Faculty of Engineering of the University of Porto

Detection and Location of Non-Technical Losses in Low Voltage Distribution Networks

Luís Acácio Mendes Marques

FINAL VERSION

Dissertation conducted under the
Integrated Master in Electrical and Computers Engineering
Major Energy

Supervisor: Helder Filipe Duarte Leite (Prof. Dr.)
Co-supervisor: Nuno Filipe Gonçalves da Silva (Dr.)

July 2016

Abstract

The undergoing changes in the paradigm of distribution networks, and particularly in Low Voltage (LV) networks, which are starting to integrate decentralized and smart management systems such as smart meters, enable the implementation of an Advanced Metering Infrastructure (AMI). These changes provide an opportunity to the deployment of new features such as the detection and location of Non-Technical Losses (NTLs). In fact, the problem of non-technical losses occurs mainly in LV networks as the majority of the consumers is present in these networks.

An efficient electrical power system, which supplies energy to customers in the most economical way, is the main goal of network's users. NTLs represent energy supplied that is not billed despite being reflected in the price paid by all the customers. In addition, these losses affect the quality of service and increase not only the technical losses in networks but, moreover, the amount of energy that needs to be produced in power plants. Therefore, the detection and location of NTLs is of the utmost importance for reducing the system's operational costs, increasing the revenues for distribution system operators as well as reducing the energy price for customers.

This dissertation advances a new approach that leverages the information (e.g. electrical measures) provided by the smart meters installed at the costumers' premises to perform, in the first algorithmic step, the detection of NTLs and, in the second algorithmic step, proceed to their location. Even in the presence of an AMI, the distribution system operator frequently does not have all the data that characterizes the low voltage network (e.g. branches' physical parameters). Nonetheless, the proposed method is applicable even when most of these characteristics are unknown. In addition, the advanced methodology is not dependent of an accurate estimation of technical losses, reducing the uncertainty in the overall process. A case study of a real LV network is assessed to validate the adequacy of the advanced methodology under different scenarios of knowledge of the characteristics of the network.

Resumo

As atuais mudanças no paradigma das redes de baixa tensão, nas quais começam a ser integrados sistemas de gestão descentralizados e com funcionalidades avançadas, como os contadores inteligentes, possibilitam a implementação de uma infraestrutura avançada de medição nestas redes. Estas mudanças proporcionam uma oportunidade singular para o desenvolvimento de novas ferramentas e funcionalidades como a deteção e localização de perdas não técnicas em redes de baixa tensão. O potencial da deteção e localização de perdas não técnicas em redes de baixa tensão está diretamente relacionado com o facto da maioria dos consumidores estar presente nas mesmas.

Um sistema elétrico de energia eficiente, que alimenta os seus utilizadores da forma mais económica possível é o principal objetivo para os intervenientes presentes na cadeia de valor do sector elétrico. A perdas não técnicas representam energia fornecida que não é faturada, apesar de ser refletida no preço da energia pago por todos os consumidores. Além disso, estas perdas afetam a qualidade de serviço e energia, aumentando não só as perdas técnicas como também a quantidade de energia produzida nas centrais elétricas. A deteção e localização de perdas não técnicas, é assim da maior importância, no sentido de reduzir os custos de operação do sistema, aumentando as receitas para os operadores do sistema e diminuindo a fatura energética para os clientes.

Esta dissertação propõe uma nova abordagem que, utilizando as medidas fornecidas pelos contadores inteligentes nas instalações de consumo, realiza numa primeira fase a deteção de perdas não técnicas e na segunda fase procede à sua localização. Mesmo na presença de uma infraestrutura avançada de medição, frequentemente o operador da rede de distribuição não tem todos os dados que caracterizam a rede de baixa tensão, como por exemplo os parâmetros físicos das linhas/cabos. Não obstante, a metodologia desenvolvida é aplicável mesmo quando a maior parte destas características são desconhecidas. A metodologia desenvolvida não depende de uma estimativa das perdas técnicas na rede, reduzindo a incerteza no processo.

A metodologia desenvolvida é avaliada usando como caso de estudo uma rede típica de baixa tensão. A sua validade é testada sob diferentes cenários de conhecimento das características da rede de baixa de tensão.

Acknowledgements

First of all, I would like to acknowledge my supervisor, Professor Doctor Helder Leite, for his advice and trust since the first moment.

I would like to express my gratefully to my co-supervisor Dr. Nuno Silva for all of his support and for the opportunity to develop my dissertation at EFACEC.

I also would like to address my special thank to Eng. Eduardo Rodrigues and to Dr. Ismael Miranda. I have no words to express all of my gratitude for their availability and encouragement. Their guidance has been essential for the conclusion of my dissertation.

Finally, I would like to acknowledge all of my friends and family for supporting me in the difficult moments.

Luís Marques

Contents

List of figures

List of tables

Abbreviations and Symbols

List of abbreviations

AMI	Advanced Metering Infrastructure
DA	Distribution Automation
DER	Distributed Energy Resources
DRP	Demand Response Programs
DSO	Distribution System Operator
DTC	Distribution Transformer Controller
HV	High Voltage
MDMS	Meter Data Management System
ERSE	Energy Services Regulatory Authority
LV	Low Voltage
MV	Medium Voltage
NEV	Neutral to Earth Voltage
NTLs	Non-Technical Losses
QoE	Quality of the Energy
QoS	Quality of Service
SCADA	Supervisory Control and Data Acquisition
SMs	Smart Meters
TLs	Technical Losses
TS	Transmission System
TSO	Transmission System Operator

List of symbols

A	Amperes
R	Resistance
X	Reactance
V	Volt
Ω	Ohm

Chapter 1

Introduction

The main objective of this work is to study the problem of Non-Technical Losses (NTLs) in distribution networks, and to advance a methodology that is capable of tackling this problem, particularly in Low Voltage (LV) networks. Therefore, a methodology has been developed consisting of the methodological steps, first, to detect the presence of NTLs and, second, to proceed to their location.

In this first Chapter, the motivation, the objectives and the structure of the dissertation are presented.

1.1 - Smart Grid Concept: Benefits of an Advanced Metering Infrastructure

The smart grid concept represents the last and the most evolved generation of electric power grids designed so far. It may be defined as an electricity network that is able to integrate the behaviour and actions of all users connected to it. Nevertheless, this integration is performed in a cost efficient manner in order to ensure economically efficient, sustainable power system with reduced losses and high levels of quality and security of supply and safety [1]. This concept is achievable through the transformation of electric power grids using automatic control, the communications infrastructures and other forms of information technologies [2]. Smart Grids have been designed to introduce an intelligent management system in conventional networks, providing an opportunity to tackle some of the present challenges in LV networks. In fact, the smart grid concept will enable the monitoring, in real time, of the operational conditions of LV networks which is not feasible in the majority of the current LV networks. Therefore, the Distribution System Operator (DSO) will have available additional information regarding the network, such as electrical measures as voltages in nodes and the consumers' load diagrams. This information leverages the development of new tools, as the detection and location of NTLs, which may be used to maximize the efficient and the Quality of Service (QoS) in LV networks in a smart grid environment.

The implementation of smart grids relies on the use of an Advanced Metering Infrastructure (AMI) since this structure allows two-way communications between different entities present in the grid, namely consumers at one side and the Meter Data Management System (MDMS) on another side, with the onus of collecting data into software application platforms [3]. The information exchanged between these entities is performed through the use of communication networks at different levels of the infrastructure hierarchy as shown in Figure 1.1.

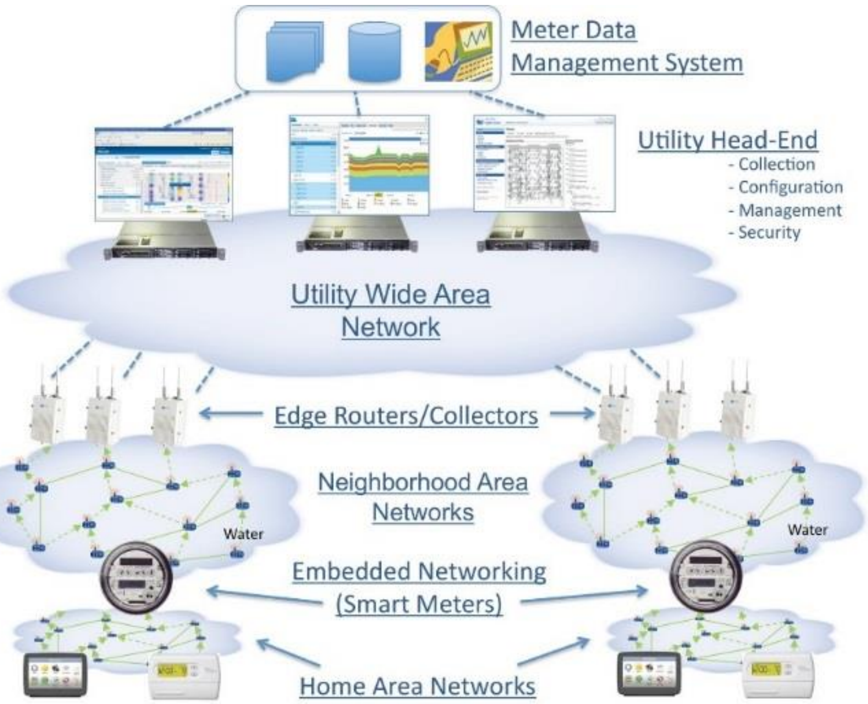

Figure 1.1 - Advanced Metering Infrastructure [4].

These changes enable the integration of consumers in the system's management, enhancing its operability. With the presence of an AMI, the consumers and the system's operators will have in real time information about the consumption. Thus it is possible, for example, to implement Demand Response Programs (DRP). In DRP, consumers may reduce or shift their consumption during peak periods. This enables a cooperation, in real time, between the system's operator and consumers with the main goal of increasing the benefits for both parts. The participation of consumers in DRP may provide a reduction in their energy bill and system's operator will have an additional resource, for instance to solve congestions issues in the network.

AMI is based on Distribution Automation (DA) which refers to a set of technologies, incorporated in Supervisory Control and Data Acquisition (SCADA) systems and in communication infrastructures [5]. These technologies enable the operation of electrical networks, being capable of monitoring (e.g. voltages and currents) and operating in real time (automatically) remote units, providing a higher flexibility to the system's operation. The implementation of DA in LV networks may be performed through smart metering, i.e., through the incorporation of individual devices all over the network (at the costumers' premises) for measuring electrical variables (e.g. voltages) and communicate such measurements. Smart metering will the gateway between the consumers and the centralized management systems.

AMIs and sensorization systems are already implemented in the majority of Transmission Systems (TS) in Medium Voltage (MV) and High Voltage (HV) distribution networks as the operation of these networks requires the implementation of an intelligent management system, namely SCADA systems. These systems enable the monitoring of high quantities of energy flowing through electrical grids and control its impacts on the assets (e.g. faults).

Nevertheless, when the focus is turned to distribution networks, namely to LV networks, which have always been explored without a centralized management system or without considering DA, the development of smart metering will completely change the paradigm of these networks in the overall system. In fact, smart metering will become the foundation of AMIs in LV networks. The presence of an AMI in LV networks will improve their observability from the point of view of its operational conditions, leading to the development of new features such as State Estimation (SE) and enabling the implementation of the smart grid concept.

1.2 - NTLs Detection Relevance for Network's Users

The problem of NTLs in this work will be treated as all energy supplied to consumers that is not billed regardless of its causes and origins. Despite being most related to undeveloped countries, this problem is found in the majority of the countries all over the world. Actually, according to [6], each year European utilities have revenue losses around 3700 million euros as seen in Figure 1.2.

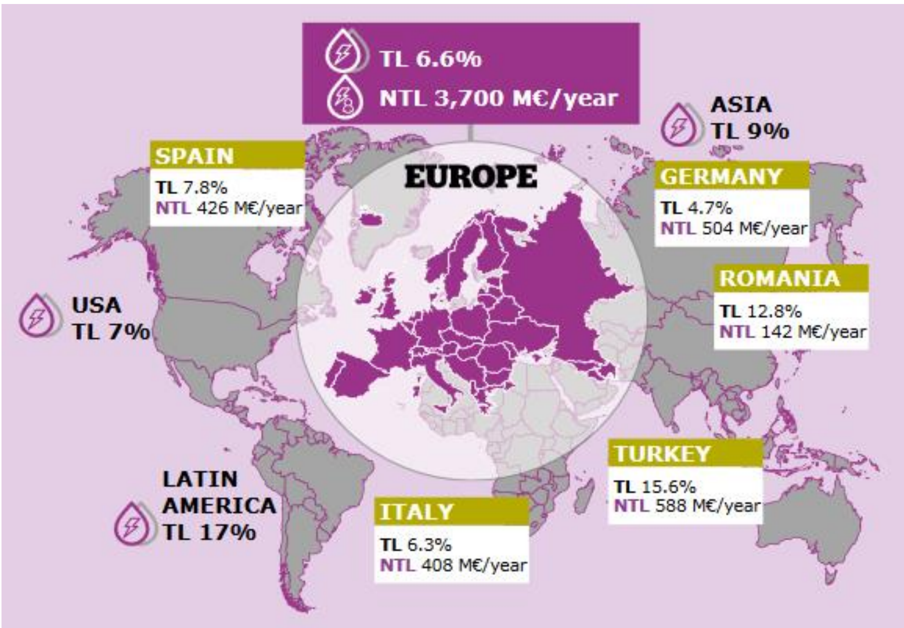

Figure 1.2 - Non-Technical Losses in Europe [6] (TL – Technical Losses).

For instance, the DSOs of the Netherlands have estimated a total of 23% of NTLs in their networks comparing with the total losses registered [7]. The respective revenue loss impact in different parts of the chain value is shown in Figure 1.3. Around 47% of the revenue loss (120M€) is related with taxes not charged due to the energy not billed. The profit loss due to the increase of technical losses in distribution networks is around 85M€. Finally, the revenue loss due to the reduction in the energy sale is about 30 M€ which implies a reduction in the retail margin around 20 M€. These costs are charged to all customers since it is reflected in the price of electricity tariffs.

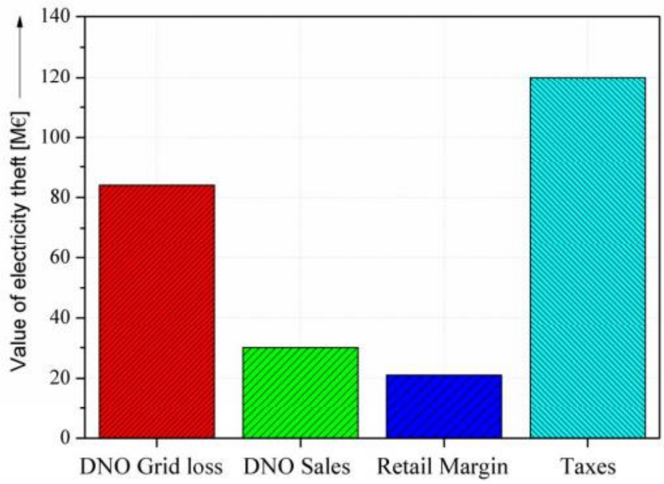

Figure 1.3 - Revenue Losses due to NTLs in Netherlands [7].

In Portugal, the Energy Services Regulatory Authority (ERSE) is responsible for the regulation of electric sector, with the objective of controlling the activities of the DSO and the Transmission System Operator (TSO). The regulated tariff has a mechanism based on incentives that remunerates the DSO taking into account the losses registered in each year. If losses are lower than a pre-set reference value, the DSO is economically rewarded. Otherwise, the DSO is penalised. The Figure 1.4 represent the evolution of the total losses in distribution networks in Portugal and the reference values defined by the regulator for the period between 2015 and 2018. The evolution of the value of the incentive mechanism during the last years is shown in Figure 1.5.

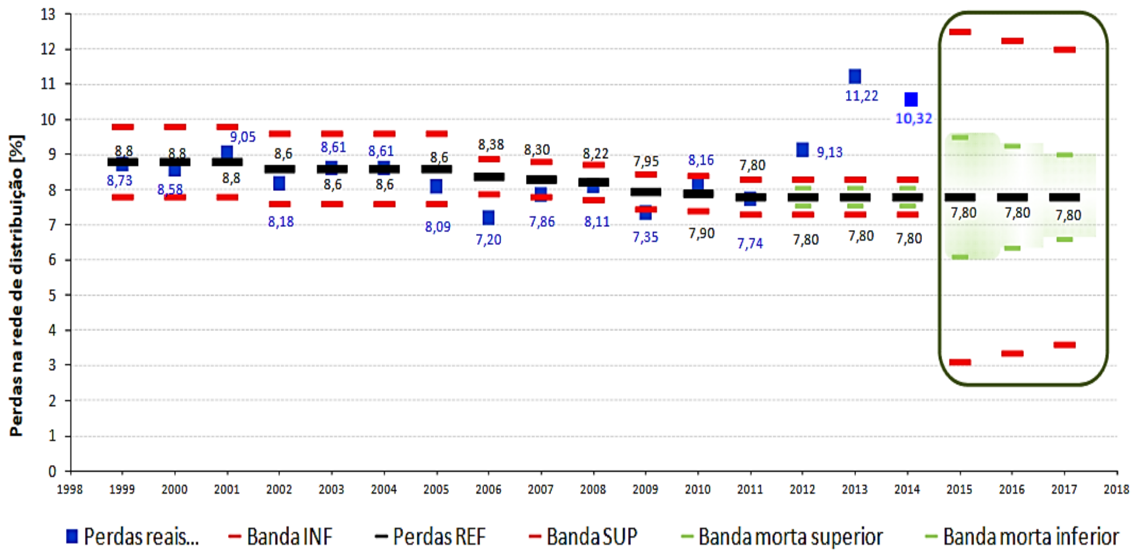

Figure 1.4 – Evolution of the total losses during the last years.

As can be seen in Figure 1.4. the total losses in the period between 2012 and 2014 were higher that the superior band, therefore the DSO had revenue losses around 5M € as shown in Figure 1.5.

Figure 1.5 - Monetary Value of the Incentive Mechanism

Furthermore, NTLs represent additional currents flowing through branches of the entire system and, thus, network's operators may be driven to invest in the reinforcement of the lines capacity. These additional currents increase the technical losses and the probability of congestions issues deteriorating the reliability and the Quality of Service (QoS) in distribution networks. Additionally, the presence of NTLs increases the quantity of energy that needs to be produced in power plants comparing with the value that would be produced in the absence of NTLs. Once all energy produced is paid, the operational costs of the entire electric system rises, being reflected in the price paid by all consumers. Depending on the value of NTLs and its evolution over time, the need to make investments in new capacity of generation may be increased. This may jeopardize the achievement of the European Energy Strategy for 2030 which requires a reduction of 40% in greenhouse gas emissions and at least 27% in energy savings [8]. Concluding, NTLs represents a transversal problem that implies drawbacks for all the parts of the electrical value chain, from consumers to systems operators.

1.3 - Motivation and Objectives

The NTLs occurs main in LV distribution networks, as a distribution company may have millions of domestic customers [6] and the monitoring of energy losses in these networks has not been accomplished due to the high cost of the installation in equipment such as Current Transformers (CTs) and Voltage Transformers (VTs). Additionally, the on-site inspections by utilities' teams are time consuming and, therefore, present significant costs. Nevertheless, with the directive publish by the European Union (EU) [9] in order to implement in the majority of the LV networks smart meters provides an opportunity to tackle the absence of monitoring in these networks. In fact, it is expected that until 2020 over than 200 million of SMs will be installed in customers' premises. These undergoing changes in the paradigm of LV networks allows the development of an AMI.

This work aims to present the advantages of the smart metering/ AMI deployment in LV networks and to detail its intrinsic characteristics that may be used to tackle the problem of NTLs. The assessment of the NTLs problem is also addressed, exposing its drawback for network operators and global society.

In order to address the problem of NTLs a methodology is advanced to systematically detect and locate them. The detection is performed by comparing the currents measured at the secondary substation by the Distribution Transformer Controller (DTC) with the sum of the currents measured by consumers with SMs. The location of NTLs is performed comparing the currents in branches, based on the measured currents consumed and using the Kirchhoff's Current Laws (KCL), with an estimation of the real currents in branches considering the voltages in nodes provided by SMs. Nonetheless, even in the presence of an AMI, the DSO most of the times does not have all the data that characterize the network (such as the topology and the branches impedances). Therefore, this work addresses some of the technical challenges of the implementation of the detection and location of NTLs in LV networks.

The adequacy of the advanced methodology is tested in a real LV network. The case study used is based on a typical Portuguese LV network where the main features of a smart grid such as microgeneration and SMs are already implemented. Different scenarios, that characterize the majority of expected real situations, have been defined to demonstrate the adaptability and the robustness of the proposed methodology.

1.4 - Structure of the Dissertation

This work is composed by six Chapters. In Chapter 1 is presented a framework of the problem of NTLs, where is expressed the future role of AMI in LV networks and the advantages of the smarting in these networks.

The Chapter 2 presents an overview of the problem, by clearly identifying the causes and origins behind it. It is also exposed the consequences of the problem to network's users, namely to consumers and the DSOs. Lastly, the strategies developed used to tackle the problem are assessed and a critical analysis is performed.

The following chapter, Chapter 3, addresses a full characterization of LV networks in order to describe in detail the particular characteristics of these networks, as well as the smart metering features that may be used to address the problem of NTLs.

The Chapter 4 presents the developed methodology to detect and locate NTLs in LV networks considering different levels of network's knowledge. A step by step explanation of the methodology is carried out by presenting in a first instance the process of detection and later the process of location.

In Chapter 5 the different case studies are presented to demonstrate the adequacy of the advanced methodology under different conditions that represent the majorly of real situations. The results are discussed in detail.

Lastly, in Chapter 6, the main conclusions of the developed work are exposed as well as the work contribution, the methodology limitations and future work perspectives.

