Development of a Universal Adaptive Voltage Control Policy for Power Distribution Networks

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Development of a Universal Adaptive Voltage Control Policy for Power Distribution Networks

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Abstract

In an era defined by the rapid evolution of energy technologies and the necessity of sustainable power generation, effective voltage control is a critical component in optimizing the performance of the power distribution grid and the seamless integration of renewable energy sources. This thesis presents the development and evaluation of an adaptive voltage control policy for high voltage to medium voltage transformers aimed at mitigating voltage limit violations in modern power distribution networks.

The motivation for this research arises from the increasing integration of distributed energy resources and the growing complexity of power grids, which require dynamic and robust voltage management strategies. The proposed policy utilizes a voltage control curve, optimized using a genetic algorithm, which systematically identifies the best parameters for the curve to ensure voltage stability and minimize violations across diverse grid configurations.

The methodology involves quasi-dynamic simulations performed on 30 real-world distribution grids, which test the effectiveness of the voltage control curves in maintaining grid stability under varying load and generation conditions. This was done by setting a stricter ±3% voltage limit for the medium voltage grid. Results show an average reduction of 88.54% in voltage limit violations and a 17.19% decrease in the maximum difference between the maximum and minimum voltage levels in the medium voltage grid throughout a complete year (2023). This study highlights the importance of a grid-specific voltage control curve, as every distribution grid exhibited unique voltage regulation needs.

Furthermore, the policy was evaluated under projected grid scenarios, demonstrating sustained effectiveness across two future timeframes: one set five years and the other ten years into the future. In the first scenario (2028), an 80.06% reduction in voltage limit violations was achieved, while the second scenario (2033) still showed a reduction of 62.25%.

Through the genetic algorithm optimization, the voltage control policy adapts to fluctuating grid dynamics, contributing to improved power quality and the successful integration of distributed energy resources. While effective in medium voltage grids, further research is needed to explore the policy's applicability to low voltage networks and in environments with limited data availability.

The simplicity and universality of the proposed adaptive voltage control strategy make it a practical solution for real-world deployment, as it can be implemented on existing hardware. In contrast, the proposed strategy alone will not be enough to completely eliminate all the voltage stability problems in distribution grids and additional measures are necessary. However, by minimizing voltage violations and improving grid resilience, this work offers a robust framework for voltage management in modern, evolving power distribution networks, particularly in the context of the global energy transition towards sustainable energy sources.

Foreword & Acknowledgments

Seven years ago, I started pursuing my Bachelor's degree in Electrical Engineering at the Delft University of Technology. At the time, I was unsure whether I would even make it through my first year. However, here I am, having completed my final assignment to obtain the title of engineer, something I have always aspired to. I have consistently aimed for the highest possible, and these last seven years have shaped me into the person I am today.

The journey to this point has been fueled by my interest in electrical engineering, especially in power grids, and my desire to contribute to making them future-proof as we navigate through the energy transition. My choice to pursue a Master's degree in Electrical Power Engineering was driven by this passion, and the subject of this thesis project aligns perfectly with my interests. I am deeply grateful to Stedin for providing me with this incredible opportunity to explore my passion in a real-world setting.

As I reflect on the process of completing this thesis, I recognize how much I have evolved throughout the project. In the beginning, it was unclear what direction the project would take, which made the initial stages quite challenging. The scope of the project changed several times before evolving into what it is now, a thesis that I am proud of. This journey taught me patience, adaptability, and the importance of persistence.

I would like to express my sincerest gratitude to Pedro Vergara, my academic supervisor, for his immediate positive response to my request for supervision. His guidance, feedback, and our informative conversations were invaluable throughout the process. Additionally, I would like to thank Zeynab Kaseb, the PhD student who supervised me weekly. Her expertise in optimization was crucial, especially in the early stages of the project, and her willingness to help me tackle problems was greatly appreciated. Also, I extend my thanks to Milos Cvetkovic and Sebastian Rivera for their invaluable role as members of my thesis committee. I am grateful for the time and effort they dedicated to thoroughly reading and evaluating my thesis.

A special thank you goes to my supervisors from Stedin, Edward Coster and Bart Kers. Despite their busy schedules, they always made time to support and guide me through the project. Their enthusiasm, careful reading of every version of my thesis, and thoughtful feedback were instrumental in shaping the final outcome. Whenever I needed motivation, their mentorship and encouragement were a source of inspiration, helping me stay focused and confident throughout the process. I also appreciated being included in the team meetings and discussions, which helped make the experience not only educational but also enjoyable.

To my family, thank you for your patience and understanding as I navigated the demands of my studies. Your unconditional support provided me with the strength and motivation to keep going, even when the path seemed uncertain. To my friends, I am deeply grateful for your encouragement, humor, and especially your patience as I tried to explain my thesis. Thank you for always being there, for allowing me to share my thoughts, and for keeping me grounded through this intense process. I also want to extend my appreciation to the professors and teachers who has helped me in any way throughout my studies, and colleagues from Stedin who were always quick to offer help whenever I needed it.

This thesis project has had a profound impact on me, both personally and professionally. It has taught me to handle uncertainty, sharpen my problem-solving skills, and manage large-scale projects with confidence. I am now more prepared than ever for the next chapter in my professional journey, and I look forward to the challenges and opportunities that lie ahead.

C.B.J. Zevenbergen
Rotterdam, October 2024

Contents

List of Abbreviations

AC	Alternating Current
ACM	Authority for Consumers and Markets
ADMM	Alternating Direction Method of Multipliers
ADN	Active Distribution Network
API	Application Programming Language
AVC	Automatic Voltage Control
AVR	Automatic Voltage Regulator
CB	Capacitor Bank
CENELEC	European Committee for Electrotechnical Standardization
CPPV	Photovoltaic Power Curtailment
CVC	Coordinated Voltage Control
DER	Distributed Energy Resource
DG	Distributed Generation
DPL	DIgSILENT Programming Language
DSO	Distribution System Operator
EN	European Norm
GA	Genetic Algorithm
GWO	Grey Wolf Optimizer
HV	High Voltage
KPI	Key Performance Indicator
LDC	Line Drop Compensation
LV	Low Voltage
MIL	Mixed-Integer Linear
MINP	Mixed-Integer Nonlinear Programming
MPC	Model Predictive Control
MV	Medium Voltage
NSGA	Non-Dominated Sorting Genetic Algorithm
OLTC	On-Load Tap Changer
OPF	Optimal Power Flow
OVC	Optimal Voltage Control
POA	Power Allocation Optimization
PCC	Point of Common Coupling
PV	Photovoltaic
QD	Quasi-Dynamic
SDP	Semi-Definite Programming
SOCP	Second-Order Cone Programming
STATCOM	Static Synchronous Compensator
SVR	Step Voltage Regulator
TMM	Transformer Monitoring Module
TMR	Tap Movement Rate
TSO	Transmission System Operator
VCC	Voltage Control Curve
VCM	Voltage Control Method

1

Introduction

1.1. Background Information

The development of electric power systems has been intricately linked to industrial advancement, primarily centered around large centralized power plants without extensive voltage control, fueled predominantly by fossil energy sources, since the industrial revolution. These traditional power systems operate on the premise of centralized generation, followed by transmission over long distances through interconnected transmission systems, characterized by stepped-up voltages to ensure efficient long-distance transmission. Subsequently, at the distribution level, the voltage is stepped down to accommodate medium and low voltage distribution systems. To ensure efficiency in transmitting high power, the voltage is increased, which is crucial for reducing losses caused by line resistance. To mitigate these losses, it is vital to minimize current, as larger currents result in increased losses. Additionally, the increased voltage results in the use of conductor diameters that are within acceptable limits. When operating at Low Voltage (LV) levels, conductors would require unrealistically large cross-sectional areas to accommodate the high currents. However, as mentioned, the voltage has to be brought back down to a safe level close to the customers' connection points [1], [2].

As noted above, a traditional electrical power system can be divided into three main stages: generation, transmission, and distribution, as depicted in the left part of Figure 1.1. Traditional power plants typically possess significant generation capacity and are often located a distance from end consumers. This positioning is primarily determined by their primary energy source. For instance, coal plants are often located near large ports or transportation hubs to facilitate efficient fuel transport and the need for cooling water. Similarly, hydropower plants are strategically positioned near dams to harness water resources. Additionally, the operation of large-scale facilities such as nuclear plants requires extensive land and infrastructure, often making urban areas unsuitable [3].

Historically, fossil fuels such as coal, natural gas, and oil have been the primary sources of energy due to their operational flexibility, reliability, and scalability. However, their extensive use has resulted in significant environmental challenges, including greenhouse gas emissions contributing to climate change, air and water pollution, health effects, and habitat destruction. Moreover, the finite nature of fossil fuel resources raises concerns about long-term energy security and economic stability.

Recognizing the urgent need to transition to sustainable energy sources, the electric power grid has undergone a fundamental shift from a centralized to a more dynamic network, accommodating distributed generation (DG) alongside traditional production. This transformation highlights the indispensable role of electricity in modern society, supporting not only residential, commercial, and industrial consumers but also critical infrastructure like hospitals and water supplies.

In response to growing concerns about climate change, there has been a global push to increase the integration of renewable energy sources into the power grid. Initiatives such as the Paris Agreement aim to limit global warming and reduce CO_2 emissions, with countries like the Netherlands setting ambitious renewable energy targets. For instance, the Dutch government has set a goal for 2030 of achieving 27% of energy use from renewable sources, predominantly solar and wind [4].

Despite these efforts, challenges remain, including the need for significant infrastructure and operational changes to accommodate the rapid implementation of distributed generation. Nevertheless, with global electricity demand projected to double by 2050 and with the share of renewable energy on the rise, the transition to cleaner and more resilient energy systems is imperative for ensuring a sustainable future [5]. However, as distributed generation increases, managing our energy system becomes more complex, emphasizing the critical need to maintain high levels of resilience and security.

In contrast to conventional power plants, these sources of renewable energy represent small-scale power generators, typically located close to the consumer. Photovoltaic (PV) panels could, for example, be rooftop-mounted and a wind turbine could be placed on a farmer's field. Due to this placement, these energy sources are most of the time connected to medium or low voltage distribution networks (see Figure 1.1). Distribution grids incorporating generation capacity and control systems to manage such resources are denoted as Active Distribution Networks (ADNs). In an ADN, changes have been made to enhance the power system's capability to manage two-way power flows and exhibit flexibility in operation for both generation and demand. After achieving these characteristics, the distribution grid has made the transition from being passive to becoming active.

The transition from a passive to an ADN has positive and negative sides. It can be argued that integrating DG into the grid is simpler in an ADN, and incorporating DGs aids in cutting down distribution losses by generating energy closer to where it is needed. However, a significant challenge for an ADN is the requirement for effective communication among key stakeholders such as system operators and consumers. Without proper coordination within the system, distributed generation sources can cause voltage limits to be violated. The definition of a voltage limit violation is further elaborated in Section 2.1. To mitigate these risks, enhanced voltage control and monitoring are crucial for ensuring voltage levels in the distribution stage, which historically prioritizes monitoring at the transmission and generation stages [4].

Voltage control reveals the historical dependence on conventional approaches in electric power distribution systems, which frequently lacked flexibility and widespread applicability. Historically, voltage control strategies were developed to maintain stable and reliable electricity supply, primarily focusing on adjusting generation output or transformer tap settings to regulate voltage levels. However, these approaches were typically reactive and lacked the ability to effectively manage the complexities of modern power systems characterized by distributed generation and evolving grid dynamics. Moreover, traditional voltage control methods often required significant manual intervention and were constrained by the limitations of existing infrastructure. As such, there emerged a growing recognition of the need for more innovative and adaptable voltage control solutions capable of addressing the challenges posed by increasing renewable energy integration, fluctuating demand patterns, and aging grid infrastructure [6]. This is the reason why significant exploration has been conducted in the development of innovative voltage control strategies. Various voltage control methods can be identified in the literature, reflecting the absence of a singular perfect solution to the voltage problem and the existence of diverse approaches to addressing this challenge. However, they are all aimed at enhancing grid stability, optimizing voltage levels, and improving overall reliability within electric power distribution networks.

Although there are many different ways of tackling the voltage limit violation problems via voltage control, there are similarities between the methods. First of all, the control architecture can be either centralized or decentralized. Second, if an optimization based algorithm is used, there are around a dozen different optimization methods considered, e.g. sensitivity analysis, optimal power flow or consensus algorithm. Next, almost all methods have voltage control, voltage deviation minimization, a combination of both or some other voltage related function as the objective function. A more extensive overview of all the (adaptive) voltage control methods available in the literature can be found in Section 2.7.

In this context, understanding the complexities of electric power production, transmission, and distribution becomes increasingly important. The accelerated electrification and the increase of energy re-

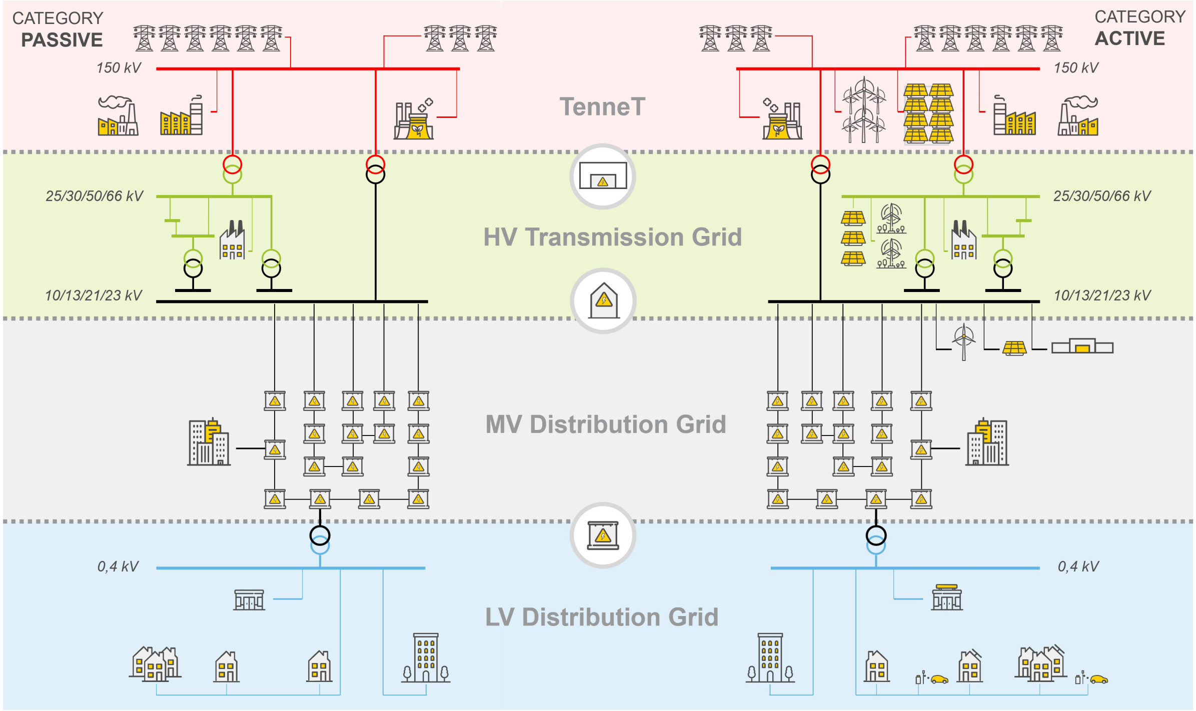


Figure 1.1: Overview of the difference between a passive (left) and an active (right) electrical power distribution network. The active network illustrates the incorporation of distributed generation across all levels of the distribution network.

quired poses challenges for the power infrastructure, potentially leading to issues such as over-voltage, under-voltage, and current violations. The Distribution System Operator (DSO) carries the responsibility for ensuring the long-term capacity and viability to meet reasonable electricity demands within the distribution network. In this critical stage, the DSO must heavily invest in enhancing and reinforcing the distribution network to accommodate increased energy demands from both consumer and generation sides. Additionally, the demand side introduces intermittent and uncontrollable factors from DG. While the ideal solution involves replacing, reinforcing, and expanding segments of the distribution network to accommodate larger loads and Distributed Energy Resources (DERs), this process is costly and time-intensive. Therefore, a preferable approach involves improving the existing distribution network by selectively modifying components. Enhancements in power electronics, data communications, and network control mechanisms can boost capacity usage by optimizing the utilization of existing infrastructure without necessitating an increase in peak capacity. However, achieving this optimization requires a fundamental shift in how the current distribution network is utilized and controlled.

In the Netherlands, the transmission network is controlled by TenneT, the national Transmission System Operator (TSO). Besides the TSO, there are the regional DSOs which operate the distribution part of the electrical power grid. Among these DSOs, is Stedin, and along with the TSO, these organizations must address the challenges previously outlined that the power grid encounters.

While voltage control methods offer substantial benefits in enhancing grid reliability and efficiency, DSOs face numerous challenges in their deployment, including high investment costs, scalability issues, interoperability challenges, and cybersecurity risks. Addressing these challenges requires strategic planning, collaboration with stakeholders, and investment in innovative solutions that can overcome barriers to implementation.

1.2. Problem Statement

The addition of DG to a distribution grid is recognized for its tendency to lead to more frequent (upper) voltage violations and the potential for bi-directional power flows. These violations and the presence of the problem, in Stedin-operated distribution grids, can be seen in Figure 1.2. Moreover, the presence of small single-phase distributed generators can further complicate matters, potentially causing imbalances in the network that need to be carefully managed and addressed [7]. Further technical details regarding this principle can be found in Section 2.5.

Despite advancements in voltage control technologies, power systems face increasing challenges in maintaining stable and reliable voltage levels, particularly in the context of evolving grid dynamics. Voltage control plays a crucial role in ensuring the quality and reliability of electricity supply to consumers, yet traditional voltage control methods may not be sufficient to address the complexities of modern power systems. On top of that, the transition towards smart grids, which are modernized electrical grids that utilize digital communication technology to monitor and manage electricity supply more efficiently, introduces new opportunities and challenges for voltage control. While advanced control algorithms and real-time monitoring technologies offer potential solutions to voltage issues, the implementation and integration of these technologies into existing grid infrastructure is complex, time-consuming, and expensive. Smart grids enable enhanced monitoring, automation, and control of electricity distribution, facilitating more precise voltage regulation and improving overall grid performance.

Addressing these challenges requires innovative voltage control strategies that can effectively manage voltage fluctuations, optimize grid performance, and ensure grid stability in the presence of variable generation and changing load patterns without being too complicated. Additionally, these strategies must be adaptable, scalable, and cost-effective to meet the evolving needs of power system operators and stakeholders.

In less robust distribution networks, the capacity to integrate DG is frequently limited by the challenge of voltage rise. Nowadays, the conventional approach to mitigating voltage increase involves reinforcing the network infrastructure without altering its operational principles. This method typically involves measures, such as upgrading conductors and transformers or adding MV/LV transformers, to accommodate the additional power generation. However, while this approach maintains the existing operational framework of the network, it often results in considerable expenses associated with connecting DG sources. Upgrading infrastructure components like conductors or transformers can be capital-intensive, leading to higher overall costs for integrating DG into the distribution grid [6].

This thesis focuses solely on addressing voltage limit violations in distribution networks. The rationale for this focus is derived from the observed voltage-related challenges faced by DSOs. These challenges arise due to the growing demand for electric power and the increased installation capacity of DG, particularly solar (PV) panels. In 2023, Stedin conducted an internal pilot study in one of its rural Medium Voltage (MV) distribution networks. The objective of the internal study was to test an adaptive control method that utilizes existing grid control equipment instead of upgrading the grid to address voltage issues caused by the expanding capacity of DG.

The primary objective of the research presented in this thesis is to investigate the feasibility of creating a universally applicable policy that effectively implements the control method in other MV distribution networks. This includes ensuring appropriate voltage levels across various networks, especially at consumer connection points, which is crucial for grid control and operation. Deviations from optimal voltage levels can lead to several operational challenges, including equipment malfunction, failure, or inverter disconnection in solar plants. This is primarily a problem for households and small businesses. By addressing these challenges, this research aims to develop and evaluate a novel voltage control policy that effectively manages the impact of distributed energy resources, increased demand, and grid modernization. This policy is intended to be universally applicable and implementable in any other MV distribution networks. Through these efforts, this study seeks to advance voltage control in power systems and facilitate the transition towards a more sustainable, reliable, and resilient electricity infrastructure.

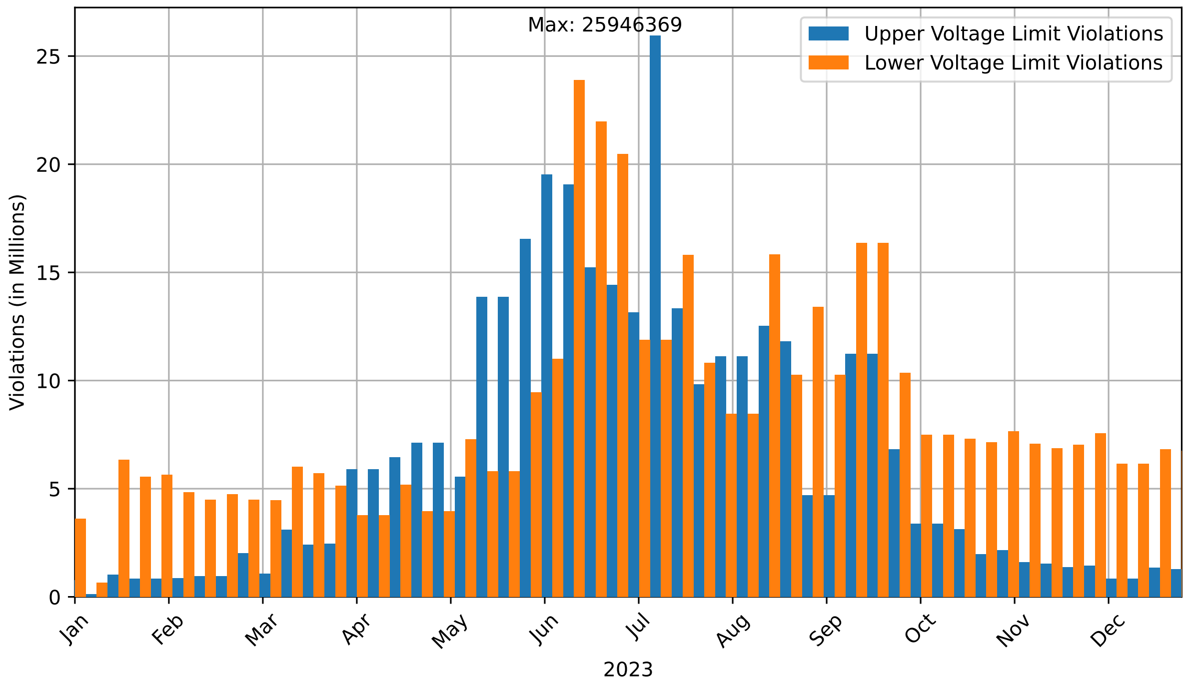


Figure 1.2: This graph shows the number of voltage limit violations per week across all distribution grids operated by Stedin in 2023. A maximum of 25,946,369 upper voltage limit violations during a week in July is indicated in the graph. A violation occurs when the voltage, measured at the end-user by a smart meter, exceeds the regulatory range of 207-249 V for more than 30 seconds. The data provides insight into the frequency and distribution of voltage issues throughout the year.

1.3. Research Objectives

Based on the problem outlined in Section 1.2, the research objectives are defined. The main research objective, presented as the main research question, is detailed in the next section. Prior to addressing the main research question, several preliminary questions must be answered, which are outlined in subsection 1.3.2. An extensive answer to the research question is provided in the conclusion of this thesis (Chapter 6).

1.3.1. Main Research Question

The main objective of this thesis relates to the following research question:

*How can a **universally applicable adaptive voltage control policy** be developed for a **HV/MV transformer** in a power distribution network to mitigate **voltage limit violations** for the end-user, while prioritizing **simplicity** and **ease of implementation**?*

1.3.2. Sub-Research Questions

There are key elements in finding the answer to the main research question which are defined below:

1. Which distribution grid data is available by a DSO and which available data can be used to develop an adaptive voltage control policy?
2. How can the parameters which define the setting points of the voltage control curve be found or calculated, and what is needed to create a unique curve for every distribution grid and thereby make the policy universally applicable?
3. Which factors affect the parameters which define the setting points of the voltage control curve the most, even if they are not accessible for the DSO?

4. What are new adjustment rules to determine the best tap position of the MV/LV transformer to gain the best voltage stability in combination with the voltage control curve?
5. How often should the adaptive voltage control curve be reset? What developments within the distribution grid influence the control curve?

1.4. Research Motivation and Contributions

The motivation behind this thesis arises from the recognition of the inherent complexity and limited applicability of existing voltage control solutions within electric power distribution networks. While various advanced voltage control strategies exist, such as those briefly mentioned in Section 1.1 and further detailed in Section 2.7, they often necessitate sophisticated algorithms, extensive data collection, and complex infrastructure upgrades, making them impractical for widespread implementation. Moreover, many of these solutions are tailored to specific network configurations, operating conditions, or benchmarks, limiting their universal applicability across diverse distribution systems. Consequently, there is a pressing need for simple, yet effective, voltage control policies that can be readily implemented without significant investment or specialized expertise. Addressing this gap, this thesis aims to develop a practical and universally applicable voltage control policy that enhances grid stability, optimizes voltage levels, and improves the overall reliability of electric power distribution networks.

The contribution of this thesis to the existing literature and research lies in the development of a novel adaptive voltage control policy that fills a gap in current research and practice. While previous studies have explored various voltage control strategies, few have focused on developing simple, yet universally applicable, solutions that address implementation and scalability challenges. By proposing a straightforward voltage control policy leveraging readily available data and existing infrastructure, this thesis offers a practical approach to voltage regulation in electric power distribution networks. Another element of this contribution is the implementation of a closed-loop optimization process. This loop enables dynamic adjustment of voltage control parameters in real-time, ensuring adaptability to varying conditions. The explanation not only demonstrates that the loop is feasible, but is also easily replaceable with alternative optimization methods. Additionally, the thesis contributes to the literature by evaluating the proposed policy's effectiveness through rigorous simulation studies and multiple real-world case studies within a DSO's network, providing valuable insights into its performance under different operating conditions and network configurations. This research not only advances understanding of voltage control in distribution networks but also offers guidance for operators and policymakers seeking to enhance grid stability and reliability cost-effectively.

1.5. Structure of Thesis

This thesis consists of six chapters. The past chapter, Chapter 1, served as an introduction to the topic, offering background information, defining the research problem and objectives, and discussing the research motivation and contributions. Continuing, Chapter 2 will provide deeper insights into crucial additional background information, such as the components of the power distribution network and their characteristics, essential for understanding the topic. It will also analyze the existing methods for voltage control in passive and active distribution networks. Following this, Chapter 3 will detail the methodology used in this study, beginning with an outline of the selected voltage control technique and followed by a detailed description of the optimization algorithm. Subsequently, Chapter 4 will first introduce and discuss the different case studies investigated. While the developed methodology is universally applicable to any MV network, it is important to outline the modeling considerations taken into account. Next, Chapter 4 presents the simulation setup and all the results obtained. This will be followed by an analysis and discussion of the results in Chapter 5, highlighting the advantages, limitations, recommendations, and directions for future research. Finally, Chapter 6 will offer a brief overview of the key findings and insights, followed by the answers to the research questions and an overall conclusion to the thesis.

2

Power Distribution Networks

2.1. Grid Code Requirements for Power Distribution Networks

Having a stable distribution network and stable voltage levels are intertwined. However, ensuring this consistency can be challenging, particularly towards the extremities of the feeder lines. Typically, in traditional distribution networks with limited DER, voltage levels at the far end of feeder lines may experience a notable decrease due to the inherent resistance and reactance (depending on $\cos\varphi$) of the lines. Larger voltage drops are commonly observed in suburban or rural regions compared to urban areas where power cables are considerably shorter. On the other hand, the integration of additional DER such as PV systems can lead to voltage elevation when a substantial amount of PV power is connected to the power lines. This voltage increase is a result of active power injections and the R/X ratios of LV feeders. As the R/X ratio of LV feeders is relatively high it makes them sensitive to voltage rise when a large amount of PV power is injected, especially at the end of the line.

Voltage stability is a key factor in assessing the power quality of a power distribution network. The European Committee for Electrotechnical Standardization (CENELEC) have created an European standard to standardize and oversee power quality within the electricity grid. Modifications specific to a particular country can be made to these *European Norm* (EN) standards. In such instances, reference should be made to NEN-EN when specifying Dutch standards. EN 50160 pertains to voltage characteristics in public electricity networks and is particularly relevant to this study. This standard addresses both continuous voltage fluctuations and voltage disturbances. The former typically results from variations in the nominal voltage signal due to load fluctuations, non-linear loads, or load changes. The disturbances involve deviations from the expected voltage waveform caused by unforeseen events such as faults and weather conditions. For continuous fluctuations, the thresholds for each event are generally determined based on statistical analysis.

As explained in Section 1.2, the objective of the policy that will be presented in this thesis is to mitigate the voltage limit violations within a distribution grid. That is why next, the exact definition of a voltage limit violation will be given. In accordance with the EN 50160 standard, the supply voltage variations should not exceed ±10% of the nominal voltage V_n, under normal operating conditions excluding the periods of interruptions. One of the primary considerations is that within each seven-day interval 95% of the 10 minutes rms-values V_{rms} of the supply voltage shall be within the range of V_n ±10%. On top of that, all 10 minutes rms-values shall be within the range of V_n +10% / -15% [8]. If a problem would occur in the distribution network, the voltage variations may temporarily, for the time needed to solve the problem, be within the range of +10% / -15% of V_n (-15% is allowed for all the time during a seven-day interval measured in 10-minute average values). These requirements are tested under normal operation conditions by measuring if two conditions are satisfied. In addition, various additional requirements apply to the Netherlands which have been defined by the Ministry of Economic Affairs in the *Netcode Elektriciteit*. The supervisory authority, the Dutch Authority for Consumers and Markets (ACM), monitors compliance with these requirements. The *Netcode Elektriciteit* contains the conditions regarding the manner in which grid operators and customers behave with regard to the operation of the electricity grids, the provision of a connection to the grid and the transport of electricity over the grid [9].

Concerning the transmission grid, the TSO, TenneT, has to provide a voltage of 150 kV ±10% to the DSOs. During one week, deviation from this is allowed for one of the 10-minute average values. Legislation mandates that in normal operating conditions, all connected customers at the transfer points are provided with a voltage of U_n ±10%. For the 10, 13, 21, 23, 25, and 30 kV networks, deviation is permitted for 8 hours and 20 minutes per week, however a voltage of U_n +10% or -15% must always be provided. For the 50 and 66 kV networks, deviation from this is allowed for one of the 10-minute average values per week. For 23 kV networks, there is a technical upper limit of U_n +4.3% to not exceed 24 kV [10]. This is all true for the HV transmission grids of Stedin.

For the connection between the HV transmission and MV distribution grids there are again different regulations. The maximum variation of the voltage at the connection points complies with the explained grid code (±10%). However, this allowed variation is usually divided over both the MV network and the LV network, with both network levels being assigned a deviation of 5%. This scenario applies to grids managed by Stedin. A visual representation has been given in Figure 2.1. The voltage deviation in MV networks is then divided over the following components: HV/MV or *Tussen* Voltage (66, 50 or 25 kV) to MV, MV feeder, and MV connection cable. The total voltage deviation of 5% in the MV network is calculated from the HV side of the transmission transformer to the MV side of the distribution transformer. However, one should keep in mind that the 1% is the value used for the deadband of the voltage control. The voltage variation across the transformer is not considered because the MV rail is regulated. For fault conditions, a voltage deviation, meaning a voltage drop or voltage rise, in the MV network of up to 6% is allowed. Together with the 1% voltage deviation of the HV/TV-MV transformer, the total voltage deviation is then a combined 7% [11].

