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MÁSTER UNIVERSITARIO EN INGENIERÍA INDUSTRIAL (MII)

TRABAJO FIN DE MÁSTER

“Application of smart meter phase connectivity to voltage unbalance in low voltage networks”

Autor: Andrés Garcerán Sánchez

Director: Francisco José Pazos Filgueira

Codirector: Javier Matanza Domingo

Madrid

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Madrid

“APPLICATION OF SMART METER PHASE CONNECTIVITY TO VOLTAGE UNBALANCE IN LOW VOLTAGE NETWORKS”

Autor: Garcerán Sánchez, Andrés.
Codirector: Matanza Domingo, Javier.
Codirector: Pazos Filgueira, Francisco José.
Entidad Colaboradora: i-DE: Grupo Iberdrola

RESUMEN DEL PROYECTO

En este proyecto los conceptos de *smart meter phase connectivity* y *la supervisión avanzada de baja tensión (SABT)* son aplicadas para optimizar la conexión de nuevos clientes a la red de baja tensión. Con las ecuaciones que permitan el cálculo de redes desequilibradas se llega a la conclusión de la posibilidad de simplificar el cálculo de intensidades y tensiones utilizando unos coeficientes elaborados durante el proyecto.

Palabras clave: Smart meter phase connectivity, SABT, baja tension.

Gracias a técnicas de *big data* se han conseguido el dato de la fase y centro de transformación al que está conectado cada medidor inteligente. En el proyecto se propone elaborar un modelo que calcule la intensidad y la tensión en las tres fases y el neutro, así como también conseguir una imagen de la topología de la red.

Se han tenido en cuenta cuatro casos de estudio diferentes que corresponden a cuatro líneas de las cuáles tres pertenece al mismo centro de transformación (A2, A5 y A6) y un cuarto de un centro de transformación diferente (B1). Una de las características más importantes de las redes, se pueden ver en la Tabla 1, es el porcentaje de cargas trifásicas debido a que las cargas trifásicas varían la potencia que circula por cada fase dependiendo del momento del día y del uso que haya dentro de la carga.

Caso de estudio	Nº Clientes	Nº Nudos	Cargas trifásicas (%)	Cargas sin fase asignada (%)
A2	32	6	3.13	6.25
A5	16	3	25.00	6.25
A6	29	3	3.45	13.79
B1	32	65	0.00	0.00

Tabla 1. Características de las líneas que son objeto de estudio.

La importancia del porcentaje de cargas trifásicas se puede ver en la Tabla 2 como el peor desempeño de los cuatro casos.

El primer paso en el proyecto será la creación de una herramienta programada que calcule la tensiones y las intensidades, utilizando las ecuaciones mostradas debajo del párrafo, en función de los contadores asignados a cada fase.

$$\vec{I}_{inyectado,fase} = \frac{\vec{S}_{medidor,fase}}{\vec{V}_{nudo}}$$

$$\vec{I}_{línea} = B_{inyectada} * \vec{I}_{Inyectada} + \sum \vec{I}_{nudos-aguas\_abajo}$$

$$\vec{V}_{nudo(1,2,3)} = cte$$

$$\vec{I}_{neutro} = \vec{I}_1 + \vec{I}_2 + \vec{I}_3$$

En el modelo se utilizará un modelo iterativo para calcular la tensión debido a que la corriente depende de la tensión en el nudo, dato que es desconocido a priori. Como se puede ver en la Figura 1, para calcular las corrientes y tensiones las cargas trifásicas se modelarán con un coeficiente que las multiplica y asigna un porcentaje de la potencia a cada fase y ese coeficiente es obtenido de un algoritmo de optimización que minimiza el error cuadrático medio.

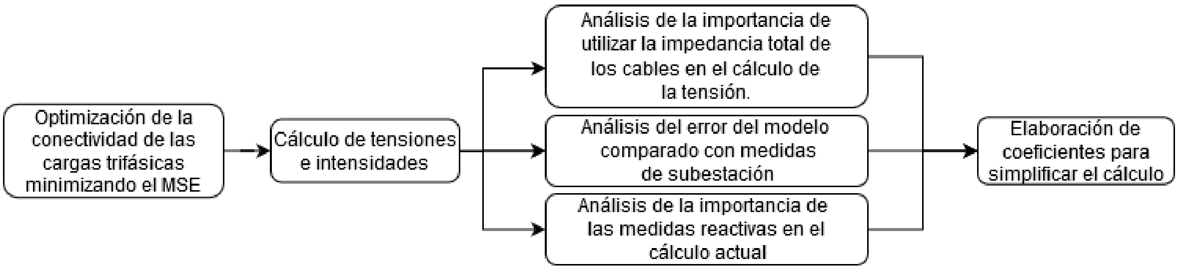

Figura 1. Metodología aplicada para cada caso de estudio.

Para cada caso de estudio se utilizará la metodología explicada previamente. Una vez se han llevado a cabo los tres análisis para los cuatro casos de estudio se procederá a calcular los coeficientes que se utilizarían cuando se intente acoplar un cliente nuevo. Los coeficientes se usarían de la siguiente manera para redes con un bajo porcentaje de cargas trifásicos:

$$I_{línea,fase} = i_{línea,fase} * C_{error} * C_Q$$

$$Capacity \geq I_{línea,fase} + \frac{P_{consumidor}}{V_{CT} + \Delta V_{nudo} * C_{Reac}}$$

Los coeficientes permiten simplificar el cálculo sin utilizar ni las reactancias de las líneas, las medidas de potencia reactiva y tener un coeficiente de seguridad para las ecuaciones utilizadas para el modelo.

Los errores máximos que tienen los cálculos del modelo comparado con las medidas del centro de transformación se pueden ver en la Tabla 2. Los errores máximos han sido utilizados para crear el coeficiente C_{error} que tiene la función de ser un coeficiente de seguridad para el error máximo que tiene el modelo.

Caso de estudio	**Error máximo en las fases (%)**	**Error máximo en el neutro (%)**
A2	10.8	41.2
A5	58,6	67.4
A6	22.4	26.7
B1	14.6	17.3

Tabla 2. Errores máximos que tienen los cálculos del modelo.

Los errores promedio resultado de los análisis del impacto de las reactancias de las líneas en el cálculo de tensiones y del impacto de las medidas de potencia reactiva en el cálculo de intensidades son 6% y 4% respectivamente y con ellos se obtienen los coeficientes C_{Reac} que multiplicaría a la caída de tensión calculada y C_Q que iría multiplicando a la intensidad.

“APPLICATION OF SMART METER PHASE CONNECTIVITY TO VOLTAGE UNBALANCE IN LOW VOLTAGE NETWORKS”

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ABSTRACT

In this project the concepts of smart meter phase connectivity and advanced supervision of low voltage are applications used for optimizing the connection of new customers to the low voltage grid. With the equations used in the model, it is concluded that it is possible to simplify the calculation of intensities and voltages using coefficients developed during the project for simplifying the calculation from reactance of the cables and reactive measures.

Keywords: Smart meter phase connectivity, SABT, low voltage network.

Thanks to big data techniques, the data of the phase and secondary substation to which each smart meter is connected has been obtained previously to this project. The project proposal is to develop a model that calculates the intensity and voltage in the three phases and the neutral, as well as to get an image of the network topology and trying to opmtimize the information which has been used to adjust new clients.

Four different case studies have been considered that correspond to four lines, of which three belong to the same secondary substation (A2, A5 and A6) and a quarter to a different secondary substation (B1). One of the most important characteristics of the networks, can be seen in Table 1, is the percentage of three-phase loads because three-phase loads vary the power that circulates through each phase depending on the time of day and the use that exists within load.

Case study network	Nº Smart Meters	Nº Buses	Three-phase loads (%)	No-phase loads (%)
A2	32	6	3.13	6.25
A5	16	3	25.00	6.25
A6	29	3	3.45	13.79
B1	32	65	0.00	0.00

1 Characteristics of the lines under study.

The importance of the percentage of three-phase loads can be seen in **¡Error! No se encuentra el origen de la referencia.** as the worst performance of all four cases.

The first step in the project will be the creation of a programmed tool that calculates voltages and currents, using the equations shown below the paragraph, based on the smart meters assigned to each phase.

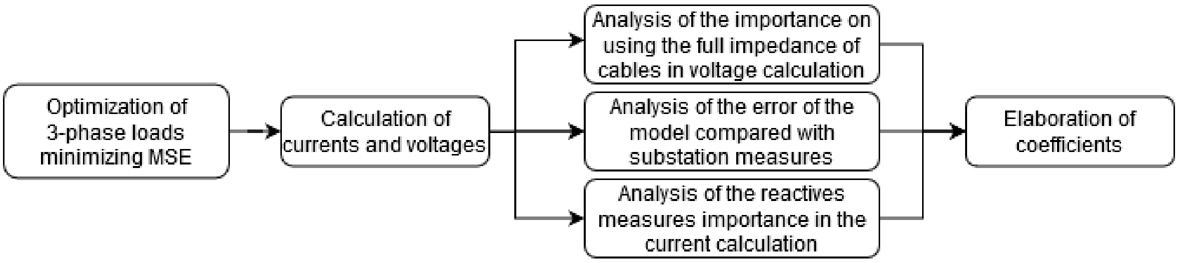
$$\vec{I}_{injected,phase} = \frac{\vec{S}_{meter,phase}}{\vec{V}_{Bus}} \tag{1}$$

$$\vec{I}_{branch} = B_{injected} * \vec{I}_{Injected} + \sum \vec{I}_{previous-buses} \tag{2}$$

$$\vec{V}_{Bus(1,2,3)} = cte \tag{3}$$

$$\vec{I}_{neutral} = \vec{I}_1 + \vec{I}_2 + \vec{I}_3 \tag{4}$$

In the model, an iterative model will be used to calculate the voltage because the current depends on the voltage in the bus, a value which is unknown. As it can be seen in Figure 1, to calculate the currents and voltages, the three-phase loads will be modelled with a coefficient that multiplies them and assigns a percentage of the power to each phase and that coefficient is obtained from an optimization algorithm that minimizes the mean square error compared to secondary substations measures.



For each case study, the previously explained methodology will be used. Once the three analyses have been carried out for the four case studies, the coefficients that would be used when trying to match a new client will be calculated. The model has a good performance for low percentage three-phase loads which the next conclusions could only be applied to one-single phase loads.

The coefficients would be used as follows:

$$I_{Line-phase} = i_{Line-phase} * C_{phase} * C_Q$$

$$Capacity \geq I_{Line-phase} + \frac{P_{consumer}}{V_{SS} + \Delta V_{drop} * C_{Reac}}$$

The coefficients allow the model to simplify the calculation without using either the reactance's of the lines, the reactive power measurements and to have a safety factor for the equations used for the model.

The maximum errors that the model calculations have compared to the measurements of the secondary susbtation can be seen in Table 2. The maximum errors have been used to create the C_{phase} coefficient, which has the function of being a safety factor for the maximum error that has the model.

Case study line	Max Error in phases (%)	Max Error in neutral phase (%)
A2	10.8	41.2
A5	58,6	67.4
A6	22.4	26.7
B1	14.6	17.3

2 Maximum errors that the model calculations have.

The average errors resulting from the analysis of the impact of the reactances of the lines in the calculation of voltages and of the impact of the reactive power measurements in the calculation of currents are 6% and 4% respectively and with them the C_{Reac} coefficients are obtained. it would multiply the calculated voltage drop and C_Q that would multiply the intensity.

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Chapter 1. INTRODUCTION

Since the deployment of smart meters in the European Union members with the directive 2009/72/EC, in which it was mandatory to deploy a 80% of smart meters by 2020, DSO companies have been trying to transform the new information provided from the smart meters into a competitive advantage or a cost reduction.

The deployment of smart meters reaches an ambitious objective: the creation of smarter grids in the EU which can provide new functionalities which traditional grids are not able to, like for example: the integration of the electric vehicle and the charging stations which are needed for them, demand response programs or a more automated grid when responding to faults in the low and medium voltage grid. These new functionalities share one common objective, to make a more flexible grid which can provide the new functionalities using new information, monitoring the grid, using power electronics or automated systems avoiding new investments in transformers or wires, which will be a much more expensive solution for the new problems the distribution grids are facing.

It in this context is where the master thesis takes place, which will be explain in the next sections. In this project future application of smart meter phase connectivity to voltage unbalance in low voltage networks will be analysed. For this project measures from smart meters, measures from the advanced low voltage supervision (this concept will be explained later on), wires technical characteristics, phase connectivity of the smart meters and the information of the topology of the network are the information used in this project for analysing how advanced low voltage supervision and phase connectivity could be used to make more efficient investments, to improve the number of clients which can fit on each feeder or to obtain new information based on the smart meters measures which can be useful for adding more flexibility to the system including for example electric vehicles.

In this project *Advanced Low Voltage Supervision* has a main role as only secondary substations with this new feature would be considered. *Advanced Low Voltage Supervision* consists of a solution in which the main objective is to obtain more information from the power flows, the voltages, quality of the sinusoidal wave, non-technical losses, connectivity, fuses, neutral wires. For obtaining more information some sensors are installed connected to the neutral and phase wires and the secondary substation send the information through PLC technology to substation upwards which collects the information.

The other important new concept of this master thesis is the *Phase Connectivity*, in many countries including Spain, where the data used in the project belongs, the information of which phase the smart meters are connected to is unknown. Without having the smart meter *Phase Connectivity* it is less efficient to try to calculate the power flows and voltages on the network as statistics values for a mean unbalance between the phases, in the end a hypothesis has to be done for estimating it. Here is where big data and data science take part, with these tools by knowing the measures on the secondary substation and the measures on the smart meters using artificial intelligence techniques such as clustering [1] or using correlation techniques [2]. When using clustering techniques such as k-means clustering as in the model used in [2] an accuracy up to 90% can be achieved in clearing which is the phase in which each smart meter is connected to, as they say on their investigation depending on the month in which the data is picked as it is relevant for the output of their model. In the model they create 3 clusters and after they group the data, which phase is each cluster must be decided.

The data related to phase connectivity of the smart meters used in the project came from big data techniques, but it is unknown which one was used. A scheme of the explanation above can be seen in Fig. 1.

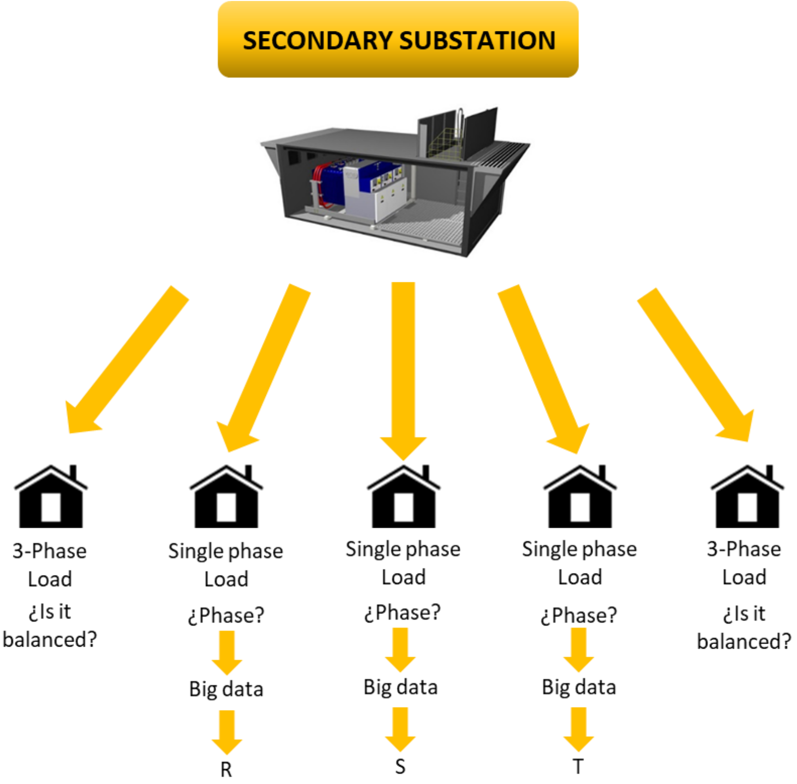


Fig. 1. Example of Phase Connectivity. Source: self-made.