1.5 - Results Dissemination

In consequence of the developed work during this dissertation, a paper will be submitted (the extended abstract has already been accepted) to the MedPower Conference 2016, Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion sponsored by the Institution of Engineering and Technology (IET). The conference will take place on November 6-9, 2016 in Belgrade, Serbia. The paper title is “Detection and Location of Non-Technical Losses in Low Voltage Distribution Networks” and presents the methodology proposed to detect and locate Non-Technical Losses in LV distribution networks.

Chapter 2

Non-Technical Losses: Literature Review

This chapter presents the characterization of Non-Technical Losses (NTLs) in the electric power systems distinguishing the types of losses that may occur, and explaining their causes and origins. It is also included a review of the technical and economic impacts of NTLs. Lastly, a review of the works related with the detection and location of NTLs is performed. A critical analysis is performed by explaining their advantages and disadvantages in tackling the challenge of NTLs.

2.1 - Definition of Non-Technical Losses

Electrical power systems which have the main objective of supplying energy to consumers, are constituted by several components, namely lines and transformers. These components in virtue of their intrinsic resistance, consume energy when currents flow through them. This energy of losses is designated as Technical Losses (TLs). This phenomenon occurs mainly due to the Joule effect and is given by:

$$TLs = R \times I^2 \tag{2.1}$$

where R represent the resistance of the component and I is the current that flows through it.

Considering the difference between the total energy produced ($E_{produced}$) and the total consumed energy ($E_{consumed}$) that is measured, the total losses (L) and given by Equation 2.2.

$$L = E_{produced} - E_{consumed} \tag{2.2}$$

Without NTLs, the sum of TLs would be equal to the total losses. NTLs may, therefore, be calculated by the difference between the total losses and the TLs:

$$NTLs = L - TLs \tag{2.3}$$

NTLs may be defined as a portion of the energy of losses, being caused by an extern action to the power system [10]. The NTLs are also referred, in the literature, as commercial losses [11], as they represent energy supplied that is not billed, being, consequently converted into operational costs.

In practice NTLs are difficult to calculate, since the real value of TLs is obtained by estimation. The basic method for the estimation of NTLs is performed by calculating the difference between the energy supplied and the energy measured consumed, subtracted the technical losses [12]. These TLs are obtained using power flow studies considering the measured consumptions. An accurate estimation requires a full knowledge of the network, namely the topology and branches' impedances. In addition, the losses in the networks are continuously changing due to the variations of consumption. Thus, it is also required that energy meters present the ability of providing the consumer's load profiles measured at regular periods of the day.

2.2 - Causes and Origins of Non-Technical Losses

NTLs may have several origins and the most referred in the literature is related with the presence of fraudulent consumers, which consume energy without paying for it [13]. This problem is generally observed in Low Voltage (LV) networks where the ability of monitor the consumers' consumption and estimate the conditions of operation of the network is lower than in other voltage levels. The reason behind this fact is associated with the absence of a structure with the ability of providing, in real time, electrical measurements from different locations of the LV network.

The most common techniques used by fraudulent consumers are [13-17]:

- Tampering energy meters in order to read a lower consumption than the real consumption: this may be performed by the interruption of the rotating disk in electromagnetic energy meters or using radio frequency devices to tamper the electronic energy meters;
- Tapping of low voltage wires: illegal connections to the network, mostly in overhead lines;
- Bypassing energy meters: for example, a three phase meter can be adulterated in order to read the consumption of only one phase;
- Grounding the neutral wire of the consumers' premises: by disconnecting the neutral wire from the distribution feeder, and grounding the neutral wire of consumer's load the voltage measured by the energy meter will be zero. Therefore, the energy consumed is not measured.

NTLs may also result from non-detected High Impedance Faults (HIFs) in LV networks, and energy meters' parametrization errors. HIFs are faults which have currents of similar amplitude of the load currents [18] and, therefore, are non-detected by the conventional overcurrent protections such as fuses. The origins of non-detected HIF are mainly related with insulation cable defects (which typically occur in underground networks), or when a primary conductor comes in contact with a quasi-insulating object such as a tree, structure or equipment [19]. At the opposite side, the energy meters' parametrization errors may be a consequence of manufacturing errors, leading consumption measurements to present a significant difference comparing with the real consumption.

The Figure 2.1 summarizes the causes and origins of NTLs.

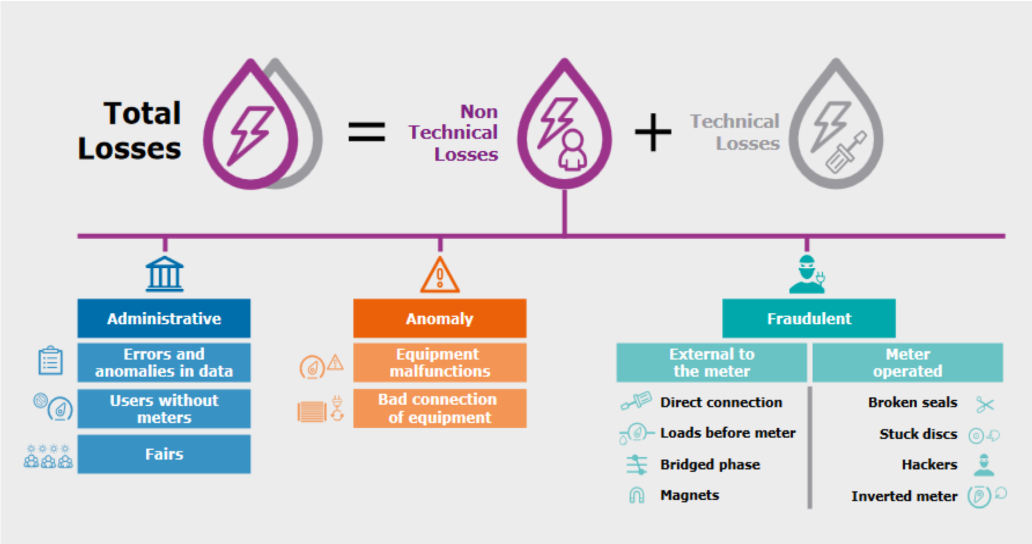

Figure 2.1 - Causes of NTLs in electric power systems [6].

2.3 - Technical and Economic Impacts of NTLs

In Portugal, the regulator for electricity ERSE, is responsible for monitoring and controlling the activity of the utilities present in the value chain of the electrical sector. This regulation is expressed through the Tariff Regulation Mechanism. For example, the DSO is required to accomplish some reference patterns, namely in terms of QoS and in what concerns to value of total losses in distribution networks. The DSO is rewarded or penalized according to the of total losses in the network as expressed in the mechanism of incentive to reduce losses in distribution networks.

2.3.1 Mechanism of Incentive to Reduce Losses in Distribution Networks

The current Regulated Tariff in Portugal [20], establishes an incentive mechanism to reduce losses in distribution networks, in order to stimulate the DSO to take investment decisions in projects with the objective of reducing losses. The investment decisions may be applied for instance in the reinforcement of the lines capacity or in the installation of capacitors banks to reduce the reactive energy in lines. The idea behind this mechanism is increasing the efficiency of the networks operation. Thus, the regulator defines for each year the reference value for the losses. Discounting a threshold, the DSO may have an additional profit for its performance, in case the losses are below of that value. Otherwise, the distribution operator is penalized. The losses are calculated by the difference between the energy delivered by the transmission system to the distribution networks and the consumed energy measured at all the customers’ locations present in the network.

The incentive mechanism is applied based on the difference between the real value of losses and the reference value of the losses, discounting a threshold. Nevertheless, the mechanism limits the maximum and the minimum value of the energy losses taking into account the following parameters:

- Reference value of the losses – P_{ref}
- Value of the unitary losses – V_p
- Maximum variation – ΔP
- Deadband Variation (ΔZ) in which the losses valorisation is not applied

The Figure 2.2 presents the incentive mechanism for losses reduction in distribution networks.

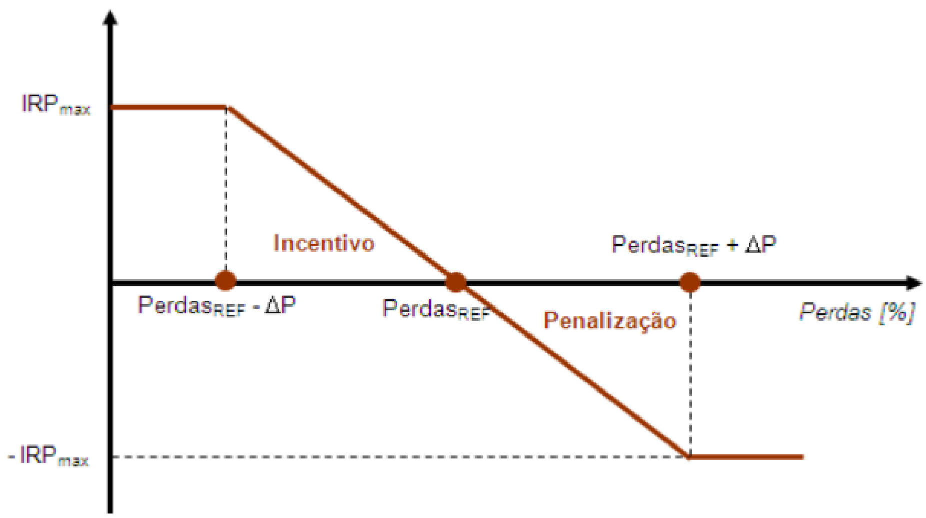

Figure 2.2 - Incentive Mechanism to Reduce Losses

The reference values used for the period between the period of regulation between 2015 and 2017 are presented in the Table 2.1.

Table 2.1 - Reference values for the period between 2015 and 2017

	2015	2016	2017
Lower Limit (P_{REF} - ΔP) (%)	3.10	3.35	3.6
Dead Band's Lower Limit (P_{REF} -ΔZ) (%)	6.10	6.35	6.6
Losses Reference Value (%)	7.8	7.8	7.8
Dead Band's Upper Limit (P_{REF}+ ΔZ) (%)	9.50	9.25	9.0
Upper Limit (P_{REF} + ΔP) (%)	12.5	12.25	12.0

The incentive mechanism to reduce losses in distribution networks ($PP_{URD,\ t-2}$) depends of the losses, P_{t-2}, according to:

When: $P_{t-2} < P_{REF,t-2} - \Delta Z$

$$PP_{URD,t-2} = Min\left\{IRP_{max,t-2}, \left[\left(P_{REF,t-2} - \Delta Z\right) - P_{t-2}\right] \times E^{D}_{t-2} \times V_{p,t-2}\right\} \tag{2.4}$$

When: $P_{t-2} > P_{REF,t-2} + \Delta Z$

$$PP_{URD,t-2} = Max\left\{IRP_{min,t-2}, \left[\left(P_{REF,t-2} + \Delta Z\right) - P_{t-2}\right] \times E^{D}_{t-2} \times V_{p,t-2}\right\} \tag{2.5}$$

When: $P_{REF,\,t-2} - \Delta Z \leq P_{t-2} \leq P_{REF,\,t-2} + \Delta Z$

$$PP_{URD,t-2} = 0 \tag{2.6}$$

Where:

$$IRP_{max,t-2} = -IRP_{min,t-2} = (\Delta\Delta - \Delta Z) \times E^{D}_{t-2} \times V_{p,t-2} \tag{2.7}$$

$PP_{URDj,t-2}$ is the value of the incentive for reducing losses by level of voltage in year t-2

$IRP_{max,t-2}$ is the maximum value of the incentive, in year t-2

$IRP_{max,t-2}$ is the maximum value penalization of the mechanism, in year t-2

$V_{p,t-2}$ is the losses valorisation value in distribution network in year t-2. This value is defined in Euros/kWh by ERSE

$P_{REF,t-2}$ is the losses reference level of the distribution network in year t-2, in percentage

P_{t-2} is the level of losses in year t-2, in percentage

E^{D}_{t-2} is the total energy delivered in distribution networks in year t-2, in kWh

The reference level of losses ($P_{REF,\,t-2}$) is defined for each year of the regulation period as can be seen in Table 2.1. The periods of regulation are generally constituted by 3 years.

2.3.2 Quality of Service

In Portugal the network's operators are compelled by the regulator to accomplish some reference patterns in what concerns to the QoS and the Quality of the Energy (QoE) present in the regulation for the QoS [21]. For example, the QoE is assessed by monitoring the voltage waveform such as the frequency, amplitude (Root Mean Square (RMS) value), and voltage imbalance (between the 3 phases). The criteria used to assess the quality of the energy in distribution networks is expressed through the norm NP EN 50160:2001.

The norm expresses that the voltage in LV networks (Un =230 V) should accomplish the following patterns:

- 95% of the time the average RMS value should be within ±10% of Un;

- All of the average RMS values measured at each 10 minutes should be within +10% and -15% of Un.

NTLs represent additional currents flowing through branches of the entire system. These additional currents increase the TLs and increase voltage drop in branches. Considering the particular case of non-detected HIF, the fault implies additional currents through the lines, that besides the impact on the location of the fault, influences the voltages in all nodes. Therefore, the QoE is deteriorated since the measured voltages may not accomplish the aforementioned quality patterns.

A further impact of the NTLs is related with the system's operation. Since NTLs represent additional loads, thus, increasing the power flows in lines of the distribution and transmission systems, the probability of congestions in the networks increases. The congestions occur when the power flow in the elements present in the networks (e.g. lines and transformers) surpass their thermal capacity. Consequently, the presence of NTLs reduces the reliability of systems [13]. The reliability of the systems decreases since the DSO may be impelled to curtail the loads in order to maintain the safety of supply. In addition, despite the operators may have an estimation of the NTLs, their behaviour over time is difficult to forecast. For instance, the current of an HIF depends on the voltages in the network. These currents will be as higher as the voltages in the network. Therefore, the presence of NTLs makes the system's operation more challenging.

2.3.3 Economic Impacts

Non-Technical Losses represent additional loads for electric power systems and, therefore, their impacts are reflected in the overall system. NTLs increase the energy generated in power plants [7], therefore the need to have backup generation rises in order to maintain the security of supply. As the amount of energy produced in power plants is increased, the price of the energy rises.

The impacts of NTLs for network's operators are related with the increasing of TLs due to the additional energy that flows through the networks. Due to the presence of NTLs, the DSO may be required by the regulator to invest in the reinforcement of the electric system's infrastructures in order to accomplish the patterns concerning the losses in the network and the QoS. Nevertheless, the incentive mechanisms are calculated based on the difference between the energy supply and the energy measured consumed, meaning that NTLs influence directly the value of the total losses. Thus, the DSO may have revenue losses due to the incentive mechanisms. In practice, when the presence of NTLs in networks is observed, the most efficient way for the DSO to have revenue with the incentive mechanisms is through investments that enable the reduction of NTLs.

The NTLs represent an increase of the operational costs, by overloading the power plants and the need to the reinforcement of the system's infrastructures. The increase of the operational costs is charged to costumers through tariffs. Taking into account that NTLs represent energy supplied that is not billed there will be as well revenue losses for the governments due to taxes not charged. The increasing the energy price for the companies that may result from the presence of NTLs reduces their competitiveness as their operational costs increase. This may be particularly relevant for energy intensive industries. Moreover, higher electricity tariffs reduce the economic power of consumers which in turn may affect the economy of the country.

2.4 - Detection and Location of NTLs

The detection and the location of NTLs can be performed using several methods that can be divided in two categories: Artificial Intelligence Methods (AIM), which have been the most widely investigated, are based on customers' load profiles analysis and pattern recognition using data mining techniques; the second approach, Smart Metering Based Method, takes advantage of the existing Smart Meters in LV networks to perform the detection and location of NTLs.

The different methods may be evaluated and compared considering several characteristics:

- The quantitate and the type of costumers' data required;
- The computational effort;
- The type of networks in which they are used and the modelling of the network required;
- The impact on consumers;
- The type of NTLs identified;

2.4.1 AIM Methods

This category of methods extract relevant features from the data of the consumers such as the load profile and the ratio between the average load and the maximum load of the consumer [22]. Based on these features, these methods implement a training algorithm that provides the ability to classify consumers' behaviour.

For example, in [23] is presented a scheme based on Artificial Neural Networks (ANNs), which is used when the exact relationship between the inputs and the outputs is unknown. Specifically, this scheme uses Kohonen networks (see Figure 2.3) that allows the design of an objective way of clustering data.

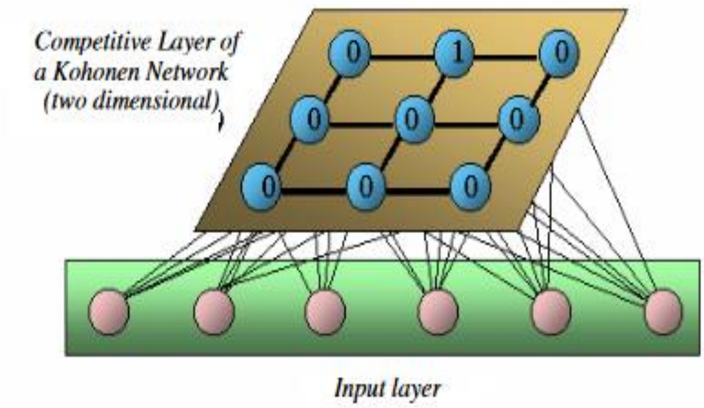

Figure 2.3 - A particular type of neural networks – Kohonen networks [23].

The selection of fraudulent consumers is performed by searching the similarities between the consumption pattern of the records and the consumption patterns of the customers' database.

In [24] the author proposes a 4 class Support Vector Machines (SVM) to learn the behaviour of the electric demand considering four different load profiles. This process of training is performed in order to obtain a Quadratic Programing (QP) problem resulting in the definition of a hyperplane that divides the feature space in two or more labelled classes [25]. Considering a set of values that have similar characteristics, they will be included in a region of the space delimited by a hyperplane, being therefore defined as a specific labelled class. The Figure 2.4 shows a hyperplane that divides the featured space into 2 labelled classes.

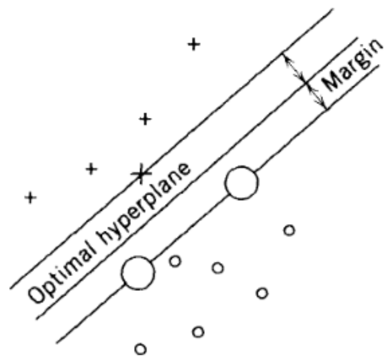

Figure 2.4 - Hyperplane example [25].

Finally, the approach based in an Optimum-Path Forest [22], which uses the graphs theory, has been developed to tackle the problem of slow convergence evidenced by other methods as the SVM approach. The training process is carried out by constructing a complete graph, as represented in Figure 2.5, whose nodes are the samples and the arcs link all nodes [26]. A weighted function is after applied to arcs depending on the distances between the feature vectors of their corresponding nodes. Each class will be created by those nodes, which have arcs with low weights, meaning with similar characteristics.

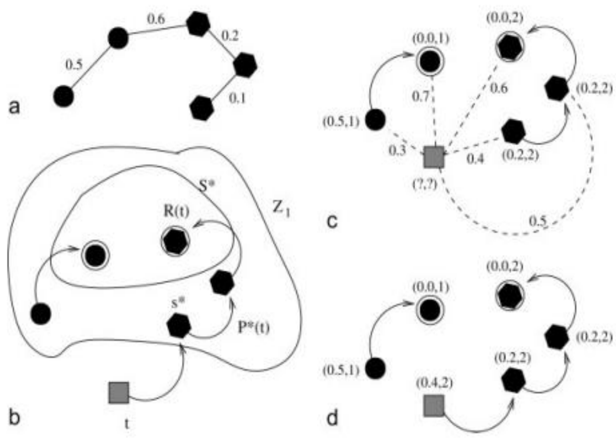

Figure 2.5 - Training process used by OPF [26].

The last step of these methods consists of the process of detection that is performed by comparing the present consumers' loads profiles with the database's profiles used during the process of training, assuming that NTLs are highly correlated with abnormal consumption behaviours.

This class of methods has the main advantage of being applicable in networks with conventional energy meters and/or smart meters. Additionally, these AIM methods only use the information of each specific consumer, being therefore independent of the LV network. However, their ability to detect NTLs may be limited as the historic data may be already affected by the presence of NTLs. In addition, they only are able to detect a part of the causes behind NTLs, related with the presence of fraudulent consumers. As the network is not considered they are not capable of detecting other NTLs such as HIF. A further limitation of these methods results from the need to take into account a large number of consumers which need to be verified individually, leading to a significant computational effort and a slow convergence. These methods are not able to pre-select different suspect locations of the network.

2.4.2 Smart Metering Based Methods

The second category of methods have been developed for detecting and locating NTLs under the presence of an AMI in LV networks. The work in [27] proposes a State Estimation (SE) of the Medium Voltage (MV) network to detect the presence of NTLs or inconsistent data measurements at the secondary side of the distribution transformers. The SE is performed using electrical measures provided by SMs present in each LV network, such as voltages and the power consumption, and the voltage (magnitude and angle) at the MV substation. Figure 2.6 shows the data required by this methodology and the communications infrastructure used.