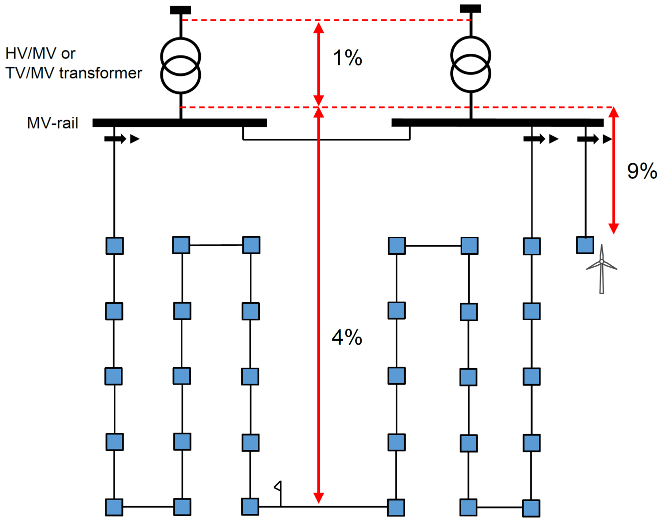


Figure 2.1: Overview of the allowed voltage deviation per component in the HV grid. 1% is assigned to the transformer and 4% to the feeder, or 9% to the feeder if the DG is connected directly to the MV grid. From [11]

As explained, the allowed deviation within Stedin's distribution grids is divided over both the MV and LV networks, with both network levels being assigned a variation of 5%. The voltage variation in LV networks is then divided over the following components: MV/LV transformer, LV main cable, LV connection cable [12]. These components, including the allowed voltage variation, are shown in Figure 2.2. Table 2.1 provides a summary of the allowed voltage deviations.

In order to enhance power quality and improve network reliability, distributed generators, whether renewable or not, that are connected to the MV distribution grid must adhere to specific operational criteria as well. These criteria are established by regulatory bodies at the national level, however there is an European standard too. Namely, the network code on the requirements for generators (RfG Regulation). The RfG regulation, for example, state PV panels and wind turbines can have a maximum power

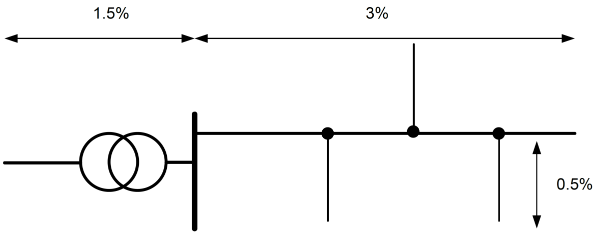


Figure 2.2: Overview of the allowed voltage deviation per component in the LV grid. 1.5% is assigned to the transformer and 3% to the LV cable and 0.5% to the connection cable. From [12]

Table 2.1: Overview allowed percentage voltage deviation per component. 5% is allocated to the MV grid components and 5% to that of the LV grid, to make a total of ±10% allowed voltage deviation.

Component	**Δ U**	
HV/MV- or TV/MV Transformer	1%	
MV Feeder	4%	
	5%	MV Total
MV/LV Transformer	1.5%	
LV Cable	3%	
Connection Cable	0.5%	
	5%	LV Total
	10%	Total

factor of ±0.95, measured at the Point of Common Coupling (PCC).

2.2. Integration of Distribution Networks with the Transmission Grid

In the broader power delivery system, electricity is distributed directly to consumers at lower voltages, originating from large-scale generation plants where voltage is initially stepped up. The transmission grid acts as a bridge, efficiently transferring bulk electrical energy over long distances using high voltages to minimize resistive losses (Figure 1.1). High voltage substations at the distribution network's outer edge step-down transmission line voltages to MV levels suitable for distribution.

Connecting to the high voltage grid ensures a dependable power source for local distribution networks, enhancing reliability and fostering the integration of renewable energy sources like wind and solar farms. Real-time power exchange between regions aids in balancing supply and demand fluctuations, strengthening grid stability [4].

The TSO has a high voltage transmission grid running at 150 kV throughout the the Netherlands. This means the DSOs connects to this grid at 150 kV as well. The DSO will convert these high voltages to lower voltages suitable for distribution in main distribution stations. These voltages can be 66 kV, 50 kV, 30 kV, 25 kV, 23 kV, 21 kV, or 10 kV. Further voltage reduction happens at transformer stations. Here, voltages like 66 kV, 50 kV, or 25 kV are stepped down again to even lower levels like 23 kV, 21 kV, 13 kV, or 10 kV. For the final delivery to homes and businesses, there is preferred to transform directly from 23 kV or 21 kV down to the LV of 0.4 kV (400 Volts) used in our appliances. However, in the majority of cases, an additional step-down transformation to 13 kV or 10 kV might be necessary before reaching the final 0.4 kV level [12].

2.3. Medium and Low Voltage Distribution Network Infrastructure

The medium and low voltage distribution network forms the final leg of electricity delivery, transporting power from the bulk transmission system to individual consumers (Figure 1.1).

The distribution network comprises two layers:

1. Medium Voltage Network: This primary distribution layer receives power from substations connected to the high voltage transmission grid, operating at voltages ranging from 10 kV to 23 kV. Distribution substations step down HV to MV using transformers. Underground cables distribute MV electricity over longer distances to neighborhoods or industrial zones.
2. Low Voltage Network: Responsible for supplying electricity directly to end users such as residential and commercial buildings, the LV network receives power from distribution transformers. These transformers, equipped with off-load tap changers, reduce voltage to 230 or 400 V (1 or 3 phase). Underground cables branch out from distribution transformers, connecting individual buildings to the power grid.

Key components within the distribution grid include:

- Distribution Substations (HV/MV): Linking transmission and distribution systems, these substations house transformers that step down HV electricity to MV for further distribution.
- Distribution Feeders: Main power lines carrying MV electricity from substations to various locations within the distribution network.
- Distribution Transformers (MV/LV): Closer to consumption points, these transformers further step down MV to LV suitable for homes and businesses.
- Low Voltage Lines: Deliver LV electricity from distribution transformers directly to consumers.

Off-load tap changers on distribution transformers regulate voltage between MV and LV networks by adjusting the turns ratio, although requiring the transformer to be de-energized during adjustment. Despite this limitation, off-load tap changers offer reliability and simplicity, enabling operators to effectively set voltage levels to meet diverse consumer loads.

As the energy landscape shifts towards sustainability, medium- and low voltage transmission grids adapt to integrate renewable energy sources. Coordinating the integration of DERs is crucial to be able to manage voltage fluctuations, grid congestion, and power quality issues while maximizing renewable energy benefits. However, the increasing demand for power, including electric vehicle charging, adds complexity to grid management, presenting both opportunities and challenges for future grid operations. This thesis addresses these challenges in Section 1.4.

2.4. Distribution Network Characteristics

Distribution network characteristics define the fundamental aspects of an electric power distribution system. Key characteristics include:

1. Voltage Levels: Distribution networks operate at MV or LV levels, with MV networks stepping down voltage from the high voltage transmission system and LV networks delivering electricity directly to end-users.
2. Network Topology: Variations in feeder lengths and distribution transformer placements impact the reliability, redundancy, and fault tolerance of distribution networks.
3. Transformer Settings: Configuration parameters like tap positions and voltage ratios determine the operational behavior of transformers within the network.
4. Load Profiles: Consumption patterns across residential, commercial, and industrial sectors influence overall load distribution and operational requirements.

5. Distributed Energy Resources: Integration of renewable energy sources, energy storage systems, and distributed generation units alters power flows and voltage regulation dynamics.

Understanding these characteristics is vital for designing, planning, and optimizing distribution systems to meet evolving consumer needs and support the transition to sustainable energy.

Inputs for voltage control methods often include:

- Current and voltage measurements at transformer secondary sides [13].
- Voltage measurements from different feeders [14].
- Feeder load data, PV profiles, and regulator warnings [15].
- Active power, reactive power, and voltage deviations [16].
- Characteristics of the network and control of OLTC transformers [5].

Similarities exist among the grid characteristics utilized by various voltage control methods, such as feeder-related data and PV generation profiles, highlighting common inputs used for voltage control techniques.

2.5. Modeling Techniques for Power Distribution Networks

Power grid modeling represents a crucial element of comprehension and analyzing the behavior, operation, and performance of distribution networks. Through accurate and comprehensive modeling, researchers and operators can simulate various scenarios, assess system vulnerabilities, and evaluate the effectiveness of voltage control strategies. By clarifying the fundamental principles and methodologies that support power grid modeling, this section provides a solid foundation for subsequent discussions on voltage control, system optimization, and resilience enhancement within power distribution networks.

To subsequently illustrate the effects of distributed generation on voltage profiles in distribution networks, an initial analysis of the voltage magnitude at the receiving end using a typical 2-bus feeder example with only a load bus is introduced, as described in [6]. Figure 2.3 depicts the simplified feeder circuit and Figure 2.4 shows the phasor diagram. Here, V_1 represents the per unit voltage phasor at the supply side, while V_2 denotes the per unit voltage phasor at the receiving end. It is assumed that the supply side maintains a constant voltage phasor V_1, a realistic scenario in distribution grids where the feeder originates from the primary substation. The substation is typically connected to a robust external high voltage grid via a transformer equipped with an automatic OLTC. Further details on OLTCs and its controller, the Automatic Voltage Control (AVC) relay, are presented in Section 2.7.

On the load side, it is assumed that active (P) and reactive (Q) power are consumed independently of external factors, employing a constant power load model [17]. The cable linking the supply and load is modeled as a series connection of lumped resistance (R) and reactance (X). The focus of interest lies in understanding the V_2 voltage magnitude of the feeder's voltage drop and its relationship with other relevant quantities. For now, there is assumed only a load bus is presented at V_2 and there is only power flow from V_2 to the load as is depicted in Figure 2.3.

It is usual practice in power systems to represent part of a network by its Thévenin equivalent circuit. Thévenin circuit comprises a voltage source (e.g. sending-end voltage of a feeder) and a series impedance (e.g. impedance of the feeder), where a line represented by a series impedance, $R + jX$, is supplying a load drawing a power $P + jQ$ [6]. This is shown in Figure 2.3 as well. The phasor diagram of the equivalent circuit is again shown in Figure 2.4.

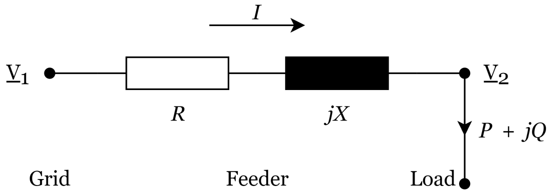


Figure 2.3: A simplified representation of a line section, where V_1 denotes the voltage at bus 1, and V_2 represents the voltage at bus 2. The feeder has a resistance R and a reactance X. The real power P and reactive power Q are absorbed at bus 2. Adapted from [6]

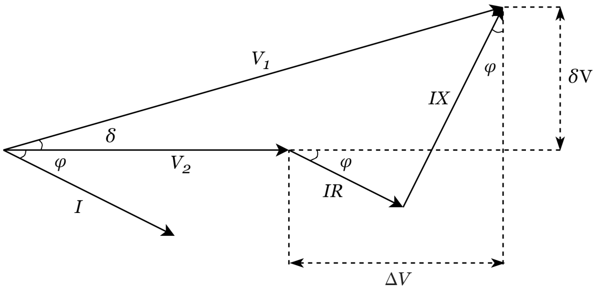


Figure 2.4: Phasor diagram of simplified model of line section showcasing all individual phasors. Also, ΔV and δV are given. Adapted from [7]

From the phasor diagram can be found that:

$$V_2 \approx V_1 - \frac{R}{V_2} P - \frac{X}{V_2} Q \qquad [\mathrm{V}] \quad (2.1)$$

Examining Equation 2.1 reveals that the magnitude of the receiving end's voltage, V_2, is contingent upon the consumption of active power and reactive power. So, as power consumption increases, V_2 decreases. Variations in the magnitude of the supply side's local voltage control introduce fluctuations in the magnitude of V_1, which are also evident at the feeder's receiving end. The primary objective of voltage control is to maintain all nodal voltages as close to nominal as possible, thereby ensuring that both V_1 and V_2 remain within their allowed limits. Upon reviewing Equation 2.1, one could list the following solutions to address voltage-related issues:

- Suppressing the fluctuations of V_1 with a well-selected tap changer-equipped transformer and AVC relay at the feeder's supply side (primary substation), also results in a smoother profile of V_2.
- Line Drop Compensation (LDC): compensation for the voltage drop along the line, caused by the series impedance, to V_2 by raising V_1.
- Changing the reactive power consumption Q at the receiving end with the help of a compensator device. This could mitigate V_2 fluctuations without disturbing the load's active power (P) consumption. For this scheme to be feasible, the feeder cannot have large a R/X ratio as it would make the V_2 voltage less sensitive to changes in Q.
- Grid reinforcement, which results in smaller R and X values, and effectively a smaller difference between V_1 and V_2. This requires the laying of new cables, which is a very costly procedure and hence should be avoided if possible.

Equation 2.1 demonstrates that in addition to active power, reactive power has the capability to effectively adjust the voltage. This adjustment is achieved through the injection or absorption of reactive power in the opposite direction of active power. Nevertheless, the impact of this injection/absorption on the system is somewhat limited compared to active power, primarily because of the relatively low reactance in a distribution feeder (resulting in a high R/X ratio) [4].

The insights obtained from Equation 2.1 can be extrapolated to more complex feeder configurations and broader distribution grid contexts as follows: voltage fluctuations originating from the supply side, namely, variations in voltage at the primary substation due to fluctuations in the stiff external grid and inaccuracies in local voltage controllers, are, to some extent, propagated to all nodes within the distribution grid and thus should be mitigated. Moreover, the efficiency of conventional reactive power injection-based voltage control or support schemes diminishes as the R/X ratios of the grid lines increase. Keeping these findings in mind, the following subsection will clarify the impact of distributed generation on grid voltages.

2.6. Effects of Distributed Generation on Network Operation

In transmission networks, the R/X ratio typically allows for the exclusion of resistance, with network voltages primarily dependent on reactive power transfer. However, in MV networks, the resistance and reactance are generally comparable, resulting in both reactive power and active power flows influencing network voltage levels. Consequently, the voltage at the load side (bus 2 in Figure 2.3) is contingent upon various factors, including the active and reactive power of the generator or load, the feeder's resistance and reactance, as well as the voltage at the feed's sending end (bus 1 in Figure 2.3). As illustrated in Figure 2.4 and described by Equation 2.3, practical scenarios demonstrate that DG typically elevates the network voltage level, as the generated real power often exceeds the potentially consumed reactive power. Depending on factors such as the size, type, location, and temporal variability of the DG unit, this voltage rise can either be advantageous or detrimental to the network. For example, when DG is active during times of high load in the distribution network, it supports the network voltages, thus improving the quality of voltage for consumers. Conversely, large DG units operating during low-load conditions may elevate network voltages beyond acceptable limits. In weak distribution networks, the hosting capacity, or the maximum generation capacity that can be connected to an existing distribution network, is often constrained by the voltage rise effect.

So, distributed generation significantly impacts the operation of distribution networks across various dimensions. The implementation of DG alters power flows and fault currents, leading to potential issues concerning voltage quality, protection, and escalating fault levels. When conducting studies on DG interconnection, it is crucial to analyze the effects on network reliability and stability. This thesis primarily focuses on voltage quality concerns. Distribution network voltages must adhere to specific power quality standards to prevent adverse effects on network components or customer devices, as elaborated on in Section 2.1. Furthermore, the target voltage range utilized in distribution network planning typically exhibits a narrower range compared to the acceptable voltage range.

The quality of voltage in distribution networks include several elements: frequency, voltage magnitude, fluctuations, rapid voltage transitions, dips, interruptions, unbalance, and harmonics. Distributed generation notably affects many of these voltage quality factors. It alters the voltage level in the network, potentially causing rapid voltage shifts and dips, and may either escalate or diminish harmonic distortion and voltage imbalance. Furthermore, distributed generation raises the fault level in the distribution network, thus impacting voltage quality. Also, distributed generation can alter the frequency and timing of interruptions [6].

To demonstrate the impact of DG on voltages within a distribution grid, a PV generator with a reactive power-injecting compensator device is added at the receiving end of the previously discussed simple feeder (Figure 2.3), as depicted in Figure 2.5. The PV plant injects an amount of active power denoted as P_{PV}, while the compensator device injects a reactive power amount denoted as Q_c. If the PV plant's inverter is capable of handling reactive power exchange, it can also act as a reactive power compensator and Q_c becomes negative. Additionally, a load consuming active power (P_l) and reactive power (Q_l) is connected at the receiving end. The stiff external grid connection is shown in Figure 2.5 as V_1, responsible for maintaining a relatively constant voltage magnitude. It should be noted that the voltage control scheme on the supply side is only aware of the magnitude of V_1 and does not consider other

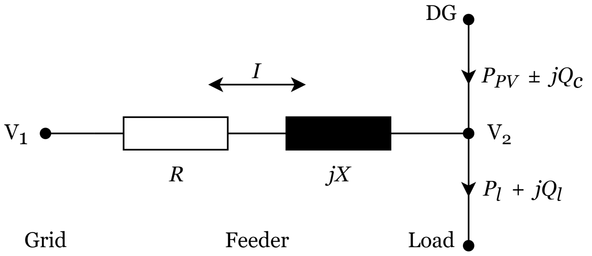


Figure 2.5: Simplified feeder diagram with distributed generation. V_1 is the voltage of bus 1 and V_2 the voltage of bus 2. R is the resistance and X the reactance of the feeder. P_{PV} and P_l are the real power from the DG and to the load. Q_c and Q_l are the reactive power absorbed to bus 2. Adapted from [6]

nodal voltages like V_2.

The active power consumption at the receiving terminal is given by $P = P_l - P_{PV}$, and a comparable equation can be formulated for the reactive power consumption at the receiving end: $Q = Q_l - Q_c$ (if Q_c is assumed positive). Substituting these power equations into Equation 2.1 yields:

$$V_2 \approx V_1 - \frac{R}{V_2}(P_l - P_{PV}) - \frac{X}{V_2}(Q_l - Q_c) \qquad [\mathrm{V}] \quad (2.2)$$

However, the reactive power of the distribution generation, PV in this case, can be positive or negative, so the difference in voltage across the feeder can be approximated by:

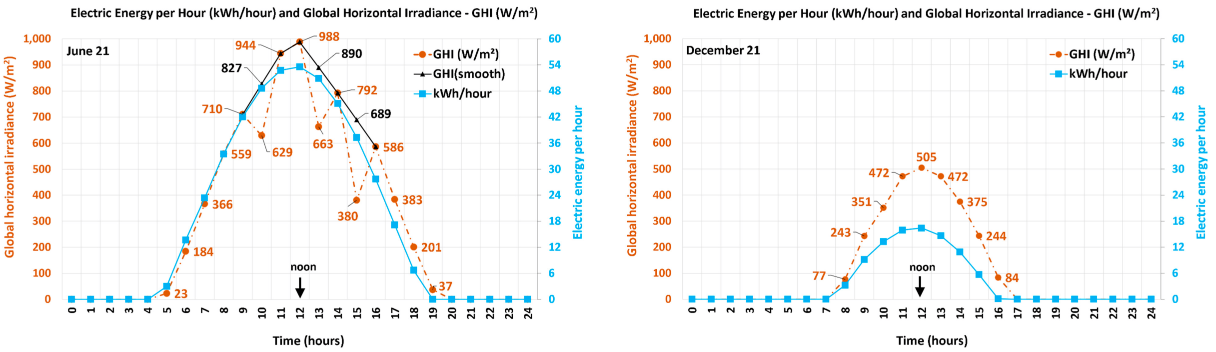
$$V_1 - V_2 = \Delta V \approx \frac{R(P_l - P_{PV}) + X\,(Q_l - (\pm Q_c))}{V_2} \qquad [\mathrm{V}] \quad (2.3)$$

where P_{PV} and Q_c represent the active and reactive power output of the DG unit, respectively. The ensuing observations consider the cumulative impact of active and reactive power interchange of a DG unit. As shown in Equation 2.3, if the DG unit generates reactive power or remains uninvolved in reactive power exchange with the grid, there is a reduction in voltage drop along the feeder. Furthermore, when the generated active power exceeds the feeder's demand, power will flow back from the DG unit to the substation, causing an increase in voltage. On the other hand, if the DG unit draws reactive power, the voltage drop along the feeder could rise or fall. This effect depends on the balance between the DG unit's active and reactive power relative to the load's active and reactive power, as well as the line's impedance ratio (R/X) [18].

In networks where cables, particularly transmission lines and overhead distribution cables, exhibit lower R/X ratios, fluctuations in the voltage magnitude at the receiving end (V_2) caused by variations in active and reactive loadings (P_l and Q_l) and PV generation (P_{PV}) can be effectively mitigated by adjusting the amount of reactive power (Q_c) injected or absorbed using the compensator device. However, in underground MV distribution grids typical in Western Europe, the high R/X ratios render these strategies unfeasible. When the R/X ratio approaches 1, the required reactive power flow to address voltage issues would be comparable to the active power flow in the feeder, resulting in a low power factor and inefficient energy transmission. Moreover, when $R/X >> 1$, the voltage magnitudes in the grid become virtually unaffected by reactive power flow [19].

Equation 2.2 illustrates how the inclusion of distributed generation leads to a rise in voltage at the feeder's receiving end. This occurrence is regulated by the same fundamental principles: DERs elevate local voltage magnitudes, and when resistance greatly exceeds reactance ($R/X >> 1$), voltage levels are primarily influenced by active power flow. These principles extend to larger, intricate distribution networks. However, determining voltage magnitudes in such networks typically necessitates the utilization of power system simulation software, like PowerFactory which numerically solves the power flow equations [17].

The challenges posed by voltage issues arising from renewable energy-based distributed generation are compounded by the inherent unpredictability of renewable sources. Unlike traditional power generation methods, renewable sources offer less to none controllability to operators. This varying behavior is illustrated by the generation profile of a photovoltaic plant for a summer and winter day as depicted in Figure 2.6. While some trends are apparent, sudden fluctuations, such as power dips (P_{PV}) caused by clouds, can occur unpredictably. In addition to managing reverse power flows, modern active network management schemes must also anticipate and/or withstand these fluctuations.



(a) June 21: Summer Day

(b) December 21: Winter Day

Figure 2.6: Hourly profiles of the global horizontal irradiation and the electric energy output for from PV panels located in Spain. The clear difference between a summer and winter day can be observed. From [20]

As demonstrated in the problem statement, conventional voltage controllers struggle to maintain voltage limits in the presence of DG, necessitating novel approaches in the voltage control schemes of modern distribution grids. As explained in Section 1.2, the objective of this thesis is to explore a novel adaptive voltage control policy that solves the voltage regulation issues in active distribution grids characterized by extensive renewable energy generation and high R/X ratios due to underground cable usage, while being universally applicable. Mainly designed for Stedin's MV distribution grids and is aimed at resolving voltage limit violations, particularly upper limit violations.

2.7. Voltage Control in Distribution Networks

The primary objective of distribution network voltage control is to maintain voltage magnitudes within a predefined and acceptable operating range, as set by the grid code (Section 2.1), across the entire network. This imperative arises from the inherent design of customer equipment and network components, which are engineered to function (optimally) at specific voltage levels. Deviations beyond this acceptable range can lead to detrimental consequences. Moderate voltage fluctuations may result in equipment malfunctions, while more extreme voltage excursions can cause permanent damage or even catastrophic failure of network components and customer devices [4] [21].

Several techniques are used to maintain voltage stability within a distribution network. One approach is the already mentioned OLTC equipped transformer. This transformer can modify its output voltage while still in operation by adjusting the tap position of its secondary coil based on real-time voltage or current readings. Similarly, Step Voltage Regulators (SVRs) utilize transformers to regulate voltage levels, but are positioned directly along the feeder itself, making them particularly advantageous for extended distribution lines. Another method for voltage control involves Capacitor Banks (CBs). These banks can elevate voltage and improve the power factor by injecting reactive power into the network. A downside is that CBs are not able to lower the voltage in a distribution grid when the voltage is increased by DERs. On top of that, grids are constantly changing due to load fluctuations. CBs only inject reactive power, not real power. Over-reliance on capacitor banks without considering real power flow management can lead to unintended consequences. Voltage-controlled circuit breakers manage the connection and disconnection of these capacitor banks. For more precise control over voltage fluctuations, Static Synchronous Compensators (STATCOMs) can be employed. These devices have the unique ability to both generate and absorb reactive power, making them ideal for compensating for the demands of large, fluctuating loads like factories [17].

Following this, a list of the specified voltage control methods will be presented along with their pros and cons for clearer comparison:

1. OLTC-equipped Transformers [22]

- Advantages:
  - Real-time voltage regulation through tap adjustment
  - Adaptability to both voltage and current fluctuations
  - Widespread adoption
- Disadvantages:
  - High installation and maintenance costs
  - Potentially limited voltage adjustment range

2. Step Voltage Regulators [23]

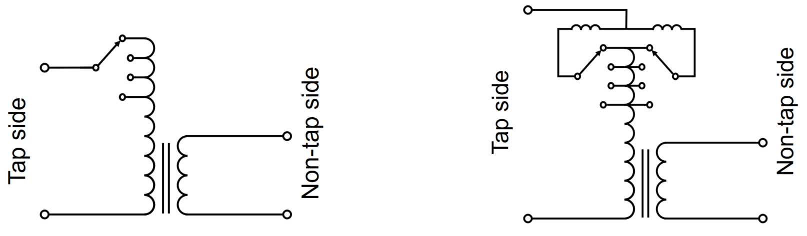
- Advantages:
  - Effective voltage regulation along lengthy distribution lines
  - Simple and reliable technology
- Disadvantages:
  - Potential for voltage fluctuations due to step changes
  - Limited voltage adjustment range

3. Capacitor Banks [24]

- Advantages:
  - Cost-effective improvement of power factor and voltage raising
  - Ease of installation and operation
- Disadvantages:
  - Inability to lower voltage
  - Potential for adverse effects if over-relied upon without proper real power flow management
  - Limited to reactive power compensation

4. Static Synchronous Compensators [25]

- Advantages:
  - Bidirectional reactive power control for enhanced flexibility
  - Suitability for large, fluctuating loads
  - Rapid response to voltage fluctuations
- Disadvantages:
  - High initial cost and complexity
  - Need for specialized expertise for installation and maintenance



(a) Off-Load Tap Changer (b) On-Load Tap Changer

Figure 2.7: Simplified schematic of an Off- and On-Load Tap Changer. From [17]

The choice of method depends on the specific needs of the distribution network. For example, OLTC transformers may be suitable for substations, while SVRs are better for long feeders. Capacitor banks are a cost-effective option for general voltage support, but STATCOMs offer more advanced control for critical loads. For the policy explained in this thesis, the OLTC-equipped transformer is the method of choice due to its widespread use, real-time control capabilities, and compatibility with centralized voltage management strategies. These factors make it a practical and effective solution for addressing voltage regulation challenges in active distribution networks with high renewable energy penetration. Additionally, the widespread use of OLTC transformers in distribution networks contributes to the universal applicability of the proposed policy. By focusing on the control of OLTCs, the policy can be readily implemented in a variety of networks without requiring significant modifications or additional infrastructure. This adaptability to different network configurations enhances the practicality and potential impact of the research.

The two types of tap changer mechanisms shown in Figure 2.7 are typically installed on the high voltage side of transformers to minimize wear on their contact points due to lower current flow. In grids operated by Stedin, tap changers are exclusively fitted to the high voltage side of transformers for this reason. Off-load tap changers (Figure 2.7a) can only be adjusted when the transformer is de-energized and are usually set during installation, with infrequent adjustments made by the DSO. On-load tap changers, shown in Figure 2.7b, allow adjustment of the turns ratio without interrupting power delivery, achieved by utilizing two selector switches that move successively. Reactor coils limit the circulating current during switching, preventing shorting of subsequent taps. While larger primary substations (HV/MV) typically use on-load tap changers, smaller secondary substations (MV/LV) generally employ off-load tap changers. However, on-load tap changers have drawbacks, including inherent discreteness due to finite tap numbers, slow operation, and high maintenance requirements, since they are electromechanical devices. Research into solid-state tap changers, which utilize fast semiconductor switches for more sophisticated and faster control actions with reduced maintenance, is ongoing, however, not yet widespread in commercial applications. As a result, commercially available tap changers remain electromechanically actuated and can only change transformer taps in discrete steps [17].

Within distribution grids, the tap position of the OLTC is controlled by an AVC relay, i.e. the control device which keeps the measured voltage magnitude as close to the setpoint as possible. As explained in more detail later, almost all AVC relays use a deadband and an integrator to avoid (too) frequent switching as this causes the OLTCs to wear out more quickly.

2.7.1. Passive Distribution Networks

Figure 2.8 illustrates the voltage profile of a radial distribution feeder solely containing load at both maximum and minimum voltage scenarios. In such unidirectional power flow networks, voltage control strategies are relatively straightforward. Planning focuses on maximum and minimum loading conditions, ensuring that customer supply point voltages remain within the permitted voltage range. Network design and voltage control are coordinated such that the minimum customer voltage approaches the lower limit, while the maximum customer voltage approaches the upper limit of the acceptable range [6]. Typically, only the substation voltage undergoes automatic control. The presence of a OLTC can be recognized by observing the arrow passing through the typical transformer symbol, as depicted in the primary transformer of Figure 2.8. The network itself is designed to maintain all voltages within acceptable levels across various loading conditions.

Substation main transformers (HV/MV) incorporate OLTCs for voltage regulation. These discrete, mechanical devices adjust the transformer's winding ratio while the transformer remains energized, directly controlling the MV busbar voltage within the substation. As explained in the previeous section. The OLTC can be operated manually or automatically using an AVC relay, with the latter being the standard method for HV/MV transformers.

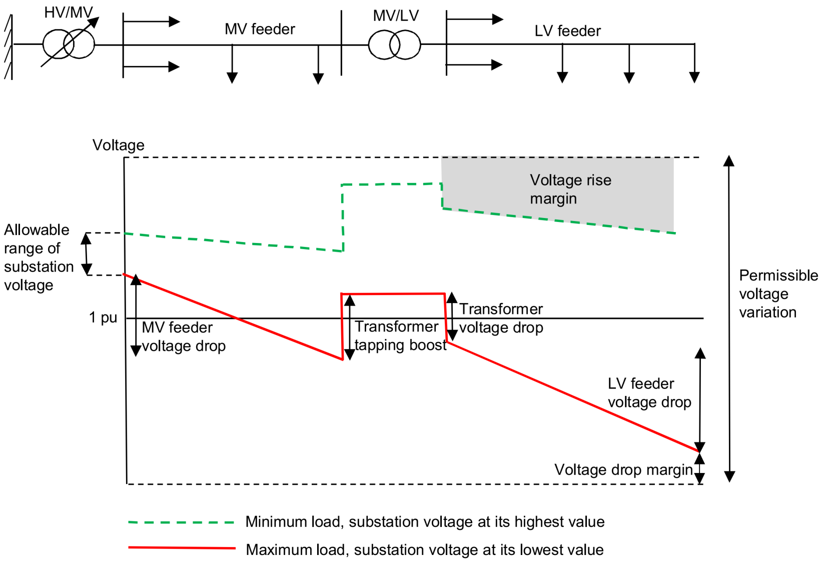


Figure 2.8: Voltage profile of a radial feeder with only load where the locations MV feeder voltage drop, transformer tapping boost, transformer voltage drop and LV feeder voltage drop are given. Additionally, the allowable range of substation voltage, voltage rise margin, voltage drop margin and permissible voltage variation are provided. From [26]

The fundamental function of the AVC relay is to maintain a constant voltage at the substation. However, due to the discrete nature of the OLTC, a *deadband* is implemented to prevent excessive tap adjustments. Additionally, a time delay element is included to avoid unnecessary tap changes during transient voltage fluctuations. The AVC relay continuously compares the measured substation voltage with a reference value. If the measured voltage deviates from the reference by a value exceeding the deadband, a delay timer activates. This timer remains active as long as the voltage stays outside the predefined limits of the AVC relay. Once the timer reaches its set value, a tap change is initiated. The delay can be set with either a definite or inverse time characteristic. The inverse characteristic provides a shorter delay for larger voltage deviations, as illustrated in Figure 2.9.

