A Study on the Restructuring of LV Networks

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***Abstract*—The growing interest in renewable energy and non-polluting transportation methods, driven by the scarcity of non-renewable resources and environmental awareness, has led many countries to incentivize local electricity production and electric vehicle usage. However, integrating these resources into the electrical grid poses challenges related to distributed generation and increased power flow during periods of excess photovoltaic generation or simultaneous electric vehicle charging. This study focuses on the impact of DG and EV integration on the quality of service in the low-voltage electrical grid and proposes a restructuring approach to ensure compliance with power quality requirements. The effectiveness of the proposed solution is evaluated through simulation results from both a model network and a realistic network.**

***Index Terms*—Distributed Generation, Electric Vehicles, Low Voltage, Quality of Service, Power Quality**

I. INTRODUCTION

A. Distributed Generation

Towards the end of the 20th century, growing concerns over the finite nature of fossil fuels such as coal, oil, and natural gas, coupled with an increased environmental consciousness, brought about a fundamental shift in the global energy landscape. The imperative to generate energy without compromising the environment and to ensure a sustainable future led to the emergence of renewable energy sources such as hydro, wind, and photovoltaic energy.

This shift was further reinforced by the United Nations Framework Convention on Climate Change [1], a significant international treaty signed by nearly all countries in 1992. The treaty, periodically updated with important milestones like the Kyoto Protocol, imposes limits on greenhouse gas emissions. The latest milestone was achieved during the 2015 conference held in Paris, where 195 countries, including Portugal, reached a consensus on a new set of goals and measures to combat global warming.

Portugal, with its favorable attributes for harnessing and utilizing renewable energy sources, has experienced remarkable progress in renewable energy production, driven by government incentives and the need to meet international commitments. As depicted in Figure 1, renewable sources have accounted for over half of the installed power since 2011. Notably, hydroelectric power has played a significant role throughout the 21st century and has witnessed substantial growth in the past decade. Additionally, solar energy has seen widespread integration, making a substantial contribution in 2021 and 2022.

Similarly, Figure 2 illustrates the energy production in Portugal from different sources since 2015. It is evident that non-renewable thermal energy production has experienced a substantial decline since 2017, while renewable energy production has steadily increased. Among these renewable sources, photovoltaic energy production has witnessed the most significant percentage increase in recent years. Although it currently represents a relatively small portion of the overall energy mix, Portugal's immense potential in harnessing solar energy, with the highest number of sunshine hours per year in Europe, suggests that photovoltaic solar energy will become a major focus of investment in the upcoming years.

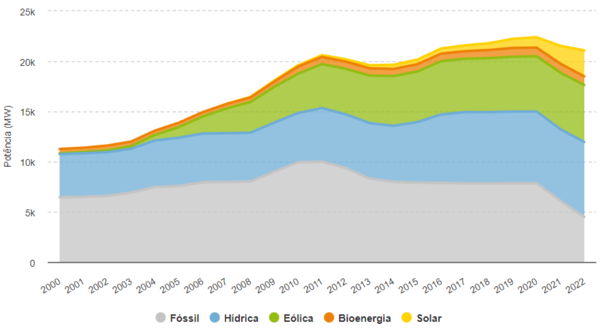

Fig. 1. Power installed by different sources in Portugal in the 21st century [2]

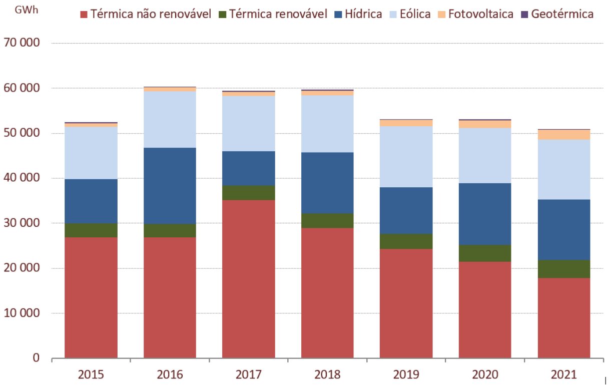

Fig. 2. Electricity production by different sources in Portugal since 2015 [3]

Given the growing importance of renewable energy generation, it becomes imperative to comprehensively understand the concept of distributed generation (DG) and its integration into the energy grid, along with its associated implications. This thesis places a significant emphasis on exploring this aspect as one of its primary pillars of investigation.

B. Electric Vehicles

Amidst the backdrop of increasing environmental consciousness and the pursuit of a sustainable future, it is crucial to acknowledge that rapid changes are not limited to energy generation alone. Numerous awareness initiatives and public campaigns are shaping people's everyday lives and influencing their choices, including the consumption of goods and services. One notable example is the rise of electric mobility, which is poised to have a substantial impact on a significant portion of the population in the near future.