One of the biggest concerns on the data provided and obtained of the big data algorithm are the three-phase load such as industries or big consumptions in the urban areas. These loads can change the unbalance they have inside, the same load can have the biggest peak on phase 1 in the morning due to the nature of the industry or the consumption like for example, motor starting current which happen in the beginning of the morning, and at the same time have the highest power consumption in phase 2 on the afternoon in winter do to the luminaires.

For clearing the concern about the 3-phase loads connectivity it will be explain by a simple example, scheme of the load distribution can be found in Fig. 2. All three phases are balanced when loads are being used simultaneously, the main concern is about not having all loads consuming at the same hour of the day. Based on a load (in this case a house) with five devices and based on the schedule of a student, three possible scenarios will be explained:

Scenario 1→ In the morning lights are on and for preparing coffee to boil water in the pan is needed so:

- Phase 1: 2000W, Phase 2: 0W, Phase 3: 0W.

Scenario 2→ For lunch kitchen is needed and maybe in summer air conditioner:

- Phase 1: 1200W, Phase 2: 2000W, Phase 3: 0W.

Scenario 3→ At night a possible combination could be using laptop, lights on and the washing machine:

- Phase 1: 800W, Phase 2: 0W, Phase 3: 2000W.

As a conclusion from the example even if the information of the devices distribution inside a load is available it can depend on the nature of the load and the time schedule it has, how it unbalances the current and the voltages. This will be a mayor challenge of the project and the method used to model the 3-phase loads will be explained in section 4.1.4.

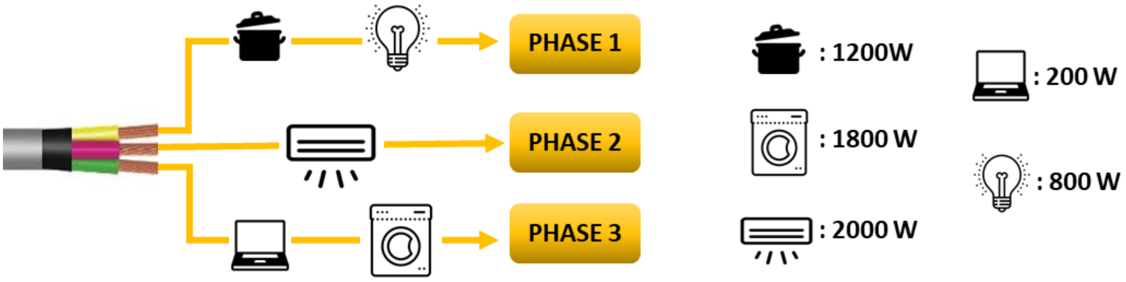


Fig. 2. Scheme of an example of a 3-phase load. Source: self-made.

Another type of load which can appear in the data used for this project are the loads such called as no-phase loads, these loads have the particularity that big data couldn´t assign to which phase they are connected or if they are three-phase loads. These couldn`t happen for some reasons:

- The load has small power consumptions and the algorithm has not been able to assign the load a phase.

- The load is not used all weeks or days of the year (as it can be a second home or a business dedicated to tourism) and the big data algorithm has been provided of enough data to determine the phase.

1.1 MOTIVATION OF THE PROJECT

In 2016 in Spain, from about 17.7 thousand million euros calculated by the CNMC [3] for regulated costs, 28.7% of them came from the distribution grid (5 thousand million euros), only exceeded by the specific remuneration for renewables, waste and cogeneration and being clearly higher than the cost of the transmission network (1.7 thousand millions).

From the previous data it can be seen the first main reason behind this master thesis and the interest in phase connectivity and advanced low voltage supervision is the importance and the impact of a cost reduction on the distribution network for consumers as it is one of the biggest costs for the system.

Cost efficiency is not the only reason behind all the interest it has be shown in smart meters phase connectivity as low voltage networks have brought in the previous years some new functionalities, like some other new technologies and ways of understanding the world related to sustainable growth. The new possibilities brought from power electronics, the interest on the electric vehicle as a way of having less polluted cities and reducing CO_2 emissions or the inclusion of demand on the energy market (demand response). The develop of the electric vehicle is one of the biggest challenges for the distribution grid as charging stations must be included and reinforcements in transformer and electric wires must be made as the electric demand will grow. This last argument has a mayor importance as in 2019 electric car share in the world was near 0.8% and in 2030 it is expected to continue growing and reach a 13.4% world. [4] As the electric vehicle is starting to be a big issue of the distribution grid because of the charging stations which will be need to implement.

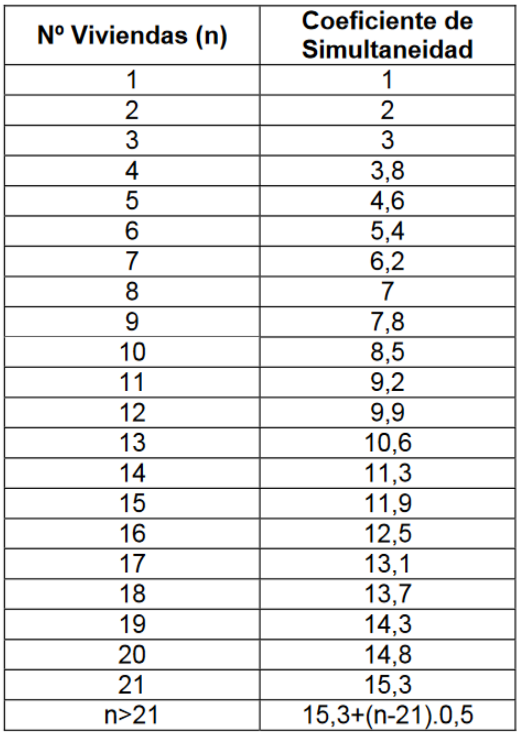
Chapter 2. STATE OF THE ART

One of the mayor advantages of the phase connectivity model of the smart meters is the possibility of using this new information for optimizing the entry of new consumers into the network as the power flows and voltages in the network are better known.

Distribution companies in Spain use the low and medium voltage electrotechnical regulation when deciding if a new client can be added to a line which already has been built or how many clients a line can host. In the regulation used for low and medium voltages networks when distribution companies try to estimate the consumptions the section used is called the ITC-BT-10 [5]. Regulation dictates the method it must be used to estimate correctly the consumptions making a differentiation between living places and the different uses those type of building can have and between offices, commercial buildings, or industrial estates.

When making the installation for a living place first step consists in estimating the contracted power each consumer will have (in the ITC-BT-10 it is distinguish between high intensive houses with 9200W and low intensive ones with 5750W), distribution companies as they have access to the clients information there is no need to estimate the contracted power as they already know it.

Once the contracted power is a known data an estimation of the power which is used simultaneously in the line is carried out taking into account simultaneity coefficients depending on the number of living places as it is shown in the, which can be found below:



Nº Viviendas (n)	Coeficiente de Simultaneidad
1	1
2	2
3	3
4	3,8
5	4,6
6	5,4
7	6,2
8	7
9	7,8
10	8,5
11	9,2
12	9,9
13	10,6
14	11,3
15	11,9
16	12,5
17	13,1
18	13,7
19	14,3
20	14,8
21	15,3
n>21	15,3+(n-21).0,5

Fig. 3. Simultaneity coefficients, according to the number of living places. Source: REBT, ITC-BT-10.

The coefficients are based on the average consumption a living place has in Spain, without taking into consideration the possible unbalanced which can be produced by the distribution on each phase of the loads. Smart phase connectivity can provide the information needed to use the unbalance in the network to be able to add that information and optimize the use of the network. As it is as important the power which will be needed through the transformer as the maximum power it could be measured in the lines and to which an estimated unbalance or an actual measurement of the three currents which could lead to smaller simultaneity coefficients and to an more optimized low voltage network.

To the loads in the living places it must be added the loads of generals use services such as the elevator, heat pumps and illumination of shared areas, which share the same problem mentioned before for the living houses. In ITC-BT-10 power estimations are used to estimate the consumption and the power needs those common places will require, as little information of them is known about the possible uses' consumers can make of the common areas of a building of houses.

As it can be seen in the previous explanation none of the modern's ideas of the distribution network have been applied to the way low voltage installation and distribution companies deal with the load estimation.

Chapter 3. TECHNOLOGIES DESCRIPTION

When the Smart meter deployment started in Europe one of the most important actors was the PRIME Alliance which now has as members utility companies such as EDP, Iberdrola, E.ON or Naturgy. PRIME (PoweRline Intelligent Metering Evolution) is a PLC Standard for Advanced Metering, Asset Monitoring and Grid Control. The smart meters which data will be used as an input for the model of the networks uses data which is provides from PRIME technology smart meters [6] some of the technical standards PRIME technology follows are: ITU-T Recommendation G.9901, ITU-T Recommendation G.9904 and IEEE 1901.2.

Along with PRIME technology and standard, smart meters also had to fulfil Spain regulation. The most important regulation is the RD 1110/2007 [7] in which some characteristic of the consumer installation and metering technique used are regulated:

- The distribution company is responsible for the metering and the concentrator which will storage the information.
- The metering equipment will consist of an active power meter, a reactive power meter, measurement transformers and other elements which could be needed such as recorders, power control elements, modem, and time switch clocks.
- Metering must be prepared for bidirectional flows.
- The main concentrator will act as a computer server of data which will the distribution company will be responsible of.

Chapter 4. METHODOLOGY & MODEL EXPLANATION

The first step for considering smart metering phase connectivity is to create a model of the LV network with the calculations required for making the comparison between the current measures of the advance supervision on the secondary substation and to estimate the voltage on the consumers connection buses of the network.

The information used for the creation of the model was collected in excels files and MATLAB code was used for extracting the information as the model was created in the MATLAB programming script tool. The excel files description used for this project can be seen below:

- For each secondary substation a file would have the same information: the topology of the network: type of cable used, end and beginning bus for each branch, the length of each branch, number of lines each secondary substation has and characteristics of the electrical protection box.
- Common to all secondary substations there is a file where the characteristics of the cables can be found and an excel file where the information of each smart meter about the line and secondary substation is ubicated and the most important data of the project: the phase in which each smart meter whose has been through the big data algorithm has its phase assigned.
- For each electrical protection box: a file that collects the hourly power active and reactive consumption of each meter of the electrical protection box for a giving period (typically 1 year).
- A file of the advanced low voltage supervisory measures for each line of the secondary substation: current of the three phases and the neutral, voltage of the three phases and the power exported and imported. This data was collected through a period of typically a year. An important fact about the advanced supervision is that

data come within 5 minutes instead of hour consumption as smart meters, so the mean of those measures must be carried out.

- For each line there is an excel which connect the manufacturer code for each smart meter with the code number it has been assigned to each smart meter depending on the secondary substation they belong to.

The model will use the previous information and as a final goal estimate the current and voltage of the lane in all buses and branches. The model will work for the information of one lane of the secondary substation, not all lines of it. The model can be divided into the next parts:

1. Acquire the network *topology*: the first step consists of using the information recovered previously to have an image of the LV network for each case.
2. Compilation of the *impedance* of the cables of the network, phase wires and neutral and assign them to their respective branch
3. Assignment of each electrical protection box to the respective bus where it belongs, and the power consumptions of the smart meters are divided into their respective phase.
4. Calculation of the *power flows* in the network using an iterative calculation method and applying overlap techniques.
5. Last step is an optional step just if there are three phases or non-phase assigned consumers in which an *optimization* is realized to achieve the optimal three phase distribution compared to the secondary substation. Once the optimal three-phase consumers distribution has been achieved, step 4 is repeated.

Once the power flow has been calculated, the analysis of the data takes place:

- An example of a comparison between the optimal solution and the measurements of the advanced supervision takes place for a given period, in most cases a day comparison for all phases will take place.

- As the most important data for making an investment or the operation of the LV grid are the maximum current, so an analysis for the 5% biggest current would take part to see the mean square error of the model for each line.
- An error analysis for measuring the cosine of the 5% max currents to discern the importance of the reactive power.
- An error analysis for estimating the importance of the reactive impedance on the voltage calculations.

4.1 MODEL EXPLANATION

The model of the network was created with the invaluable aid of another colleague which also is currently making his master thesis. In the next sections the parts of the model develop for this project will be explained in detail and in case some sections of the model where created by another entity, it will be referenced and a brief explanation will be given.

4.1.1 TOPOLOGY OF THE LINES

In the data which was provided for this project each branch it was included the origin bus and the final bus of each branch. An example of an image of the topology of the network can be seen in Fig. 4:

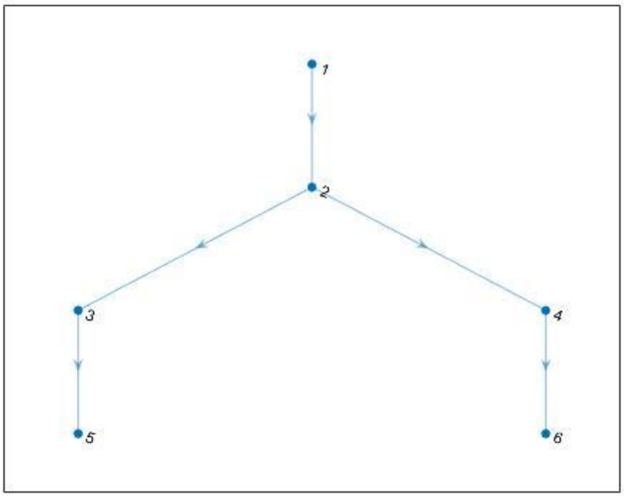


Fig. 4. Example of the topology of a network. Source: self-made.

Once the topology is already known and included in the software, the characteristics of the cables for each branch are included in a matrix for calculating the voltages. [8]

4.1.2 CURRENT CALCULATION

Once the topology and every branch has been assigned its correct impedance a function which was called *createCurrentFile* created from the data smart meters had for each hour of each day a unique matrix with three phases. For example, if the network has 36 users it means that there are 36 measures for each hour, this function assigns each electrical protection box (and the smart meters inside of it) to the corresponding bus and then allocates each smart meter on their respective phase and as a result there is just a matrix with 3 phases instead of 36 columns and as long as the period of the consumptions has been taken.

The strategy followed for trying to reduce the computational complexity of the model was to apply overlap techniques. A conventional overlap way of solving the problem was to overlap the power injected from all buses (if there are 6 buses, the overlap of 6 superpositions calculations).

In this project the technique used was to connect the initial bus (there is assumed there is just one initial bus) with all the final buses, as it can be seen in Fig. 5 the network is divided in two *subnetworks* which include buses 1,2,3 and 5 and 1,2,4 and 6. The main challenge of these overlap technique is that bus 2 appears in both *subnetworks* which will double the power injected by that bus. This issue is solver by adding a binary matrix in which if the bus power injected has already been included by another subnetwork, it doesn`t add to this one.

The main advantage of these difference on the overlap is the reduction from 6 calculations of the different buses to 2, as in this technique explained you just need to know the *subnetworks*. A very important advantage as the function will be used as many times as the iteration of the voltages occur and can decrease the time needed.