Advanced AVC relays commonly incorporate Line-Drop Compensation (LDC) as a standard feature. This functionality transcends maintaining a constant substation voltage. Instead, it adjusts the voltage based on the current flowing through the main transformer. The objective is to ensure consistent voltage at a designated remote load center. This is achieved by mathematically calculating an adjusted voltage (V_2) using the following formula: $V_2 = V_1 - (R + jX) \cdot I$, where R and X represent the resistance and reactance between the substation and the load and I is the main transformer current. Through this approach, the substation voltage is dynamically regulated: increasing at high load to compensate for line drops and decreasing at low load to prevent over-voltage at the remote location.

The prior explanation of basic AVC relay operation is insufficient for scenarios with multiple transformers operating in parallel. Component tolerances can lead to *tap divergence*, a situation where individual transformers settle on different tap positions. This creates circulating currents between transformers, resulting in increased losses and a complete loss of voltage control if extreme tap divergence occurs. To address this, more sophisticated control algorithms are employed in AVC relays, ensuring the tap changers remain within a maximum of two steps from each other.

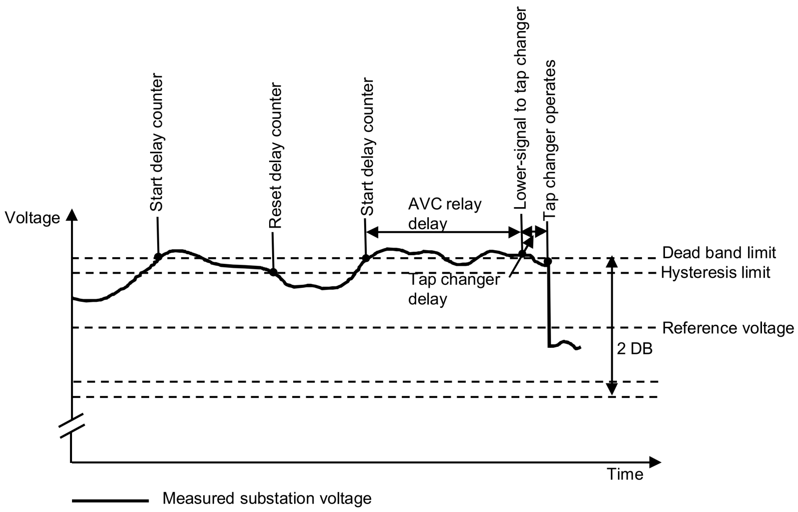


Figure 2.9: Time domain operation of an AVC relay where the definite time characteristic is used. Different names for certain voltage peaks and dips are indicated and the dealy of the relay and tap changer is indicated. From [27]

MV/LV transformers often utilize off-load tap changers to adjust their winding ratios. Unlike OLTCs, these taps require interrupting power delivery for adjustments. Therefore, their positions are determined during the planning stage and remain fixed throughout normal operation. The optimal tap selection considers factors such as voltage drop along the MV feeder, the MV/LV transformer itself, the LV feeder, and the chosen control strategy of the substation's AVC relay. Typically, the distribution network is segmented into zones where all transformers within a zone operate on the same tap setting.

Figure 2.8 illustrates the voltage profile of a radial distribution network containing only loads. Network planning assumes unidirectional power flow, resulting in a limited margin to the upper voltage limit (voltage rise margin in Figure 2.8). However, when DG is introduced, this unidirectional flow assumption may no longer hold true. Consequently, the voltage profile can deviate significantly from the original scenario. Figure 2.10 depicts the voltage profile of the same network with DG connected to the MV feeder. Unlike the continuously decreasing profile without DG, the presence of DG introduces both descending and ascending sections. During peak load conditions, the DG unit acts to elevate voltage levels within the network, improving overall voltage quality. Conversely, during minimum load periods, the maximum voltage can surpass the feeder's upper limit, rendering voltage performance unacceptable.

Figure 2.10 assumes the substation's AVC relay does not utilize LDC or negative-reactance compounding. If either technique is employed, the influence of DG must be considered when setting control parameters. Current practices treat DG solely as negative load in distribution network planning, excluding it from any network control participation. The voltage control principles outlined in the beginning of this section remain unchanged, with planning focusing solely on determining if the DG unit can connect to the designated network node. Two polarizing loading scenarios, namely maximum generation with minimum load and minimum generation with maximum load, are assessed. In the latter scenario, should there be an excessive voltage increase, passive strategies are implemented to lower the network's peak voltage to an acceptable threshold. Common strategies include network reinforcement through enlarging conductor size or connecting the distributed generation to a dedicated feeder. While this approach maintains existing network operation principles, it can lead to high DG connection costs due to network upgrades or dedicated feeder construction.

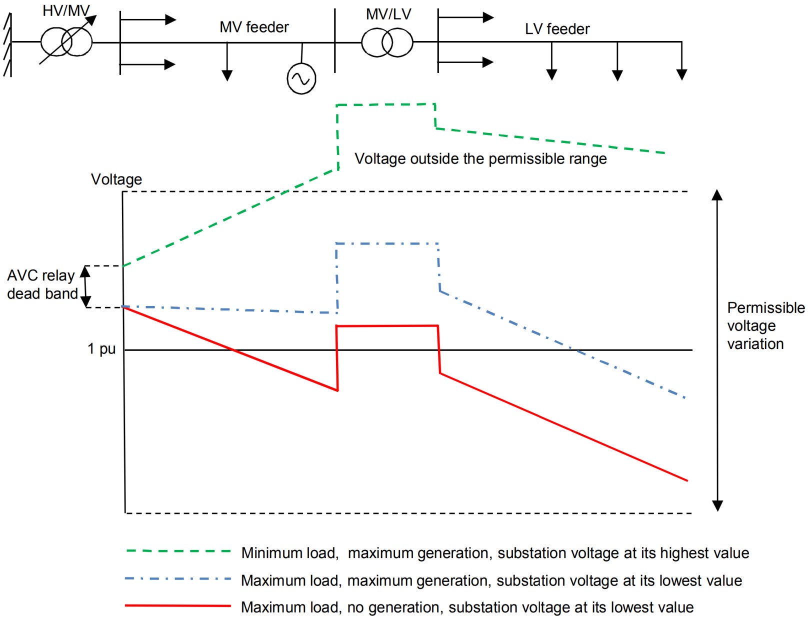


Figure 2.10: Voltage profile of a radial feeder with load and generation. The AVC relay dead band is also indicated. From [26]

2.7.2. Active Distribution Networks

Until now, distribution networks have been viewed as passive systems with voltage control centralized at the substation. However, with the increasing integration of active resources like DG into distribution networks, this method can lead to elevated overall distribution network expenses. By utilizing the voltage control capabilities of DERs and specifically implementing active voltage management strategies, there is a significant potential to decrease total distribution network costs in a variety of situations. Consequently, the network transitions to active as the distribution grids incorporate generation capacity and control systems to manage these resources, now referred to as ADNs.

When it comes to weak distribution networks, the biggest obstacle to adding more DG is usually the rise in voltage caused by the DG itself. Fortunately, there are methods to mitigate this increase in voltage. Techniques include reducing the impedance of the feeder lines, managing the flow of real and reactive power across the network, and adjusting the voltage at the substation or other points along the feeder (see Section 2.6). The next sections will explore different methods for the control of voltage levels with a distribution network divided into categories which indicates the overlap in their control methods.

2.7.3. Decentralized or Distributed Voltage Control Methods

Decentralized and distributed voltage control methods refer to approaches that utilize local information and control strategies to manage voltage levels within a power distribution network. These methods typically involve making voltage control decisions based on measurements taken at specific locations within the network, without relying on centralized control or extensive communication between network components. Distributed voltage control methods are often employed in scenarios where centralized control may be impractical or where communication infrastructure is limited [28]. Various decentralized voltage control strategies have been explored to enable greater integration of distributed generation. [13], [24], [28]–[38] all use (a form of) decentralized or distributed voltage control.

The methods described in [13], [29]–[31], [35], [37] all use local measurements to support the voltage control. While [29] uses a demand response program with real-time data collected via a remote terminal unit and a voltage sensitivity matrix to apply load curtailment, [30] uses computationally efficient model free voltage control method to control the reactive power generation within the grid. On the other hand, [13] takes the data from existing SCADA measurements to correct the false image of DG loads and implement a simple, efficient, and inexpensive adaptive OLTC controller. [31] collects real-time data from the network for a two-level Voltage Control Method (VCM) with local reactive power control and centralized voltage control measurements. However, next to the centralized control part [35] presents a data-driven 3D deep reinforcement learning based local voltage control method. Finally, [37] uses substation measurements, a sensitivity analysis and a time series Monte Carlo analysis to remove the need for remote monitoring and to present a generic and practical remote voltage estimation method to mitigate the voltage limit violations via OLTC-fitted transformers.

2.7.4. Reactive Power Control

Reactive power control is a key method for voltage control in power distribution networks. It plays a crucial role in maintaining the power factor close to one and compensating for voltage drops during high-load situations. This helps in maintaining the voltage stability of the distribution grids. Various devices with adjustable reactive power, such as capacitor batteries, transformers, and reactors, are used to improve voltage stability, grid protection, and reduce harmonics. Traditional unidirectional, passive distribution power grids are rapidly evolving into bidirectional, interactive, multi-coordinated smart grids. Reactive power curtailment is a form of reactive power control and involves reducing or limiting the output of reactive power from specific sources within the power distribution grid. This is done to minimize voltage fluctuations and adhere to grid code regulations. Controlling the voltage in the distribution network can be accomplished by reactive power injection or absorption, as explained in Section 2.6. The capability of distributed generators to control reactive power depends on their type of network connection.

As mentioned previously in Section 2.7, [30], [31] use measurements from the network in combination with reactive power control. [39] introduces a local voltage control strategy that leverages short-term (15-second) forecasts of PV power to prevent potential violations of the upper voltage limits or over-voltage conditions at the point where the PV systems connect to the ADN. These forecasts are generated using a hybrid method rooted in Kalman filter theory, which incorporates physical modeling of PV generation based on high-resolution (15-second) data gathered from local measurements. The algorithm developed in this work implements active power reduction based on these forecasts, particularly when the reactive power adjustments determined by a droop-control approach are insufficient for achieving the targeted voltage control within the set power factor boundaries. The thresholds for power reduction are determined to ensure that this voltage control method effectively minimizes the risk of voltage limit breaches. The purpose of [40] is to create a day-ahead coordinated voltage management approach for an ADN. It suggests a combined framework that integrates real-time dynamic thermal rating with Coordinated Voltage Control (CVC) to address issues of voltage quality and thermal constraints arising from high levels of DG in such networks. The CVC strategy includes mechanisms like OLTCs, regulation of active and reactive power in DG systems, and switchable shunt VAR compensation devices. The methods including reactive power control from [5], [6], [15], [24], [28], [41]–[43] will be later elaborated on.

2.7.5. Centralized or Coordinated Voltage Control Methods

Coordinated voltage control methods base their decisions on the overall state of the distribution network, requiring data exchange between network nodes. These methods range from straightforward rule-based algorithms, managing only one controlled resource, to sophisticated optimization algorithms overseeing all voltage-controlling components. Even the most basic coordinated voltage control algorithms often significantly increase the distribution network's capacity to accommodate distributed generation compared to methods relying solely on local measurements.

Control actions may include adjusting the setpoints of voltage-regulating devices such as transformers, capacitors, and regulators, as well as coordinating the reactive power output of distributed generators and other grid-connected devices. Centralized control algorithms consider factors such as network topology, load forecasts, and system constraints to optimize voltage control strategies. One key advantage of centralized voltage control is its ability to provide coordinated and synchronized control across the entire distribution network, ensuring efficient operation and minimizing voltage deviations. However, centralized methods require robust communication infrastructure and computational resources to gather and process real-time data, making them more complex and potentially costly to implement compared to decentralized approaches.

As mentioned, there is a wide range of different centralized or coordinated voltage control methods. The following, [5], [6], [14], [15], [18], [24], [30], [31], [34]–[36], [38], [40]–[42], [44], [45], can be found in the literature. Their exact methods will be explained in one of the two following subsections.

2.7.6. Rule-Based Algorithm

Unlike more complex optimization-based approaches, rule-based methods rely on predetermined rules or thresholds to make (voltage) control decisions. These rules are often established based on engineering rules of thumb, operating experience, or regulatory requirements. In rule-based voltage control, control actions are determined by predefined rules that dictate how voltage-regulating devices such as transformers, capacitors, and voltage regulators should respond to changes in network conditions. For example, if the voltage at a certain node exceeds a predetermined threshold, a rule-based controller may activate a voltage regulator to adjust the voltage level.

One of the main advantages of rule-based voltage control methods is their simplicity and ease of implementation. They typically require less computational resources and real-time data compared to optimization-based approaches, making them more suitable for systems with limited communication infrastructure or computational capabilities. However, rule-based methods can lack the ability to adapt to dynamic or unforeseen changes in network conditions. They are also less efficient at optimizing system performance compared to more sophisticated optimization algorithms. As a result, rule-based voltage control methods are often used in conjunction with other control strategies to achieve optimal system performance while maintaining simplicity and reliability.

The rule based control algorithm described in [6] consists of basic and restoring parts. The approach builds upon two earlier papers [46], [47], but the algorithm has been advanced to also accommodate distribution networks that incorporate multiple DERs. In addition, the real power of DERs has been incorporated as a control variable. The fundamental and restoring control algorithms are composed of three elements: control of substation voltage, control of reactive power, and control of real power.

Basic control aims to keep network voltages within feeder limits. It starts by assessing the need for substation voltage adjustments. Then, it calculates tap changer operations and sets a new point for the AVC relay, which is transmitted after a delay. Should basic control fail to return all network voltages to within acceptable ranges, it triggers the activation of basic reactive power control. If both basic substation voltage control and basic reactive power control prove ineffective in restoring the network voltages to within acceptable ranges, then basic real power control is brought into action. Restoring control aims to return the real and reactive powers of DERs to their initial values, as close as possible to their original settings. It also adjusts network voltages if they have deviated significantly due to events like disconnecting a large DG unit.

2.7.7. Optimization-Based Algorithm

Optimization-based methods in voltage control encompass a wide range of approaches that utilize mathematical optimization techniques to achieve efficient voltage regulation in distribution networks. These methods vary in complexity and approach, but share the common goal of optimizing control actions to meet specific objectives. They aim to minimize or maximize certain objective functions while satisfying operational constraints and system requirements. By considering various factors such as network topology, load profiles, and generation capacities, optimization-based approaches can determine the most effective settings for voltage-regulating devices and DERs to maintain voltage levels within specified limits and improve overall network performance. Numerous studies have thoroughly investigated optimization-based voltage control within distribution networks: [5], [6], [14], [16], [17], [24], [32]–[34], [41]–[43], [48], [49].

In [6] the optimization of distribution network voltage control is presented as a Mixed-Integer Nonlinear Programming (MINP) problem. Vectors are set as positions of tap changers, real and reactive powers or terminal voltages. The goal of the objective function is to reduce the overall expenses related to network losses and generation curtailment. Furthermore, inequality constraints are employed to represent the technical constraints of the network and the capacity limits of the controllable resources.

A fuzzy controller is implemented in [14] to coordinate the OLTC and Power Allocation Optimization (PAO) module. The PAO Module synchronizes inverters along a feeder to keep the terminal voltage within the rated range while maximizing active power output. Using state estimation, fuzzy logic collects voltage data from various feeder terminals to determine if voltage stability should be maintained by adjusting OLTC or PAOs, thereby enhancing the efficiency of PV generation.

In the next paper [41], real-time centralized evaluation of control actions involves solving a dynamic optimization problem with constraints, aiming to minimize voltage deviation from a reference value. This problem is addressed using an algorithm operating in the continuous time domain, based on a rapid artificial dynamic system employing sensitivity theory. This method enables the controller to swiftly adapt to changes in the system's operating conditions, making it suitable for continuous-time deployment.

The work of [42] introduces a new way to control voltage automatically in power grids with integrated PV. It focuses on using information from specific points in the network to adjust the power output of the solar inverters. The system works by treating the voltage control problem as a constrained optimization problem. By solving this problem, the method determines the best amount of reactive power each solar inverter needs to add or remove to keep the voltage levels within a safe range across the entire grid.

According to [32], the optimal voltage control problem originates from the non-convex Optimal Power Flow (OPF) problem. Convex relaxation methods like Semi-Definite Programming (SDP) and Second-Order Cone Programming (SOCP) are being used, achieving global optimal solutions under specific conditions (e.g., radial networks). To address this, the centralized convex problem is typically decomposed, often using dual-decomposition techniques, to enable solution by distributed algorithms.

The research detailed within [33] utilizes a unbalanced network flow modeling to develop a distributed design that employs the alternating direction method of multipliers algorithm. In order to enhance the communication network efficiency, the coupling of power flow is simplified to a linear form, focusing exclusively on adjacent buses. Notably, this linear approximation model performs adequately and enables data exchange only between neighboring buses.

The project from [17] aims to address voltage limit violations using Model Predictive Control (MPC). Coordinated control actions by the MPC include OLTC switching, low-level OLTC control relay adjustments, and active power curtailment of large PV plants. A linear, sensitivity-matrix-based model predicts the grid's state, with sensitivity values recalculated at each MPC sampling time step. To prevent unjustified PV plant curtailment, a conditional curtailment logic is integrated into the MPC policy. This logic, incorporated into the optimization problem using binary variables and Mixed-Integer Linear (MIL) constraints, ensures efficient operation.

The next paper, [48], proposes an optimal voltage control approach for distribution systems, optimizing tap movements and active power curtailment from PV units. The objective function includes managing voltage drop and rise violations, transformer Tap Movement Rate (TMR), and PV Power Curtailment (CPPV). To address this, a multi-objective Grey Wolf Optimizer enhanced with a Lévy mutation operator (GWO-Lévy) is developed for precise voltage control problem-solving.

Next, [16] introduces a novel Optimal Voltage Control (OVC) strategy utilizing a hybrid line-drop compensation technique with adaptive OLTC Transformers methods. The methods analysis the quality of the EDN voltage, by determining the parameters that characterize the OVC law by adjusting the transformation ratio from the step-down power transformer station.

The research outlined in [49], states that the further expansion of DERs is expected to lead to a worsening of the voltage situation within the German distribution grids. The paper indicates the necessity to create a fast, cheap and innovative solution to reduce the negative effects of the DERs in the MV and LV grid. So, an optimized voltage regulator of the HV/MV transformer is suggested to keep the voltage levels within the stipulated limits. To accomplish this, the voltage regulator's curve in the substation is updated with new set points alongside electricity compounding. Following these adjustments, the characteristic curve must not only elevate the voltage when energy is accessed but also reduce the voltage suitably on the bus bar by reversing the load flow. This method is similar to that of the one described in this thesis, however [49] only investigates the reached voltage levels in the past and no other characteristics are investigated.

The next paper [34] introduces both centralized and distributed voltage control strategies for a LV grid-connected microgrid with a high penetration of PV systems. The primary goal of these strategies is to optimize power flow by minimizing line losses and PV curtailments. To achieve this, the strategies are formulated as OPF problems. Specifically, SOCP relaxation is employed to make the OPF problem convex. For the distributed voltage control strategy, the Alternating Direction Method of Multipliers (ADMM) is implemented. By conducting a sensitivity analysis on the weighting parameters, different operating regions can be identified. These regions prioritize either loss reduction or curtailment minimization. Interestingly, the paper also identifies an infeasible region in cases where the considered SOCP relaxation is not valid. This shows the importance of fine-tuning the controller parameters to ensure effective performance.

The next study [43] delves into addressing the challenge of optimal voltage control in ADNs where line parameters are uncertain but bounded. Importantly, there are made no assumptions about the distribution of parameter uncertainties. There is assumed a monitoring infrastructure is present and its focused on controlling the active and reactive power injections from multiple distributed generators connected to network buses. This coordination also involves the transformers' OLTCs. To tackle the voltage issues, a optimal control is formulated as a mixed-integer linear problem using sensitivity coefficients. Additionally, a robust optimization framework is employed to handle the uncertainties arising from the network admittance matrix. By considering these uncertainties, the aim is to enhance the reliability and efficiency of voltage control in ADNs.

In [5], first, a coordinated control strategy is presented as a straightforward and robust algorithm. It leverages the sensitivity of the voltage profile to nodal reactive power injections. By doing so, it significantly reduces the need for extensive telecommunication, supervision, and control infrastructure. As a result, the strategy is well-suited for implementation in modern large distribution networks. On the other hand, a centralized control strategy is given which is a deterministic optimization algorithm. It takes into account the unique characteristics of the distribution network. Notably, it addresses common challenges encountered in such algorithms, including discrete OLTC settings and capability curve modeling. However, this approach requires an advanced telecommunication, supervision, and control system for the distribution network. This system enables real-time grid state calculation and comprehensive control.

In the next research paper [24], a centralized-decentralized voltage control scheme is proposed to coordinate the OLTC, substation CBs, feeder CBs, and PV plants with the aim of limiting the voltage of all nodes to a certain range and improving the power factor of the OLTC. Centralized voltage control is executed by considering the most severe voltage fluctuation cases in ADNs. A Multi-Objective Mixed Integer Nonlinear Programming (MINP) model is formulated with decision variables that change over time. The solution to the MINP model is found using the Non-Dominated Sorting Genetic Algorithm II (NSGA-II). Additionally, a pragmatic algorithm for decision-making is introduced to identify the optimal choice from the set of Pareto efficient solutions. Furthermore, decentralized voltage control is directed towards reducing instantaneous voltage changes at the nodes by modulating the instantaneous active and reactive power output of each PV plant.

2.7.8. Overview of Voltage Control Methods in Distribution Networks

The effective management of voltage levels within power distribution networks is crucial for ensuring the stability, reliability, and efficiency of the electrical power system. To address these challenges, various voltage control methods have been discussed, each with its own advantages and disadvantages depending on the specific network characteristics and operational objectives. Table 2.3 provides a comprehensive overview of different voltage control methods, ranging from decentralized approaches that rely on local measurements and control strategies to centralized methods that coordinate control actions across the entire network. The methods are further categorized based on their underlying principles, such as reactive power control, rule-based algorithms, and optimization-based algorithms. By understanding the key characteristics, advantages, and limitations of each method, engineers and operators can make informed decisions regarding the most suitable voltage control strategies for their specific power distribution networks.

The thesis focuses on optimizing voltage control in power distribution networks, particularly those with a high penetration of DERs. The method of choice to achieve this goal is a centralized, optimization-based algorithm for several reasons:

- Adaptability and Efficiency: Optimization-based algorithms can adapt to the dynamic and complex nature of modern distribution networks with high DER penetration. They can consider various factors like network topology, load profiles, and generation capacities to make real-time adjustments, ensuring optimal voltage regulation and overall network performance.
- Coordination and Control: Centralized algorithms provide coordinated control across the entire network, enabling efficient management of voltage-regulating devices and DERs. This coordinated approach is crucial for a simplified implementation and handling the variability and intermittency of DERs and preventing voltage fluctuations or violations.
- Focus on Optimality: The thesis likely aims to achieve the best possible voltage control solution considering various objectives like minimizing voltage deviations and maximizing DER utilization. Optimization-based algorithms are well-suited for this purpose as they can systematically explore the solution space and identify the optimal control actions.

2.7.9. Voltage Control Methods Evaluation

Evaluating a newly developed voltage control method is crucial to ensuring their effectiveness and reliability before they are implemented in real-world power distribution systems. Various test methods have been employed to assess the performance and robustness of the methods described in the previous sections. Through rigorous testing, researchers can gain insights into the behavior of these methods under various operating conditions, paving the way for their practical implementation and deployment in modern power distribution networks. An overview of various studies employing simulated test distribution systems to evaluate the performance of the suggested voltage control methods is shown in Table 2.2.

Table 2.2: Various test distribution systems cited in the literature to assess the effectiveness of proposed voltage control methods, illustrating the range of different benchmarks.

Reference	**Test System**
Hatipoglu et al. (2021) [30]	21-bus test distribution system
Bidgoli et al. (2018) [31]	75-bus test distribution system with 22 DERs
Degefa et al. (2015) [40]	147-bus test distribution system
Sun et al. (2023) [35]	33-bus and 123-bus test distribution system
Sanni et al. (2021) [42]	123-bus test distribution system
Ahmed et al. (2019) [15]	8500-node Real-life Feeder
Prins et al. (2021) [4]	IEEE European LV Feeder
Christakou et al. (2018) [43]	IEEE 13-node and 34-node Test Feeder
Murray et al. (2021) [38]	IEEE 33-node Test Feeder
Putratama et al. (2021) [34]	Microgrid
Papazacharopoulos et al. (2014) [18]	Cigré MV Distribution Network Benchmark
Rudion et al. (2006) [50]	Cigré MV Distribution Network Benchmark
Svenda et al. (2022) [13]	Real-life ADN
Procopiou et al. (2017) [37]	Real-life (British) ADN
Zollner et al. (2023) [17]	Real-life (Dutch) ADN

Table 2.3: Comparison of voltage control methods in distribution networks. This table categorizes different methods for voltage regulation in power distribution networks into four main categories: Decentralized/Distributed, Reactive Power Control, and two types of Centralized/Coordinated methods. Each method is described in terms of its key characteristics, advantages, disadvantages, and typical applications.

Method Category	**Specific Method**	**Key Characteristics**	**Advantages**	**Disadvantages**	**Applications**
Decentralized / Distributed	Local measurement-based control	Utilizes local information. Decisions based on measurements.	Reduced communication needs, scalability.	May lack coordination across the network.	Scenarios with limited communication or impractical centralized control.
Reactive Power Control	Reactive power curtailment, injection, or absorption.	Manages reactive power output to influence voltage levels.	Effective for voltage regulation and power factor correction.	May require additional reactive power compensation devices.	Maintaining voltage stability, grid protection, and reducing harmonics.
Centralized / Coordinated	Rule-based algorithms	Predefined rules or threshold trigger control actions.	Simple, easy to implement.	Limited adaptability to dynamic conditions.	Systems with limited communication or computational capabilities.
Centralized / Coordinated	Optimization-based algorithms	Mathematical optimization techniques for efficient voltage regulation.	Adaptable, optimizes system performance.	Could require robust communication and computational resources.	Modern distribution networks with advanced communication and control infrastructure.

3

Methodology

The following chapter outlines the methodological approach used in this research to address the challenges of adaptive voltage control in modern distribution networks. The growing complexity of these networks, due to the integration of distributed energy resources and varying load demands, requires innovative control strategies to maintain voltage stability and optimize system performance. The primary research question is: How can a simple, universally applicable adaptive voltage control policy be developed for HV/MV transformers in power distribution networks? This policy must effectively prevent voltage limit violations experienced by end-users. The following sections will detail the methodological approach taken to answer this question.

To tackle this problem, a novel adaptive voltage control policy has been developed. This methodology chapter aims to explain in detail the systematic process through which this policy was formulated, implemented, and evaluated. First of all, the method by which the voltage in the distribution grid is controlled, is explained. Followed by a more in depth look on the components and working of the voltage control curve. Next, the working are defining this components via optimization is presented. Before the implementation of the optimization framework is shown, an explanation is given on how the performance of the VCM is evaluated and made ready for the future. By following this structured methodology, this research attempts to provide a comprehensive guide on how to answer to the research questions.

3.1. Voltage Control Method

As stated in the main research question, the location where the voltage control method will be implemented is the HV/MV transformer within the power distribution network. Voltage regulation of the HV/MV transformer is achieved by implementing an OLTC that operates under the control of a relay-based system, as discussed in Chapter 2. As described in Section 2.7 in more detail, the default control method is the use of a AVC, however another method by which a relay manages the output voltage involves monitoring the current or active power passing through the transformer and, using predetermined parameters, activating tap changes to adjust the voltage as necessary. What type of relay is considered and how these parameters are determined, will be discussed in this section.

3.1.1. Relay

Given that the research question emphasizes the proposed voltage control method should be simple and easy to implement, the relay described in this section is considered. On top of that, as the adaptive voltage control policy is being designed for, and evaluated on, the distribution networks managed by Stedin, any limitations and existing hardware in the grid will be reflected in the voltage control policy as well. Stedin has chosen to implement the A. Eberle's REG-D Relay in their network transformers for the control of the OLTC due to its advanced capabilities and proven effectiveness in optimizing grid performance and asset management. However, the developed policy is applicable to all power distribution networks including transformers with a comparable voltage control method.

The REG-D Relay for Voltage Control & Transformer Monitoring, a solution from A. Eberle GmbH & Co. KG, is engineered to optimize the performance and longevity of electrical power systems. This device offers a comprehensive suite of features for voltage regulation and transformer health assessment. The key features and advantages of the relay are [51]:

- Precision Voltage Control: The REG-D utilizes advanced algorithms and real-time data analysis to continuously monitor voltage fluctuations, enabling precise tap changer adjustments to maintain voltage stability within predefined limits.
- Comprehensive Transformer Monitoring: Integrated with a powerful Transformer Monitoring Module (TMM), the REG-D collects and analyzes critical data points such as temperature, oil levels, and winding currents.
- Seamless Integration: Equipped with versatile communication interfaces, the REG-D integrates with SCADA systems and other automation platforms. This enables remote monitoring, control, and data exchange, enhancing operational efficiency.

3.1.2. Voltage Control Curve

One of the methods by which the REG-D Relay changes the voltage output of the HV/MV transformer is according to the so-called *current influence*. This method works with current-dependent setpoint which influences dynamic adjustment of setpoint by the load current of the transformer. For instance, this allows for compensating voltage drops on the supply line to consumers. Additionally, reducing the voltage setpoint at the transformer can counteract voltage rises induced by DG plants [51]. As described in Section 1.4, the motivation for this research is the increase and decrease in voltage levels in the LV grid beyond the limits set by the grid code, this is the reason why the *current influence* control method is chosen.

In more detail, the current-dependent setpoint influence program is chosen as this program uses the effective current to determine setpoint change. If a positive active current flows ($P > 0$, consumption), the setpoint is increased. If a negative active current flows ($P < 0$, generation), the setpoint is decreased. The magnitude by which the setpoint is increased and decreased is defined by a characteristic curve with a gradient and limitations. Figure 3.1 shows the basic course of the setpoint characteristic curve as the function of the transformer current, as provided in the manual of the REG-D Relay. For this curve a 20 kV grid with a 2500 A/1 A current transformer is considered. The base voltage setpoint of 20.0 kV, established under no-load conditions, is dynamically adjusted based on predefined slope and limit parameters. This adjustment responds to real-time measurements of current and power flow direction captured by the regulator. The tolerance band, while maintaining a consistent width, shifts in tandem with the adjusted setpoint.

The curve is a graphical representation of the relationship between voltage setpoint and active power. It shows how the transformer's voltage setpoint changes as the active power increases or decreases. As explained in Chapter 1, the active power increases as there is significant amount of DG and decreases when there is increased load in the distribution grid, for example. Understanding this curve is crucial for maintaining a stable and reliable voltage with the help of the characteristic curve. The curve has a number of important components:

- Axes: The curve is typically plotted on a graph with the voltage (setpoint) on the y-axis and current/power on the x-axis
- Slope: The slope of the curve indicates the sensitivity of the voltage setpoint to changes in current/power.
- Operating Point: The operating point of the system is where the curve intersects the desired voltage level. This point represents the ideal balance between voltage and, for example, active power for the optimal voltage levels throughout the distribution grid.