The transportation sector accounts for more than one-third of global greenhouse gas emissions, with light vehicles contributing 52%, while other modes of transport make up the remaining 48%. In response to the climate and health emergency, many countries have implemented a combination of incentive-based and regulatory policies aimed at achieving two primary objectives: improving air quality and reducing the carbon footprint associated with transportation.

In this context, electric vehicles (EVs) serve as a promising solution for decarbonizing the transportation sector. Figure 3 provides a comparison between the sales of light vehicles in Portugal in 2020 and 2022, revealing a notable decrease of approximately 15% in vehicles solely reliant on fossil fuels. This decline was offset by a 7% increase in purely electric vehicles and an 8% increase in hybrid vehicles.

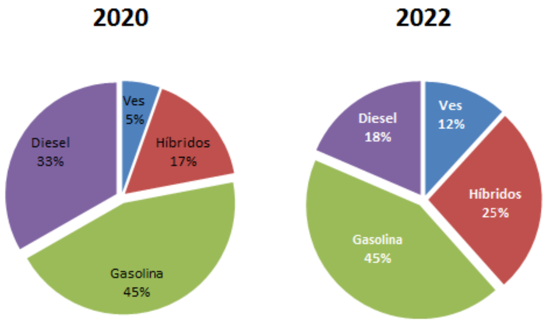

Fig. 3. Comparison of light vehicles sold in Portugal (2020 vs 2022) [4]

Importantly, while the current focus may be on hybrid vehicles due to their technological advancements, policies have already been set in motion to position electric vehicles as the primary mobility alternative within the next 20 to 30 years. These policies are being implemented predominantly in China, the United States, and the European Union, which accounted for 95% of global electric vehicle sales in 2022. The measures undertaken include [5]:

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

Figure 4 illustrates the global sales of electric cars per year since 2013. It is evident that the emergence of EVs has witnessed a remarkable growth trajectory. In 2013, electric vehicles held a mere 0.2% market share, which increased to 2.5% by 2019. Since then, the market share of electric cars has nearly doubled each year, reaching 13% in 2022. Furthermore, it is worth highlighting that when comparing the sales of fully electric cars (BEVs) with hybrid vehicles, BEVs consistently dominate the majority of sales.

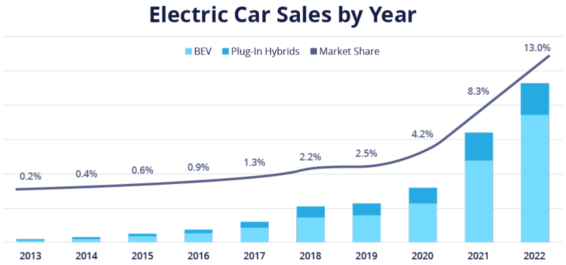

Fig. 4. Worldwide electric car sales by year [5]

Crucially, considering the assertion that the quantity of EVs in the coming decades will significantly surpass current levels, one key aspect of this study will be to examine the impact of this surge on the electrical grid.

C. *Objectives*

The primary objective of this work is to explore the restructuring of the low voltage (LV) network to accommodate the integration of photovoltaic generation and electric vehicles. The study focuses on two distinct networks: one incorporating photovoltaic generation and the other incorporating electric vehicles. Through this investigation, the network's compliance with quality of service (QoS) requirements is evaluated, leading to necessary restructuring measures. The resulting network's QoS levels are reevaluated post-restructuring. Furthermore, an investment analysis is conducted for one of the networks to determine its economic viability and whether the implemented restructuring represents a profitable investment.

II. BACKGROUND AND PROBLEM FORMULATION

A. *Historical evolution*

During the initial stages of the electrical grid's development, the primary focus was on achieving widespread electrification by establishing connections to all consumers and investing in distribution infrastructure. This involved a radial, vertically expanding approach, with the aim of connecting power generation facilities to consumers through efficient and loss-minimizing pathways.

As electricity became indispensable in people's daily lives, following successful electrification efforts, the management paradigm of the power distribution network (PDN) underwent a significant shift. The emphasis shifted towards ensuring power quality as the primary objective, recognizing that disruptions or failures in the electrical network could have significant economic consequences for consumers.

Traditional grid planning, as summarized in [6], encompassed topics such as optimal feeder placement and design, optimal load allocation, optimal substation capacity allocation, and optimal transformer allocation per substation. The objective of this planning was primarily to find the most optimal and economical solutions, considering available feeders, substations, transformers, as well as the need for future demand fulfillment (grid reinforcement).

Traditionally, distribution networks have been designed to facilitate the transmission of electric energy from conventional power plants to connected loads, resulting in a unidirectional flow of power. The network structure is crucial to handle critical load conditions and ensure reliable power delivery [7].

To address this, the evolution of the traditional grid planning has been supported by two vital methods: load forecasting and grid reinforcement.

- Load forecasting [8] involves predicting future electricity consumption patterns based on historical data, socio-economic factors, and technological advancements. This enables grid operators to anticipate changes in demand and plan infrastructure upgrades accordingly;
- Grid reinforcement, on the other hand, focuses on 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 can effectively manage the evolving energy needs and optimize the performance of the electrical grid.