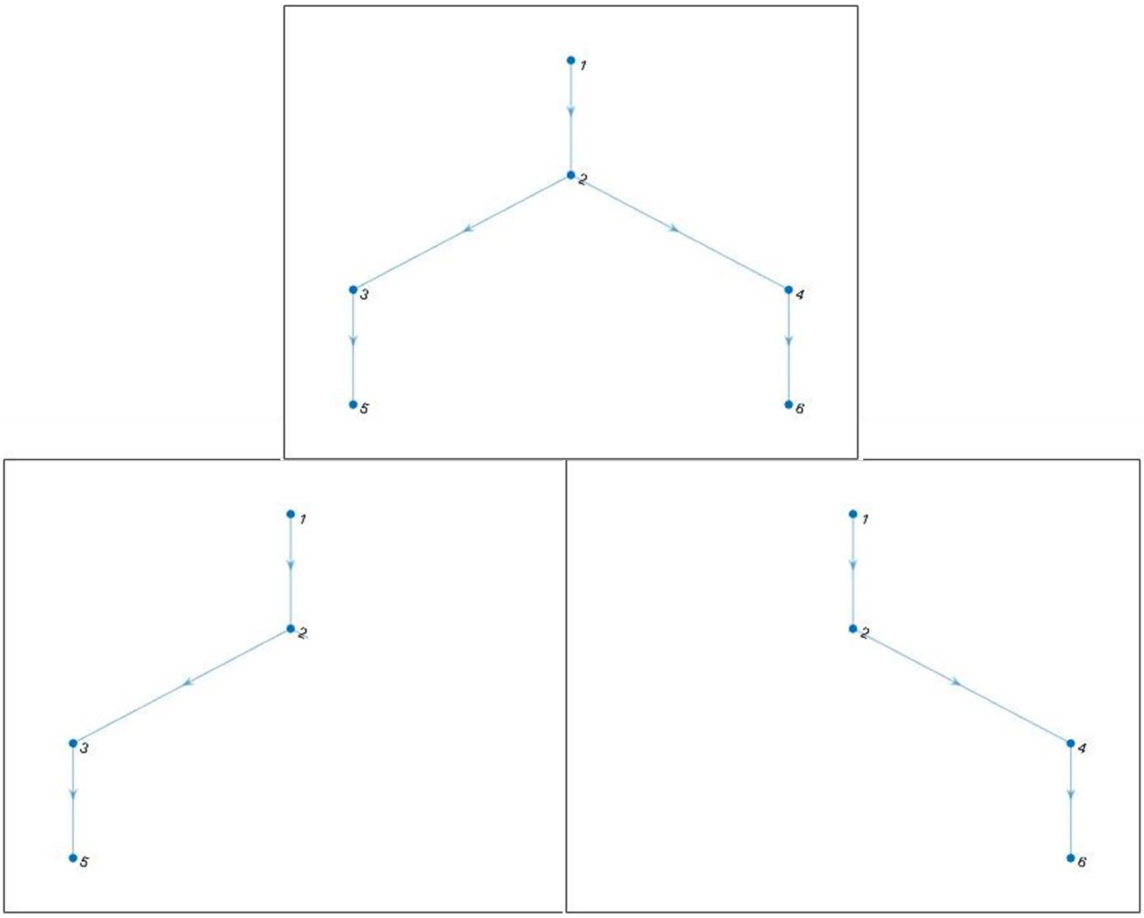


Fig. 5. Example of subnetworks. Source: self-made.

In order to be able to calculate the voltages and the current as accurate as it is possible with the data available a function (called *currentClaculation_Iter*) was created on the code of the model to include the current calculation inside of the voltage calculation iteration.

As the network is assumed it is unbalanced, the calculation can´t be done using three phase equations as they assume network is balanced. Equations used will be single phased and all of the three phases will be treated on different equations.

For calculating the current through the cables, the equations used are:

$$\vec{I}_{injected,phase} = \frac{\vec{S}_{meter,phase}}{\vec{V}_{Bus}} \tag{5}$$

$$\vec{I}_{branch} = B_{injected} * \vec{I}_{Injected} + \sum \vec{I}_{previous-buses} \quad (6)$$

$$\vec{V}_{Bus(1,2,3)} = cte \quad (7)$$

$$\vec{I}_{neutral} = \vec{I}_1 + \vec{I}_2 + \vec{I}_3 \quad (8)$$

The first time the voltage calculation code is used, in the first iteration equation (5) the V_{bus} value is the voltage on the secondary substation, but once the iteration code is running the voltage used is the voltage of the bus output of the previous calculation.

$B_{injected}$ is a binary matrix used in equation (6) has been added for not including twice the same power consumption of the bus in two different *subnetworks*.

The current calculation starts from the bottom of the networks as the first current known are the last buses of the network, which means that the term $I_{previous\text{-}buses}$ refers to the buses which are downwards compared to the one is been calculated.

4.1.3 VOLTAGE CALCULATION

The voltage calculation iteration method was created for other projects [8]and in this project this method will be explained for understanding the output needed.

The iteration method consists in calculating the currents with the function and the equations explained in section 4.1.2 and once the current calculation is done the voltage estimation takes places with the following equations:

$$\vec{V}_{bus} = \vec{V}_{previous-bus} + \vec{I}_{branch} * \vec{Z}_{branch} \quad (9)$$

$$\vec{V}_{neutral} = \vec{I}_{neutral} * \vec{Z}_{neutral} \quad (10)$$

The objective of the voltage calculation method is to iterate the calculations until the tolerance limit between the voltage calculation has been fulfilled.

4.1.4 OPTIMIZATION

An optimization algorithm is used for seeking the most optimal distributions of the power consumptions on three phases. The optimization will occur on optimization of the Mean Square Error of the difference between the secondary substation measures and the model current calculation for the 5% percentile of peak current values which are the ones which constraint more the network operation and investment. Equations used are the following ones:

$$MSE_{I-phase} = \frac{\sum(I_{TC} - I_{Model})^2}{n} \tag{11}$$

$$MSE_{TOT} = \frac{MSE_1}{n_1} + \frac{MSE_2}{n_2} + \frac{MSE_3}{n_3} + \frac{MSE_n}{n_n} \tag{12}$$

Two approaches have been used for testing the model. As one of the objectives is to be able to obtain the unbalance there is in the network the mean square error of the neutral is the most significative error on estimating the accuracy of the model of the network. Those two approaches will be:

- To minimize the total mean square error, which means considering all phases and the complete model, the objective function would be:

$$\min MSE_{TOT} \tag{13}$$

- Second approach would be minimizing the neutral mean square error as the intention would be to estimate the unbalanced on the network on a more precise way, the objective function would be:

$$\min MSE_N \tag{14}$$

After these two approaches there would be 2 different outputs, the total optimal solution, and the neutral optimal solution. These two models will be compared in the analysis of the model calculations section.

An example of the optimization output can be shown in Fig. 6, in which the algorithm has 9 iterations till it reaches the optimal point.

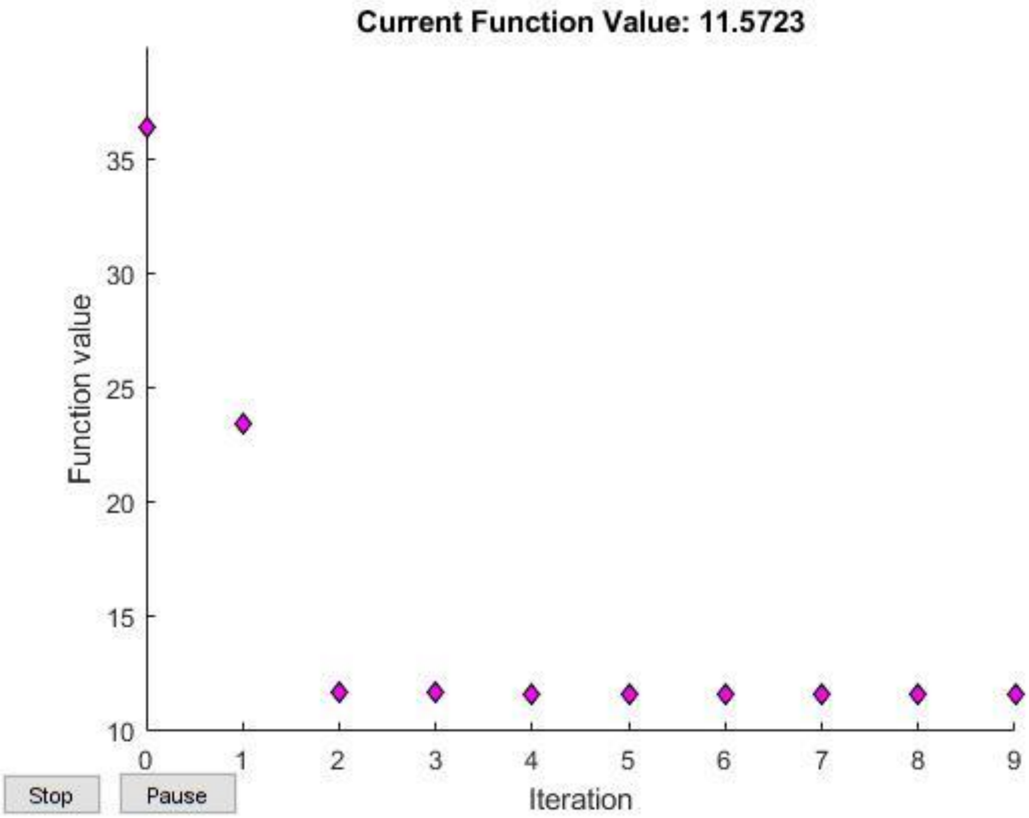


Fig. 6. Example of the output of the optimization algorithm. Source: self-made.

4.2 ANALYSIS OF THE MODEL CALCULATIONS

Once the output of the model has been collected the four analysis which were explained in the introduction to Chapter 4.

4.2.1 A ONE DAY COMPARISON

The first step once the results model output has been collected is to have a visual image of the how the model works compared with the measures of the secondary substation.

This analysis will show the difference both models have (optimal and the neutral optimal) with the measures during an entire day on the 4 phases. It can be seen an example in Fig. 7:

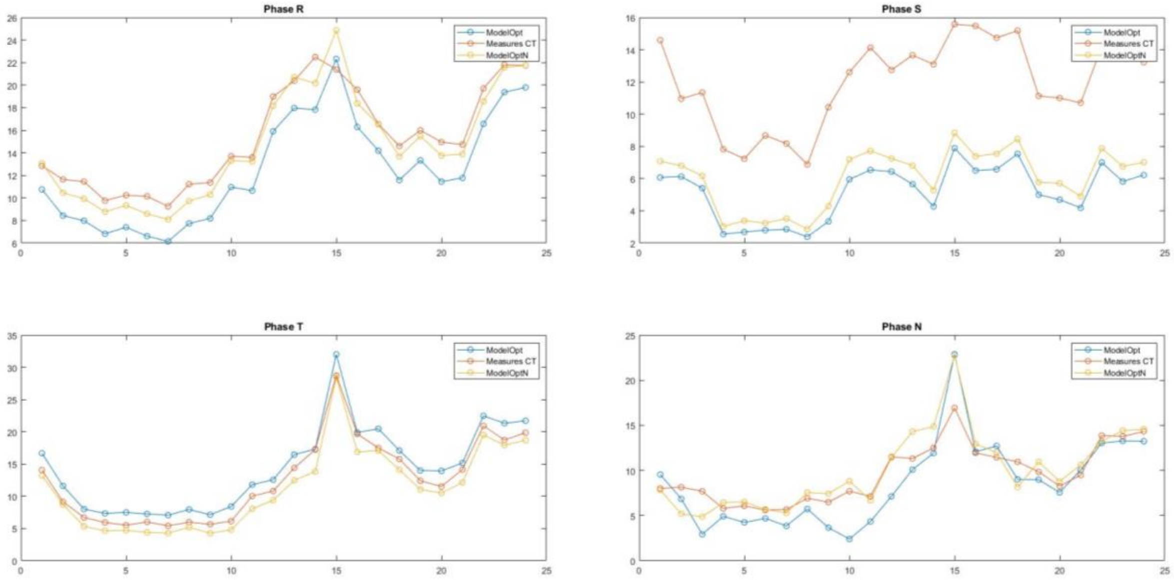


Fig. 7. Example of a one-day comparison. Source: self-made.

4.2.2 95TH PERCENTILE ERROR STUDY

As it has been mentioned before in this document, distribution companies are more concern about the currents peak. In this section the method used for testing the accuracy of the model will be explained.

The representation used was the boxplot statistical graph in which it can be seen graphically an idea of the model and how the error is distributed. An example can be seen in Fig. 8:

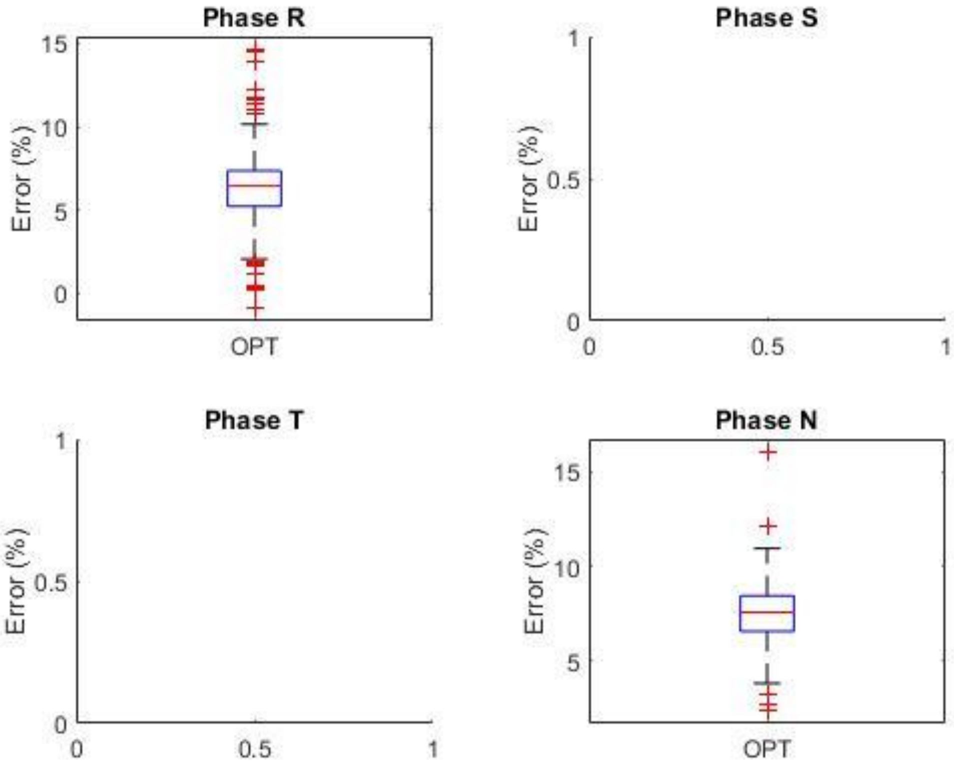


Fig. 8.Example of the boxplot used to analyse the 95th percentile of current calculations. Source: self-made.

One of the main objectives in analysing the performance of the model is to find patterns of which may difficult the estimation for the model, as it can be the three phase loads (as the optimization will never represent 100% all the loads), time of the year or the length of the network, a potential fraud.

4.2.3 ANALYSIS ON OF THE REACTANCE OF CABLES ON VOLTAGE DROP

One of the objectives of the model and the analysis is to determine how significant the reactance of the cables is to the final output of the model. The main objective of these study is to quantify the error it can be made by estimating the power flows considering the resistive part of the wires and discarding the reactance of the wires.

The concept applied was to see the incidence of just using the resistive part of the cables` impedance on the voltages the model has calculated. The comparison has been made between calculating the voltage drop with both resistive and reactance of the cables or just the resistive one and the error is calculated as it can be seen in Fig. 9.

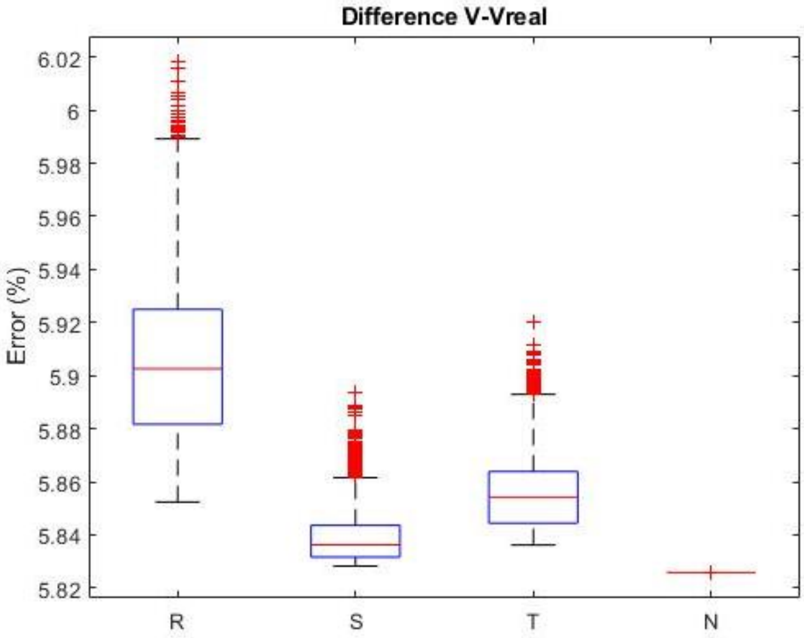


Fig. 9. An example of the analysis of the impact of reactance of cables on voltage calculation. Source: self-made.