Given the impracticality of conducting real-world experiments on the high voltage power system, simulations within the PowerFactory software environment will be employed to validate the proposed control strategy. PowerFactory is a software application used for analyzing power systems, more details

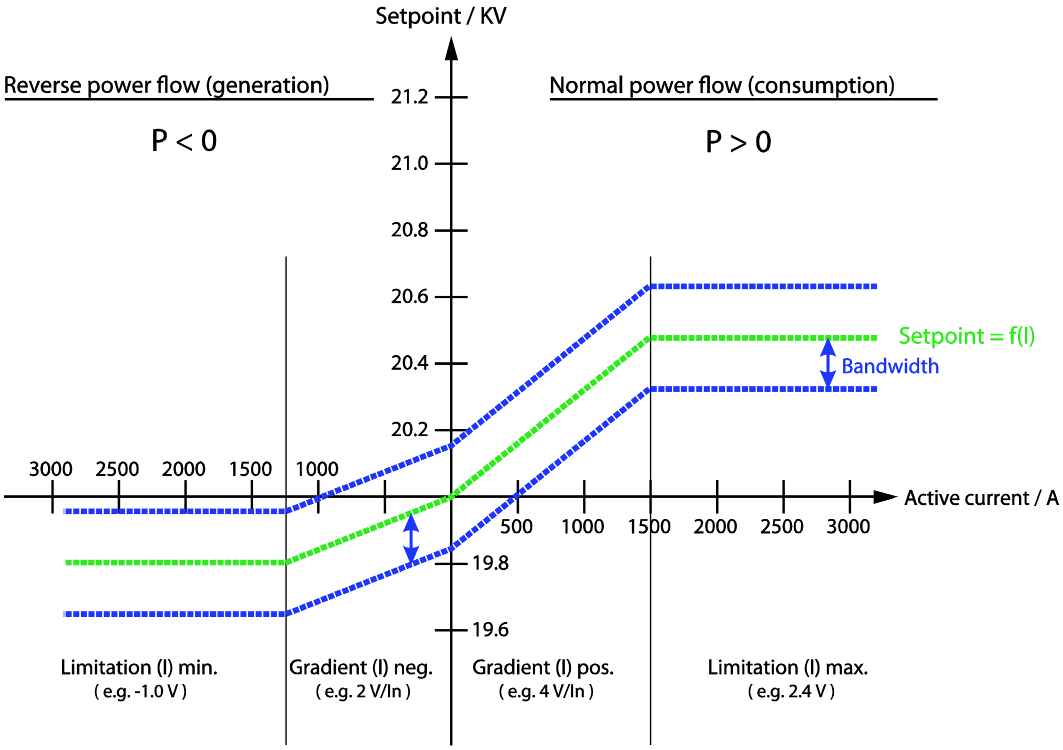
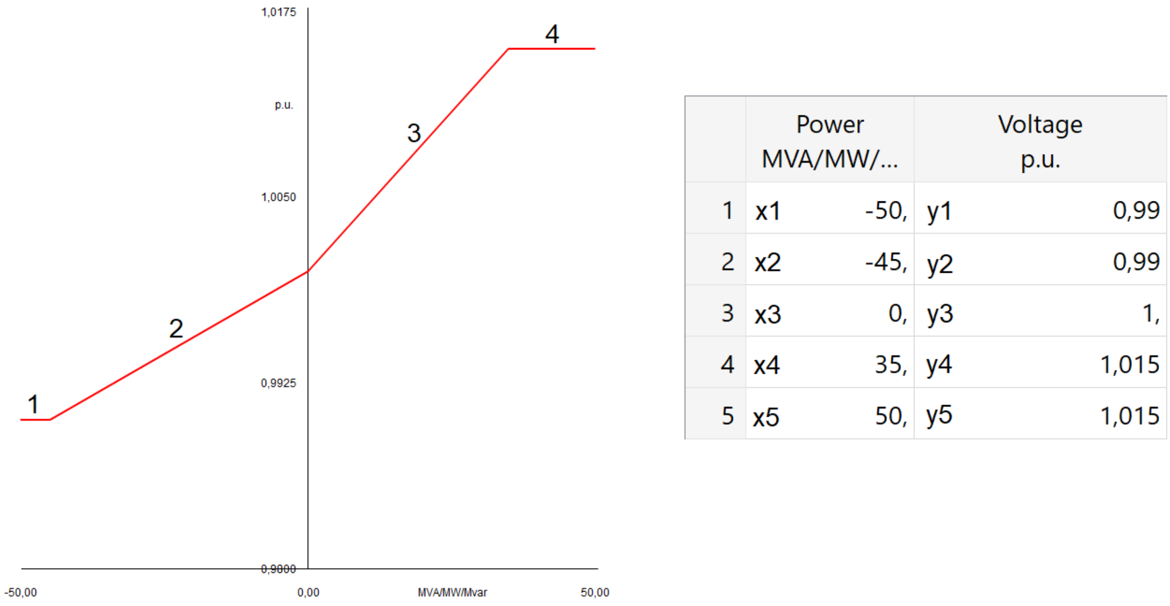


Figure 3.1: Characteristic curve for active-current dependent setpoint influence program of A. Eberle REG-D Relay. The figure shows how the curve consists of four line segments, two in the reverse power flow region and two in the normal power flow region. From [51]



	Power MVA/MW/...		Voltage p.u.	
1	x1	-50,	y1	0,99
2	x2	-45,	y2	0,99
3	x3	0,	y3	1,
4	x4	35,	y4	1,015
5	x5	50,	y5	1,015

Figure 3.2: Example of voltage control curve its data table within the PowerFactory environment. Shown is how the curve from the REG-D Relay is created in PowerFactory using five coordinates.

are provided in Section 4.2. To be able to implement the characteristic curve in PowerFactory, the aforementioned parameters derived from theoretical analysis and equipment specifications will undergo conversion into the appropriate formats compatible with PowerFactory's modeling framework. This conversion process ensures accurate representation of the system's behavior under various operating conditions within the simulation environment. In the PowerFactory software environment, the transformer has a programmable controller that includes an automatic tap changer. The compensation setting of the tap changer can be set to current compounding, and active power can be chosen as the type of compounding. Next, the curve can be set. Within PowerFactory the characteristic curve is called the *Voltage Control Curve* (VCC). From this point forward, the term voltage control curve will be used. An example of the VCC within the PowerFactory software can be seen in Figure 3.2.

When comparing Figure 3.1 and 3.2, it can be observed that the axes differ: the voltage setpoint is now given in voltage per unit compared to kilovolts, and the active current (A) is replaced by active power (MW). Furthermore, although Figure 3.2 does not display any visible bandwidth, the PowerFactory software does include a *tolerance* setting. Universal applicability is the reason the voltage setpoint is given in per unit and the x-axis is modified for several reasons that will be detailed subsequently. In the analysis of HV/MV transformer operations, the investigation of active power, rather than current, is preferred due to several inherent advantages. Active power, measured in Watts, provides a direct indication of the energy transfer between the HV and MV sides of the transformer. This is of noticeable importance for system operators, as it directly correlates with energy consumption and overall system stability.

Traditionally, power flows from the HV (source) to the MV (load) side. However, with increasing DERs the direction can reverse when generation exceeds local demand. This principle of reverse power flow has been extensively elaborated on in Section 2.6. Regardless of the direction, active power remains the most relevant metric. Its magnitude indicates the amount of energy being transferred, while its sign (positive or negative) signifies the direction of flow. A positive sign indicates conventional flow (HV to MV), while a negative sign denotes reverse power flow (MV to HV). Although current can oscillate and change direction due to phase relationships, active power maintains consistent directionality, either from HV to MV or vice versa. This eliminates ambiguity in the interpretation of the power flow, simplifies calculations, and avoids dealing with multiple negative signs arising from phase shifts.

3.1.3. Components of the Voltage Control Curve

One can observe that the voltage control curve in Figure 3.2 consists of four line segments, the same is true for the curve in Figure 3.1. That is, line segment 1: (x1, y1) - (x2, y2), 2: (x2, y2) - (x3, y3), 3: (x3, y3) - (x4, y4), and 4: (x4, y4) - (x5, y5). These line segments differ from each other as they have different slopes and lengths. The second and third line segment are the two important sections of the voltage control curve, as the relay follows these lines when determining the new voltage setpoints according to the measured active power. The first and fourth line segment are just there to indicate the upper and lower limits of the voltage setpoint. The functions of line segment 2 and 3 are explained next.

As detailed in Section 2.6, negative active power in the transformer signifies that DG sources, such as PV panels and wind turbines, are producing more power than the load demands of the system. This excess power reverses the flow, moving from the MV grid back to the HV/MV transformer, increasing voltage levels that require compensation. Conversely, when load exceeds DG output, voltage drops and also necessitates compensation. Therefore, line segment 2 represents periods of DG surplus, while line segment 3 represents periods of load surplus within the distribution grid. The power flow and thus the voltage can vary every moment of the day, however the power demand changes per month and period as well. The winter months typically experience a surge in power demand compared to the summer months due to several factors. Primarily, the increased need for heating in colder temperatures drives up electricity consumption significantly. Households and businesses rely on electric heating systems, heat pumps, or indirectly on electricity-generated heat sources, leading to higher energy usage. Additionally, shorter daylight hours in winter necessitate more extensive use of lighting, further contributing to the demand. Combined, these factors create a significant increase in power demand during the winter months compared to the relatively lower demand in summer.

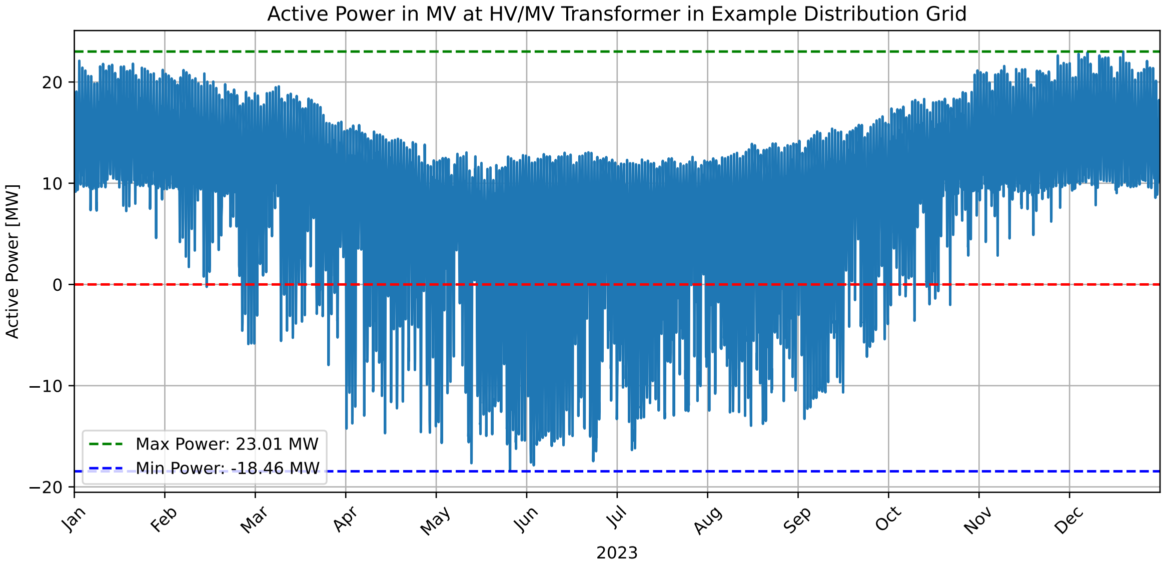


Figure 3.3: Active power in MW at the HV/MV transformer in an example distribution grid for the year 2023. There can be seen that during the winter months more power is used compared to the summer months. During the summer months, the active power can even become negative indicating a surplus of distributed generation.

On the other hand, the generated power from DG often experiences an increase in the summer months due to the increased availability of solar energy. PV systems are particularly effective during summer when there are longer daylight hours and higher solar irradiance. This abundance of sunlight allows solar PV systems to generate more electricity, contributing to the overall increase in distributed generation during this period. Additionally, in some regions, favorable wind conditions in the summer can also lead to increased electricity generation from wind turbines. Combined, these factors make the summer months a prime time for higher distributed generation compared to the winter months [17]. This increase of power demand in the winter months and increase in power generation in the summer months can be seen in Figure 3.3. Consequently, in Figure 3.4 the inverse can be observed for the voltage magnitude at a particular MV node in an example distribution grid. These figures show a negative coloration between the active power at the HV/MV and the voltage at the MV nodes in the grid. Figure 3.4 clearly shows the decrease in voltage in the winter months as the overall load increases and a less dominant presence of DG, with a minimum of $0.9595\ p.u.$ in December. From spring onward, there are more substantial peaks, reaching a maximum of $1.0394\ p.u$ in June.

Ideally, for voltage stability, the voltage at every node in the distribution grid should be $1.0\ p.u.$ throughout every season if losses are neglected. However, as illustrated in Figure 3.4, this is not observed in reality and there are significant variations in voltage levels. It can be concluded that achieving a voltage of exactly $1.0\ p.u.$ for a complete year is unattainable. Which is expected due to losses and variation in inductances and capacitance in the cables. Consequently, the aim shifts to approximating $1.0\ p.u.$ as closely as possible throughout the entire year, or at least improving upon the voltage levels depicted in Figure 3.4. Upon closer examination of Figure 3.4, it becomes evident that raising the voltage levels in January, February, March, October, November, and December while lowering them in April, May, June, July, and August would bring the voltage closer to the $1.0\ p.u.$ level. As mentioned earlier, line segments 2 and 3 handle the compensation of higher and lower voltages. Therefore, careful selection of these line segments for the specific distribution grid would enhance overall voltage stability. The outcome of implementing adaptive voltage control using an optimized voltage control curve for the previously discussed scenario is shown in Figure 3.5. A comparison of Figure 3.4 and 3.5 reveals the beneficial impact of the voltage control curve, with the voltage bandwidth decreasing from $\Delta V_{old} = 0.0799$ ($V_{oldMAX} = 1.0394\ p.u.$ & $V_{oldMIN} = 0.9595\ p.u.$) to $\Delta V_{new} = 0.0512$ ($V_{newMAX} = 1.0273\ p.u.$ & $V_{newMIN} = 0.9761\ p.u.$). One could conclude that without the VCC. the voltage variation is within ±5%,

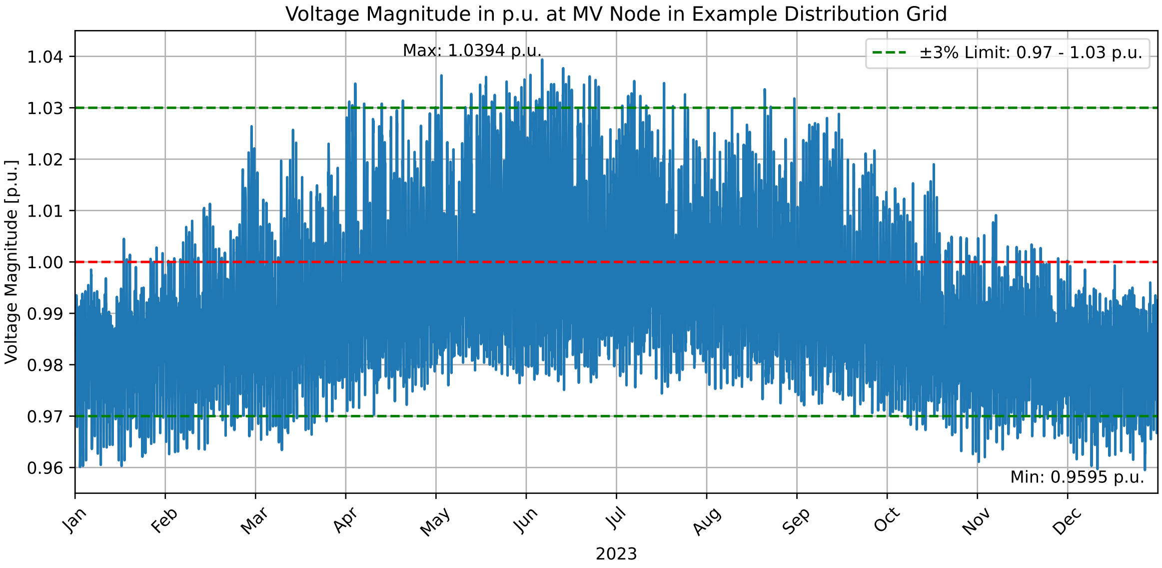


Figure 3.4: Voltage magnitude in per unit at a MV node in an example distribution grid for the year 2023. The graph looks like a mirror version (x-axis) of the active power graph.

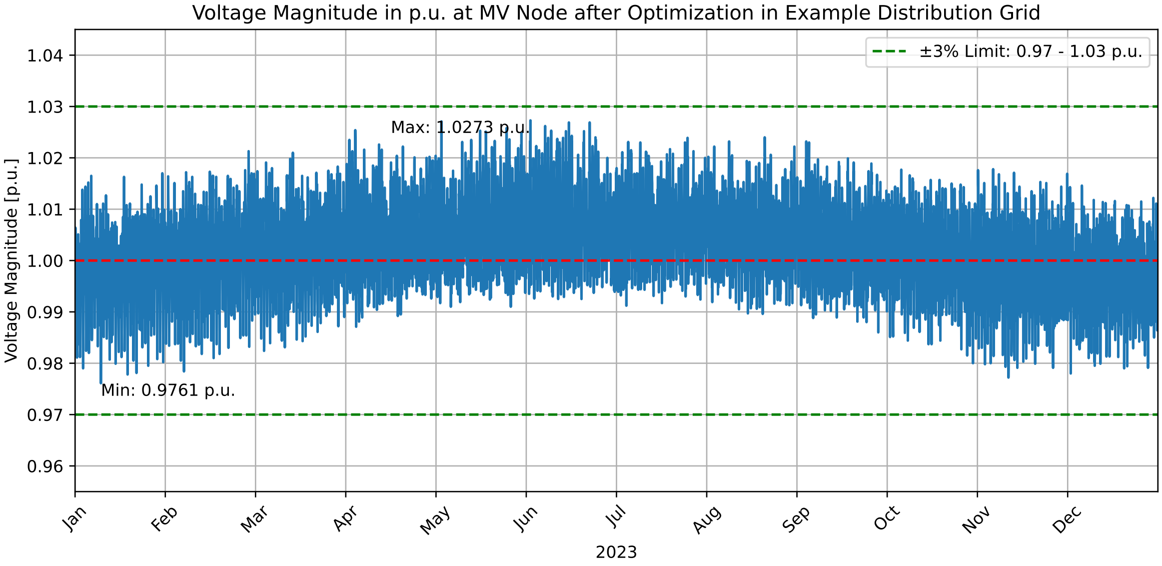


Figure 3.5: Voltage magnitude in per unit at a MV node in an example distribution grid for the year 2023 with a voltage control curve implemented. A smaller amplitude can be observed which is the consequence of an optimized voltage control curve.

however with the addition of the VCC, this variation stays between ±3%. Although the new situation is not perfect, the voltage levels are closer to the $1.0\ p.u.$ target than previously. The remaining question pertains to the method of determining the voltage control curve. Additionally, the curve's optimization applies not just to a single node, as analyzed previously, but to the entire distribution grid.

The grid code (Section 2.1) limits voltage variations at connection points to ±10%, additionally, Stedin's policy has a 5% allowance assigned to both the medium voltage and low voltage networks (Table 2.1). However, by enforcing stricter hourly voltage limits within the MV grid, reduced from ±5% to ±3%, greater flexibility for voltage fluctuations within the LV grid and between these hourly measurements is indirectly achieved. This tighter MV control acts as a buffer, enhancing LV flexibility without compromising overall grid stability. This is true as any significant event on the MV grid, such as a fault, voltage fluctuation, or load change, will have repercussions on the LV grid. This is because the transformer steps down the MV voltage to the LV level, but it also transmits any disturbances or changes along with it. Similarly, events on the LV grid can be observed on the MV side as variations of the low voltage levels are in the same direction due to common cause. Focusing solely on MV grid voltage levels, as low voltage consumers are aggregated as combined loads in the available PowerFactory models, this thesis implements stricter voltage limits of $0.97\ p.u.$ to $1.03\ p.u.$ for MV grid nodes. Therefore, the objective is now to minimize the percentage of voltage violations of these newly established lower and upper limits, all to improve voltage levels in the unobservable LV grid. The per unit voltage magnitude limits will be denoted the following way in this remainder of this thesis with V_{low} being the lower and V_{high} being the higher limit respectively:

$$V_{low} \ = \ 0.97\ p.u. \qquad V_{high} \ = \ 1.03\ p.u. \tag{3.1}$$

As previously mentioned, the voltage control curve is made up out of 10 variables, as can be seen in Figure 3.2. From Equation 3.2 can be concluded that there are only four variables that will need to be changed to create a new voltage control curve as some variables are linked or fixed. So, for a new curve, variable *x2, x4, y1 & y4* need to be determined. Next, it will be explained why all the conditions in Equation 3.2 hold. First, Equation 3.2a holds because $x1$ & $x5$ are the negative and positive active power limits of the HV/MV transformer and will be set according to the type of transformer used in the particular distribution grid. Second, Equation 3.2b and 3.2c are fixed as the curve will always cross the (0, 1) point. This point indicates the changeover from negative to active power as for $P \ = \ 0\ W$, the voltage setpoint is set to the nominal value of 1.0 per unit as this is the target voltage. Lastly, Equation 3.2d and 3.2e must hold to create the limit for the voltage setpoint (Limitation min. & max from Figure 3.1).

$$x1 = -\ x5 \tag{3.2a}$$

$$x3 = 0 \tag{3.2b}$$

$$y3 = 1 \tag{3.2c}$$

$$y1 = y2 \tag{3.2d}$$

$$y4 = y5 \tag{3.2e}$$

As discussed earlier, it is necessary to identify four variables to establish a new voltage control curve. This curve impacts every node within the distribution grid, necessitating the consideration of all nodes when specifying these variables. A Genetic Algorithm (GA) has been chosen to determine these variables and optimize them for the selected distribution grid. The subsequent section will explore the algorithm and its advantages in greater detail.

3.2. Optimization

Optimization problems typically involve defining an objective function, which quantifies the desired outcome, and identifying the decision variables that can be manipulated to achieve the optimal solution. Optimization algorithms are then employed to systematically search the solution space and find the values of the decision variables that maximize or minimize the objective function. As extensively elaborated on in Section 2.7, many different methods of optimization have been used to tackle the voltage control problem in the literature.

In the context of voltage control in distribution grids, optimization plays a crucial role in determining the optimal parameters of the adaptive voltage control method, particularly the four voltage control curve variables. As discussed earlier, the VCC parameters directly influence the VCM's responsiveness and effectiveness in maintaining voltage stability and ensuring overall grid performance. The complex and dynamic nature of modern distribution grids, with varying loads, distributed generation, and diverse topologies, makes manual tuning of VCC parameters impractical. Optimization offers a systematic and data-driven approach to tackle this challenge.

To be able to find best voltage control curve for every distribution grid, and in that way making it universally applicable, optimization is essential for several reasons:

- Complex Interactions: Distribution grids exhibit complex interactions between various components and operating conditions. Optimization can account for these interactions and find solutions that balance multiple objectives and constraints.
- Dynamic Nature: Grid conditions change constantly due to load variations, renewable energy fluctuations, and other factors. Optimization can identify VCC parameters that are suited for these dynamic changes.
- Large Solution Space: The space of possible VCC parameter combinations is vast. Optimization algorithms can efficiently explore this space and find near-optimal solutions that would be difficult to discover manually.

A variety of optimization algorithms can be employed to enhance voltage control. Various optimization algorithms were considered for this study, including Particle Swarm Optimization, Differential Evolution, Simulated Annealing, Ant Colony Optimization, Grey Wolf Optimizer, and Artificial Bee Colony. These algorithms, along with Genetic Algorithms, fall under the category of meta-heuristics, which are particularly useful for solving complex, non-linear, and multi-dimensional problems.

Nevertheless, the genetic algorithm was selected. The choice of a GA for determining the VCC parameters is based on the nature of the problem and the advantages that GAs offer over classical optimization methods and machine learning approaches. Classical optimization techniques, such as gradient-based methods or linear programming, often provide guaranteed convergence and can assess whether a solution is optimal. However, these methods typically rely on assumptions like convexity and differentiability, which are not easily met in the highly non-linear and dynamic environment of voltage control in modern distribution grids. The problem's complexity, combined with the presence of discrete variables and non-linear interactions, limits the effectiveness of classical optimization in this context.

GAs, in contrast, offer global search capabilities and are less prone to becoming trapped in local optima. They are well-suited to handling non-linearities and discontinuities without requiring gradient information. This makes GAs a practical choice for problems where the objective functions are complex and non-differentiable. Moreover, GAs can accommodate the mixed continuous and discrete nature of the voltage control problem, which would be challenging for classical methods.

Machine learning approaches, while useful for predictive tasks, require extensive training data and may not perform as effectively in optimization problems such as the one presented in this thesis, where control parameters must be tuned dynamically. Furthermore, machine learning models may struggle to generalize to unseen conditions, which could limit their applicability in the continuously evolving power distribution environment.

Therefore, GAs are selected for their robustness in handling uncertainties, their adaptability to changing conditions, and their ability to explore large solution spaces efficiently without requiring strict assumptions about the structure of the problem. Although, they do not guarantee optimality in the same way classical methods do, their flexibility and ability to search globally make them a more suitable choice for this particular optimization problem.

3.2.1. Genetic Algorithms

Genetic algorithms are a class of computational optimization algorithms inspired by the principles of natural evolution. In the context of engineering problems, GAs operate on a population of potential solutions, represented as chromosomes, which are iteratively refined over multiple generations. Each chromosome encodes a set of parameters that define a candidate solution to the problem at hand. The quality or performance of each solution is evaluated using a fitness function, which quantifies how well the solution satisfies the desired objectives [52].

The evolutionary process in GAs is driven by four fundamental operators:

1. Selection: This operator mimics the *survival of the fittest* principle, where individuals with higher fitness scores (i.e., better solutions) have a higher probability of being selected for reproduction.
2. Crossover: Selected individuals (parents) exchange genetic material through crossover, creating new offspring. This allows the algorithm to explore new combinations of parameters and potentially discover better solutions. Common crossover operators include single-point, multi-point, and uniform crossover.
3. Mutation: Random changes in the genetic makeup of offspring, known as mutations, introduce diversity into the population. This helps to prevent the algorithm from prematurely converging to suboptimal solutions and encourages exploration of the entire solution space. Common mutation operators include bit-flip mutation, Gaussian mutation, and swap mutation.
4. Elitism: This operator preserves the best individuals from the current generation and directly passes them to the next generation, ensuring that the best solutions found so far are not lost due to stochastic processes.

By iteratively applying these operators, GAs progressively improve the fitness of the population, ultimately converging towards optimal or near-optimal solutions.

Compared to other optimization algorithms, GAs offer several distinct advantages for tackling adaptive voltage control problems in distribution networks [53]:

- Global Search Capability: Unlike local search algorithms (e.g., gradient descent) that can get trapped in local optima, GAs are inherently global search algorithms. They explore the entire solution space through mechanisms like crossover and mutation, increasing the likelihood of finding the true global optimum for voltage control settings.
- No Gradient Information Required: Many optimization algorithms, such as gradient descent and Newton's method, require the gradient (derivative) of the objective function. However, in voltage control problems, the objective function may be complex and non-differentiable. GAs are gradient-free algorithms, meaning they do not require gradient information and can handle such complex objective functions.
- Ability to Handle Discrete Variables: Many voltage control settings, such as tap positions of voltage regulators, are discrete variables. GAs can naturally handle discrete variables without requiring any special modifications or approximations, unlike some continuous optimization algorithms.
- Implicit Parallelism: The evaluation of individuals in a GA population can be easily parallelized, which can significantly speed up the optimization process, especially for large-scale distribution networks. This parallelism is inherent to the GA's structure and does not require complex parallelization strategies.

- Ease of Implementation: While GAs have a conceptual foundation in evolutionary biology, they are relatively easy to implement compared to some other complex optimization algorithms. Many software libraries and frameworks are available for implementing GAs, further simplifying the development process.

3.2.2. Determination of Voltage Control Curve Parameters

To acquire a new unique VCC, it is evident that four parameters must be identified. The GA is responsible for finding the optimal set of these parameters to determine the best VCC for each distribution grid. Next is a more detailed explanation of how the genetic algorithm generates new VCC parameters based on the performance of previously known parameters.

In the GA, each VCC solution is represented as a chromosome. Since there are have four variables, the chromosome will have four genes, each representing one of the VCC variables. The decimal precision is maintained throughout the process.

First of all, a randomly generated example chromosome is given to showcase the structure. It should be noted that each of the four genes is randomly generated within a defined variable range to avoid generating unrealistic chromosomes, these variable ranges are discussed in more detail in Section 4.2.

```
Structure: [x2, x4, y1, y4]
Example: [-25.831097, 18.429563, 0.954321, 1.051872]
```

The recombination process, crossover, is combining genetic information from two parent chromosomes to create offspring. There are several crossover methods, however in this research, the method of single-point crossover is used: a random point is chosen within the chromosome, and the genes after that point are swapped between the two parents. Next, an example will be given applied on two new randomly generated *parents*.

```
Parent 1: -38.271945, 41.652890, 0.936174, 1.029568
Parent 2: -12.987621, 6.530982, 0.972468, 1.081234
```

For this example, the crossover point is after the second gene.

```
Offspring 1: -38.271945, 41.652890, 0.972468, 1.081234
Offspring 2: -12.987621, 6.530982, 0.936174, 1.029568
```

Mutation next introduces random changes into the offspring chromosomes to maintain genetic diversity. Small random values are added, however there is ensured that the values stay in the specified range. For example, below can be seen that for *y4*, the numbers *08* are changed to *06* because the limit is set to *1.15* for *y4*; thus, the zero cannot be altered to a one when the eight is modified to a six. For this research, Gaussian mutation is used: a small random value, drawn from a normal (Gaussian) distribution, is added to the gene. The magnitude of the change is controlled by the standard deviation of the distribution.

```
Offspring 1: -38.271945, 41.652890, 0.972468, 1.081234
Offspring 1 (mutated): -38.258945, 41.652815, 0.972608, 1.061234
```

3.2.3. Performance Evaluation

As explained, the genetic algorithm uses the *survival of the fittest* principle to find the best performing VCCs. The fitness of each VCC candidate is assessed based on its performance in the simulation. To find the optimal voltage control curve for a given distribution grid, it is essential to have a way to evaluate the performance of each candidate curve. This evaluation is crucial for the GA to determine the fitness of each curve and guide the optimization process towards the best solution. In complex systems, where the performance of a solution depends on its interaction with dynamic environments, direct fitness assessment can be challenging. This thesis proposes the utilization of Quasi-Dynamic (QD) simulations as a means to bridge this gap.

Quasi-dynamic simulation is a method used to model the behavior of systems over time, combining aspects of static and dynamic simulations. It is particularly useful for systems with relatively slow-changing dynamics compared to the time scales of interest, allowing for a simplified and computationally efficient approach. This makes it particularly well-suited for evaluating the fitness of solutions generated by GAs, where a large number of individuals (VCCs in this context) need to be assessed.

The QD simulation method consists of a few key steps:

1. Discretization of Time: The simulation period is divided into discrete time steps. The size of these steps is chosen based on the system's dynamics and the desired level of accuracy.
2. Static Calculation at Each Time Step: At each time step, the system is assumed to be in a steady state or quasi-equilibrium. A static calculation, such as a load flow analysis in a power system, is performed to determine the system's variables at that specific moment.
3. Updating System Parameters: Between time steps, certain system parameters (e.g., loads, generation, network topology) may change based on predetermined profiles or control actions. These changes are incorporated into the next time step's static calculation.
4. Iterative Process: This process is repeated for each time step, effectively creating a series of snapshots of the system's state over time.

The precise manner in which the QD simulation is integrated into the overall procedure for determining the optimal VCC is illustrated in Figure 4.1.

The integration of QD simulation into the GA framework allows for the generation of realistic scenarios that mimic the system's behavior under varying conditions. Each VCC generated by the GA is subjected to these simulated scenarios. The performance data from each scenario is then used to calculate the fitness of each individual, guiding the GA towards solutions that exhibit superior performance in the simulated environment.

When considering the fitness assessment of GA-generated solutions (VCCs in this case) using QD simulations, Key Performance Indicators (KPIs) serve as the specific metrics against which the performance of each individual is measured. KPIs represent the quantifiable factors that determine the success or effectiveness of a solution within the simulated environment. In this study, a VCC is examined on a power distribution network using QD simulation. During each QD simulation run, the voltage levels at all MV nodes are continuously monitored and recorded at each time step. MV nodes include both MV customers (general loads) and MV/LV transformers (MV loads). The simulation data includes the magnitude and duration of any voltage deviations exceeding the predefined limits (both over-voltage and under-voltage) with time steps of one hour. After the QD simulation run, the total amount of hourly measurement data points in which voltage violations occurred is summed up. In this case, the updated voltage limits from Equation 3.1 are used. The found value is then converted to a percentage of the total number of measurements and is seen as the main performance indicator. The definition of this main KPI is given next.