B. Centralized vs Distributed Generation

The electric power system (EPS) traditionally relies on Centralized Generation, where the majority of electrical energy is generated in large power plants located far from consumption centers. This approach ensures economies of scale, reliability, and quality of energy delivery through centralized control. Centralized Generation offers a high level of reliability and consistent power supply, making it suitable for critical infrastructure and residential consumers. However, this model faces limitations such as reliance on long-distance transmission networks, potential transmission losses, and vulnerability to disruptions.

To address these challenges, Distributed Generation (DG) has gained interest [9] [10]. Figure 5 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.

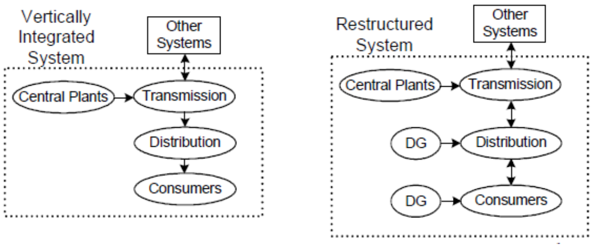

Fig. 5. Comparison of the power system before and after DG [11]

DG allows for localized generation and increased utilization of renewable energy sources, enhancing the resilience and flexibility of the power system [12] [13]. It injects energy at various points within the distribution network, potentially altering the power flow direction. DG offers advantages such as reduced energy losses during transportation, low environmental impact, decreased dependence on centralized generation, and opportunities for commercial market participation. However, it also introduces complexity in planning and operation, potential disturbances in quality of service, and intermittent generation due to factors like renewable resource availability [14] [15].

Incorporating DG into the EPS can help address the increasing demand and complexity resulting from the integration of electric vehicles (EVs) and emerging operational flexibility management technologies. EVs pose a significant demand on the grid, and DG can contribute to managing the associated challenges. Moreover, the stringent quality criteria of modern technological applications, such as constant frequency, voltage stability, and high reliability, are difficult to achieve solely with centralized generation. The inclusion of DG offers a potential solution to meet these requirements.

Therefore, DG represents a promising solution to enhance the sustainability, reliability, and flexibility of the EPS, especially in the context of integrating renewable energy sources and accommodating the increasing demand from EVs [16] [17].

C. Electric Mobility and Flexibility

Electric mobility, also known as e-mobility, is a transformative shift in the transportation sector, driven by advancements in battery technology, government policies, and the need to reduce greenhouse gas emissions. Electric vehicles (EVs) are categorized into three types [18]:

- Battery Electric Vehicles (BEVs), which rely solely on rechargeable batteries for power;
- Plug-in Hybrid Electric Vehicles (PHEVs), combining an internal combustion engine with a battery and electric motor [19] [20];
- Hybrid Electric Vehicles (HEVs), which use both an engine and an electric motor.

The increased adoption of EVs contributes to environmental concerns and poses challenges for the power grid, especially in residential settings.

The global investment in energy transition technologies, including renewable energy sources, electrified transportation, and energy efficiency, has been steadily growing, as seen in Figure 6. Energy efficiency is closely linked to operational flexibility [21] in the electric power system, which refers to the system's ability to adjust and adapt its operations to changes in demand, supply, and external conditions. Operational flexibility enables the integration of variable energy sources, variable loads such as electric vehicles, and effective management of electricity demand fluctuations. It is a key aspect of the concept of a smart grid, which aims to enhance observability and control within the power system [22] [23].

Assessing the available operational flexibility in the energy system is crucial for optimal management and mitigation of

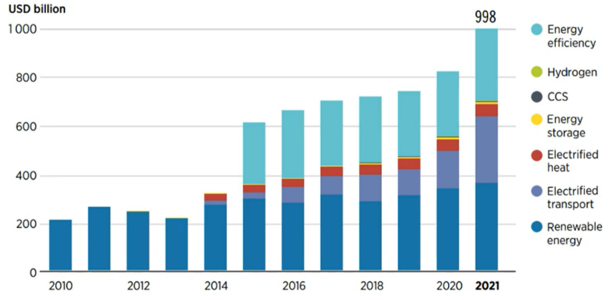

Fig. 6. Global investment in energy transition technologies

challenges. Sources of operational flexibility can be categorized as fully controllable, allowing adjustable power injection, or curtailable, which can be removed from operation. With the right technology, curtailable sources can be transformed into fully controllable ones, expanding the capabilities of the power system [24].

Overall, the inclusion of electric mobility and the pursuit of operational flexibility are vital for the energy transition, promoting greener transportation and enabling the efficient management of the power grid.

D. Problem Formulation

The ongoing energy transition focuses on minimizing reliance on fossil fuels, upgrading infrastructure, investing in renewable energy, and implementing comprehensive policies. This thesis proposes a solution focused on enhancing existing infrastructure, reinforcing the grid to ensure system resilience and support the integration of distributed generation (DG) and electric vehicles (EVs).