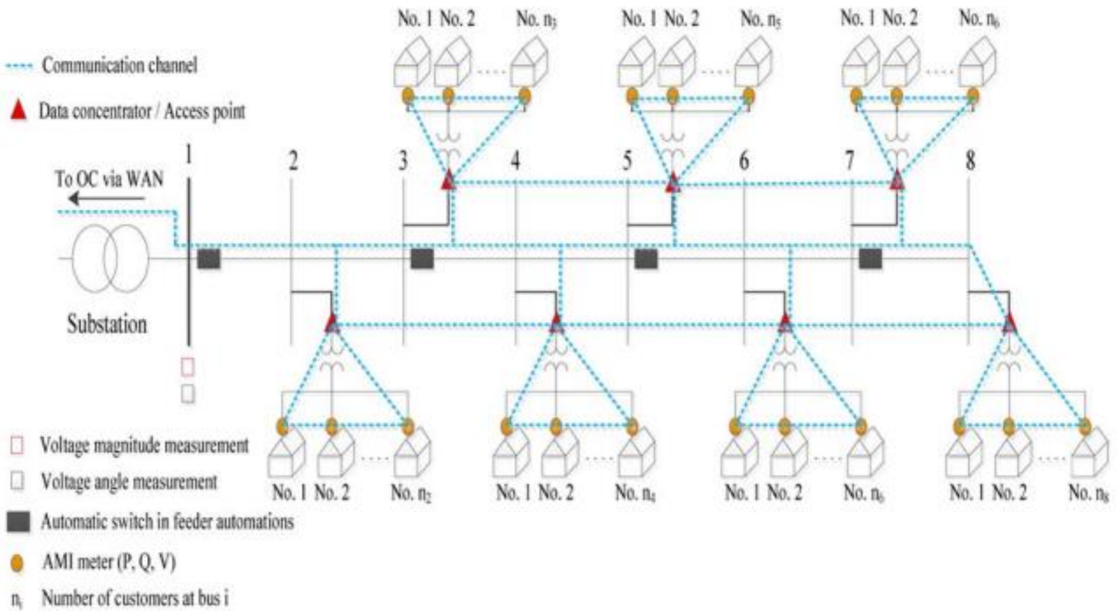

Figure 2.6 – Communications infrastructure and meter data sources [26]

The identification of the LV networks under the presence of NTLs is performed by analysing the difference between the aggregated consumption provided by the SE at each secondary substation with the sum of the SMs' measured consumptions. By contrast, in [16, 17, 28] the advanced methodologies compare the total consumption registered by the clients' meters with the energy supplied through the secondary substation. With the difference of the TLs, the total consumption must match the energy supplied. Whenever this balance does not occur, it is considered the presence of NTLs in the network. These approaches require a full model of the networks to calculate the TLs in the network. In case the technical characteristics of the network, such as the topology and the branches' physical are unknown, the calculation of the TLs is a factor of uncertainty as TLs can only be estimated. The computational effort required may be high in the first approach. The SE is performed through an iterative process that requires the availability of electrical measures from different locations of the network and a full knowledge of the network.

In spite of the location in [27] being carried out based on pattern recognition by implementing the Analysis of Variance (ANOVA) method, in [16] the location of NTLs is identified by the feeders' division into a certain number of segments, where Current Transformers (CTs) are installed. The control centre sends a load shedding command to all SMs and, in case of the presence of NTLs, the CTs will detect them, since there will be current flowing in the branches due to their presence. In order to locate NTLs, this approach requires the interruption of the electricity supply, as well as the investment in the deployment of several sensors. This method is not capable of locating NTLs due to tampered or parametrization errors in the energy meters. Nevertheless, the location can be performed without the knowledge of the network features (e.g. topology). At the opposite side, the work in [28] uses the currents measured by consumers' SMs to calculate the Estimated Voltage Drop (EVD) between the distribution transformer and each costumer. The same process is performed using the voltage measured by SMs (Real Voltage Drop (RVD)). Calculating the difference between the RVD and the EVD, the result will be the voltage drop due to the presence of NTLs. Therefore, the current due to NTLs is obtained dividing by the respective impedance between the distribution transformer and each consumer. The location where the current estimated is high is probably under the presence of NTLs. The accuracy of this approach is quite variable with the number of NTLs and its value since the presence of NTLs affect the voltages in the overall system. This method requires a full network's knowledge. Nevertheless, has the main advantage of being able to identify the different types of NTLs detailed in section 2.2. In addition, the location of NTLs is performed without interrupting the consumers' loads.

Finally, considering a smart grid environment, where the widespread implementation of Demand Response Programs (DRP) is expected to become a reality, the work in [29] advances a technique to locate NTLs based on the use of a performance evaluation method, customer baseline load calculation. This evaluation method is generally used to assess the consumer´s performance after the participation in a DRP. This approach allows the determination of the expected consumption in each period of the consumer historic data. The proposed methodology firstly proceeds to the calculation of the best base-line function (parameters), which better represents the consumption behaviour over the different periods in study. After, some statistical indices, as the Whole Data Average (WDAVG) and Whole Standard Data Deviation (WDSTD), are introduced to evaluate the difference between the actual measured values and the estimated values. Considering that the above-mentioned indices have a higher value to the actual consumption than the estimated consumption the consumer is considered suspect. This approach has the main disadvantage of being influenced by variations in the consumption that are not related with NTLs. It is also not applicable during the demand response programs. The modelling of the network is not performed in this approach, thus, the detection of NTLs is restricted to the presence of fraudulent consumers. In addition, the amount of data required and the computational effort may be high. A further limitation is related with the need to inspect all of the consumers present in the network.

2.5 - Summary

In electric power system the presence of TLs represents a natural occurring phenomenon due to their intrinsic physical characteristics. Nonetheless, there may be present an another type of losses, NTLs, which are due to externals actions to the system. The main causes of these additional losses are related with the presence of fraudulent consumers in the networks, which consume energy that is not billed. Nevertheless, beyond the causes related with fraudulent consumers, NTLs may result from non-detected HIFs and energy meters' parametrization errors. These losses increase the system's operation costs, which are reflected in the price paid by customers through higher tariffs and reduces the revenue of the network's operators that could result from incentive mechanisms.

The detection and location of NTLs represent an effective way to reduce the system's operation costs. Thus, some methodologies have been developed to tackle this challenge. The AIM methods, based on the consumer's pattern recognition, uses the information provided by energy meters to identify abnormal consumption behaviours. The applicability of these methods is directed to networks in which there is a full absence of information about the network's characteristics, thus, the only information available is provided by the energy meters. The smart metering methods, take advantage of the presence of an AMI in the networks to perform the detection and location of NTLs in LV networks. The challenges under the detection and location of NTLs, due to their diversity, require an integrated analysis, i.e., a combination of the information available from customers, provided by SMs, and their interaction with the network. By considering simultaneously this two entities, there is a great potential to fully address the problem of NTLs, since all the types of NTLs will be achievable to be detected and located. In addition, an approach that is capable to leverage the functionalities of the smart metering, reducing the uncertainty in the overall process, reduces the need of on-site inspections and reduces the area under inspection. Moreover, an approach that is capable of handling the lack of a full network knowledge increases the applicability of the detection and location of NTLs to the generality of the LV networks.

Chapter 3

Modelling of Low Voltage Distribution Networks

The majority of the consumers are connected to Low Voltage (LV) networks. Nevertheless, these networks have always been explored in a passive way when compared with other voltage levels. In fact, in LV networks most of the times the Distribution System Operator (DSO), does not have information regarding their operation conditions. This may be justified by the large number of LV networks that may be operated by the DSO which would require a massive investment in the deployment of measurement sensors and communication infrastructures. On the contrary, in other networks such as Medium Voltage (MV) and High Voltage (HV) networks, their monitoring is required in order to ensure a safety supply of the energy and control the impacts of external actions to the systems (e.g. faults) in the assets. Consequently, the DSO redirects its investments to MV and HV networks. The presence of Non-Technical Losses (NTLs) mainly concerns LV networks due to the inexistence of monitoring in these works. Nevertheless, the integration of smart metering in LV networks provides an opportunity to explore and to monitor these networks in an active way since there will be information regarding the electrical variables (e.g. voltages in nodes) from different locations.

The definition and technical description of the modelling approach for LV networks is essential to understand and address the challenge of detecting and locating NTLs. Thus, a detailed literature review of the different configurations, underground and overhead networks, used in LV networks is included. The assumptions that may be used in each configuration to tackle the problem of NTLs are also explained. Additionally, a characterization of the technical functionalities of the smart metering is addressed, explaining the role of the smart meters and the Distribution Transformer Controller (DTC) in the process of detecting and locating NTLs in LV networks.

3.1 - Characterization of Low Voltage Networks

3.1.1 – Particularities of Low Voltages Networks

LV networks ensure the delivery of energy from the secondary substations to the consumers' locations. Despite the majority of the consumers being present in these networks, comparing with other voltage levels, the available information about the technical characteristics of LV networks is scarce. In fact, the DSOs often do not have all the data that characterizes LV networks such as the topology and the physical parameters of lines/cables. One reason behind the inexistence of information is due to the fact that the planning of LV networks is substantially different from the planning at other voltage levels, namely in Transmission Systems (TS) [30]. Additionally, the extension and electric demand of LV networks are continuously being changed due to the connection of new customers. These new connections are typically performed by the utilities technicians without a previous study of the network's operation conditions such as the load imbalance. As consequence, the new single phase customers are randomly connected to the phases. Furthermore, the infrastructure of LV networks may present several decades of lifetime, and, therefore, the absence of digital databases and information systems makes difficult the storage of information [30].

3.1.2 Technical Aspects of Low Voltage Networks

In Portugal, LV networks may be divided in two main categories: the first one, underground networks, which is manly used in urban areas with a large number of habitants (typically>15000), uses underground cables to supply energy to consumers [31]. The second category, overhead networks, is mostly used in rural areas, where overhead lines are most commonly deployed. Overhead networks, due to the slower load densities allows a less expensive cost than underground networks [32].

LV networks typically have a radial configuration, i.e., an arborescent configuration, meaning that each consumer only has one electrical path to be supplied. The Figure 3.1 presents an example of a radial network.

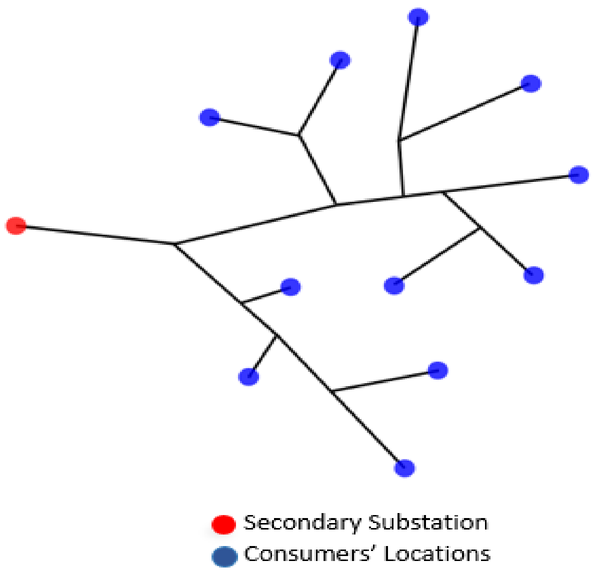

Figure 3.1 – Example of a radial network [33].

The application of the Kirchhoff Currents Laws (KCLs), which demonstrates that the algebraic sum of all currents entering and exiting a node must equal zero [34], allows the direct calculation of the currents in branches. Therefore, this means that the currents in the upstream branches will be the sum of all currents consumed in the downstream busbars.

The application of the KCLs to the simplified network schematic represented in Figure 3.2 is given by the Equation (3.1) and Equation (3.2).

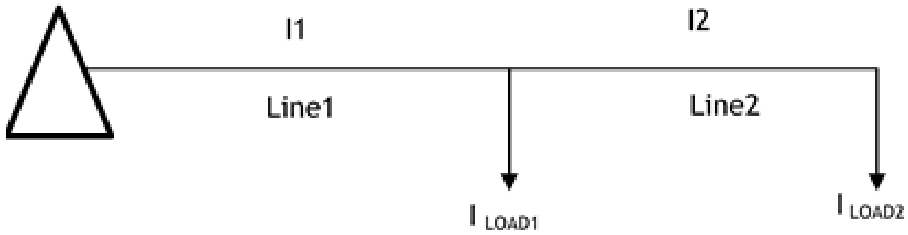

Figure 3.2 – Example of KCL application

$$I_2 = I_{LOAD2} \tag{3.1}$$

$$I_1 = I_{LOAD1} + I_2 \tag{3.2}$$

Where I_2 is the current in line 2, I_1 is the current in line 1, I_{LOAD2} is the current consumed in the end of line 2 and I_{LOAD1} is the current consumed in the end of line 1.

LV networks are typically constituted by 4-wire cables/lines corresponding to a 3-phase system plus neutral wire. This allows the connection of single-phase loads and 3-phase loads simultaneously in the same network. Due to this characteristic, LV networks may be quite unbalanced which may imply high currents flowing through the neutral wire and a high Neutral to Earth Voltage (NEV) in nodes. Nodes represent the connection between the busbar and the phase wire. The NEV depends of the neutral configuration, namely the number of locations where it is grounded. The Safety Regulation for Low Voltage Distribution Networks (RSRDEEBT) [35] establishes the configuration of neutral wire in LV networks.

3.1.2.1 Safety Regulation for Low Voltage Networks

According to the RSRDEEBT, the neutral wire should be grounded in the following locations:

- At the distribution transformer (star connection at the secondary side);
- At every 300 m of line/cable length;
- In singular points of the network, namely derivations from the primary canalization or locations with a high concentrate of loads;

In addition, the equivalent impedance of the neutral wire of the network should be lower than 10 Ω.

The practical application of this regulation has some differences depending of the type of network. In underground networks, due to the high number of clients and, therefore, a high number of ramifications from the phase wires, the neutral wire is grounded in the majority of the consumers' electrical installation. At the opposite side, in overhead lines, the distribution of the consumers alongside the network is sparser and, therefore, the number of locations where the neutral is grounded is lower than in underground networks. These differences influence the currents that flows through the neutral wire and its voltage throughout the LV network.

3.2 - Challenges for the Detection and Location of NTLs in LV Networks

In HV and MV distribution networks, where the widespread of DA is verified, the monitoring of these networks may be performed. In fact, beyond the availability of electrical measures from different locations, the characteristics of the network, such as the topology and the branches' impedances are also known. The combination of the electrical measures with the network's data allows the implementation of State Estimation (SE) and power flow algorithms. SE provides a comprehensive and reliable view of the state of the networks in quasi-real time using the available measurements (e.g. voltages) [36]. At the opposite side, in LV networks, even if the networks characteristics are known, the absence of electrical measures from different locations does not allow the implementation of SE in these networks. Additionally, in LV networks the modelling of complex multi-phase asymmetric distribution, where the representation of the neutral wire is required, represent a challenge for developing an efficient and robust SE algorithm [37]. Consequently, the detection and location of NTLs in LV networks is difficult due to the inability of monitoring these networks.

The deployment of decentralized management systems through smart metering in LV networks, leverages the availability of electrical measures from different locations, such as the load's diagrams of consumers. Thus, the use of power flow studies to assess the operation conditions of the networks may be performed *a posteriori* if the technical characteristics of the network are known. In fact, power flows with the ability of a fully LV network modelling, providing the voltages and the currents in the neutral wire may be found in literature [38, 39]. Therefore, the inexistence of information regarding the characteristics of LV networks is the main challenge for the implementation of NTLs detection and location in these networks. In order to tackle the problem of the lack of network's knowledge, some advanced functionalities have been developed, leveraging the presence of smart metering in these networks. One of these functionalities, which may play an important role in the recognition of the LV characteristics, is the automatic feeder mapping / phase identification of loads [40]. This may be performed through the use of Power Line Communications (PLC) in LV networks. In G3 PLC protocol, it consists in choosing the optimal relay nodes (meter or Data Concentrator (DC)) to propagate data packets addressed to a specific destination node [41]. The representation of the network topology may be performed since the information sent can be retrieved from every node of the network as shown in Figure 3.3.

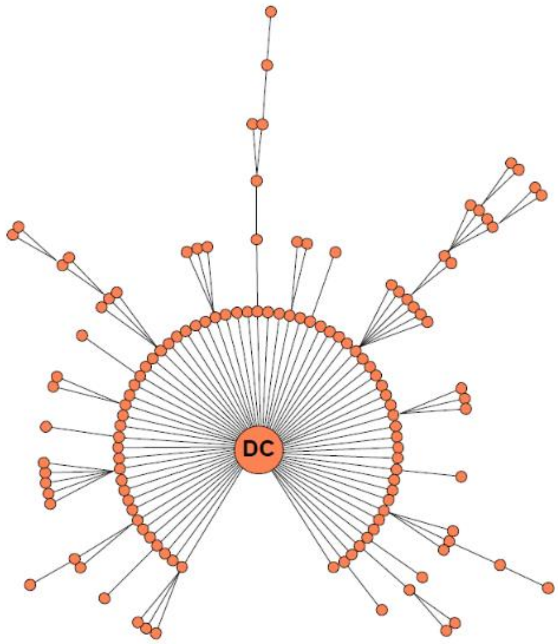

Figure 3.3 - Topology recognition using G3 PLC [41].

The integration of Distributed Energy Resources (DER) in LV networks poses many challenges for the detection and location of NTLs. DER introduces bidirectional power flows and causes disturbances in the voltages profiles throughout the network [42]. In fact, with DER the voltages in busbars may rise and lead to violations of the operational limits. An additional problem caused by the integration of DER is related with the load balancing between phases [43]. The unbalanced phase loading may lead to an increase in the neutral current and an increase of voltage unbalance, even in the case that the total phase current decreases. Under such conditions, the uncertainty regarding the presence of NTLs in LV networks may augment since the patterns of consumption and the behaviour of the electrical variables are directly influenced by the energy produced by DER.

3.3 - Smart Meters and Distribution Transformer Controller

Smart metering systems represent the next-generation of power measurement devices, that have several advanced features [44]. These advanced features comprise sophisticated measurement data and communication capabilities. A combination of the communication capabilities with the integration of advanced computing enables the enhancement of the networks' reliability. In fact, the transition to networks where an AMI is implemented brings great benefits to the operation of LV networks. The DSO and customers may have information regarding the energy consumed measured at regular periods (e.g. hourly or 15 minutes' periods. Thus, an improved management of the energy can be performed, increasing the systems' efficiency and reducing the operational costs. Nevertheless, the SMs provide other electrical measures beyond the energy consumption, namely the voltage at the consumer's energy point of delivery. On the contrary of the use of conventional energy meters which only have been designed for energy billing purposes, the SMs allow a real monitoring of the LV networks. The observability of the LV networks becomes possible which otherwise would require a massive investment in measurement equipment such as CTs, Voltage Transformers (VTs) to perform the monitoring of these networks.

The Figure 3.4 presents an example of a single and three-phase smart meter.

Figure 3.4 - Smart Meter Example.

The Table 3.1 shows the general features of the SMs present in the market.

Table 3.1 - Technical Characteristics of SMs.

General Features	Single Phase SMs	Poly Phase SMs
Voltage	220(-20%) – 230(+15%)	3x230 V/400 V (±20%)
Active Energy	Class 1 or 2 per EN IEC 62053-21	
Reactive Energy	Class 2 or 3 per EN IEC 62053-23, 4 quadrants	
Instantaneous Values	Current, Voltage, Power, Power Factor, Frequency	
Communications	PLC/ GPRS	

As can be seen in Table 3.1, SMs have the ability of providing instantaneous electrical measures. Generally, these measures are obtained at regular periods of fifteen minutes and are sent once a day to a database that can be managed by the DTC. In practice, the DSO will have access to a several snapshots of the system's electrical variables taken during the day.

The type of communications used may provide additional information about the consumers. For example, when the SMs use Power Line Communications (PLC) the phase to which the consumer is connected is available [41]. When General Packet Radio Service (GPRS) communications are used only the GPS coordinate of each consumer is available.

The DTC installed at the secondary substation interacts with SMs providing meter data management as well as electrical measures of each phase. The DTC will be the gateway between the SMs and the central system such as LV SCADA Systems present in high levels of the Advanced Metering Infrastructure (AMI) hierarchy. In the Figure 3.5 is shown a DTC equipment.

Figure 3.5 - Example of a DTC [45].

The DTC may also provide several electrical measures such as:

- Metering (3-phase active and reactive energy) for the LV side of the Distribution Transformer
- Voltage
- Current
- Power (3-phase active and reactive)
- Power Factor

3.4 - Power flow in Low Voltage Networks

The use of power flow studies is required in order to simulate the real networks' behaviour, since the information provided by SMs may be used to evaluate the operation conditions of the networks. Therefore, depending on the type of networks, namely the neutral configuration, the adopted power flow method may have different characteristics.

Most of the traditional power flow approaches merge the neutral wire into the phases using the Kron's reduction [38]. Such approximation may not be desirable when neutral wire and grounding effects need to be assessed [38, 39]. Thus, when the knowledge of NEV in nodes is required a complete model of the network should be used. Otherwise, the power flows studies may be performed by the Kron's reduction.

The power flows simulations using a complete model of the network require a full knowledge of the locations where the neutral is grounded and both impedances of phases and neutral wires. Figure 3.6 shows the line model when the neutral is considered explicitly modelled and considering the earth as a perfect conductor.

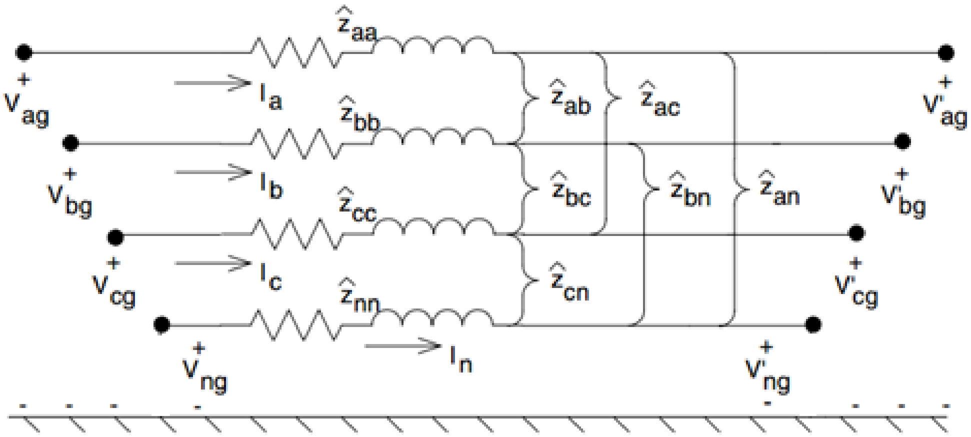

Figure 3.6 - Complete LV line model [46].