1. Voltage Limit Violations Percentage: The percentage of hourly measurements of the voltage levels of all MV nodes exceeding predefined limits of Equation 3.1. Each instance of a voltage level exceeding the limit at a node counts as one violation. If a node's voltage exceeds the limit for consecutive hours, each hour is counted as a separate violation. Similarly, if multiple nodes go beyond the limit during the same hour, each node's violation is counted individually.

An illustrative calculation is provided to clarify this KPI: an example distribution network consists of 215 MV nodes. Over the course of a year, there are 8,760 hours, resulting in a total of 1,883,400 data points (calculated as 215 nodes × 8,760 hours). To determine the percentage of voltage limit violations, there is started with counting the occurrences where node voltage levels surpass the specified ±3% threshold. After identifying the number of such violations, the percentage is calculated by dividing the total number of these violations by the total number of data points (1,883,400) and then multiplying the result by 100.

After each QD simulation, the performance of the VCC is calculated and evaluated based on this predefined KPI. This percentage provides a quantitative assessment of how well the solution performs in the simulated scenario. The KPI value obtained from the QD simulations are then used as the fitness value of each VCC in the GA population. Curves with higher fitness scores (better KPI performance, in this case a lower percentage of voltage violations) are favored for selection, crossover, and mutation, thus guiding the GA towards solutions that excel in maintaining voltage levels within acceptable limits.

The cost function used in the optimization process is the main KPI, as defined above. This KPI quantifies how well a VCC maintains voltage levels within predefined limits across the MV nodes. The GA aims to minimize this percentage by finding the optimal VCC parameters. The optimization process is focused solely on this main KPI. Additional KPIs, as elaborated on next, are not part of the optimization but are measured to compare voltage control curves that achieve similar performance on the main KPI. These additional KPIs help to analyze the impact of the VCC more comprehensively, ensuring that the best VCC not only minimizes voltage limit violations but also performs well across various other operational metrics.

In the context of optimizing power distribution networks using GAs, the evaluation of VCCs is crucial. QD simulations offer a computationally efficient method to assess VCC performance by subjecting them to realistic scenarios. The main KPI used is the proportion of time during which voltage levels exceed specified thresholds. However, relying solely on this KPI may result in multiple VCCs exhibiting identical performance in terms of voltage profile improvement. Operators are also interested in other factors that influence overall grid performance. For example, VCCs may achieve zero voltage violations but differ significantly in their effects on voltage stability or the duration and frequency of voltage limit breaches. Therefore, additional KPIs are required to comprehensively evaluate VCC performance.

To address this, multiple additional KPIs are proposed below. These KPIs provide a more nuanced evaluation of VCC performance. Taking into account these diverse KPIs ensures that the optimization process not only focuses on voltage violations but also considers a wider range of performance factors. The entire set of KPIs consists of:

2. Maximum and Average Voltage Deviations: The largest peak-to-peak amplitude ($\Delta_{MAX}V$) and average peak-to-peak amplitude ($\Delta_{AVG}V$) of voltage levels from all MV nodes.
3. Extreme Voltage Values: The highest and lowest voltage values observed across all MV nodes throughout the simulation.
4. Count of Nodes with Excessive Deviations: The total number of MV nodes where peak-to-peak amplitude of the voltage exceed predefined limits at any point during the simulation.
5. Nodes Experiencing Violations: The total number of unique MV nodes that experience at least one voltage violation during the simulation.
6. Longest Violation Interval Duration: The duration of the longest continuous period during which voltage levels at any MV node remain outside the predefined limits.
7. Total Violation Count: The total number of instances where voltage levels at any MV node cross the predefined limits (both exceeding and falling below).

3.2.4. Performance Evaluation with Future Data

After optimizing the VCC using QD simulations on 2023 data, its performance in future scenarios is tested. To ensure this VCC is effective in future scenarios, the PowerFactory models of the distribution grids are updated to predicted future scenarios. Two scenarios are considered: one for 2028 (5 years in advance) and one for 2033 (10 years in advance). These scenarios are based on prognosis data from Stedin and are developed by updating the 2023 distribution grid models to reflect anticipated grid conditions.

The future scenarios incorporate expected changes in load profiles, new loads, and increased renewable energy generation, all forecasted based on historical trends and other relevant data. By updating the current simulation model with these forecasted conditions, the VCC's performance can be tested under these anticipated future conditions. This approach verifies the VCC's effectiveness and adaptability in real-world distribution grids for both the medium-term (2028) and long-term (2033) scenarios.

The future data used in the VCC performance evaluation was obtained through a process that involved:

1. Prognoses Data: A method to incorporate prognoses data into the PowerFactory models is used. This data included predictions about future load patterns and renewable energy generation of MV nodes.
2. Model Updates: The PowerFactory models were updated with new load profiles corresponding to the chosen year in the future. This involved replacing existing load profiles with the predicted future-load profiles.
3. Addition of Future Elements: The script also added various elements to the grid to simulate future conditions:
    - EV Chargers: Both Level 2 (LV grid) and DC fast chargers (MV grid) were added to represent the increasing penetration of electric vehicles.
    - PV Generation: PV systems were added to the MV grid to simulate the growth of renewable energy sources.
4. Quasi-Dynamic Simulation: After the grid models were updated, a quasi-dynamic simulation was run using the previously optimized VCC. This simulation allowed for a comparison between the VCC's performance in the current state and the predicted future scenario.

Moreover, simulating future grid conditions helps determine how often the VCC needs adjustment. If forecasted conditions differ significantly from past data, more frequent VCC resets may be necessary to maintain optimal voltage control. On the other hand, if the VCC demonstrates strong performance under anticipated future conditions, it might suggest that the VCC needs to be adjusted less frequently. This additional research allows for the development of a dynamic and adaptive voltage control strategy that is ready for the ever-changing needs of the distribution grid, ensuring optimal performance both now and in the future.

4

Simulation Results

4.1. Case Studies

The adaptive voltage control method presented in this thesis, will be tested on 30, carefully-selected, existing distribution grids, which have been modeled in PowerFactory. These grids are managed by Stedin and are evenly sourced from the three regions of the Stedin service area. These distribution grids will be given general names (e.g., ”Distribution Grid 1” and ”Distribution Grid 30”). The case studies were conducted on a variety of distribution networks to ensure the adaptability and effectiveness of the proposed voltage control policy under diverse real-world conditions. These networks encompass a range of characteristics, including rural and urban settings, each presenting unique challenges and requirements for voltage regulation. By selecting such a diverse set of networks, the research aims to demonstrate the versatility and robustness of the proposed policy in addressing voltage fluctuations across different types of distribution grids.

The characteristics of the 30 selected distribution grids, derived from analysis of their models and topology, are presented in Table 4.1. The number of MV nodes varies significantly, ranging from 93 in the smallest grid to 456 in the largest. Similarly, the number of feeders, composed of underground cables with high R/X ratios, differs across grids. This high R/X ratio renders nodal voltage magnitudes insensitive to reactive power flow. The average feeder length is also noteworthy, as voltage drop over long feeders can affect voltage control. Finally, Table 4.1 details the installed peak DG capacity in both LV and MV grids. As discussed in Section 3.1, the amount of DG can influence voltage control, particularly in the summer when voltage rise is anticipated.

4.2. Simulation Setup

This thesis explores a case study through numerical simulations. To evaluate the adaptive voltage control policy on the examined grids, a combined simulation environment was developed using Python and PowerFactory. This section outlines the essential software tools, PowerFactory and Python. Subsequently, the integration of these tools, data exchange mechanisms, and the operational principles of the primary simulation script are detailed.

PowerFactory is a versatile power system simulation and analysis software used around the globe. PowerFactory has its own scripting language, DPL (DIgSILENT Programming Language), and offers numerous interfaces with other software [17]. Notably, its Application Programming Interface (API) for Python facilitates modifying grid parameters, initiating calculations, and retrieving results, crucial for implementing GA-based optimization. This research will specifically leverage PowerFactory’s quasi-dynamic simulation capabilities and Python API.

Python is a popular, high-level programming language known for its simplicity and readability. Python offers a versatile set of tools for various applications, including web development, data analysis, scientific computing, automation, and more. To construct the main simulation script and handle the running

Table 4.1: Studied distribution grids with grid characteristics (data as of 2023). This table shows that the distribution grids have diverse characteristics.

Region	**Studied Distribution Grid**	**Number of MV Nodes**	**Number of Feeders**	**Average Length of Feeder [km]**	**Average Number of Nodes per Feeder**	**Installed DG LV Grid [kWp]**	**Installed DG MV Grid [kWp]**
Middle	1	211	17	6.38	13.88	29352.8	5928.5
	2	153	30	1.75	5.27	9657.3	4732.7
	3	329	25	4.66	17.17	45394.3	15945.5
	4	110	20	4.67	10.65	26982.1	7748.1
	5	222	13	5.79	19.38	25325.3	6261.0
	6	182	17	3.42	11.07	13359.1	9131.3
	7	215	38	2.80	6.79	26758.7	43599.3
	8	456	63	2.98	8.05	58257.9	19613.3
	9	194	21	6.44	10.71	31112.4	1271.7
	10	191	13	5.61	17.08	21302.9	2322.4
North	11	93	13	5.08	8.54	8565.5	23403.7
	12	295	30	2.94	10.77	15400.6	6394.2
	13	136	21	3.60	6.81	3138.3	1826.4
	14	201	20	3.13	9.80	7900.0	273.0
	15	119	16	3.79	7.00	17975.3	1776.3
	16	109	12	7.84	9.83	17580.3	1002.0
	17	290	19	5.37	13.84	1747.9	293.8
	18	144	16	4.20	9.94	18837.4	246.4
	19	121	26	2.52	5.15	3159.3	101.0
	20	180	23	2.90	9.00	4914.7	148.5
South	21	291	22	8.61	13.5	42209.2	5086.0
	22	97	19	3.89	10.37	4350.0	38928.6
	23	184	31	3.73	6.19	18648.5	4064.6
	24	259	23	5.78	12.22	39892.0	11247.9
	25	310	25	8.56	12.44	45779.2	6289.3
	26	133	17	6.33	9.65	27217.4	21207.5
	27	233	25	5.11	8.60	23511.1	10209.6
	28	136	18	5.67	6.67	23908.4	23483.8
	29	152	21	7.14	8.67	21680.8	12934.3
	30	188	23	6.28	8.22	30286.1	2054.5

of the QD simulation in PowerFactory, Python will be the tool used.

The developed co-simulation framework relies on the interaction of two software tools. Data exchange between PowerFactory and Python is illustrated in Figure 4.1 by the bold arrow, showcasing the utilization of the DIgSILENT Python API. PowerFactory functions as both a repository for the studied grid's structure and a calculation engine for simulating the distribution grid. Conversely, the Python script manages the simulation data, such as identifying hourly measurements that exceed predetermined thresholds. Regarding data exchange, Python transmits the chosen distribution grid, simulation parameters, and initial voltage control curve coordinates to PowerFactory. In return, PowerFactory sends the simulation results, including voltage magnitudes at all MV nodes for each hour of the year, back to the Python script.

A crucial part of this research involves the development and implementation of the closed-loop optimization framework that will be explained next. This framework integrates QD simulations and a GA to address voltage control challenges. This loop enables dynamic adjustment of voltage control curve parameters and is straightforward to implement. The loop is part of one of the key contributions of this thesis and is essential to improve the efficiency and flexibility of voltage control in modern power distribution networks.

The flexibility of this optimization loop allows for alternative approaches to be integrated. For instance, instead of the genetic algorithm, machine learning-based optimization or rule-based algorithms can be employed, depending on the specific requirements and constraints of the network. This adaptability is crucial in making the loop universally applicable across different grid configurations and operational scenarios.

Scripting and optimization were performed using Python 3.10.14, with key libraries such as *pandas* for data manipulation, *matplotlib* for visualization, *numpy* for numerical operations, and *PowerFactory Python API* for interfacing with PowerFactory for distribution grid simulations. The simulations were conducted using PowerFactory 2022 SP1 and PowerFactory 2023 SP3A. All the functions utilized within PowerFactory leverage the digital models of the distribution grids provided by Stedin, which include all components, data, and profiles provided and pre-loaded. These models include the complete configuration of the grid, allowing for accurate simulations and analysis. Additionally, PowerFactory's ability to execute quasi-dynamic simulations on these distribution grids was used too, facilitating various scenario analyses under specific simulation settings. The function used to modify voltage control by implementing a voltage control curve through the current compounding compensation settings of the HV/MV transformer was also applied, allowing for the evaluation of the generated VCCs.

4.2.1. Implementation of the Optimization Framework

To evaluate and optimize the adaptive voltage control method, a comprehensive simulation framework is established. This framework integrates a QD simulation model of a distribution grid with a GA optimization engine. A real-world distribution grid is selected as the testbed for the VCM. This grid is modeled in PowerFactory with detailed representation of its components, including lines, transformers, loads, and DG sources. A year-long QD simulation is performed in PowerFactory to capture the dynamic behavior of the grid under varying operating conditions and addition of the VCC. The simulation time step is set to one hour, as all grid data is given in the same resolution. However, this provides sufficient detail to capture load variations and renewable energy fluctuations. The algorithm will calculate the fitness of the simulated VCC based on the percentage of all hourly voltage magnitudes of all MV nodes in the distribution grid that exceed the predefined thresholds (main KPI). The objective is to minimize the percentage, striving ultimately for a value of 0%.

In the framework used, the GA optimization algorithm is configured with the following parameters:

- Initial Population Size (*nPop*): A diverse initial population of VCC candidates is generated to ensure adequate exploration of the solution space. Found was that an initial population size of 35 provided the best VCC the fastest.
- Maximum Iterations (*MaxIT*): The GA will run for a predetermined number of iterations, balanc-

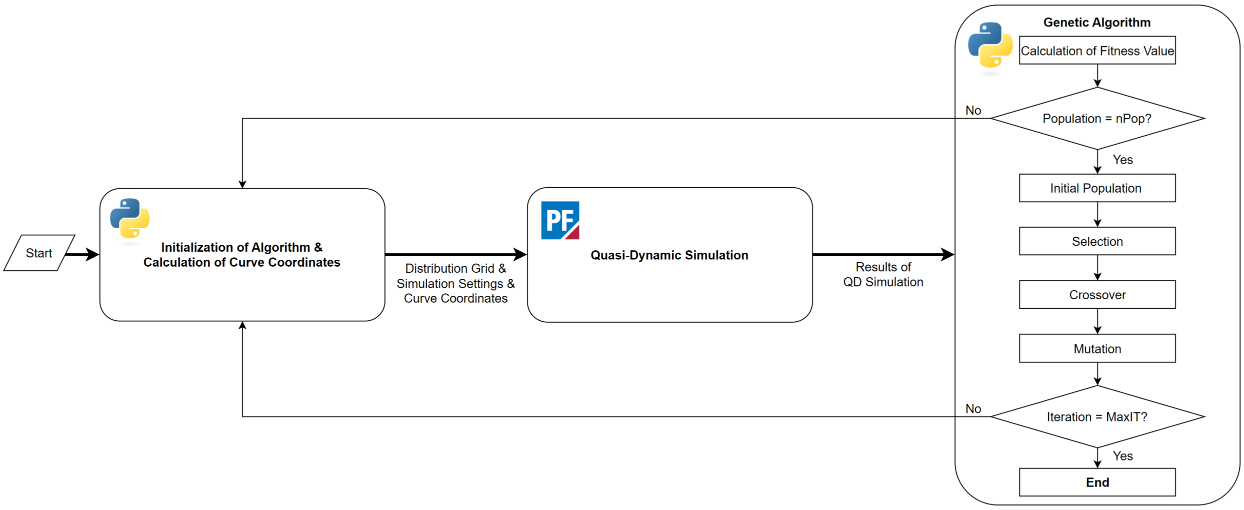


Figure 4.1: Flowchart of the genetic algorithm-based optimization process. The process starts in the Python environment with the initialization and the calculation of the initial curve coordinates. After that, a quasi-dynamic simulation in ran in the PowerFactory software with a number of inputs given by the Python script. The results of the quasi-dynamic simulation is imported back into the Python environment where the genetic algorithm goes trough its calculations.

ing computational efficiency with the need for thorough optimization. The optimal value for the maximum iterations was determined to be 15.

- Number of Variables: As explained, four variables are considered for every VCC. $x1$ (and $x5$) is set corresponding to the active power limits of the HV/MV transformer.
- Variable Ranges: The ranges of these variables are constrained by the technical specifications of the transformer and the grid operational limits. Nearly all HV/MV transformers have a maximum power capacity of 40 MVA or lower, thus the active power variable range was defined as ±50 MW. The voltage setpoint was established with a minimum of $0.85\ p.u.$ and a maximum of $1.15\ p.u.$. Although these limits exceed realistic expectations, the extended range was intentionally included to allow the optimization algorithm the potential to identify unforeseen outcomes.
- Crossover Percentage: A high crossover percentage promotes the exploration of diverse VCC combinations. This is the reason why a crossover percentage of 70% was chosen, after simulation was determined that this percentage produced satisfactory results.
- Mutation Percentage: A moderate mutation percentage introduces occasional random variations to prevent premature convergence to suboptimal solutions. A mutation percentage of 20% was selected.

The optimization workflow follows these steps:

1. Start:
    - The Python script initiates the process.
    - Initialization of Algorithm & Calculation of Curve Coordinates: The algorithm is initialized and the first candidate VCC is randomly generated.
    - Distribution Grid & Simulation Settings & Curve Coordinates: The selected distribution grid model is loaded into PowerFactory along with simulation settings and the initial VCC coordinates.
2. Quasi-Dynamic Simulation:
    - PowerFactory: PowerFactory performs the QD simulation, using the provided grid model, settings, and VCC coordinates.

  - Results of QD Simulation: PowerFactory produces simulation results (e.g., hourly voltage measurements of all MV nodes).

3. Genetic Algorithm:
   - Calculation of Fitness Value: The Python script retrieves the simulation results and calculates the fitness value of the VCC based on the limits defined in Equation 3.1.
   - A check is performed to see if the current population size has reached the maximum population size (*nPop*). If this is not the case, the algorithm moves to increase the population count by generating new parameters and running a new QD simulation. If *nPop* is reached, the process proceeds to the next step.
   - Selection: Fitter VCC solutions are selected based on their fitness values.
   - Crossover: Selected solutions are combined (crossover) to create new offspring solutions.
   - Mutation: Offspring solutions are slightly modified (mutated) to introduce diversity.
4. Iteration Check:
   - The process checks if the maximum number of iterations (*MaxIT*) has been reached.
   - If not, the modified population (after crossover and mutation) is fed back into the ”Quasi-Dynamic Simulation” stage. If *MaxIT* is reached, the algorithm terminates, outputting the best VCC solution found during the optimization process.

By combining the power of QD simulation with the adaptive capabilities of the GA, this framework enables the identification of VCC parameters that maximize the performance and resilience of the adaptive voltage control system in a realistic distribution grid environment. This process is graphically shown in Figure 4.1.

4.2.2. Simulation Environment

The subsequent section provides a comprehensive analysis of four fundamental algorithms of the presented process implemented in the Python programming language. This analysis encompasses detailed explanation of each algorithm’s procedural steps, computational complexity, and practical use cases within the Python ecosystem. The function descriptions of the crossover, mutation and sorting function are given in Algorithm 1, Algorithm 2, and Algorithm 3. Followed by the Algorithm 4, which presents the details of the implementation of the GA.

Algorithm 1 Crossover Function for Genetic Algorithm

```
function Crossover($a$, $b$)
    $VarRanges \leftarrow [(-55.0, -5.0), (5.0, 55.0), (0.85, 1.0), (1.0, 1.15)]$
    $delta \leftarrow 0.2$
    $alpha \leftarrow$ array of random values in [-delta, 1+delta] for each element of $a$
    $y1 \leftarrow$ empty array
    $y2 \leftarrow$ empty array
    for $i \leftarrow 0$ to $length(a) - 1$ do
        $t \leftarrow alpha[i] \times a[i] + (1 - alpha[i]) \times b[i]$
        $u \leftarrow alpha[i] \times b[i] + (1 - alpha[i]) \times a[i]$
        $y1[i] \leftarrow \min(\max(t, VarRanges[i][0]), VarRanges[i][1])$    ▷ Clip within range
        $y2[i] \leftarrow \min(\max(u, VarRanges[i][0]), VarRanges[i][1])$    ▷ Clip within range
    end for
    return $y1$, $y2$
end function
```

Algorithm 2 Mutate Function for Genetic Algorithm

```
function Mutate($c$, $VarRanges$)
    $n \leftarrow length(c)$                                        ▯ Get the number of parameters
    $j \leftarrow$ random integer in $[0, n-1]$                     ▯ Select a random parameter index
    $VarMin \leftarrow VarRanges[j][0]$
    $VarMax \leftarrow VarRanges[j][1]$
    $sigma \leftarrow (VarMax - VarMin)/10$                         ▯ Calculate standard deviation
    $y \leftarrow c$                                                ▯ Create a copy of the solution
    $y[j] \leftarrow y[j] + sigma \times random\_normal(0, 1)$      ▯ Add Gaussian noise
    $y[j] \leftarrow \min(\max(y[j], VarMin), VarMax)$              ▯ Clip within range
    return $y$
end function
```

Algorithm 3 Sort Population Function for Genetic Algorithm

```
function SortPopulation($a$)
    $le \leftarrow length(a)$                                       ▯ Get length of population array
    $C \leftarrow []$                                               ▯ Initialize empty cost array
    for $i \leftarrow 0$ to $le - 1$ do                             ▯ Iterate over each individual
        append $a[i].Cost$ to $C$                                   ▯ Extract and store cost
    end for
    $sorted\_index \leftarrow$ argsort($C$)                         ▯ Get indices that sort costs
    $sorted\_population \leftarrow []$                              ▯ Initialize empty sorted array
    for $i$ in $sorted\_index$ do                                   ▯ Iterate over sorted indices
        append $a[i]$ to $sorted\_population$                       ▯ Build sorted population
    end for
    return $sorted\_population, C$                                  ▯ Return sorted population and costs
end function
```

Algorithm 4 Genetic Algorithm Optimization

```
Require: $nVar, VarRanges, MaxIT, nPop, pCrossover, pMutation, CostFunction$
$nCrossover \leftarrow round(nPop \times pCrossover/2) \times 2$
$nMutation \leftarrow round(nPop \times pMutation)$
$pop \leftarrow$ InitializePopulation($nPop, nVar, VarRanges$)          ▷ See initialization steps
$sorted\_pop, Costs \leftarrow$ SortPopulation($pop$)
$BestSol \leftarrow sorted\_pop[0]$
$BestCost \leftarrow$ array of size $MaxIT$ initialized to 0
for $it \leftarrow 0$ to $MaxIT - 1$ do
    $popc \leftarrow$ empty array
    $popm \leftarrow$ empty array
                                                                      ▷ Selection and Crossover
    for $k \leftarrow 0$ to $nCrossover/2 - 1$ do
        $i1 \leftarrow$ random integer in $[0, nPop - 1]$
        $i2 \leftarrow$ random integer in $[0, nPop - 1]$
        $p1 \leftarrow pop[i1]$
        $p2 \leftarrow pop[i2]$
        $child1, child2 \leftarrow$ Crossover($p1.Position, p2.Position$)
        append $child1$ and $child2$ to $popc$
        $child1.Cost \leftarrow$ CostFunction($child1.Position$)
        $child2.Cost \leftarrow$ CostFunction($child2.Position$)
    end for
                                                                      ▷ Selection and Mutation
    for $k \leftarrow 0$ to $nMutation - 1$ do
        $i \leftarrow$ random integer in $[0, nPop - 1]$
        $p \leftarrow pop[i]$
        $mutant \leftarrow$ Mutate($p.Position, VarRanges$)
        append $mutant$ to $popm$
        $mutant.Cost \leftarrow$ CostFunction($mutant.Position$)
    end for
    $pop\_overall \leftarrow pop + popc + popm$                        ▷ Merge populations
    $sorted\_pop, Costs \leftarrow$ SortPopulation($pop\_overall$)
    $pop \leftarrow sorted\_pop[0 : nPop]$                             ▷ Truncate population
    $BestSol \leftarrow pop[0]$                                        ▷ Update best solution
    $BestCost[it] \leftarrow BestSol.Cost$
    Output "Iteration $it + 1$: Best Cost = $BestCost[it]$"
end for
return $BestSol, BestCost$
```

4.3. Results

This section will present the outcomes of the case studies conducted in terms of the found optimal voltage control curves. To evaluate the effectiveness of the adaptive voltage control methods, the performance of the VCC is compared to that of a base case situation. In the so-called base cases, no voltage control curve is applied to the HV/MV transformer. Only the AVC relay that switches the primary substation transformer's OLTC is used, based on local voltage magnitude measurements. This traditional voltage control method keeps the output voltage of the transformer within a predefined lower and upper bound, for example 0.99 and $1.01\ p.u.$, and no (active power) compensation is used. So, the voltage levels of the MV nodes in the distribution grid, or any other data from the grid, are not considered when the output voltage is changed. For ease of comprising, the base case situation is denoted as the situation without a VCC in the coming section.

4.3.1. Optimized Voltage Control Curves

Following the methodology outlined in Chapter 3 and after running the optimization algorithm described in Section 4.2, a total of 30 voltage control curves were identified for all of the 30 different distribution grids. These curves represent the optimal solutions for the adaptive voltage regulation within the studied grid. The exact values for the four parameters, *x2, x4, x1 & y4*, which have been found after the optimization algorithm are given in Table A.1. Figure 4.2 presents all the unique and diverse voltage control curves tailored to each distribution grid, highlighting the necessity for individualized VCCs and their non-interchangeability. For easier comparison, line segments 2 and 3 of the VCCs have been adjusted to ensure a uniform limit, either by extending or shortening them while maintaining their original slopes. This modification will not impact the functionality of the adaptive voltage control system since the relay will still select the same setpoint, given that the operative sections of the VCCs are unchanged. Cropped views of this figure can be found in Figure A.1 and A.2, where these figures exclusively depict sections with positive active power and a setpoint greater than one, or negative active power and a setpoint less than one. These figures are provided to facilitate the improved examination of the optimized line segments.

4.3.2. Performance Analysis

The efficacy of the 30 voltage control curves was evaluated across a range of key performance indicators, as discussed in Section 3.2. Table 4.2 below summarizes the comparative performance of these curves, providing insights into their relative strengths and weaknesses. Performance analysis was conducted on all 30 distribution grids, and the ten distribution grids with the most interesting results are presented in Table 4.2. The last two rows of the table show the average values for all 30 grids and the standard deviation.

For instance, without voltage control curves, an average of 1.50% of hourly voltage measurements in 2023 violated the ±3% boundaries. Implementing VCCs reduced this to 0.02%, an average decrease of 88.54% across all case studies. Furthermore, the difference between maximum and minimum voltage levels at MV nodes saw an average reduction of 17.19%. On average, the optimal VCC was determined in 714 minutes (11 h. and 54 min.), requiring 10.5 iterations of the genetic algorithm.

Table A.2 presents the complete data for all 30 distribution grids, expanding on the summary in Table 4.2. Additionally, Table A.3 shows VCC performance with a stricter ±2% voltage limit. This is particularly relevant for urban grids, which often do not show violations at the ±3% threshold. Table A.4 compares the remaining KPIs from Section 3.2 for the original case (no VCC) and the optimized case (with VCC). The percentage and absolute improvements per KPI are detailed in Table A.5.

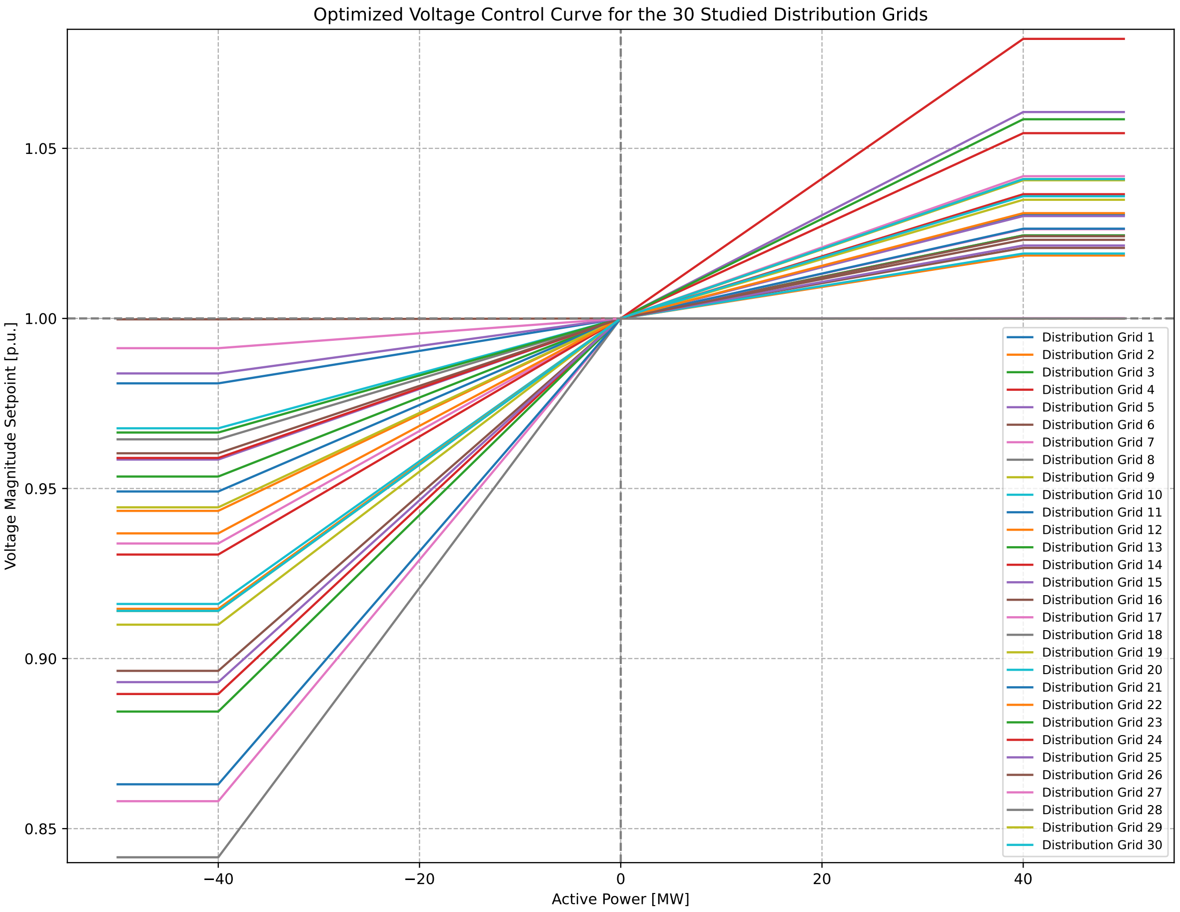


Figure 4.2: All 30 optimized voltage control curves found with the GA-based optimization algorithm. The graph shows that all calculated curves are different and a one-size-fits-all solution is not possible.

Table 4.2: Performance of the best VCC found for each individual distribution grid using the optimization algorithm (based on 2023). A selection of ten distribution grids is given with an average value of and standard deviation for all 30 distribution grids. These results show the positive effect of the VCC in terms of a reduction in the percentage of violations and maximum and minimum voltage levels. Additionally, data is provided on the computational time and number of iterations required to find the optimal voltage control curve.