4.2.4 ANALYSIS OF THE PHASE COSINE OF THE POWER CONSUMPTIONS OF THE 95TH PERCENTILE

In this section an analysis of the reactive current importance for the calculation of the model will be carried out for the 95th percentile of the current peaks. The cosine of the phase the current has in the closest branch to the substation will be plotted as it can be seen in Fig. 10.

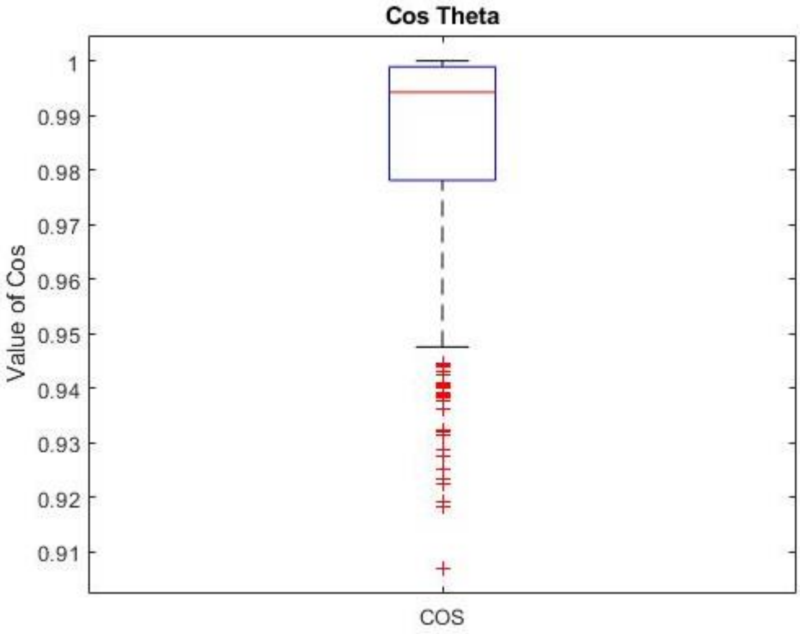


Fig. 10. An example of an analysis of the reactive current importance for the current calculation. Source: self-made.

When looking at Fig. 10 it is trying to see if the calculation for the model could be carried out without reactive power and reduce the computational complexity of the model.

Chapter 5. RESULTS

Results presented in this project are related to four different lines which belong to two different secondary substations which had advanced supervision and the smart meter phase connectivity is known.

The process followed for the networks: the first point is obtaining the topology of the network, the presentation of the results of the optimization algorithm for three phases loads in case there are and the presentation of the case studies described in sections 5.4, 5.5 and 0.

Once the results have been collected an analysis of the results takes places in Chapter 5.

5.1 CHARACTERISTICS OF THE LINES

The lines used for the case studies are the next ones:

- From secondary substation A, lines A2, A5 and A6.
- From secondary substation B line B1.

Characteristics of the lines which take place as case studies can be seen in TABLE 1:

Case study network	Nº Smart Meters	Nº Buses	Three-phase loads (%)	No-phase loads (%)
A2	32	6	3.13	6.25
A5	16	3	25.00	6.25
A6	29	3	3.45	13.79
B1	32	65	0.00	0.00

TABLE 1. Characteristics of the case studies lines.

A5 was the first line which was analysed, and it's a short line with a high percentage of three-phase loads, this line was used to create the model as it is a line with a few number of smart meters (16) compared to the rest of lines, just 3 buses and the line has three-phase and no-phase load. These characteristics will make the model have less computational periods compared to the rest of lines and as all type of loads are included it is possible to verify if the model is following the calculations desires.

Line B1 was chosen to see how accurate the model can be if all loads are single-phase loads as with a "*perfect*" connectivity the accuracy of the equations used in the model and described in sections 4.1.2 and 4.1.3. Lines A6 and A2 have a small percentage of three-phase loads, 3.13% and 3.45% respectively, and both were chosen to study the impact of having loads with no phase assigned in the model total error estimating the secondary substation.

In the next page TABLE 2 collects the information of the smart meters which belong to each line.

A2				A5				A6				B1			
Smart Meter	**Contracted Power (W)**	**Phase**	**Bus**	**Smart Meter**	**Contracted Power (W)**	**Phase**	**Bus**	**Smart Meter**	**Contracted Power (W)**	**Phase**	**Bus**	**Smart Meter**	**Contracted Power (W)**	**Phase**	**Bus**
1	13200	RST	6	1	0	RST	3	1	3300	'-	3	1	4600	R	53
2	4600	'-	6	2	13856	-'	3	2	3300	R	3	2	2300	R	56
3	2200	R	6	3	9900	RST	3	3	3300	'-	3	3	4600	S	54
4	4400	S	6	4	6928	RST	3	4	11500	T	3	4	4400	R	54
5	4600	T	6	5	13200	RST	3	5	1100	'-	3	5	4400	T	43
6	3300	R	6	6	4400	R	3	6	9900	RST	3	6	5750	S	43
7	3300	R	6	7	3300	T	3	7	3450	T	3	7	3300	T	44
8	4600	T	6	8	5500	R	3	8	3300	T	3	8	3450	R	44
9	3300	S	6	9	3450	S	3	9	3300	S	3	9	4400	R	45
10	3450	T	6	10	4400	T	3	10	4400	R	3	10	3450	R	57
11	4600	S	6	11	5500	S	3	11	4400	S	3	11	4400	R	55
12	3300	R	6	12	4600	R	3	12	4400	R	3	12	5500	R	49
13	5500	S	6	13	3300	T	3	13	3300	R	3	13	5500	T	49
14	5000	S	5	14	3300	S	3	14	3300	T	3	14	4600	R	58
15	5500	T	5	15	4400	R	3	15	3450	T	3	15	5500	T	58
16	3450	S	5	16	5500	T	3	16	4600	S	3	16	5500	R	50
17	3300	'-	5					17	3300	S	3	17	5750	R	51
18	4600	S	5					18	2300	R	3	18	5500	T	51
19	4400	R	5					19	4400	T	3	19	4400	R	52
20	4400	S	5					20	4400	R	3	20	3300	T	52
21	3300	R	5					21	4400	T	3	21	5500	R	46
22	5500	S	5					22	3300	'-	3	22	4400	T	46
23	4600	R	5					23	3300	R	3	23	4600	R	62
24	4400	T	5					24	3300	R	3	24	5500	R	47
25	4400	T	5					25	3300	S	3	25	4600	S	42
26	4400	R	5					26	4400	T	3	26	3300	R	48
27	4400	S	5					27	3300	R	3	27	4400	T	48
28	3300	T	5					28	4400	S	3	28	3300	S	59
29	3450	S	5					29	4400	R	3	29	3450	T	59
30	3450	R	5									30	4400	R	63
31	5500	T	5									31	4400	T	63
32	3300	R	5									32	5500	R	61

TABLE 2. Smart meters characteristics of all lines.

5.2 TOPOLOGY OF THE LINES

The topology of the lines can be seen in Fig. 11.

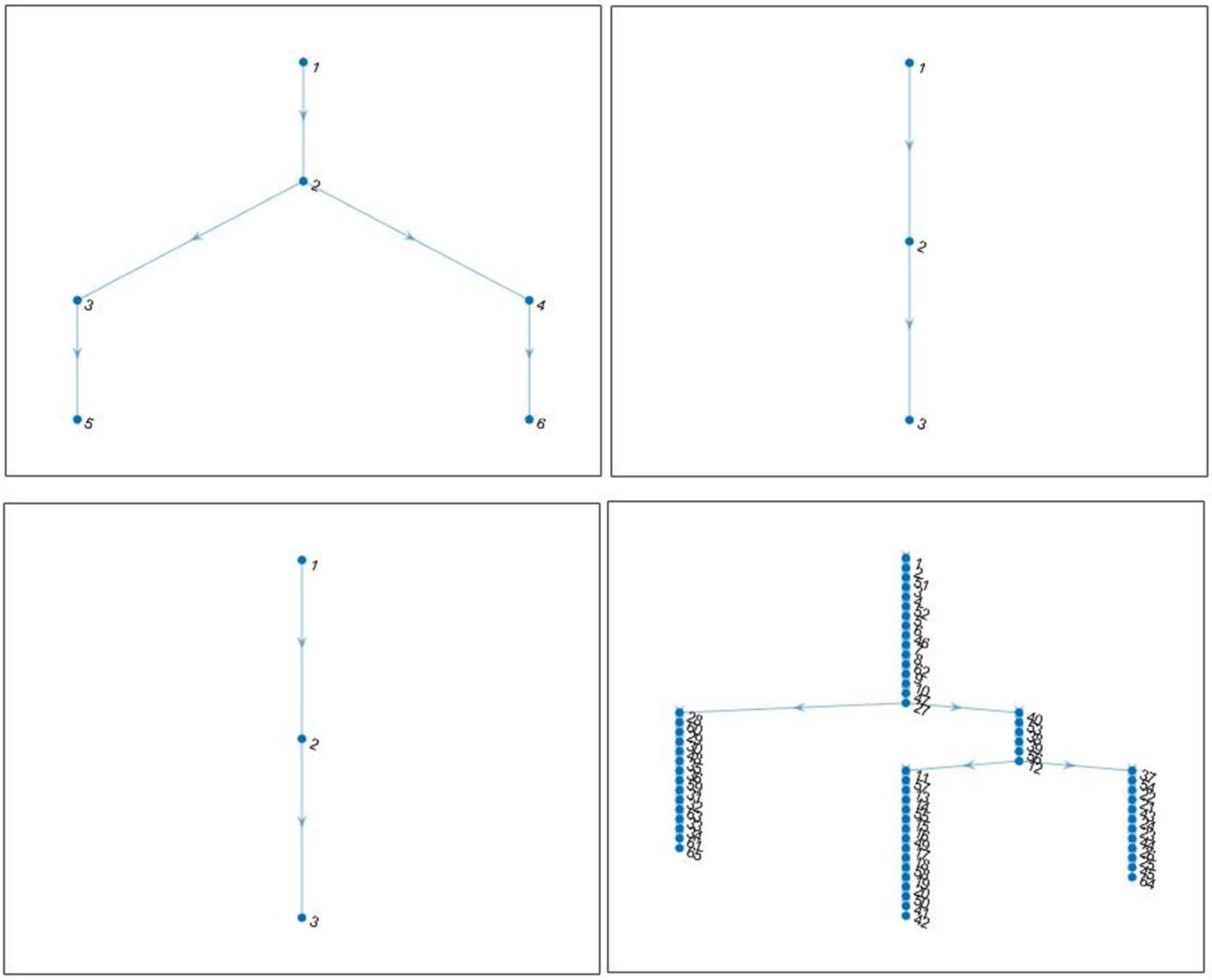


Fig. 11. Topologies of 4 lines. Upper let: A2, Upper-right: A5, Bottom-Left: A6 and Bottom-Right: B1. Source: self-made.

5.3 OPTIMIZATION RESULTS

A resume of the optimal solutions provided from the optimization algorithm is shown in TABLE 3 for all four lines. As a first sight it is clear the minimization algorithm has a big difference when looking for the optimal MSE of the neutral and the total MSE as line A5 which is the network with the highest percentage in three-phase loads, the percentage of three-phase loads can be seen in TABLE 1, neutral and total error solutions are similar in the three phases, with Phase S having the biggest difference. In lines A2 and A6 as they have a smaller percentage of no-phase and three-phase loads difference in optimal neutral error and total are clearer.

Line B1 as it has no no-phase and no three-phase loads the optimization algorithm was not used for these case study.

Initial hypothesis for the algorithm as a start point was always an equilibrated load equally distributed on the three phases, as it is clear by the results that estimation was not a good estimation in any of the lines as some cases such as A2-OPT$_{N}$ the algorithm find the optimal point in distributing all the power to the T phase.

Case study network	Type	Phase R (%)	Phase S (%)	Phase T (%)
A2	OPT-TOT	48.11	43.19	8.71
	OPT-N	0	0	1
A5	OPT-TOT	25.27	21.69	53.04
	OPT-N	29.03	13.13	57.85
A6	OPT-TOT	51.30	0	48.70
	OPT-N	75.62	12.49	11.89
B1	-	-	-	-

TABLE 3. Optimization resume of the case studies.

5.4 95TH PERCENTILE ERROR STUDY RESULTS

In this section an analyse of the performance of the model on the 5% highest peaks of current compared to the measures of the secondary substation will be carried out. In TABLE 4 a resume of the results of the study can be seen.

An important detail is about how the 95th percentile has been chosen taking into account all phases considering too the neutral, which means that if the line has a huge unbalance in one phase, for example in phase R, as R has higher currents on the 5% percentile would have more current of the R phase than other and maybe other simply don't have any point due to never having significant peak loads. An example can be seen in B1 case, as there are only phase R and neutral currents values in the 95th percentile.

As it can be seen neutral errors are lower for the three-phase distribution of the optimal neutral error. On taking the same line, for example A2, the mean error of the phases is always lower in the three-phase distribution of the optimal total error compared to the distribution for the neutral error. The highest error for the OPT-TOT distribution is for A5 line with an 10.31% mean error, as A5 is the line with higher percentage of three-phase loads it is the line more affected about the optimization result and as it was explained in the introduction of the document three-phase loads can have the same power consumption with different distribution of the power.

The best mean error of the phases belongs to B1 the only line without three-phase loads or loads with no phase assigned.

Case study line	Optimization data	Phase	Mean Error per phase (%)	Mean of the Error of Phases (%)
A2	OPT-TOT	R	-	4.87
		S	2.49	
		T	6.65	
		N	31.71	
	OPT-N	R	-	8.32
		S	4.53	
		T	10.21	
		N	27.26	
A5	OPT-TOT	R	6.95	10.31
		S	12.38	
		T	9.66	
		N	22.98	
	OPT-N	R	20.59	14.66
		S	29.82	
		T	12.61	
		N	15.22	
A6	OPT-TOT	R	12.90	6.81
		S	-	
		T	4.24	
		N	16.39	
	OPT-N	R	14.93	6.97
		S	-	
		T	4.65	
		N	8.87	
B1	OPT-TOT	R	6.40	6.60
		S	-	
		T	-	
		N	7.35	

TABLE 4. Resume of 95th percentile error study.

From the analysis of the error the model performed on the 5th percent peak the additional error the three-phase loads add to the model is much more significant compared to the load which phase was not provided but the model for having a minimum error the line must have only one-phase lines. The model on B1 (a line with only one-phase loads) in TABLE 4 it is shown a 6.60% of error while A5 (the line with most three-phase loads) has an 10.31% mean error. A2 and A6 have a considered number of loads without any phase assigned but these loads are less significant to the model as the reason must haven`t been assigned is due to their lower consumption making in the end a smaller impact in the current.

Some of the issues which the model had to deal with were wrong assignations of the connectivity of the smart meters as a wrong assignation of the phase could lead to a big error. Another issue the model had to deal with is the fact that the supervised measures of the secondary substations are taken each 5 minutes while the measures of the smart meters are an average over one hour. Which could lead to values which one of the devices captures and the other doesn´t. Last big issue which could appear are fraud connections, as a big error in one single phase could happen one possible explanation would be fraud and the only way to assure it is by going physically to the cable.

Limitation of data is a big concern for the model as possible fraud, mistakes in the phase or secondary substation assignation could lead to big errors on the respective phase and mostly the neutral wire which is the more sensitive to errors. More case studies could help to minimize the impact of fraud and wrong phase connectivity models.

5.4.1 CASE STUDY: A2

The data collected for TABLE 4 comes from the boxplot of the error of the lines. In it can be seen the boxplot of A2.

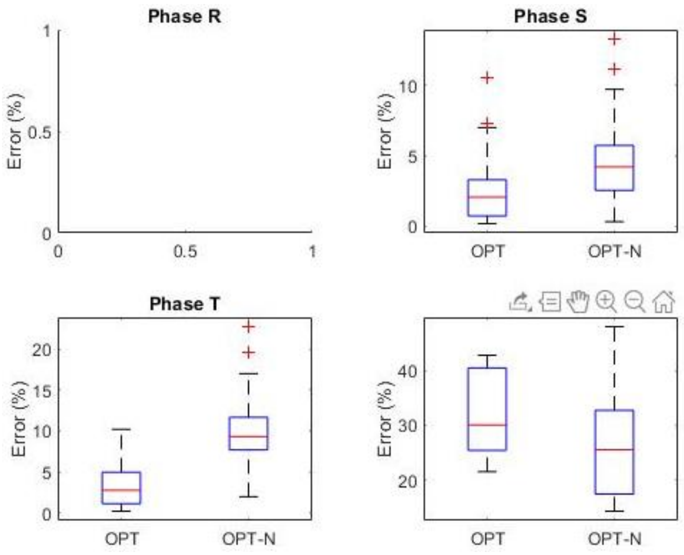


Fig. 12. Boxplot of A2 model error. Source: self-made

Phase N error is the highest one of the lines, one of the reasons is that as phase N the smallest amount of values in the 95th percentile which lead to the model having the best mean error besides having the worst neutral error both on the total error optimization and the neutral optimization as phases S and T have a really good performance with the equations used.