The Equation (3.3) represents the matrix approach to calculate the electrical variables of the model presented in the Figure 3.6.

$$\begin{bmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \\ V_{ng} \end{bmatrix} = \begin{bmatrix} V'_{ag} \\ V'_{bg} \\ V'_{cg} \\ V'_{ng} \end{bmatrix} + \begin{bmatrix} \hat{Z}_{aa} & \hat{Z}_{ab} & \hat{Z}_{ac} & \hat{Z}_{an} \\ \hat{Z}_{ba} & \hat{Z}_{bb} & \hat{Z}_{bc} & \hat{Z}_{bn} \\ \hat{Z}_{ca} & \hat{Z}_{cb} & \hat{Z}_{cc} & \hat{Z}_{cn} \\ \hat{Z}_{na} & \hat{Z}_{nb} & \hat{Z}_{nc} & \hat{Z}_{nn} \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_n \end{bmatrix} \tag{3.3}$$

In order to simplify the notation used, the Equation (3.3) may be rewritten by grouping the similar matrix as shown in the Equation (3.4).

$$\begin{bmatrix} [V_{abc}] \\ [V_{ng}] \end{bmatrix} = \begin{bmatrix} [V'_{abc}] \\ [V'_{ng}] \end{bmatrix} + \begin{bmatrix} [Z_{ij}] & [Z_{in}] \\ [Z_{nj}] & [Z_{nn}] \end{bmatrix} \cdot \begin{bmatrix} [I_{abc}] \\ [I_n] \end{bmatrix} \tag{3.4}$$

Where:

$[V_{abc}]$ is the phase voltages' vector in the emission busbar referred to the ground

$[V'_{abc}]$ is the phase voltages' vector in the emission busbar referred to the ground

$[V_{ng}]$ is the neutral voltages' vector in the emission busbar referred to the ground

$[V'_{ng}]$ is the neutral voltages' vector in the emission busbar referred to the ground

$[I_{abc}]$ is the phase currents' vector referred to the ground

$[I_n]$ is the neutral current

$[Z_{ij}]$ is the matrix impedance between the conductors i and j

$[Z_{in}]$ is the matrix impedance between the conductors i and n

$[z_{nj}]$ is the matrix impedance between the conductors j and n

$[Z_{nn}]$ is the self-matrix impedance the conductors n

At the opposite side, the Kron's reduction by considering a multi-grounded system and the NEV at the ground's potential, merges the neutral effects to the phase wires. This is accomplished by considering that at both nodes of the line, the neutral is grounded, therefore the NEV at both nodes is zero. Applying the Kirchhoff's Voltage Law (KVL) to the circuit and taking into account that the neutral is grounded and, thus, the voltages vector $[V_{ng}]$ and $[V'_{ng}]$ are equal to zero, results:

$$[V_{abc}] = [V'_{abc}] + [\hat{Z}_{ij}] \cdot [I_{abc}] + [\hat{Z}_{in}] \cdot [I_n] \tag{3.5}$$

$$[0] = [0] + [\hat{Z}_{ij}] \cdot [I_{abc}] + [\hat{Z}_{nn}] \cdot [In] \tag{3.6}$$

Solving the Equation (3.6) in relation to [In], the result is expressed in Equation (3.7):

$$[I_n] = -[\hat{Z}_{nn}]^{-1} \cdot [\hat{Z}_{nj}] \cdot [I_{abc}] \tag{3.7}$$

Replacing Equation (3.7) into Equation (3.5):

$$[V_{abc}] = [V'_{abc}] + \left([\hat{Z}_{ij}] - [\hat{Z}_{in}] \cdot [\hat{Z}_{nn}]^{-1} \cdot [\hat{Z}_{nj}]\right) \cdot [I_{abc}] \tag{3.8}$$

$$[V_{abc}] = [V'_{abc}] + [\hat{Z}_{abc}] \cdot [I_{abc}] \tag{3.9}$$

Where:

$$[Z_{abc}] = [\hat{Z}_{ij}] - [\hat{Z}_{in}] \cdot [\hat{Z}_{nn}]^{-1} \cdot [\hat{Z}_{nj}] \tag{3.10}$$

The resultant matrix impedance is expressed in Equation (3.11). As can be observed, the initial matrix with dimensions 4 x 4 has been reduced into a 3 x 3 matrix. This is similar to solving a power flow ignoring the neutral wire, with the difference that lines' impedances have been modified to represent the neutral effects.

$$Z_{abc} = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ab} & Z_{bb} & Z_{bc} \\ Z_{ac} & Zbc & Z_{cc} \end{bmatrix} \tag{3.11}$$

With the kron's reduction the final model of the line is shown in Figure 3.7.

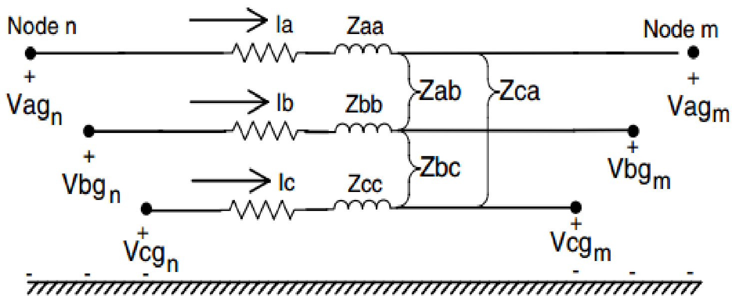

Figure 3.7 - Line model after Kron's reduction [46].

3.5 - Estimation of Branches Currents in LV Networks

As a consequence of the distributed automation deployment in LV networks and the implementation of an AMI there will be available electrical measures such as voltages in busbars to which customers are connected. This allows an improvement in the systems observability and enables the development of new approaches to estimate the operation conditions of LV networks, such as the currents in branches.

3.5.1 Current Estimation in Branches

In LV networks the resistance of wires is typically much higher than the reactance (R>>X) [30], mainly in overhead lines. The voltage drop in lines is given by Equation (3.12)

$$\Delta V = R \times I \times cos(\varphi) + jX \times I \times sen(\varphi) \tag{3.12}$$

Where R is the resistance of the line, X is the reactance, I is the current in the line and φ is the angle between the voltage and the current.

As the reactance is much lower than the resistance the second term of the Equation (3.12) may be neglected and, thus, the voltage drop in lines is nearly in phase with the current that flows through them.

Depending on the network configuration, namely the disposition of the neutral wire throughout the network and the load imbalance, the NEV may have a high impact in voltages nodes and, therefore, in the calculation of the estimated currents.

The residual currents that flows through neutral wire are calculated by a vector sum of the currents consumed in each busbar as shown in Figure 3.8.

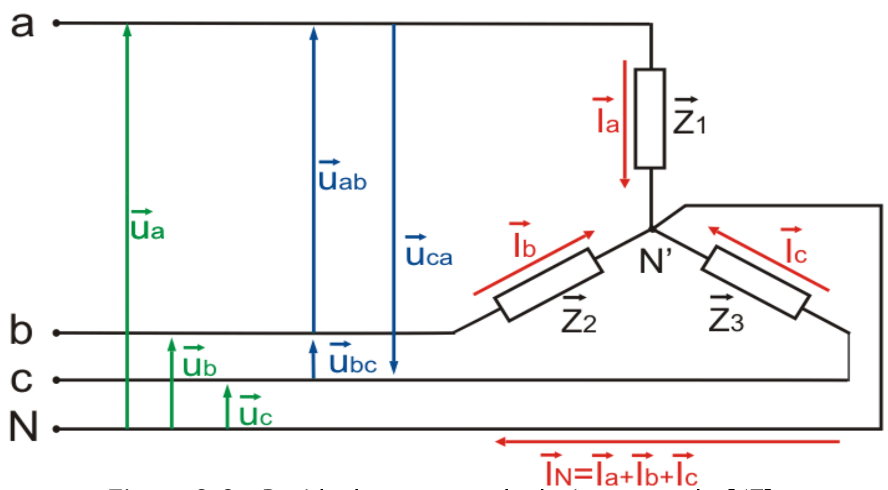

Figure 3.8 - Residual currents calculation example [47].

According to the aforementioned assumption, a distinction may be performed in order to define the impact of the NEV in voltages. On one hand, when the neutral is single grounded (generally at the secondary substation) or multi-grounded, and the load imbalance is quite notorious in the network, the NEV is not negligible [48]. On the other hand, when the load is almost balanced, the NEV may be neglected. The first scenario is mostly related to overhead lines while the second scenario is related to underground networks.

Figure 3.9 represents a 3-phase 4-wire line model, that may be used to estimate branches' currents, based on the voltage in nodes.

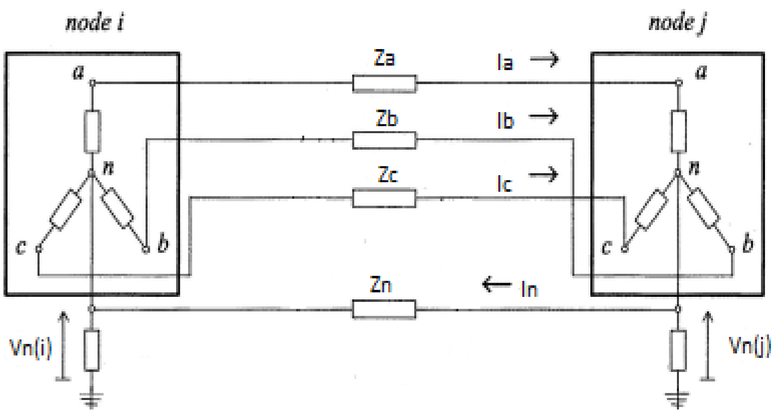

Figure 3.9 - Model of a three-phase 4-wire line (adapted from [49]).

Scenario in multi-grounded LV networks - NEV Negligible:

When the NEV is nearly or equal to zero:

$$V_n(i) \cong V_n(j) \cong 0V \tag{3.13}$$

An estimation of the real currents in branches, exemplifying for the phase a, is given by the Equation (3.14).

$$I_a = \frac{\vec{V}_{an}(i) - \vec{V}_{an}(j)}{Z_a} \tag{3.14}$$

Where $V_n(i)$ is the NEV at node i, $V_n(j)$ is the NEV at node j, I_a is the current in phase a, Z_a is the impedance line, $V_{an}(i)$ and $V_{an}(j)$ are the phase to neutral voltages at nodes i and j respectively.

NEV Non-Negligible:

Since the NEV is not neglected, Equation (3.15):

$$V_n(i) \neq V_n(j) \neq 0V \tag{3.15}$$

The phase to ground voltages, Vag(i) and Vag(j), at the nodes i and j respectively are given by:

$$V_{ag}(i) = \vec{V}_{an}(i) + \vec{V}_n(i) \tag{3.16}$$

$$V_{ag}(j) = \vec{V}_{an}(j) + \vec{V}_n(j) \tag{3.17}$$

Equation (3.16) and Equation (3.17) enable the estimation of the voltage drop in the phase a of the line, due to the real current that flows through it.

The estimation of the branches' currents is, therefore, performed using the Equation (3.18).

$$I_a = \frac{V_{ag}(i) - V_{ag}(j)}{Z_a} \tag{3.18}$$

In addition, the currents cannot be obtained using power flow studies since the only available information is the voltages in nodes, which cannot be used as input to solve the power flow. In fact, power flow studies have as main input the consumers' loads, which are unknown when the presence of NTLs in networks is observed.

SMs do not provide phase to ground voltages' measurements, since they are connected between the phase and the neutral wires, which means that the impact of NEV in voltages needs to be calculated using the Equation (3.16) and Equation (3.17). In addition, SMs do not provide the voltage angle in each node. Thus, the only approach to have an estimation of the phase to ground voltages is solving a power flow. Since the real loads are unknown due to the presence of NTLs, the phase to ground neutral voltages are obtained considering as input the measured consumptions by SMs.

3.6 - Summary

Chapter 3 presents an overview of the LV networks characteristics, explaining the difference of these networks comparing with other voltage levels in order to understand the challenges of the detection and location of NTLs is these networks. In fact, most of the times the technical characteristic of these networks are unknown in what concerns to their structure such as the per phase consumers and the physical parameters of the branches. The absence of information about the network represents, therefore, the main challenge to perform the detection and location of NTLs. Thus, in section 3.2 the main components of the AMI are described, being the technical features of SMs and DTC explained, focusing on their advantages in the system management.

Despite the presence of smart metering in the network, the monitoring of these networks is difficult to accomplish through the use of SE since the modelling of LV networks is complex due to their intrinsic characteristics such as three-phase plus neutral wire lines. In addition, with the presence of NTLs, the real loads are unknown, which makes difficult the estimation of the real currents in branches.

In section 3.5 an approach to estimate de real branches currents, based on the voltages measured by SMs has been presented. This approach is based on the assumptions that the voltages angles in nodes show a small variation throughout the network since the resistance in LV networks is typically much higher than the resistance. Thus, the estimation of the currents may be performed only considering the voltage modules in nodes when the NEV in nodes is negligible. When the NEV in nodes is not negligible, it is required an estimation of the equivalent phase to ground voltages to calculate the real branches' currents. The phase to ground voltages are obtained through the use of power flow studies. Since the knowledge of the NEV in nodes is required to estimate the phase to ground voltages a full network model needs to be considered

Chapter 4

NTLs Detection and Location in Low Voltage Networks

The relevance of Non-Technical Losses (NTLs) detection and location in distribution networks has been introduced in Section 1.2. The development of schemes to address the NTLs problem in distribution networks provides an effective way to increase the system's efficiency, by reducing the Technical Losses (TLs) and the energy produced in power plants. This enables a reduction of the operational costs and decreases the need of new investments in system's infrastructures. The strategies to detect and locate NTLs have been addressed in Section 2.4. The problem of NTLs occurs majority in Low Voltage (LV) networks, due to the amount of clients present in these networks. Additionally, the absence of monitoring capacity of LV networks is a drawback, since the real conditions of operation are unknown. Thus, Chapter 3 presents a characterization of LV networks, exposing their particularities that may be used to address the challenge of NTLs. The advanced methodology, detailed in this Chapter, aims to provide a tool that enables the detection and location of NTLs systematically. This is accomplished using the SMs' ability to provide electrical measures from different locations of the network. Section 4.1 exposes the proceedings of the NTLs detection and the Section 4.2 includes the steps for their location.

4.1 - Methodology Description: Detection of NTLs

The present section describes the methodology developed to detect NTLs. The detection is performed for each LV network. Considering a Medium Voltage (MV) distribution network, to which are connected several LV networks, the methodology uses the available information regarding SMs' measurements of clients and measurements at the secondary substation to perform the detection in each one individually. This allows the implementation of the advanced methodology in a LV management system or even at the Distribution Transformer Controller (DTC). The main proceeding of the detection algorithm is performed by comparing the currents measured at the DTC with the sum of the measured currents by SMs. The Figure 4.1 shows the methodology flowchart.

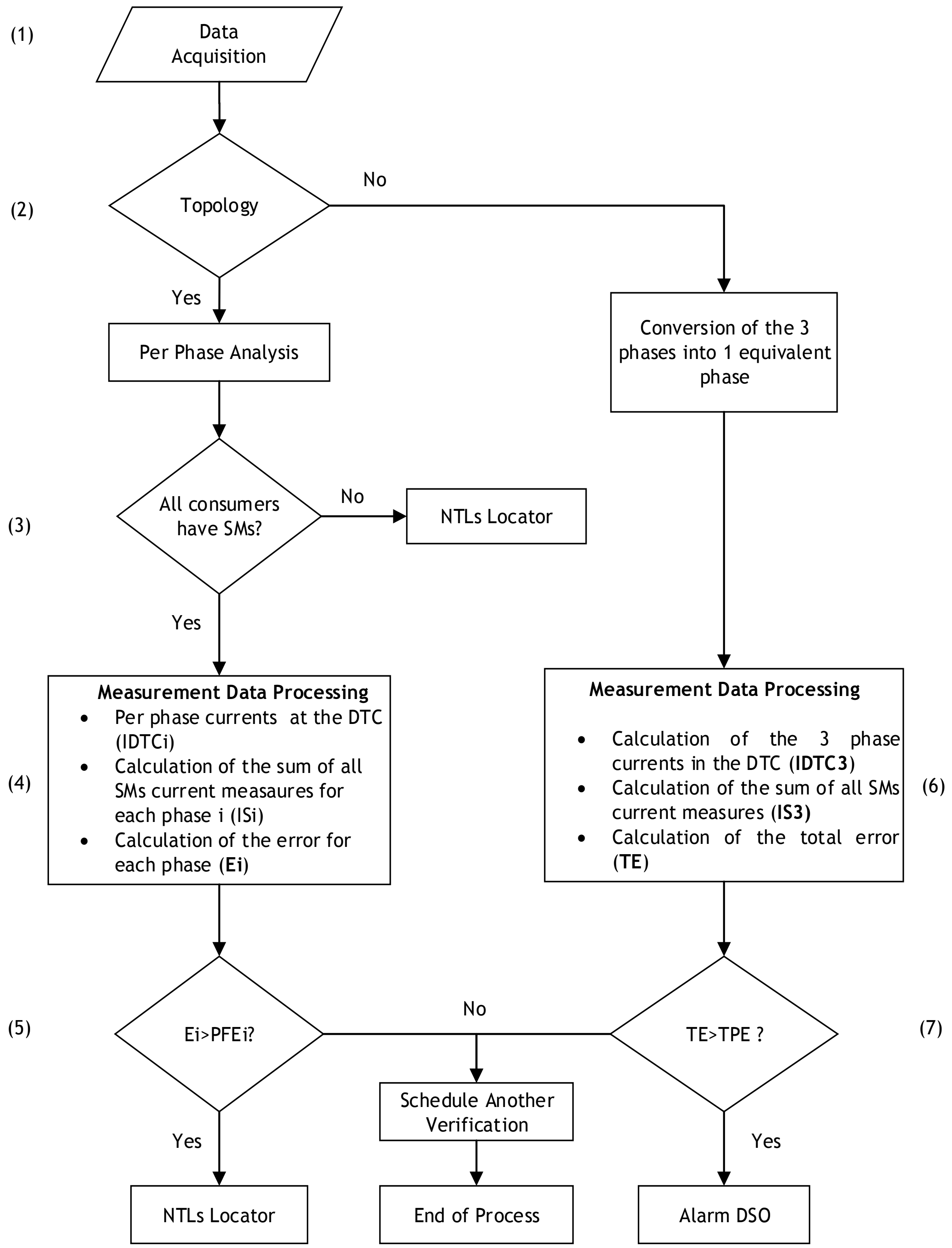

Figure 4.1 - Methodology Flowchart for detection of NTLs

4.1.1 Data Acquisition – Step (1)

The first algorithmic stage, detection of NTLs, starts with the acquisition of the historical records. The records required comprise the SMs' currents, the respective power factors and the per phase currents measured by the DTC at the secondary substation. Since miscommunications between the SMs and the DTC may occur, during their operation, the periods in which all of the measures from all SMs are not available will be excluded. The amount of data required for the methodology may be variable. In practice one snapshot of the SMs' electrical measures would be sufficient. Nevertheless, the certainty of the NTLs presence in the network may be increased using a higher number of measures at different instants of the day (e.g. hourly or 15 minutes' periods).

The process of NTLs detection is based on the assumption that the voltages' angles in nodes is nearly the same in the entire network. As a consequence, the detection of NTLs has an associated error that needs to be estimated. This error is used as a threshold to decide about the presence of NTLs in the network. When the consumers of each phase are known a Per Phase Error (PFE) is used. In case the phase of each customer is not available, a Three-Phase Error (TPE) is used. The PFE and the TPE are calculated a priori by performing power flow studies, without the presence of NTLs. The rationale behind the estimation of these errors without the presence of NTLs is to assess the margin of error that should be used to ensure that the methodology has a low value of false positive rate (detection of NTLs when they are not present). In case of being known the topology and the branches' impedances of the network, only the PFE is estimated using the real loads profiles as input to the power flow study. Otherwise, an average margin of error is considered to the TPE, by simulating power flows in other known networks with similar characteristics, i.e., with a similar number of clients and with a similar topology. These margins of errors are estimated applying the methodology of detection to the results provided by the power flow. Thus, the PFE_i for each phase i is calculated using the Equation (4.1) and the TPE is given by Equation (4.2).

$$PFE_i = \frac{ISS_i - ITL_i}{ISS_i} \times 100 \ (\%) \tag{4.1}$$

$$TPE_i = \frac{ISS_3 - ITL_3}{ISS_3} \times 100 \ (\%) \tag{4.2}$$

Where ISS_i is the current of each phase i in the secondary substation, ITL_i is the sum of the load currents of the phase i, ISS_3 is the sum of the 3 currents at the secondary substation and ITL_3 is the sum of all load currents present in the network.

In practice, the PFE and TPE obtained may be increased for instance in 30%, to reduce the probability of the detection of NTLs when they are not present in the network due to the variation in the consumption.

4.1.2 Definition of the Analysis – Step (2)

As detailed in section 3.1 the DSO most of the times does not have the data that characterizes the network. Therefore, depending on the available information, the methodology performs a distinct analysis. When the topology is available, i.e., the per phase consumers, a Per Phase Analysis is carried out. Otherwise, there is a Conversion of the 3 Phases into 1 Equivalent Phase which, regardless of the phase of the measured currents, is converted into a single phase current. This current correspond to an aggregated current of the overall network.

4.1.3 Per Phase Analysis

Despite the advanced methodology has been designed to networks where the deployment of the SMs cover all the clients present in the network, situations may occur in which some customers are still using conventional energy meters. In these situations, the detection cannot be performed since the information of all SMs measurements is required. Consequently, the process of detection is finished and the process of location – NTLs locator is carried out, without a previous phase of detection, step (3).

