A Study on the Restructuring of LV Networks

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Electrical and Computer Engineering

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Para o meu avô.

Declaration

I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

The scarcity of non-renewable energy resources such as coal, oil, and natural gas, combined with growing environmental awareness among the population, has sparked interest in renewable generation alternatives and non-polluting transportation methods. Many countries have implemented legislation to encourage consumers to produce electricity locally and offer incentives for electric vehicle (EV) users.

However, the widespread integration of these resources into the electrical grid presents two major challenges. Firstly, the inclusion of distributed generation (DG) enables power injection at the distribution level or even at the end-consumer level, disrupting the traditional centralized generation paradigm. Secondly, the power flow through the grid significantly increases during periods of excess photovoltaic generation or simultaneous EV charging, ultimately causing problems in the quality of service (QoS).

While investing in operational flexibility technologies helps distribute power flow more efficiently throughout the day, the average load still experiences a substantial rise. Thus, successfully managing these changes depends on the network operator's investment in new infrastructure and grid reinforcement to ensure all network functions are maintained and the quality of service (QoS) is upheld.

Given the anticipated growth in DG penetration and EV adoption, it is crucial to reinforce the low-voltage electrical grid (LV). This study aims to assess the impact of DG and EV integration on QoS and propose a restructuring approach for the LV grid to accommodate these technologies while adhering to standard power quality requirements.

To achieve this objective, two distinct networks are examined: a model network and a realistic network. The proposed restructuring is applied to both networks, and the simulation results are then compared to evaluate the effectiveness of the proposed solution.

Keywords: Electric Vehicles, Distributed Generation, Quality of Service, Grid Reinforcement

Resumo

A escassez dos recursos energéticos não renováveis como carvão, óleo e gás natural, aliada a uma maior consciencialização ambiental por parte da população, suscitou o interesse em alternativas de geração renováveis e em maneiras de transporte não-poluentes. Em muitos países surgiu legislação para incentivar os consumidores a produzirem eletricidade localmente, assim como benefícios para utilizadores de veículos elétricos (VEs).

A integração destes recursos em massa na rede elétrica vai causar dois grandes problemas: Em primeiro lugar, a integração de geração distribuída (GD) torna possível a injeção de potência na rede a nível da distribuição ou mesmo no nível do consumidor final. Sendo que o sistema elétrico foi concebido com o paradigma da geração centralizada, existe uma alteração de dinâmica do sistema. Em segundo lugar, a potência que estará a transitar na rede elétrica será muito mais elevada durante alturas em que existe um excesso de geração fotovoltaica ou quando existe um carregamento simultâneo de EVs, podendo causar problemas na qualidade do serviço (QoS).

O investimento em tecnologias de uso de flexibilidade operacional sem dúvida que ajudará a distribuir melhor o transito de potência ao longo das 24h do dia, mas a carga média ainda sofrerá uma subida considerável. Assim, toda esta nova gestão estará dependente do investimento do operador de rede em novas infraestruturas e no reforço da rede elétrica, assegurando assim todas as funções da rede e toda a qualidade de serviço.

Numa perspetiva de grande crescimento de penetração de GD e de compra de VEs, é então fundamental reforçar a rede elétrica de baixa tensão (BT). O objetivo deste trabalho é avaliar o impacto que a introdução de GD e de VEs tem na QoS e restruturar a rede elétrica de BT de maneira a tornar a rede capaz de acomodar estas tecnologias, mantendo-se dentro dos valores standard de qualidade de energia.

De maneira a atingir o objetivo deste trabalho, são analisadas duas redes distintas: uma rede modelo e uma rede realista, aplicando a restruturação proposta a cada uma delas e comparando os resultados obtidos na simulação.

Palavras-Chave: Veículos Elétricos, Geração Distribuída, Qualidade de Serviço, Reforço na Rede Elétrica

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Acronyms

BEV	Battery Electrical Vehicle
DER	Distributed Energy Resources
DG	Distributed Generation
DSO	Distribution System Operator
EHV	Extra-High Voltage
EPS	Electric Power System
EV	Electrical Vehicle
HEV	Hybrid Electric Vehicle
HV	High Voltage
KCL	Kirchhoff's Current Law
KVL	Kirchhoff's Voltage Law
LV	Low Voltage
MV	Medium Voltage
OPF	Optimal Power Flow
PHEV	Plug-in Hybrid Electric Vehicle
PDN	Power Distribution Network
QoS	Quality of Service
RES	Renewable Energy Systems

Nomenclature

C_t Total Investment

I Current

m Transformer Tap Regulator

n Total number of nodes of the grid

p Perturbance Variables

P Active Power

P_{max} Grid Capacity

Q Reactive Power

S Apparent Power

S_C Load Power

S_G Generated Power

u Control Variables

V Voltage

x State Variables

Y Admittance

Z Impedance

Z_{cc} Short-Circuit Impedance

γ Price per Kilowatt

ϵ Minimum Error

ν Current Iteration of the Power Flow

Chapter 1

Introduction

This chapter provides a comprehensive overview of the dissertation topic and explains the motivation and relevance behind the development of this work.

The main objectives to be achieved are outlined and the structure of the thesis is presented, briefly introducing the topics covered in each chapter.

1.1 Motivation

At the end of the 20th century, the perception that fossil fuels such as coal, oil, and natural gas are finite resources, as well as a greater environmental awareness, caused a shift in the world's energy paradigm. The need to generate energy without polluting the environment and to ensure a sustainable future resulted in the advent of the so-called renewable energies such as hydro, wind, and photovoltaic energy.

In this sense, in 1992, almost all countries in the world signed the United Nations Framework Convention on Climate Change, an international treaty that imposes limits on greenhouse gas emissions [7]. Periodically, the Convention's member countries meet to update the treaty, and the Kyoto Protocol was one of the most important updates. The last conference was held in Paris in 2015, where 195 countries, including Portugal, agreed on a new set of goals and measures to combat global warming.

Portugal is a country with favorable characteristics for the exploitation and use of renewable energies, and the incentives given by the government, as well as the need to comply with the above-mentioned international commitments, have led to an increase in renewable production year after year.

As can be observed in Figure 1.1, since 2011, over half of the installed power comes from renewable sources. Special mention goes to hydro sources, which have had significant importance since the beginning of the 21st century, but have been increasing in the last decade. Another special mention goes to solar sources, which have experienced a mass integration in recent years, with a significant increase in contribution in 2021 and 2022.

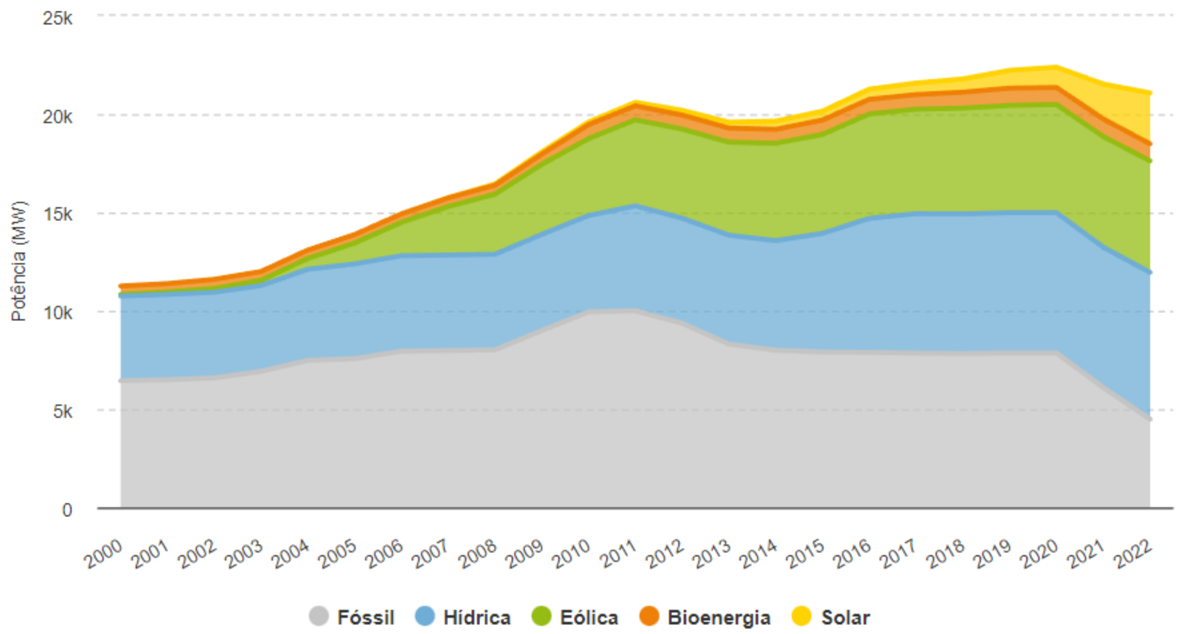

Figure 1.1: Power installed by different sources in Portugal in the 21st century [2]. As seen, recently, solar generation has been increasing.

In the same line of thought, Figure 1.2 displays the energy production in Portugal from different sources since 2015. It is evident that non-renewable thermal energy production has been decreasing sharply since 2017, while renewable energy production has been increasing. Among these renewable energies, the one that experienced the most significant percentage increase in recent years was photovoltaic energy production. Although it still represents an insignificant value in the energy mix, its high potential in Portugal, as it is the country with the highest number of sunshine hours per year in Europe, predicts that photovoltaic solar energy will be the major renewable investment in the coming years.

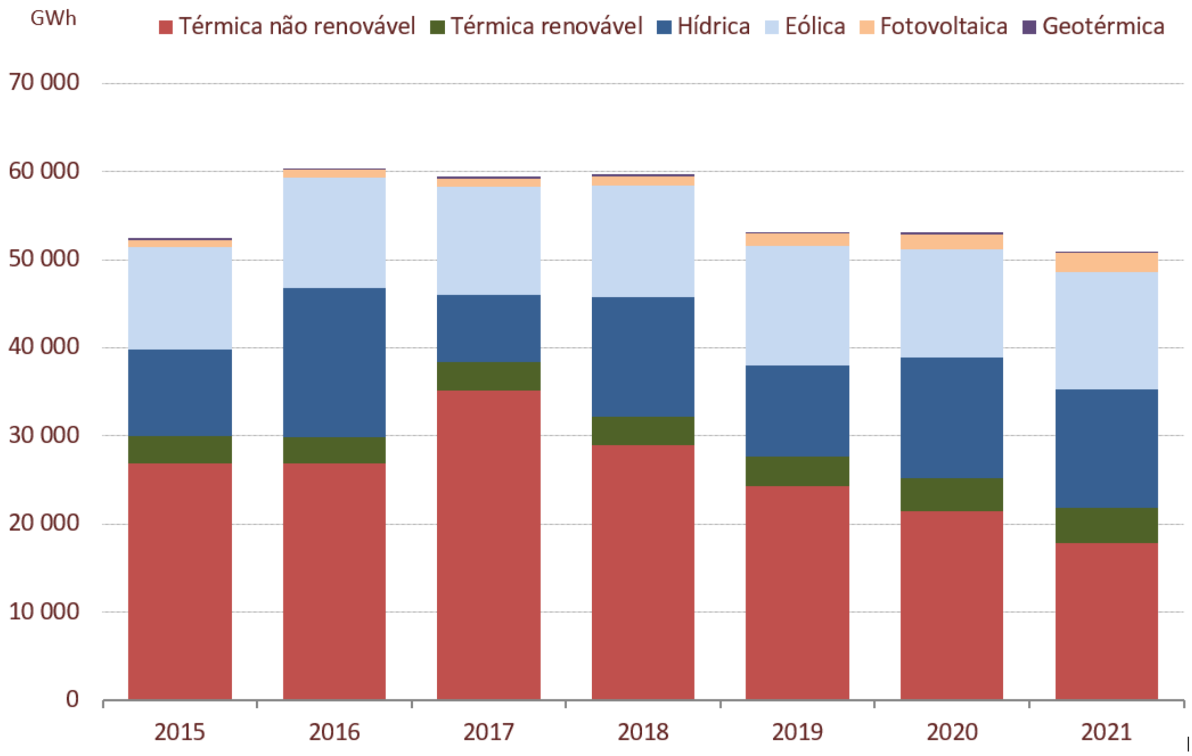

Figure 1.2: Electricity production by different sources in Portugal since 2015 [9]. Notice, once more, the recent rise in photovoltaic energy produced.

In this sense, it is essential to have a thorough understanding of this type of energy generation, particularly in its distributed generation (DG) aspect and its insertion into the energy grid, along with its consequences. This will be one of the main pillars that this work will focus on.

Within the context of environmental awareness and the guarantee of a sustainable future, it is crucial to recognize that it is not only energy generation that is experiencing rapid changes. Various other propaganda and awareness initiatives are influencing people's everyday lives, shaping their actions and consumption choices. One notable example is electric mobility, which is poised to impact a significant portion of the population in the near future.

The transportation sector is responsible for over one-third of global greenhouse gas emissions, with light vehicles accounting for 52% and other modes of transport making up the remaining 48%. In light of the climate and health emergency, many countries have implemented a combination of incentive-based and coercive public policies. These policies aim to achieve two main objectives: enhancing air quality and mitigating the carbon footprint of transportation.

In this way, electric vehicles (EVs) serve as a launching pad for decarbonizing the transportation sector. Figure 1.3 illustrates a comparison between the sales of light vehicles in Portugal in 2020 and 2022. It can be observed that the purchase of light vehicles solely fed by fossil fuels decreased by approximately 15%. This decrease was offset by a 7% increase in purely electric vehicles and an 8% increase in hybrid vehicles.

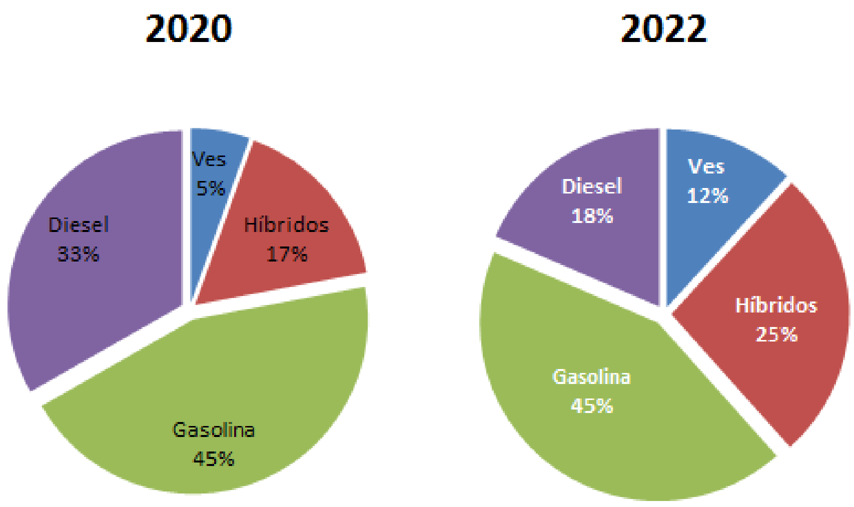

Figure 1.3: Comparison of light vehicles sold in Portugal (2020 vs 2022) [3]. Notice there's been an uprising in "cleaner" vehicles.

It is worth noting that, although the current focus is on hybrid vehicles due to their inherent technologies, policies have already been implemented to ensure that electric vehicles become the primary mobility alternative within the next 20 to 30 years. These policies are mainly being implemented in China, the United States, and the European Union, which accounted for 95% of global electric vehicle sales in 2022. These include [23]:

- Progressive government incentives for electric vehicles;
- Substantial investment in electric vehicle charging infrastructure;
- Strong promotion of sustainable transportation.

In Figure 1.4, the worldwide sales of electric cars per year can be observed since 2013. Upon inspection, it is evident that the emergence of EVs has been increasing dramatically. In 2013, the sale of electric vehicles represented only 0.2% of the market share, whereas by 2019, this value had already increased to 2.5%. Furthermore, from 2019 onwards, the market share of electric cars has nearly doubled each year, reaching 13% in 2022. It is also worth noting that when comparing sales of fully electric cars (BEVs) with hybrid vehicles, BEVs have consistently accounted for the majority of sales.

Assuming the assertion that the quantity of EVs in the coming decades will significantly exceed the current levels, the impact of this surge on the electrical grid will be another key aspect of this study.

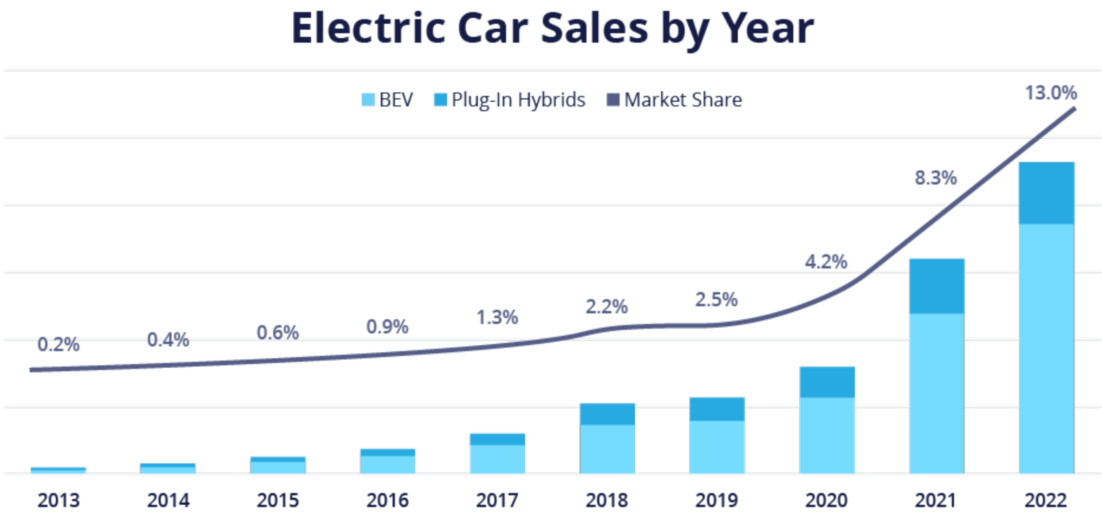

Figure 1.4: Worldwide electric car sales by year [23]. Notice the exponential rise of the market share of the electric car sales in recent times.

1.2 Objectives

This dissertation aims to restructure the low voltage (LV) network to accommodate the integration of photovoltaic generation and electric vehicles. Two distinct networks are studied, one with photovoltaic generation and the other with electric vehicles. After incorporating these elements, the network's compliance with quality of service (QoS) requirements is assessed, and the network is restructured accordingly. Subsequently, the resulting network's QoS levels are taken into account once again.

Additionally, an investment analysis is conducted for one of the networks to determine whether the implemented restructuring leads to a profitable investment or if it lacks economic advantages.

This dissertation endeavors to bridge gaps and enhance previous research in the field, which has primarily focused on sustainability culture and energy efficiency. It offers a potential solution to address the infrastructure needs essential to achieve the desired goals, while simultaneously preserving all existing network functionalities and maintaining quality of service. By doing so, it aims to complement and provide valuable insights into this area of study.

1.3 Structure of the dissertation

The following dissertation is divided into six chapters:

- Chapter 1 provides the contextualization of the topic within the current energy landscape, highlighting its relevance, the motivations behind the research, the problem addressed, and the objectives to be achieved.
- Chapter 2 presents the key concepts that characterize distributed generation, along with its advantages and disadvantages compared to centralized production. The topic of decentralized production is combined with electric vehicles, incorporating the theme of operational flexibility, evaluating its consequences for the energy grid. Relevant work in the field are presented, and the proposed restructuring solution is introduced.
- Chapter 3 presents the mathematical foundation of power flow, which serves as the primary tool for network calculations in the subsequent chapters.
- Chapter 4 presents a study of a grid model, where the proposed restructuring solution is applied. Various sources of distributed generation are included alongside the loads, and the performance of the model grid is compared before and after the process of restructuring.
- Chapter 5 presents a study of a realistic and therefore more complex grid. The proposed restructuring solution is implemented gradually, considering the practical nature of the network. Electric vehicles are introduced, and the performance of the original grid is compared with each iteration of the restructured ones. Additionally, an investment analysis is conducted for each of the cases under study, taking into account the associated equipment costs.
- Finally, Chapter 6 provides a summary of the obtained results, draws conclusions, and suggests possible future work to continue and/or complement the research conducted in this dissertation.

Chapter 2

Background and Related work

This chapter is mainly focusing on further developing of the background of the problem being discussed and on the related work done on that topic.

Firstly, the key aspects of the motivation behind the restructuring of the LV grid are discussed and given thorough explanation:

- The Generation paradigms - the shifting between a centralized generation system and a distributed generation system;

- The electrified transportation (or electric mobility) - mainly the insurgence of EVs in the present and in the future;

- The problem of electric efficiency - depicted in the form of a smart grid perspective and operational flexibility usage.

Then, a summary of all the information gathered and the importance these topics have to the purpose of this thesis is done, revisiting and further developing the problem being dealt with.

Afterwards, the proposed solution is exposed, depicting its main goals, along with its expected advantages.

Finally, a review of the related work done on the topic is done, starting by the studies in the inclusion distributed generation, and ending on the flexibility usage and EV inclusion.