Without proper grid management, the integration of DG and EVs would cause power spikes and grid overload. However, active grid management, achieved through widespread EV charging stations and optimal utilization of operational flexibility sources, can distribute the load more evenly throughout the day, improving overall grid performance.

Regardless of grid management, the power transmitted through the network will increase significantly in the coming years. Therefore, the solution proposes restructuring the low voltage (LV) network by shortening it and covering the shortened distance in the medium voltage (MV) network.

The solution involves increasing the penetration of the MV network, placing MV to LV transformers closer to customers, using more MV to LV transformers, potentially with lower power ratings, and implementing smaller LV feeders. This restructuring offers technical and economic advantages, such as reduced voltage drops, energy losses, and improved power quality.

The use of customer substations, where a customer purchases an exclusive substation from the distribution network operator, serves as validation for the proposed solution. This practice ensures improved service quality and validates the concept of utilizing dedicated transformers, especially in large establishments like shopping centers.

Overall, the proposed solution aims to enhance infrastructure, optimize grid management, and restructure the LV network to support the integration of DG and EVs, improving grid performance, and ensuring a reliable and resilient power system.

III. MODEL GRID STUDY

A. Grid description

The objective of this project is to strengthen the distribution grid through the restructuring of the LV network. The proposed solution involves increasing the penetration of the MV network. To understand the fundamentals of the proposed solution, a simplified MV to LV grid model is studied. The key aspects examined include the dynamics of a power flow, the impact of heavier loads on voltage and QoS for clients, and the influence of the inclusion of DG on the grid.

The grid used for this study is obtained from [15]. It represents a model of a residential zone and consists of a simple three-feeder LV grid with nodes that incorporate generation. The feeder data is summarized in Table I, providing information on feeder length, the number of customers, and conductor specifications.

Table II presents data related to the single transformer in the grid. It includes transformer ratings, maximum demand, and the number of clients served, with a distinction made for clients with 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 I
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 II
MODEL GRID - TRANSFORMER DATA

To define the remaining grid data, the distances between buses and loads are required. To avoid overloading the transformer, the maximum allowed load is set to 50% of the transformer's rated power. For simplicity, it is assumed that each bus has the same load, resulting in the load being divided among the 36 available LV buses.

Each feeder consists of 12 LV buses, and it is assumed that the distance between each bus is equal, resembling a typical residential street. In this case, the distance is set to 30 meters. Table III provides the remaining distances, specifically the distances between the transformer and the closest client for each feeder.

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

TABLE III
MODEL GRID - DISTANCES BETWEEN TRANSFORMER AND CLOSEST CLIENT

Due to the limitations on the size of the figures, the grid figures cannot be presented. However, the described tables and distances serve as a representation of the grid structure and provide the necessary information for the subsequent analysis and simulation.

B. Restructured Grid

The aim of the project is to modify the previous model grid based on the proposed solution. In the case of the simple model grid studied in this chapter, the key aspect is to introduce multiple MV to LV transformers distributed among smaller groups of loads. This restructuring involves replacing the single larger rated transformer that served all the loads with three lower rated transformers per feeder.

In the restructured grid, the load properties remain the same as in the original model grid, and the distances between LV buses are unchanged at 30 meters.

To maintain the grid's structure, adjustments need to be made to the distances between MV buses. The distance between two MV buses that have transformers is set at 120 meters. The distances between the slack bus (the reference bus in power system analysis) and the nearest MV bus are provided in Table IV.

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

TABLE IV
RESTRUCTURED GRID - DISTANCES BETWEEN SLACK BUS AND CLOSEST MV BUS

C. Case Study and Results

The comparison between the ”traditional grid” model and the ”restructured grid” model is conducted based on several parameters:

- The loads in both grid models are evenly distributed among the buses for simplicity and uniformity of analysis;
- Similarly, the generation from solar photovoltaic (PV) units is also distributed equally. It is assumed that each PV unit generates the same amount of active power at unity power factor, adhering to the IEEE 1547-2003 standard [25];
- The presence of PV generation varies depending on the feeder. Feeder 1 has 4 PV units, feeder 2 has 8 PV units, and feeder 3 has 12 PV units;
- The PV generation is adjusted to simulate different penetration levels, ranging from 0% to 70%. Higher penetration levels correspond to a greater total generated power from all PV units. This range of penetration levels also covers scenarios where there is no generation and only consumption from the loads.

By examining the performance and behavior of both the traditional grid and the restructured grid under different penetration levels and load conditions, the study aims to evaluate the impact of the proposed restructuring solution on system reliability, voltage levels, power losses, and other relevant parameters.