In step (4), since the topology is available, the current of each phase i at the DTC, $IDTC_i$, may be used directly in step (5). In addition is performed the sum of all measured currents by SMs for each phase, given by the Equation (4.3):

$$IS_i = ABS(\sum_{j=1}^{N} I_{SMj} \times (cos(\varphi_j) + jsen(\varphi_j))) \tag{4.3}$$

Where IS_i is the sum of currents for each phase i, N is the total number of SMs present in the phase i, I_{SMj} is the measured current by the SM j and φ_j is the angle between the voltage and the current measured by the SM j. The angle φ_j is obtained from the power factor of each load. In fact, the term $cos(\varphi_j)$ in Equation (4.3) is the power factor (pf) of the load j, which is measured by SMs. Thus the angle φ_j is obtained by:

$$pf_j = cos(\varphi_j) \tag{4.4}$$

$$\varphi_j = ar\,cos(pf_i) \tag{4.5}$$

In LV networks Distributed Energy Resources (DER), such as microgeneration, may be present, allowing the injection of currents in the network. These currents need to be considered since their presence influence the balance between the currents supplied by the secondary substation and the currents measured in the SM of each costumer. Therefore, it is considered that the currents measured by SMs have reflected the presence of microgeneration in their value. If a consumer is injecting power into the network, the SMs will read a negative current.

In step (5) the error E_i between the current measured $IDTC_i$ for each phase and the summed current IS_i is calculated in percentage of the per phase DTC current using the Equation (4.6).

$$E_i = \frac{|IDTC_i - IS_i|}{IDTC_i} \times 100 \ (\%) \tag{4.6}$$

Whenever E_i is higher than the PFE_i, the methodology considers the existence of NTLs. Therefore, the process of location – NTLs locator is carried out. Otherwise, another verification is scheduled and the process of detection is finished.

4.1.4 Conversion of the 3 phase into 1 phase

Since per phase consumers are unknown, the methodology does not have the ability to perform the detection of NTLs for each phase individually. Consequently, the DSO will only have the information regarding the presence of the NTLs in the LV network. Depending on the estimated value of the NTLs (difference between $IDTC_3$ and IS_3), the DSO may decide if the cost of the on-site inspections of the network is covered by the revenue obtained due to the location of the NTLs.

In step (6), the currents at each phase of the DTC are summed using the Equation (4.7).

$$IDTC_3 = \sum_{i=1}^{3} IDTC_i \tag{4.7}$$

Where $IDTC_3$ is the summed current of the 3 phases. It is also performed the sum of all measured currents by SMs present in the network, given by Equation (4.8).

Despite the currents of each phase being out of phase by approximately 120° between them, the Equation (4.8) convert them into one quadrant as shown in Figure 4.2.

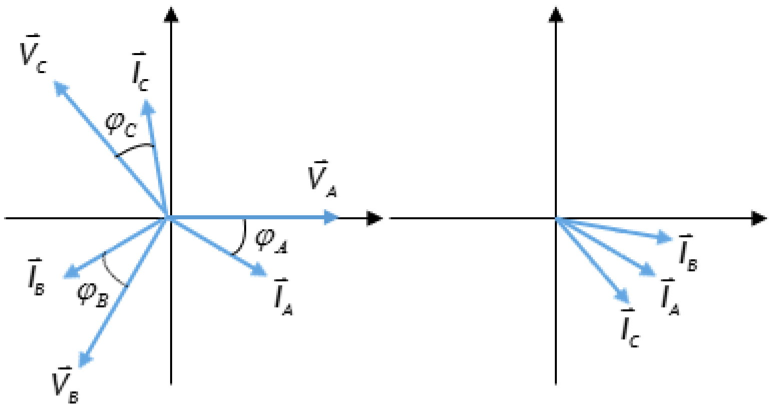

Figure 4.2 - Conversion of the 3 phases into 1 phase

$$IS_3 = ABS(\sum_{k=1}^{L} I_{SM\,k} \times (cos(\varphi_k) + jsen(\varphi_k))) \tag{4.8}$$

Where IS_3 is the summed current of the L SMs present in the network, I_{SMk} is the current measured by SM k and φ_k is the angle between the voltage and the current measured by the SM k.

The following step, step (7), is similar to the performed in step (5). The TE is obtained by calculating the difference between the summed currents at the DTC with the sum of all SMs' measurements, in percentage of the summed currents at the DTC as shown in Equation (4.9).

$$TE = \frac{|IDTC_3 - IS_3|}{IDTC_3} \times 100\ (\%) \tag{4.9}$$

In step (7) if TE is higher than the TPE an alarm is sent to DSO since the absence of the network's topology does not allow the location of NTLs. Additionally, if the presence of NTLs has not been detected a new verification is scheduled and the process is finished.

4.2 - Methodology Description: Location of NTLs

The flowchart of the second algorithmic stage that allows the location of NTLs is presented in Figure 4.4. This process is performed for the phases that have been identified with the presence of NTLs in the first algorithmic stage (detection). The process of location is also performed for the phases in which the SMs does not cover all the consumers.

The process of location could be carried out without a previous process of detection. Nevertheless, the process would be slower since the entire network should be verified even without the presence of NTLs.

4.2.1 Acquisition of the Network Model

The NTLs Locator begins with the acquisition of the network's model, step (1). The modelling comprises the following features:

- Topology of the LV network including the per phase consumers and their location alongside the network;
- Physical parameters of lines (impedances), including phase and neutral, if available;
- Number of connections and the locations where neutral wire is grounded, if available;
- Load imbalance survey and assessment of Neutral to Earth Voltage (NEV) in nodes;

The process of location requires not only the knowledge of the per phase consumers as well as their distribution throughout the network. The consumption of each one is addressed to a respective busbar. It is also considered that the voltage drop between the busbar to which the customer is connected and its SM is negligible as shown in Figure 4.3.

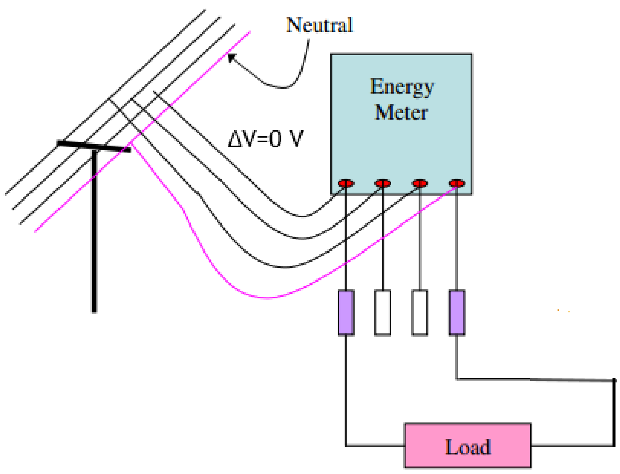

Figure 4.3 – Representation of the consumer connection to the network (adapted from [17]).

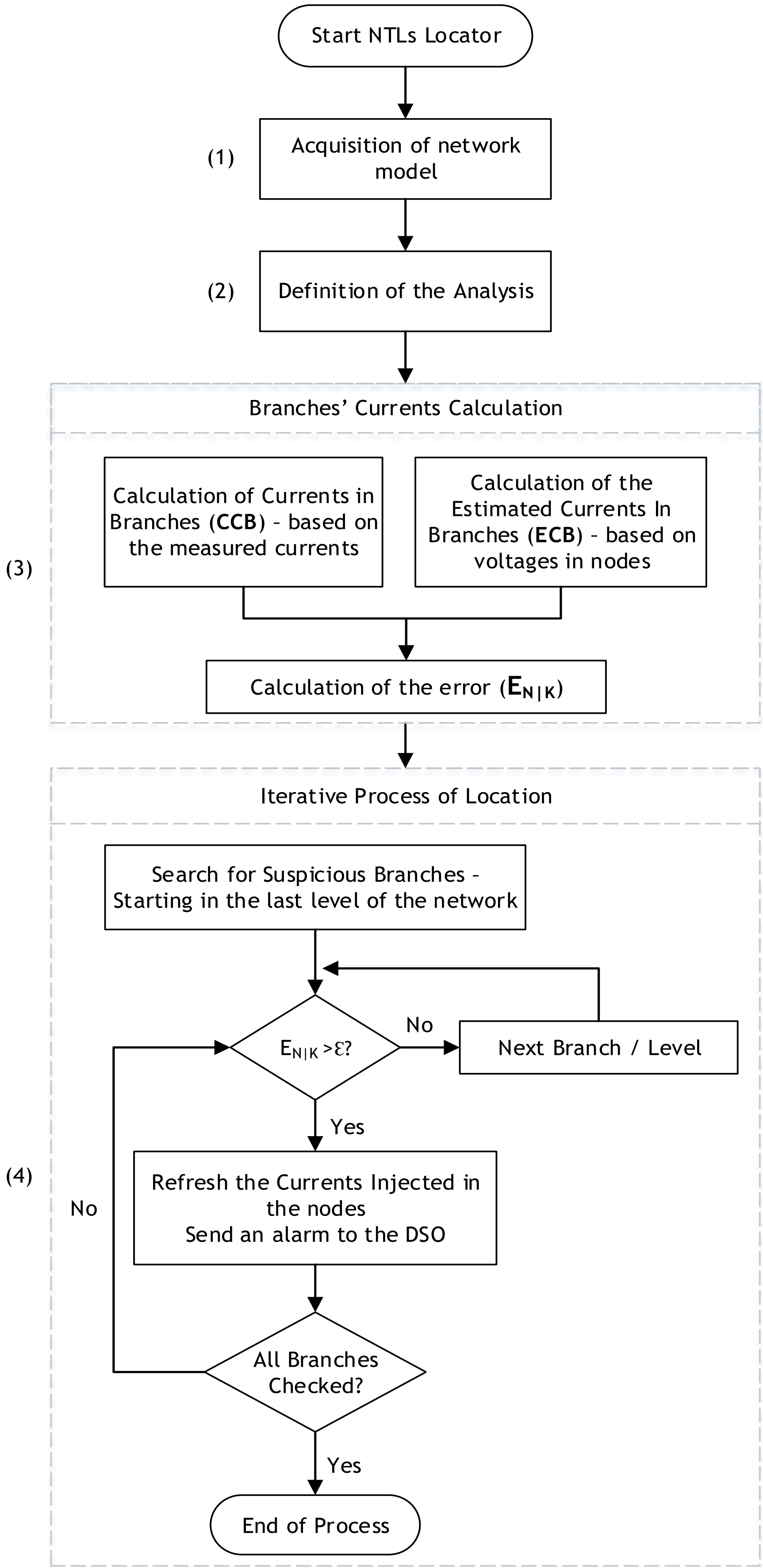

Figure 4.4 - Flowchart of the NTLs location.

As have been exposed in Chapter 3, section 3.5, the NEV in nodes may have a high impact in voltages' nodes and therefore in the estimation of the currents in branches. Since the real loads are unknown the calculation of NEV in nodes is an estimation of the real value. Therefore, the estimated currents may have an associated error. Consequently, a margin of error needs to be defined as threshold to decide when a branch/busbar is under the presence of NTLs. This margin of error will be influenced by the configuration of the network, namely the disposition of the neutral wire and the load imbalance present in the network. The criteria used to the acceptable margin of error depends on the type of the network: in networks where the NEVs are neglected, the margin of error considered (in amperes) is given by 50% of the lowest current measured consumed in the network. This margin of error is used to reduce the false positives due to errors in the estimation of the branches currents. In networks where the NEVs are non-negligible, the margin of error is given by the lowest current measured. This margin of error is higher since the presence of NEV introduces a higher uncertainty in the estimation of the branches' currents.

4.2.2 Definition of the analysis

According to the information obtained in step (1), when the physical parameters of lines/cables are unavailable, there is the need to obtain the branches' impedances by estimation using historic records. The impedance estimation needs to be performed using data that has been considered without the presence of NTLs in the process of detection.

The impedances of each branch Z_k, that connect the busbars i and j, is given by the Equation (4.10).

$$Z_k = \frac{V_i - V_j}{I_{ij}} \tag{4.10}$$

Where V_i and V_j is voltage in busbar i and j respectively. I_{ij} is the current that flows from thw busbar i to the busbar j.

When the impedances are estimated the representation of the neutral wire cannot be explicitly modelled. Thus the estimation of currents in branches is performed using the Equation (3.14) regardless the impact of the NEV in nodes' voltages. Actually these impedances take into account the effects of the neutral wire in voltages. The Figure 4.5 represent a typical situation of unbalanced loads in a network.

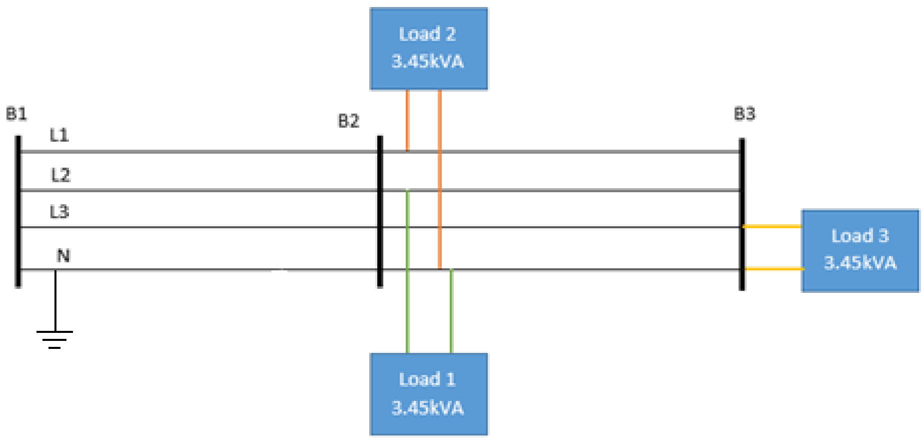

Figure 4.5 - Representation of unbalanced loads in networks.

Considering the 3 loads equal, in the branch that connects the busbar B2 to the busbar B3 there will be a current flowing through the neutral. Therefore, the NEV in busbar B3 will rise. At the opposite side, in busbar B2 the load will be balanced, since the currents that flows from the busbar B1 is equal in the three phases. Consequently, the current in the neutral wire will be nearly zero. The NEV in busbars B1 and B2 is for that reason nearly zero.

The Table 4.1 shows the results of estimation process for the presented example in Figure 4.5.

Table 4.1 - Impedance estimation example.

B2 (V)	B3 (V)	ΔV (V)	Iload3 (A)	Z (Ω) (estimated)	Z(Ω) (real)
242,22	242,06	0,15	2,99	0,05	0,03

In fact, the estimated impedances may vary depending on the behaviour of the consumption, when the NEV is non negligible. In order to introduce the impacts of the loads variation in the impedances, they may be estimated using a dataset of a period (e.g. hourly or 15 minutes' periods during a week) and calculating the respective average value using the Equation (4.11).

$$Z_{k\,AVG} = \frac{\sum_{i=1}^{n} Z_k(i)}{N} \qquad (4.11)$$

where Z_{kAVG} is the average impedance of the branch k, $Z_k(i)$ is the impedance obtained using the Equation (4.10) to the sample i, and N is the total number of samples.

Despite being possible to tackle the problem of branches' impedances absence using the process of impedance estimation, in step (1) is also performed a recognition of the network model, namely in what concerns to the neutral wire configuration. Consequently, 5 different cases have to be analysed. These cases are the result of combining the information that may be available with the presence/absence of the neutral effects in voltages nodes. The Table 4.2 shows the 5 combinations expected and the analysis that should be followed.

Table 4.2 - Cases Expected - x: available or present; - unavailable or not present;

Features	Case 1	Case 2	Case 3	Case 4	Case 5
Impedances	x	x	x	-	-
NEV	x	x	-	x	-
Locations where the neutral is ground	x	-	x/-	x/-	x/-
Type of Analysis	F	P/E	P	E	E

The type of analysis considering the information exposed in Table 4.2 is shown in Table 4.3.

Table 4.3 - Characterization of the different analyses

Type of analyse	Neutral wire/Neutral effects
Full Model (F)	Explicitly Modelled
Partial Model (P)	Non represented
Estimated Impedances (E)	Represented in the estimated impedances

The main difference between the full model and the partial model is that in the first one the currents are estimated using the equivalent phase to ground voltages whereas in the second one the phase to neutral voltages are used.

The full model is particularly required when the NEV is present in voltage nodes. Thus in overhead networks, where this condition is generally observed, a full model should be used. Nevertheless, in these networks, the locations where the neutral is grounded may be not fully known. Therefore, a process of impedance estimation should be used in opposition to the partial model, since the neutral effects are merged into the estimated impedances. The partial model, which does not consider the effect of NEV in nodes is used just in case of not being possible to perform the process of impedance estimation.

The partial model is adequate when the NEV is negligible or has a small impact in voltage nodes. These conditions are commonly observed in underground networks where the load balance and a multi-grounded neutral are characteristic. Despite the full model being applicable in networks with small impact of NEV in node voltages, the additional computational effort does not justify its application.

Regardless of the impact of NEV in voltage nodes, if the network's impedances are unknown, the process of estimation is the only option available.

4.2.3 Branches' Currents Calculation

In step (3) of the Figure 4.4, is performed the Calculation of the Currents in Branches (CCB) using the consumption's measurements provided by SMs (currents). Also, it is calculated an Estimation of the real Currents in Branches (ECB) using the voltages in nodes provided by SMs. The rationale behind the use of the voltage in nodes to estimate the currents in branches is related with the fact that they are the only electrical measure available that has reflected in their value, the presence of NTLs.

Defining the Branches' Connections Matrix (BCM), which represent the network's topology given in Equation (4.12):

$$\begin{cases} BCM_{ij} = 1, \text{ if } i = j \text{ or } (i \neq j \text{ and } j \text{ is a downstream busbar of busbar } i) \\ BCM_{ij} = 0, \text{ in other cases} \end{cases} \tag{4.12}$$

BCM has dimension n x n where n is the total number of busbars. Defining the vector of per phase Current Consumption (CC) in each busbar i as expressed in the Equation (4.13), the CCB is calculated using the Equation (4.14).

$$\begin{cases} CCi = SMs_z \ current, \ if \ SMs_z \in busbar_i \\ CCi = 0, \ in \ other\,cases \end{cases} \tag{4.13}$$

$$[CCB] = [BCM] \cdot [CC] \tag{4.14}$$

Calculating the Voltage Drop (VD) matrix, which contains in each position VD_{jk} the voltage drop between the busbar j and the busbar k, given by:

$$\begin{cases} VD_{jk} = V_j - V_k, \ if \ j \ and \ k \ are \ connected \\ VD_{jk} = 0, \ in \ other\,cases \end{cases} \tag{4.15}$$

Where V_j is the voltage at the busbar j and V_k is the voltage at busbar k. Using the VD matrix and the impedance of each branch the calculation of the ECB is performed by Equation (4.16):

$$ECB_{jk} = \frac{VD_{jk}}{Z_{jk}} \tag{4.16}$$

When a full model of the network is used and the NEV is not negligible, the calculation of ECB is performed using phase to ground voltages. Since the SMs' voltage measurements correspond to a phase to neutral voltage, the phase to ground voltages need to be calculated, using a power flow study. The calculation of the difference between CCB and ECB, $E_{N|K}$, for each branch K of the level N is performed. A level represents the location of a busbar j, taking into account the number of branches that connects it to the reference busbar. In Figure 4.6 is shown an example of the levels representation in a network.

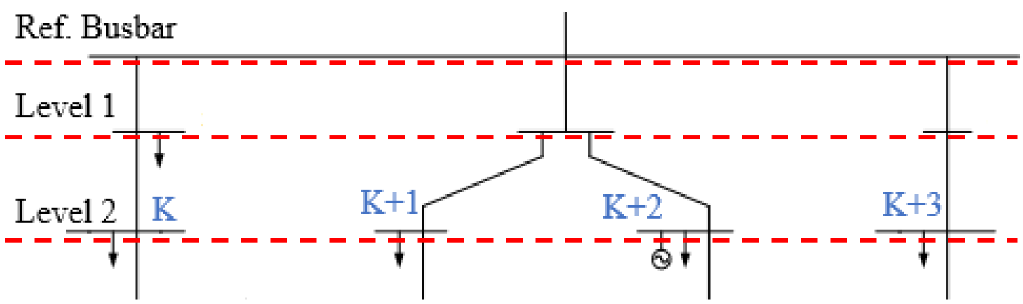

Figure 4.6 - Network's levels exemplification.

4.2.4 Iterative Process of Location

In order to locate the NTLs, an iterative process in step (4) is performed, starting in the last level of the network. For each branch of each level, if $E_{N|K}$ is higher than the margin of the acceptable error it is considered suspicious and an alarm is sent to the DSO. In addition, the respective value of $E_{N|K}$ is summed to the respective position of the vector of the currents consumption, CC, and the recalculation of CCB is performed. By doing this, the error is not reflected in the upstream levels. In case the NEVs are not negligible, every time that a location of NTLs is found, the voltages in nodes are updated to introduce the impact of the new current found in the NEVs. Therefore, the estimated currents in branches, ECB, are recalculated.

The process is performed iteratively until all branches were checked.

4.3 - Summary

In this Chapter, a step by step explanation of the two algorithmic stages of advanced methodology have been performed. The section 4.1 includes the proceedings used to detect the presence of NTLs in the network focusing the results provide by the methodology under different condition of network's deployment. It is also included an analysis of the errors under the process of location, and is explained how to define those errors in order to maximize the robustness of the process. The section 4.3 comprises a description of the process used to locate NTLs. The impacts of the NEVs in the process of location have been presented and the additional steps under these conditions have been explained. The advanced methodology adapts the calculations performed considering a realistic model of the networks, enabling its application in real networks.