2.1 Historical evolution

In the initial stages of the electrical grid's development, its primary objective was to achieve widespread electrification by establishing connections to all consumers and investing in distribution infrastructure. This process followed a radial, vertically expanding approach, aiming to connect power generation facilities to consumers through efficient and loss-minimizing pathways.

Under this framework, serving new customers was relatively straightforward, involving the extension of cables and the creation of new independent feeder systems that were easy to protect.

However, as electricity became indispensable in the daily lives of the majority of the population, thanks to the successful electrification efforts, the predominant paradigm of electrical grid management underwent a significant shift. The focus shifted towards ensuring power quality as the primary objective of the power distribution network (PDN), recognizing that any disruptions or failures in the electrical network could have substantial economic consequences for consumers.

This new paradigm was tackled in the planning of the distribution grid: In 1997, the authors in [20] summarized the topics considered in the traditional grid planning:

- Optimal feeder placement (location) and individual design;
- Optimal allocation of load;
- Optimal substation capacity allocation;
- Optimal allocated transformers per substation.

The objective of this type of planning is to mainly find the most optimal (economical) solution regarding all the available feeders, substations and transformers available, as well as creating new ones to supply future demand [14] (grid reinforcement).

Distribution networks have traditionally been designed to facilitate the transmission of electric energy from conventional power plants to connected loads, resulting in a unidirectional flow of power. This topological arrangement requires the network to be appropriately structured to handle critical load conditions and ensure reliable power delivery.

In order to achieve this, planning the evolution of the traditional grid has been facilitated by two crucial methods: load forecasting and grid reinforcement.

- Load forecasting [18] involves predicting future electricity consumption patterns based on historical data, socio-economic factors, and technological advancements. This allows grid operators to anticipate changes in demand and plan infrastructure upgrades accordingly.
- Grid reinforcement, on the other hand, involves upgrading and expanding the existing grid infrastructure to accommodate increased load requirements and ensure its reliable operation.

By employing load forecasting and grid reinforcement strategies, grid planners could effectively manage the evolving energy needs and optimize the performance of the electrical grid.

2.2 Generation Paradigms

2.2.1 Centralized Generation

In a typical Electric Power System (EPS), the majority of electrical energy is generated in large power plants (thermal or hydro) located far away from consumption centers due to technical and economic reasons, such as the availability of primary energy resources and infrastructural and environmental constraints. Subsequently, this energy is transmitted through extra-high voltage (EHV) lines and then, by means of transformers, is transferred to high, medium, and low voltage distribution networks (HV, MV, and LV) that deliver the energy to consumers (Figure 2.1). This type of structure ensures economies of scale, reliability, security, and quality of energy delivery through centralized control. This configuration is known as Centralized Generation.

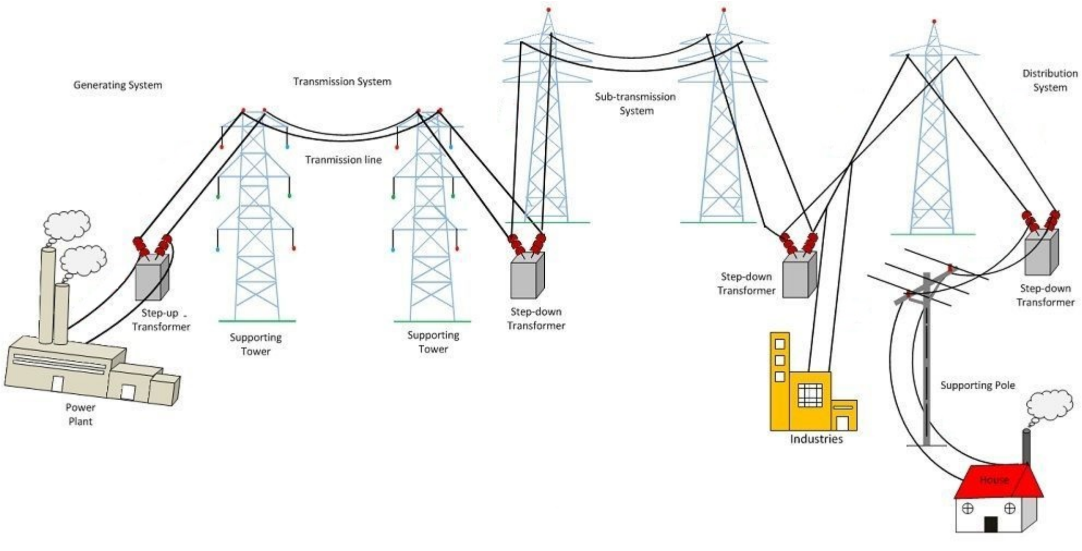

Figure 2.1: Centralized Electric Power System. The flow of power is unidirectional, flowing from the big power stations onto the clients, without other possible paths.

Furthermore, Centralized Generation provides a high level of reliability and quality of energy delivery. Large power plants are designed to operate continuously and efficiently, providing a stable and consistent power supply to consumers. The centralized nature of the generation infrastructure allows for effective maintenance and repairs, ensuring minimal downtime and quick restoration of service in the event of disruptions or outages. This reliability is essential for critical infrastructure, industrial operations, and residential consumers who depend on a continuous and uninterrupted power supply.

Despite the advantages of Centralized Generation, there are also some limitations and challenges associated with this model. These include the reliance on long-distance transmission networks, potential transmission losses, and vulnerability to disruptions in centralized generation facilities. Additionally, the centralized nature of this model may not be well-suited for accommodating distributed energy resources (DER) such as renewable energy systems (RES), which are increasingly being integrated into the grid [25].

In recent years, there has been a growing interest in exploring alternative models, such as Distributed

Generation [21] and Microgrids, which aim to decentralize power generation and enhance the resilience and flexibility of the power system. These models offer opportunities for localized generation, increased utilization of renewable energy sources, and improved grid resilience through enhanced local control and coordination. The integration of these decentralized approaches with Centralized Generation represents a significant research and development area in the quest for a more sustainable and resilient Electric Power System [24] [17].

2.2.2 Distributed Generation

The emergence and advancement of distributed generation (DG) have been driven by the pressing need to address the current energy crisis and the primary motivation to preserve the environment. This form of electricity production initially gained momentum at the medium and high voltage levels, leveraging cogeneration systems, small-scale hydroelectric plants, and wind farms that establish direct connections to distribution grids through dedicated branches or T-connections linked to existing lines, as seen in Figure 2.2 taken from [27].

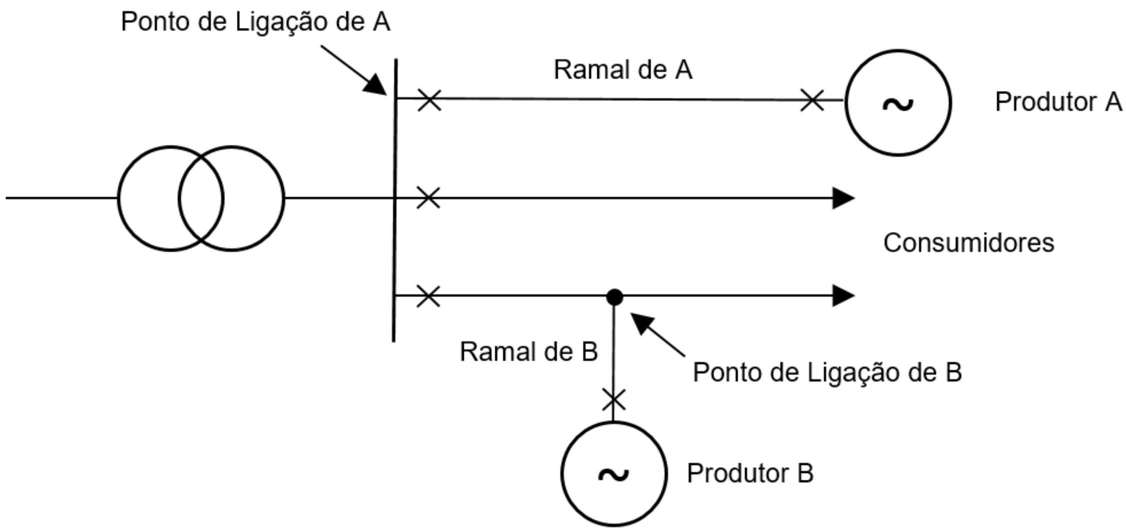

Figure 2.2: Connection between DG and the distribution grid [27]

Distribution networks, with a radial topology, were designed to deliver energy supplied by the transmission network to consumers following a well-defined path with unidirectional power flow. The introduction of DG changes this situation, as energy is injected at various points within the network, potentially altering the direction of power flow. This can be observed in Figure 2.3, which depicts a comparison between the classical power system with centralized generation and the current electrical power system with potential generation at all levels, potentially resulting in bidirectional power flow - when local consumption is low compared to distributed generation, the surplus energy causes a reversal of power flow at the connection points with the transmission network. In terms of the distribution network, for safety reasons, the capacity of transmission lines and the breaker interrupting capacity must not be exceeded by the connection of DG to the network [27].

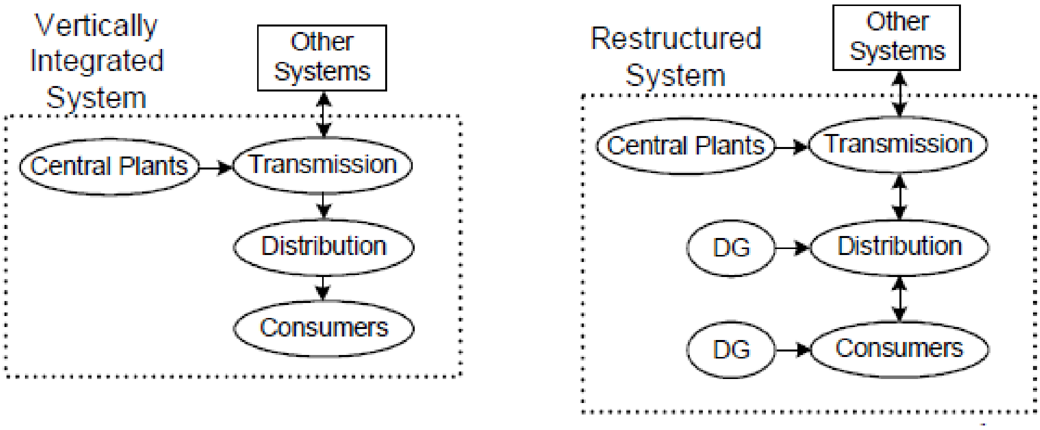

Figure 2.3: Comparison of the power system before and after DG [1]. DG appears at every level, even at the lowest consumer/client level.

When compared to the centralized generation system, the inclusion of DG presents various advantages, such as:

- Allows for the generation of energy near the consumption locations, reducing losses associated with electrical energy transportation and contributing to a decrease in power flows;
- Has a low environmental impact, as most employed technologies are renewable;
- Reduces dependence on centralized generation, enabling partial or total supply to load centers;
- Contributes to the opening of the energy market by creating specific legal regulations that can represent significant commercial opportunities.

On the other hand, DG also comes with several disadvantages [4] [6]:

- Increases complexity in the planning and operation of the EPS, as decision-making power is not centralized;
- Increases complexity in procedures and maintenance, including safety measures and coordination of activities;
- Causes disturbances in the QoS, such as voltage fluctuations, unbalance in the three-phase voltage system, harmonic distortion, among others;
- Exhibits intermittent generation, as it depends on uncontrollable factors such as wind or solar availability and consistency;

Nowadays, electrical energy must comply with well-defined quality criteria such as constant frequency, voltage within narrow limits, sinusoidal waveform, and high reliability. Modern technological applications require extremely high levels of reliability (around 99.99%, which corresponds to less than 1 minute of unavailability per year), something practically impossible to achieve solely with centralized generation. Therefore, the inclusion of DG can emerge as a solution to address these types of issues.

Furthermore (and connecting to the next topic), an increasing number of people are acquiring EVs, which impose a high demand on the grid. This represents another application of DG, along with the increasingly prevalent operational flexibility management technologies [22] [35].

2.3 Electric mobility

Electric mobility, also known as e-mobility, encompasses the utilization of electric vehicles (EVs) as a greener alternative to conventional internal combustion engine vehicles. It represents a transformational shift in our transportation sector, driven by advancements in battery technology, supportive government policies, and the growing recognition of the urgent need to reduce greenhouse gas emissions and combat air pollution.

Currently, there are various types of electric vehicles. What sets them apart is the amount of time the vehicle operates in electric mode (using batteries) compared to the time it operates using a combustion engine. Naturally, the more the vehicle relies on battery usage, the more dependent it becomes on electric charging stations, the larger the batteries need to be in terms of storage capacity, and consequently, the higher the consumption on the electrical grid. The types of EVs are [16]:

- Battery Electric Vehicles (BEVs): These vehicles are fully electric and rely solely on rechargeable batteries for power. They produce zero tailpipe emissions and offer a longer range compared to other types of EVs;

- Plug-in Hybrid Electric Vehicles (PHEVs): PHEVs combine an internal combustion engine with a battery and electric motor. They can operate in electric mode for shorter distances and switch to gasoline/diesel mode for longer trips [29] [8];

- Hybrid Electric Vehicles (HEVs): HEVs use both an internal combustion engine and an electric motor. The electric motor assists the engine and improves fuel efficiency but cannot be solely powered by electricity.

The environment is an increasingly prominent concern among the public. This is evidenced by initiatives such as the "WeEuropeans" campaign at the European level, which involved the participation of nearly 1.5 million Europeans in April 2016. It indicates that environmental issues are gaining importance in people's daily lives. In France [28], 40% of respondents identified the environment as a top concern. Specifically, air pollution is considered a priority issue for action by 20% of the respondents. The public concern directly translates into an increase in sales of electric vehicles, as shown in Figure 1.4.

As each electric vehicle draws a substantial amount of power during the charging process (ranging from 2 or 3 kW for PHEVs to as high as 10 kW for BEVs), the notable surge in electric vehicle adoption leads to disruptive effects on the power grid, primarily due to simultaneous charging concerns in residential settings [8] [26].

2.4 Flexibility

The ongoing energy transition is leading to an increasing investment in this field year after year. Figure 2.4 illustrates the global investment in energy transition technologies between 2010 and 2021. It can be observed that the investment has been growing every year, reaching 998 billion USD in 2021. Furthermore, it can be noted that there are three major segments within the investments in this area: renewable energy sources, electrified transportation, and energy efficiency.

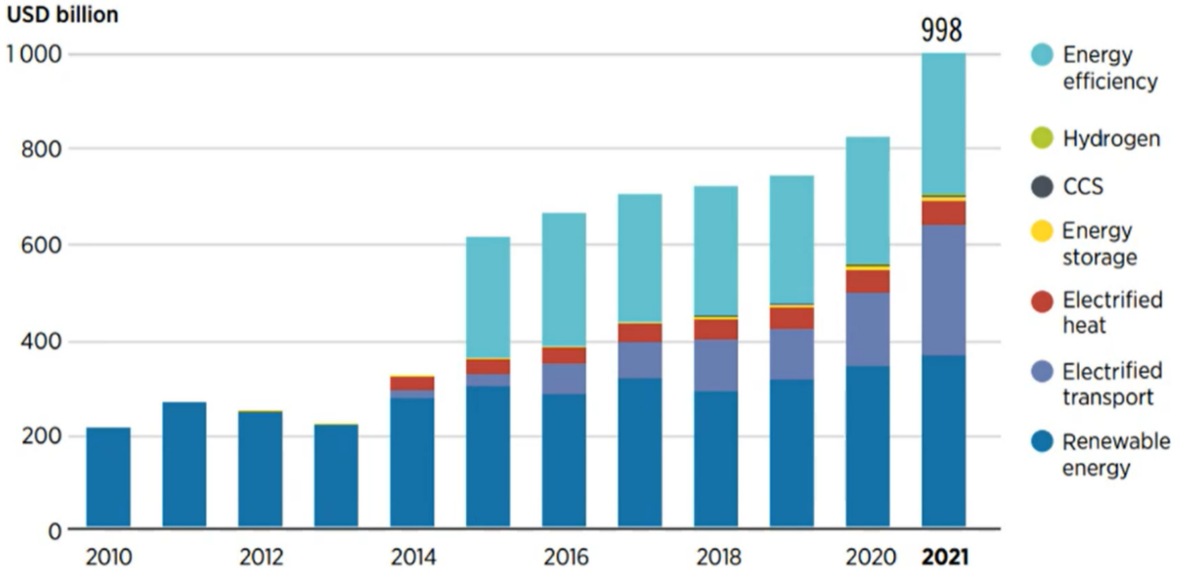

Figure 2.4: Global investment in energy transition technologies.

Having already discussed the impact of renewable energies and electrified transportation on the electrical grid, in the form of DG and EVs respectively, energy efficiency is another highly prominent topic in the present time. This is evident from the significant amount of investment in this area, which is closely linked to the topic of operational flexibility in the electric power system [11].

Operational flexibility refers to the ability of a system or organization to adjust and adapt its operations in order to better respond to changes in demand, supply, or external conditions. In the context of the electric power system, operational flexibility refers to the capability of the system to accommodate and integrate variable energy sources (such as renewable energy generation), variable loads (such as electric vehicles) and to effectively manage fluctuations in electricity demand.

From a practical perspective, operational flexibility is nothing more than the system's ability to change the power consumed by an electric vehicle during charging or the power injected into the grid by a solar panel, transforming these formerly uncontrollable variables into controllable variables for the electric system. This opens up an infinite range of possibilities in actively managing the grid, which inevitably adopts the term ”smart grid” [32] [15].

The concept of a smart grid has emerged as a catalyst for transforming the operation of power systems [32]. Drawing on the framework of control theory, the term ”smart grid” encompasses all endeavors aimed at enhancing the ability to observe and control various processes within the power system. This includes managing the inflow and outflow of power to and from the grid, as well as the power exchanges occurring on both the demand and supply sides at all voltage levels of the electricity grid. By improving the observability and controllability of individual units within the power system, there is an expectation for a corresponding enhancement in the overall observability and controllability of the entire power system and its underlying processes.

Operating power systems in this increasingly complex environment necessitates a thorough evaluation of the available operational flexibility at each moment in time. This comprehensive assessment enables optimal management and mitigation of the challenges that arise. Figure 2.5 depicts the potential sources of operational flexibility in the energy system. As suggested, these sources of flexibility can be categorized as either fully controllable (allowing for adjustable injection of power) or curtailable (allowing these to be removed from operation, like a binary variable [5]). It is worth noting that, with the right technology, many of these curtailable sources of flexibility can be transformed into fully controllable ones, such as wind power plants or industrial loads.

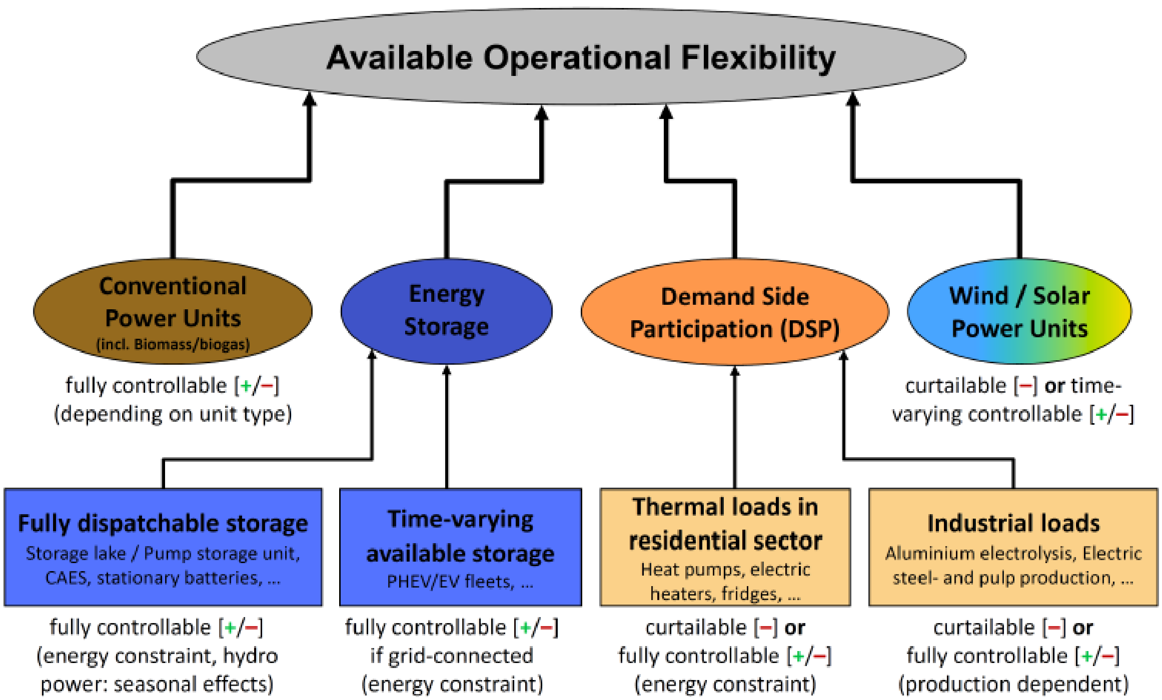

Figure 2.5: Sources of operational flexibility [34]. Some of them are fully controllable, while others are only curtailable.