5.4.2 CASE STUDY: A5

Boxplot can be seen in Fig. 13 of line A5. Case study 5 has the worst performance in the mean error as it can be seen in TABLE 4 as this line has the biggest amount of three-phase loads (25%) and also a high percentage of meters without any phase connection (6.25%), it is concluded the huge impact three-phase loads have on the error of the model as three-phase loads have also the bigger contracted power compared to single-phase loads.

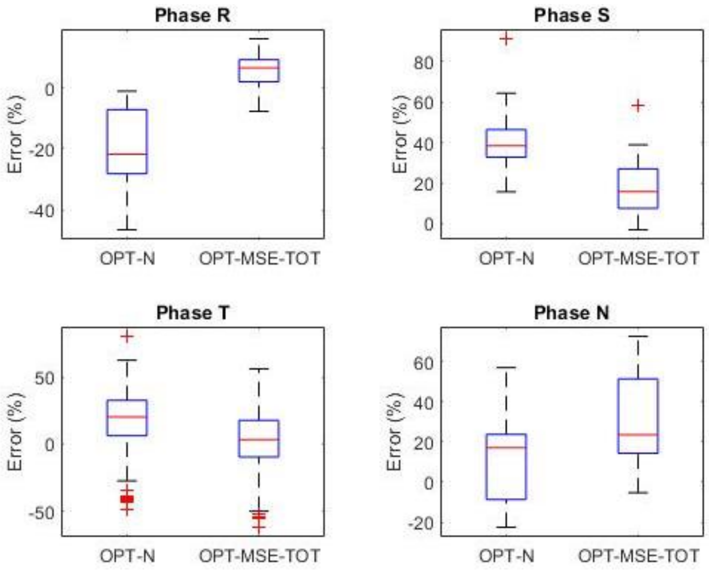


Fig. 13. Boxplot of A5 model error. Source: self-made

5.4.3 CASE STUDY: A6

Boxplot of line A6 can be seen in Fig. 14 . There can be seen a big difference in the amplitude of the box of the phase N currents as the OPT-N distribution has a smaller box.

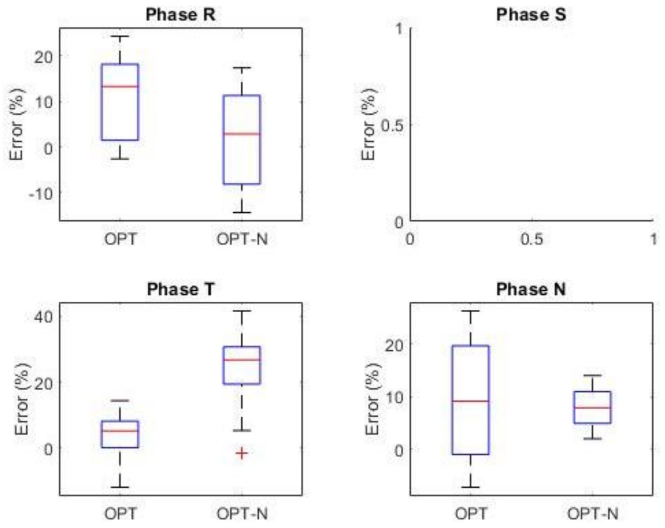


Fig. 14. Boxplot of A6 model error. Source: self-made

A6 phase S has a peculiarity in which the model is far from the secondary substation measures and will be explained in more detail in Chapter 6.

5.4.4 CASE STUDY: B1

Boxplot of line B1 can be seen in Fig. 15. B1 line has the best results of the errors due to only having single-phase loads.

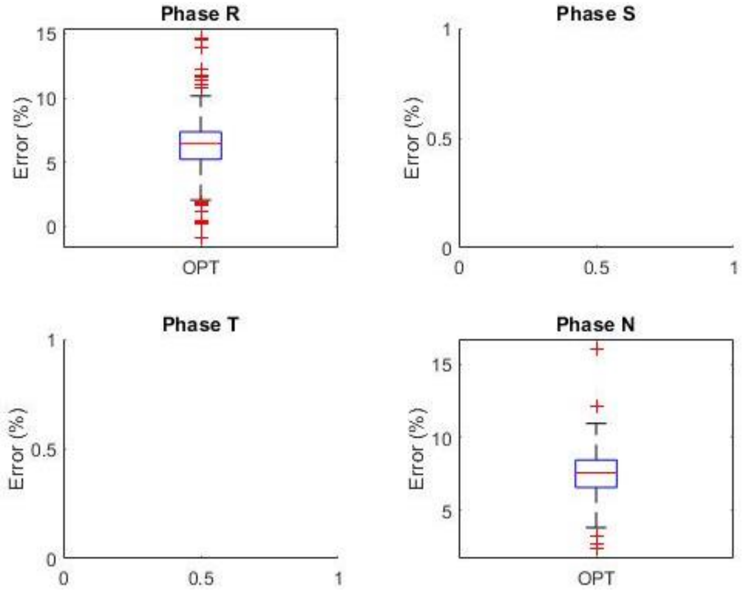


Fig. 15. Boxplot of B1 model error. Source: self-made

Maximum errors found in case study B1 are near 15% on both neutral and R phase which are due to the lack of three-phase loads and to loads without phase assigned.

5.5 RESULTS OF THE ANALYSIS ON THE REACTANCE OF CABLES IMPACT ON VOLTAGE DROP

The main objective for analysing the difference on the voltage drop calculation between considering the full impedance of the cables of the line or just the resistance. In TABLE 5 the results of the analysis can be seen, all error including the phases and the neutral phase are all similar as cables used in the lines have similar characteristics of R/X. A5 and A2 lines just have 2 branches and as the same current is circulating on them the cables are the same, and neutral in these two cases are the same to the phase cables which makes it the same error.

Case study line	Error in phases (%)	Error in neutral phase (%)
A2	5.43	5.36
A5	5.64	5.65
A6	5.13	5.13
B1	5.83	5.88

TABLE 5. Analysis on the reactance of cables impact on voltage drop results.

All errors are on values from 5 to 6%, both on the phases and the neutral which means the R/X relation would be near 3,as it can be seen in equation (15). If a 6% is an acceptable error, you can consider the resistance of the wires instead of the whole impedance when R/X has a relation of 3 or higher.

$$Error \approx 0.06 = \frac{\sqrt{\left(\frac{R}{X}\right)^2 + 1^2} - \frac{R}{X}}{\sqrt{\left(\frac{R}{X}\right)^2 + 1^2}} \rightarrow \frac{R}{X} \approx 3 \qquad (15)$$

5.6 RESULTS OF THE ANALYSIS OF THE PHASE COSINE OF THE CONSUMPTIONS OF THE 95TH PERCENTILE

Phase cosine of the power consumptions (smart meters measurements) of the 5% peak consumption is analysed for the same reason the impedance of the cables was, to see the impact of reactive current in the calculation of the model.

TABLE 6 and Fig. 16 shows the results of the analysis, in all case studies cosine values oscillate between 0.9 and 1 having some outliers data below the 0.9 on A2, A5 and A6. Cosine values of the highest peak consumptions, in this case 5% peak loads, have statistically higher cosine phase values than low consumptions which means that reactive measures are more representative for low consumptions, which creates an opportunity of simplifying the calculations in high-load scenarios without the reactive values.

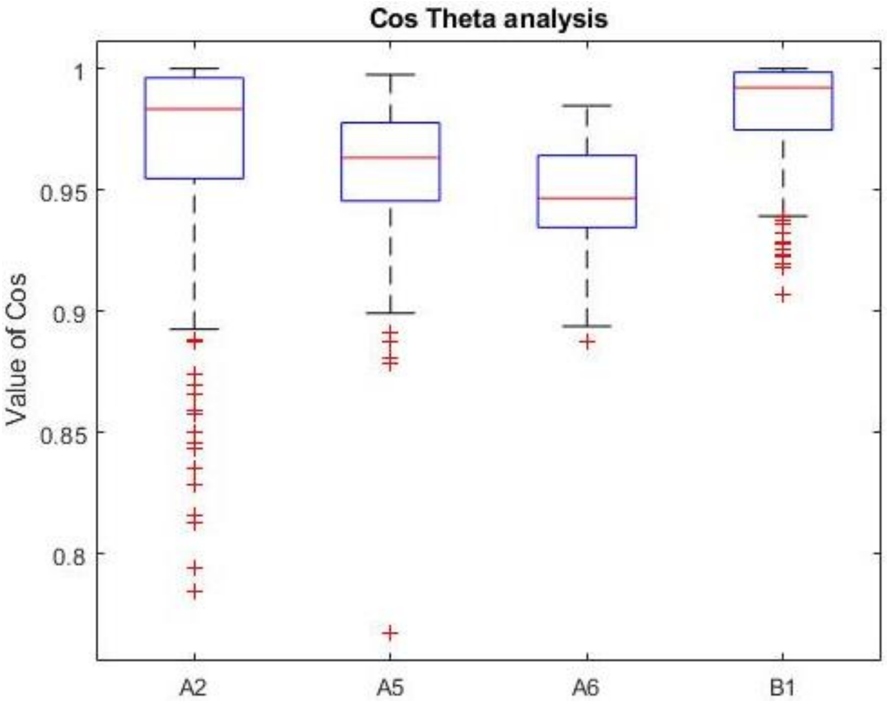


Fig. 16. Boxplot of the analysis of the phase cosine of the power consumptions. Source: self-made.

Case study line	Cosine average	Cosine average of all lines
A2	0.969	0.962
A5	0.958	
A6	0.946	
B1	0.986	

TABLE 6. Analysis of the phase cosine of the power consumptions.

Having an average cosine of the measurements of 0.962 means the relation P/Q is 3.5, so the difference on the size of active and reactive measurements its clear. In equation (17) it can be seen the error made by not using reactive power is up to a 3.85%.

$$Cos\emptyset \approx 0.962 = \frac{\frac{P}{Q}}{\sqrt{\left(\frac{P}{Q}\right)^2 + 1^2}} \rightarrow \frac{P}{Q} \approx 3.5 \qquad (16)$$

$$Error = \frac{\sqrt{(3.5)^2 + 1^2} - 3.5}{\sqrt{(3.5)^2 + 1^2}} * 100 = 3.85\% \qquad (17)$$

Chapter 6. CONCLUSIONS

In this project due to the multiple case studies and analysis which took place there are a variety of conclusions to be mentioned. There would be four mayor conclusions explained in this chapter.

First conclusion is not related to the objectives of the project and was an unexpected feature which appeared in the line A6. As it can be seen in Fig. 17 where it is shown the load curve of the phase S in amperes of a random day of the database comparing the secondary substation with both the optimal for the neutral error and for the total error distribution of three phase loads. As it can be seen measures of the centre are clearly on higher values than the model's output. An exhaustive look at the measures took place looking for a mistake in the model calculations and once it was sure the model was doing the calculations correctly, three hypotheses appeared:

- The possibility of having some meters which aren`t in the list of meters of the line A6.
- A potential illegal connection can be occurring in the phase S.
- The measurement device of phase S of the secondary substation could not work at the efficiency it should.

The conclusion from this hypothesis is the power tool which smart phase connectivity can add to detect more fraud, to correct misinformation in the database or a possible malfunction measure device.

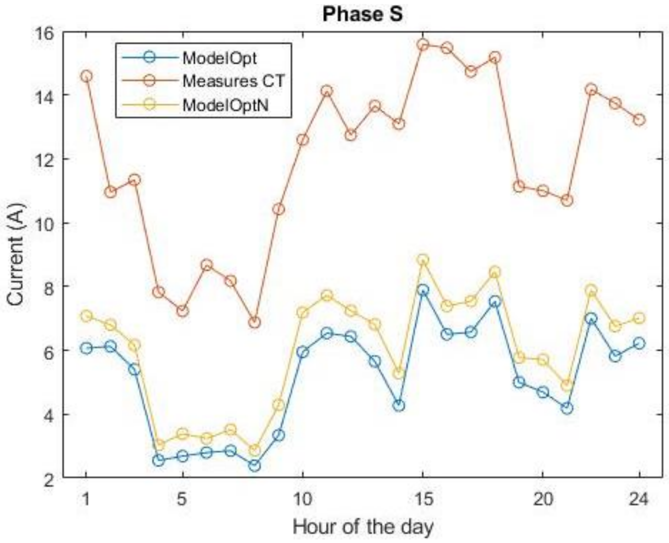


Fig. 17. Phase S current curve of a day A6. Source: self-made.

From the analysis of the error the model performed on the 5th percent peak, section 5.4, it was proven the total error minimization lead to fewer errors and was chosen as the best model. It can be seen in TABLE 7 a summary of the maximum errors of the case studies and the coefficient of safety taken from the calculation will be considered.

Case study line	Max Error in phases (%)	Max Error in neutral phase (%)
A2	10.8	41.2
A5	58,6	67.4
A6	22.4	26.7
B1	14.6	17.3

TABLE 7. Maximum errors of the model for the case studies.

As it can be seen in section 5.4 and TABLE 7, case studies with low three-phase percentage such as A2, B1 and A6 (lower or equal to 3.63%) have less error than A5 which has a 25% of three-phase loads. Lines with high percentage of three-phase loads would need a different optimization algorithm in order to be more efficient and not exceed error of the 25%, this new scope will be discussed in Chapter 7.

For case studies with low three-phase percentage such as A2, B1 and A6 neutral error could go up to 41% which is a considerable error and would need a higher security coefficient than the phase which maximum is 22.4%. The coefficients would be:

$$C_{phase} = \frac{1}{1 - 0.224} \cong 1.30 \tag{18}$$

$$C_{neutral} = \frac{1}{1 - 0.41} \cong 1.70 \tag{19}$$

When analysing the result of the importance of the reactance of the cables in section 5.5 the error which is always below the value of the calculation with the full impedance is 6% and it could be multiplied by a coefficient to minimize the error as it can be seen in equation (20).

$$C_{Reac} = \frac{1}{0.94} \cong 1.05 \tag{20}$$

In section 5.6 results of the importance of the reactive power of the loads consumes a mean error of 3.85% it is a small error which in case of trying to avoid the bias of just taking into account for the calculation the active power a coefficient could be multiplying the module of the power. The coefficient could be:

$$C_Q = \frac{1}{0.965} \cong 1.05 \tag{21}$$

As a summary of the conclusions which were described in this chapter the utilization of this coefficient would follow the next indications:

- Calculation of the currents and voltages using the equations (5),(6),(7),(8),(9) and (10).

- If reactive measures are not used C_Q must be used multiplying the currents of the model to take considered the negative error which would appear.
- Voltage drop should get multiplied by C_{Reac} in case the reactance of the wires is not been considered.
- Depending on the percentage of three-phase loads if there is near to 4% or lower the security coefficients C_{Phase} and $C_{Neutral}$ would be used for multiplying the current.

The use of the previous coefficient using the indications above could be the next one:

A consume with a $P_{consumer}$ is a candidate for connecting to a line, a software with the model equations added up would calculate the current ($i_{Line\text{-}phase}$) and multiply by the coefficient considered.

With the current estimated the voltage drop is calculated without considering the reactance of the wires and multiplied by the respective coefficient.

$$I_{Line-phase} = i_{Line-phase} * C_{phase} * C_Q \tag{22}$$

$$Capacity \geq I_{Line-phase} + \frac{P_{consumer}}{V_{SS} + \Delta V_{drop} * C_{Reac}} \tag{23}$$

The same calculation would be to see if the neutral wire has capacity for the consumer joining a phase of it is the limitation factor.

If the capacity of the phase wire or the neutral wire is not big enough the consumer would have to get a new line built or to be connected to a different line.

Chapter 7. POTENTIAL FUTURE WORKS

Potential future works could go on three directions: using the equations and the methodology try to get more information of the smart meters measures, change the scope and use the model for another features or to add some mathematical complexity to the optimization model to optimize the error.