Distr. Grid Number	**Percentage of Violations (>±3%) without VCC**	**Percentage of Violations (>±3%) with VCC**	**Reduction in Violations (>±3%)**	**Reduction in $\Delta_{MAX}V$**	**Time used to find Best VCC [minutes]**	**Number of Iterations used**	**V_{MAX} without VCC [p.u.]**	**V_{MAX} with VCC [p.u.]**	**V_{MIN} without VCC [p.u.]**	**V_{MIN} with VCC [p.u.]**	**$\Delta_{MAX}V$ without VCC [p.u.]**	**$\Delta_{MIN}V$ with VCC [p.u.]**
3	1.62%	0.06%	96.04%	33.93%	745	15	1.0596	1.0422	0.9427	0.9625	0.1126	0.0744
4	0.21%	0.01%	96.82%	13.69%	48	1	1.0477	1.0322	0.9641	0.9629	0.0751	0.0648
7	4.32%	0.00%	100.00%	57.51%	408	6	1.0276	1.0234	0.9447	0.9832	0.0746	0.0317
9	11.00%	0.02%	99.80%	-0.06%	1403	15	1.0344	1.0344	0.9630	0.9630	0.0671	0.0671
16	0.33%	0.00%	100.00%	24.29%	487	13	1.0297	1.0291	0.9593	0.9700	0.0704	0.0533
20	6.37%	0.00%	100.00%	51.99%	1305	13	1.0100	1.0100	0.9363	0.9740	0.0733	0.0352
21	0.89%	0.04%	95.38%	27.09%	536	5	1.0379	1.0382	0.9432	0.9600	0.0948	0.0691
24	18.18%	0.05%	99.71%	48.09%	424	9	1.0870	1.0373	0.9082	0.9598	0.1387	0.0720
25	0.09%	0.00%	100.00%	69.46%	163	2	1.0394	1.0273	0.9595	0.9704	0.0799	0.0244
30	0.76%	0.11%	84.96%	20.96%	806	15	1.0441	1.0444	0.9501	0.9595	0.0940	0.0743
Average	**1.50%**	**0.0152%**	**88.54%**	**17.19%**	**637.6**	**10.5**	**-**	**-**	**-**	**-**	**-**	**-**
Stdev.	**0.04%**	**0.0003%**	**23.05%**	**20.03%**	**377.9**	**6.8**	**-**	**-**	**-**	**-**	**-**	**-**

Figure 4.3 illustrates the impact of an optimized VCC on the voltage magnitudes in a distribution grid for visualization purposes. This figure shows a split violin plot comparing the voltage magnitudes in Distribution Grid 24, which is a grid with 259 MV nodes and a total of 23 feeders (Table 4.1), for two scenarios: without a VCC and with a VCC, on a monthly basis for the year 2023. The data is aggregated by month, with the blue areas representing the voltage levels without a VCC and the orange areas representing the voltage levels with a VCC. The plot illustrates that when VCC is implemented, the voltage magnitudes are more consistently maintained within the ±3% limit across all months. This suggests that VCC helps regulate voltage more effectively, ensuring that the grid operates within acceptable limits, compared to the scenario without VCC where voltage fluctuations are larger.

While aggregate system-level metrics provide valuable insights, it is crucial to recognize that a voltage control curve's impact is not uniform across all nodes within a distribution network. Individual nodes may experience varying degrees of voltage deviation and fluctuation depending on their location, load characteristics, and network topology. Furthermore, seasonal variations in load demand and generation profiles necessitate the selection of a voltage control curve that can effectively regulate voltage throughout the year. A curve optimized for peak summer loads may perform poorly during periods of low winter demand, potentially leading to over-voltage conditions and increased system losses.

To underscore the importance of these considerations, Figure A.3 illustrates the individual performance of all nodes within a representative distribution network across every hour of a year without the implementation of a VCC. This visual representation highlights potential variations in node-level voltage regulation and emphasizes the need for a carefully selected curve that balances system-level performance with node-specific requirements across different operating conditions. By providing a comprehensive understanding of the impact of voltage control curves on both aggregate and individual node performance, Figure A.4 serves as a valuable tool for the visualization of the impact of the VCC on the complete distribution grid. A more in-depth explanation of, and elaboration on these figures in given in Appendix A.

4.3.3. MV/LV Transformer Tap Settings

Section 1.3 presented a sub-research question which explored the relationship between the voltage control curve and the optimal tap position for MV/LV transformers. To address this, LV-side measurement data from Distribution Grid 21 is presented under various tap settings. While this data focuses on a single grid, the conclusions drawn are applicable to all other case studies.

To be able to compare the different tap settings scenarios for the MV/LV transformer, Figure 4.4 is given. This figure presents a split violin plot comparing voltage magnitudes from the LV-side of the MV/LV transformer in Distribution Grid 21, under two scenarios: adjusted tap settings (blue areas) and neutral tap settings (orange areas). The adjusted tap settings represent real-life configurations applied to the transformer, while neutral tap settings indicate that the transformer is set to tap setting 3, its neutral position. The MV/LV transformer features tap settings ranging from 1 to 5. The figure illustrates that when neutral tap settings are used, the voltage magnitudes stay consistently within the ±3% limit. However, with adjusted tap settings, voltage deviations occur more frequently. This suggests that the transformer should ideally be configured at neutral tap settings to maintain voltage levels within acceptable limits, as deviations with adjusted settings push the voltage closer to the limits, increasing the risk of exceeding them.

Additional explanatory figures are presented in Appendix A. The first figure, Figure A.7, presents the situation with the optimal VCC and adjusted tap settings, indicating that in PowerFactory, the tap settings are configured to match the real-life settings. Over the recent years, these tap settings have been modified to ensure voltage stability. Figure A.8 presents the case where every MV/LV transformer in Distribution Grid 21 has been set to the neutral settings, 3, with the voltage control curve implemented.

Table 4.3 will offer further understanding regarding the voltage stability differences in Distribution Grid 21 under the two outlined conditions: one with real-life tap settings and another with all MV/LV transformers set to their neutral tap settings. The table shows a positive reduction over all columns.

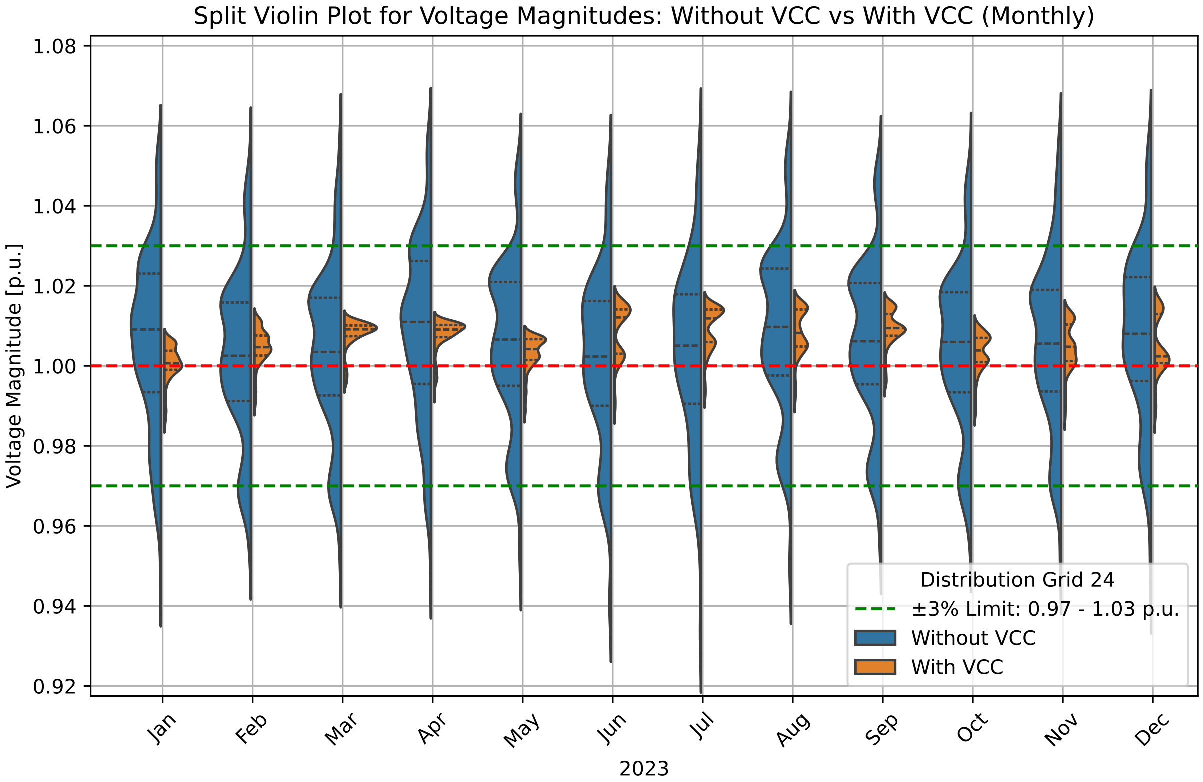


Figure 4.3: Split violin plot to compare the voltage magnitudes (in $p.u.$) in Distribution Grid 24 for the scenario without a VCC (traditional voltage control) and with a VCC implemented. Data is arranged by month, with hourly measurements for all nodes throughout the year (2023) aggregated within each respective month. This visualization allows for straightforward observation of how a VCC impacts voltage magnitudes in a distribution grid. It demonstrates that the VCC maintains voltage levels within ±3% limit, in contrast to the scenario with traditional voltage control.

4.3.4. Impact on Grid Currents

The adaptive voltage control technique mentioned in this work, by altering voltage levels, indirectly impacts the currents in the distribution network. This connection arises from fundamental power equations. Assuming that the active power demand and the power factor remain relatively constant, a change in voltage due to the VCC will necessarily lead to a corresponding inverse change in current. This interaction between voltage and current is crucial to consider, particularly in scenarios where the VCC lowers the voltage. Increased currents could potentially lead to reaching or exceeding the current limits of various grid components, such as lines and transformers. This could trigger protection mechanisms, leading to undesirable outages or damage to equipment.

Therefore, it is essential to investigate the impact of the adaptive voltage control method on grid currents to understand whether the results were expected and if the current levels remain below the maximum expected value, preventing the activation of protection mechanisms. The influence of the adaptive voltage control method on grid currents was investigated by conducting load flow analyses on three representative distribution grids (6, 20 & 30). The analysis focused on the time period with the largest active power load, representing the most demanding scenario for the grid's infrastructure in that year. For each distribution grid, a different time period of peak load in 2023 was identified. The maximum and average values for the cable loading and current magnitudes were initially determined for the baseline case, where the transformers' output voltage was set to the nominal value. Subsequently, two additional scenarios were created to simulate extreme, unrealistic, VCC conditions: one with the transformer output voltage set to nominal +10% and another with the voltage set to nominal -10%. These scenarios aimed to assess the impact of the voltage control curve on grid currents under high and low voltage conditions, providing insights into the potential for current limit violations and informing the

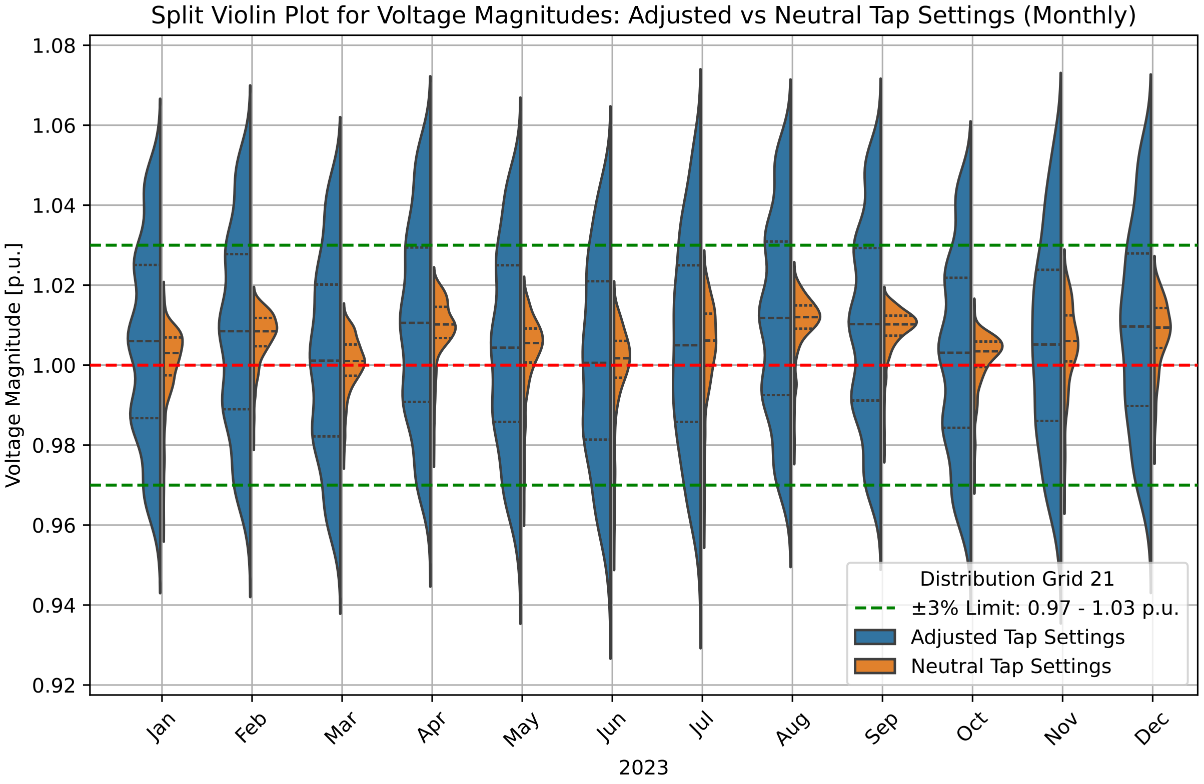


Figure 4.4: Split violin plot to compare the voltage magnitudes (in $p.u.$) from the LV-side of the MV/LV transformer in Distribution Grid 21 for the scenario with adjusted tap settings and neutral tap settings (MV/LV transformer). Adjusted tap settings means that the real-life tap settings of the transformers are applied (ranging form 1 to 5), neutral tap settings means the transformer is set to tap setting 3. In this figure, adaptive voltage control with its VCC is already applied. This visualization shows that voltage levels are within the ±3% limit when neutral tap settings are used, unlike the situation with adjusted tap settings, indicating that tap settings should to be configured to the neutral position.

Table 4.3: Difference in performance of the LV-side voltage levels of the MV/LV Transformers in Distribution Grid 21 when comparing the situation with adjusted and neutral tap settings of the MV/LV transformers. The data indicates the positive effect of the neutral tap position in terms of a reduction in the percentage of violations and voltage levels.

Tap Settings	**Percentage of Violations (>±3%) with VCC**	**Number of Violations (>±3%) with VCC**	**V_{MAX} [p.u.]**	**V_{MIN} [p.u.]**	**Number of Nodes with ΔV >±3% (out of 234)**	**Average ΔV [p.u.]**	**$\Delta_{MAX}V$ [p.u.]**
Adjusted	27.32%	559902	1.0913	0.9399	106	0.0604	0.1111
Neutral	0.074%	1512	1.0380	0.9541	20	0.0398	0.0796
Difference	**27.25%**	**558390**	**0.0533**	**0.0142**	**86**	**0.0206**	**0.0315**

Table 4.4: Effect on the current levels within Distribution Grid 6, 20 and 30 when the transformer output voltage is either nominal, nominal +10% or nominal -10% to imitate an extreme high and low voltage setpoint.

Distr. Grid Number	**Max. / Average**	**Cable Loading (V_{NOM})**	**Current Magnitude (V_{NOM}) [kA]**	**Cable Loading (V_{NOM} +10%)**	**Current Magnitude (V_{NOM} +10%) [kA]**	**Cable Loading (V_{NOM} -10%)**	**Current Magnitude (V_{NOM} -10%) [kA]**
6	Max.	81.72%	1.544	73.91%	1.397	91.24%	1.724
20	Max.	64.65%	0.103	65.28%	0.104	64.65%	0.103
30	Max.	31.71%	0.043	30.24%	0.041	31.72%	0.043
6	Average	11.87%	0.042	10.69%	0.038	13.13%	0.046
20	Average	9.89%	0.040	10.02%	0.040	10.35%	0.041
30	Average	7.32%	0.020	7.59%	0.020	7.79%	0.021

development of appropriate mitigation measures. The results of these analyzes are given in Table 4.4 and these results are elaborated in Section 5.1.

4.3.5. Future Performance

Testing the performance of the VCC in future scenarios is crucial for ensuring tomorrow's grid stability, anticipating challenges, future-proofing the system, making informed investment decisions, and optimizing the performance of the adaptive voltage policy. By simulating different future conditions, the VCC's ability can be assessed to adapt to changing grid dynamics, identify potential bottlenecks, evaluate its robustness, ensure regulatory compliance, make informed decisions about resource allocation and infrastructure investments, and determine the optimal reset frequency for the adaptive voltage policy.

Table 4.5 shows the results of the VCCs, which were optimized based on the 2023 data, and evaluated under the 2028 scenario. Table 4.6 also presents this data, but the scenario considers the year 2033. These tables illustrate 15 analyzed distribution grids, which were chosen from an initial set of 30 grids based on prior findings indicating that these grids gain advantages from a VCC, whereas the remaining 15 grids experience little to no gain from the VCC. The tables will show the percentage of voltage limit violations for the base case and the optimized case of 2028 or 2033, initially under the existing voltage control and subsequently without a VCC in place. Table 4.5 shows the average of the studied distribution grids is 6.40% without a VCC and 1.82% with a VCC. Table 4.6 presents an average of 12.09% for the base case and an average of 4.68% for the case with an active VCC. Additionally, the tables will provide the reduction in violations of the two scenarios; an average of 80.04% in 2028 and 62.25% in 2033. Next, the tables also provide data on the maximum difference between the maximum and minimum voltage measured of a MV node, and their difference in percentage, for both situation in 2028 and 2033. For 2028, the average maximum difference is $0.1171\ p.u.$ for the situation without a VCC, and $0.0983\ p.u.$ for the case with a VCC. Table 4.5 shows an average reduction in the maximum voltage difference of 22.45% for 2028. In 2033, the average reduction is 17.23%, while the maximum difference without a VCC was $0.1841\ p.u.$ and $0.1544\ p.u.$ for the case with a VCC (Table 4.6). On top of that, the tables finally provide numbers of the increase of violations and the maximum difference in voltage when the case of 2023 is compared with that of 2028 or 2033. How these results were obtained, is explained in Section 3.2.

Table 4.5: Performance and comparison of 2023-optimized voltage control curve in a 2028 scenario for all the distribution grids that benefit from the adaptive voltage control policy. The average value provided is an average of the 15 studied distribution grids. Also, the standard deviation from the provided data is given. The table shows that the VCC is able to decrease the voltage limit violations by an average of 80.04%, even if the curve is tested on the 2028 scenario.

Distr. Grid Number	**Percentage of Violations (>±3%) without VCC for 2028**	**Percentage of Violations (>±3%) with VCC for 2028**	**Reduction in Violations for 2028 (>±3%)**	**$\Delta_{MAX}V$ without VCC for 2028 [p.u.]**	**$\Delta_{MAX}V$ with VCC for 2028 [p.u.]**	**Reduction in $\Delta_{MAX}V$ for 2028**	**Increase in Violations (>±3%) without VCC 2023-2028**	**Increase in Violations (>±3%) with VCC 2023-2028**	**Increase in $\Delta_{MAX}V$ without VCC 2023-2028**	**Increase in $\Delta_{MAX}V$ with VCC 2023-2028**
1	1.93%	0.21%	89.08%	0.1003	0.0827	17.55%	580.63%	-	30.26%	51.47%
3	4.23%	0.45%	89.41%	0.1390	0.0881	36.62%	160.79%	600.00%	23.45%	18.41%
4	0.81%	0.13%	84.14%	0.0911	0.0818	10.21%	287.98%	1728.57%	21.30%	26.23%
6	8.62%	2.97%	65.50%	0.0954	0.0823	13.73%	99.54%	-	27.88%	159.62%
8	15.05%	1.67%	88.93%	0.1453	0.1418	2.41%	36.84%	7472.73%	116.54%	111.33%
9	9.42%	1.38%	85.33%	0.1538	0.1025	33.36%	5047.54%	4218.75%	122.25%	67.48%
10	1.12%	0.07%	93.38%	0.0704	0.0671	4.69%	1028.28%	-	34.61%	73.83%
11	1.19%	0.63%	46.88%	0.0749	0.0691	7.74%	354.41%	967.80%	6.70%	-3.09%
16	5.78%	0.04%	99.27%	0.1136	0.0683	39.88%	1678.15%	-	61.36%	28.14%
20	6.37%	1.34%	78.91%	0.0927	0.0565	39.05%	54.40%	-	26.47%	60.51%
21	3.00%	0.41%	86.50%	0.1313	0.0876	33.28%	236.97%	887.80%	38.50%	26.77%
24	30.45%	16.52%	45.73%	0.2062	0.1526	25.99%	67.52%	31075.47%	48.67%	111.94%
26	2.65%	1.01%	61.78%	0.1218	0.1069	12.23%	1124.54%	3788.46%	68.70%	49.51%
28	1.27%	0.06%	95.59%	0.0848	0.0627	26.06%	1169.00%	-	20.80%	13.59%
30	4.19%	0.41%	90.19%	0.1362	0.0899	33.99%	452.17%	260.53%	44.89%	21.00%
Average	**6.40%**	**1.82%**	**80.06%**	**-**	**-**	**22.45%**	**825.25%**	**5666.68%**	**46.16%**	**54.45%**
Stdev.	**7.46%**	**4.01%**	**16.43%**	**-**	**-**	**12.81%**	**1227.94%**	**9248.52%**	**32.65%**	**43.10%**

Table 4.6: Performance and comparison of 2023-optimized voltage control curve in a 2033 scenario for all the distribution grids that benefit from the adaptive voltage control policy. The average value provided is an average of the 15 studied distribution grids. Also, the standard deviation from the provided data is given. The table shows that the VCC is able to decrease the voltage limit violations by an average of 62.25%, even if the curve is tested on the 2033 scenario.

Distr. Grid Number	**Percentage of Violations (>±3%) without VCC for 2033**	**Percentage of Violations (>±3%) with VCC for 2033**	**Reduction in Violations for 2033 (>±3%)**	**$\Delta_{MAX}V$ without VCC for 2033 [p.u.]**	**$\Delta_{MAX}V$ with VCC for 2033 [p.u.]**	**Reduction in $\Delta_{MAX}V$ for 2033**	**Increase in Violations (>±3%) without VCC 2023-2033**	**Increase in Violations (>±3%) with VCC 2023-2033**	**Increase in $\Delta_{MAX}V$ without VCC 2023-2033**	**Increase in $\Delta_{MAX}V$ with VCC 2023-2033**
1	7.77%	1.85%	76.16%	0.1531	0.1126	26.45%	2635.92%	-	98.83%	106.23%
3	12.92%	3.35%	74.06%	0.1928	0.1400	27.39%	696.49%	5135.94%	71.23%	88.17%
4	9.12%	1.56%	82.88%	0.1514	0.0936	38.18%	4286.54%	22214.29%	101.60%	44.44%
6	18.81%	9.02%	52.03%	0.1450	0.1449	0.07%	335.54%	-	94.37%	357.10%
8	11.38%	6.00%	47.25%	0.2379	0.2185	8.15%	3.50%	27186.36%	254.55%	225.63%
9	20.35%	7.36%	63.84%	0.2614	0.2075	20.62%	11021.86%	22900.00%	277.75%	239.05%
10	6.59%	1.30%	80.35%	0.1150	0.0949	17.48%	6560.61%	-	119.89%	145.85%
11	0.30%	0.22%	26.60%	0.0843	0.0821	2.61%	13.79%	269.49%	20.09%	15.15%
16	18.41%	2.71%	85.28%	0.1508	0.1001	33.62%	5565.85%	-	114.20%	87.80%
20	9.82%	4.02%	59.08%	0.1053	0.0882	16.24%	138.01%	-	43.66%	150.57%
21	8.83%	4.37%	50.52%	0.2764	0.2595	6.11%	892.58%	10560.98%	191.56%	275.54%
24	34.68%	20.59%	40.62%	0.3415	0.3321	2.75%	90.82%	38756.60%	146.21%	361.25%
26	6.40%	3.95%	38.34%	0.1847	0.1639	11.26%	2862.04%	15073.08%	155.82%	129.23%
28	3.73%	0.58%	84.46%	0.1121	0.0833	25.69%	3633.00%	-	59.69%	50.91%
30	12.19%	3.39%	72.21%	0.2494	0.1950	21.81%	1506.32%	2871.93%	165.32%	162.45%
Average	**12.09%**	**4.68%**	**62.25%**	**-**	**-**	**17.23%**	**2682.86%**	**16107.63%**	**127.65%**	**162.63%**
Stdev.	**8.08%**	**4.87%**	**18.26%**	**-**	**-**	**11.43%**	**3032.48%**	**12006.41%**	**70.50%**	**100.53%**

5

Discussion

The previous chapter has presented the findings of the case studies, showcasing the effectiveness of the adaptive voltage control method in mitigating voltage violations and fluctuations. The subsequent discussion chapter serves as a platform for interpreting these findings, analyzing their implications, and exploring the broader context of the research. It will dive deeper into the significance of the results, address potential limitations, and propose directions for future research. The discussion chapter aims to bridge the gap between the findings and their theoretical and practical implications, promoting a comprehensive understanding of the potential of the adaptive voltage control strategy in real-world applications.

5.1. Interpretation of the Results

The objective of the thesis was to develop an adaptive voltage control method that could be universally applied. The results of the optimized voltage control curves for the 30 different studied distribution grids can be found in Figure 4.2. The figure clearly shows that all the found VCCs are very different from each other, which leads to the conclusion that every distribution grid needs its own optimized VCC.
The other findings presented in Chapter 4 highlight the effectiveness of the adaptive voltage control method in real-world scenarios. The study involved 30 different distribution grids, and the results showed that the optimized voltage control curves significantly reduced voltage violations. The average reduction in violations was a remarkable 88.54% (of the ±3% threshold), and the difference between the highest and lowest voltage levels also decreased considerably, by an average 17.19%. These improvements translate into a more stable power grid.

Also, there was shown how the VCC effects the voltage magnitudes within a distribution grid in the form of Figure 4.3. By controlling voltage more effectively, the VCC reduces the deviations from the nominal voltage, as seen in the narrowed distribution of voltage magnitudes within the ±3% limit. This creates a more stable voltage profile across the distribution grid, particularly within the MV network. As a result, the addition of the VCC leaves more room for voltage fluctuations in the LV network without violating the operational limits. The results also emphasized the importance of considering the unique characteristics of each node within the grid and the seasonal variations in load and generation when designing voltage control curves. The visualizations provided in Figure 4.3, A.3, and A.4 offer a valuable tool for understanding the complex voltage dynamics within the power grid and the positive impact of the adaptive control strategy.

Furthermore, Section 4.3 investigated the relationship between the voltage control curve and the optimal tap settings for MV/LV transformers. The findings indicated that optimized tap settings further enhance voltage stability, contributing to the overall improved grid performance.

Next, Table 4.4 confirms the fundamental relationship between voltage and current: increasing voltage leads to lower currents and vice-versa, assuming constant power. The adaptive voltage control method, by adjusting the transformer output voltage, can influence both cable loading and current magnitudes in the distribution grid. This influence is particularly important to consider when the VCC decreases the voltage, as it could potentially lead to increased currents that might approach or exceed cable limits. However, the three distribution grids referenced in Table 4.4 demonstrate that the currents remain within allowable limits, even under the most extreme voltage setpoints.

Furthermore, within a distribution grid, the diverse nature of connected loads results in a complex interplay of responses to voltage fluctuations. Each load, whether residential appliances, industrial machinery, or commercial equipment, possesses unique characteristics that dictates its behavior when voltage changes. Some loads may demonstrate high sensitivity to voltage variations, while others remain relatively unaffected. Furthermore, loads can be broadly categorized based on their response to voltage changes: constant power loads maintain a consistent power draw, leading to an inverse relationship between voltage and current; constant current loads maintain a steady current flow, causing power consumption to vary directly with voltage; and constant impedance loads exhibit a linear relationship between voltage and current, as dictated by Ohm's Law. Consequently, voltage fluctuations within the grid trigger diverse reactions among loads, with some drawing more current, others less, and some even maintaining a constant current. This complex interplay of load responses adds another layer of complexity to managing power distribution systems and ensuring a stable and reliable power supply for all connected devices.

Finally, the simulation outcomes presented in Table 4.5 and 4.6 offer a comprehensive assessment of the VCC's anticipated performance under future scenarios. These results facilitate a quantitative evaluation of the VCC's effectiveness over the coming years and an investigation of the reset frequency. While a marginal decrease in performance is projected, the VCC is anticipated to maintain a significant positive influence on the grid for the next decade.

In conclusion, the provided results strongly support the practical implementation of adaptive voltage control in real-world distribution networks. This approach offers a promising solution to the challenges posed by the increasing integration of distributed energy resources and the fluctuating nature of modern power grids.

5.1.1. Analysis

The analysis of the results reveals several key trends, patterns, and interesting observations that clarify the effectiveness, or the poor performance, of the adaptive voltage control method:

1. Need for Distribution Grid Specific Voltage Control Curves: The found optimal VCCs shown in Figure 4.2 emphasizes the importance of tailoring voltage control curves to each distribution grid. The diversity of the 30 optimized curves reflects the unique challenges and requirements of different grids, highlighting the necessity for a customized approach to voltage control. This pattern suggests that a one-size-fits-all curve is not be effective in addressing the complexities of modern power systems.

2. Compensation for Generation Surplus: Figure 4.2 demonstrates that when active power is negative (indicating a surplus of generation compared to consumption), the VCCs tend to exhibit a steeper downward slope. This implies that more aggressive voltage compensation is generally required in such scenarios. The observation that multiple VCCs extend below the 0.90 voltage magnitude setpoint further reinforces this notion. In contrast, for positive active power (where consumption surpasses generation), the VCCs display a gentler upward slope, and the 1.10 voltage magnitude setpoint is never reached. This suggests that less aggressive compensation is typically sufficient when the grid experiences a higher load demand compared to generation. The steeper slopes for negative active power scenarios align with expectations, as they counteract the voltage rise from increased distributed generation. The VCCs actively lower the voltage setpoint to ensure voltage stability. In contrast, gentler slopes during positive active power scenarios reflect the smaller voltage drop typical of higher load demand. The VCCs make minor upward adjustments to the voltage setpoint, compensating for the voltage drop and ensuring sufficient voltage for consumers.

3. Absence of Setpoint >1: Figure 4.2 reveals another interesting observation: three of these opti-

mized VCCs have a voltage magnitude setpoint of $1.0\ p.u.$ even when the active power is positive. This is noteworthy because positive active power usually indicates higher consumption than generation, causing voltage drops. Typically, the VCC would compensate for these drops by raising the voltage setpoint above $1.0\ p.u.$, as observed in other cases. However, in these specific grids, the optimized VCCs suggest that maintaining the setpoint at the nominal value is sufficient to ensure voltage stability, even under higher load conditions.

4. Absence of Setpoint <1: Similarly, Figure 4.2 also shows that two optimized VCCs have a voltage magnitude setpoint close to $1.0\ p.u.$ even when the active power is negative. Negative active power signifies excess generation, which typically leads to voltage rise in the grid. In these cases, one might expect the VCC to significantly lower the voltage setpoint below $1.0\ p.u.$ to mitigate the voltage rise. However, for these particular grids, the optimized VCCs suggest that only a slight reduction in the setpoint, or even maintaining it near the nominal value, is adequate for voltage regulation. It is important to note that the optimization process used in the GA does not explicitly aim to keep the voltage setpoint as close to $1.0\ p.u.$ as possible. Instead, the cost function is designed to minimize the number of voltage limit violations across the entire distribution network. In other words, the cost function is designed to keep the voltage at the MV nodes as close to $1.0\ p.u.$ as possible. The resulting behavior, a setpoint near $1.0\ p.u.$, is a natural outcome of this optimization approach. The VCCs are optimized to reduce voltage violations, and the additional KPIs, are considered only in the evaluation phase to better understand the impact of the optimized voltage control curves.

5. Significant Reduction in Voltage Violations: The implementation of optimized voltage control curves led to a substantial decrease in voltage violations in the MV grid across all 30 distribution grids. The average 88.54% reduction in violations exceeding the ±3% threshold (Table 4.2) demonstrates the adaptive approach's effectiveness in maintaining acceptable voltage levels. This trend underscores the potential of the strategy to enhance grid stability and reliability, particularly in the face of increasing distributed generation and load variability.

6. Improved Voltage Regulation: The 17.19% average reduction in the difference between maximum and minimum voltage levels (Δ_{MAX}V, Table 4.2) shows the adaptive control's positive impact on voltage regulation. This improvement indicates a more balanced and controlled voltage profile across the grid, which can lead to reduced power losses and improved energy efficiency.