2.5 Summary and solution proposal

It is now pertinent to summarize the four cornerstones of the ongoing energy transition:

1. Minimizing reliance on fossil fuels in industry, transportation, and residential heating;

2. Upgrading, modernizing, and expanding infrastructure to bolster system resilience and enable adaptability in a diversified and interconnected system;

3. Boosting and sustaining investment in renewable energy generation, energy security, and efficiency technologies;

4. A comprehensive and transparent set of policies for the successful implementation of renewable technologies, encompassing structured energy procurement mechanisms, financial incentives, and tax incentives.

The solution proposed in this thesis is centered around the second topic, which involves enhancing the existing infrastructure to ensure system resilience and enabling a paradigm shift in grid management.

2.5.1 Revisiting the Problem

It is logical to acknowledge that in the absence of proper grid management, the mass integration of DG and EVs into the grid would cause significant power spikes at specific times of the day. During peak solar intensity periods, there would be an excess generation, while during the nighttime, when all EVs are being charged, there would be an overload on the grid.

However, active grid management, achieved through the widespread installation of EV charging stations in various locations, combined with the optimal utilization of operational flexibility sources, allows for a better distribution of the load throughout the entire 24-hour day. This, in turn, improves the overall performance of the grid.

It is crucial to highlight that irrespective of the grid management implemented, the power transmitted through the network will experience a significant increase in the upcoming years. Consequently, the performance of the grid and the quality of service still becomes reliant on the existing infrastructure of the electrical grid and on the investment commitment of each grid operator to enhance network capacity.

2.5.2 Solution proposed

The solution proposed is the restructuring of the LV network by shortening it, ultimately covering the shortened distance in MV.

In Europe, the current practice for transforming medium voltage (MV) to low voltage (LV) involves using transformers with high power capacities. The distribution feeders connecting these transformers to the end consumers are typically long, as each feeder serves multiple loads. These long LV feeders result in major voltage drops due to the nature of LV having higher currents and higher impedance cables. The proposed solution aims to:

- Increase of the penetration of the MV network. This means that the MV to LV transformers are closer to the final customers;

- Increase the usage of more MV to LV transformers, potentially with a lower rated power, depending on the grid's needs;

- Usage of smaller LV feeders.

The solution proposed should not only give technical advantages but also economical ones, mainly because MV grids have smaller currents than LV one. At the same time, LV feeders are also smaller because the MV to LV transformer are closer to the client. All of this results in several advantages:

- Smaller voltage drops;
- Smaller energy losses;
- Increased power quality.

As a validation of this solution, there is the extreme case of using customer substations - a situation where a customer purchases a medium voltage (MV) branch and an exclusive substation from the distribution network operator. This network practice is common because it ensures improved service quality for the customer and reduces dependence on third parties in the majority of cases.

This extreme case of utilizing a dedicated transformer is more commonly seen in large establishments such as shopping centers but serves as validation for the solution proposed in this thesis.

2.6 Related Work

Extensive research has been conducted on the integration of DG and EVs into the electrical power system. However, the majority of these studies have primarily focused on improving the network through methodological approaches rather than through direct investment in network assets, as proposed in this thesis.

In [24], the methodology proposed provides a comprehensive and effective framework for dynamic expansion planning of active distribution networks, taking into account DG integration and uncertainties. The results obtained demonstrate the model's ability to generate high-quality solutions with reduced costs, and highlight the importance of considering uncertainties and adopting a multistage planning approach for improved system efficiency.

In [17], the paper analyzes the simultaneity of solar and wind power feed-in and its implications for integrating renewable energy into distribution grids. It provides recommendations for planning specifications to ensure economically and technically sufficient grids at low and medium voltage levels. The study finds that as the number of renewable power plants increases, the simultaneity of photovoltaic (PV) power feed-in decreases. The calculated simultaneity factor, G, offers insights into the level of simultaneity for medium voltage lines. The paper concludes that while comprehensive grid expansion may solve technical challenges, it must be balanced with economic considerations. The findings contribute to updating planning specifications and inform the integration of solar and wind power into distribution grids.

In [36], the paper discusses the challenges posed by distributed renewable electricity generators, specifically solar panels, in residential distribution grids. It explores the impact of different levels of solar panel penetration and the resulting voltage violations. The study proposes the use of local battery storage as a solution to mitigate these problems. The analysis reveals that a high penetration of solar panels can lead to the shutdown of a significant percentage of PV installations, resulting in energy losses. However, the introduction of batteries at each house can alleviate these issues and recover a substantial portion of the lost energy. Overall, the findings highlight the importance of battery storage in facilitating the integration of renewable energy sources and ensuring the optimal utilization of green energy in distribution grids.

In [8], this paper examines the feasibility of EV integration into the electrical grid and its environmental impact. The analysis is based on real-world data from a PHEV used as the primary vehicle for a typical Portuguese family. The study concludes that the current market-available EVs possess the necessary characteristics to support a progressive increase in EV adoption without significant grid infrastructure investments.

The results in [8] demonstrate that PHEVs can meet the daily travel requirements of a large portion of the population, with the remaining mobility needs addressed through hybrid operation. The paper emphasizes the positive effects of EVs on the economy, environment, and grid operation, highlighting their potential to absorb surplus renewable energy generation during off-peak periods. This can be seen in Figure 2.6, where the load profile is shown.

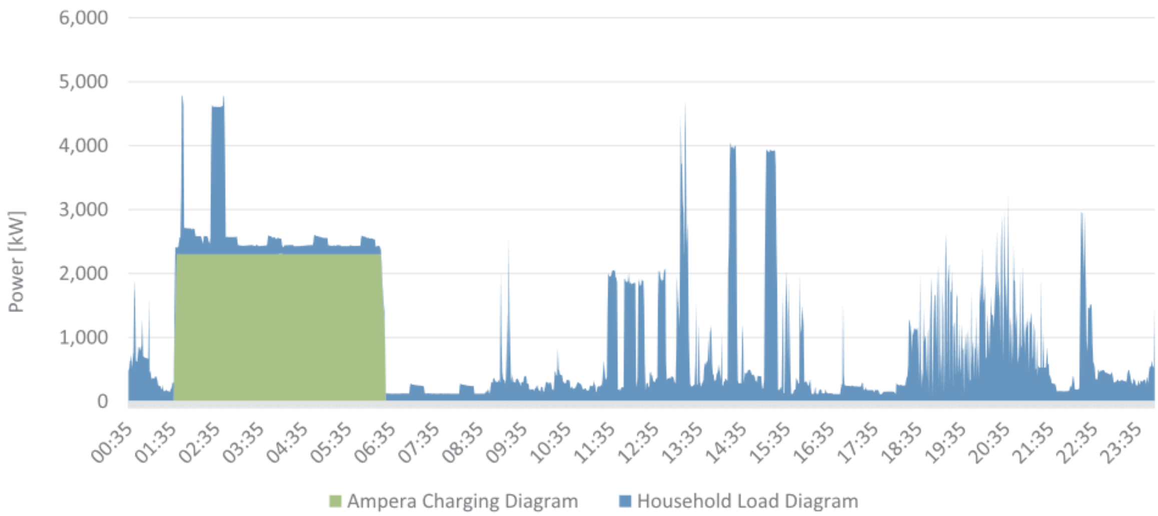

Figure 2.6: Daily load profile considered in [8]. The PHEV charging was inserted during the nighttime.

The study indicates that the introduction of a substantial number of EVs can be accommodated within the existing grid infrastructure, with minimal impact on the daily and annual load patterns. It suggests that a fleet of one million EVs could be supported, primarily utilizing surplus renewable generation from November to April, with some supplementary thermal generation during the remaining months.

The paper [8] also anticipates future developments in EV technology, including intelligent systems that regulate grid parameters and contribute to grid stability. Overall, the findings demonstrate that EVs offer significant potential for sustainable and efficient personal transportation, reducing emissions and dependence on fossil fuels while leveraging renewable energy sources.

Other studies evaluate the impact of EVs in the residential network by considering the usage of vehicle to grid technology [13] and by doing peak shaving algorithms [22].

Chapter 3

Power Flow

In this chapter, the main tool that is used for this thesis, the power flow (or load flow) is presented.

Firstly, the methodology is presented, alongside the mathematical model, including all the deductions made.

The base model includes only transmission lines, so the inclusion of transformers is covered.

Afterwards, the different types of busses in the model of the grid are presented and explained. The different mathematical algorithms are also presented, with references that point out to their main contributors.

It is important to note that this chapter was done completely based on the contribution of the book ”Redes de Energia Elétrica: Uma Análise Sistemática” [27]. Hence, this book represented a cornerstone for the development of this thesis and for the successful development of the *Matlab* code.

3.1 Methodology

A power flow (or load flow) is the static solution of an electric system, taking into account generation, the grid and the loads.

For a usual electrical grid, with a high number of nodes and branches, the equations that define the power flow become non-linear, requiring computational methods to be solved.

In this work, the power flow methodology is the following:

- Creating a mathematical model that represents the electrical grid with a certain degree of reliability;
- Understanding and specifying the different types of buses (or nodes) and the variables related to each of them;
- Solving the power flow equations, defining a certain state for the operation of the electrical system;
- Calculating the power that flows in each branch of the grid.

This is the base methodology behind a usual power flow. Several other steps can be added, according to the needs of the user. For example, in the optimal power flow (OPF), this becomes an optimization problem where the cost function (that corresponds to generation) should be minimized. This adds an extra step to the methodology represented above and creates a cycle on the calculation of the power flow, until the optimal point is found.

Nevertheless, understanding the base methodology of the power flow is key, because it is included in every other more complex algorithm that studies electrical systems.

3.1.1 Mathematical Model

To create a mathematical model to represent any electrical grid, the Kirchhoff's laws are used: specifically Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL).

KCL states that the sum of all currents entering a node in a network must equal the sum of all currents leaving the node, while KVL states that the sum of all voltage drops in a closed loop must equal zero. These equations are used to solve for the unknown voltages and currents in the power system and to ensure that the power balance is maintained.

In a usual electronic circuit, currents are used to represent energy flows, but as the name suggests, in a power flow, this energy flow is always represented as power (active and reactive, or complex). Consequently, it is possible to easily relate power and current through the equation (3.1).

$$\mathbf{I} = \frac{\mathbf{S}^*}{\mathbf{V}^*} = \frac{P - jQ}{\mathbf{V}^*} \tag{3.1}$$

Now that the laws used are known, a general node (or bus) should be defined.

A generic node *i* is comprised of a certain amount of generation and load, corresponding to the current entering and leaving the grid through the node *i*, respectively.

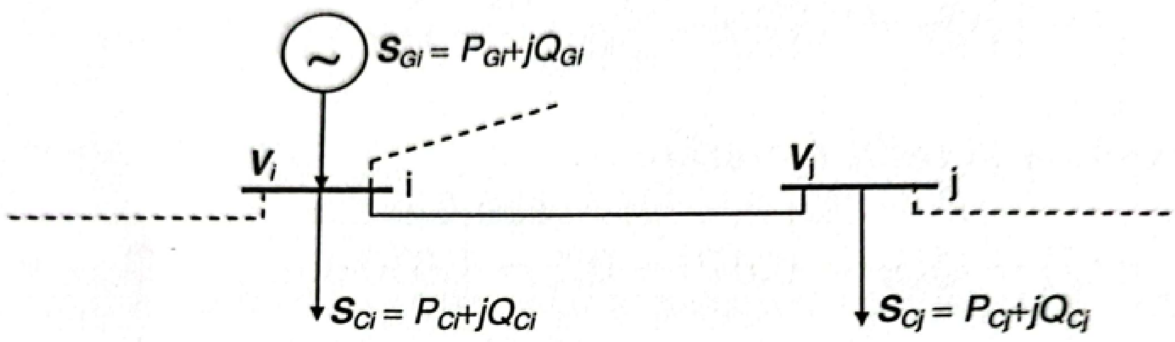

Figure 3.1: Single Line schematic of a generic bus [27]. Each bus can have any amount of branches connected to it.

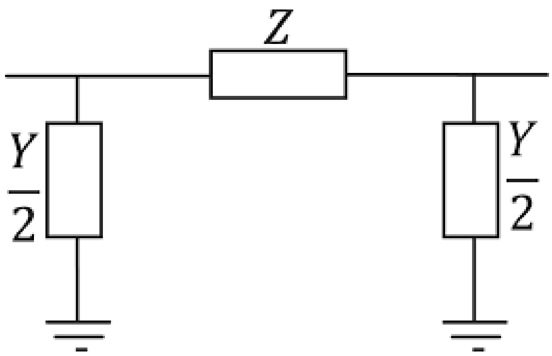

Figure 3.2: Transmission line equivalent π model (single-phase)

$$\mathbf{S}_i = \mathbf{S}_{Gi} - \mathbf{S}_{Ci} \tag{3.2}$$

The power injected in the grid through the node i is calculated as in Equation (3.2), where $\mathbf{S}_{Gi}$ is the generated power and $\mathbf{S}_{Ci}$ is the consumed power (or load). This means that the injected power $\mathbf{S}_i$ is positive if the generation is greater than the load and is negative if the load surpasses the generation.

A generic node i is also connected to other nodes via any number of branches, as shown in Figure (3.1). Therefore, applying the first Kirchhoff law (KCL) to bus i leads to:

$$\mathbf{I}_i = \sum_{\substack{j=1 \\ j\neq i}}^{n} \mathbf{I}_{ij} \tag{3.3}$$

Where the injected power at bus i, $\mathbf{I}_i$, is given by Equation (3.1).

The branch currents, $\mathbf{I}_{ij}$, are given by assuming that each transmission line is modelled by its equivalent π model, as seen in Figure (3.2).

Using the Ohm's law, it is now possible to rewrite Equation (3.3) into:

$$\begin{aligned}\frac{\mathbf{S}_i^*}{\mathbf{V}_i^*} &= \sum_{\substack{j=1\\j\neq i}}^{n} \frac{\mathbf{Y}_{ij}}{2}\mathbf{V}_i + \sum_{\substack{j=1\\j\neq i}}^{n} \frac{1}{\mathbf{Z}_{ij}}(\mathbf{V}_i - \mathbf{V}_j)\\ &= \sum_{\substack{j=1\\j\neq i}}^{n}\left(\frac{\mathbf{Y}_{ij}}{2} + \frac{1}{\mathbf{Z}_{ij}}\right)\mathbf{V}_i + \sum_{\substack{j=1\\j\neq i}}^{n}\left(-\frac{1}{\mathbf{Z}_{ij}}\right)\mathbf{V}_j\end{aligned} \tag{3.4}$$

Equation (3.4) can be further simplified:

$$\begin{aligned}\frac{\mathbf{S}_i^*}{\mathbf{V}_i^*} &= \mathbf{y}_{ii}\mathbf{V}_i + \sum_{\substack{j=1\\j\neq i}}^{n} \mathbf{y}_{ij}\mathbf{V}_j\\ &= \sum_{j=1}^{n} \mathbf{y}_{ij}\mathbf{V}_j\end{aligned} \tag{3.5}$$

Applying Equation (3.5) to every bus in the grid (n buses), and putting it in matrix form:

$$\left[\frac{\mathbf{S}^*}{\mathbf{V}^*}\right] = [\mathbf{Y}][\mathbf{V}] \tag{3.6}$$

In Equation (3.6), $[\mathbf{V}]$ and $[\mathbf{S}]$ are column matrices ($n \times 1$) containing the injected power and the voltage in each node, respectively. The term $[\mathbf{Y}]$ corresponds to the nodal admittance matrix ($n \times n$):

$$[\mathbf{Y}] = \begin{bmatrix} \mathbf{y}_{11} & \dots & \mathbf{y}_{1n} \\ \dots & \dots & \dots \\ \mathbf{y}_{n1} & \dots & \mathbf{y}_{nn} \end{bmatrix} \tag{3.7}$$

Where (from Equation 3.4):

$$\begin{aligned}\mathbf{y}_{ii} &= \sum_{\substack{j=1\\j\neq i}}^{n}\left(\frac{\mathbf{Y}_{ij}}{2} + \frac{1}{\mathbf{Z}_{ij}}\right)\\ \mathbf{y}_{ij} &= \mathbf{y}_{ji} = -\frac{1}{\mathbf{Z}_{ij}}\end{aligned} \tag{3.8}$$

The Y-matrix completely characterizes the grid, having information of all branches and nodes included, as seen in Equation (3.8).

It is important to note that most grids have sparse Y-matrices, since each node only connects to his neighbours, and the average number of neighbours of a node is much smaller than n.

3.1.2 Inclusion of Transformers

Until now, all the calculations leading to Equation (3.8), it was assumed that all the branches in the electrical grid in study were lines.

As it is true that a great majority of the branches are in fact, lines and can be represented by the π model in Figure (3.2), there are cases where two nodes are separated by a transformer instead (in many substations for example). Therefore, a model for the inclusion of transformers in the power flow calculations needs to be adopted.

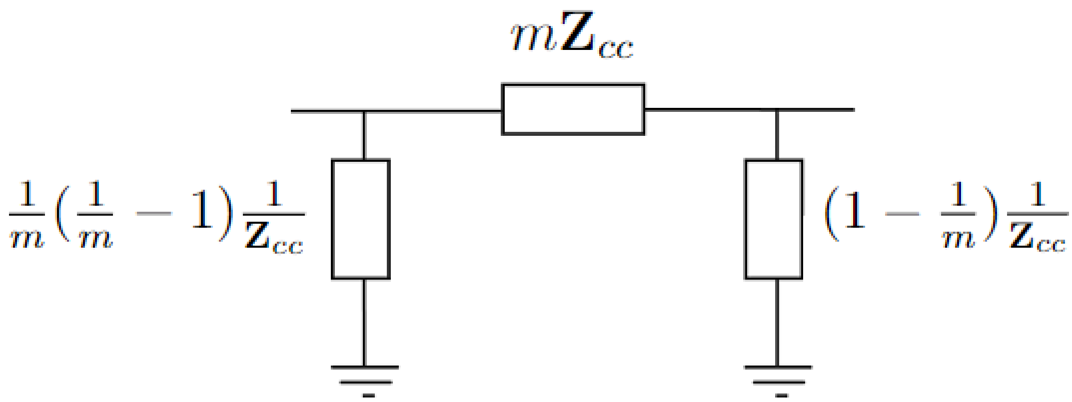

Figure 3.3: Transformer equivalent π model (single-phase)

For that purpose, the transformer π model is considered, shown in Figure (3.3). This model assumes that the transformer is equipped with a tap changer on the primary side, meaning it is possible to change the parameter m to adjust the voltage. Note that when $m = 1$, the transformer is only given by its short-circuit impedance.

In the same note as in Equation (3.4), applying KCL on both nodes:

$$\begin{bmatrix} \mathbf{I}_i \\ \mathbf{I}_j \end{bmatrix} = \begin{bmatrix} \frac{1}{m^2\mathbf{Z}_{cc}} & -\frac{1}{m\mathbf{Z}_{cc}} \\ -\frac{1}{m\mathbf{Z}_{cc}} & \frac{1}{\mathbf{Z}_{cc}} \end{bmatrix} \begin{bmatrix} \mathbf{V}_i \\ \mathbf{V}_j \end{bmatrix} \tag{3.9}$$

A transformer is normally integrated in a more complex grid, so these equations need to be included in the Y-matrix (nodal admittance matrix). To do this, one simply adds the terms determined in Equation (3.9) on the corresponding indexes as shown in Equation (3.10):

$$\begin{aligned} \mathbf{y}_{ii} &= \dots + \frac{1}{m^2\mathbf{Z}_{cc}} + \dots \\ \mathbf{y}_{jj} &= \dots + \frac{1}{\mathbf{Z}_{cc}} + \dots \\ \mathbf{y}_{ij} &= \mathbf{y}_{ji} = -\frac{1}{m\mathbf{Z}_{cc}} \end{aligned} \tag{3.10}$$

3.1.3 Variable classification and bus types

Now that the power flow equations were determined, it is possible to approach this problem from a control-oriented standpoint. The problem can be represented generally, in matrix form by:

$$[f([x],[u],[p])] = [0] \tag{3.11}$$

In Equation (3.11), $[x]$ represents the state variables, $[u]$ represents the control variables and $[p]$ represents the perturbation variables:

The state variables, $[x]$, are calculated as a result of the problem, and define the operation point of the system. State variables cannot be changes directly, as the user does not have access to them.

In opposition to the state variables, the control variables, $[u]$, are the ones that can be manipulated directly by the user and are used to control the state of the system.

Finally, the perturbation variables, $[p]$, are the variables that the user is not able to control, and affect the state of the system. Most of the time these are imposed by the system in study.

In the context of a power flow, the variables present in Equation (3.11) are present in each bus (or node). Consequently, these variables depend on the type of bus that is being dealt with. It is possible to distinguish 3 types of buses:

- Reference bus (or slack bus): Used as the angle reference for the balancing of the energy in the grid;
- PQ bus: Standard load and/or generation bus;
- PV bus: Generation bus where the voltage is regulated/controlled.

In a real grid, 80% to 90% of the nodes are loads, that are modelled by PQ buses. In these types of buses, the state variables ($[x]$) correspond to the voltage absolute value and argument. In PQ buses, there can also be generated power (active and reactive), that correspond to the control variables ($[u]$).

