692
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14	21	2429.59463
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14	29	797.6539332
14	30	1455.679977
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14	32	675.100194
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14	36	1241.43752
14	37	7663.430795
14	38	3438.056789
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14	43	2166.119491
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14	45	2357.565419
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14	49	2638.886831
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15	2	1913.255773
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15	13	2146.171055
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15	51	9398.778851
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16	6	534.5667878
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16	17	1681.244987
16	18	9570.286857
16	19	2692.81591
16	20	2150.991402
16	21	1187.301884
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16	23	445.265738
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16	25	2335.768372
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16	27	3470.092378
16	28	2800.306042
16	29	2990.304696
16	30	1155.413689

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16	33	1757.477536
16	34	2902.050078
16	35	270.1235809
16	36	1560.8321
16	37	5229.270389
16	38	945.5218845
16	39	2388.143605
16	40	2435.780801
16	41	3102.801598
16	42	1296.192619
16	43	443.945888
16	44	270.1240534
16	45	898.4200136
16	46	1910.515342
16	47	2226.848889
16	48	1918.702479
16	49	477.4720091
16	50	1099.417138
16	51	8573.333238
16	52	2558.357782
16	53	6861.864048
16	54	2717.394064
17	1	1225.559604
17	2	1200.278678
17	3	6356.123653
17	4	3045.211711
17	5	776.7120078
17	6	1749.665781
17	7	4022.55168
17	8	1724.259543
17	9	702.6838136
17	10	1519.844865
17	11	1994.675919

Table E.1 continued from previous page

17	12	3655.628922
17	13	902.9269587
17	14	1563.709463
17	15	1519.844865
17	16	1681.244987
17	18	11250.34414
17	19	2008.289684
17	20	3059.641187
17	21	945.5357043
17	22	1432.903286
17	23	1674.825935
17	24	381.5606761
17	25	3973.422563
17	26	1481.092459
17	27	5116.525116
17	28	1629.936044
17	29	1537.457796
17	30	1079.210559
17	31	3791.601905
17	32	1367.956911
17	33	1481.873186
17	34	1356.595886
17	35	1554.225552
17	36	464.4676349
17	37	6892.566528
17	38	2626.282168
17	39	2149.084571
17	40	1061.83271
17	41	4674.992651
17	42	580.9869101
17	43	1301.937043
17	44	1418.294825
17	45	997.6304522
17	46	3569.35066
17	47	1115.060102

Table E.1 continued from previous page

17	48	432.0646318
17	49	1451.034012
17	50	2592.370061
17	51	10239.70697
17	52	2046.041173
17	53	8510.904897
17	54	1887.71185
18	1	10666.04225
18	2	12147.56873
18	3	5758.656069
18	4	8265.237726
18	5	10509.04274
18	6	9622.009412
18	7	7385.252152
18	8	11089.39431
18	9	11361.60725
18	10	11365.73794
18	11	9373.437225
18	12	7867.289357
18	13	12141.68361
18	14	11845.11447
18	15	10291.16733
18	16	9570.286857
18	17	11250.34414
18	19	11609.69385
18	20	9151.317904
18	21	10559.50139
18	22	10133.09709
18	23	9627.840558
18	24	10873.29492
18	25	7336.208757
18	26	9879.758432
18	27	6215.771759
18	28	12089.12103
18	29	12443.80043

Table E.1 continued from previous page

18	30	10513.98993
18	31	8095.571273
18	32	11171.19204
18	33	10811.97129
18	34	12414.63597
18	35	9725.949329
18	36	11093.52605
18	37	4433.332723
18	38	8624.765255
18	39	11007.5493
18	40	11900.48706
18	41	6833.416994
18	42	10802.24636
18	43	9975.074937
18	44	9832.072808
18	45	10347.12749
18	46	7699.626192
18	47	11601.86203
18	48	11468.41462
18	49	9844.590399
18	50	8838.36388
18	51	1376.202222
18	52	11367.53875
18	53	3067.186332
18	54	11757.40563
19	1	1257.577543
19	2	1356.293925
19	3	6137.560872
19	4	4060.146732
19	5	2410.196302
19	6	2310.803896
19	7	5027.489477
19	8	564.3124324
19	9	1306.289626
19	10	509.9530299