7. Limited Time Required: Table 4.2 highlights that the optimization process, which involves running quasi-dynamic simulations and the genetic algorithm, takes an average of only 714 minutes (11 h. and 54 min.) to find an optimized voltage control curve that improves voltage stability for an entire year. This is particularly noteworthy considering that the computations were performed on a standard laptop. The short optimization time and few genetic algorithm iterations (average 10.5) suggest the method's computational efficiency. With access to a more powerful computer with increased processing capabilities and parallelization potential, the optimization time could be reduced even further. This could allow for exploring larger, more complex networks, potentially yielding even better voltage control solutions. High-performance computing could enable real-time or near-real-time optimization, letting the voltage control policy adapt faster to grid changes, improving stability and resilience.

8. Increase in Δ_{MAX}V: Inspecting Table 4.2 reveals that in the case of Distribution Grid 9, there is a slight increase in Δ_{MAX}V, despite a reduction in the percentage of violations, suggests a trade-off between these two performance indicators. The optimization process, driven by the genetic algorithm, prioritizes minimizing voltage violations as the primary objective. In this grid, further reducing violations might have slightly widened the voltage range, causing the observed Δ_{MAX}V increase. Table A.2 confirms this is also the case for grids 4 and 11.

9. Decrease in V_{MAX} & Increase in V_{MIN}: Table 4.2 showcases the positive impact of the adaptive voltage control policy on the maximum and minimum voltage in the grid. The columns V_{MAX} without VCC and V_{MAX} with VCC show the maximum voltage levels reached in the distribution grid during the complete year without and with the implementation of the VCC, respectively. The decrease observed in the V_{MAX} values across all distribution grids, 1.0316 to 1.0294, indicates

that the VCC effectively mitigates excessive voltage rise. Similarly, the columns V_{MIN} without VCC and V_{MIN} with VCC present the minimum voltage levels experienced in the grid. The increase in V_{MIN} values, 0.9628 to 0.9730, demonstrates the VCC's ability to prevent significant voltage drops. The decreased V_{MAX} and increased V_{MIN} result in a narrower voltage range within the MV grid. This tighter control has a cascading positive effect on the LV grid, as it receives a more stable and regulated voltage input from the MV grid. The reduced voltage fluctuations in the MV grid translate to improved voltage stability and power quality in the LV grid, benefiting the end-users connected to it.

10. Absence of Initial Limit Violations: Analysis of Table 4.2 and A.2 reveals that half the studied grids (specifically 2, 5, 7, 12, 13, 14, 15, 17, 18, 19, 22, 23, 25, 27, 29), mostly urban ones, may not significantly benefit from adaptive voltage control. This is because these grids, due to their inherent design and operational characteristics, already show excellent voltage regulation within the MV grid, with minimal or no violations of the ±3% threshold even without the implementation of the VCC. Urban grids, which typically have shorter feeders due to higher population density and more compact infrastructure, are be less prone to voltage drops caused by line resistance. Additionally, urban areas usually have less space for large-scale DG installations compared to rural areas, resulting in lower DG penetration levels and reduced risk of voltage rise. In these cases, the adaptive control strategy may offer little improvement since the grid already operates within safe voltage limits. Applying a VCC in these scenarios could yield negligible gains, or even add unnecessary complexity. Despite these findings, their applicability is restricted to the MV grid, and their impact on the LV grid remains uncertain.

11. Impact of MV/LV Transformer Tap Settings: The investigation into the relationship between voltage control curves and MV/LV transformer tap settings revealed a positive correlation between neutral tap positions and improved voltage stability. The reduction in voltage violations, observed in Table 4.3 and Figure 4.4, with neutral tap settings underscores the importance of considering this aspect in combination with the adaptive control strategy.

12. Impact of Adaptive Voltage Control on Grid Currents: The analysis of Table 4.4 highlights the need to consider the impact on grid currents when designing and implementing adaptive voltage control strategies, especially in scenarios where voltage reduction is employed. For an alternative evaluation, there can be observed that the current levels remain within secure boundaries, even under instances of extreme voltage setpoints. This is why the analysis provides valuable insights into the relationship between voltage control and grid currents, but it is important to note that it considers the extreme voltage adjustments (±10%) which may not be realistic in practical operation. The results align with expectations, as increasing voltage reduces current, and lowering voltage increases current. This inverse relationship between voltage and current is consistent with Ohm's Law, where the current is inversely proportional to voltage for a constant power demand. The table also reveals that the impact of voltage adjustments on current magnitude varies significantly among the three distribution grids studied. While grids 20 and 30 exhibit only minor changes in current magnitude even with substantial ±10% voltage alterations, Distribution Grid 6 demonstrates a notable sensitivity to voltage changes. In grid 6, a 10% increase in voltage results in a 10.6% decrease in maximum current magnitude, and a 10% voltage decrease leads to a 12.4% increase in current. This heightened sensitivity suggests that grid 6's electrical characteristics, such as its impedance and load distribution, make it more susceptible to current fluctuations in response to voltage adjustments. This observation underscores the importance of considering grid-specific sensitivities when implementing adaptive voltage control strategies.

13. Future Performance of Violation Reduction: Table 4.5 and 4.6 provide data on the performance of the VCC in future scenarios. While there is a substantial increase in violations from 2023 to 2028 and 2033, the tables still demonstrate a positive effect of the voltage control curve. In 2028, for instance, the VCC manages to reduce voltage limit violations by 80.04%, compared to the 94.71% reduction achieved in 2023 for the same 15 grids. By 2033, this reduction drops to 62.45%, which, while still effective, reflects a significant decline. However, it is clear that relying solely on VCC in future scenarios will not be sufficient to maintain grid stability. The decrease in effectiveness over time suggests that the DSO must consider complementing the VCC with other voltage control strategies to manage the increasing challenges in the power grid effectively. This

demonstrates that, although VCC is a reliable tool, additional solutions are essential to ensure long-term grid performance.

14. Future Performance of Reduction in V_{MAX}: Table 4.5 and 4.6 also provide information on the maximum difference between the maximum and minimum voltage levels (V_{MAX}). While in 2023 there was a reduction of 24.34% for the 15 studied distribution grids, V_{MAX} was reduced by 22.45% for the 2028 scenario. A very minimal decrease in performance for a five year difference. Lastly, a reduction of 17.23% was obtained for the 2033 scenario. Once more, a decline in performance is evident, but even after ten years, a beneficial impact of the VCC remains. The findings indicate that the voltage control strategy remains effective and reliable for future applications.
15. Stricter ±2% Voltage Limit: Table A.4 and A.5 presents the VCC performance with a stricter ±2% voltage limit, which is particularly relevant for urban grids that often do not show violations at the ±3% threshold. Even with stricter limits, the VCC's positive impact (violation reduction) shows it does more than just keep voltage levels below ±3%. It actively regulates voltage closer to nominal, improving performance even under stricter requirements. This demonstrates the VCC's effectiveness in both preventing large deviations and fine-tuning voltage for better grid stability.

Some of these results are unexpected, however they highlight the dynamic nature of real-world distribution grids and the need for continuous monitoring and adaptation of voltage control strategies. The optimal solution can evolve due to changes in grid topology, load patterns, or the integration of distributed energy resources. This underscores the importance of ongoing research and development in adaptive voltage control methods to ensure their effectiveness in an ever-changing power system landscape. Furthermore, the observation that some grids do not benefit significantly from adaptive voltage control emphasizes the need for a context-specific approach to voltage regulation. Careful assessment of individual grid characteristics is crucial before deploying any control strategy. In well-performing grids, alternative or more targeted approaches might be more suitable. The focus should be on tailoring control strategies to the specific needs and challenges of each grid, rather than adopting a single solution. This ensures efficient resource utilization and maximizes the benefits of voltage control while minimizing complexity and costs.

5.1.2. Correlation

Beyond direct performance analysis of the voltage control curves, it is of significant interest to investigate potential correlations between the performance indicators and the inherent characteristics of the distribution grid itself. Understanding how specific grid attributes influence VCC performance could lead to a better understanding of VCC operations and enable the prediction of optimal curve types for new or modified grids without extensive simulations. Identifying key grid characteristics that strongly impact voltage regulation could guide the design and planning of future distribution networks to be inherently more suitable for effective voltage control. If correlations are dynamic and vary with operating conditions, this knowledge could inform the development of adaptive voltage control strategies that adjust curve parameters in response to changing grid states. Investigating these relationships may reveal key principles that influence how voltage control curves interact with distribution grids, leading to more effective voltage regulation strategies.

After observing the contents from Table 4.1, 4.2 and the additional data from Table A.2, a correlation matrix can be build which shows the correlation between different pairs of columns or performance indicators. A high positive value indicates a strong positive correlation, while a high negative value indicates a strong negative correlation. A value close to zero indicates a weak correlation. Some key correlations that can be observed are:

- Strong Positive Correlation
  - Percentage of violations with VCC & Maximum voltage with VCC (0.78)
  - Percentage of violations with VCC & $\Delta_{MAX}V$ with VCC (0.72)
  - Maximum voltage levels with VCC & $\Delta_{MAX}V$ with VCC (0.84)
- Moderate Negative Correlation

  - Percentage of violations with VCC & Minimum voltage with VCC (-0.59)
  - Minimum voltage levels with VCC & Average length of a feeder (-0.49)
  - Minimum voltage levels with VCC & Average number of nodes per feeder (-0.43)

Despite the potential outlined benefits, the in-depth analysis of correlations between VCC performance indicators and distribution grid characteristics yielded disappointingly few meaningful relationships. While some minor trends were observed, they lacked the statistical significance and consistency to be considered reliable predictors or design guidelines for the development of a voltage control curve.

Specifically, correlations between VCC voltage levels and readily quantifiable grid attributes, such as feeder length or the number of nodes, were not found to be statistically significant. Such correlations, if present, would have been particularly valuable, as they could have informed the selection of VCCs based on easily obtainable grid parameters.

The absence of strong correlations underscores the complexity of the interaction between voltage control curves and distribution grid behavior. It suggests that voltage regulation is influenced by a multitude of factors, including network topology, load distribution, and dynamic operating conditions, which may not be easily captured by simple grid metrics. The lack of easily identifiable correlations highlights the importance of continued simulation and analysis in designing and implementing voltage control strategies. It also emphasizes the importance of ongoing research into the underlying principles guiding voltage regulation in complex distribution networks.

5.1.3. Connection to Research Question

The research question, which requested to develop a universally applicable, simple, and easy-to-implement adaptive voltage control policy for HV/MV transformers to mitigate voltage violations for the end-user, is directly addressed by the results presented in Chapter 4.

The successful development and testing of a genetic algorithm-based optimization framework proves the feasibility of creating such an adaptive voltage control policy. The policy's adaptability is clear in its ability to generate unique voltage control curves that are tailored to the specific characteristics of each of the 30 distribution grids studied. This adaptability directly addresses the *universally applicable* aspect of the research question, showcasing the policy's potential to function effectively across a variety of real-world grid configurations.

The research aims to mitigate voltage limit violations for end-users, which occur in the LV grid. However, the PowerFactory models used in the study did not include detailed LV grids. Therefore, the focus was on providing a more stable voltage from the MV grid to the LV grid. This allows for greater voltage fluctuations without exceeding the threshold limits in the LV grid. The underlying assumption is that by ensuring a stable MV grid voltage, the connected LV grids will also experience improved voltage regulation, indirectly addressing the end-user voltage violation issue.

Furthermore, the focus on using readily available measurements (active power and voltage magnitude) and the integration with existing OLTC systems indicate a prioritization of simplicity and ease of implementation. The use of a genetic algorithm, a well-established optimization technique, further supports this aim. The case studies on real-world distribution grids also demonstrate the practicality and applicability of the developed policy, reinforcing its potential for real-world deployment.

In conclusion, the research findings validate the objective of the research question by showcasing the successful development and testing of an adaptive voltage control policy that tries to mitigate voltage violations in the LV grid with a more stable MV input voltage while adhering to the principles of simplicity and ease of implementation. The research provides a strong foundation for further exploration and potential real-world application of such adaptive voltage control strategies in power distribution networks.

5.1.4. Implications

The findings presented in this research have several significant implications for the practical implementation and future development of adaptive voltage control strategies in real-world distribution networks. These implications span several categories and highlight the broader relevance of the proposed voltage control policy in modern power systems.

- Technical Implications, Enhancing Grid Stability and Resilience: The substantial reduction in voltage violations and fluctuations across diverse distribution grids underscores the effectiveness of the adaptive voltage control strategy in enhancing grid stability. By optimizing voltage control curves tailored to specific grid conditions, this method can better manage the dynamic behavior of distribution networks, particularly in the context of increasing DERs and fluctuating loads. This has significant implications for grid operators, suggesting that adaptive voltage control can serve as a valuable tool for maintaining power quality and reliability, even under challenging conditions such as high DER penetration or sudden load changes.
- Operational Implications, Need for Customized Voltage Control Solutions: The study highlights the importance of grid-specific voltage control solutions, demonstrating that a one-size-fits-all approach may not be effective given the diverse nature of distribution networks. This implies that grid operators need to adopt more customized strategies that consider the unique characteristics of each network. The development and deployment of tools and methodologies for efficient grid modeling and optimization will be crucial for enabling this tailored approach, potentially requiring new investments in data analytics and grid management technologies.
- Economic Implications, Cost-Effectiveness and Efficiency Gains: The policy's simplicity and adaptability, coupled with the significant reductions in voltage violations, suggest that adaptive voltage control can be a cost-effective solution for many distribution networks. By reducing the need for extensive infrastructure upgrades or the installation of expensive voltage regulation devices, this approach offers a practical alternative that minimizes operational costs while maximizing grid performance. Moreover, the potential for decreased power losses and improved energy efficiency can lead to further cost savings, enhancing the overall economic viability of the proposed method. Grid operators should consider these potential benefits when evaluating investment decisions and operational strategies.
- Technological Implications, Leveraging Emerging Technologies: The study demonstrates the potential benefits of using optimization-based approaches, such as genetic algorithms, to enhance voltage control strategies. This has broader implications for leveraging emerging technologies, including artificial intelligence, machine learning, and advanced data analytics, to further improve voltage regulation. The integration of these technologies could enable more responsive and predictive control mechanisms, enhancing the grid's ability to maintain stability under dynamic conditions. Future grid management systems should incorporate these capabilities to fully realize the potential of adaptive voltage control methods.
- Implications for Grid Modernization and Smart Grid Development: Adaptive voltage control strategies align with the ongoing transformation toward smarter, more flexible power systems. The ability to dynamically adjust to changing grid conditions supports the vision of a modern, digitalized grid that can self-optimize and self-heal in response to disturbances. The findings suggest that implementing such adaptive strategies can play a crucial role in enhancing grid flexibility, resilience, and sustainability, facilitating the integration of renewable energy sources, and accommodating new technologies, such as electric vehicles and distributed storage systems.
- Implications for Future Research and Innovation: The unexpected findings in certain grid configurations, such as the limited benefits observed in well-performing urban grids, highlight the need for continuous innovation and research in adaptive voltage control methods. The study suggests that while the proposed policy is effective in many scenarios, it may not be universally applicable without further refinement. This emphasizes the need for ongoing research to explore new optimization techniques, real-time control mechanisms, and hybrid strategies that can handle a broader range of grid conditions. It also points to the importance of pilot projects and field trials to validate and refine these methods in real-world settings.

- Implications for Stakeholder Collaboration and Knowledge Sharing: The findings indicate a need for closer collaboration between grid operators, technology providers, researchers, and policymakers to successfully implement adaptive voltage control strategies. Sharing knowledge and expertise across these stakeholder groups can accelerate the development of innovative solutions and facilitate their deployment in real-world applications. Collaborative efforts could include joint research initiatives, development of best practices, and the establishment of open platforms for data sharing and analysis.

By adopting adaptive voltage control strategies, grid operators can enhance grid performance, support the integration of renewable energy, and contribute to a more sustainable, resilient, and efficient power system. Policymakers and stakeholders should recognize these implications and work together to create an enabling environment that fosters innovation, investment, and collaboration in this critical area of modern power distribution.

5.2. Advantages and Limitations

The adaptive voltage control method proposed in this research demonstrates several key strengths that contribute to its potential effectiveness in real-world distribution networks.

- Simplicity: The fundamental idea of the policy is to optimize a voltage control curve using only four essential parameters, which leads to an overall positive effect on the entire distribution grid. This simplicity facilitates easier understanding and implementation compared to more complex control strategies, making it particularly appealing for utilities and grid operators seeking practical solutions.
- Universal Applicability: The policy is designed to be adaptable to various distribution networks, regardless of their size, topology, or levels of distributed generation. This adaptability arises from applying a genetic algorithm that optimizes the VCC parameters based on the specific characteristics and operational conditions of each network.
- Adaptability to Dynamic Conditions: The research incorporates the performance of the adaptive control policy for future grid conditions to anticipated changes in load profiles and renewable energy generation. This made clear that the control method remains effective even as the grid evolves and experiences fluctuations.

The adaptive voltage control strategy provides a hopeful solution to tackle the issues of voltage regulation in power distribution systems. Its emphasis on simplicity, universal applicability, and adaptability to dynamic grid conditions makes it a valuable tool for utilities and grid operators. The use of a data-driven optimization framework and the focus on real-world distribution networks further enhance its practical relevance and potential for real-world deployment.

While the adaptive voltage control method proposed in this research demonstrates significant potential for enhancing voltage regulation in distribution networks, several limitations must be acknowledged to contextualize its findings and guide future research and implementation efforts.

- Simulation Constraints vs. Real-World Complexity: The study relies heavily on simulations using PowerFactory software to model the behavior of distribution grids under various voltage control settings. While these simulations provide valuable insights, they cannot perfectly capture the complexities, uncertainties, and dynamic behaviors of real-world power systems. Factors such as unexpected equipment failures, unplanned outages, and real-time communication delays between grid components may affect the actual performance of the proposed voltage control policy.
- Data Availability and Quality Limitations: The adaptive voltage control strategy depends on the availability of high-quality, detailed data, including accurate grid models, historical load profiles, and forecasts of renewable energy generation. However, such data may not always be readily accessible or sufficiently accurate, particularly in less advanced grid infrastructures or regions with limited monitoring capabilities. Inaccurate or incomplete data could compromise the optimization of the voltage control curves and reduce the effectiveness of the policy. Addressing these data

limitations may require the development of advanced data analytics and forecasting techniques, as well as improved data collection and management systems.

- Focus on Medium Voltage Grids: The research primarily focuses on voltage control at the MV level and assumes that maintaining a stable MV grid voltage will indirectly improve voltage regulation in LV grids. However, the study does not directly address voltage regulation challenges specific to LV networks, which may have different characteristics.
- Dependence on Accurate Forecasting: The effectiveness of the voltage control policy relies on accurate forecasting of load demands and renewable energy generation. Forecasting errors, which are inevitable due to the variable nature of DERs and consumer behaviors, can lead to sub-optimal voltage control settings.
- Limited Scope of Voltage Control Mechanisms: The study focuses on a specific adaptive voltage control strategy that optimizes voltage control curves primarily through adjustments at HV/MV transformers using OLTCs. This narrow focus may not fully account for other voltage regulation methods or devices.
- Computational and Hardware Limitations: The optimization process, while computationally efficient, still requires significant computational resources, particularly for larger and more complex networks. The study's simulations were performed on a standard laptop, and even with optimized algorithms, the process took several hours for some grids. In practical applications, operators may need access to high-performance computing resources to perform real-time or near-real-time optimization. On top of that, while GAs offer several advantages for adaptive voltage control in distribution networks, they also come with potential disadvantages compared to other optimization algorithms. Some key points are computational cost, no guarantee of global optimally, sensitivity to parameter settings, and the stochastic nature of the algorithm.
- Generalizability and Applicability to Different Grid Conditions: The research findings are based on case studies from 30 different distribution grids, which may not be representative of all possible grid configurations or conditions. The need for grid-specific voltage control curves, as demonstrated by the diversity of optimized VCCs, indicates that the proposed method may not be universally effective without further customization.
- Hardware and Technology Dependency: The study's reliance on specific hardware, such as the REG-D relay for voltage control, may limit the exploration of alternative technologies or configurations. Different grid operators may have varying levels of access to advanced hardware, and the proposed solution may not be compatible with all existing grid infrastructure.
- Assumption of Static Network Topology: The current methodology assumes a relatively static network topology and load distribution, which may not always hold true in real-world scenarios. Distribution grids are subject to ongoing changes. These dynamic conditions may affect the performance of the voltage control policy over time.

While the adaptive voltage control policy proposed in this study offers a promising approach to improving grid stability and accommodating DERs, these limitations must be considered to understand its applicability and effectiveness fully. Addressing these challenges will require further research, real-world validation, and the development of more robust, flexible, and adaptive voltage control strategies that can operate effectively in diverse and evolving grid environments.

5.3. Comparison with Existing Voltage Control Methods

Section 2.7 provided a comprehensive overview of existing voltage control methods found in the literature. The adaptive voltage control policy proposed in this thesis distinguishes itself from existing methods by adopting a unique combination of simplicity, adaptability, and data-driven optimization. Its emphasis on practicality and ease of implementation, achieved by optimizing a limited set of parameters within the voltage control curve, contrasts with many existing approaches that rely on complex models, extensive communication infrastructure, or computationally intensive algorithms.

The policy's focus on real-world distribution networks and its validation through extensive case studies on 30 diverse grids further strengthens its practical relevance and applicability. The emphasis on data-driven optimization, utilizing forecasted and historical grid data, ensures that control settings are continuously refined and adapted to the evolving needs of the network, contrasting with traditional methods that may rely on fixed settings or rule-based control.

In summary, the adaptive voltage control policy presented in this thesis offers a unique and promising approach to voltage regulation in modern distribution networks. By combining simplicity, adaptability, and data-driven optimization, the policy addresses the limitations of existing methods and provides a practical and effective solution for enhancing grid performance and stability in the face of increasing complexity and variability. It prioritizes universal applicability, proactive adaptation, and data-driven optimization, contributing to improved voltage regulation, enhanced grid stability, and increased efficiency in power distribution.

5.4. Recommendations

The proposed methodology, which combines quasi-dynamic simulations with a genetic algorithm optimization framework, provides a systematic way to determine optimal voltage control parameters for specific grid conditions. The use of real-world distribution networks in the case studies further strengthens the practical relevance of the findings. The results demonstrate the effectiveness of the adaptive voltage control policy in reducing voltage violations and improving overall grid performance, even under dynamic and uncertain conditions. Based on this research, several suggestions can be provided to grid operators:

- Embrace Data-Driven Voltage Control: The research highlights the importance of utilizing historical grid data to make voltage control decisions. Investing in advanced metering infrastructure and data analytics capabilities can enable utilities to develop more responsive and effective voltage control strategies in contrast to methods relying solely on historical data.
- Adopt Optimization-Based Approaches: The use of optimization algorithms, such as the genetic algorithm employed in this research, can help utilities to systematically explore the extensive solution space of voltage control parameters and identify optimal settings for specific grid conditions.
- Consider Future Grid Conditions: The research emphasizes the importance of incorporating forecasts of future grid conditions, such as load profiles and renewable energy generation capacity, into the voltage control optimization process. This proactive approach can ensure that the control system remains effective and adaptable as the grid evolves.
- Invest in Computational Resources: The optimization-based approach to voltage control may require significant computational resources, especially for large and complex distribution networks. Utilities should consider investing in adequate hardware and software infrastructure to support the implementation and management of such systems.
- Collaborate with Technology Providers and Researchers: The development and deployment of adaptive voltage control systems often require collaboration between grid operators, technology providers, and researchers. By working together, these stakeholders can leverage their expertise and resources to develop innovative and effective solutions that address the challenges of modern distribution grids.

By considering these recommendations, grid operators can leverage the findings of this research to develop and implement adaptive voltage control systems that enhance the performance, stability, and resilience of their distribution networks. This can contribute to a more reliable and sustainable electricity supply, while also accommodating the increasing penetration of distributed energy resources and other emerging technologies.

5.5. Future Research

While the adaptive voltage control policy developed in this thesis has shown promise in improving voltage regulation in distribution networks, several areas remain for further exploration to enhance the policy's effectiveness, robustness, and applicability. The following future research directions are proposed:

- Incorporating Additional Grid Components and Control Devices: Future studies should broaden the scope of voltage control by including additional grid components such as energy storage systems. Exploring how these elements interact with the adaptive voltage control policy can provide a more holistic approach to voltage regulation. Research could focus on the coordinated control of various devices to optimize overall grid performance, reduce power losses, and enhance voltage stability across all network levels.
- Extending Analysis to Low Voltage Networks: Given that the current study primarily focuses on MV grids, further research should investigate the policy's effectiveness in low voltage networks. LV networks have unique characteristics, such as shorter line lengths, higher variability in load types, and greater sensitivity to voltage fluctuations. Extending the analysis to LV grids will help assess the adaptive voltage control policy's full applicability and potential impact across different distribution network levels, especially in grids with high penetration of distributed energy resources.
- Development of Real-Time Control and Adaptation Mechanisms: To further improve the adaptability and resilience of the voltage control policy, future research should focus on developing real-time control mechanisms that can respond dynamically to sudden changes in grid conditions, such as unexpected load shifts or generation outages. This could involve integrating advanced control algorithms that allow for continuous adjustment of voltage settings based on real-time data. Real-time control could significantly enhance the grid's ability to maintain voltage stability under rapidly changing conditions.
- Exploration of Alternative Optimization Algorithms: While this study employed a genetic algorithm to optimize voltage control curves, there are numerous other optimization techniques that could potentially improve performance. Future research could explore alternative algorithms to identify more efficient or effective solutions. Comparing the performance, computational requirements, and robustness of different algorithms could help identify the most suitable approach for varying grid conditions and complexities.
- Investigation of Advanced Forecasting Techniques: The effectiveness of the adaptive voltage control policy is closely tied to the accuracy of load and renewable energy generation data and forecasts. Future research should investigate advanced forecasting techniques, such as machine learning models or hybrid approaches that combine statistical and AI-based methods, to enhance prediction accuracy. Improved forecasting could enable more precise voltage control, minimizing the risk of over- or under-compensation and enhancing grid stability.
- Integration with Emerging Technologies: The arrival of new technologies, such as smart meters and communication systems, offers significant opportunities to enhance adaptive voltage control strategies. Future studies could explore how these technologies can be integrated to provide more detailed monitoring, faster communication, and more responsive control.
- Assessment of Economic and Environmental Impacts: While the current study focuses primarily on technical performance indicators, future research should consider the economic and environmental implications of implementing adaptive voltage control policies. This could involve conducting cost-benefit analyses to evaluate the financial viability of different voltage control strategies or assessing their impact on greenhouse gas emissions and overall energy efficiency. Such studies would provide a more comprehensive understanding of the trade-offs involved and help guide policy and investment decisions.

- Incorporation of Uncertainties and Stochastic Modeling: To better capture the uncertainties inherent in power distribution systems, future research could incorporate stochastic modeling techniques that account for variability in load demand, generation output, and equipment performance. This approach could help in developing more robust voltage control strategies that can adapt to unpredictable changes in grid conditions. Additionally, probabilistic risk assessments could be used to evaluate the likelihood of voltage violations under various scenarios and inform more resilient voltage control designs.
- Exploration of Multi-Objective Optimization: The current study primarily focuses on minimizing voltage violations. However, other objectives, such as minimizing power losses, maximizing energy efficiency, or optimizing economic costs, could also be considered. Future research could explore multi-objective optimization techniques that balance these competing objectives, potentially leading to more holistic and effective voltage control strategies.
- Validation Through Field Trials and Pilot Projects: Finally, future research should focus on validating the adaptive voltage control policy through field trials or pilot projects in collaboration with grid operators. Real-world testing would provide critical insights into the practical challenges and benefits of implementing the policy, helping to refine the approach and ensure its readiness for widespread deployment. Such trials could also facilitate the collection of real-world data to further improve the models and algorithms used in the voltage control strategy.

By pursuing these future research directions, the adaptive voltage control policy can be refined, expanded, and better integrated into modern power distribution networks. These efforts will contribute to developing more advanced, robust, and flexible voltage control solutions that can meet the evolving needs of a resilient and sustainable power grid.

6

Conclusion

The preceding chapters have thoroughly detailed the development, implementation, and evaluation of an adaptive voltage control strategy designed to enhance the stability and efficiency of modern power distribution networks. The research journey initiated in this thesis has explored the complexities of voltage regulation in the face of increasing distributed generation and load variability. The findings presented in the results chapter offer compelling evidence of the effectiveness of the proposed approach in mitigating voltage violations in the MV grid and fluctuations across a diverse range of real-world distribution grids. The adaptive nature of the voltage control curves, tailored to the unique characteristics of each grid, has proven instrumental in achieving significant improvements in voltage regulation.

6.1. Answers to Research Questions

Based on the research motivation, Section 1.3 presented the research objectives of this thesis. The main research objective was given in the form of the main research question. The answer to this question will be given later in this section, however prior to addressing the main research question, the sub-research questions will be answered:

Which distribution grid data is available by a DSO and which available data can be used to develop an adaptive voltage control policy?

The development of an adaptive voltage control policy necessitates a comprehensive software model of the MV grid, constructed within a platform like PowerFactory. This model should accurately incorporate all relevant components of the MV grid, including lines, transformers, loads, and distributed generation sources. The accuracy and effectiveness of the policy depend on the inclusion of historical load profiles and generation patterns for these components, providing a baseline understanding of the grid's behavior under various operating conditions. Furthermore, the model must include predictions of future load and generation profiles, allowing the testing of the policy on changing grid dynamics. If data on the individual LV grid customers is available, it can be incorporated into the model to further refine and optimize the adaptive voltage control method. The inclusion of detailed LV grid data would allow for a more granular understanding of voltage behavior at the consumer level, potentially leading to even more effective voltage regulation strategies. However, if LV grid data is not available, an adaptive voltage control policy can still be developed, as this thesis has proven.

How can the parameters which define the setting points of the voltage control curve be found or calculated, and what is needed to create a unique curve for every distribution grid and thereby make the policy universally applicable?

These parameters can be determined using a genetic algorithm. The GA is an optimization algorithm inspired by natural evolution that operates on a population of potential solutions, represented as chromosomes. In this context, each chromosome encodes a set of four parameters that define a candidate VCC. The GA iteratively refines these candidate solutions over multiple generations, evaluating their fitness based on their performance in quasi-dynamic simulations of the power distribution network. The fitness of each VCC is assessed using key performance indicators that measure its ability to maintain voltage levels within acceptable limits and minimize voltage violations. The GA uses selection, crossover, and mutation operators to evolve the population of VCCs, favoring those with higher fitness scores. This process continues until an optimal or near-optimal VCC is found that effectively regulates voltage levels in the distribution grid. On top of that, the research proposes that the development of a Python optimization script is the key to making the adaptive voltage control policy universally applicable. The script, which integrates a genetic algorithm with quasi-dynamic power system simulations, can be executed for any unique distribution grid. The GA systematically explores various voltage control curve parameter combinations, evaluating their performance in the simulated grid environment. The script's output is the optimal VCC that minimizes voltage violations and enhances grid stability for that specific MV distribution grid.

Additionally, as discussed in Section 5.1, it should be noted that VCCs are proven effective for maintaining grid stability in many distribution grids, however they may not be necessary for all grids. Some grids may not experience significant voltage issues at all. Adding a unique VCC to a grid that does not require one can introduce unnecessary complexity. It is important to assess the specific characteristics of each distribution grid to determine whether a VCC is warranted. If a grid does not exhibit significant voltage issues, a simpler control strategy or even no active voltage control may be sufficient to maintain grid stability.

Which factors affect the parameters which define the setting points of the voltage control curve the most, even if they are not accessible for the DSO?

The research was unable to provide a definitive answer to the question. The research explored the relationship between grid characteristics (such as the number of MV nodes, feeders, average feeder length, and installed DG capacity) and the resulting VCC parameters. However, the analysis did not reveal a clear correlation or definitive ranking of factors influencing the VCC parameters. There is acknowledged that the complexity of distribution networks and the interplay of various factors, suggesting that the impact of individual factors on VCC parameters may vary depending on the specific network configuration and operating conditions. The absence of a clear correlation underscores the need for further research to fully understand the complex relationship between grid characteristics and VCC parameters. The study emphasizes the importance of using optimization techniques, such as genetic algorithms, to identify the optimal VCC parameters for each specific network, considering its unique characteristics and operational requirements.