For PV buses, that always have regulated generation, the state variables are the reactive power generated and the voltage argument, while the control variables correspond to the active power generated and the absolute value (or magnitude) of the voltage.

On the reference bus (or buses) the generated powers, both active and reactive, are state variables and the voltage, both magnitude and argument, are the control variables.

Only the perturbation variables ($[p]$) are undefined. In a power flow context, these correspond to the loads in each bus, since these are imposed by the consumers.

It is important to note that inside the vastness of the electrical grid, more control variables can be defined (but will not be used in this thesis), such as the position of the circuit breakers, that can change the topology of the grid, the taps of the transformers, or even some loads that can be shut down temporarily by the grid operator when in need.

In the solution of the power flow, and in the scope of this thesis, the control and perturbation variables are given as data in the problem, while the state variables are calculated.

3.1.4 Solution and algorithms

Ultimately, the power flow solution is the complete chart of powers that flow through the each branch of the network, but as it was stated in section 3.1, once all the voltages (absolute value and argument) are determined, everything else can be calculated using basic circuit analysis (Kirchhoff's laws and Equation 3.1). So naturally, determining the voltages in every bus should be the most important and hardest step of the power flow.

Given the non-linearity of the equations, as seen in Equation (3.6), the numeric solution is given by iterative methods. The most used are:

- The Gauss-Seidel method [31];
- The Newton-Raphson method [33];
- The Fast Decoupling method [30].

The basis of all these computational methods, starts with an initial estimate for all the voltages (magnitudes and arguments). Then for each iteration of the procedure, a deviation is calculated and added to the current value, until it converges to the final solution (the final solution is defined by a certain error between the current and the previous iterations).

The quality of each method is given by its robustness: By how often the method converges and how fast the convergence is. Normally, an increase in convergence speed is paid with a more complex algorithm and an increased usage of resources (this happens when comparing the Newton-Raphson with the Gauss-Seidel methods).

Chapter 4

Model Grid Study

In order to grasp the fundamentals of the solution proposed, as well as the general dynamics of a power flow, a model grid is studied in this section.

The case study is presented, with all the data of the grid and all the assumptions made regarding the distances and the loads.

Afterwards, the methodology that is going to be used to get results is presented: The process of restructuring the grid and the procedure programmed in *Matlab*.

Then, the detailed results are presented, considering the ”consumption only” case and considering generation with various penetration levels.

To close out this chapter, the results are analysed and discussed.

4.1 Grid description

The aim of this project is to reinforce the distribution grid by proposing a restructuring of the LV network. The proposed solution is to change the distribution network by increasing the penetration of the MV.

For starters, a simple (model) MV to LV grid is studied, so that it is possible to understand the fundamentals of the solution proposed, mainly:

- Understanding a power flow;
- How heavier loads affect the voltage, and consequently, the QoS of the clients;
- How the inclusion of DG affects the system.

With this in mind, the grid proposed is presented in Figure 4.1, taken from [6]. This grid is a model produced for the purposes of the study: it is a simple 3 feeder LV grid that resembles a residential zone, that accommodates some nodes with generation.

The feeder data is presented in Table 4.1. This table encapsulates the length of each feeder, the number of customers and the conductor specifications.

Moreover, the transformer data is presented in Table 4.2. The transformer ratings, maximum demand and number of clients served are presented, specifying how many of the clients have generation (rooftop solar PV generators).

	Feeder 1	Feeder 2	Feeder 3
Length of main feeder	510 m	400 m	610 m
Conductor type	3 phase Aerial Bundle Cable (ABC) Type: 3x70mm^2 + 54mm^2 R = 0.443 Ω/Km, X = 0.26 mH/Km		

Table 4.1: Model grid - Feeder data

Transformer Rating	250 kVA / 11 kV / 400 V
Maximum demand	154 kW
Number of customers served	336
Number of customers with rooftop solar PV generators (Solar capacities range from 1 kWp to 15 kWp)	24
Number of outgoing LV feeders from the transformer	3

Table 4.2: Model grid - Transformer data

For the rest of the grid data to be defined, the distances between buses and the loads are needed.

In order to not overload the transformer, the maximum load allowed is changed to 50% of the transformer rated power. For simplicity, it is assumed that each bus has the same load, so the power is divided by the 36 available LV buses.

Each feeder has 12 LV buses. It is assumed that the distance between each of those buses is equal (resembling a common residential street, for example) and it is equal to 30 m. In Table 4.3, the remaining distances are presented (between the transformer and the closest client of each feeder).

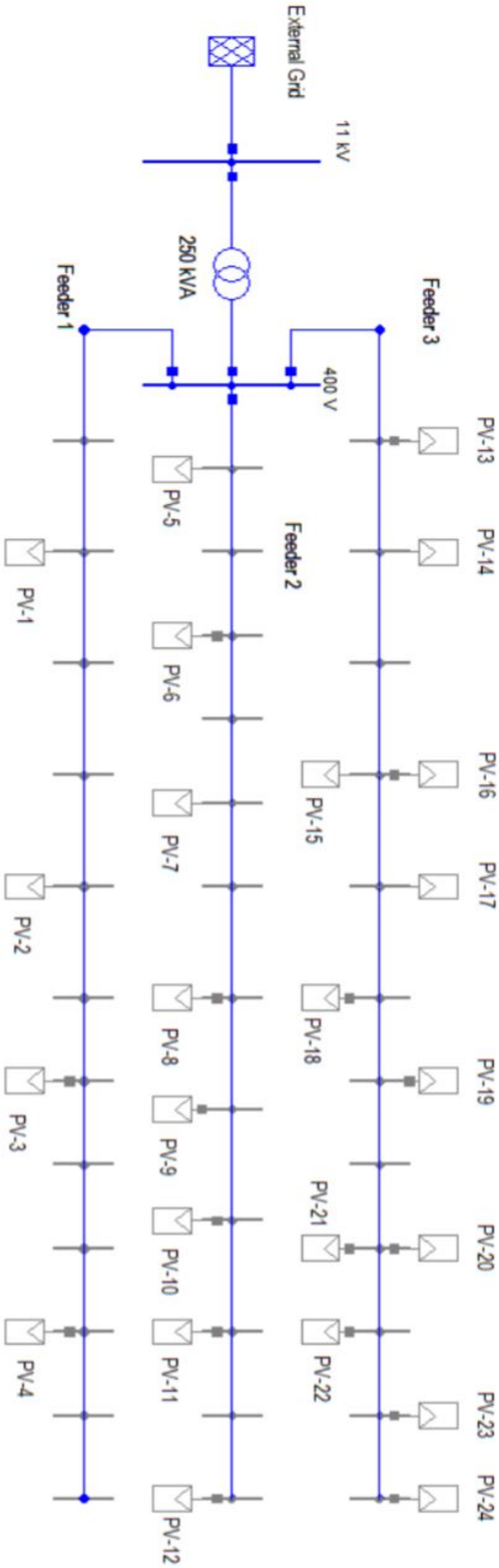

Figure 4.1: Model grid taken from [6]. The single transformer feeds all three LV feeders, each comporting different amounts of generation.

Feeder	Distance from distribution transformer (to the closest client)
Feeder 1	150 m
Feeder 2	40 m
Feeder 3	250 m

Table 4.3: Model grid - Distances between transformer and closest client

4.2 Restructured Grid

The objective of the project is to change the previous model grid according to the solution proposed. In the simple case of the grid in Figure 4.1, the main point is to multiply the MV to LV transformer across smaller groups of loads. This means that each transformer has a smaller power than the 'big' original one, that had to accommodate for all the loads.

The restructured grid is presented in Figure 4.2. Within this restructured grid, the properties of the loads remain the same as in the original model grid, in Figure 4.1, along with the distances between LV buses (30 m).

To maintain consistency, the distances between MV buses have to be adjusted to maintain the structure of the grid. The distance between 2 MV buses that have transformers is 120 m whilst the distances between the slack bus and the closest MV bus are presented in Table 4.4.

Feeder	Distance from slack bus (to the closest MV bus)
Feeder 1	195 m
Feeder 2	85 m
Feeder 3	295 m

Table 4.4: Restructured grid - Distances between slack bus and closest MV bus

4.2.1 *Matlab* implementation

In this thesis, the main tool used and implemented in *Matlab* is the power flow, explained in Chapter 3.

The mathematical method implemented in *Matlab* is the Gauss-Seidel on a vector scale (also known as the Jacobi-Gauss-Seidel method) [31].

In this method, the injected currents of the current iteration ν are calculated using the voltages of the past iteration $\nu - 1$, as stated in Equation 4.1.

$$\mathbf{I}^{\nu} = \left(\frac{\mathbf{S}}{\mathbf{V}^{\nu-1}}\right)^{*} - \mathbf{Y}(:,1)\mathbf{V}_1^{\nu-1} \tag{4.1}$$

With the injected currents calculated, the voltages of the current iteration are calculated as in Equation 4.2, closing the cycle.

$$\mathbf{V}^{\nu} = \mathbf{Y}^{-1}\mathbf{I}^{\nu} \tag{4.2}$$

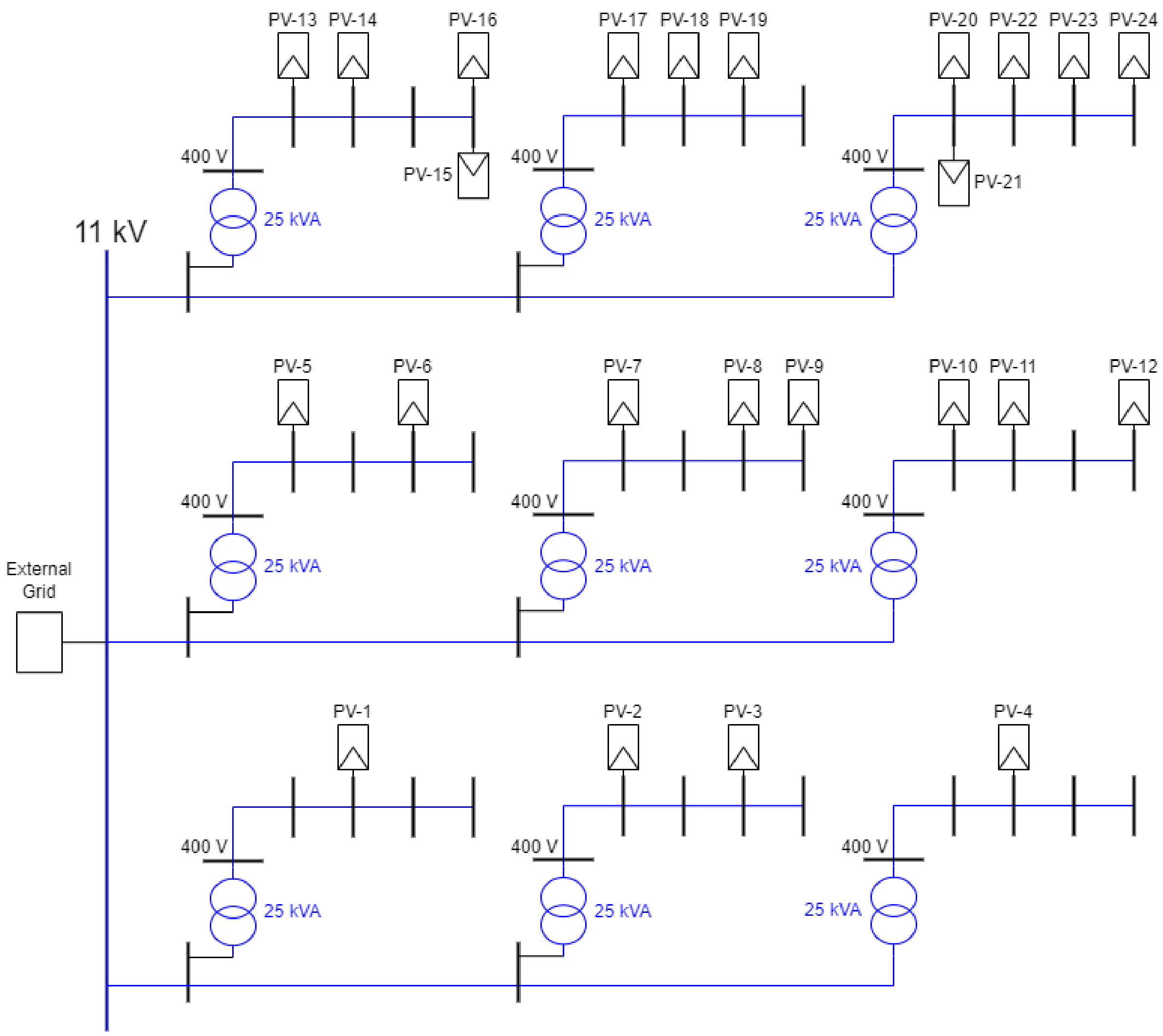

Figure 4.2: Restructured LV network adapted from Figure (4.1). The bigger distances are covered in MV, extending the MV line closer to each group of loads.

This process finished when the difference in voltages (the biggest along all the voltages) between two consecutive iterations is smaller than the error parameter, ϵ, defined by the user, as described in Equation 4.3:

$$\max(\mathbf{V}^{\nu} - \mathbf{V}^{\nu-1}) < \epsilon \tag{4.3}$$

Obviously, a smaller the error, ϵ, means that the solution is more precise, with the downside of the power flow taking more iterations and, consequently, more time to converge.

Another condition for the end of the iterative process is the number of maximum iterations. This needs to be defined to make sure that the divergent power flows do not end up in an infinite loop.

4.3 Case study and results

The model 'traditional grid' (Figure 4.1) and the 'restructured grid' (Figure 4.2) are compared according to several parameters:

- As already stated, for simplicity, the loads are distributed equally;
- On the same note, generation is also distributed equally, meaning every PV is considered to have the same generation. All installed solar PV units are assumed to provide active power at unity power factor which is compliant with IEEE 1547-2003 [19];
- PV generation exists according to the Figures 4.1 and 4.2. This means that the nodes with 2 PVs attached have double the generation of nodes with 1 PV attached. This also means that nodes with 0 PVs attached never have generation associated with them.
- The generation is adjusted for various penetration levels. These are 0%, 40%, 50%, 60% and 70%. Higher penetration level means higher generated power for all PVs. This also covers the case where there is no generation and only consumption.

For each of the main 3 feeders, the results displayed are the voltage of each bus, this corresponds to the magnitude and the argument of the voltage.

In the graphic results, each feeder has 5 plots, each represented by a distinct penetration level, respectively labeled in each figure. For clarity reasons, each feeder is represented on distinct figures.

4.3.1 Feeder 1

The bottom feeder (Feeder 1) has the lowest amounts of PVs installed, meaning the lowest amounts of generation amongst the 3 feeders: Figures 4.3 and 4.4 represent the results of the traditional grid and the restructured grid, respectively.

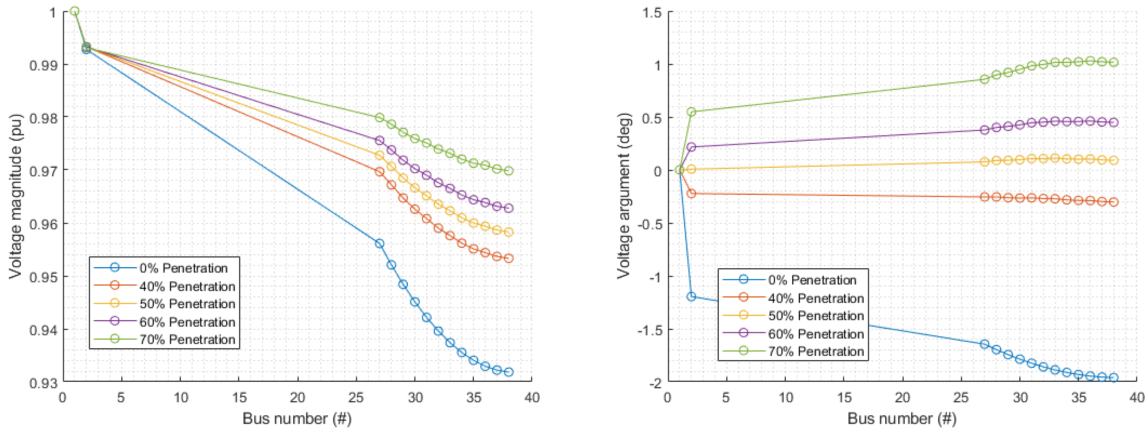

Figure 4.3: Voltages in Feeder 1 for each penetration level (traditional grid)

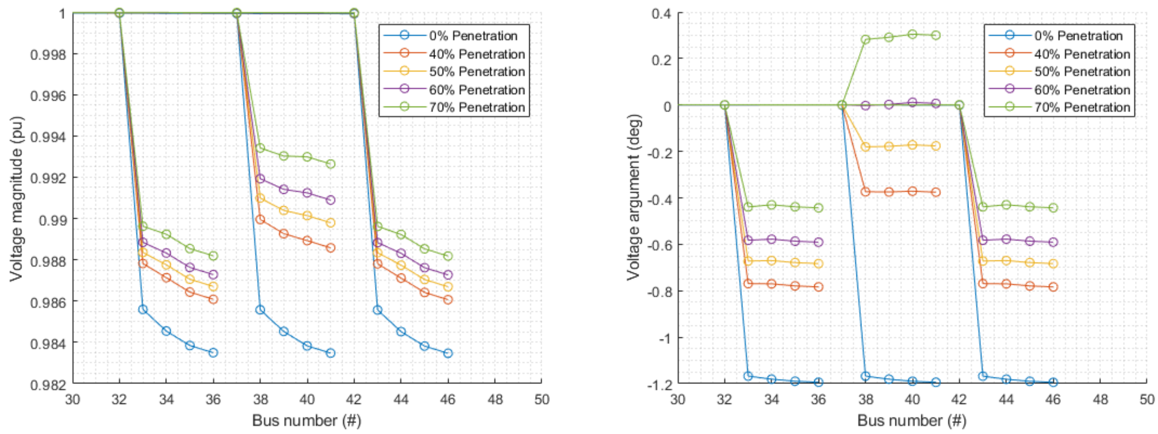

Figure 4.4: Voltages in Feeder 1 for each penetration level (restructured grid)

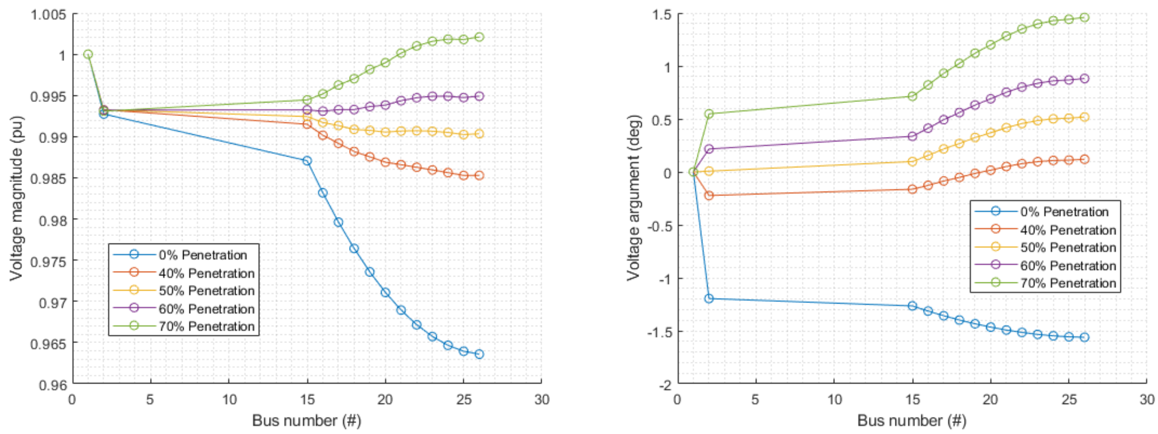

Figure 4.5: Voltages in Feeder 2 for each penetration level (traditional grid)

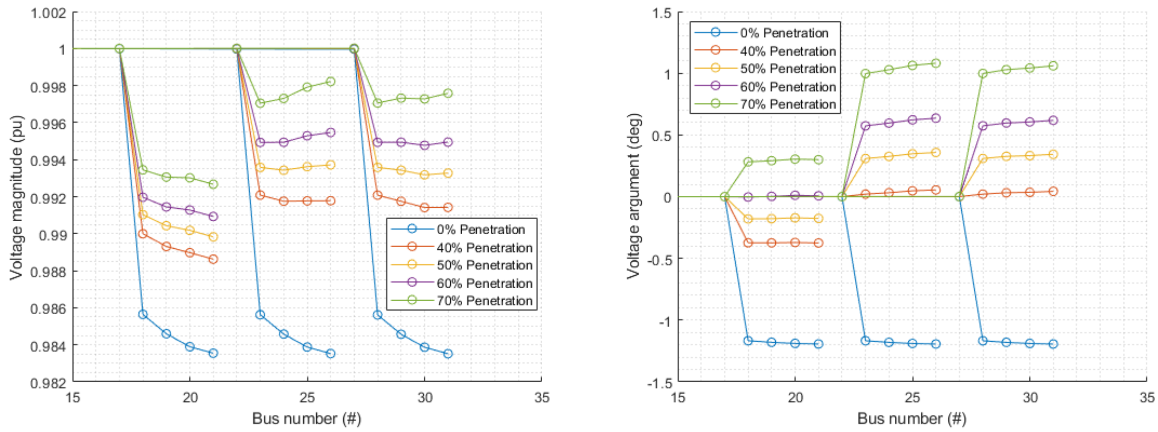

Figure 4.6: Voltages in Feeder 2 for each penetration level (restructured grid)

4.3.2 Feeder 2

The middle feeder (Feeder 2) has its results represented in Figure 4.5 and Figure 4.6. This feeder represents a middle point of generation between the other two feeders.