Chapter 5

Case Study: Detection and Location of NTLs in an Overhead LV Network

The developed methodology is validated in a typical Portuguese Low Voltage (LV) overhead distribution network. This Chapter presents a complete description of the different scenarios assessed, under different condition of network's deployments in what concerns to the available information regarding the LV network and the neutral configuration. In section 5.1 the network that will be used in as test case is presented and the different scenarios that will be studied are detailed. In section 5.2 the case study assesses the advanced methodology considering the process of detection individually. In this section is also performed a sensitivity analysis to the threshold used to decide about the presence of NTLs in the network. In section 5.3 the results for the location are presented considering 3 distinct scenarios, namely assuming the system single and multi-grounded. It is also included a sensitivity analysis in order to evaluate the behaviour of the methodology when the threshold used to decide about the location of NTLs is varied.

5.1 - Case Study: Description

5.1.1 Characterization of the network used as test case

The network used to assess the advanced methodology comprises the typical characteristics of the Portuguese LV networks used in rural places, where overhead lines are commonly used. The single line diagram of the LV distribution network used is shown in Figure 5.1. The network also includes Distributed Energy Resources (DER), as microgeneration in some clients (photovoltaic panels). The network has a total of 33 busbars and a total of 48 consumers. Their contracted power varies in a range between 3,45 kVA and 10,35 kVA – single phase loads. The locations where is installed microgeneration and the respective installed power is shown in Table 5.1. It has been considered that the load's power factor varies randomly between 0,8 and 1 and the power factor of the microgeneration is equal to 1. The power contracted of each customer and the lines' impedances may be found in Table A1 and Table A2 present in Annex A, respectively.

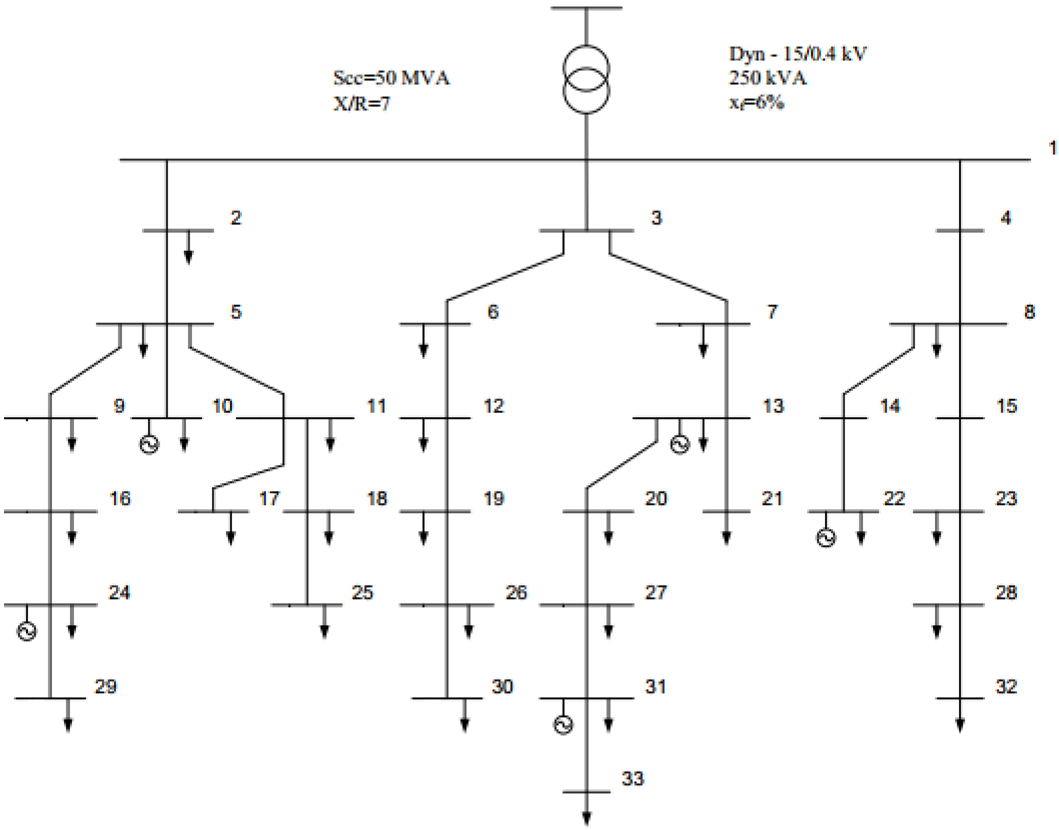

Figure 5.1 - Network used as test case.

Table 5.1 – Microgeneration Data

Phase	Busbar	Power(kVA)
2	10	3,68
1	13	3,68
1	22	3,68
3	24	3,68
2	31	3,68

The network presents a radial configuration and 3 phase plus neutral wire lines. The network is unbalanced and the load imbalance is particularly notorious in the downstream busbars.

In order to simulate different consumptions behaviours, six different load diagrams have been created using the aggregated diagram at the distribution transformer. Thus, a Gaussian distribution with mean equal to the diagram and a standard deviation of 8% has been used [36].The six diagrams are shown in Figure 5.2. For the microgeneration, a production diagram that follows a typical Portuguese profile has been used. The microgeneration diagram is shown in Figure 5.3.

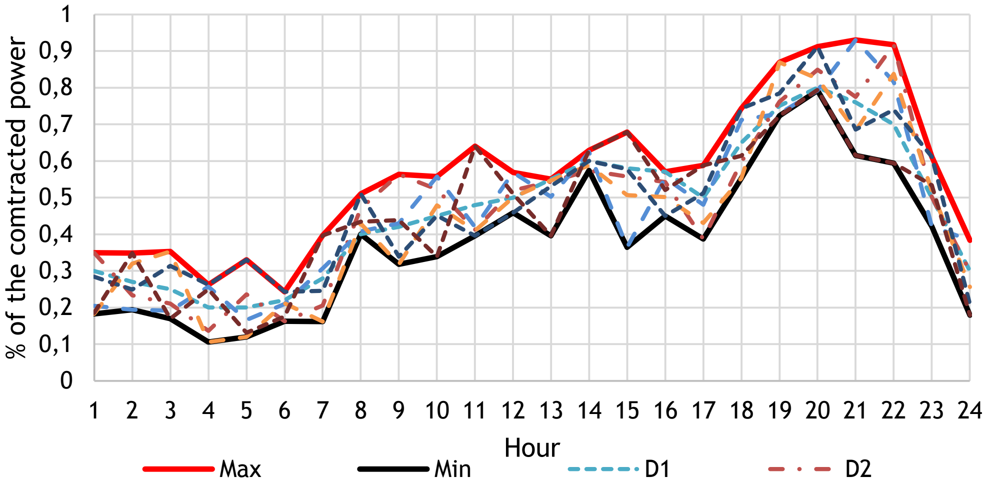

Figure 5.2 - Example of 6 six load's diagrams.

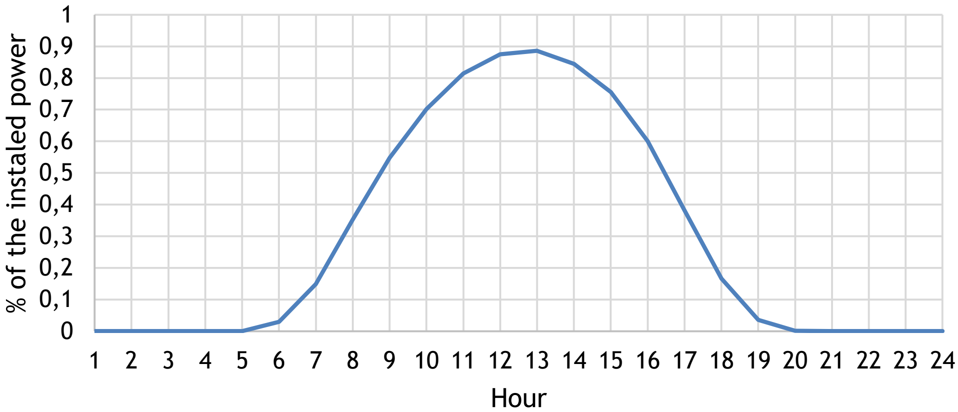

Figure 5.3 - Production Profile.

5.1.2 Definition of the scenarios under analysis

In order to assess the advanced methodology, it is required the definition of different scenarios that represent the majority of the expected real situations.

Considering the information that may be available about the network: topology (consumers per phase and their location), branches' impedances, and the type of communication used, four different cases have been defined. The Table 5.2 shows the available information in each one.

Table 5.2 – Cases used to assess the advanced methodology x: available; - unavailable

Features	Case 1	Case 2	Case 3	Case 4
Topology	x	x	-	-
Branches' Impedances	x	-	-	-
Communications Used	PLC/GPRS	PLC/GPRS	PLC	GPRS

According to the information presented in Table 5.2 the cases may be grouped in different scenarios considering the process of detection and location of NTLs individually. Therefore, two major scenarios may be considered to the process of detection:

- **Scenario 1 - Topology Available:** the consumers per phase are known allowing the detection of NTLs for each phase corresponding to the first third cases of the Table 5.1. Despite in case 3 the topology be unknown the PLC communications may provide the phase to each consumer is connected;
- **Scenario 2 - Full absence of network's knowledge:** none of the network's characteristics are known corresponding to the scenario 4 of Table 5.1, since the GPS coordinate provided by SMs with GPRS communication does not provide the per phase consumers.

Proceeding in the same way to the process of location, three major scenarios may be defined also considering difference configuration of the neutral wire:

- **Scenario 1 - Full network's knowledge considering multi-grounded system:** the impact of the NEV is not considered in the process of location;
- **Scenario 2 – Full network's knowledge considering single-grounded system:** a complete model of the network is used;
- **Scenario 3 - Network's topology available in single - grounded system:** only the consumers per phase and their location is.

5.1.3 Assumption Made

Since the advanced methodology is tested using the results of the power flow studies there is the need to define the criteria used to simulate the presence of NTLs in the network. Thus the following assumptions have been made:

- The number of locations under the presence of NTLs varies between 0% and 10% of the total number of consumers;
- The location (phase and busbar) of the NTLs is randomly generated;
- The value of each NTL varies between 30% and 80% of the contracted power of the respective consumer.

The power flows studies, for scenarios 2 and 3, which use a complete model of the network are performed using the Matlab - Simulink environment. In scenario 1, since the system is considered multi-grounded the power flows studies have been performed through the Kron's reduction using the OPENDSS open source software [50].

5.1.4 Calculation of the errors for the detection and location of NTLs

The process of detection and location of NTLs, beyond the characteristics of the networks and the measurement's data, needs as input the margins of the acceptable errors in order to decide about the presence of NTLs in the network and decide about their location. In this section, the calculation of the Per Phase Error (PFE), the Total Error (TE) and the Location Error (LE) is demonstrated.

5.1.4.1 Calculation of the PFE

Considering the topology available, the PFE is obtained by simulating power flow studies using as input the load's diagrams of the customers present in Figure 5.2. These diagrams would be provided by SMs in real cases. The PFE is obtained by applying the methodology of detection to the results of the power flow simulations. The results required are the per phase currents in the DTC and the measured currents by SMs (in module) and the respective power factor. The PFE for the network used as test case is shown in Figure 5.4.

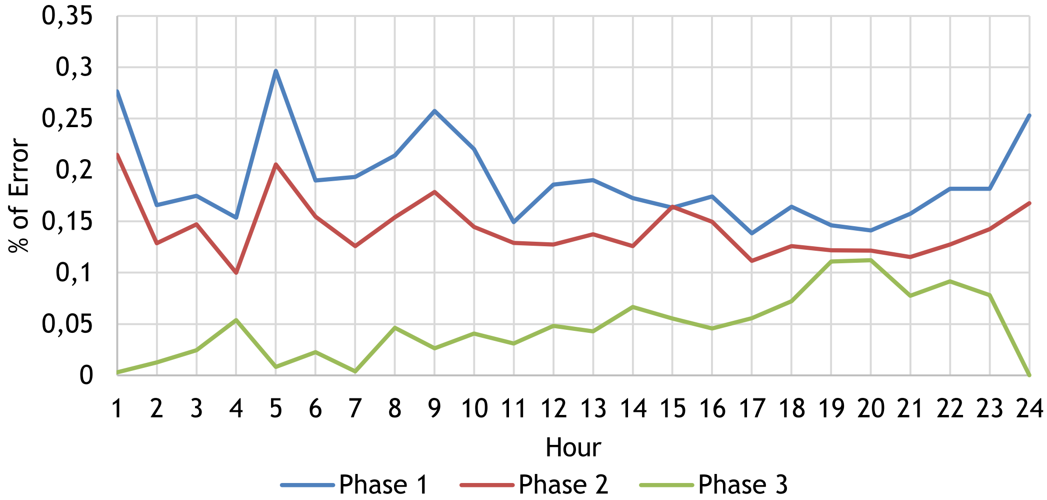

Figure 5.4 – PFE evolution during the day.

The PFE is always higher in phase 1 than in the other phases with a maximum value of 0,3%. Considering that the load may present variations and influencing the PFE, this value is increased in 30% and is considered the same error for the 3 phases. Thus, the PFE considered is given by Equation (5.1):

$$PFE = 0,3 \times 1,3 = 0,39\% \tag{5.1}$$

The PFE is considered to be the maximum value of Figure 5.4, i.e., 0,39%. Nonetheless, the PFE could also be considered to be the average value for the 24h (i.e. 0,19%). Considering for the PFE the maximum value, the methodology detects the presence of NTLs in case the error obtained during the process of detection is higher than the PFE for at least an hour of the day. Otherwise, the methodology only considers the presence of NTLs if the average error of the 24h is higher than the average PFE.

5.1.4.2 Calculation of the TE

When the topology of the network is unknown a per phase analysis cannot be performed. Therefore, the TE is estimated using the characteristics of other LV networks. In this work, the network used as test case will be considered to estimate the TE. Nonetheless, another 6 load's diagrams have been generated using a Gaussian distribution with mean equal to the aggregated diagram at the secondary substation and considering a standard deviation of 20%. The Figure 5.5 shows the evolution of the TE during the day.

The maximum error is verified at 7:00h with a value around 0,225%. The maximum error is verified for this hour since the currents measured at the secondary substation are the lowest of the currents measured during the day. In addition, the difference between the sum of the currents at the DTC and the sum of all currents measured by SMs shows a low variation during the day. The highest difference is 0,25A and the lowest difference is 0,12A.

Increasing in 30% the error, the TE considered has a value equal to 0,3%.

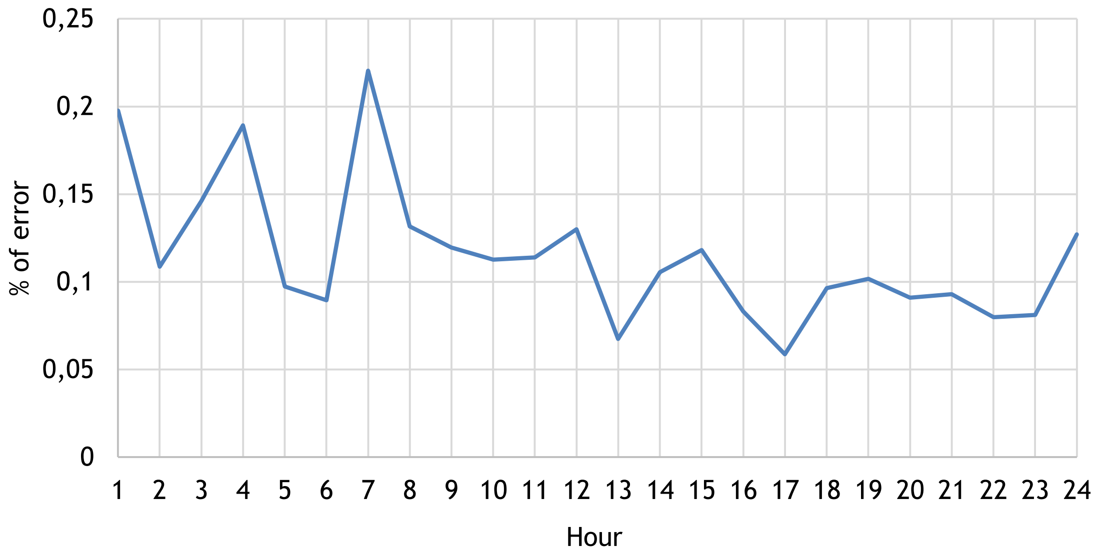

Figure 5.5 - Evolution of the TE during the day.

5.1.4.3 Calculation of the LE for locating NTLs

Since the network is unbalanced and the presence of the NEVs in voltages may be notorious, the LE is given by the lowest current measured in the network. The Figure 5.6 presents the consumer with the lowest current measured.

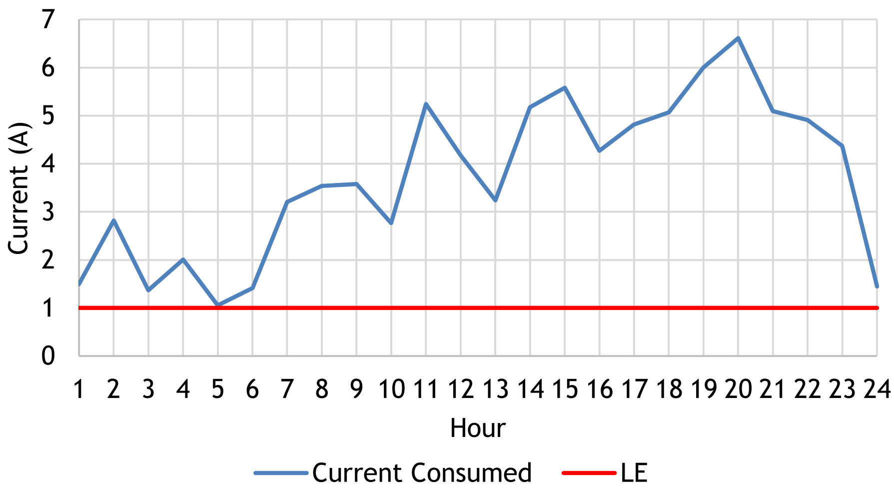

Figure 5.6 - Determination of the LE to use in the location of NTLs

As can be seen in Figure 5.6 the lowest current measured is around 1 A. This error will be used to decide about the presence of NTLs in the busbars.

5.2 - Results Analysis: Detection of NTLs

In this section, the results of the first algorithmic stage of the advanced methodology, which allows the detection of NTLs are presented.

In order to present the detection results of the different scenarios an example of the simulation is shown in Table 5.3. The presence of the microgeneration in the network has been considered according to the information present in Table 5.1.

Table 5.3 - Simulated NTLs - Example 1.

Phase	Busbar	Power(kVA)
1	13	1,25
1	19	1,62
1	11	1,59

5.2.1 Results for the Detection: Topology Available

Since in this scenario the consumers per phase are known, a per phase analysis is performed. The results for the simulation presented in Table 5.3 are shown in Figure 5.7.

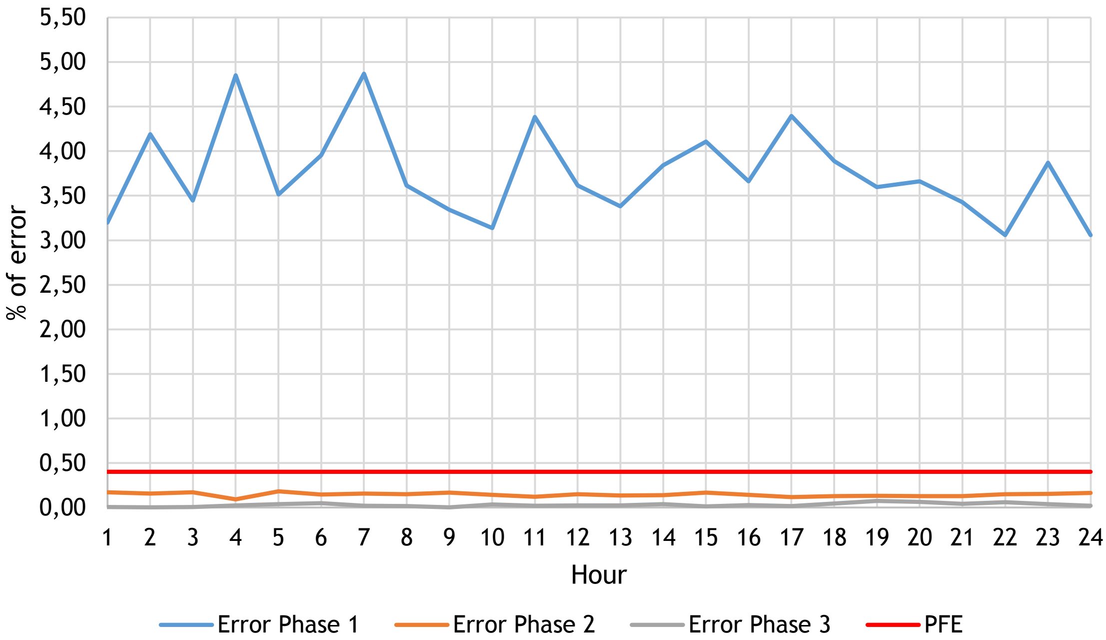

Figure 5.7 - Results of the detection considering the topology available.

As shown in Figure 5.7 due to the presence of NTLs in phase 1, the error in the same phase is higher than the PFE. In the other phases the error is lower than the PFE due to the absence of NTLs. Therefore, the methodology is well succeeded in the detection of NTLs.

5.2.2 Results for the Detection: Full absence of network’s knowledge

In this scenario the consumers per phase are unknown. Therefore, the comparison between the currents supplied by the secondary substation and the currents measured consumed is performed considering the three phases simultaneously. The Figure 5.8 presents the evolution of the error during the day.