Table E.1 continued from previous page

19	11	3343.763948
19	12	4827.607364
19	13	1979.517215
19	14	607.3420509
19	15	1489.920237
19	16	2692.81591
19	17	2008.289684
19	18	11609.69385
19	20	4715.69193
19	21	2773.300487
19	22	1764.258622
19	23	2996.762723
19	24	2022.127786
19	25	4846.726655
19	26	2153.68019
19	27	5899.525462
19	28	791.7961023
19	29	1376.802463
19	30	1559.979387
19	31	5171.75889
19	32	729.6206949
19	33	941.6869209
19	34	1589.022199
19	35	2426.96822
19	36	1604.516728
19	37	7525.958834
19	38	3419.606251
19	39	639.5840324
19	40	1216.463251
19	41	5685.539864
19	42	2447.160394
19	43	2283.901825
19	44	2569.523868
19	45	2644.178544
19	46	4393.207954

Table E.1 continued from previous page

19	47	933.4424291

Table E.2: Table of the distance between a substation to each other substation in the proximity.

E.2 Table of the line length after the GIS modelling

Comparative table of transmission line length modeled of the national transmission system using GIS tools, with respect to transmission line length from official data. This comparative table validate the GIS approach for the transmission line length computation. This table is also useful to identify the accuracy of the approach in the modeling of the line length. See chapter 4.2

#	Substation Hub 1	#	Substation Hub 2	LENGTH [km]	Length [km]-Neplan
			Table ontinued from previous page		
109	Alferez	113	San Bernardino	96.401	97.36501
108	Pance	106	Alto Anchicaya	40.965	41.37465
70	Ancon Sur ISA	71	San Carlos 220kV	106.871	107.93971
70	Ancon Sur ISA	74	esmeralda	124.673	125.91973
68	Ancon Sur	57	miraflores	18.656	18.84256
56	Occidente EPM	68	Ancon Sur	40.378	40.78178
72	Bacata 500kV	90	Nueva Esperanza 500kV	28.013	28.29313
77	Bacata 220kV	78	Torca	16.722	16.88922
83	Noroeste	77	Bacata 220kV	3.592	3.62792
86	Balsillas	89	La Mesa	25.364	25.61764
47	Guatiguara	45	Bucaramanga	30.376	30.67976
88	Cartago	96	San Marcos 220kV	140.419	141.82319
26	cerromatoso 500kV	48	primavera 500kV	212.505	214.63005
79	Chivor	93	Corocora	154.629	156.17529
79	Chivor	92	Jaguey	115.935	117.09435
79	Chivor	67	Sochagota	98.481	99.46581
91	Circo	84	el guavio	66.72	67.3872
91	Circo	99	Nueva Esperanza 220kV	24.396	24.63996
35	Comuneros	47	guatiguara	89.952	90.85152

35	Comuneros	46	primavera 220kV	107.248	108.32048
93	Corocora	94	Quifa	58.433	59.01733
71	San carlos 220kV	74	Esmeralda	193.998	195.93798
18	Bolivar 220kV	14	El Bosque	16.801	16.96901
15	Ternera	14	El Bosque	6.694	6.76094
79	Chivor	84	el guavio	32.921	33.25021
78	Torca	84	el guavio	60.907	61.51607
91	Circo	84	el guavio	66.075	66.73575
99	Nueva Esperanza 220kV	84	el guavio	90.185	91.08685
86	Balsillas	83	Noroeste	12.526	12.65126
89	La Mesa	83	Noroeste	39.817	40.21517
47	guatiguara	67	Sochagota	145.749	147.20649
58	Guatape	71	San Carlos 220kV	32.404	32.72804
84	el guavio	105	La reforma	74.302	75.04502
59	Jaguas	58	Guatape	12.541	12.66641
45	Bucaramanga	39	Hidrosogamoso 220kV	34.835	35.18335
110	BETANIA	115	Altamira	90.854	91.76254
107	Juanchito	112	Salvajina	61.188	61.79988
58	Guatape	71	San Carlos 220kV	32.19	32.5119
46	primavera 220kV	59	Jaguas	103.784	104.82184
117	Jamondina	118	Pomasqui	195.718	197.67518
117	Jamondina	118	Pomasqui	195.719	197.67619
117	Jamondina	118	Pomasqui	194.129	196.07029
117	Jamondina	118	Pomasqui	195.522	197.47722
117	Jamondina	113	San Bernardino	161.419	163.03319
107	Juanchito	111	Paez	93.388	94.32188
73	Purnio	65	la sierra	100.395	101.39895
85	La virginia 220kV	81	Hermosa	36.122	36.48322
56	Occidente EPM	62	envigado	30.759	31.06659
56	Occidente EPM	51	Guadalupe	63.831	64.46931
56	Occidente EPM	54	La Tasajera	21.55	21.7655
108	Pance	107	Juanchito	14.971	15.12071
108	Pance	112	Salvajina	49.271	49.76371
65	La sierra	73	Purnio	56.922	57.49122