4.3.3 Feeder 3

The top feeder (Feeder 3) has the highest amounts of PVs installed: Its results are represented in Figure 4.7 and Figure 4.8.

4.4 Results analysis and discussion

From inspecting the results, there are a lot of advantages from the restructuring of the grid as suggested in this thesis.

The main point is that with the increased penetration of the MV, 'power spends less time' in the LV lines (high currents) and more time in the MV (small currents). This means that the voltage drops in become lower in general, contributing to a more stable grid and better QoS.

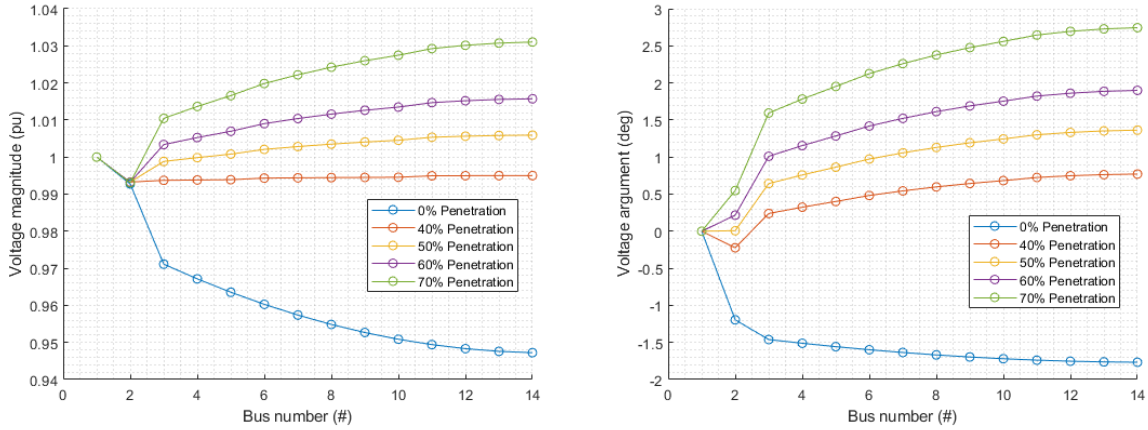

Figure 4.7: Voltages in Feeder 3 for each penetration level (traditional grid)

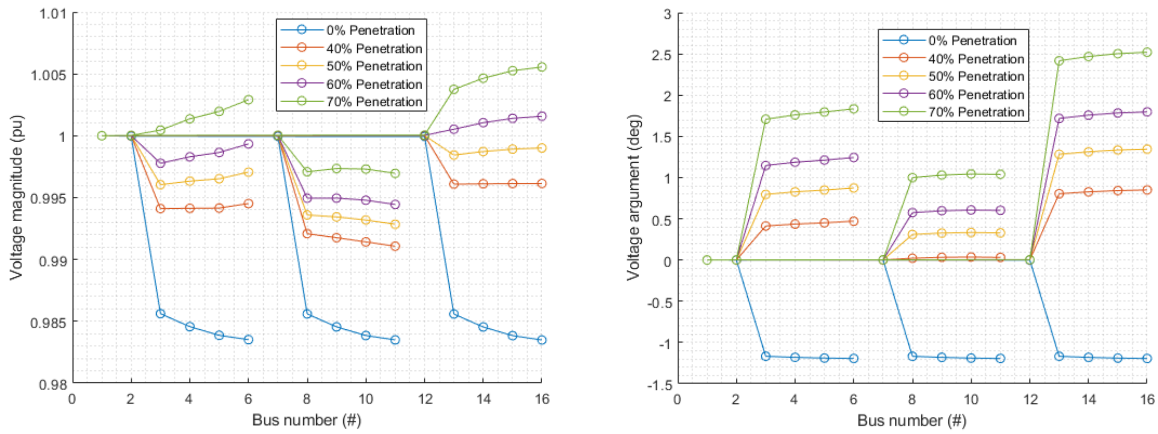

Figure 4.8: Voltages in Feeder 3 for each penetration level (restructured grid)

4.4.1 Results analysis

As mentioned, the obtained results demonstrate that the proposed restructuring leads to improvements in the performance of the electrical system. In Tables 4.5 and 4.6, we can see a summary of the results in tabular format. The values in these tables (Tables 4.5 and 4.6) correspond to the voltage drop at the furthest node from the network in each feeder, specifically, according to the grids in Figures 4.1 and 4.2, the rightmost nodes of each feeder, across all five simulated PV penetration levels.

Tradicional Grid				
Voltage Drops (%)	Feeder 1	Feeder 2	Feeder 3	**Feeder #**
0	6,80	3,65	5,30	
40	4,70	1,50	0,50	
50	4,20	0,95	-0,60	
60	3,70	0,50	-1,60	
70	3,00	-0,20	-3,10	
PV Penetration (%)				

Table 4.5: Furthest Node Voltage drops in the traditional grid

Restructured Grid				
Voltage Drops (%)	Feeder 1	Feeder 2	Feeder 3	**Feeder #**
0	1,65	1,70	1,65	
40	1,40	0,85	0,40	
50	1,33	0,68	0,10	
60	1,28	0,50	-0,15	
70	1,18	0,25	-0,55	
PV Penetration (%)				

Table 4.6: Furthest Node Voltage drops in the restructured grid

Starting with the analysis of the results when there is no photovoltaic generation: Figure 4.9 presents a graphical representation of the maximum voltage drop in each of the feeders in the case where there is no PV generation. It can be observed that even in the traditional grid, the voltage drops never exceed 7%, as the loads were designed not to overload the feeders, corresponding to 50% of the transformer's power. However, it is worth noting the difference in voltage drop: in the traditional network, the voltage drop varies significantly due to the different distances covered by each feeder, whereas in the restructured network, the voltage drops are nearly the same because the differences in distance are covered in the MV level.

When photovoltaic generation is included with different penetrations and each feeder is analyzed, conclusions can be drawn regarding the PV penetration:

- In feeder 1, given the low presence of PVs, an increase in generation causes the voltage levels to rise because part of the load is supplied by the photovoltaic panels, resulting in a lower power injection from the grid. The voltage levels in the traditional grid decrease by approximately 3.8%, while in the restructured one, they decrease only by 0.47%.

- The same occurs in feeder 2, but due to its shorter length and higher concentration of PVs, the voltage levels in the traditional grid decrease by about 3.85%, resulting in an overvoltage of 0.20%, while in the restructured grid, they decrease significantly less, by approximately 1.45%.

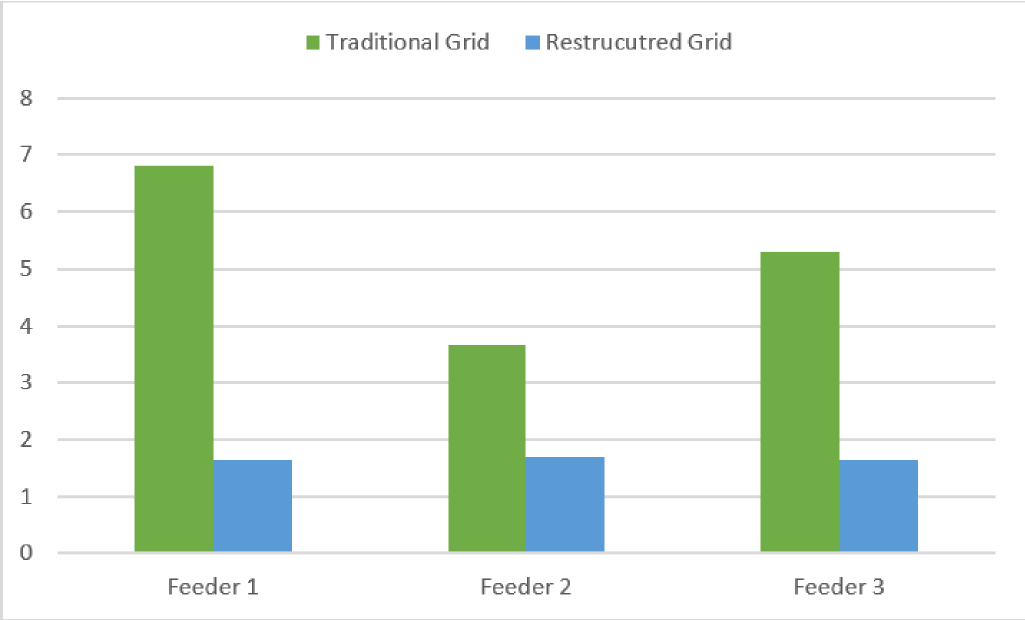

Figure 4.9: Comparison of the voltage drops without generation. The green bars (traditional grid) vary around 4%, while the blue bars (restructured grid) vary less than 0.1%.

- Feeder 3 has the highest amount of PVs, consistently leading to overvoltages in both grids. The difference is that in the traditional grid, it experiences an overvoltage of 3.1%, while in the restructured grid, it is only 0.55%.

It can be observed that fluctuations in generation cause much larger variations in the traditional grid compared to the restructured one. This is once again due to the fact that currents need to flow less in LV and more in MV, resulting in smaller voltage differences.

It is important to highlight that in this simple case, in the feeder with the highest PV load, overvoltages reached values of up to 3% in the traditional grid. If this example were extended to a more complex network with a higher PV load, overvoltage levels could reach harmful values for the network and its customers, thus affecting QoS. But, the proposed solution resulted in smaller voltage fluctuations and the overvoltage only reached values of 0.55%, an almost negligible value.

About the voltage argument: It is interesting to observe that normally, in a vertical and centralized system, the argument of the voltage always decreases, following the radial setting of the grid, as it can be seen in the 0% PV penetration results. But as the PV generations goes up, there are a lot of nodes that have positive signalled voltage arguments, meaning that they are fed before the slack node.

This parameter only represents a delay between the load in analysis and the slack node, it is normally not an important factor taken into account for the QoS standards.

4.4.2 Investment

The restructured grid shows more stable results, originating better QoS in the long term, but this restructuring comes with an associated cost.

In this case, the cost is investment in infrastructure: The MV grid is more expensive than the LV grid in every aspect:

- Infrastructures require more space, since the higher voltage level requires bigger safety distances between equipment to maintain isolation;
- The protections of the system are very different and operate differently - LV grids have little to almost no protection systems whereas MV grids have considerable protection systems.

Taking all of this into account, this restructuring comes with a high investment cost.

As it was already stated in an introductory chapter, for the grid to be allowed to handle the upcoming 'tsunami' of prosumers and EVs, along with flexibility solutions, there needs to be a reinforcement of the grid. This thesis proposes this grid restructuring as an investment option, showing that in the case limit where the funding doesn't matter, this solution has its advantages and could represent an option for the future of the distribution systems.

The solution presented applied to this model grid, despite giving a good base point for the solution presented, should be credited using a larger, more complex grid, where electrical vehicles could be inserted and tested.

Chapter 5

Realistic Grid Study

Although the solution presented in this thesis was validated and got studied in the last chapter, a more thorough approach is done in this chapter by applying it to a realistic grid.

The grid is firstly presented, along with *DPlan*: the program used to study the power flow.

Then, the complete process of creating the load diagrams that are going to be considered in the grid is explained.

The three different case studies are shown, along with the results obtained.

Following this, and to finish this chapter, the results are analysed, discussed and ideas for future work in the same topic are given.

5.1 Software and Grid description

In this chapter, the grid in study is given in a software called *DPlan*. *DPlan* is a geographic based integrated analysis and optimization system for distribution networks.

This software was produced by *AmberTree* and it is widely used in many countries, specially inside the Portuguese Distribution System Operator, E-REDES.

DPlan is mainly used in MV and LV studies, as it can be used to simulate a plethora of electrical grid studies. These functionalities include [10]:

- Optimization;
- Fiability and QoS;
- Power flow and short circuit analysis;
- Load allocation;
- Production and visualization of reports;
- Data edition and management.

For the topic of this thesis, the most relevant software functionality is the power flow, which has two different types of analysis:

- ”Peak” mode: Each load is represented by a random variable, that follows a Bernoulli distribution. However, the sum of all the loads follows a Gaussian distribution. The power flow results are also described as having a type of probability of occurrence;
- ”Chronometric” mode: Each load is represented by a 24h profile that tries to emulate the data gathering of a smart meter. There occurs a measurement every 15 minutes.

For the sake of the proposed study, the LV grid chosen needs to contain a considerable amount of loads, with some of them relatively distanced from the MV to LV transformer.

Since the MV grid is being modified also has a part of the restructuring proposed, it also needs to be well characterized.

Following these criteria, the grid chosen is shown in Figure 5.1. From the figure it is possible to see several characteristics of the grid in study: the medium to low voltage transformer is represented by a triangle so, the MV feeder is the blue line whilst the LV grid is represented as pink. The grid also seems to have a diverse density of loads, having a big quantity of loads in some places, but being rather sparse at others.

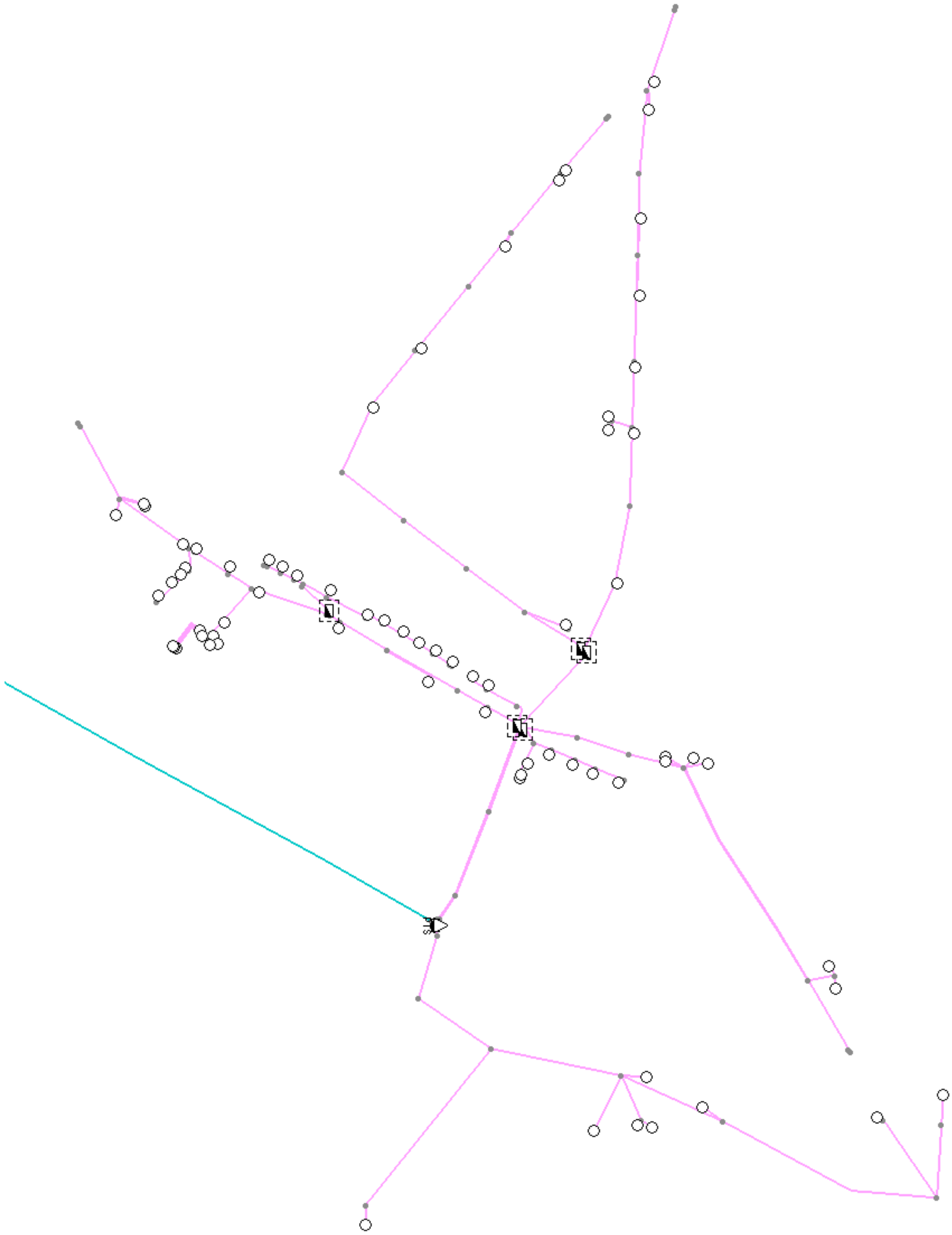

Figure 5.1: Realistic Grid in study (taken from *DPlan*). The single transformer feeds the entirety of the pink LV grid. The load dense south-west area is even nearer the MV line than the transformer.

In this chapter, the focus shifts to integrating electric vehicles (EVs) into the grid. Unlike the previous chapter, where PV penetration was studied, this chapter introduces heavier and more disruptive loads in the form of EVs. The process followed in this chapter involves two main steps:

- Load profile creation and assignment: A comprehensive load profile is developed for the EVs, considering factors such as charging patterns and duration of charging sessions. This load profile is then assigned to the respective nodes in the grid;
- Grid restructuring by progressive phases: The grid is restructured to accommodate the EV loads effectively. This restructuring process is carried out gradually in phases, allowing for a systematic analysis of the grid's performance and the impact of EV integration. The objective is to assess the grid's ability to handle the increased demand from EVs and ensure its stability and reliability.

By integrating EVs into the grid and following this two-step process of load profile creation and grid restructuring, the chapter aims to evaluate the effects of EVs on the grid's performance, including aspects such as voltage stability, power flow, and overall system reliability.

5.2 Integration of EVs

As said before: *DPlan* has two different power flow modes: the "peak" mode and the "chronometric" mode.

For the purpose of this thesis, the "chronometric" mode is used, as it fits better into the objectives of the project. It allows for the user to project the load profile (in 15 minute intervals), allowing for the integration of generation or consumption at any given period.

On the other hand, the "peak" mode doesn't offer much for this project, since there is no need to meddle with probability distributions in the scope of this thesis, and could result in overcomplicating the problem.

Now that the *DPlan* operating mode is chosen, there are two tasks that still need tackling:

- Creation and assignment of a consumer at each load node;
- Creation of a plausible load profile, with the integration of the EVs charging.

5.2.1 Consumer creation and assignment

For the power flow to operate in "chronometric" mode, it is required that each load node has a consumer assigned to it. The consumer is described as Meter Point Administration Number (MPAN) that varies in size depending on the country or even depending on the distribution system operator (DSO). For example, in Portugal the equivalent of the MPAN has 20 digits (16 numbers and 4 letters) while in Great Britain, the MPAN has 1 letter in the beginning and 21 digits after it.

In the realistic grid in study (Figure 5.1) there are 53 load nodes and *DPlan* offers a command file functionality that allows us to add consumers directly to a load node using the "ADDCPE" command that uses the following structure:

[ID No] [ID CPE] [TYPE] [STATUS] [PHASE] [SCON]

where:

- ID No: ID from the node that will be assigned a consumer or producer;
- ID CPE: Consumer identifier (the MPAN, for example);
- TYPE: C or P for consumer or producer, respectively;
- STATUS: 1 or 0 depending if it is enabled or disabled;
- PHASE: 0, 1, 2, 3 or 4 for unknown, phase A, phase B, phase C or three-phase, respectively;
- SCON: Contracted Power, in kVA.

By extracting all the load nodes IDs from *DPlan* and then structuring the command file, it is possible to add all 53 consumers in one go.

For simplicity sake, in this simulation, the consumer identifiers will be numbers from 1 to 53. Figure 5.2 shows an example of a load node that has a consumer already assigned to it.