Following the first direction of potential future works there would be included to add more data and use more case study lines or to study new features which weren't treated on this project such as the mean unbalance of the networks to get an statistically significant value and based on them try to optimize the connection of new clients.

Second direction of potential future works could be on the line of using the model directly and not the data provided for it, some example could be potential fraud detection or errors in the phase connectivity model like the one explained in Chapter 6. or using directly an optimized model of the one used in this project to be able to look on each phase and compare with its capacity if a new costumer could fit in.

Last upgrade of the model could be to model all three-phase loads and loads without connectivity in different variable not all united in one, and a more complex optimization model would be the solution.

Chapter 8. REFERENCES

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ANNEX I: PROJECT ALIGNMENT WITH THE SDGS

The project which was already explained in detail is related with the next SDGs:

- Goal 7: Affordable and clean energy.
- Goal 9: Industry, innovation and infrastructure.
- Goal 13: Climate action.

The relation with Goal 9 is the clearest one as in this project the use of data analytics and an upgrading in the digitalization of the information of the smart meters, the innovation is clearly reflected. As the case studies are focus on the optimization of the grid for utilities it can be seen a reduction of the infrastructure and an upgrade in the possibility the monitoring and new information can provide.

The project itself is not related to any affordable or clean energies but the addition of monitoring or a better understanding of the network could lead to an inclusion of the electric vehicle, the incorporation of the demand on the market (demand response) or a higher percentage of inclusion of distributed generation which are cleaner energy sources than conventional ones.

About climate action some point made on the goal 7 above could also be included and it could also been added a reduction of metals such as copper or aluminium as a more optimized grid will use less raw materials helping to a more sustainable development of the society.

ANNEX II: CODE

8.1 NETWORK CALCULATION MAIN CODE

```
%% Network calculation
%% Excel data gathering
[data_segment,text_segment] = xlsread('RED
CT200006160.xlsx','SEGMENTOS');
[data_CGP,text_CGP] = xlsread('RED CT200006160.xlsx','CGP');
SM_measures = importfile("consumos línea 5.csv", [2, Inf]);
[data_phase,text_phase,raw_phase] = xlsread('20-
04_MC_Flex_conectividad.xlsx','Conec CN');
[data_SM,text_SM,raw_SM] =
xlsread('Inf_ConsultaLecturas_25_05_2020.xlsx', '1 - 142');
[data_cable_neutro,text_neutro] = xlsread('Tipos de conductores BT para
asignar impedancia de neutro simple.xlsx','Resumen');
[data_cable,text_cable] = xlsread('Tabla valores cableado','Hoja1');

% Spot occupied on the excel RED CT and CGP
initial_buses = 7;
final_buses = 8;
distance_data = 20;
CT_num_Line = 11;
reactance_per_km = 23;
resistence_per_km = 22;

% Spot occupied on the excel of Phase connectivity
Phase_num_Line = 9;
Phase_num_CT = 4; %In data_phase, CT number is 1 and in raw_phase CT
number is 4

% Spot occupied on the excel of Consulting Informacion of Smart meters
SM_num_Line = 14;
SM_CUPS = 4;
SM_ManCode = 1;
SM_PowerSupplied = 8;

% Parameters
V_CT = 222;
line_LV = 5;
CT_number = 200006160;

% We just consider data from the line and CT we need
length_data = size(data_segment,1);
for i = length_data:-1: 1
    if (data_segment(i,CT_num_Line) ~= line_LV)
        data_segment(i,:) = [];
    end
```

```
end

for i = size(data_CGP,1):-1: 1
    if (data_CGP (i,CT_num_Line) ~= line_LV)
        data_CGP(i,:) = [];
    end
end

for i = size(raw_SM,1):-1: 1
    a = strcmp(raw_SM(i,SM_num_Line), int2str(line_LV));
    if (a == 0)
        raw_SM(i,:) = [];
    end
end

raw_phase(1,:) = [];
raw_phase(2,:) = [];
raw_phase(3,:) = [];
for i = size(raw_phase,1):-1: 1
%     a = strcmp(raw_phase(i,Phase_num_Line), '05');
%     if (a == 0) || (data_phase(i,Phase_num_CT-3) ~= CT_number)
    if (data_phase(i,Phase_num_CT-3) ~= CT_number)
        raw_phase(i,:) = [];
        data_phase(i,:) = [];
    end
end

%% Renumbering each bus
codi = data_segment(:,initial_buses); %Initial bus for each branch
codf = data_segment(:,final_buses); %Final bus for each branch
com = unique([codi,codf]);
for iter=1:length(com)
    codi(codi == com(iter)) = iter;
    codf(codf == com(iter)) = iter;
end
data_segment(:,initial_buses) = codi;
data_segment(:,final_buses) = codf;

%% Network representation in a plot
G = digraph(codi,codf);
figure,plot(G)

%% Allocating final edges
v_vector_final = 0;

for iter_final_a = 1:length(codf)
    m_final_a=0;
    for iter_final_b=1:length(codf)

        if codf(iter_final_a)==codi(iter_final_b)
            m_final_a=m_final_a+1;
        end
    end
```

```
        if m_final_a==0
            v_vector_final=v_vector_final+1;
            finalpoints(v_vector_final)=codf(iter_final_a);
        end
end

%% Allocating initial edges
v_vector_initial=0;

for iter_initial_a=1:length(codi)
     m_initial_a=0;
    for iter_initial_b=1:length(codi)

        if codi(iter_initial_a)==codf(iter_initial_b);
            m_initial_a=m_initial_a+1;
        end
    end
        if m_initial_a==0
            v_vector_initial=v_vector_initial+1;
            initial_points(v_vector_initial)=codi(iter_initial_a);
        end
end

%% Defining main network
auxiliary_lenght = 0;
for itera = 1:length(initial_points)
    for iterb=1:length(finalpoints);
        P=shortestpath(G,initial_points(itera),finalpoints(iterb));
        real_length=length(P);
        if real_length>auxiliary_lenght
            main_network=P;
            n_levels= real_length;
            auxiliary_lenght=real_length;
        end
    end
end

%% Creating matrix for initial to final points relation
for iter1 = 1:length(com)
    for iter2=1:length(com)
        for iter3=1:length(codi)
            test_seg=[com(iter1),com(iter2)];
            if test_seg(1)==codi(iter3) && test_seg(2)==codf(iter3)
                initial_final_connection(iter1,iter2)=1;
            end
        end
    end
end

%% Creating subnetworks matrix for superposition calculation
for iterc = 1:length(initial_points)
    for iterd=1:length(finalpoints)

sub_net_vec=shortestpath(G,initial_points(iterc),finalpoints(iterd));
        for itere=1:length(sub_net_vec)
```

```
            SN(itere,iterd)=sub_net_vec(itere);
        end
    end
end

%% Calculating distance for each segment
distance = data_segment(:,distance_data);
for iter=1:length(distance)
   real_distance(codi(iter),codf(iter)) = distance(iter);
end

%% Assigning cable code for each segment and neutro
seg_resistance = data_segment(:,resistence_per_km);
seg_reactance = data_segment(:,reactance_per_km);
I_adm = data_cable(:,2);
res_cable = data_cable(:,3);
reac_cable = data_cable(:,4);
for iter=1:length(codi)
    for iter2=1:length(res_cable)
       if seg_resistance(iter)==res_cable(iter2) &&
seg_reactance(iter)==reac_cable(iter2)
           phase_cable_seg(codi(iter),codf(iter))=data_cable(iter2,1);
           for iter3=1:length(data_cable_neutro(:,2))
               if phase_cable_seg(codi(iter), codf(iter)) ==
data_cable_neutro(iter3,1)
                   neutro_cable_seg(codi(iter),codf(iter)) =
data_cable_neutro(iter3,2);
               end
           end
       end
    end
end

%% Assigning resistance,reactance and admisible current for a coded
neutro
for iter=1:length(codi)
    for iter2=1:length(data_cable(:,1))
        if neutro_cable_seg(codi(iter),codf(iter)) == data_cable(iter2,1)
            resistance_neutro_seg(codi(iter),codf(iter)) =
res_cable(iter2);
            reactance_neutro_seg(codi(iter),codf(iter)) =
reac_cable(iter2);
            I_adm_neutro_seg(codi(iter),codf(iter)) = I_adm(iter2);
        end
    end
end

%% Assigning resistance,reactance and admisible current for a coded phase
for iter=1:length(codi)
    for iter2=1:length(data_cable(:,1))
        if phase_cable_seg(codi(iter),codf(iter))== data_cable(iter2,1)
            resistance_phase_seg(codi(iter),codf(iter))=res_cable(iter2);
            reactance_phase_seg(codi(iter),codf(iter))=reac_cable(iter2);
            I_adm_phase_seg(codi(iter),codf(iter)) = I_adm(iter2);
        end
```

```
    end
end

%% Calculating total impedance for each segment for phase and neutro
for iter=1:length(codi)
impedance_phase_seg(codi(iter),codf(iter))=resistance_phase_seg(codi(iter
),codf(iter))*0.001*real_distance(codi(iter),codf(iter))+0.001*reactance_
phase_seg(codi(iter),codf(iter))*real_distance(codi(iter),codf(iter))*j;
impedance_neutro_seg(codi(iter),codf(iter))=resistance_phase_seg(codi(ite
r),codf(iter))*0.001*real_distance(codi(iter),codf(iter))+0.001*reactance
_phase_seg(codi(iter),codf(iter))*real_distance(codi(iter),codf(iter))*j;
end

%% Connectivity of Smart meters to their phase
Con_SM = findPhase(raw_SM,raw_phase,SM_measures,data_CGP,com);
b = [0.2761,    0.2421,    0.4818]; %MSE TOT
%b = [0.3959,    0.0000,    0.6041]; %MSE N
[power,FEC_LECTURA] = createCurrentFile_opt(SM_measures,Con_SM,com,b);
save('CT200006160_L5_phases.mat', '-struct', 'power');
save('CT200006160_L5_time.mat', 'FEC_LECTURA');

% load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\Data\CT200006160_L5_time.mat')
load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\CT200006160_L5_phases.mat')

%% Calculating of current and voltages in the network
tol = 0.00000001;
[Voltage_drop,branches,Voltage,Current] =
calculationVdrop(PHASE_R,PHASE_S,PHASE_T,SN,FEC_LECTURA,V_CT,codi,codf,to
l,impedance_phase_seg,impedance_neutro_seg);
save('CT200006160_L5_currentReactive_opt.mat', '-struct', 'Current');

% % Assuming a cos_theta, instead of using reactive
% for cos_theta = 0.85:0.01:1
%     [Voltage_drop,branches,Voltage,Current_cos] =
calculationVdrop_Cos(cos_theta,PHASE_R,PHASE_S,PHASE_T,SN,FEC_LECTURA,V_C
T,codi,codf,tol,impedance_phase_seg,impedance_neutro_seg);
%     file_cos = sprintf('CT200006160_L5_currentCos_%d.mat',
round(cos_theta*100));
%     save(file_cos, '-struct', 'Current_cos');
% end

%% Optimization of 3-Phased loads
CT_file = fileCT("S64_SABT_LBT-V-I_20-05.xlsx", "Visualización 1", [4,
57590]);
CT_measures= importSABT(CT_file);

type fmin

f =
@(x)fmin(x,SM_measures,Con_SM,com,V_CT,codi,codf,CT_measures,SN,impedance
_phase_seg,impedance_neutro_seg);
```

```
Aeq = [1,1,1]; beq = [1]; A = []; b = []; lb = [0, 0, 0]; ub = [1, 1, 1];
x0 = [1/3,1/3,1/3]; nlcon =[];

options =
optimoptions('fmincon','PlotFcns',@optimplotfval,'UseParallel',true,'MaxI
terations',10);
tic
[x,fval,exitflag,output] = fmincon(f,x0,A,b,Aeq,beq,lb,ub,nlcon,options);
toc
```

8.2 FUNCTION: CURRENTCALCULATION_ITER

```
function [Current,branches] =
currentCalculation_Iter(PHASE_R,PHASE_S,PHASE_T,SN,FEC_LECTURA,V_CT_R,V_C
T_S,V_CT_T,codi,codf,iteration_vector)

% Branch creation
for i = 1:length(codi)
    branches(i,1) = i;
    branches(i,2) = codi(i);
    branches(i,3) = codf(i);
end

% Current calculation
Current_calculation_R = zeros(length(FEC_LECTURA),size(branches,1));
Current_calculation_S = zeros(length(FEC_LECTURA),size(branches,1));
Current_calculation_T = zeros(length(FEC_LECTURA),size(branches,1));
Current_calculation_N = zeros(length(FEC_LECTURA),size(branches,1));

com = unique([codi,codf]);
BM = ones(length(FEC_LECTURA),length(com)); % Binary matrix for not
taking into account a power measure twice

 for i = 1:size(SN,2)
    Current__R = zeros(length(FEC_LECTURA),size(branches,1));
    Current__S = zeros(length(FEC_LECTURA),size(branches,1));
    Current__T = zeros(length(FEC_LECTURA),size(branches,1));

    Previous_R = zeros(length(FEC_LECTURA),1);
    Previous_S = zeros(length(FEC_LECTURA),1);
    Previous_T = zeros(length(FEC_LECTURA),1);
    for j = size(SN,1):-1:2
        for k = 1:length(FEC_LECTURA)
            if (SN(j-1,i) ~= 0 && SN(j,i)~= 0 && iteration_vector(k) ==
1)
                ind_i = find(branches(:,2) == SN(j-1,i));
                ind_f = find(branches(:,3) == SN(j,i));
                com_ind = intersect(ind_i,ind_f);

                Current__R(k,com_ind) =
BM(k,SN(j,i))*PHASE_R(k,SN(j,i))/V_CT_R(k,SN(j,i))+ Previous_R(k);
```

```
                Current__S(k,com_ind) =
BM(k,SN(j,i))*PHASE_S(k,SN(j,i))/V_CT_S(k,SN(j,i))+ Previous_S(k);
                Current__T(k,com_ind) =
BM(k,SN(j,i))*PHASE_T(k,SN(j,i))/V_CT_T(k,SN(j,i))+ Previous_T(k);

                Previous_R(k) = Current__R(k,com_ind);
                Previous_S(k) = Current__S(k,com_ind);
                Previous_T(k) = Current__T(k,com_ind);
                BM(k,SN(j,i)) = 0;
            end
        end
    end

    Current_calculation_R = Current_calculation_R + Current__R;
    Current_calculation_S = Current_calculation_S + Current__S;
    Current_calculation_T = Current_calculation_T + Current__T;
 end
Current_calculation_N = (abs(Current_calculation_R)+(0.8660-
0.5000i)*abs(Current_calculation_S)+(-0.8660-
0.5000i)*abs(Current_calculation_T));
% Creating a structure to storage it
field1 = 'Current_calculation_R';  value1 = Current_calculation_R;
field2 = 'Current_calculation_S';  value2 = Current_calculation_S;
field3 = 'Current_calculation_T';  value3 = Current_calculation_T;
field4 = 'Current_calculation_N';  value4 = Current_calculation_N;

Current =
struct(field1,value1,field2,value2,field3,value3,field4,value4);

end
```