Figures 7 and 8 present the simulation results (voltage magnitude) obtained for Feeder 3, for the traditional grid and the restructured grid, respectively. For clarity, each colour is representing a certain amount of penetration. Feeder 3 felt like the most important to show the graphic results here, since it has the most amounts of PV generation, compared to the other 2 feeders.

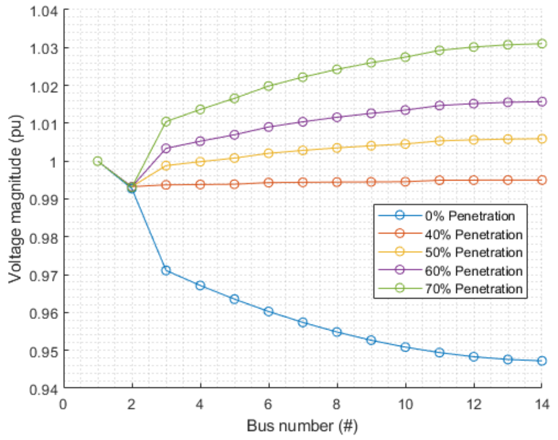

Fig. 7. Voltage magnitude in Feeder 3 for each penetration level (traditional grid)

Tables V and VI provide a summary of the results, specifically the voltage drop at the furthest node in each feeder across different PV penetration levels. These tables showcase the improvements achieved through the restructuring.

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 V
FURTHEST NODE VOLTAGE DROPS IN THE TRADITIONAL GRID

The results show that increasing the penetration of the MV network reduces the time that power spends in the LV lines with high currents and increases the time spent in the MV lines with smaller currents. This leads to lower voltage drops

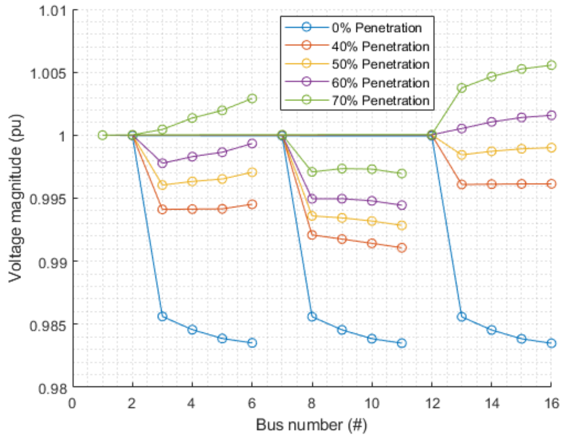

Fig. 8. Voltage magnitude in Feeder 3 for each penetration level (restructured grid)

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 VI
FURTHEST NODE VOLTAGE DROPS IN THE RESTRUCTURED GRID

in general, contributing to a more stable, reliable and resilient grid, with an improved Quality of Service (QoS).

In the traditional grid results, the voltage magnitude varies a lot between feeders, since large distances are covered in LV. In contrast, the restructured grid exhibits more consistent voltage drops as the differences in distance are covered at the MV level.

When PV generation is included at different penetration levels, the analysis reveals the following conclusions for each feeder:

- Feeder 1, with a low presence of PVs, experiences an increase in voltage levels as PV generation supplies part of the load, resulting in a lower power injection from the grid. In the traditional grid, voltage levels decrease by approximately 3.8%, while in the restructured grid, they decrease only by 0.47%;
- Feeder 2, with a shorter length and higher concentration of PVs, also shows a decrease in voltage levels. In the traditional grid, voltage levels decrease by about 3.85%, resulting in an overvoltage of 0.20%, while in the restructured grid, the decrease is significantly less, approximately 1.45%.
- Feeder 3, with the highest amount of PVs, consistently experiences overvoltages in both grids. However, the traditional grid shows overvoltages of 3.1%, whereas the restructured grid exhibits only 0.55% overvoltage.

Overall, the traditional grid is much more sensitive to load and/or generation fluctuations than the restructured grid and, in consequence, more resilient.

IV. REALISTIC GRID STUDY

A. Software and Grid description

This chapter focuses on studying a realistic grid using the software called ”DPlan” [26]. Developed by AmberTree, DPlan is a widely used geographic-based integrated analysis and optimization system for distribution networks, particularly within the Portuguese Distribution System Operator, E-REDES.

DPlan offers various functionalities for MV and LV studies, enabling simulations of different electrical grid scenarios. Some of its key features include optimization, reliability and QoS analysis, power flow and short circuit analysis, load allocation, report generation and visualization, as well as data editing and management.

For this thesis, the power flow functionality of DPlan is particularly relevant. It offers two types of power flow analysis:

- ”Peak” mode: Each load is represented by a random variable following a Bernoulli distribution, while the sum of all loads follows a Gaussian distribution. The power flow results are expressed as a probability of occurrence;
- ”Chronometric” mode: Each load is represented by a 24-hour profile, mimicking data collected by a smart meter. Measurements are taken every 15 minutes.