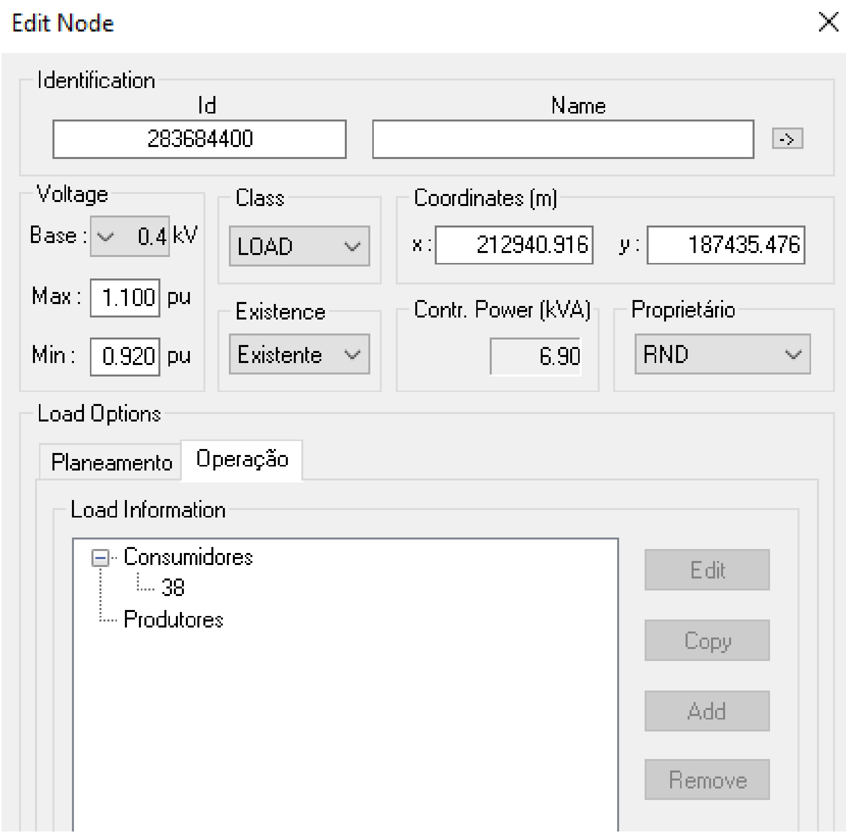

Figure 5.2: Load node with consumer assigned in *DPlan*

5.2.2 Load profiles

In order to create the load profiles, another *DPlan* functionality is used. As a software also used to plan out hypothetical grid scenarios (for example, load forecasting): in the "planning" tab, when a consumer is created, it is possible to assign it with a certain type of consumption:

- Residential;
- Commercial;
- Industrial;
- Unknown.

Each of these types of consumption has a phase load profile already pre-assigned to it and scaled up or down based on the contracted power of the load node in question.

Since the purpose of this project is not to create complex load profiles or very diverse load distributions, the methodology of using these previously designed load profiles and applying them to our grid is used.

Unfortunately, it is not that straight forward since it isn't possible to use the "planning" tab in the power flow "chronometric" mode. So, the load profiles are emulated in an excel sheet and then imported into the consumers created previously through a '.dpg' file [10].

In Figure 5.3 an example of a dpg file is shown. Following the main file headers, the "EB" block corresponds to the smart metering data. The "EB" block header contains the number of loads that are to be imported to existing consumers (in the case in Figure 5.3 - 218).

Afterwards, each block comprises of a header that identifies the consumer identifier (MPAN) and the number of phases of the consumer. Under it, depending on the number of phases, the load profile of each phase is shown. Since this is used to illustrate smart meter measurements - the data needs to have 96 power entries (15 minutes for each measurement).

```
DPlan Load Diagram Format
Version: 2
DTC: 0
EB: 218
 ,'911430011','',3,
1,1,919.181396,919.686523,882.914307,889.488281,845.263184,821.791565,814.972168,815.574280,806
2,1,919.181396,919.686523,882.914307,889.488281,845.263184,821.791565,814.972168,815.574280,806
3,1,919.181396,919.686523,882.914307,889.488281,845.263184,821.791565,814.972168,815.574280,806
 ,'911430012','',3,
1,1,740.074707,693.017822,687.527832,700.000000,699.726563,698.743591,681.221252,719.761719,679
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3,1,740.074707,693.017822,687.527832,700.000000,699.726563,698.743591,681.221252,719.761719,679
 ,'911430013','',3,
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2,1,982.014343,963.870789,965.579834,958.962402,911.914551,864.826721,817.681091,794.051575,752
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2,1,909.353943,862.998291,816.213562,769.552917,770.063477,761.092834,763.195557,722.287598,680
3,1,909.353943,862.998291,816.213562,769.552917,770.063477,761.092834,763.195557,722.287598,680
```

Figure 5.3: Example of a .dpg file with the smart metering block

Since the realistic grid being used (Figure 5.1) does not specify if it is comprised by residential, commercial or industrial load profiles, it is assumed that the loads behave with the unknown diagram, which aims to make a compromise between the other three types of consumption. In Figure 5.4, the ”unknown” load profile is shown, scaled for a 6.9 kVA consumer.

It can be seen that this load profile has traces of the other three load profiles: it has a small peak in the evening and early night, resembling the residential load profile, and it resembles the commercial and industrial load profiles by having peaks during the morning and during the afternoon, whilst having a considerable drop during lunch time.

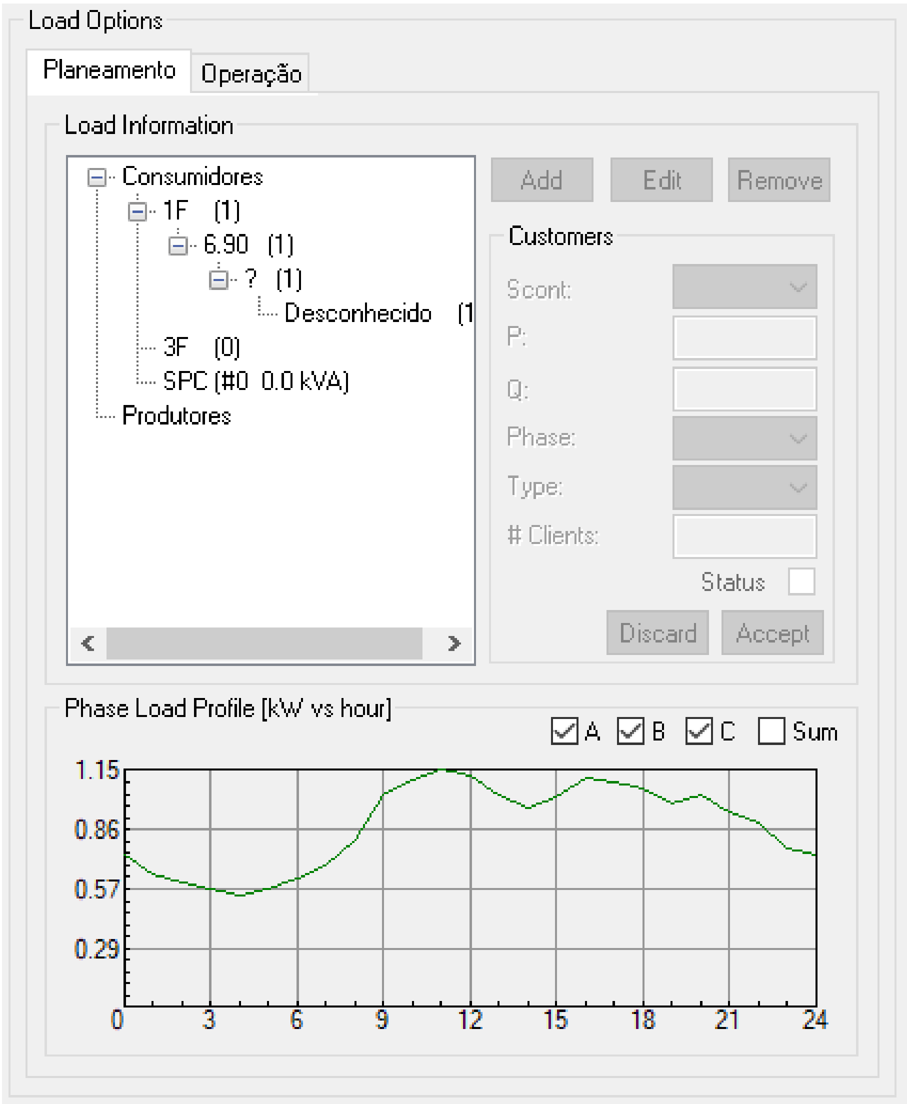


Figure 5.4: ”Unknown” load diagram for a 6.90 kVA consumer (taken from *DPlan*)

With the load profiles defined, it is possible to integrate electrical vehicles into our grid by making some assumptions:

1. The integrated EV is considered to be a Tesla model [37]: a fully electric vehicle;

2. The EV uses a 7.3 kW charger;

3. The EV completely charges in 12 hours, during nighttime, from 20h to 8h.

Therefore, the previous load profiles are altered to integrate one EV with the above description and behaviour per consumer.

In Figures 5.5 and 5.6, the load profiles of two nodes with different contracted power, with the integration of the EV charging, are displayed.

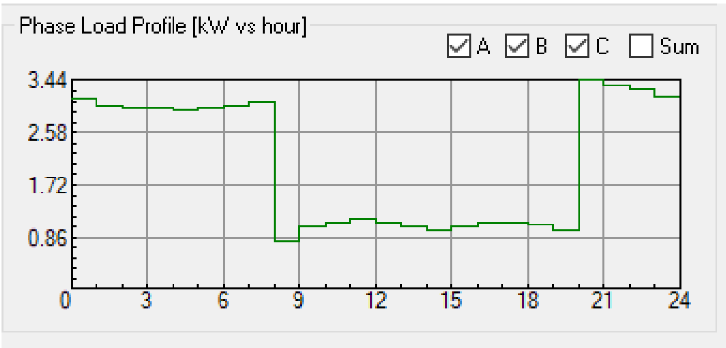


Figure 5.5: Load Profile with integrated EV for a 6.9 kVA consumer (taken from *DPlan*). EV integration very noticeable, due to normal load during nighttime being low.

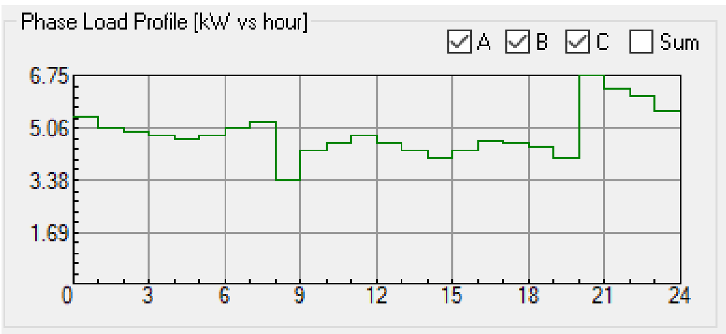


Figure 5.6: Load Profile with integrated EV for a 20.7 kVA consumer (taken from *DPlan*). EV integration less noticeable, due to high contracted power consumer.

5.3 Case studies: grid restructuring

In order to integrate EVs, that represent significantly heavier and more disruptive load to the grid, the restructuring is done by phases.

Since the grid is realistic, this phase by phase restructuring should also be realistic process of change, smoothing the change and the splitting the total investment into several phases.

The first step is to look at the original grid in Figure 5.1: the wide LV grid is fed by a single transformer, so following the same idea as in the last chapter (in the model grid case, Figures 4.1 and 4.2), the idea would be to extend the MV feeder, creating more MV to LV transformers, subdividing the load and ultimately shrinking the low voltage feeders (less distance traveled in LV).

As a good first phase approach, the MV grid should be extended to the sectioning stations (also known as ”armários” in Portuguese). Figure 5.7 illustrates this idea by trading the sectioning stations for transformers. The idea is to have the higher load density areas have more transformers as suggested by inspecting the restructured 1st phase grid.

Following this, in order to further take the idea presented in this thesis, a case to case study should be done for each distinct grid. Understanding where the grid weak spots are, where the heavier loads are placed and the smart grid solutions available in each different community should be all taken into account. In this project the next grid restructuring phase is shown in Figure 5.8. This methodology resembles an iterative procedure that reduces the amount of load ”hanging” in a transformer in each iteration, creating more and more transformers, specially in the higher load density zones.

Furthermore, 3 different cases of study are considered, being:

1. Case 1: Original realistic grid (Figure 5.1), comprised by a single MV to LV transformer;

2. Case 2: 1st phase restructured grid (Figure 5.7), comprised by 4 MV to LV transformers;

3. Case 3: 2nd phase restructured grid (Figure 5.8), comprised by 10 MV to LV transformers.

These cases serve as examples to assess the impact of grid restructuring on EV integration and overall grid performance.

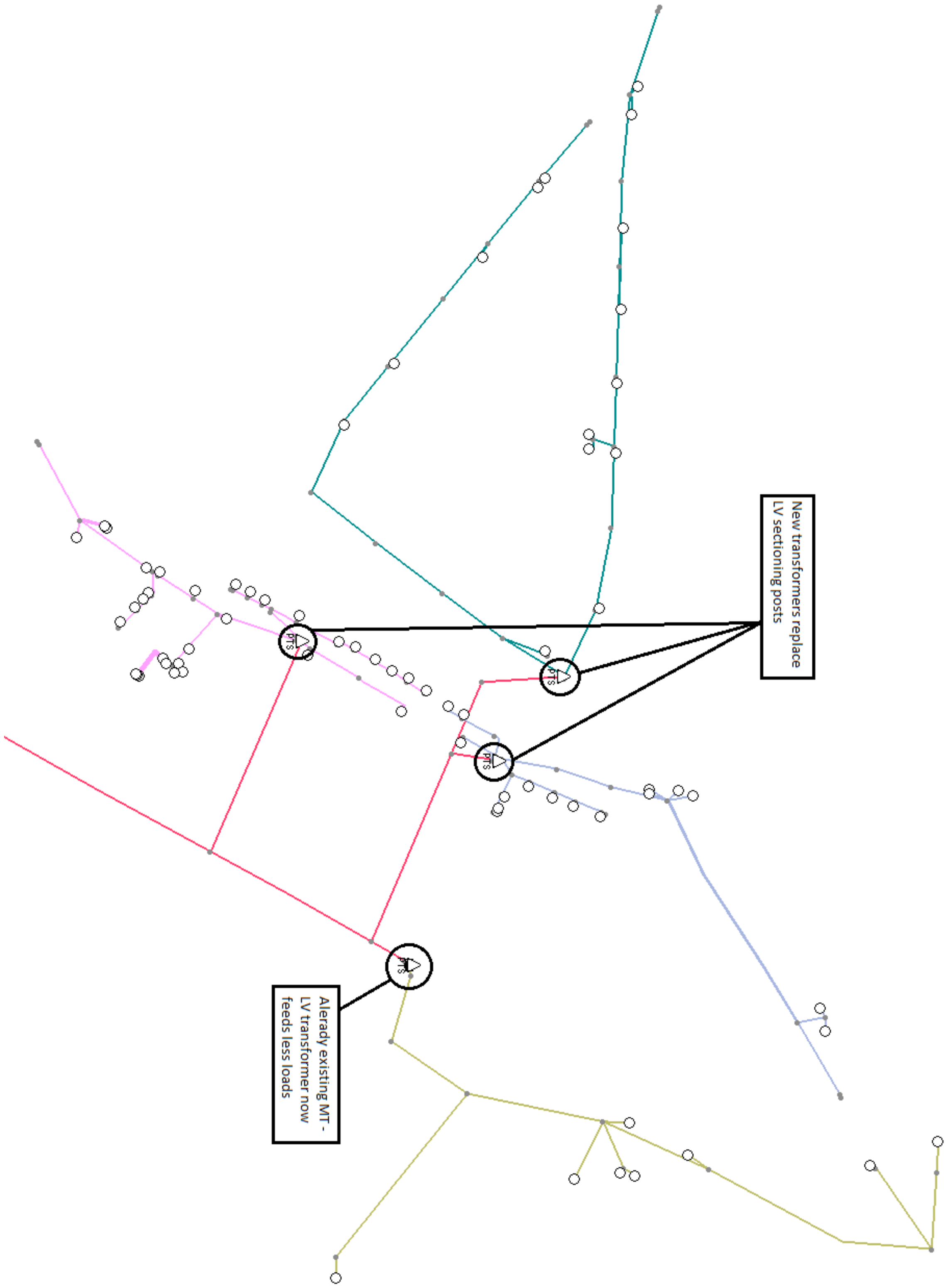


Figure 5.7: Realistic grid restructured - 1st Phase (taken from *DPlan*). New transformers placed on the previous LV sectioning posts.

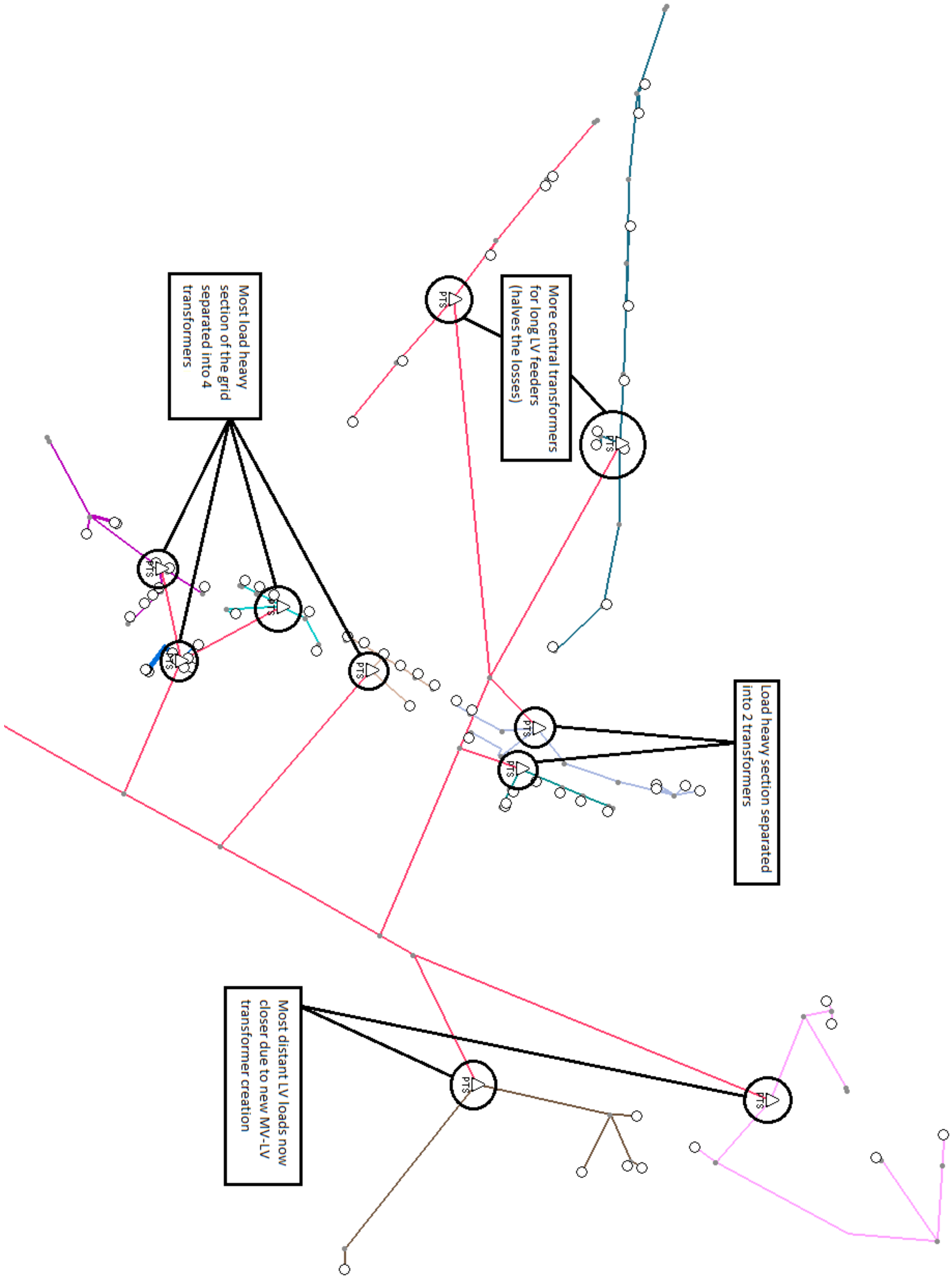


Figure 5.8: Realistic grid restructured - 2nd Phase (taken from *DPlan*). The bigger the load density, the more transformers are added to that section, closing the distance to the client, promoting a more resilient grid.

5.4 Case studies: Results

Now that the grid has been characterized, the load profiles have been built and the 3 progressive case studies have been shown, it is possible to run the grid simulations in *DPlan*.

As already stated, the power flow mode used is the "chronometric" mode, where the clients are created at the load nodes and, afterwards, the load profiles with the integrated EVs are imported. After this import, the simulation is done automatically for every hour of the day: all the currents and voltages are calculated 24 times (in reality, they are calculated 96 (24×4) times, at every 15 minute interval, but in this case, it repeats 4 times each).

Due to the inclusion of the EVs in our grid, and looking at our original load profile, in Figure 5.4, it is possible to separate the simulation in two large groups:

- 8h - 20h: The time window where no EVs are charging. For the remainder of this chapter called "**daytime**". During daytime, the peak load occurs at 11h while the minimum load occurs at 8h;
- 20h - 8h: The time window where the EVs are charging. For the remainder of this chapter called "**nighttime**". During nighttime, the peak load occurs at 20h while the minimum load occurs at 4h.

Within these two groups, the global extremes of the grid in terms of load are expected to be the daytime minimum and the nighttime maximum, since the EVs represent a lot more weight to our grid than the load consumption without the EVs. These extremes change according to the consumer (with a high enough contracted power, the global maximum could be during daytime), but is valid for the grid as a whole because the majority of the consumers have low power loads.

5.4.1 Case 1 - Original grid

In Table 5.1, the results of the simulation in *DPlan* are displayed.

Additionally, in Figures 5.9 and 5.10, the Case 1 (original grid) is presented in *DPlan*, during daytime and nighttime, respectively. The current and voltage filters are used to better display the results. This way the branches of the grid change colour according to the current they are experiencing at the simulation time, while the nodes change colour according to the voltage present.