73	Purnio	83	Noroeste	102.771	103.79871
83	Noroeste	73	Purnio	102.771	103.79871
73	purnio	71	San Carlos 220kV	91.361	92.27461
93	Corocora	94	Quifa	66.303	66.96603
94	Quifa	95	Rubiales	18.867	19.05567
94	Quifa	95	Rubiales	19.989	20.18889
71	San Carlos 220kV	70	Ancon sur ISA	106.511	107.57611
71	San Carlos 220kV	65	La sierra	29.45	29.7445
74	Esmeralda	71	San Carlos 220kV	193.998	195.93798
46	primavera 220kV	59	Jaguas	80.688	81.49488
69	San Carlos 500kV	48	Primavera 500kV	81.907	82.72607
71	San Carlos 220kV	73	Purnio	93.059	93.98959
82	San Felipe	75	La ENEA	65.3	65.953
107	Juanchito	96	San Marcos 220kV	22.219	22.44119
87	San Marcos 500kV	80	La virginia 500kV	154.659	156.20559
100	Yumbo	96	San Marcos 220kV	6.495	6.55995
103	San Mateo	99	Nueva Esperanza 220kV	8.65	8.7365
103	San Mateo	104	Tunal	7.126	7.19726
113	San Bernardino	111	Paez	66.922	67.59122
69	San Carlos 500kV	80	La virginia 500kV	201.881	203.89981
79	Chivor	67	Sochagota	101.067	102.07767
66	Termo Paipa	67	Sochagota	0.124	0.12524
16	Termo cartagena	18	Bolivar 220kV	17.832	18.01032
77	Bacata 220kV	78	Torca	16.947	17.11647
78	Torca	84	el guavio	61.073	61.68373
101	Tuluni	97	Mirolindo	82.706	83.53306
100	Yumbo	96	San Marcos 220kV	6.135	6.19635
116	Mocoa	115	Altamira	141.268	142.68068
79	Chivor	84	el guavio	33.545	33.88045
79	Chivor	78	Torca	89.34	90.2334
106	Alto Anchicaya	100	Yumbo	46.599	47.06499
109	Alferez	100	Yumbo	28.412	28.69612
108	Pance	100	Yumbo	27.242	27.51442
47	guatiguara	40	Palos	22.326	22.54926

47	guatiguara	46	primavera 220kV	147.572	149.04772
110	Betania	97	Mirolindo	191.886	193.80486
102	El paraiso	99	Nueva Esperanza 220kV	13.282	13.41482
49	PORCE III	26	cerromatoso 500kV	128.245	129.52745
69	San Carlos 500kV	49	PORCE III	100.126	101.12726
110	BETANIA	113	San Bernardino	133.177	134.50877
101	Tuluni	110	BETANIA	111.875	112.99375
114	el quimbo	115	Altamira	62.987	63.61687
98	La guaca	102	El paraiso	6.8	6.868
98	La guaca	89	La Mesa	4.66	4.7066
98	La guaca	102	El paraiso	8.412	8.49612
92	Jaguey	94	Quifa	97.163	98.13463
104	Tunal	105	La reforma	64.988	65.63788
98	La guaca	89	La Mesa	4.543	4.58843
89	La Mesa	97	Mirolindo	86.818	87.68618
73	Purnio	76	Miel I	26.288	26.55088
76	MIEL I	82	San Felipe	48.274	48.75674
89	La Mesa	97	Mirolindo	84.073	84.91373
116	Mocoa	117	Jamondina	67.38	68.0538
83	Noroeste	77	Bacata 220kV	3.273	3.30573
102	El paraiso	99	Nueva Esperanza 220kV	15.111	15.26211
76	Miel I	73	Purnio	26.288	26.55088
113	San bernardino	110	BETANIA	132.841	134.16941
89	La Mesa	82	San Felipe	76.714	77.48114
76	MIEL I	82	San Felipe	48.682	49.16882
117	Jamondina	113	San Bernardino	163.718	165.35518
47	guatiguara	67	Sochagota	132.74	134.0674
104	Tunal	91	Circo	8.705	8.79205
35	Comuneros	38	Termo Barranca	8.136	8.21736
38	Termo Barranca	39	Hidrosogamoso 220kV	52.441	52.96541
66	Termo Paipa	67	Sochagota	0.146	0.14746
79	Chivor	78	Torca	92.439	93.36339
104	Tunal	105	La reforma	90.709	91.61609