To conduct the proposed study effectively, the chosen LV grid must include a substantial number of loads, with some located at a considerable distance from the MV-to-LV transformer. Additionally, the MV grid, which is part of the proposed restructuring, needs to be well characterized.

The selected grid, depicted in Figure 9, exhibits several characteristics worth noting. The medium-to-low voltage transformer is represented by a triangle, the MV feeder is indicated by the blue line, and the LV grid is depicted in pink. The grid showcases a diverse load density, with certain areas having a significant number of loads while others are more sparsely populated.

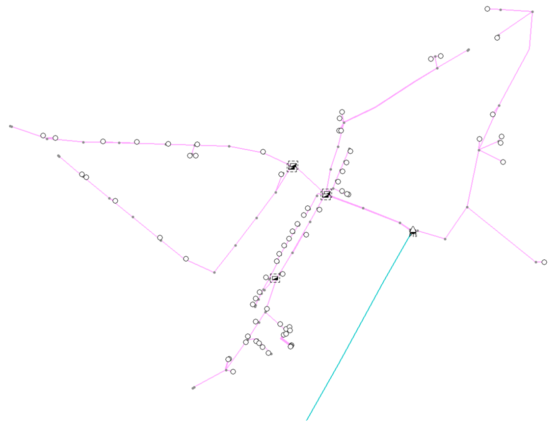

Fig. 9. Realistic Grid in study (taken from DPlan)

In this grid, the focus shifts to integrating 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;
- 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.

B. *Integration of EVs*

For the integration of EVs, the "chronometric" mode of DPlan is selected due to its compatibility with the project objectives. This mode allows for the projection of load profiles in 15-minute intervals, enabling the integration of generation or consumption at any given period. In contrast, the "peak" mode, which involves probability distributions, is not suitable for this study.

Firstly, the creation and assignment of consumers to load nodes are addressed. Each load node in the grid requires a consumer assignment to operate in the "chronometric" mode. Consumers are identified by Meter Point Administration Numbers (MPANs), which vary in size depending on the country or distribution system operator. In the chosen realistic grid, DPlan provides a command file functionality to add consumers to load nodes using the "ADDCPE" command. The command structure includes parameters such as ID number, consumer identifier, type (consumer or producer), status, phase, and contracted power. To simplify the simulation, consumer identifiers are assigned as numbers from 1 to 53 in this case.

Next, the focus shifts to creating load profiles for the assigned consumers, including the integration of EV charging. DPlan offers a functionality in the "planning" tab to assign consumers with predefined consumption types such as residential, commercial, industrial, or unknown. Each consumption type already has a phase load profile assigned, which can be scaled based on the contracted power of the load node.

In this project, instead of developing complex or diverse load profiles, the methodology involves using the existing predefined load profiles and applying them to the grid. However, as the "planning" tab is not accessible in the "chronometric" mode, load profiles are emulated in an Excel sheet and imported into the previously created consumers using a '.dpg' file format [27].

The '.dpg' file contains smart metering data, including the load profiles. Each block within the file represents a consumer and includes a header with the consumer identifier (MPAN) and the number of phases. The load profile data is then provided, typically comprising 96 power entries corresponding to 15-minute intervals. For the assumed unknown consumption type in the chosen grid, a compromise between residential, commercial, and industrial load profiles is used.

To integrate EVs into the grid, assumptions are made: a Tesla model EV is considered [28], utilizing a 7.3 kW charger and charging fully in 12 hours during nighttime from 20h00 to 08h00. The previously defined load profiles are modified to incorporate the EV charging behavior for each consumer.

Figures 10 and 11 present the load profiles of two nodes with different contracted power, showcasing the integration of EV charging.

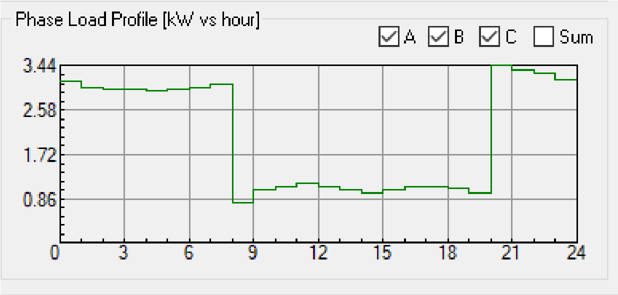

Fig. 10. Load Profile with integrated EV for a 6.9 kVA consumer (taken from DPlan)

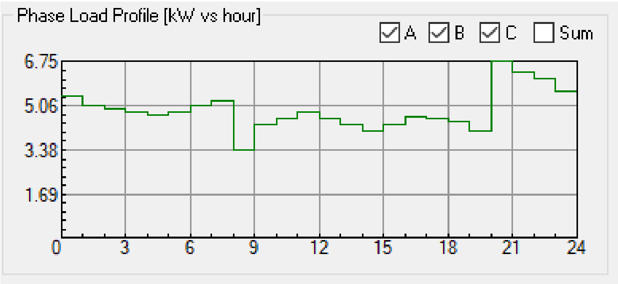

Fig. 11. Load Profile with integrated EV for a 20.7 kVA consumer (taken from DPlan)

By completing these steps of creating consumers and assigning load profiles, the integration of EVs into the grid is achieved, enabling further analysis of the grid's performance and impact in subsequent chapters.