Case 1 - Results	Daytime		Nighttime	
	Minimum	Maximum	Minimum	Maximum
Maximum Voltage Drop [%]	10.66	16.11	36.97	Divergent
Losses [kW]	15.66	35.14	144.84	Divergent

Table 5.1: Simulation results in *DPlan* for Case 1

From Table 5.1 along with Figures 5.9 and 5.10, it is possible to take several conclusions:

- During daytime, even in the best time scenario, the maximum voltage drop is already 0.66% above the 10% limit established. The most affected branches are the ones that lead to the sectioning post on the higher density zone (South-West, on the grid);

- During nighttime, due to the connection of the EVs, the power flow does not converge on the peak load scenarios: the current that is required to transit in the long LV cables is so high that the grid collapses. Even during the moments where the power flow converges, the voltage drops and the losses are high enough for the grid to not operate (almost 40%).
- The voltage drops in each branch are proportional to the currents flowing through them, according to Ohm's Law, and the power losses are proportional to the square of the current. This justifies and validates the differences between losses, when compared to the ones in the voltage drop percentages.

5.4.2 Case 2 - Restructured Grid Phase 1

In Table 5.2, the results of the simulation in *DPlan* are displayed.

Additionally, in Figures 5.11 and 5.12, the Case 2 (phase 1 restructured grid) is presented in *DPlan*, during daytime and nighttime, respectively.

Case 2 - Results	Daytime		Nighttime	
	Minimum	Maximum	Minimum	Maximum
Maximum Voltage Drop [%]	2.43	3.50	7.93	9.07
Losses [kW]	2.95	6.12	17.1	27.02

Table 5.2: Simulation results in *DPlan* for Case 2

Taking a look at Table 5.2, as well as Figures 5.11 and 5.12:

- In general, there is an improvement in quality of service - the maximum voltage drop never surpasses 10%;
- The majority of the grid is operating at an expected level, with the expected voltage drops and losses. Nevertheless, there is still room for improvement on the western side of the grid, where the load density is the highest, especially on the south-west (seen in Figure 5.12, in the red stressed branches and transformers);
- From this case, it is seen that the biggest voltage drop comes from the two nodes in the north-east of the grid, since these are the most distant nodes and the LV grid has high voltage drops. This also opens up room for improvement and further creation of a MV to LV transformer near these nodes.

5.4.3 Case 3 - Restructured Grid Phase 2

In Table 5.3, the results of the simulation in *DPlan* are displayed.

Additionally, in Figure 5.13, the Case 3 (phase 2 restructured grid) is presented in *DPlan*, during nighttime.

Looking at Table 5.3 and Figure 5.13:

- In this case, there is no need for a daytime picture of the performance of the grid, since every node and branch have a good performance during nighttime (as seen in Figure 5.13 - the worst case scenario);

Case 3 - Results	Daytime		Nighttime	
	Minimum	Maximum	Minimum	Maximum
Maximum Voltage Drop [%]	0.74	1.06	3.42	3.84
Losses [kW]	0.53	1.05	2.81	4.31

Table 5.3: Simulation results in *DPlan* for Case 3

- The overall performance of the grid is impeccable - there are no meaningful voltage drops at any time, and the losses reflect this improvement in quality of service in an even better way;
- During daytime, the grid is operating at under 5% of its total installed power.

5.5 Investment Analysis

The results of the power flow presented in the last section show clearly the increased quality of service in the restructured grids, when compared to the original realistic grid. It shows that our restructuring idea and line of thought presents valid results in improving the grid performance, but at which cost?

From an engineering standpoint it is expected that, when new grid elements (MV - LV transformers, in this case) are inserted, the grid performs better overall. Needless to say that these new inclusion require some kind of investment, so now the objective is to determine whether or not the investment done in the original grid (presented in Figure 5.1) ended up being worth.

For this purpose, there are some key factors that need to be established, for the evaluation and procedure to be fair for each one of the case scenarios:

Equipment	Prices
MV-LV Transformer Substation (15kV, 160kVA)	5000 €/substation
Transformer Substation Assembly (15kV)	5000 €/substation
15kV MV Line	30000 €/km
LV Line	7000 €/km

Table 5.4: Prices of each relevant grid component

1. The prices of the equipment installed in the MV or LV grid are constant along all cases. For privacy reasons, the prices used are rounded and not exact and can be seen in Table 5.4;
2. The maximum capacity of the grid is evaluated in each case scenario and it corresponds to the maximum sum of all the loads that guarantee a voltage drop below 5%;
3. Finally, the price per kilowatt (γ) is calculated by dividing the total cost of the grid by its maximum capacity as presented in Equation 5.1. This value represents the comparison factor between the three different case scenarios.

$$\gamma = \frac{C_t}{P_{max}} \tag{5.1}$$

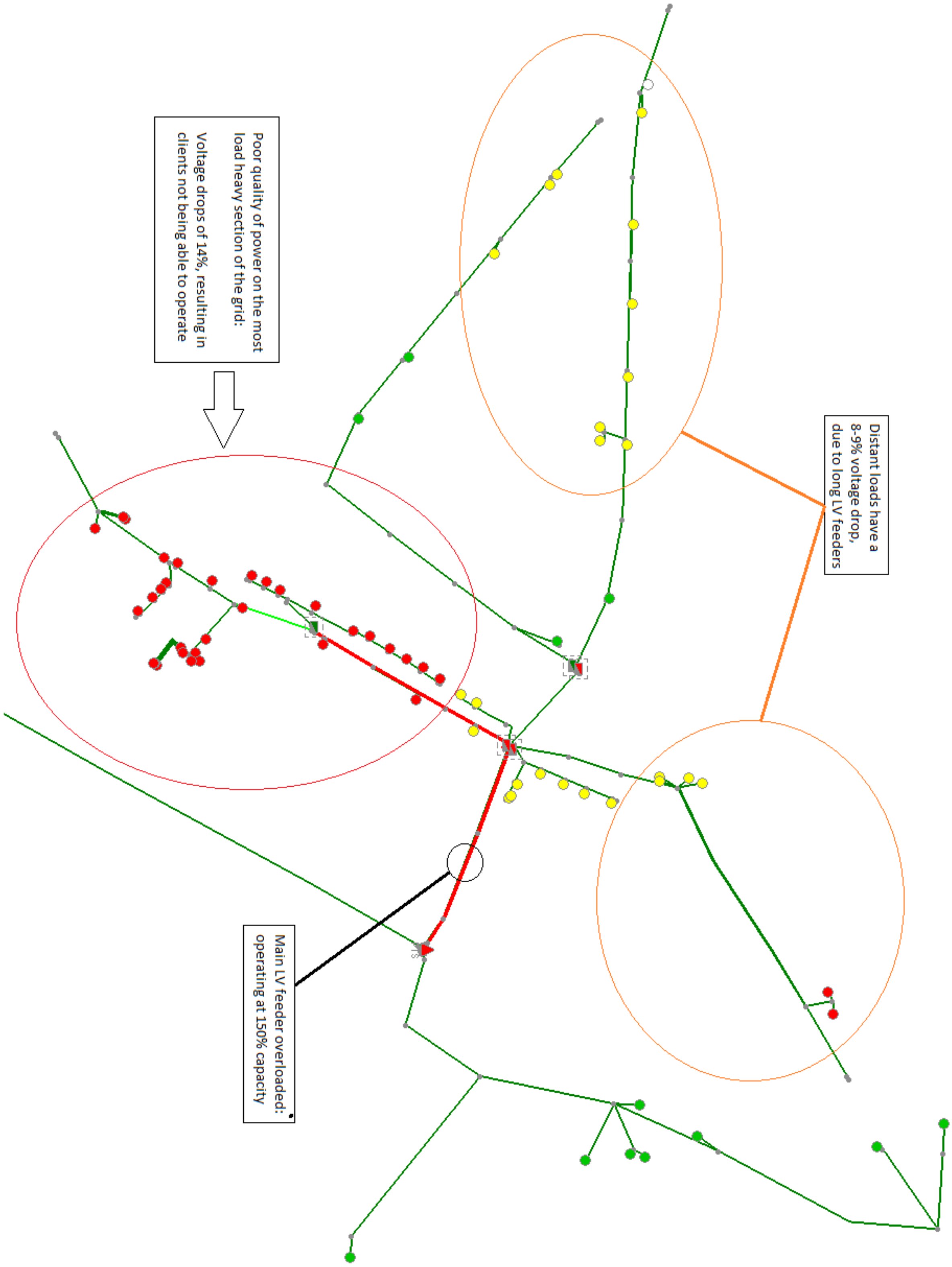


Figure 5.9: Case 1 results at 10h30 (taken from *DPlan*). Grid performance problems on the higher density zones of the grid and in the more distant loads.

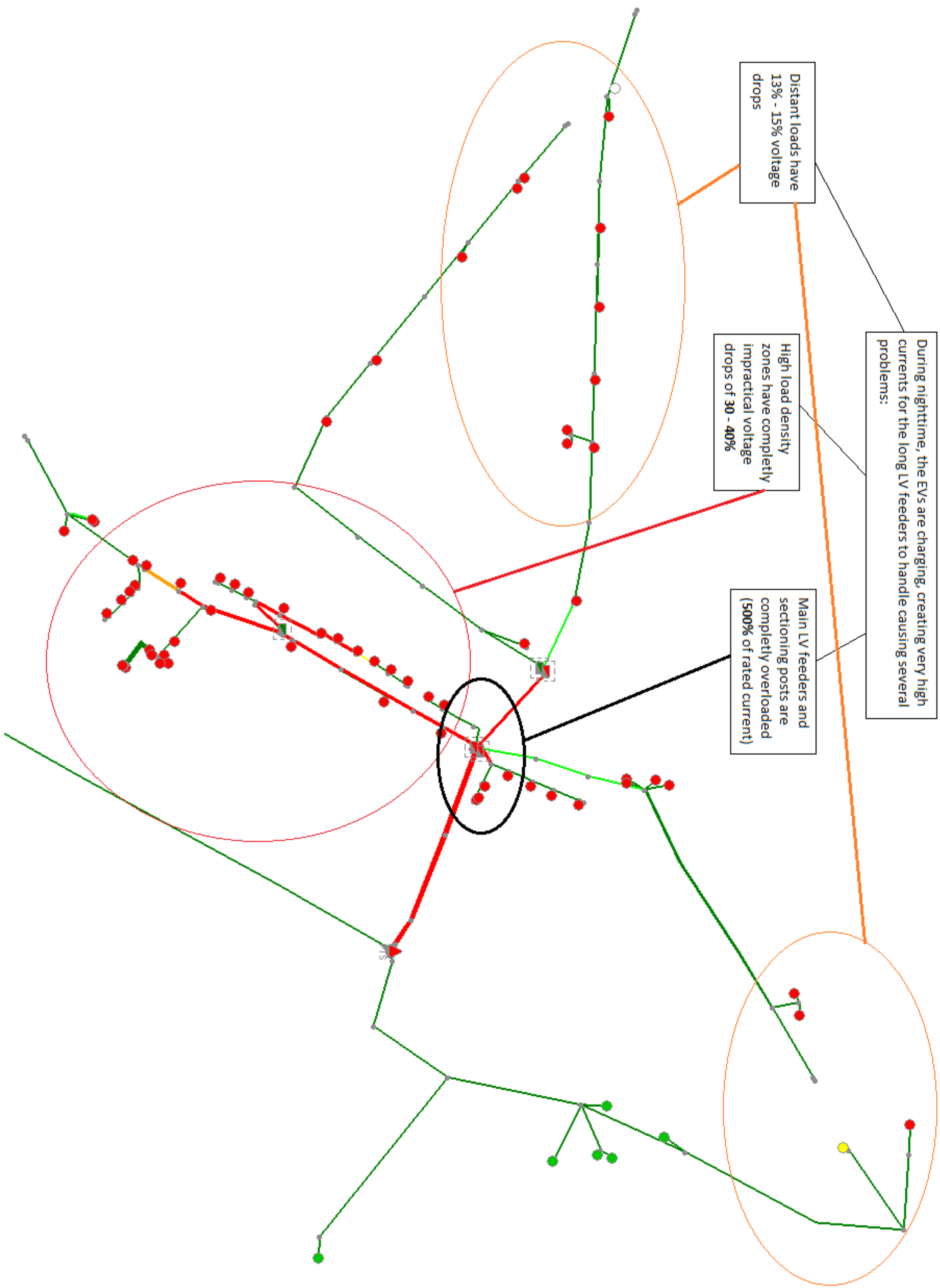


Figure 5.10: Case 1 results at 00h30 (taken from *DPlan*). Grid completely collapses, with impossible to operate voltage levels, due to EV inclusion.

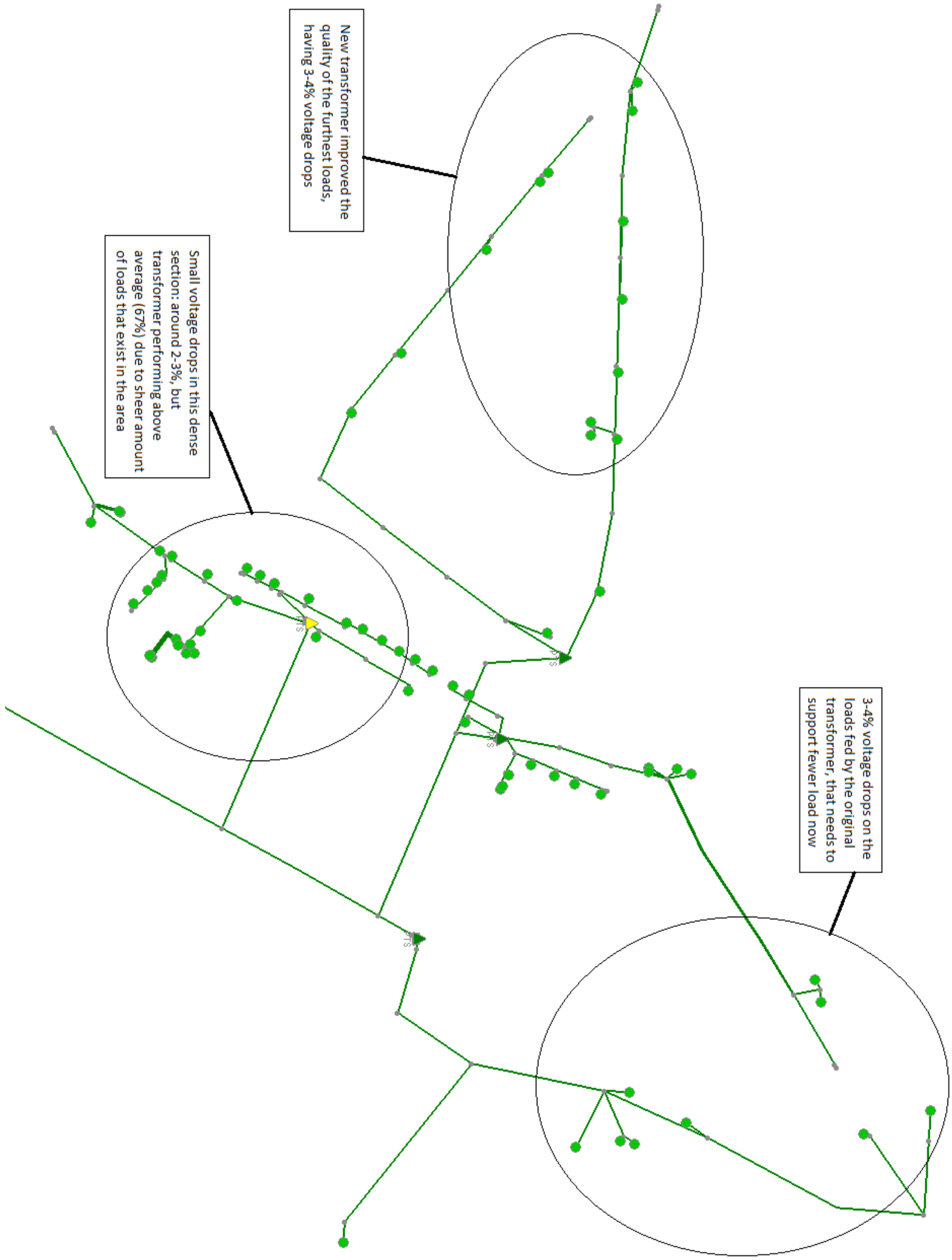


Figure 5.11: Case 2 results at 10h30 (taken from *DPlan*). Much better performing grid during daytime.

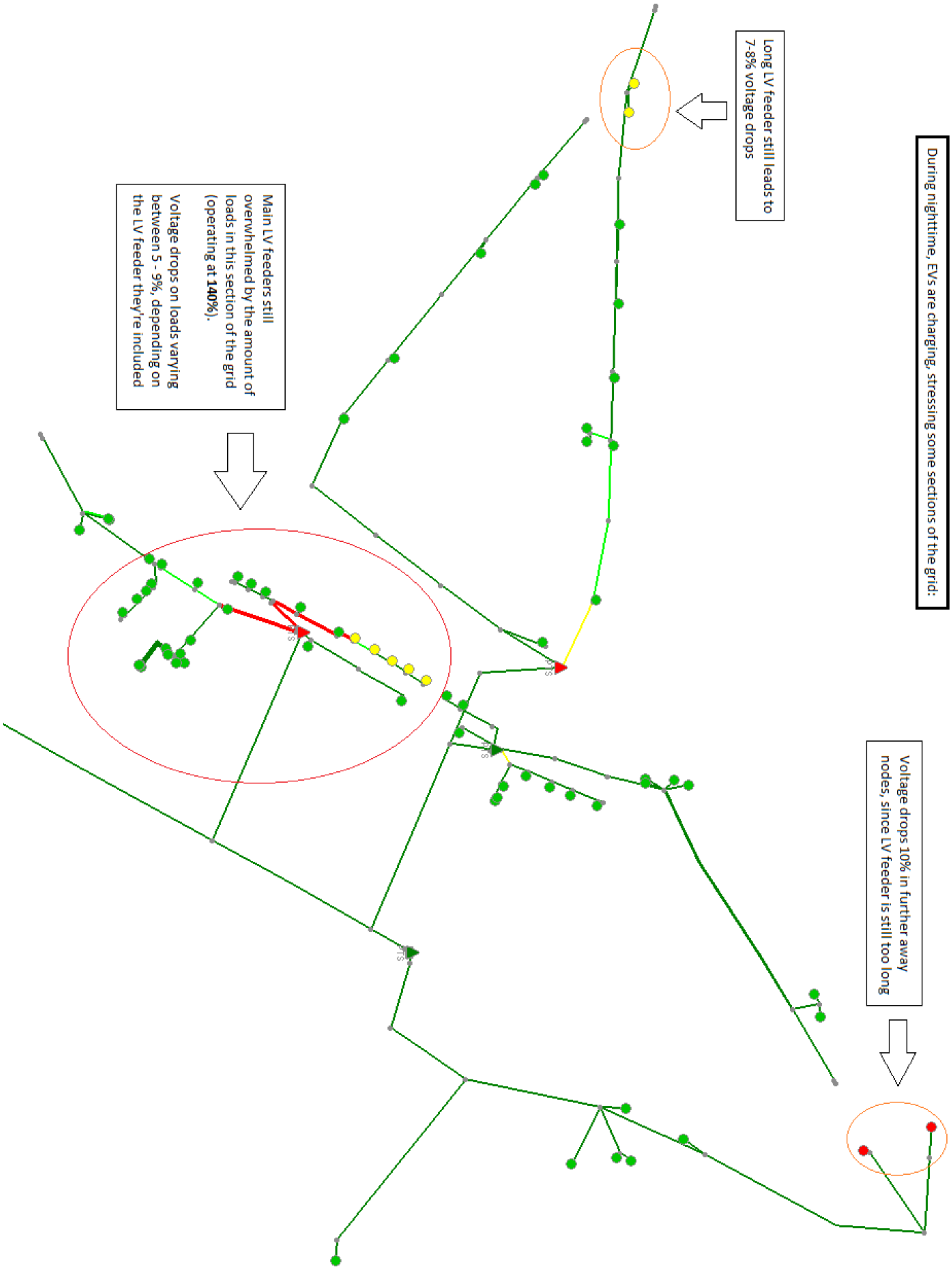


Figure 5.12: Case 2 results at 20h30 (taken from *DPlan*). Main LV feeders still overloaded by the inclusion of the EVs, but the grid is surely more resilient and completely operational.