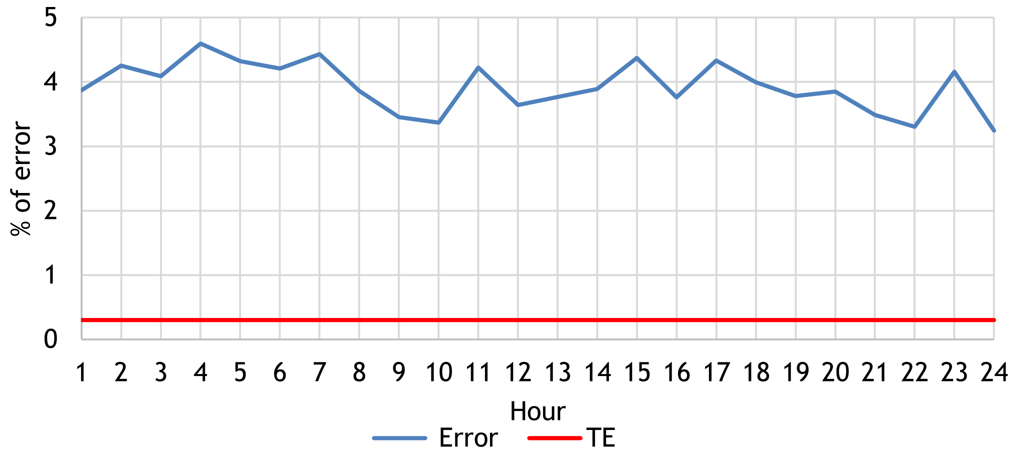

Figure 5.8 - Detection of NTLs – Full absence of network’s knowledge

The advanced methodology has detected correctly the presence of NTLs in the network, since the error is higher than the TE.

5.2.3 Sensitivity Analysis: Detection of NTLs

The sensitivity analysis aims to assess the robustness of the methodology when the technical parameters, used as input, are varied. The advanced methodology for the detection of NTLs considers a threshold to decide about the presence of NTLs in the network. Thus, in order to assess the influence of this threshold in the results, this value has been varied. In order to guarantee the worst conditions, it has been considered only the presence of NTLs in a single location. In addition, the value of the NTLs may vary between 0% and 100% of the consumers contracted power. For each threshold considered have been performed 100 simulations. The results have been obtained considering a Per Phase Analysis but considering two different approaches: in the first, the detection is performed comparing the error with the PFE for each hour, whereas in the second approach the detection is performed comparing the average value of the error during the day with an average PFE.

The Figure 5.9 shows the results for the detection considering the first approach. The results show that considering an error higher than 1% the accuracy of the methodology decreases. This is the result of the non-detected cases, that are related with small values of NTLs. Since the comparison is performed for each hour, the methodology detects the presence of the NTLs in the periods where the error is higher than the PFE. Therefore, this approach is useful to detect intermittent loads.

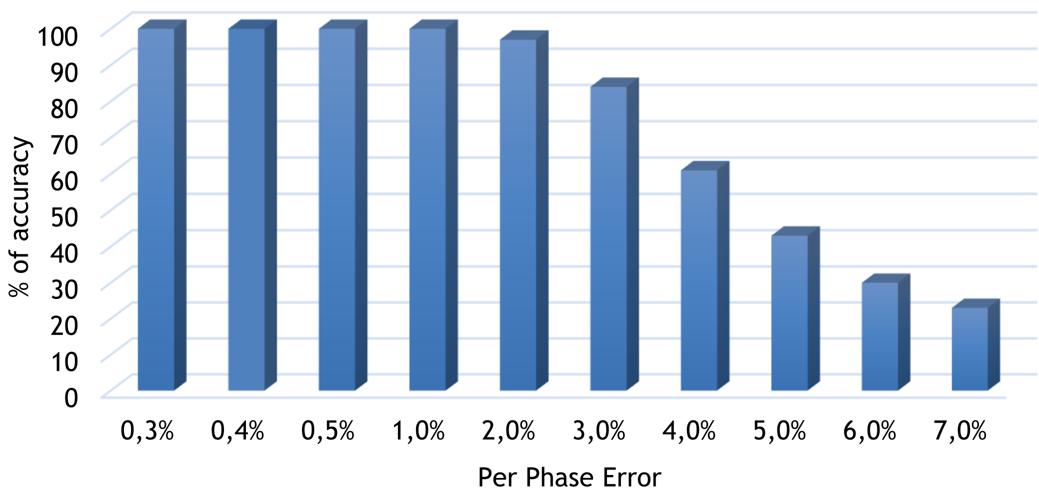

Figure 5.9 – Evolution of the accuracy varying the PFE.

For values of the PFE under 0,3% false positive cases appear. When the phase under the presence of NTLs is not the phase 1, the methodology detects the presence of NTLs in this phase. This is due to the fact, that in phase 1 during some periods of the day the error even without the presence of NTLs is around 0,3%. When the PFE is lower than 0,1% the methodology identifies always the presence of NTLs in the 3 phases.

Considering the second approach, where the average error is considered for the detection of NTLs the results are presented in Figure 5.10.

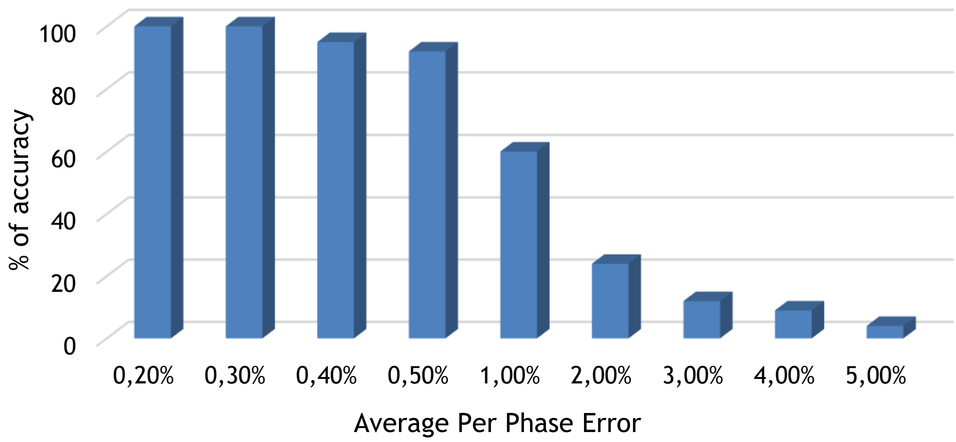

Figure 5.10 – Evolution of the accuracy varying the average PFE

The results show that using the average error during the day, the accuracy of methodology decreases when the average PFEs considered are higher than 0,4%. This is explained by the fact that considering the average error, the peak errors during the day are not observed. In addition, since the value of the NTLs may vary between 0 and 100% of the consumers' contracted power, the currents due to NTLs may present small values which are difficult to detect.

5.3 - Results Analysis: Location of NTLs

In this section the advanced methodology is assessed considering the different scenarios detailed in Section 5.1. The evaluation is performed analysing the cases correctly identified (true positive (TP) cases), the cases incorrectly identified (False Positives (FP) cases) and the cases Non-Detected (ND). This evaluation is performed varying the number of locations under the presence of NTLs.

For the scenario 1 the main steps of the advanced methodology to locate NTLs are also included.

5.3.1 Scenario 1 - Full network's knowledge considering multi-grounded system

In this scenario the network is considered multi-grounded and the power flow studies are performed using the Kron's reduction. This scenario has the main objective to assess the advanced methodology under the expected conditions to underground networks despite the load imbalance present in the network. It also allows to assess the advanced methodology when the locations where the neutral is grounded are not fully known. Since the NEV in nodes is not available, the estimated currents in branches are calculated using the phase to neutral voltages.

The location is exemplified for the busbar 11 of the phase 1 considering the example presented in Table 5.4.

Table 5.4 – Simulated NTLs: Location

Phase	Busbar	Power(kVA)
1	13	2,50
1	19	1,62
1	11	1,59
2	9	2,60
3	13	1,55

The first step passes through the calculation of the difference between ECB and CCB. The Table 5.5 presents only the error for the upstream branches of the busbar 11, since in the downstream branches the error is lower than the LE.

Table 5.5 - Calculation of the error $E_{N|K.}$

Branches	ECB(A)	CCB(A)	Error (A)
1-2	37,3	35,7	1,6
2-5	32,96	30,66	2,3
5-11	12,16	10,34	1,82

The following step is to update the per phase current consumption CC, by adding the error in line 5-11 (1,82A) to the respective position in vector CC. By recalculating the CCB the currents in branches will take into account the NTLs detected in busbar 11. The results are shown in Table 5.6.

Table 5.6 - Recalculation of the error $E_{N|K.}$

Branches	ECB(A)	CCB(A)	Error (A)
1-2	37,3	37,52	0,2
2-5	32,96	32,48	0,48
5-11	12,16	12,16	0

Since the error in all the upstream branches of the busbar 11 is lower that the LE they are not considered with the presence of NTLs. The process exemplified is performed for the entire network, until all branches were verified.

Despite considering the system multi-grounded, due to the load imbalance and the approximations made (neglecting the NEV in the estimation of the branches' currents), the estimated currents in branches, particularly in the downstream busbars may present a discrepancy comparing with the real value. Therefore, the area to inspect may be higher than the real.

The Table 5.7 shows an example of a simulation with 5 locations under the presence of NTLs in which the exposed situation is verified.

Table 5.7 - Simulated NTLs.

Phase	Busbar	Power(kVA)
1	9	2,48
1	12	2,65
1	13	4,07
1	29	5,52
2	16	2,01

In Table 5.8 the locations considered suspicious as an output of the methodology are presented.

Table 5.8 - NTLs Found.

Phase	Busbar
1	6
1	9
1	12
1	13
1	29
2	16

In the case exposed the busbar 6 has been considered under the presence of NTLs since the estimated current in branch that connects the busbars 6 and 12 is lower than the real value. The process of detection of the NTLs present in the busbar 12 is shown in Table 5.9.

Table 5.9 - Calculation of the error for NTL present in busbar 12.

Branches	ECB(A)	CCB(A)	Error (A)
3-6	11,65	4,89	6,76
6-12	8,68	3,09	5,59

Recalculating the CCB, the results are shown in Table 5.10.

Table 5.10 - Error after the recalculation of CCB.

Branches	ECB(A)	CCB(A)	Error (A)
3-6	11,65	10,48	1,17
6-12	8,68	8,68	0

As can be seen in Table 5.10, the error in line 3-6 is higher than the LE thus it will be incorrectly considered under the presence of NTLs.

The Figure 5.11 shows the results of the location varying the number of NTLs (N) present in the network.

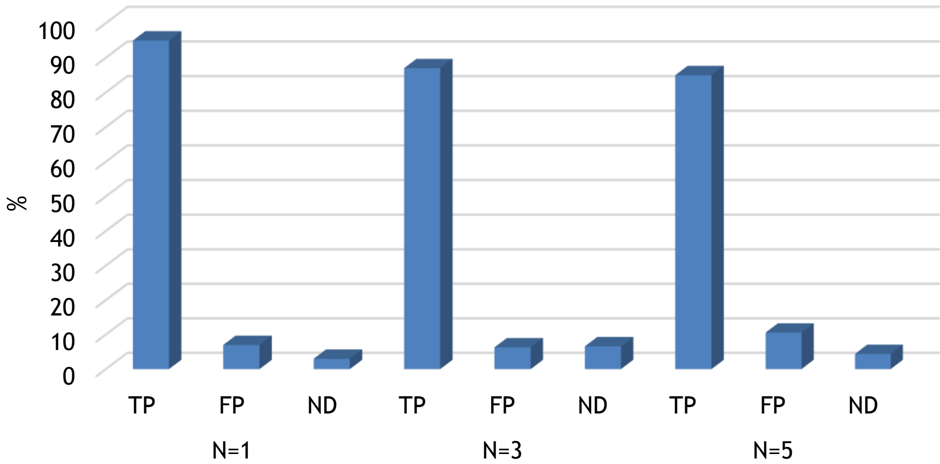

Figure 5.11 - Results for the location varying the number of locations, N, with NTLs in scenario 1.

The methodology presents better results when the number of locations under the presence of NTLs is lower. This is directly related with the number of false positives since considering a higher number of locations with NTLs, the error is propagated due to the error associated in the estimation of branches' currents.

5.3.2 Scenario 2 – Full network's knowledge considering single-grounded system

In this scenario the network is considered single-grounded at the secondary substation. Since the network is unbalanced the neutral effects will have a high impact in nodes voltages mainly in the downstream busbars. These assumptions allow the assessment of the advanced methodology under the worst conditions expected.

Since a full knowledge of the network is available, the proposed methodology takes into account the impact of NEV in voltages. Therefore, the estimated currents are obtained considering the phase to ground voltages.

The results of the NTLs location varying the number of locations is presented in Figure 5.12. Comparing with the results obtained in scenario 1, the accuracy of the method has decreased. In fact, considering the system single grounded, the NEVs are obtained by estimation assuming the currents measured by SMs which may introduce errors in the estimation of branches' currents. This is particularly noticeable when the number of locations under the presence of NTLs increases. Therefore, the number of false positives increases.

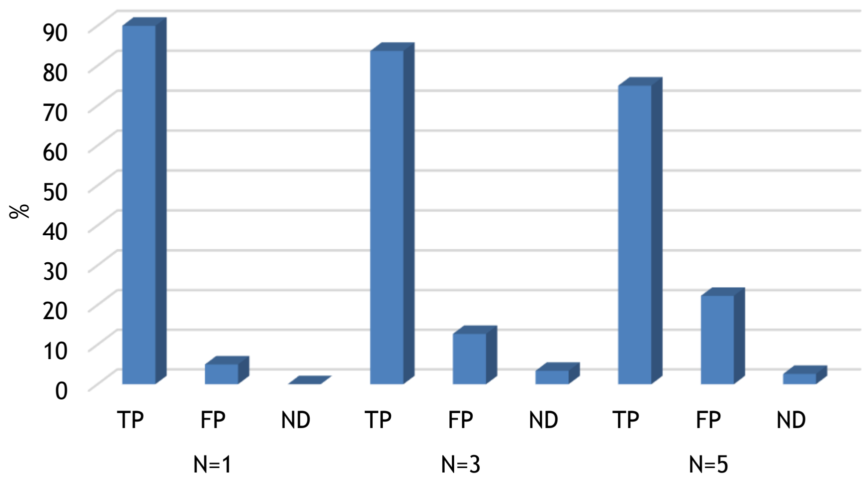

Figure 5.12 - Results for the location varying the number of locations, N, with NTLs in scenario 2.

5.3.3 Scenario 3 - Network's topology available in single grounded system

Since in scenario 3 the branches impedances are unknown, a process of estimation is performed, using historic records. The estimated impedances are obtained, by generating another 6 diagrams for 10 days using a Gaussian distribution with mean equal to the diagrams presented in Figure 5.2 and a standard deviation of 15%. This process is used to model the variations in the consumption's behaviour over the time.

In Figure 5.13 is shown the variation of the impedances in some branches comparing with the values known. This variation is due to the load imbalance present in the network, since the estimated impedances take into account the neutral effects in the voltages.

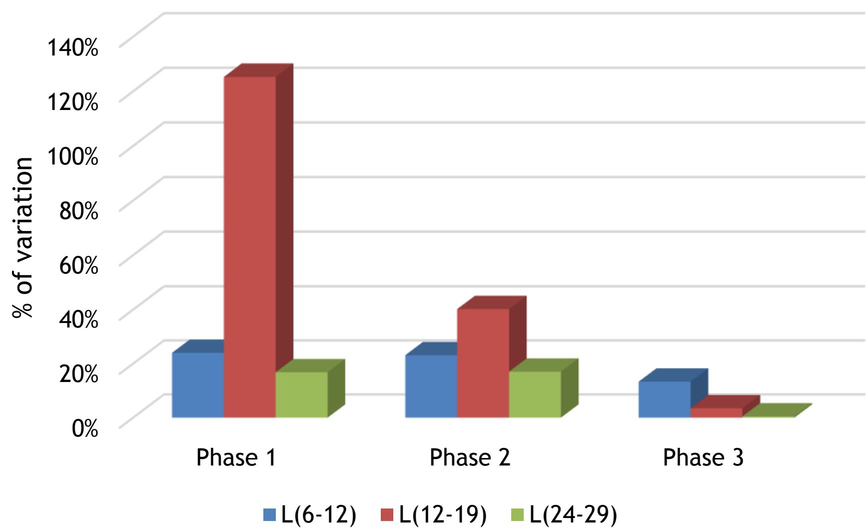

Figure 5.13 - Impedance variation comparing with the real value using 10 days of historic records.

Nevertheless, the estimated impedances in a single ground system are quite influenced by the consumption behaviour due to the impact in NEVs. The Figure 5.14 shows the impedance variation when only is considered a day of historic records.

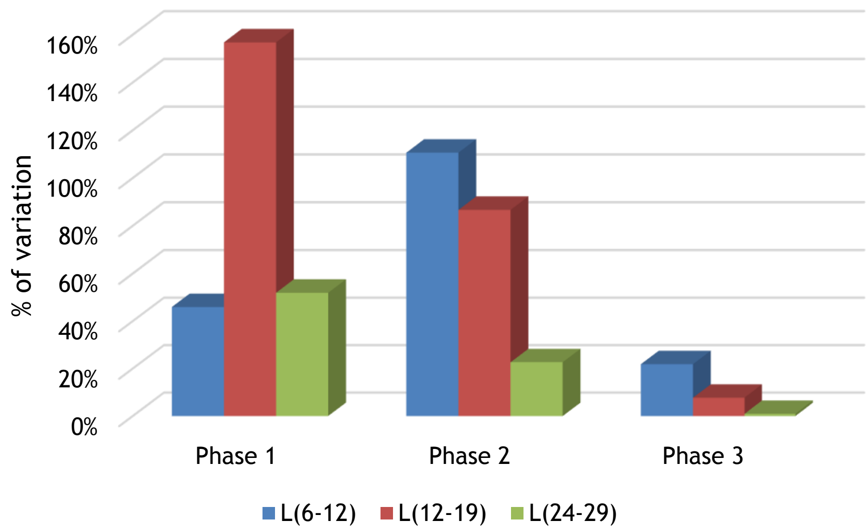

Figure 5.14 - Impedance variation comparing with the real value using a day of historic records.

The results for the detection of NTLs varying the number of locations (N) are presented in Figure 5.15.

The accuracy of the advanced methodology considering the system single grounded decreases when the network's impedances are unknown. This results due to the influence of the loads' profiles behaviour in the load imbalance of the network and, therefore, in the NEV in nodes. In fact, the percentage of false positives is as higher as the present consumption is different from the consumptions used to estimate the impedances. Nevertheless, the main reason behind the variation of the decreasing in the accuracy is due to the presence of NTLs, which are not taken into account during the process of impedance estimation.

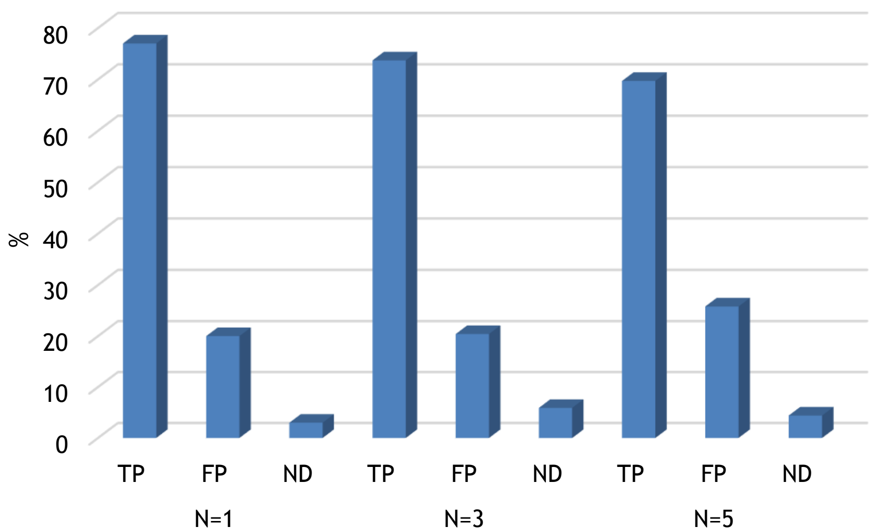

Figure 5.15 - Results for the location of NTLs in scenario 3, varying the number of locations, N.

5.3.4 Sensitivity Analysis: Location of NTLs

The process of location, during the iterative process, uses a threshold to decide about the presence of NTLs in a branch/busbar. In order to assess the influence of this threshold in the results and its correlation with the value and the number (N) of the NTLs present in the network the following analysis has been performed, considering only one location under the presence of NTLs:

- The location errors considered are: 0,5A; 1A; 2A; These errors will be used to assess the accuracy of the methodology varying the power of the NTLs.
- The power value of the NTLs may vary between 0% and 100% of the consumers' contracted power. Nevertheless, to perform a correlation between the considered error and the value of the NTLs, three different intervals have been defined: 0%-30%; 30%-65%; 65%-100%;
- 100 simulations for each case.

The results obtained for a multi-grounded system, considering the number of locations equal to 1 are shown in Figure 5.16.

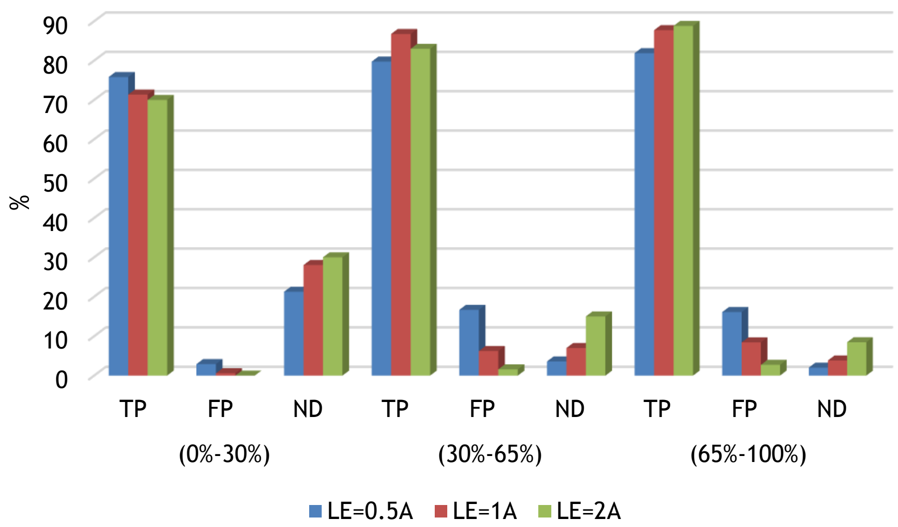

Figure 5.16 – Results for the location of NTLs considering N=1.