C. *Grid restructuring*

The integration of EVs into the grid involves a phased restructuring process to accommodate their heavier and more disruptive loads.

The initial step is to extend the MV feeder and introduce additional MV to LV transformers, subdividing the load and reducing distances in the LV network. This first phase focuses on extending the MV grid up to the sectioning stations (also known as "armários" in Portuguese), with an emphasis on placing more transformers in areas of high load density. Figure 12 represents represents the first stage of grid restructuring, illustrating this idea.

A case-by-case study is conducted for each grid, considering factors such as weak spots, heavy load areas, and available smart grid solutions specific to each community. The restructuring process continues iteratively, aiming to reduce the load

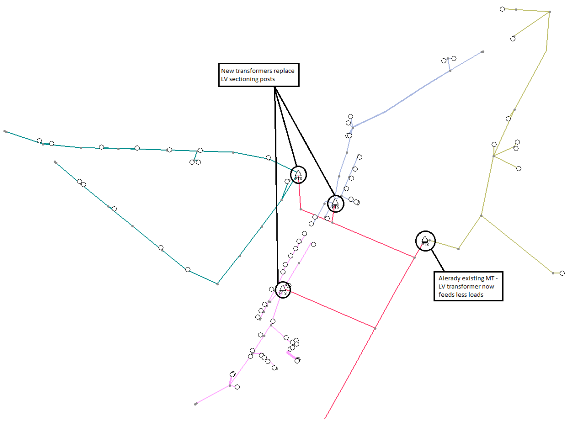

Fig. 12. Realistic grid restructured - 1st Phase (taken from DPlan)

on individual transformers and create more transformers, particularly in zones with high load density. Figure 13 represents the next grid restructuring phase.

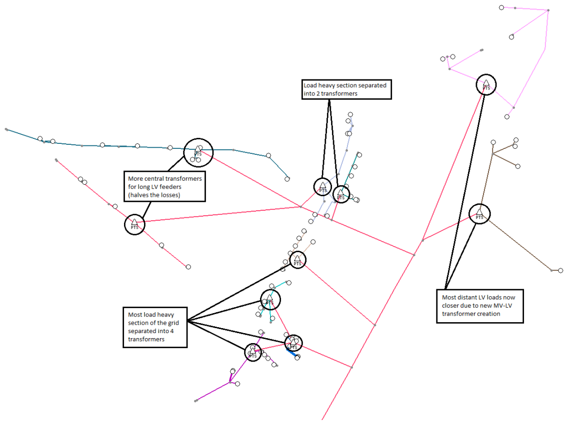

Fig. 13. Realistic grid restructured - 2nd Phase (taken from DPlan)

By gradually splitting the total investment into several phases, this approach enables a realistic and smoother process of change, minimizing the disruptive impact of EV integration on the grid.

Three distinct cases are considered for analysis: the original grid configuration with a single MV to LV transformer, the first phase restructured grid with 4 transformers, and the second phase restructured grid with 10 transformers. These cases serve as examples to assess the impact of grid restructuring on EV integration and overall grid performance.

D. Simulation Results

The simulations were carried out using the "chronometric" power flow mode, which involved creating clients at load nodes and importing load profiles with integrated EVs. The simulations were conducted for every hour of the day, with calculations repeated four times at 15-minute intervals. The results were divided into two main groups:

- Daytime (8h-20h), while no EVs were charging. The peak load during the daytime occurred at 11h, while the minimum load was observed at 8h;
- Nighttime (20h-8h) while EVs were charging. The peak load was at 20h, and the minimum load occurred at 4h.

The inclusion of EVs significantly impacted the load profile, leading to extreme load conditions during nighttime. Tables VII, VIII and IX contain the results obtained for each of the case scenarios, respectively.

Case 1	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 VII
SIMULATION RESULTS IN *DPlan* FOR CASE 1

Case 1, representing the original grid, exhibited several issues. During the daytime, even in the best scenario, the maximum voltage drop exceeded the 10% limit established. The branches leading to the sectioning post in the high-density zone were most affected. In the nighttime scenario, the power flow did not converge due to the high current required to transit in the long LV cables, resulting in significant voltage drops and losses that rendered the grid inoperable.

Case 2	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 VIII
SIMULATION RESULTS IN *DPlan* FOR CASE 2

Case 2, showed improvements in the QoS. The maximum voltage drop never exceeded 10%, and the majority of the grid operated at an expected level. However, there was room for further improvement, particularly on the south-western side of the grid, where the load density was the highest.