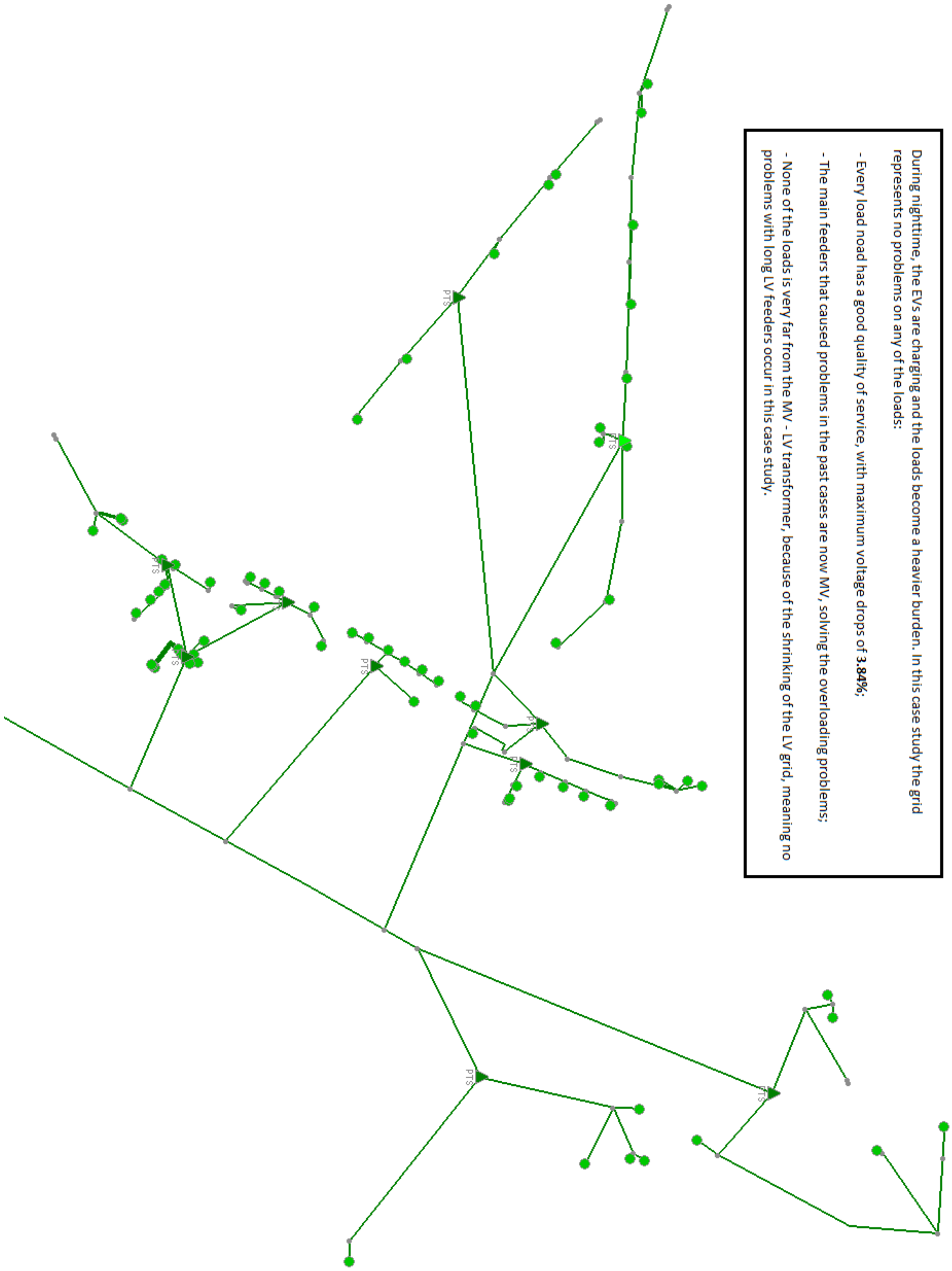


Figure 5.13: Case 3 results at 20h30 (taken from *DPlan*). Impeccable QoS during nighttime.

5.5.1 Case 1 - Original grid

In Table 5.5, the investment analysis is displayed for the Original grid (Figure 5.1).

Equipment	Quantity [unit] or Length [m]	Price [€]
MV-LV Transformer Substation (15kV, 160kVA)	1	5000
Transformer Substation Assembly (15kV)	1	5000
15kV MV Line	0	0
LV Line	2615	18305
Total Cost		28305
Maximum Power (Voltage drops <5%) [kW]		105,8
Price per kilowatt (γ) [€/kW]		**267,5**

Table 5.5: Case 1 - Investment analysis

The grid only has a single MV to LV transformer substation and it is not comprised of any MV lines, since the already existing MV feeder does not account for these expenses. Therefore, the LV grid represents the entirety of the grid lines, with a length of 2615 m. These components represent a total investment of **28305 €**.

On the flip side, the maximum grid capacity is not very high, **105.8 kW**. It is important to remember that this value represents the maximum power that leads to a maximum voltage drop of 5%.

Using Equation 5.1, the price per kilowatt of this first case scenario is **267.5 €/kW**.

5.5.2 Case 2 - Restructured Grid Phase 1

In Table 5.6, the investment analysis is displayed for the phase 1 restructured grid (represented in Figure 5.7).

Equipment	Quantity [unit] or Length [m]	Price [€]
MV-LV Transformer Substation (15kV, 160kVA)	4	20000
Transformer Substation Assembly (15kV)	4	20000
15kV MV Line	269.6	8088
LV Line	2342	16394
Total Cost		64482
Maximum Power (Voltage drops <5%) [kW]		468.4
Price per kilowatt (γ) [€/kW]		**137.7**

Table 5.6: Case 2 - Investment analysis

In this case, the total cost had an increase of 128%, caused by the inclusion of 3 new MV-LV substations and the need to extend the already existing MV feeder, that has much larger costs per kilometer than the LV feeder. This increase led to a total investment of **64482 €**.

As a result of this grid investment, the maximum grid capacity had an increase of 342%, having a value of **468.4 kW**.

Consequently, the price per kilowatt had a decrease of 49%, meaning that the investment on the grid had a good payoff. This decrease led to a γ of **137.7 €/kW**.

5.5.3 Case 3 - Restructured Grid Phase 2

In Table 5.7, the investment analysis is displayed for the phase 2 restructured grid (represented in Figure 5.8).

Equipment	Quantity [unit] or Length [m]	Price [€]
MV-LV Transformer Substation (15kV, 160kVA)	10	50000
Transformer Substation Assembly (15kV)	10	50000
15kV MV Line	940.3	28209
LV Line	1799	12593
Total Cost [€]		140802
Maximum Power (Voltage drops <5%) [kW]		1451.2
Price per kilowatt (γ) [€/kW]		**97.02**

Table 5.7: Case 3 - Investment analysis

The quantity of transformers drastically increased in this case - from 4 to 10 substations. This, alongside the MV grid having a length of 940.3 m, leads to a total cost of **140802 €**. This cost represents an increase of 397%, when compared to the first case scenario, and an increase of 118%, when compared to the second case scenario.

The maximum grid capacity also suffered an increase to **1451 kW**, representing an increase of 1272%, when compared to the first case scenario, and an increase of 210%, when compared to the second case scenario.

Finally, the price per kilowatt (γ) suffered a new decrease to **97.02 €/kW**, meaning that the case 2 grid is the most profitable - each kilowatt is cheaper than in the other case scenarios.

Figure 5.14 represents the price per kilowatt in each of the cases analysed. By inspection, it is possible to confirm that the decrease in γ is significantly higher between the first and second scenarios than between the second and third scenarios.

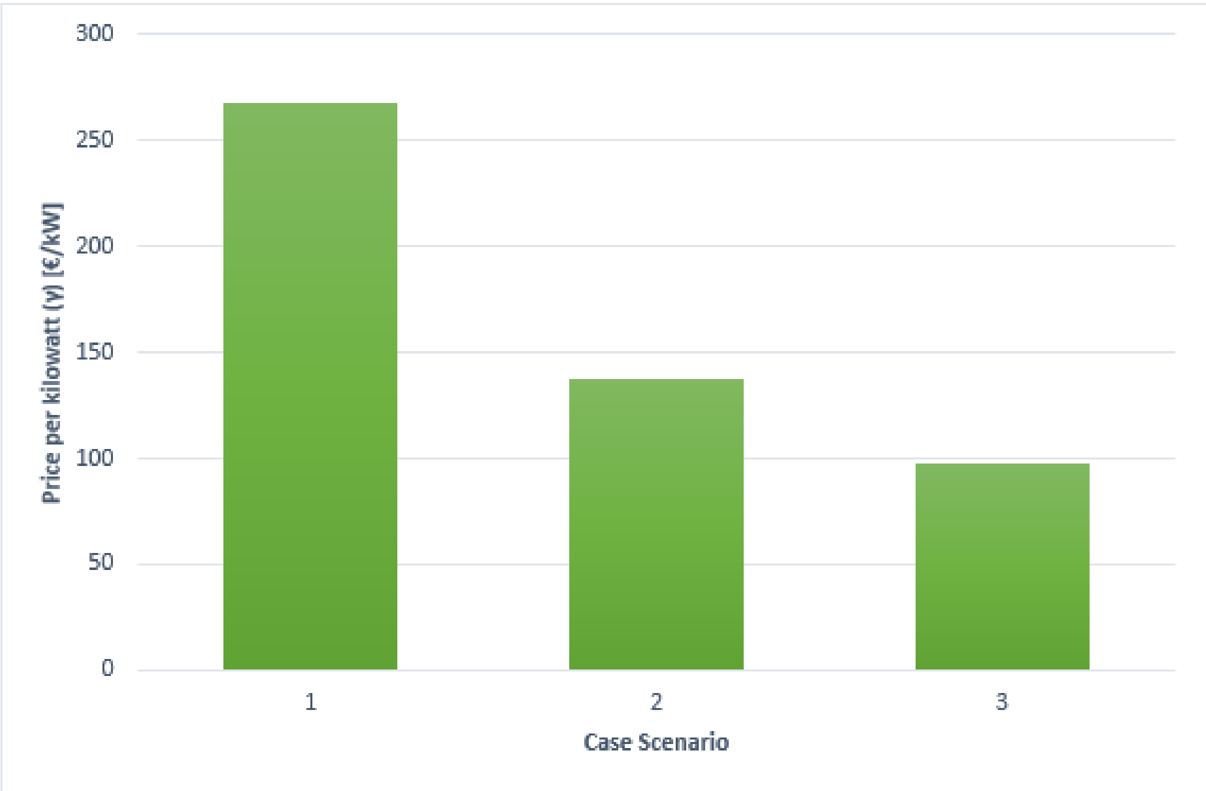


Figure 5.14: Graphic representation of the price per kilowatt (γ) per case scenario. Each restructuring iteration has proved to be worthwhile.

Chapter 6

Conclusion and Future Work

In this last chapter, the conclusions of the dissertation regarding the two grids analysed are taken, along with future work in the topic that could prove relevant.

6.1 Conclusions

The starting point of this dissertation was to understand the impact of distributed generation (DG) from photovoltaic (PV) sources and electric vehicles (EVs) on the power quality of low-voltage (LV) distribution networks. Following this analysis, the focus of the study became the restructuring of LV networks through increased penetration of MV networks and their proximity to end consumers. This network restructuring represented a reinforcement option for the electrical distribution network, serving as infrastructure to support the implementation of smart grid technologies and the utilization of operational flexibility.

The proposed restructuring analysis was conducted through the study of two distinct networks:

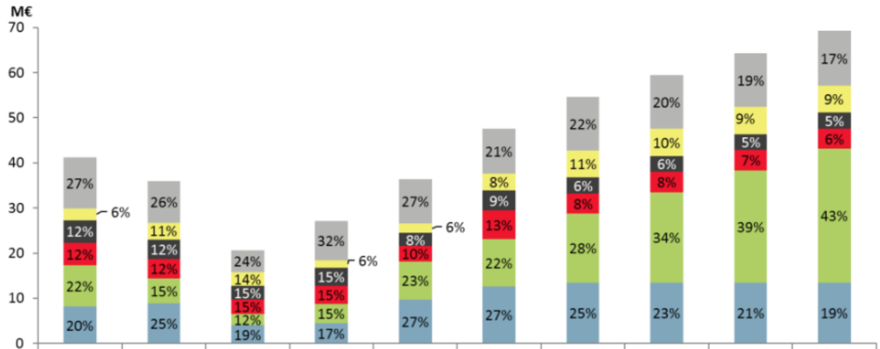
- A model grid, programmed in *matlab*, enabling a better understanding of energy flow processes and network dynamics. Different levels of DG penetration were integrated into this model.

- A realistic network provided in *DPlan*, where EV charging was implemented to evaluate its disruptive potential. This realistic network was progressively developed based on the proposed solution through two distinct phases, with the investment involved also analyzed in each phase of restructuring.

In the model network, the obtained results validated the initial assumption of improved quality of service (QoS). The findings showed that network restructuring reduced voltage drop by more than 5% in the absence of any generation, improving the voltage of the longest feeder from a drop of 7% to just 1.5%. With the integration of generation and increasing levels of DG penetration, it was also observed that the proposed restructuring alleviated overvoltages. In the most overloaded feeder with DG, the overvoltage decreased from 3% to 0.5%, which is practically negligible.

In the case of the realistic network studied in DPlan, the results obtained for quality of service, along with the investment perspective, also validated the proposed solution. After the introduction of EV charging, the original realistic network collapsed completely during the peak load hours, experiencing minimum voltage drop values of 37% during EV charging. The improvement in quality of service was evident from the first phase of restructuring, where the network reached maximum voltage drop values of 9%, while in the second phase of restructuring, the network only reached maximum voltage drop values of about 4%. In terms of investment analysis, the network restructuring revealed a decrease in price per kW by 48% and 30% for each phase of restructuring, respectively.

Figures 6.1 and 6.2 illustrate the investment plan of the Portuguese distribution system operator (DSO), E-REDES, until 2025 in the areas of ”Technical Service Quality” and ”Network Efficiency”, respectively. The figures clearly show an upward trend in investments related to the proposed restructuring discussed in this dissertation. With the observed investment levels, it is evident that the proposed solution represents a viable option for grid reinforcement during the integration period of DG and EVs, a phase where we are already entered.



	2016	2017	2018	2019	2020E	2021E	2022E	2023E	2024E	2025E
TOTAL	41,2	36,0	20,6	27,2	36,4	47,6	54,6	59,5	64,3	69,3
Outros*	11,3	9,2	4,9	8,7	9,8	10,0	11,8	12,0	12,0	12,1
Sist. Intelig. de Supervisão e Operação e Telec.	2,6	3,8	3,0	1,6	2,2	3,8	6,0	6,0	6,0	6,0
Aut. SEs e Moderniz. SPCC	5,0	4,3	3,1	4,1	2,9	4,4	3,5	3,5	3,5	3,5
Aut. e Telec. Rede MT	5,0	4,3	3,1	4,1	3,5	6,3	4,5	4,5	4,5	4,5
Renovação e Reabilitação de Ativos AT/MT	9,2	5,5	2,5	4,2	8,4	10,5	15,3	20,1	24,9	29,7
Melhoria da Qualidade de Serviço Técnica	8,1	8,9	4,0	4,5	9,7	12,6	13,4	13,4	13,4	13,4

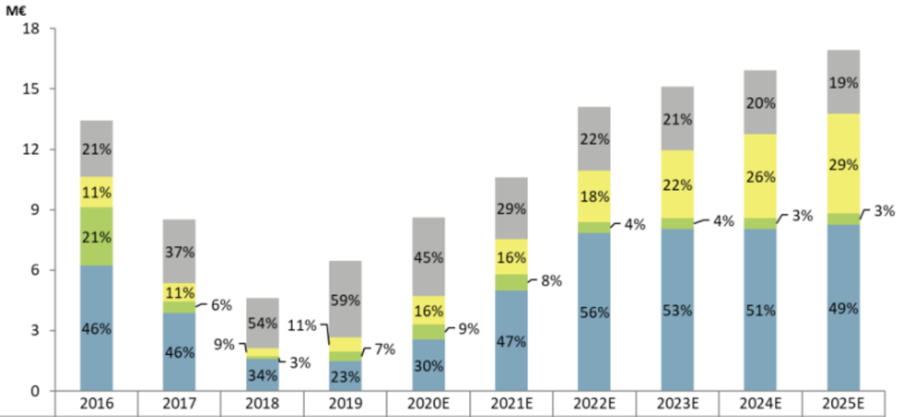
* **Inclui:** Inv. Obrigatório (excluindo eq. contagem) - Desenvolvimento de Rede - Aquisição de Terrenos para Subestações - Redução de Perdas Técnicas AT/MT - Investimento Inovador Beneficiações Extraordinárias - Abertura e Restabelecimento da RSFGC - Ligações aos Operadores de Redes BT - Programa de Inv. Corrente Urgente

Figure 6.1: E-REDES investment proposition on Technical Service Quality until 2025 [12]. Notice the investment in "Improvement of QoS" has a tendency to increase, being promised 13.4 M€ until 2025.

6.2 Future Work

The analysis shown in Figure 5.14 revealed a noteworthy trend: as the investment in the network increases, following the proposed solution in this dissertation, the price per kW, γ, decreases, leading to an increase in grid efficiency. However, it is important to note that this study assumes that regardless of the investment made in the network, there will always be sufficient demand to fully utilize the new infrastructure, defined as a 5% voltage drop. In reality, this assumption may not hold true, as the growth of loads in a network occurs gradually rather than boundlessly. Figure 6.3 showcases two curves representing the behavior of the price per kW as the investment increases. The blue curve corresponds to a scenario where network demand always matches the investment, resulting in a continuous decrease in the price per kW. Conversely, the orange curve represents a more realistic scenario observed in actual networks.

In future work, it would be highly intriguing to combine the proposed restructuring outlined in this dissertation, along an optimization problem to determine the optimal investment for each network.



	2016	2017	2018	2019	2020E	2021E	2022E	2023E	2024E	2025E
TOTAL	13,4	8,5	4,6	6,5	8,6	10,6	14,1	15,1	15,9	16,9
Outros*	2,8	3,2	2,5	3,8	3,9	3,1	3,2	3,2	3,2	3,2
Renovação e Reabilitação de Ativos AT/MT	1,5	0,9	0,4	0,7	1,4	1,8	2,6	3,4	4,2	5,0
Redução de Perdas Técnicas AT/MT	2,9	0,5	0,1	0,5	0,7	0,8	0,6	0,6	0,6	0,6
Desenvolvimento de Rede	6,2	3,9	1,6	1,5	2,6	5,0	7,9	8,1	8,1	8,3

* **Inclui:** Inv. Obrigatório (excluindo eq. contagem) - Aquisição de Terrenos para Subestações - Melhoria da Qualidade de Serviço Técnica - Beneficiações Extraordinárias Ligações aos Operadores de Redes BT - Programa de Inv. Corrente Urgente

Figure 6.2: E-REDES investment proposition on Network Efficiency until 2025 [12]. Investment in "Grid development" is proposed to be 8.3 M€ in 2025.

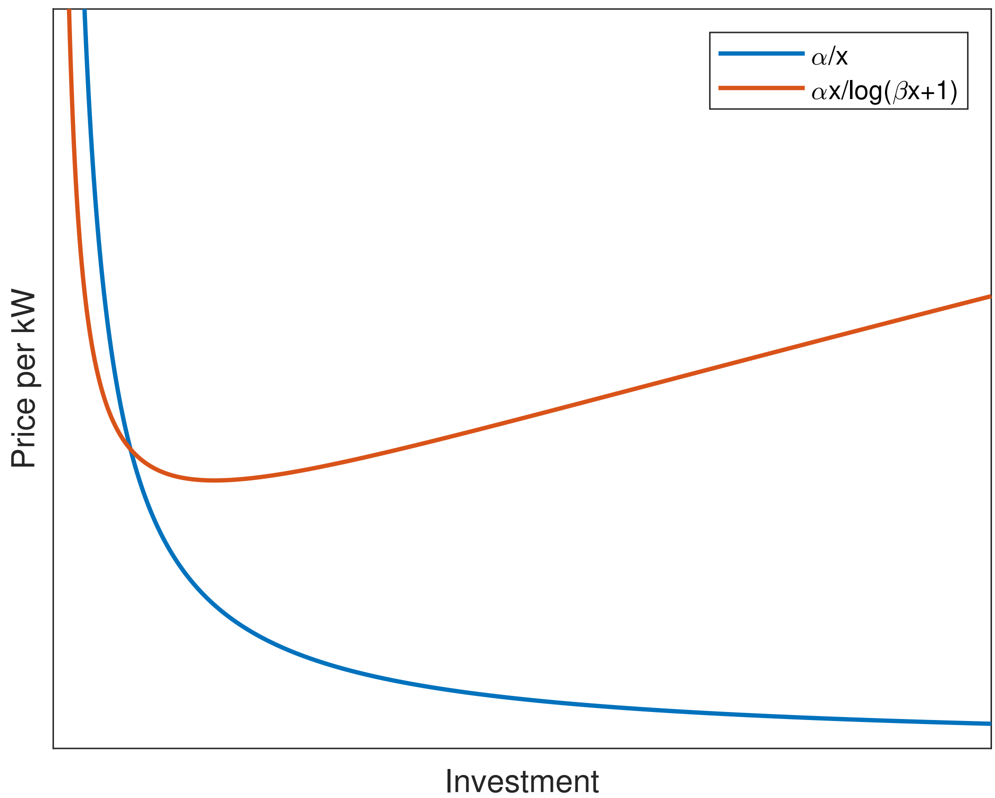


Figure 6.3: Theoretical curves of γ versus investment. Blue curve attempts to model hypothetical grid with infinite capacity to respond. Orange curve attempts to model the real behaviour of a grid.

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TÉCNICO LISBOA

A Study on the Restructuring of LV Networks

João Miguel Branco Gomes