8.3 FUNCTION: CREATECURRENTFILE_OPT

```
function [Phases,FEC_LECTURA] =
createCurrentFile_opt(SM_measures,Con_SM,com,b)
%% Finding the dates of the excel file
FEC_LECTURA = unique(SM_measures.FEC_LECTURA);
t =
datetime(string(SM_measures.FEC_LECTURA),'TimeZone','local','InputFormat'
,'yyyy-MM-dd HH');
t2 = datetime(string(FEC_LECTURA),'TimeZone','local','InputFormat','yyyy-
MM-dd HH');
[idx,loc] = ismember(t,t2);
%% Adding the phase to SM_measures
for i = 1:length(Con_SM.Phase)
    ind_CUPS = find(string(SM_measures.CUPS) == string(Con_SM.CUPS(i)));
    SM_measures.VAL_PHASE(ind_CUPS) = Con_SM.Phase(i);
end

%% Allocation of CGPs and measures in a table
Num_CGP (:,1) = unique(Con_SM.CGP);
for i = 1:size(Num_CGP,1)
     ind = find(Con_SM.CGP == Num_CGP (i,1));
```

```
     Num_CGP (i,2) = Con_SM.Bus(ind(1));
end
PHASE_R = zeros(length(FEC_LECTURA),length(com));
PHASE_S = zeros(length(FEC_LECTURA),length(com));
PHASE_T = zeros(length(FEC_LECTURA),length(com));
for k = 1:size(Num_CGP,1)
    for i = 1:length(com)
        if (i == Num_CGP(k,2))
            for index = 1:length(FEC_LECTURA)
                aux = find((loc) == index);
                for j = 1:length(aux)
                    if
(strcmp('R',cellstr(SM_measures.VAL_PHASE(aux(j)))) == 1 &&
SM_measures.COD_CAJA(aux(j)) == Num_CGP(k,1))
                        PHASE_R(index,i) = PHASE_R(index,i)+
SM_measures.VAL_AI(aux(j))+SM_measures.VAL_R1(aux(j))*exp(1i*pi/2)-
exp(1i*pi/2)*SM_measures.VAL_R4(aux(j));
                    elseif
(strcmp('S',cellstr(SM_measures.VAL_PHASE(aux(j)))) == 1  &&
SM_measures.COD_CAJA(aux(j)) == Num_CGP(k,1))
                        PHASE_S(index,i) = PHASE_S(index,i)+ (0.8660-
0.5000i)*(SM_measures.VAL_AI(aux(j))+SM_measures.VAL_R1(aux(j))*exp(1i*pi
/2)-exp(1i*pi/2)*SM_measures.VAL_R4(aux(j)));
                    elseif
(strcmp('T',cellstr(SM_measures.VAL_PHASE(aux(j)))) == 1  &&
SM_measures.COD_CAJA(aux(j)) == Num_CGP(k,1))
                        PHASE_T(index,i) = PHASE_T(index,i)+ (-0.8660-
0.5000i)*(SM_measures.VAL_AI(aux(j))+SM_measures.VAL_R1(aux(j))*exp(1i*pi
/2)-exp(1i*pi/2)*SM_measures.VAL_R4(aux(j)));
                    elseif (SM_measures.COD_CAJA(aux(j)) == Num_CGP(k,1))
                        PHASE_R(index,i) =
PHASE_R(index,i)+b(1)*(SM_measures.VAL_AI(aux(j))+SM_measures.VAL_R1(aux(
j))*exp(1i*pi/2)-exp(1i*pi/2)*SM_measures.VAL_R4(aux(j)));
                        PHASE_S(index,i) = PHASE_S(index,i)+b(2)*(0.8660-
0.5000i)*(SM_measures.VAL_AI(aux(j))+SM_measures.VAL_R1(aux(j))*exp(1i*pi
/2)-exp(1i*pi/2)*SM_measures.VAL_R4(aux(j)));
                        PHASE_T(index,i) = PHASE_T(index,i)+b(3)*(-
0.8660-
0.5000i)*(SM_measures.VAL_AI(aux(j))+SM_measures.VAL_R1(aux(j))*exp(1i*pi
/2)-exp(1i*pi/2)*SM_measures.VAL_R4(aux(j)));
                    end
                end
            end
        end
    end
end
%% Output handling
field1 = 'PHASE_R';  value1 = flipud(PHASE_R);
field2 = 'PHASE_S';  value2 = flipud(PHASE_S);
field3 = 'PHASE_T';  value3 = flipud(PHASE_T);

FEC_LECTURA = transpose(flipud(FEC_LECTURA));
Phases = struct(field1,value1,field2,value2,field3,value3);
end
```

8.4 FUNCTION: ERROR ANALYSIS OF 95TH PERCENTILE

```
function Findpercentile_3P

load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\CT200006160_L5_measures.mat')
filePath = 'C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\';
fileList = dir(['C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\Data_Percentile\Comparacion a 222V suponiendo
distintos equilibrios\' 'CT200006160_L5_currentReactive*']);
Current = load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\Data_Percentile\CT200006160_L5_currentReactive_o
pt.mat'); % Tomando la suma directa e MSE
Current_OPT = load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de
instalaciones
completas\CT200006160\L5\Data_Percentile\CT200006160_L5_currentReactive_o
ptN.mat');
Current_OPT_Nuevo = load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de
instalaciones
completas\CT200006160\L5\Data_Percentile\CT200006160_L5_currentReactive_o
pt.mat'); % HAciendo el MSE de todos los puntos

load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\Data_Percentile\CT200006160_L5_time.mat');

%% Time

DateStrings  = string(FEC_LECTURA);
t = datetime(DateStrings,'TimeZone','local','InputFormat','yyyy-MM-dd
HH');
t2 =
datetime(string(CT_measures.FEC_LECTURA),'TimeZone','local','InputFormat'
,'dd/MM/yyyy HH:mm:ss');
% fechaIni = '20/11/2019 23:35:00';
% fechafin = '30/3/2020 23:25:00';

fechaIni = '7/02/2020 23:35:00';
fechafin = '30/03/2020 23:25:00';

% fechaIni = '20/11/2019 23:35:00';
% fechafin = '30/01/2020 23:25:00';
t_fin = datetime(fechafin,'TimeZone','local','InputFormat','dd/MM/yyyy
HH:mm:ss');
t_ini = datetime(fechaIni,'TimeZone','local','InputFormat','dd/MM/yyyy
HH:mm:ss');

ind_fecha_SM = transpose(fliplr(find(t>t_ini & t<t_fin)));
ind_fecha_CT = find(t2>t_ini & t2<t_fin);

%% 95 percentile
Aux = [transpose(CT_measures.I_R(:,1)) transpose(CT_measures.I_S(:,1))
transpose(CT_measures.I_T(:,1)) transpose(CT_measures.I_N(:,1))];
```

```
Y = prctile(Aux,95);

n = table();
n.R = abs(Current.Current_calculation_R(ind_fecha_SM,1));
n.S = abs(Current.Current_calculation_S(ind_fecha_SM,1));
n.T = abs(Current.Current_calculation_T(ind_fecha_SM,1));
n.N = abs(Current.Current_calculation_N(ind_fecha_SM,1));

r = table();
r.R = abs(Current_OPT.Current_calculation_R(ind_fecha_SM,1));
r.S = abs(Current_OPT.Current_calculation_S(ind_fecha_SM,1));
r.T = abs(Current_OPT.Current_calculation_T(ind_fecha_SM,1));
r.N = abs(Current_OPT.Current_calculation_N(ind_fecha_SM,1));

q = table();
q.R = abs(Current_OPT_Nuevo.Current_calculation_R(ind_fecha_SM,1));
q.S = abs(Current_OPT_Nuevo.Current_calculation_S(ind_fecha_SM,1));
q.T = abs(Current_OPT_Nuevo.Current_calculation_T(ind_fecha_SM,1));
q.N = abs(Current_OPT_Nuevo.Current_calculation_N(ind_fecha_SM,1));

m = table();
m.R = CT_measures.I_R(ind_fecha_CT,1);
m.S = CT_measures.I_S(ind_fecha_CT,1);
m.T = CT_measures.I_T(ind_fecha_CT,1);
m.N = CT_measures.I_N(ind_fecha_CT,1);

ind95_R = find(Y <= m.R(:,1));
ind95_S = find(Y <= m.S(:,1));
ind95_T = find(Y <= m.T(:,1));
ind95_N = find(Y <= m.N(:,1));

ind95 = vertcat(ind95_R, ind95_S,ind95_T, ind95_N);
% Plotting

for iterFile = 1:length(fileList)
    load(fileList(iterFile).name)
    p = table();
    p.R = abs(Current_calculation_R(ind_fecha_SM,1));
    p.S = abs(Current_calculation_S(ind_fecha_SM,1));
    p.T = abs(Current_calculation_T(ind_fecha_SM,1));
    p.N = abs(Current_calculation_N(ind_fecha_SM,1));

    MSE (iterFile) = sum((n.R(ind95_R,1) -
m.R(ind95_R)).^2)/length(m.R(ind95_R));
    MSE_S (iterFile) = sum((n.S(ind95_S,1) -
m.S(ind95_S)).^2)/length(m.S(ind95_S));
    MSE_T (iterFile) = sum((n.T(ind95_T,1) -
m.T(ind95_T)).^2)/length(m.T(ind95_T));
    MSE_N (iterFile) = sum((n.N(ind95_N,1) -
m.N(ind95_N)).^2)/length(m.N(ind95_N));

    rMSE (iterFile) = sum((r.R(ind95_R,1) -
m.R(ind95_R)).^2)/length(m.R(ind95_R));
```

```
    rMSE_S (iterFile) = sum((r.S(ind95_S,1) - 
m.S(ind95_S)).^2)/length(m.S(ind95_S));
    rMSE_T (iterFile) = sum((r.T(ind95_T,1) - 
m.T(ind95_T)).^2)/length(m.T(ind95_T));
    rMSE_N (iterFile) = sum((r.N(ind95_N,1) - 
m.N(ind95_N)).^2)/length(m.N(ind95_N));

    qMSE (iterFile) = sum((q.R(ind95_R,1) - 
m.R(ind95_R)).^2)/length(m.R(ind95_R));
    qMSE_S (iterFile) = sum((q.S(ind95_S,1) - 
m.S(ind95_S)).^2)/length(m.S(ind95_S));
    qMSE_T (iterFile) = sum((q.T(ind95_T,1) - 
m.T(ind95_T)).^2)/length(m.T(ind95_T));
    qMSE_N (iterFile) = sum((q.N(ind95_N,1) - 
m.N(ind95_N)).^2)/length(m.N(ind95_N));

    MSE_Reac (iterFile) = sum((p.R(ind95_R,1) - 
m.R(ind95_R)).^2)/length(m.R(ind95_R));
    MSE_Reac_S (iterFile) = sum((p.S(ind95_S,1) - 
m.S(ind95_S)).^2)/length(m.S(ind95_S));
    MSE_Reac_T (iterFile) = sum((p.T(ind95_T,1) - 
m.T(ind95_T)).^2)/length(m.T(ind95_T));
    MSE_Reac_N (iterFile) = sum((p.N(ind95_N,1) - 
m.N(ind95_N)).^2)/length(m.N(ind95_N));

    ind95_1 = ind95_R;
    ind95_2 = ind95_S;
    ind95_3 = ind95_T;
    ind95_4 = ind95_N;
    for i = 1:4
    eval(sprintf('ind_X = ind95_%d;', i));
        Error_media(i,1)  = sum((p.R(ind_X,1) - 
m.R(ind_X)))/length(m.R(ind_X));
        Error_media(i,2)  = sum((p.S(ind_X,1) - 
m.S(ind_X)))/length(m.S(ind_X));
        Error_media(i,3)  = sum((p.T(ind_X,1) - 
m.T(ind_X)))/length(m.T(ind_X));
        Error_media(i,4)  = sum((p.N(ind_X,1) - 
m.N(ind_X)))/length(m.N(ind_X));
    end
    Error_media_tot (iterFile,:) = Error_media(4,:);

    for i = 1:4
        eval(sprintf('ind_X = ind95_%d;', i));
        Error(i,1)  = sum(abs((p.R(ind_X,1) - 
m.R(ind_X))))/length(m.R(ind_X));
        Error(i,2)  = sum(abs((p.S(ind_X,1) - 
m.S(ind_X))))/length(m.S(ind_X));
        Error(i,3)  = sum(abs((p.T(ind_X,1) - 
m.T(ind_X))))/length(m.T(ind_X));
        Error(i,4)  = sum(abs((p.N(ind_X,1) - 
m.N(ind_X))))/length(m.N(ind_X));
    end
    Error_tot (iterFile,:) = Error(4,:);
```

```
    Error_peak (iterFile,:) = [Error(1,1), Error(2,2), Error(3,3), 
Error(4,4)];
end


MSE_TOT = 
1/length(m.R(ind95))*(MSE*length(m.R(ind95_R))+MSE_S*length(m.R(ind95_S))
+MSE_T*length(m.R(ind95_T))+MSE_N*length(m.R(ind95_N)));
rMSE_TOT 
=1/length(m.R(ind95))*(rMSE*length(m.R(ind95_R))+rMSE_S*length(m.R(ind95_
S))+rMSE_T*length(m.R(ind95_T))+rMSE_N*length(m.R(ind95_N)));
MSE_Reac_TOT = 
1/length(m.R(ind95))*(MSE_Reac*length(m.R(ind95_R))+MSE_Reac_S*length(m.R
(ind95_S))+MSE_Reac_T*length(m.R(ind95_T))+MSE_Reac_N*length(m.R(ind95_N)
));
qMSE_TOT 
=1/length(m.R(ind95))*(qMSE*length(m.R(ind95_R))+qMSE_S*length(m.R(ind95_
S))+qMSE_T*length(m.R(ind95_T))+qMSE_N*length(m.R(ind95_N)));

[minimo,ind_minimo] = min(MSE_Reac_TOT);


figure
tiledlayout(2,2)

nexttile
plot(MSE_Reac)
hold on
plot(rMSE)
hold on
plot(qMSE)
title('Phase R')
ylabel('Mean Square Error)'); title('Comparision MSE for MSE-N and MSE-
TOT models');
legend('Euristic data','OptN','Opt')

nexttile
plot(MSE_Reac_S)
hold on
plot(rMSE_S)
hold on
plot(qMSE_S)
title('Phase S')
ylabel('Mean Square Error)'); title('Comparision MSE for MSE-N and MSE-
TOT models');
legend('Heuristic data','OptN','Opt')

nexttile
plot(MSE_Reac_T)
hold on
plot(rMSE_T)
hold on
plot(qMSE_T)
title('Phase T')
```

```
ylabel('Mean Square Error)'); title('Comparision MSE for MSE-N and MSE-
TOT models');
legend('Heuristic data','OptN','Opt')

nexttile
plot(MSE_Reac_N)
hold on

plot(rMSE_N)
hold on
plot(qMSE_N)
title('Phase N')
ylabel('Mean Square Error)'); title('Comparision MSE for MSE-N and MSE-
TOT models');
legend('Heuristic data','OptN','Opt')

figure
plot(MSE_Reac_TOT)
hold on
plot(rMSE_TOT)
hold on
plot(qMSE_TOT)
ylabel('Mean Square Error)'); title('Comparision MSE for MSE-N and MSE-
TOT models');
legend('Heuristic data','OptN','Opt')

minimo
fileList(ind_minimo).name
ind_minimo

%% Box plots
a = 100;
Error_caja_R  = a*(-n.R(ind95_R,1) + m.R(ind95_R))./m.R(ind95_R);
Error_caja_S  = a*(-n.S(ind95_S,1) + m.S(ind95_S))./m.S(ind95_S);
Error_caja_T  = a*(-n.T(ind95_T,1) + m.T(ind95_T))./m.T(ind95_T);
Error_caja_N  = a*(-n.N(ind95_N,1) + m.N(ind95_N))./m.R(ind95_N);

Error_caja_OPT_R  = a*(-r.R(ind95_R,1) + m.R(ind95_R))./m.R(ind95_R);
Error_caja_OPT_S  = a*(-r.S(ind95_S,1) + m.S(ind95_S))./m.S(ind95_S);
Error_caja_OPT_T  = a*(-r.T(ind95_T,1) + m.T(ind95_T))./m.T(ind95_T);
Error_caja_OPT_N  = a*(-r.N(ind95_N,1) + m.N(ind95_N))./m.N(ind95_N);

Error_caja_OPT_Nuevo_R  = a*(-q.R(ind95_R,1) +
m.R(ind95_R))./m.R(ind95_R);
Error_caja_OPT_Nuevo_S  = a*(-q.S(ind95_S,1) +
m.S(ind95_S))./m.S(ind95_S);
Error_caja_OPT_Nuevo_T  = a*(-q.T(ind95_T,1) +
m.T(ind95_T))./m.T(ind95_T);
Error_caja_OPT_Nuevo_N  = a*(-q.N(ind95_N,1) +
m.N(ind95_N))./m.N(ind95_N);


Mean_Error_PHASE_R = mean(abs(Error_caja_OPT_R));
Mean_Error_PHASE_S = mean(abs(Error_caja_OPT_S));
```

```
Mean_Error_PHASE_T = mean(abs(Error_caja_OPT_T));
Mean_Error_PHASE_N = mean(abs(Error_caja_OPT_N));
Mean_Error_PHASE_TOT =
mean((Mean_Error_PHASE_R*length(Error_caja_OPT_R)+Mean_Error_PHASE_S*leng
th(Error_caja_OPT_S)+Mean_Error_PHASE_T*length(Error_caja_OPT_T)+Mean_Err
or_PHASE_N*length(Error_caja_OPT_N))/length(ind95));

Mean_Error_N_R = mean(abs(Error_caja_OPT_Nuevo_R));
Mean_Error_N_S = mean(abs(Error_caja_OPT_Nuevo_S));
Mean_Error_N_T = mean(abs(Error_caja_OPT_Nuevo_T));
Mean_Error_N_N = mean(abs(Error_caja_OPT_Nuevo_N));
Mean_Error_N_TOT =
mean((Mean_Error_N_R*length(Error_caja_OPT_R)+Mean_Error_N_S*length(Error
_caja_OPT_S)+Mean_Error_N_T*length(Error_caja_OPT_T)+Mean_Error_N_N*lengt
h(Error_caja_OPT_N))/length(ind95));

figure
tiledlayout(2,2)
% First plot
nexttile
boxplot([Error_caja_OPT_R,Error_caja_OPT_Nuevo_R],'Labels',{'OPT-N','OPT-
MSE-TOT'}); ylabel('Error (%)'); title('Phase R');
% Second plot
nexttile
boxplot([Error_caja_OPT_S,Error_caja_OPT_Nuevo_S],'Labels',{'OPT-N','OPT-
MSE-TOT'}); ylabel('Error (%)'); title('Phase S');
% Third plot
nexttile
boxplot([Error_caja_OPT_T,Error_caja_OPT_Nuevo_T],'Labels',{'OPT-N','OPT-
MSE-TOT'}); ylabel('Error (%)'); title('Phase T');
% Fourth plot
nexttile
boxplot([Error_caja_OPT_N,Error_caja_OPT_Nuevo_N],'Labels',{'OPT-N','OPT-
MSE-TOT'}); ylabel('Error (%)'); title('Phase N');
```