89	La Mesa	82	San Felipe	76.876	77.64476
85	La virginia 220kV	88	Cartago	32.02	32.3402
58	Guatape	63	oriente	49.962	50.46162
64	Playas	63	oriente	67.047	67.71747
62	envigado	63	oriente	12.392	12.51592
86	Balsillas	89	La Mesa	25.294	25.54694
84	el guavio	105	La reforma	71.33	72.0433
88	cartago	85	La virginia 220Kv	31.327	31.64027
29	Ocana 220kV	40	Palos	133.417	134.75117
40	Palos	41	Toledo	73.651	74.38751
52	PORCE II	51	Guadalupe	11.68	11.7968
33	Termotasajero	40	Palos	93.217	94.14917
58	Guatape	53	Barbosa	31.587	31.90287
51	Guadalupe	50	SALTO EPM	2.343	2.36643
58	Guatape	57	miraflores	49.415	49.90915
58	Guatape	59	Jaguas	12.395	12.51895
33	Termotasajero	47	guatiguara	110.202	111.30402
85	la virginia 220kV	74	esmeralda	24.08	24.3208
22	Ocana 500kV	13	Copey 500kV	225.125	227.37625
40	Palos	45	Bucaramanga	3.128	3.15928
55	Bello	61	Guayabal	8.848	8.93648
42	Samore	43	Banadia	45.546	46.00146
46	primavera 220kV	65	La sierra	37.263	37.63563
60	MALENA	46	primavera 220kV	7.497	7.57197
61	Guayabal	68	Ancon Sur	8.923	9.01223
50	SALTO EPM	55	Bello	67.907	68.58607
43	Banadia	44	cano limon	84.287	85.12987
68	Ancon Sur	74	esmeralda	123.82	125.0582
57	miraflores	74	esmeralda	134.265	135.60765
75	La ENEA	74	esmeralda	30.923	31.23223
74	esmeralda	74	esmeralda	0	0
82	San Felipe	74	esmeralda	93.231	94.16331
100	Yumbo	74	esmeralda	183.677	185.51377
81	Hermosa	74	esmeralda	21	21.21
85	la virginia 220kV	74	esmeralda	23.743	23.98043

30	San Mateo (Santander)	32	cucuta	4.61	4.6561
58	Guatape	59	Jaguas	17.1	17.271
52	PORCE II	50	SALTO EPM	9.347	9.44047
53	Barbosa	50	SALTO EPM	39.63	40.0263
59	Jaguas	60	MALENA	66.563	67.22863
55	Bello	54	La Tasajera	22.449	22.67349
27	Merielectrica	35	Comuneros	1.572	1.58772
29	Ocana 220kV	30	San Mateo (Santander)	99.73	100.7273
41	Toledo	42	Samore	38.544	38.92944
32	Cucuta	33	Termotasajero	12.223	12.34523
32	Cucuta	33	Termotasajero	12.223	12.34523
25	Cerromatoso 220kV	24	Urra	161.4191425	163.0333339
25	Cerromatoso 220kV	24	Urra	191.8859827	193.8048425
10	Sabanalarga 220kV	6	Fundacion	132.8410741	134.1694848
10	Sabanalarga 220kV	6	Fundacion	133.1771868	134.5089587
6	Fundacion	11	Copey 220kV	161.4191425	163.0333339
10	Sabanalarga 220kV	6	Fundacion	191.8859827	193.8048425
5	Santa Marta	6	Fundacion	132.8410741	134.1694848
5	Santa Marta	6	Fundacion	133.1772	134.5089587
5	Santa Marta	3	Termo Guajira	161.4191	163.0333339
3	Termo Guajira	4	Termocol	191.886	193.8048425
3	Termo Guajira	2	Cuestecitas	132.8411	134.1694848
3	Termo Guajira	2	Cuestecitas	133.1772	134.5089587
12	Valledupar	2	Cuestecitas	161.4191425	163.0333339
7	Tebsa	10	Sabanalarga 220kV	191.8859827	193.8048425
7	Tebsa	10	Sabanalarga 220kV	132.8410741	134.1694848
7	Tebsa	10	Sabanalarga 220kV	133.1771868	134.5089587
7	Tebsa	9	Nueva Barranquilla	161.4191425	163.0333339
9	Nueva Barranquilla	8	Termoflores LN824	191.886	193.8048425
10	Sabanalarga 220kV	18	Bolivar 220kV	132.8410741	134.1694848
9	Nueva Barranquilla	8	Termoflores LN825	133.1771868	134.5089587
9	Nueva Barranquilla	10	Sabanalarga 220kV LN826	161.4191425	163.0333339