The number of non-detected cases when the NTLs vary between 0%-30% of the contracted power is related with their small currents. In fact, the number of non-detected cases is as higher as the LE considered. Therefore, when the value of the NTLs increases, the number of non-detected cases decreases.

The accuracy of the methodology increases with the power value of the NTLs since the currents in branches will be higher. However, the number of FP may rise due to errors in the estimation of the branches' currents. During the iterative process, if the estimated currents present a significant discrepancy comparing with the real value, this error will be propagated to the upstream branches.

When the value of the NTLs is lower, the use of a smaller LE provides a higher number of TP cases. At the opposite side, the accuracy of the methodology when the value of the NTLs is higher is observed for higher values of the LE.

5.4 - Summary

In this Chapter are addressed the results of the application of the methodology advanced in the Chapter 4. The case study is presented in Section 5.1. The network used as teste case is characterized and the different scenarios that are used to assess the advanced methodology are detailed. Since the process of detection and location requires as input the margins of the acceptable errors to decide about the presence of NTLs, its calculation is exemplified.

The results obtained for the first algorithmic stage, detection of NTLs, are presented and analysed in Section 5.2. Two different scenarios have been considered: in the first the topology of the network is available allowing a per phase analysis; in the second the only information available is the load's currents and the currents at the secondary substation. The results show the adequacy of the methodology in both situations. The results of the sensitivity analysis show that when the average error is used the detection of NTLs with small value is more difficult. At the opposite side, analysing the error for each hour is possible to detect intermittent loads.

In section 5.3 the results of the advanced methodology in the location of NTLs are presented. Three different scenarios have been used to assess the developed methodology. An exemplification of the main steps used during the process of location is included. The results show that the accuracy is influenced by the configuration of the network namely in what concerns to the neutral wire. The advanced methodology has a higher accuracy in multi-grounded systems since the impact of the NEVs is nodes and therefore in the estimated currents is lower when comparing with single grounded networks. When the impedances of the lines are unknown the accuracy of the advanced methodology decreases due to the higher number of FP.

Chapter 6

Conclusions and Future Work

In this work a methodology is advanced to detect and locate Non-Technical Losses (NTLs) in Low Voltage (LV) distribution networks. This methodology takes advantage of the Advanced Metering Infrastructure (AMI) present in the network to perform the detection and location of NTLs based on an analysis of the currents in the system.

This Chapter presents the final remarks of this work. The conclusions resulting from the assessment of the advanced methodology to a case study, of a typical LV network under different scenarios are presented. A critical analysis of the developed methodology and its limitations are also described.

This Chapter also includes suggestions for further improvements to the advanced methodology and future work.

6.1 - Conclusions

The implementation of the detection and location of NTLs in LV networks provides and efficient way to improve the efficiency of system's operation, by reducing the losses in networks and the need for investments in the reinforcement of the system's infrastructures.

In addition, the detection and location of NTLs allows a reduction of the energy produced in power plants thus a reduction of the energy price.

The reduction of NTLs allows the reduction of the tariffs charged to consumers, improves the revenue for the Distribution System Operator (DSO) due to the incentive mechanisms and increases the profits of the governments due to the energy taxes.

The deployment of an AMI through the use of smart metering in LV networks will provide an opportunity to a real management of these networks. Smart Metering improves the observability in what concerns to the operation conditions of LV networks leveraging the detection and location of NTLs.

The detection can be performed without the knowledge of the networks characteristics and does not need the estimation of TLs, which can be considered an advantage, since the uncertainty in the overall process is reduced. Furthermore, the detection is not influence by the load diagrams of customers.

The accuracy of the methodology in the location of NTLs decreases with the number of locations under the presence of NTLs since the errors in the estimation of the branches' currents are propagated during the iterative process of location. This occurs mainly when the NTLs are presented in the downstream busbars.

The advanced methodology has a better accuracy in networks where the neutral effect does not have a high impact in the voltages. The accuracy of the methodology in the location of NTLs is strictly related with the exactness of the estimated currents in branches. In fact, the uncertainty in the overall process is related with the simplifications introduced for estimating the currents. The absence of the voltages angles in nodes does not allow the exact calculation of voltage drops in branches. The methodology may be complemented with other tools. For example, the currents in branches could be provided by an algorithm of State Estimation for LV networks.

6.2 - Work Contribution and Methodology Limitations

The differencing aspects of this work are related with:

- The developed methodology performs the detection and location of NTLs considering simultaneously the customers and the network. Thus, the location of NTLs is addressed considering not only the presence of fraudulent consumers in LV networks but also the presence of non-detectable (by traditional protection devices) High Impedance Faults (HIFs).
- The method can be applied to LV networks even when the technical characteristics of the conductors have not been mapped. The results show a high accuracy for all considered scenarios.
- The developed approach considers a real model of the LV network: three-phase networks with unbalanced loads considering different configurations of the neutral wire: multi and single grounded.
- The presence of Distributed Energy Resources (DER) in the network has been considered taking into account the heterogeneity of the profile of these resources.
- The methodology developed is auto-adaptive to the available characteristics of the network and allows the detection and location of NTLs in a systematic way.

The developed methodology tackles the problem of the NTLs by performing the detection and the location, individually. This allows the reduction of the uncertainty and the computational effort. Therefore, the location of NTLs is only performed if their presence has been detected during the first algorithmic stage. In addition, the detection is based on the analysis of the currents, thus an estimation of the technical losses in networks is not required.

The proposed methodology also provides two approaches to estimate the currents in branches: the first is based on the measured currents by SMs and the second is based on the voltages measured. These approaches may be used to improve the development of other tools as the State Estimation (SE) for LV networks.

This work covers the problem of NTLs in the different perspectives of the network's users namely focusing its impact in the operation of the power system. A characterization of the LV networks is performed and the challenges in the detection of NTLs in these networks are addressed. The main advantages of the smart metering have been explained.

Some limitations of the advanced methodology are related with two different aspects:

- The available data of the network;
- An accurate estimation of the branches' currents;

When there is no knowledge of the network's topology, the location of NTLs cannot be performed. In addition, if the deployment of the SMs does not cover all the clients present in the network the methodology is not capable of detecting NTLs.

The accuracy of the methodology in the detection of NTLs is related with the estimation of the branches' currents based on the voltages in nodes measured by SMs. When the impact of the NEV in voltages nodes is not negligible, and the presence of NTLs is observed, the equivalent phase to ground voltages are obtained by estimation. If the impact of NTLs introduces a higher load imbalance, the estimated currents may be quite different than the real value. Therefore, the number of false positives and non-detected cases increases.

Another limitation of the advanced methodology is related with the assumptions made: the resistance of the wires in LV networks may not be always much higher than the reactance. As a consequence, the angles of the voltages in the nodes may present a higher variation throughout the network and the error in the detection of NTLs increases. In addition, the estimation of the branches' currents, using the voltages' modules provided by SMs, may present a discrepancy comparing with the real value, since the impact of the reactance in the voltage drop is not negligible.

6.3 - Future Work

Future work may be related with the improvement of the advanced methodology mainly in the process of NTLs location. As the accuracy of the NTLs location is influenced by an accurate estimation of the branches' currents, the development of a new approach for their calculation is an important step. This may be achievable through the use of a three-phase SE for the currents in branches. The SE would be performed using the information available provided by costumers' SMs and the measurements of the Distribution Transformer Controller (DTC). Additionally, the incorporation of an Artificial Intelligence Method (AIM) for the location of NTLs when the topology of the network is unknown would increase the applicability of the methodology to the generality of LV networks.

The estimated impedances for the location of NTLs does not take into account the operation conditions of the network. Thus, an improvement in the process of NTLs location, could be achieved by using the branches' impedances considering the operation conditions of the network.

A further improvement in the methodology could be achieved by evaluating the margin of the acceptable error for the location of NTLs, considering the load imbalance present in the network. This may be performed using power flow studies, without the presence of NTLs, by analysing the difference between the currents estimated in branches and the currents provided by the power flow studies.

Finally, considering a network in which the resistance of the wires is not much higher than the reactance, the angle of the voltages in nodes could be estimated using power flow studies. Therefore, the voltage drop in branches is calculated using the voltages' modules measured by SMs and the respective angles provided by the power flow studies. This assumption is performed considering that the influence of the NTLs in the voltages' angles is negligible.

References

[1] *CENELEC Smart Grid definition*. Available: https://www.cenelec.eu/aboutcenelec/whatwedo/technologysectors/smartgrids.html. Accessed 20/06/2016.

[2] C. Cecati, G. Mokryani, A. Piccolo, and P. Siano, "An overview on the smart grid concept" presented at the IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society Glendale, AZ, 2010.

[3] R. R. Mohassel, A. S. Fung, F. Mohammadi, and K. Raahemifar, "A survey on advanced metering infrastructure and its application in Smart Grids," presented at the Electrical and Computer Engineering (CCECE), 2014 IEEE 27th Canadian Conference on Toronto, 2014.

[4] R. Acra and M. Thaker.. *Internet Standards Come to the Advanced Metering Infrastructure* Available: http://www.electricenergyonline.com/show_article.php?mag=&article=525 Accessed: 05/06/2016

[5] E. N. R. Rodrigues, "Evaluation of Coordinated Protection SchemesFramed in Self-Healing Schemes", Master Dissertation, Electrical Department, University of Porto - Feup, Porto, 2015.

[6] ATOS. *Revenue Protection for Smart Utilities*. Available: http://atos.net/content/dam/global/documents/your-business/atos-revenue-protection-for-smart-utilities-brochure-lowres.pdf Accessed: 15/05/2016

[7] P. Kadurek, J. Blom, J. F. G. Cobben, and W. L. Kling, "Theft detection and smart metering practices and expectations in the Netherlands " presented at the 2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe) Gothenburg 2010.

[8] European Union. *A policy framework for climate and energy in the period from 2020 to 2030*, 2014.

[9] European Union. *Benchmarking smart metering deployment in the EU-27 with a focus on electricity*, 2014.

[10] D. Suriyamongkol, "NON-TECHNICAL LOSSES IN ELECTRICAL POWER SYSTEMS " Master Degree, Ohio University, 2002.

[11] U. H. Bezerra, T. M. Soares, M. V. A. Nunes, M. E. L. Tostes, J. P. A. Vieira, P. Agamez, *et al.*, "Non-Technical Losses Estimation in Distribution Feeders Using the Energy Consumption Bill and the Load Flow Power Summation Method", presented at the ENERGYCON 2016, Leuven, Belgium, 2016.

[12] S. Agrawal and V. Bhuria, "Determination of Nontechnical Losses via Matlab Environment " *International Journal of Advanced Research in Computer Engineering and Technology (IJARCET)* vol. 2, June 2013 2013.

[13] A. Chauhan and S. Rajvanshi, "Non-Technical Losses in power system: A review", presented at the International Conference on Power, Energy and Control (ICPEC), Sri Rangalatchum Dindigul, 2013.

[14] J. R. Aguero, "Improving the efficiency of power distribution systems through technical and non-technical losses reduction", presented at the Transmission and Distribution Conference and Exposition (T&D), 2012 IEEE PES, Orlando, FL, 2012.

[15] M. Anas, N. Javaid, A. Mahmood, S. M. Raza, U. Qasim, and Z. A. Khan, "Minimizing Electricity Theft using Smart Meters in AMI", presented at the 2012 Seventh International Conference on P2P, Parallel, Grid, Cloud and Internet Computing, Victoria, BC, 2012.

[16] P. Rengaraju, S. R. Pandian, and C.-H. Lung, "Communication networks and non-technical energy loss control system for smart grid networks", presented at the Innovative Smart Grid Technologies - Asia (ISGT Asia), 2014 IEEE, Kuala Lumpur, 2014.

[17] S. S. S. R. Depuru, L. Wang, and V. Devabhaktuni, "Electricity theft: Overview, issues, prevention and a smart meter based approach to control theft", *Elsevier,* vol. 39, pp. 1007-1015, 2 November 2010 2010.

[18] R. D. Christie, H. Zadehgol, and M. M. Habib, "High impedance fault detection in low voltage networks," *IEEE Transactions on Power Delivery* vol. 8, pp. 1829 - 1836 Oct 1993.

[19] J. Vico, M. Adamiak, C. Wester, and A. Kulshrestha, "High impedance fault detection on rural electric distribution systems," presented at the Rural Electric Power Conference (REPC), 2010 IEEE Orlando, FL 2010.

[20] ERSE -Energy Services Regulatory Authority, *"Regulated Tariffs and Prices for 2016".*

[21] ERSE – Energy Services Regulatory Authority, “Parâmetros de Regulação da Qualidade de Serviço do Setor Elétrico”, (in Portuguese) “Diário da República”, 2th Series – Nº227 Nov. 2013: pp.34305-34313.

[22] C. C. O. Ramos, A. N. Souza, J. P. Papa, and A. X. Falcao, "Fast Non-Technical Losses Identification Through Optimum-Path Forest", presented at the ISAP '09. 15th International Conference on Intelligent System Applications to Power Systems, Curitiba, 2009.

[23] Í. Monedero, F. Biscarri, C. León, J. Biscarri, and R. Millán, "MIDAS: Detection of Non-technical Losses in Electrical Consumption Using Neural Networks and Statistical Techniques", in *Computational Science and Its Applications - ICCSA 2006: International Conference, Glasgow, UK, May 8-11, 2006,* pp. 725-734.

[24] J. Nagi, A. M. Mohammad, K. S. Yap, S. K. Tiong, and S. K. Ahmed, "Non-Technical Loss analysis for detection of electricity theft using support vector machines", presented at the Power and Energy Conference, 2008. PECon 2008. IEEE 2nd International, Johor Bahru, 2008.

[25] V. N. Vapnik, *Statistical Learning Theory*: Wiley-Interscience, 1998.

[26] J. P. Papa, A. X. Falcão, and C. T. N. Suzuki, "Supervised Pattern Classification based on Optimum-Path Forest", *Intl. Journal of Imaging Systems and Technology,* vol. 19, pp. 120–131, Jun 2009 2009.

[27] S.-C. Huang, Y.-L. Lo, and C.-N. Lu, "Non-Technical Loss Detection Using State Estimation and Analysis of Variance", *IEEE Transactions on Power Systems,* vol. 28, pp. 2959 - 2966, 10.1109/TPWRS.2012.2224891 2013.

[28] F. V. D. BERGH, P. KADUREK, S. COBBEN, and W. KLING, "ELECTRICITY THEFT LOCALIZATION BASED ON SMART METERING", presented at the 21st International Conference on Electricity Distribution, Frankfurt, 2011.

[29] P. Faria, Z. Vale, P. Antunes, and A. Souza, "Using baseline methods to identify non-technical losses in the context of smart grids," presented at the Innovative Smart Grid Technologies Latin America (ISGT LA), 2013 IEEE PES Conference On Sao Paulo 2013.

[30] M. I. d. M. P. M. Vaz, "Controlo de Tensão em Redes de Baixa Tensão por Atuação em Recursos Distribuídos", Master Dissertation, Electrical, FEUP, Porto, 2015.

[31] J. N. d. Santos and J. R. Ferreira, *Redes de Distribuição de Energia Eléctrica Em Baixa Tensão*. Available: http://paginas.fe.up.pt/~jns/material_didatico/redesBT.pdf. Accessed: 10/05/2016

[32] E. Diaz-Dorado, E. Miguez, and J. Cidras, "Design of large rural low-voltage networks using dynamic programming optimization", *IEEE Transactions on Power Systems,* vol. 16, Nov 2001.

[33] *Electrical Grid*. Available: http://tacs.eu/analyses/Energy/electrical-grid.htm. Accessed: 15/06/ 2016

[34] W. H. A. SCHILDERS and E. J. W. T. MATEN, *Numerical Methods in Electromagnetics, Volume 13: Special Volume*, 1st Edition ed.: North Holland, 2005.

[35] *Regulamento de Segurança de Redes de Distribuição em Baixa Tensão,* 177-184, 1984.

[36] P. N. P. Barbeiro, J. Krstulovic, H. Teixeira, J. Pereira, F. J. Soares, and J. P. Iria, "State estimation in distribution smart grids using autoencoders", presented at the Power Engineering and Optimization Conference (PEOCO), 2014 IEEE 8th International Langkawi 2014.

[37] A. Abdel-Majeed, S. Tenbohlen, D. Schöllhorn, and M. Braun, "Development of state estimator for low voltage networks using smart meters measurement data " presented at the PowerTech (POWERTECH), 2013 IEEE Grenoble.

[38] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, "A Three-Phase Power Flow Approach for Integrated 3-Wire MV and 4-Wire Multigrounded LV Networks With Rooftop Solar PV", *IEEE Transactions on Power Systems,* vol. 28, pp. 1728 - 1737 16 November 2013.

[39] R. M. Ciric, A. P. Feltrin, and L. F. Ochoa, "Power flow in four-wire distribution networks-general approach", *IEEE Transactions on Power Systems* vol. 18, pp. 1283 - 1290 17 Novembro 2003

[40] "Phase identification in smart grids" presented at the Smart Grid Communications (SmartGridComm), 2011 IEEE International Conference on Brussels 2011.

[41] H. PULCE and P. ACHAICHIA, "ERDF G3-PLC LINKY SYSTEM: A ROBUST AND FUTURE PROOF SOLUTION FOR LARGE SCALE AMM PROJECTS", presented at the 23rd International Conference on Electricity Distribution, Lyon, 2015.

[42] P. D. F. Ferreira, P. M. S. Carvalho, L. A. F. M. Ferreira, and M. D. Ilic, "Distributed Energy Resources Integration Challenges in Low-Voltage Networks: Voltage Control Limitations and Risk of Cascading," *IEEE Transactions on Sustainable Energy* vol. 4, pp. 82 - 88, 25 Julho 2012

[43] IEEE. *Distributed Energy Resources Integration in Distribution*. Available: http://smartgrid.ieee.org/newsletters/november-2015/distributed-energy-resources-integration-in-distribution

[44] "Smart metering and functionalities of smart meters in smart grid - a review," presented at the Electrical Power and Energy Conference (EPEC), 2015 IEEE London, ON.

[45] N. Silva, "Smart Grid solutions and current projects deployment: InovGrid project," *Energize Journal,* Jan/Feb 2013. 2013.

[46] W. H. Kersting, *Distribution System Modeling and Analysis, Third Edition*, Third Edition ed.: CRC Press.
[47] *Conexión de receptores en un sistema trifásico*. Available: http://www.proyecto987.es/trifasica_3.html. Accessed: 15/05/2016
[48] T.-H. Chen and W.-C. Yang, "Analysis of multi-grounded four-wire distribution systems considering the neutral grounding," *IEEE Transactions on Power Delivery,* vol. 16, pp. 710-717, Oct. 2001.
[49] L. F. O. Pizzali, "Cálculo De Fluxo De Potência Em Redes De Distribuição Com Modelagem A Quatro Fios," Master Dissertation, Electrical, Universidade Estadual Paulista "Júlio De Mesquita Filho", São Paulo, 2003.
[50] R. C. Dugan, "The Open Distribution System Simulator (OpenDSS) - Reference Guide", I. Electric Power Research Institute, 2013.

Annex A

Table A1 - Consumers' Contracted Powers

Busbar	**Phase A (kVA)**	**Phase B (kVA)**	**Phase C (kVA)**
2	3,45	3,45	0
5	0	0	3,45
6	3,45	0	0
7	10,35	0	0
8	0	0	6,9
9	6,9	3,45	3,45
10	3,45	10,35	0
11	3,45	0	6,9
12	3,45	3,45	0
13	6,9	3,45	3,45
16	0	6,9	0
17	10,35	0	0
18	0	3,45	3,45
19	3,45	3,45	0
20	0	3,45	3,45
21	0	6,9	0
22	10,35	3,45	3,45
23	0	0	3,45
24	0	6,9	10,35
25	0	3,45	10,35
26	0	10,35	0
27	6,9	3,45	3,45
28	0	6,9	0
29	3,45	3,45	10,35
30	0	0	10,35
31	0	6,9	0
32	0	3,45	3,45
33	0	0	3,45

Table A2 - Branches' Impedances

Branch	From Busbar	To Busbar	R [Ω] (Phase and Neutral)	X [Ω] (Phase and Neutral)
1	1	2	0,0567	0,0085
2	1	3	0,0190	0,0040
3	1	4	0,0367	0,0055
4	2	5	0,0310	0,0065
5	3	6	0,0769	0,0180
6	3	7	0,0700	0,0105
7	4	8	0,0667	0,0100
8	5	9	0,0467	0,0070
9	5	10	0,1040	0,0053
10	5	11	0,2187	0,0105
11	6	12	0,2917	0,0140
12	7	13	0,0233	0,0035
13	8	14	0,1989	0,0098
14	8	15	0,1242	0,0098
15	9	16	0,0233	0,0035
16	11	17	0,2496	0,0053
17	11	18	0,0955	0,0075
18	12	19	0,0381	0,0080
19	13	20	0,1528	0,0120
20	13	21	0,4841	0,0158
21	14	22	0,1212	0,0255
22	15	23	0,2674	0,0210
23	16	24	0,0467	0,0035
24	18	25	0,1614	0,0053
25	19	26	0,0238	0,0050
26	20	27	0,1875	0,0090
27	23	28	0,0935	0,0210
28	24	29	0,1844	0,0060
29	26	30	0,0533	0,0040
30	27	31	0,2142	0,0105
31	28	32	0,3227	0,0105