Case 3	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 IX
SIMULATION RESULTS IN *DPlan* FOR CASE 3

In Case 3, the overall performance was impeccable. There were no significant voltage drops at any time, and the losses reflected the improvement in QoS. During daytime, the grid operated at under 5% of its total installed power.

Overall, the case studies provided insights into the behavior of the grid under different conditions and highlighted the improvements achieved through grid restructuring.

E. Investment Analysis

The investment analysis evaluates the cost-effectiveness of the grid restructuring project. The power flow analysis demonstrated improved grid performance in the restructured grids compared to the original grid. However, the investment costs associated with the restructuring need to be considered.

To conduct a fair evaluation, certain factors are established:

- The prices of the grid components are constant across all the case scenarios;
- The maximum grid capacity is determined for each scenario, representing the maximum sum of loads that originate a maximum voltage drop of 5%;
- The price per kilowatt (γ) is calculated by dividing the total cost of the grid by its maximum capacity.

In Case 1, the original grid consists of a single MV-LV transformer substation and only includes LV lines. The total investment for this case is 2830 €, and the maximum grid capacity is 105.8 kW. The price per kilowatt is calculated as 267.5 €/kW.

In Case 2, which represents Phase 1 of the restructured grid, the grid includes four MV-LV transformer substations, extending the existing MV feeder and adding MV lines and LV lines. The total investment increases to 64482 €, but the maximum grid capacity significantly increases to 468.4 kW. Consequently, the price per kilowatt decreases to 137.7 €/kW.

Case 3 represents Phase 2 of the restructured grid. It involves ten MV-LV transformer substations and further extensions of the MV and LV lines. The total cost of this scenario greatly increased to 140802 €. However, the maximum grid capacity also increases significantly to 1451 kW, making it the most cost-effective scenario among the three, with the price per kilowatt decreasing further to 97.02 €/kW.

The graphical representation in Figure 1 displays the price per kilowatt (γ) for each case scenario. The analysis reveals that the decrease in γ is significantly higher between the first and second scenarios than between the second and third scenarios.

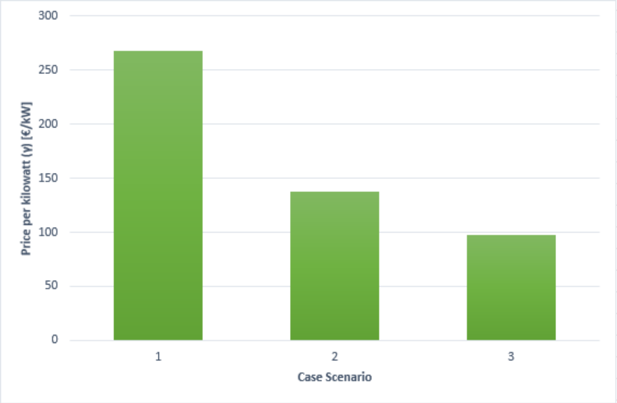

Fig. 14. Graphic representation of the price per kilowatt (γ) per case scenario

V. CONCLUSION

In this dissertation, the impact of DG from PV sources and EVs on the power quality of LV distribution networks was analyzed. The study focused on the restructuring of LV networks by increasing the penetration of MV networks and their proximity to end consumers, which would provide infrastructure support for smart grid technologies and operational flexibility.

The analysis involved two grids: a model grid programmed in MATLAB and a realistic grid provided in DPlan. The model grid allowed for a better understanding of energy flow processes and network dynamics, while the realistic network incorporated EV charging to assess its disruptive potential. The restructuring analysis was conducted in two phases, and investment considerations were analyzed for each phase.

The results from the model network confirmed the initial assumption of improved QoS, making the grid more resilient. The restructuring reduced voltage drop by over 5% even in the absence of any generation, significantly improving the voltage in the longest feeder. With the integration of generation and increasing levels of DG penetration, the proposed restructuring also alleviated overvoltages. The most overloaded feeder with DG experienced a decrease in overvoltage from 3% to just 0.5%.

In the realistic network studied in DPlan, the introduction of EV charging caused the original network to collapse during peak load hours, with significant voltage drop values observed. However, the phased restructuring led to improvements in QoS, with maximum voltage drop values reduced from 37% to around 4%. The investment analysis also showed a decrease in price per kW by 48% and 30% for each phase of restructuring, respectively.

PDIRD [29] is the investment plan of the Portuguese distribution system operator (DSO), E-REDES, until 2025. It is possible to see that in the areas of ”Technical Service Quality” and ”Network Efficiency”, the upward trend in investments aligns with the proposed solution, indicating its viability for grid reinforcement during the integration period of DG and EVs.

Overall, the findings of this paper demonstrate that grid restructuring, with increased MV penetration and proximity to end consumers, can effectively improve power quality and support the integration of DG and EVs. The proposed solution not only alleviates voltage drop and overvoltage issues but also offers cost benefits in terms of investment. These insights provide valuable guidance for grid operators and policymakers in designing and implementing sustainable and resilient distribution networks.

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