8.5 FUNCTION: COMPARISION CT MEASURES WITH MODEL

```
function ComparisionCT_MeasuresWithModel

CT_file = fileCT("S64_SABT_LBT-V-I_20-05.xlsx", "Visualización 1", [4,
57590]);
CT_measures= importSABT(CT_file);
save('CT200006160_L5_measures.mat', 'CT_measures');
% Current_optN= load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de
instalaciones
completas\CT200006160\L5\CT200006160_L5_currentReactive_optN.mat');
Current = load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\CT200006160_L5_currentReactive_opt.mat');
load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\CT200006160_L5_time.mat');

n = table();
```

```
n.FEC_LECTURA = transpose(FEC_LECTURA);
n.R = abs(Current.Current_calculation_R(:,1));
n.S = abs(Current.Current_calculation_S(:,1));
n.T = abs(Current.Current_calculation_T(:,1));
n.N = abs(Current.Current_calculation_N(:,1));

% m = table();
% m.FEC_LECTURA = transpose(FEC_LECTURA);
% m.R = abs(Current_optN.Current_calculation_R(:,1));
% m.S = abs(Current_optN.Current_calculation_S(:,1));
% m.T = abs(Current_optN.Current_calculation_T(:,1));
% m.N = abs(Current_optN.Current_calculation_N(:,1));

DateStrings  = string(n.FEC_LECTURA);
t = datetime(DateStrings,'TimeZone','local','InputFormat','yyyy-MM-dd
HH');
t2 =
datetime(string(CT_measures.FEC_LECTURA),'TimeZone','local','InputFormat'
,'dd/MM/yyyy HH:mm:ss');
fechaIni = '11/2/2020 23:50:00';
fechafin = '12/2/2020 23:25:00';
t_fin = datetime(fechafin,'TimeZone','local','InputFormat','dd/MM/yyyy
HH:mm:ss');
t_ini = datetime(fechaIni,'TimeZone','local','InputFormat','dd/MM/yyyy
HH:mm:ss');

ind_fecha_SM = transpose(fliplr(transpose(find(t>t_ini & t<t_fin))));
ind_fecha_CT = find(t2>t_ini & t2<t_fin);

%% Plots
figure
tiledlayout(2,2)
aux = 24;
% Top plot
nexttile
plot((1:aux),n.R(ind_fecha_SM), '-o')
hold on
plot((1:aux),transpose(CT_measures.I_R(ind_fecha_CT)),'-o')
% plot((1:aux),m.R(ind_fecha_SM), '-o')
title('Phase R')
legend('Model-opt','Measures CT')

% Middle plot
nexttile
plot((1:aux),n.S(ind_fecha_SM), '-o')
hold on
plot((1:aux),transpose(CT_measures.I_S(ind_fecha_CT)),'-o')
% plot((1:aux),m.S(ind_fecha_SM), '-o')
title('Phase S')
legend('Model-opt','Measures CT')

% Bottom plot
nexttile
plot((1:aux),n.T(ind_fecha_SM), '-o')
hold on
```

```
plot((1:aux),transpose(CT_measures.I_T(ind_fecha_CT)),'-o')
% plot((1:aux),m.T(ind_fecha_SM), '-o')
title('Phase T')
legend('Model-opt','Measures CT')

% Bottom plot
nexttile
plot((1:aux),n.N(ind_fecha_SM), '-o')
hold on
plot((1:aux),transpose(CT_measures.I_N(ind_fecha_CT)),'-o')
% plot((1:aux),m.N(ind_fecha_SM), '-o')
title('Phase N')
legend('Model-opt','Measures CT')

%datetick('x', 'dd/MM/yyyy HH')
%datetick('x', 'dd/MM/yyyy HH')
```

8.6 FUNCTION: ANALYSIS OF REACTANCE OF THE WIRES

```
function AnalysisReactiveWires
%% Parameters
V_CT = 222;

%% Data loading
load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\Data_Percentile\CT200006160_L5_time.mat');
load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\Data_ReactiveWires\impedance_phase.mat');
load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\Data_ReactiveWires\impedance_neutro.mat');
load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\Data_Percentile\CT200006160_L5_phases.mat');
load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\Data_ReactiveWires\codi.mat');
load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\Data_ReactiveWires\codf.mat');
load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\Data_ReactiveWires\SN.mat')

%% Voltage calculation
tol = 0.00000001;
[Voltage_drop,branches,Voltage,Current] =
calculationVdrop(PHASE_R,PHASE_S,PHASE_T,SN,FEC_LECTURA,V_CT,codi,codf,to
l,impedance_phase_seg,impedance_neutro_seg);

[Voltage_drop_Real,branches,Voltage_Real,Current_Real] =
calculationVdrop(PHASE_R,PHASE_S,PHASE_T,SN,FEC_LECTURA,V_CT,codi,codf,to
l,real(impedance_phase_seg),real(impedance_neutro_seg));

Diff_R = 100*(sum(Voltage_drop.R(:,[1,2]),2)-
sum(Voltage_drop_Real.R(:,[1,2]),2))./sum(Voltage_drop.R(:,[1,2]),2);
```

```
Diff_S = 100*(sum(Voltage_drop.S(:,[1,2]),2)-
sum(Voltage_drop_Real.S(:,[1,2]),2))./sum(Voltage_drop.S(:,[1,2]),2);
Diff_T = 100*(sum(Voltage_drop.T(:,[1,2]),2)-
sum(Voltage_drop_Real.T(:,[1,2]),2))./sum(Voltage_drop.T(:,[1,2]),2);
Diff_N = 100*(sum(Voltage_drop.N(:,[1,2]),2)-
sum(Voltage_drop_Real.N(:,[1,2]),2))./sum(Voltage_drop.N(:,[1,2]),2);

Mean_Phase = mean(mean(Diff_R)+mean(Diff_S)+mean(Diff_T))/3;
Mean_N = mean(Diff_N);

boxplot([Diff_R,Diff_S,Diff_T,Diff_N],'Labels',{'R','S','T','N'});
ylabel('Error (%)'); title('Difference V-Vreal');
end
```

8.7 FUNCTION: ANALYSIS OF THE REACTIVE POWER MEASURES

```
function AnalysisReactiveMeasures

load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\Data_Cos\CT200006160_L5_measures.mat')
filePath = 'C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\';
fileList = dir(['C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\Data_Cos\' 'CT200006160_L5_currentCos*']);
Current = load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\Data_Cos\CT200006160_L5_currentReactive_optNuevo
.mat'); % HAciendo el MSE de todos los puntos
% Current_OPT = load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de
instalaciones
completas\Data_Percentile\CT200006160_L5_currentReactive_optN.mat');

load('C:\Users\USUARIO\Desktop\ICAI\TFM\Datos de instalaciones
completas\CT200006160\L5\Data_Cos\CT200006160_L5_time.mat');

%% Time

DateStrings  = string(FEC_LECTURA);
t = datetime(DateStrings,'TimeZone','local','InputFormat','yyyy-MM-dd
HH');
t2 =
datetime(string(CT_measures.FEC_LECTURA),'TimeZone','local','InputFormat'
,'dd/MM/yyyy HH:mm:ss');
% fechaIni = '20/11/2019 23:35:00';
% fechafin = '30/3/2020 23:25:00';

fechaIni = '7/02/2020 23:35:00';
fechafin = '30/03/2020 23:25:00';

% fechaIni = '20/11/2019 23:35:00';
% fechafin = '30/01/2020 23:25:00';
t_fin = datetime(fechafin,'TimeZone','local','InputFormat','dd/MM/yyyy
HH:mm:ss');
```

```
t_ini = datetime(fechaIni,'TimeZone','local','InputFormat','dd/MM/yyyy
HH:mm:ss');

ind_fecha_SM = transpose(fliplr(find(t>t_ini & t<t_fin)));
ind_fecha_CT = find(t2>t_ini & t2<t_fin);

%% 95 percentile
Aux = [transpose(CT_measures.I_R(:,1)) transpose(CT_measures.I_S(:,1))
transpose(CT_measures.I_T(:,1)) transpose(CT_measures.I_N(:,1))];
Y = prctile(Aux,95);

n = table();
n.R = abs(Current.Current_calculation_R(ind_fecha_SM,1));
n.S = abs(Current.Current_calculation_S(ind_fecha_SM,1));
n.T = abs(Current.Current_calculation_T(ind_fecha_SM,1));
n.N = abs(Current.Current_calculation_N(ind_fecha_SM,1));

m = table();
m.R = CT_measures.I_R(ind_fecha_CT,1);
m.S = CT_measures.I_S(ind_fecha_CT,1);
m.T = CT_measures.I_T(ind_fecha_CT,1);
m.N = CT_measures.I_N(ind_fecha_CT,1);

ind95_R = find(Y <= m.R(:,1));
ind95_S = find(Y <= m.S(:,1));
ind95_T = find(Y <= m.T(:,1));
ind95_N = find(Y <= m.N(:,1));

ind95 = vertcat(ind95_R, ind95_S,ind95_T, ind95_N);

% Analyze cos of 95 percentile measures
Aux2 = [transpose(Current.Current_calculation_R(ind95_R,1))
transpose(Current.Current_calculation_S(ind95_S,1))/exp(1i*-2/3*pi)
transpose(Current.Current_calculation_T(ind95_T,1))/exp(1i*+2/3*pi)];
Aux3 = cos(angle(Aux2));
A5 = Aux3
figure
boxplot(Aux3,'Labels',{'COS'}); ylabel('Value of Cos'); title('Cos
Theta');

% Plotting

for iterFile = 1:length(fileList)
    load(fileList(iterFile).name)
    p = table();
    p.R = abs(Current_calculation_R(ind_fecha_SM,1));
    p.S = abs(Current_calculation_S(ind_fecha_SM,1));
    p.T = abs(Current_calculation_T(ind_fecha_SM,1));
    p.N = abs(Current_calculation_N(ind_fecha_SM,1));

    MSE  (iterFile) = sum((n.R(ind95_R,1) -
m.R(ind95_R)).^2)/length(m.R(ind95_R));
    MSE_S  (iterFile) = sum((n.S(ind95_S,1) -
m.S(ind95_S)).^2)/length(m.S(ind95_S));
```

```
    MSE_T (iterFile) = sum((n.T(ind95_T,1) -
m.T(ind95_T)).^2)/length(m.T(ind95_T));
    MSE_N (iterFile) = sum((n.N(ind95_N,1) -
m.N(ind95_N)).^2)/length(m.N(ind95_N));

    MSE_Reac (iterFile) = sum((p.R(ind95_R,1) -
m.R(ind95_R)).^2)/length(m.R(ind95_R));
    MSE_Reac_S (iterFile) = sum((p.S(ind95_S,1) -
m.S(ind95_S)).^2)/length(m.S(ind95_S));
    MSE_Reac_T (iterFile) = sum((p.T(ind95_T,1) -
m.T(ind95_T)).^2)/length(m.T(ind95_T));
    MSE_Reac_N (iterFile) = sum((p.N(ind95_N,1) -
m.N(ind95_N)).^2)/length(m.N(ind95_N));

end

MSE_TOT =
1/length(m.R(ind95))*(MSE*length(m.R(ind95_R))+MSE_S*length(m.R(ind95_S))
+MSE_T*length(m.R(ind95_T))+MSE_N*length(m.R(ind95_N)));
MSE_Reac_TOT =
1/length(m.R(ind95))*(MSE_Reac*length(m.R(ind95_R))+MSE_Reac_S*length(m.R
(ind95_S))+MSE_Reac_T*length(m.R(ind95_T))+MSE_Reac_N*length(m.R(ind95_N)
));

[minimo,ind_minimo] = min(MSE_Reac_TOT);


figure
tiledlayout(2,2)

nexttile
plot(MSE_Reac)
hold on
plot(MSE)
title('Phase R')
legend('Cos','Opt')

nexttile
plot(MSE_Reac_S)
hold on
plot(MSE_S)
title('Phase S')
legend('Cos','Opt')

nexttile
plot(MSE_Reac_T)
hold on
plot(MSE_T)
hold on
title('Phase T')
legend('Mano','Opt')

nexttile
plot(MSE_Reac_N)
```

```
hold on
plot(MSE_N)
title('Phase N')
legend('Mano','Opt')

figure
plot(MSE_Reac_TOT)
hold on
plot(MSE_TOT)
legend('Mano','Opt')

minimo
fileList(ind_minimo).name
ind_minimo
%% Box plots
load(fileList(ind_minimo).name)
p = table();
p.R = abs(Current_calculation_R(ind_fecha_SM,1));
p.S = abs(Current_calculation_S(ind_fecha_SM,1));
p.T = abs(Current_calculation_T(ind_fecha_SM,1));
p.N = abs(Current_calculation_N(ind_fecha_SM,1));

a = 100;
Error_caja_R  = a*(-p.R(ind95_R,1) + m.R(ind95_R))./m.R(ind95_R);
Error_caja_S  = a*(-p.S(ind95_S,1) + m.S(ind95_S))./m.R(ind95_S);
Error_caja_T  = a*(-p.T(ind95_T,1) + m.T(ind95_T))./m.R(ind95_T);
Error_caja_N  = a*(-p.N(ind95_N,1) + m.N(ind95_N))./m.R(ind95_N);

Error_caja_OPT_R  = a*(-n.R(ind95_R,1) + m.R(ind95_R))./m.R(ind95_R);
Error_caja_OPT_S  = a*(-n.S(ind95_S,1) + m.S(ind95_S))./m.R(ind95_S);
Error_caja_OPT_T  = a*(-n.T(ind95_T,1) + m.T(ind95_T))./m.R(ind95_T);
Error_caja_OPT_N  = a*(-n.N(ind95_N,1) + m.N(ind95_N))./m.R(ind95_N);

figure
tiledlayout(2,2)
% First plot
nexttile
boxplot([Error_caja_R,Error_caja_OPT_R],'Labels',{'COS','OPT'});
ylabel('Error (%)'); title('Phase R');
% Second plot
nexttile
boxplot([Error_caja_S,Error_caja_OPT_S],'Labels',{'COS','OPT'});
ylabel('Error (%)'); title('Phase S');
% Third plot
nexttile
boxplot([Error_caja_T,Error_caja_OPT_T],'Labels',{'COS','OPT'});
ylabel('Error (%)'); title('Phase T');
% Fourth plot
nexttile
boxplot([Error_caja_N,Error_caja_OPT_N],'Labels',{'COS','OPT'});
ylabel('Error (%)'); title('Phase N');
```