9	Nueva Barranquilla	10	Sabanalarga 220kV LN827	191.8859827	193.8048425
9	Nueva Barranquilla	10	Sabanalarga 220kV LN828	132.8410741	134.1694848
18	Bolivar 220kV	10	Termo cartagena LN832	133.1771868	134.5089587
16	Termo Cartagena	17	Termo candelaria LN830	161.4191425	163.0333339
16	Termo Cartagena	17	Termo candelaria LN829	191.8859827	193.8048425
15	Ternera	17	Termo Candelaria	132.8410741	134.1694848
15	Ternera	17	Termo Candelaria	133.1771868	134.5089587
18	Bolivar 220kV	15	Ternera	161.4191425	163.0333339
10	Sabanalarga 220kV	18	Bolivar 220kV	191.8859827	193.8048425
10	Sabanalarga 220kV	15	Ternera	132.8410741	134.1694848
12	Valledupar	11	Copey 220kV	133.1771868	134.5089587
12	Valledupar	11	Copey 220kV	161.4191425	163.0333339
5	Santa marta	4	Termocol	191.8859827	193.8048425
72	Bacata 500kV	48	Primavera 500kV	132.8410741	134.1694848
13	Copey 500kV	19	Bolivar 500kV	133.1771868	134.5089587
21	Chinu	20	Sabanalarga 500kV	161.4191425	163.0333339
21	Chinu	20	Sabanalarga 500kV	191.8859827	193.8048425
26	Cerromatoso 500kV	21	Chinu	132.8410741	134.1694848
26	Cerromatoso 500kV	21	Chinu	133.1771868	134.5089587
114	El Quimbo	115	Altamira	161.4191425	163.0333339
114	El Quimbo	117	Jamondina	191.8859827	193.8048425
58	Guatape	64	Playas	51.114776	51.62592376
46	Primavera 220kV	64	Playas	103.783876	104.8217148
22	Ocana 500kV	34	HidroSogamoso 500kV	150.999897	152.509896
48	Primavera 500kV	34	HidroSogamoso 500kV	151.655975	153.1725348
24	Urra	23	uraba	51.115	51.62615
39	HidroSogamoso 220kV	47	guatiguara	47.345	47.81845

39	HidroSogamoso 220kV	47	guatiguara	47.61	48.0861
46	Primavera 220kV	36	Termocentro	6.234	6.29634
10	Sabanalarga 220kV	20	Sabanalarga 500kV	0	0
10	Sabanalarga 220kV	20	Sabanalarga 500kV	0	0
10	Sabanalarga 220kV	20	Sabanalarga 500kV	0	0
11	Copey 220kV	13	Copey 500kV	0	0
11	Copey 220kV	13	Copey 500kV	0	0
26	cerromatoso 500kV	25	cerromatoso 220kV	0	0
22	Ocana 500kV	29	Ocana 220kV	0	0
30	San Mateo (Santander)	31	corozo	49.506101	50.00116201
30	San Mateo (Santander)	31	corozo	49.506101	50.00116201
35	Comuneros	28	cira infanta	18.589703	18.77560003
35	Comuneros	37	Magdalena	-	-
35	Comuneros	37	Magdalena	-	-
46	Primavera 220kV	48	Primavera 500kV	0	0
69	San Carlos 500kV	71	San Carlos 220kV	0	0
69	San Carlos 500kV	71	San Carlos 220kV	0	0
69	San Carlos 500kV	71	San Carlos 220kV	0	0
68	Ancon Sur	70	Ancon Sur ISA	0.18095	0.1827595
68	Ancon Sur	70	Ancon Sur ISA	0.18095	0.1827595
80	La virginia 500kV	85	La virginia 220kV	0	0
96	San Marcos 220kV	87	San Marcos 500kV	0	0
110	Betania	114	El Quimbo	31.813374	32.13150774
77	Bacata 220kV	72	Bacata 500kV	0	0
99	Nueva Esperanza 220kV	90	Nueva Esperanza 500kV	0	0
58	guatape	62	envigado	63.284865	63.91771365
53	barbosa	57	miraflores	32.7933	33.121233
53	barbosa	52	porce 2	44.93271	45.3820371
53	barbosa	51	guadalupe IV	38.329279	38.71257179
53	barbosa	54	la tasajera	11.375698	11.48945498

30	San Mateo (Santander)	33	Termotasajero	16.612267	16.77838967
2	Cuestecitas	1	Cuatricentenario	126.173149	127.4348805
39	HidroSogamoso 220kV	34	HidroSogamoso 500kV	0	0

Table E.4: Comparative table of the line length modeled of the national transmission system using GIS tool, and the line length from official data.