What are new adjustment rules to determine the best tap position of the MV/LV transformer to gain the best voltage stability in combination with the voltage control curve?

The main finding is that the introduction of a VCC at the HV/MV transformer can significantly impact the voltage profile on the MV side, which in turn affects the LV side through the MV/LV transformers. This research demonstrates this by comparing the LV-side voltage profiles in one the studied distribution grid under two scenarios: one with real-life (adjusted) tap settings and another with all MV/LV transformers set to their neutral tap setting. The results show a marked improvement in voltage stability when using the neutral tap setting in combination with the optimized VCC. So, there is suggested that the optimal tap position for MV/LV transformers might shift towards the neutral setting when a VCC is actively managing voltage at the HV/MV level. The improved voltage regulation at the MV level, thanks to the VCC, reduces the need for MV/LV transformers to compensate for voltage deviations through tap adjustments. Therefore, the adjustment rule could be: *In the presence of an optimized VCC at the HV/MV transformer, consider setting the MV/LV transformers to their neutral tap positions.*

How often should the adaptive voltage control curve be reset? What developments within the distribution grid influence the control curve?

The optimal reset frequency for the adaptive voltage control curve differs for each distribution grid and depends on various factors, including grid dynamics and complexity, desired performance level, and computational resources. Several developments within the distribution grid can influence the performance of the voltage control curve, such as increased load, increased generation, new connections, and grid changes. Monitoring these factors is essential for ensuring the VCC's effectiveness, and can be achieved through periodic voltage measurements, grid data analysis, and simulation studies. Findings from this research indicate a decrease in performance over 5 and 10 years, yet the application of the voltage control curve continues to produce beneficial outcomes in both scenarios. The decision on whether to recalculate the VCC should be based on the DSO's specific performance requirements. If the observed performance drop falls below the DSO's minimum acceptable level, it may be necessary to recalculate the VCC. However, if the performance remains within acceptable limits, the DSO may choose to delay recalculation to optimize computational resources and minimize control actions.

All these answers contribute to addressing the main research question outlined at the beginning of this thesis:

*How can a **universally applicable adaptive voltage control policy** be developed for a **HV/MV transformer** in a power distribution network to mitigate **voltage limit violations** for the end-user, while prioritizing **simplicity** and **ease of implementation**?*

The answer to this question can be found by following the four steps that are provided next:

1. Leverage Existing Hardware and Control Mechanisms: The policy utilizes the existing OLTC and relay-based systems commonly found in HV/MV transformers. This eliminates the need for additional hardware installations, promoting simplicity and ease of implementation. For this particular study, the policy is developed for the REG-D relay from A. Eberle.
2. Utilize the Current Influence Control Method: The REG-D Relay's current influence control method is employed to dynamically adjust the voltage setpoint based on the transformer's load current or active power. This method enables compensation for voltage drops and rises caused by load variations and DG, respectively, addressing the core issue of voltage limit violations.
3. Optimize the Voltage Control Curve: The VCC, which defines the relationship between the voltage setpoint and active power, is optimized using a genetic algorithm. This algorithm systematically explores various VCC parameter combinations to find the optimal settings that minimize voltage limit violations across the entire distribution grid. This data-driven approach ensures that the policy is tailored to the specific characteristics and operational conditions of each network, promoting universal applicability.
4. Employ Quasi-Dynamic Simulations for Evaluation: The performance of the optimized VCC is evaluated using quasi-dynamic simulations in PowerFactory. These simulations capture the dynamic behavior of the grid under varying operating conditions, allowing for a realistic assessment of the policy's effectiveness in mitigating voltage limit violations.

By combining these elements, the proposed adaptive voltage control policy offers a practical and effective solution for mitigating voltage limit violations in distribution networks. The focus on simplicity, universal applicability, and adaptability ensures that the policy can be readily implemented and effectively manage voltage fluctuations in diverse grid environments.

6.2. Overall Conclusion

The thesis successfully developed and evaluated a universally applicable adaptive voltage control policy for HV/MV transformers in power distribution networks, aimed at mitigating voltage limit violations at end-user connections. This policy improves grid stability and reliability, especially with the rise of distributed energy resources and varying load requirements. Through the optimization of voltage control curve parameters, the research achieved significant reductions in voltage variations and violations across a broad spectrum of real-world medium voltage distribution networks, demonstrating the policy's capacity to handle diverse (future) grid conditions effectively.

The research findings underscore the effectiveness of the adaptive voltage control policy in dynamically adapting to the evolving nature of power distribution networks. The policy demonstrated a high degree of flexibility by adjusting voltage control settings in response to changes such as variable loads and the intermittent nature of DER generation. The optimization process, driven by a genetic algorithm, enabled the identification of optimal voltage control curve parameters tailored to specific network conditions, resulting in enhanced voltage stability, improved power quality, and increased resilience of the grid. This adaptability is particularly crucial given the growing trend toward decentralized energy systems and the corresponding increase in voltage management challenges.

Furthermore, the policy's ability to maintain voltage levels within stricter regulatory limits facilitates greater integration of DERs. The research also provided an in-depth examination of the impact of DERs on grid operation, highlighting the complexities introduced by reverse power flows and voltage fluctuations. By incorporating quasi-dynamic simulations and key performance indicators, the study established a robust framework for evaluating the policy's effectiveness and provided a data-driven basis for further optimization and refinement. The policy is also evaluated using scenarios projected 5 and 10 years into the future.

A notable strength of the developed policy lies in its simplicity and ease of implementation. Unlike many existing voltage control approaches that require complex, network-specific tuning, the adaptive policy offers a streamlined solution that can be universally applied across various distribution networks. This universality reduces the need for bespoke solutions, thereby lowering operational costs and minimizing the technical burden on grid operators. Additionally, the policy's adaptability to dynamic grid conditions ensures it remains effective despite evolving challenges, such as increasing DER penetration and fluctuating demand profiles. Its flexibility makes it an ideal candidate for real-world application, where grid conditions are inherently unpredictable and vary across regions.

However, the thesis also recognizes certain limitations and directions for future exploration. The research was primarily focused on medium voltage grids, indicating the need for further investigation into the policy's applicability to low voltage networks, where voltage regulation can present different challenges. Additionally, the study assumed the availability of detailed grid models and historical data to inform the optimization process. In practice, such data may not always be available, particularly in less advanced grid infrastructures or in emerging markets. Future research could explore methodologies to enhance the policy's robustness in data-scarce environments, such as leveraging machine learning techniques to predict grid behavior or using real-time data to adapt voltage control settings dynamically.

The research findings contribute significantly to the field of voltage control in power distribution networks by providing valuable insights into the development of more effective, adaptable, and accessible control strategies. The adaptive voltage control policy developed in this thesis offers a practical solution for mitigating voltage limit violations and enhancing grid stability, especially in the context of increased DER integration and evolving grid dynamics. By demonstrating a clear path forward for future research and development, the thesis paves the way for innovations that could further improve grid performance and ensure the reliability of power systems in the face of ongoing energy transitions. The work aligns with global efforts to create a more resilient and sustainable power grid, positioning itself as a critical contribution to the advancement of modern electrical distribution networks.

A

Additional Results

Table A.1: Optimized values for the VCC's parameters, *x2, x4, y1, y4*, found for each individual distribution grid using the GA-based optimization algorithm (Based on 2023).

Distribution Grid Number	**Voltage Control Curve Parameters**			
	x2	**x4**	**y1**	**y4**
1	-23.3365	23.9989	0.9889	1.0183
2	-23.3453	32.6101	0.9670	1.0151
3	-25.3876	18.6378	0.9705	1.0190
4	-23.1704	22.3901	0.9360	1.0305
5	-23.9589	23.9158	0.9751	1.0180
6	-25.8808	26.6524	0.9330	1.0138
7	-16.1680	16.7199	0.9733	1.0000
8	-32.7961	24.4151	0.9709	1.0149
9	-36.8165	28.1407	0.9171	1.0286
10	-21.2095	32.5760	0.9555	1.0155
11	-19.8599	30.5953	0.9747	1.0000
12	-30.0931	29.1334	0.9358	1.0000
13	-25.6379	9.6617	0.8862	1.0141
14	-30.6002	24.0172	0.9116	1.0147
15	-21.7280	31.5775	0.9623	1.0288
16	-30.1717	26.6472	0.9193	1.0404
17	-15.3016	38.6580	0.9134	1.0049
18	-40.0000	40.0000	0.9997	1.0242
19	-19.8944	12.1523	0.9294	1.0080
20	-32.1527	37.0468	0.8727	1.0000
21	-49.6226	35.9088	0.9311	1.0313
22	-30.9319	24.1318	0.9750	1.0217
23	-27.9239	46.4397	0.9044	1.0306
24	-54.1012	29.8237	0.9145	1.0231
25	-14.5328	11.1158	0.9878	1.0163
26	-20.0696	5.0212	0.9794	1.0103
27	-24.1134	30.2025	0.9903	1.0162
28	-16.7566	25.4360	0.9834	1.0147
29	-33.3171	44.0541	0.9927	1.0460
30	-32.6597	23.0186	0.9298	1.0236

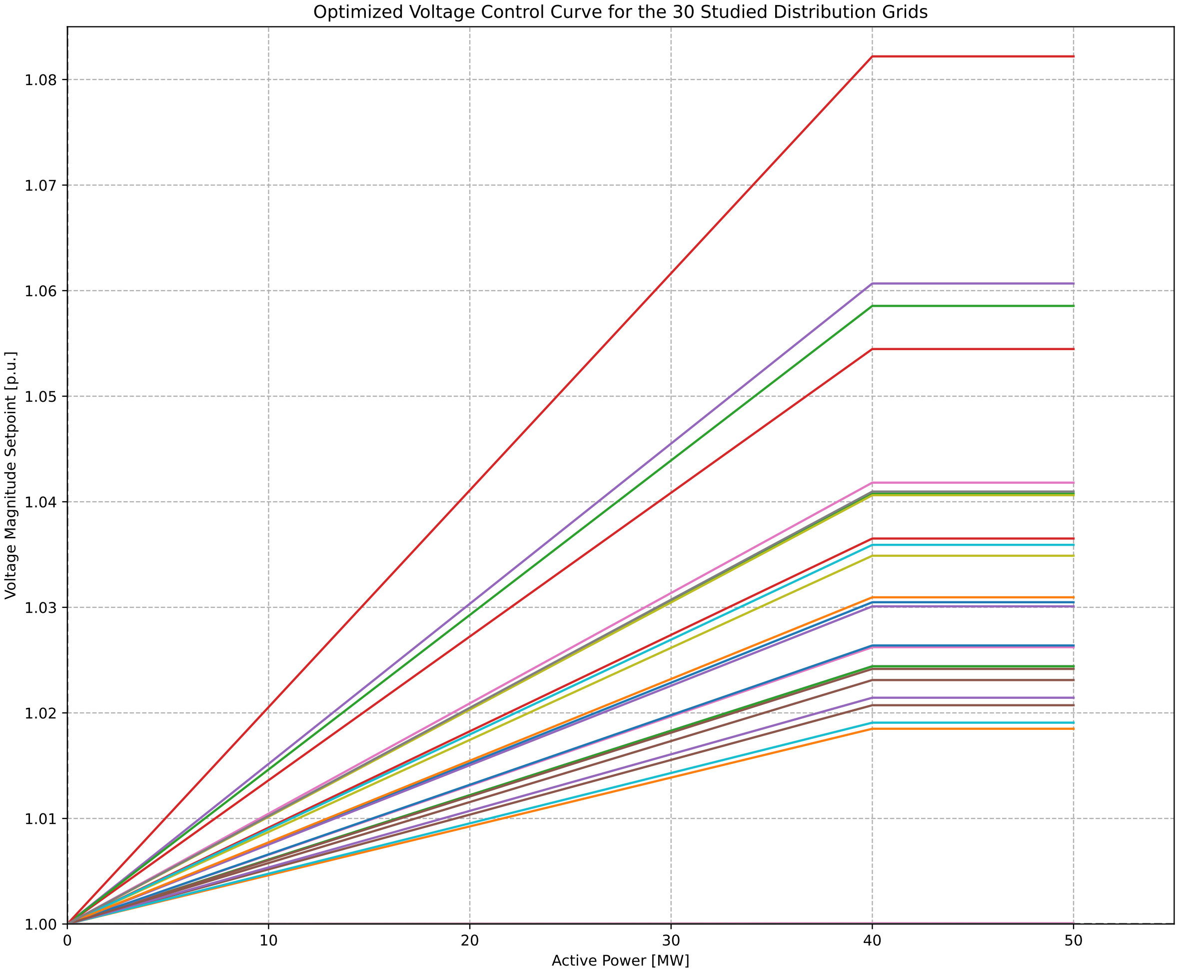


Figure A.1: Cropped version for only positive active power of all 30 optimized voltage control curves found with the GA-based optimization algorithm.

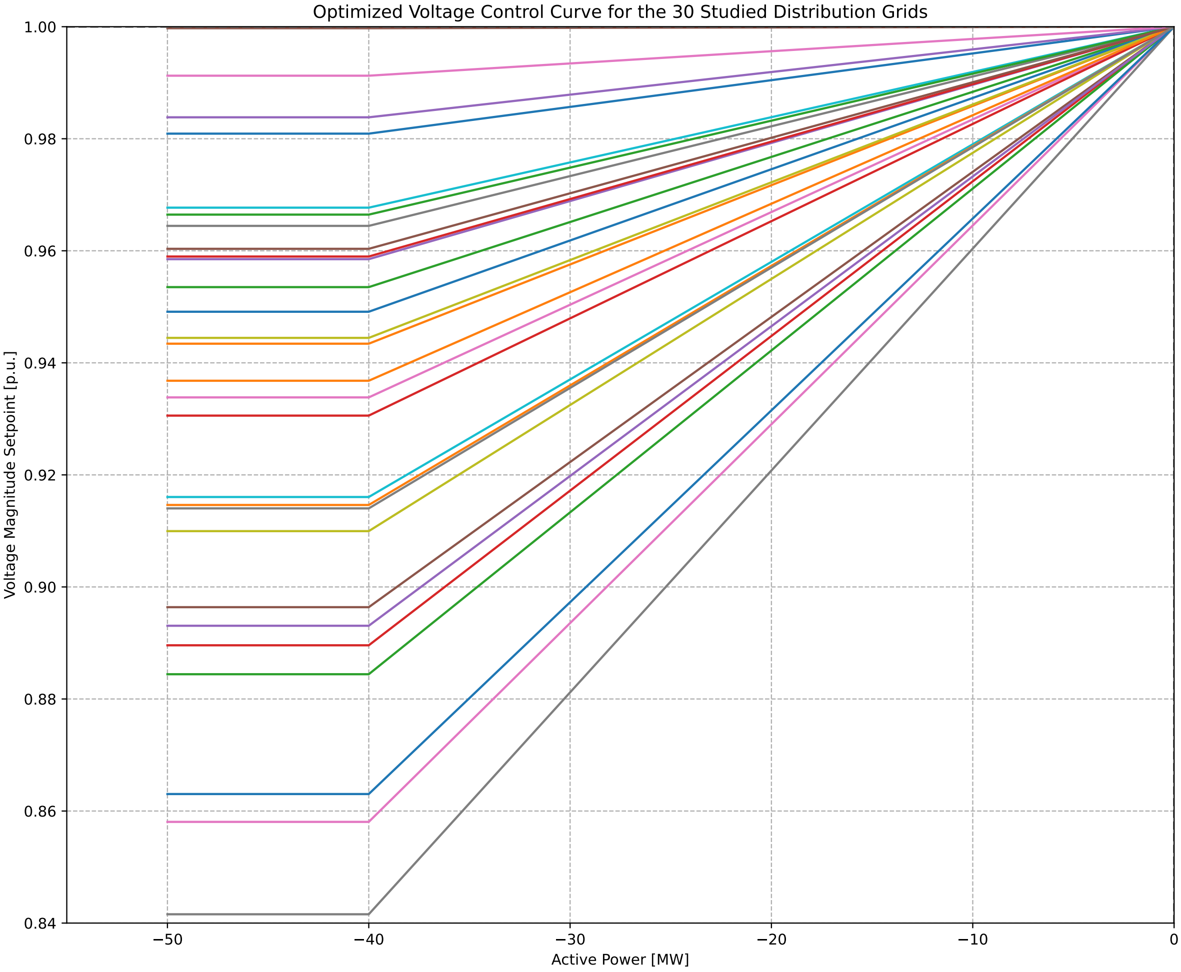


Figure A.2: Cropped version for only negative active power of all 30 optimized voltage control curves found with the GA-based optimization algorithm.

Table A.2: Performance of the best VCC found for all 30 distribution grid using the optimization algorithm (based on 2023). Average values are provided of all 30 distribution grids. These results show the positive effect of the VCC in terms of a reduction in the percentage of violations and maximum and minimum voltage levels. Additionally, data is provided on the computational time and number of iterations required to find the optimal voltage control curve.

Distr. Grid Number	**Percentage of Violations (>±3%) without VCC**	**Percentage of Violations (>±3%) with VCC**	**Reduction in Violations (>±3%)**	**Reduction in $\Delta_{MAX}V$**	**Time used to find Best VCC [minutes]**	**Number of Iterations used**	**V_{MAX} without VCC [p.u.]**	**V_{MAX} with VCC [p.u.]**	**V_{MIN} without VCC [p.u.]**	**V_{MIN} with VCC [p.u.]**	**$\Delta_{MAX}V$ without VCC [p.u.]**	**$\Delta_{MIN}V$ with VCC [p.u.]**
1	0.28%	0.00%	100.00%	29.09%	1285	15	1.0322	1.0295	0.9533	0.9726	0.0770	0.0546
2	0.00%	0.00%	-	7.94%	620	15	1.0253	1.0286	0.9774	0.9819	0.0428	0.0394
3	1.62%	0.06%	96.04%	33.93%	745	15	1.0596	1.0422	0.9427	0.9625	0.1126	0.0744
4	0.21%	0.01%	96.82%	13.69%	48	1	1.0477	1.0322	0.9641	0.9629	0.0751	0.0648
5	0.02%	0.01%	75.79%	-9.82%	788	8	1.0343	1.0330	0.9664	0.9536	0.0601	0.0660
6	4.32%	0.00%	100.00%	57.51%	408	6	1.0276	1.0234	0.9447	0.9832	0.0746	0.0317
7	0.02%	0.02%	0.43%	0.00%	1285	15	1.0346	1.0346	0.9696	0.9696	0.0587	0.0587
8	11.00%	0.02%	99.80%	-0.06%	1403	15	1.0344	1.0344	0.9630	0.9630	0.0671	0.0671
9	0.18%	0.03%	82.77%	11.56%	704	15	1.0387	1.0358	0.9601	0.9640	0.0692	0.0612
10	0.10%	0.00%	100.00%	26.26%	377	11	1.0216	1.0241	0.9617	0.9760	0.0523	0.0386
11	0.26%	0.06%	77.39%	-1.52%	1026	15	1.0476	1.0465	0.9670	0.9656	0.0702	0.0713
12	0.00%	0.00%	-	0.00%	322	4	1.0278	1.0278	0.9716	0.9716	0.0562	0.0562
13	0.00%	0.00%	-	2.55%	75	1	1.0100	1.0241	0.9819	0.9961	0.0275	0.0268
14	0.00%	0.00%	-	12.73%	500	6	1.0115	1.0244	0.9712	0.9869	0.0377	0.0329
15	0.00%	0.00%	-	-16.57%	923	15	1.0150	1.0212	0.9798	0.9790	0.0344	0.0401
16	0.33%	0.00%	100.00%	24.29%	487	13	1.0297	1.0291	0.9593	0.9700	0.0704	0.0533
17	0.00%	0.00%	-	0.00%	75	1	1.0149	1.0149	0.9884	0.9884	0.0249	0.0249
18	0.00%	0.00%	-	0.00%	760	14	1.0227	1.0227	0.9823	0.9823	0.0325	0.0325
19	0.00%	0.00%	-	0.00%	230	4	1.0202	1.0202	0.9922	0.9922	0.0243	0.0243
20	6.37%	0.00%	100.00%	51.99%	1305	13	1.0100	1.0100	0.9363	0.9740	0.0733	0.0352
21	0.89%	0.04%	95.38%	27.09%	536	5	1.0379	1.0382	0.9432	0.9600	0.0948	0.0691
22	0.01%	0.00%	100.00%	10.50%	547	6	1.0260	1.0238	0.9674	0.9703	0.0564	0.0505
23	0.00%	0.00%	-	25.16%	32	1	1.0214	1.0270	0.9716	0.9879	0.0465	0.0348
24	18.18%	0.05%	99.71%	48.09%	814	9	1.0870	1.0373	0.9082	0.9598	0.1387	0.0720
25	0.09%	0.00%	100.00%	69.46%	163	2	1.0394	1.0273	0.9595	0.9704	0.0799	0.0244
26	0.22%	0.03%	87.76%	0.96%	698	9	1.0357	1.0349	0.9587	0.9634	0.0722	0.0715
27	0.00%	0.00%	100.00%	24.63%	680	10	1.0256	1.0271	0.9691	0.9835	0.0475	0.0358
28	0.10%	0.00%	100.00%	21.32%	637	10	1.0371	1.0337	0.9607	0.9700	0.0702	0.0552
29	0.02%	0.01%	62.50%	23.97%	849	15	1.0272	1.0293	0.9628	0.9694	0.0580	0.0441
30	0.76%	0.11%	84.96%	20.96%	806	15	1.0441	1.0444	0.9501	0.9595	0.0940	0.0743
Average	**1.50%**	**0.0152%**	**88.54%**	**17.19%**	**637.6**	**10.5**	**-**	**-**	**-**	**-**	**-**	**-**
Stdev.	**0.04%**	**0.0003%**	**23.05%**	**20.03%**	**377.9**	**6.8**	**-**	**-**	**-**	**-**	**-**	**-**

Table A.3: Additional performance for stricter ±2% voltage limits of the best VCC found for each individual distribution grid using the optimization algorithm. Showing that the VCC not only suppresses the voltage levels just below the ±3% threshold but also below the ±2% threshold for some distribution grids.

Distr. Grid Number	**Percentage of Violations (>±2%) without VCC**	**Number of Violations (>±2%) without VCC**	**$\Delta_{MAX}V$ without VCC [p.u.]**	**Percentage of Violations (>±2%) with VCC**	**Number of Violations (>±2%) with VCC**	**$\Delta_{MAX}V$ with VCC [p.u.]**	**Reduction In Violations**	**Reduction In $\Delta_{MAX}V$**
1	3.21%	59339	0.0770	0.54%	10042	0.0546	83.09%	29.09%
2	0.01%	100	0.0428	0.02%	209	0.0394	-128.57%	7.94%
3	7.35%	211767	0.1126	2.92%	84056	0.1363	60.31%	-21.05%
4	2.76%	45999	0.0751	1.57%	26071	0.0648	43.31%	13.72%
5	1.30%	25501	0.0601	1.57%	30647	0.0659	-20.38%	-9.65%
6	17.90%	285269	0.0746	17.90%	285093	0.0745	0.01%	0.13%
7	0.94%	17753	0.0587	0.94%	17753	0.0587	0.00%	0.00%
8	11.00%	439129	0.0671	11.00%	439129	0.0671	0.00%	0.00%
9	5.11%	86814	0.0692	3.45%	58616	0.0731	32.49%	-5.64%
10	2.28%	38303	0.0523	2.27%	38185	0.0523	0.26%	0.00%
11	1.83%	14869	0.0702	1.44%	11699	0.0713	21.36%	-1.57%
12	0.01%	371	0.0562	0.01%	371	0.0562	0.00%	0.00%
13	0.00%	0	0.0275	0.00%	0	0.0268	0.00%	2.55%
14	0.16%	2831	0.0271	0.16%	2841	0.0329	-1.24%	-21.40%
15	0.00%	6	0.0344	0.00%	6	0.0344	0.00%	0.00%
16	6.01%	57382	0.0704	6.01%	57382	0.0704	0.00%	0.00%
17	0.00%	0	0.0249	0.00%	0	0.0249	0.00%	0.00%
18	0.01%	180	0.0325	0.01%	180	0.0325	0.00%	0.00%
19	0.00%	7	0.0243	0.00%	7	0.0243	0.00%	0.00%
20	7.92%	106763	0.0733	0.17%	2075	0.0352	97.89%	51.98%
21	4.70%	118461	0.0948	2.26%	57615	0.068	51.88%	28.27%
22	1.57%	27348	0.0564	0.41%	3438	0.0511	74.19%	9.40%
23	0.17%	2738	0.0465	0.09%	1511	0.0515	45.88%	-10.75%
24	42.15%	956156	0.1387	2.95%	67815	0.072	93.00%	48.09%
25	2.60%	70698	0.0799	0.28%	7620	0.0538	89.21%	32.67%
26	1.79%	26421	0.0722	1.06%	12356	0.0715	40.79%	0.97%
27	0.28%	5694	0.0475	0.09%	1809	0.0423	68.10%	10.95%
28	2.27%	35225	0.0702	0.41%	4909	0.0574	81.87%	18.23%
29	1.02%	13612	0.0580	0.10%	1366	0.0441	89.93%	23.97%
30	3.87%	63641	0.0940	1.86%	30547	0.0743	52.01%	20.96%
Average	**4.27%**	**-**	**-**	**1.98%**	**-**	**-**	**11.06%**	**7.63%**
Stdev.	**8.03%**	**-**	**-**	**3.71%**	**-**	**-**	**46.77%**	**17.26%**

Table A.4: Simulation results for the remaining Key Performance Indicators, mentioned in Section 3.2, with and without Voltage Control Curve. It includes columns such as the average voltage deviation without and with VCC, the number of nodes with voltage deviations exceeding ±3% limit, and the number of nodes with violations both with and without VCC. Additional metrics include the duration of the longest violation events and the total number of voltage violations. The table shows how VCC significantly reduces the number of nodes with violations, the duration of events, and the total number of violations in many distribution grids.

Distr. Grid Number	**$\Delta_{AVG}V$ without VCC**	**$\Delta_{AVG}V$ with VCC**	**Number of Nodes with $\Delta V>\pm3\%$ without VCC**	**Number of Nodes with $\Delta V>\pm3\%$ with VCC**	**Number of Nodes with Violations without VCC**	**Number of Nodes with Violations with VCC**	**Duration Longest Violation Event without VCC**	**Duration Longest Violation Event with VCC**	**Total Number of Violations without VCC**	**Total Number of Violations with VCC**
1	0.0394	0.0366	15	0	73	0	7	0	5248	0
2	0.0255	0.0270	0	0	0	0	0	0	0	0
3	0.0533	0.0465	101	59	163	129	9	8	46739	5709
4	0.0461	0.0453	28	5	54	25	7	4	3461	110
5	0.0345	0.0379	1	2	21	27	3	3	377	143
6	0.0654	0.0645	158	158	182	182	16	16	68839	4
7	0.0375	0.0375	0	0	7	7	6	6	450	450
8	0.0513	0.0513	37	37	211	211	3	3	1874	23
9	0.0512	0.0476	24	28	90	70	4	5	3117	176
10	0.0311	0.0337	0	0	28	37	3	3	1661	0
11	0.0702	0.0437	4	9	8	20	10	8	2129	1143
12	0.0267	0.0267	0	0	0	0	0	0	0	0
13	0.0275	0.0233	0	0	0	0	0	0	0	0
14	0.0271	0.0283	0	0	0	0	0	0	0	0
15	0.0344	0.0344	0	0	0	0	0	0	0	0
16	0.0438	0.0438	7	7	53	53	5	5	3104	0
17	0.0249	0.0217	0	0	0	0	0	0	0	0
18	0.0325	0.0325	0	0	0	0	0	0	0	0
19	0.0243	0.0243	0	0	0	0	0	0	0	0
20	0.0733	0.0352	12	0	24	0	126	0	85901	0
21	0.0416	0.0384	34	22	71	66	10	5	22454	1049
22	0.0564	0.0347	0	0	9	0	2	0	97	0
23	0.0465	0.0272	0	0	0	0	0	0	0	0
24	0.0651	0.052	122	89	224	160	4055	6	412267	1218
25	0.0799	0.0538	24	0	60	0	5	0	2542	0
26	0.0722	0.0515	13	8	31	4	7	5	3200	373
27	0.0298	0.0423	0	0	6	0	1	0	12	0
28	0.0702	0.0574	1	0	41	4	4	2	1553	10
29	0.0580	0.0441	0	0	11	1	4	1	267	1
30	0.0940	0.0399	21	5	42	6	8	3	12490	131

Table A.5: Comparison of data for Key Performance Indicators with and without the implementation of an optimized Voltage Control Curve. This table presents a summary of grid-level improvements for the studied distribution grids, focusing on voltage violations and overall grid performance. It includes metrics such as the reduction of average voltage deviation, improvements in the number of nodes with voltage deviations exceeding ±3% limit, reductions in the number of nodes with violations, and improvements in the duration and total number of voltage violations.

Distr. Grid Number	**Reduction Of $\Delta_{AVG}V$ [p.u.]**	**Impr. Of $\Delta_{AVG}V$**	**Reduction in Number of Nodes with ΔV>±3%**	**Impr.t in Number of Nodes with ΔV>±3%**	**Reduction in Number of Nodes with Violations**	**Impr. in Number of Nodes with Violations**	**Reduction in Duration Longest Violation Event**	**Impr. in Duration Longest Violation Event**	**Reduction in Total Number of Violations**	**Impr. in Total Number of Violations**
1	0.0028	7.11%	15	100%	73	100%	7	100%	5248	100%
2	-0.0015	-5.88%	0	-	0	-	0	-	0	-
3	0.0068	12.76%	42	42%	34	21%	1	11%	21030	45%
4	0.0008	1.74%	23	82%	29	54%	3	43%	3351	97%
5	-0.0034	-9.86%	-1	-100%	-6	-29%	0	-	-291	-77%
6	0.0009	1.38%	0	-	0	-	0	-	47	0%
7	0	0.00%	0	-	0	-	0	-	0	-
8	0	0.00%	0	-	0	-	0	-	0	-
9	0.0036	7.03%	-4	-17%	20	22%	-1	-25%	-2048	-66%
10	-0.0026	-8.36%	0	-	-9	-32%	0	-	17	1%
11	0.0265	37.75%	-5	-125%	-12	-150%	2	20%	986	46%
12	0	0.00%	0	-	0	-	0	-	0	-
13	0.0042	15.27%	0	-	0	-	0	-	0	-
14	-0.0012	-4.43%	0	-	0	-	0	-	0	-
15	0	0.00%	0	-	0	-	0	-	0	-
16	0	0.00%	0	-	0	-	0	-	0	-
17	0.0032	12.85%	0	-	0	-	0	-	0	-
18	0	0.00%	0	-	0	-	0	-	0	-
19	0	0.00%	0	-	0	-	0	-	0	-
20	0.0381	51.98%	12	100%	24	100%	126	100%	85901	100%
21	0.0032	7.69%	12	35%	5	7%	5	50%	21405	95%
22	0.0217	38.48%	0	-	9	100%	2	100%	97	100%
23	0.0193	41.51%	0	-	0	-	0	-	0	-
24	0.0131	20.12%	33	27%	64	29%	4049	100%	411049	100%
25	0.0261	32.67%	24	100%	60	100%	5	100%	2542	100%
26	0.0207	28.67%	5	38%	27	87%	2	29%	2827	88%
27	-0.0125	-41.95%	0	-	6	100%	1	100%	12	100%
28	0.0128	18.23%	1	100%	37	90%	2	50%	1543	99%
29	0.0139	23.97%	0	-	10	91%	3	75%	266	100%
30	0.0541	57.55%	16	76%	36	86%	5	63%	12359	99%
Average	**0.0084**	**11.54%**	**-**	**35.31%**	**-**	**45.63%**	**140.4**	**60.99%**	**-**	**62.65%**
Stdev.	**0.0138**	**20.46%**	**-**	**72.03%**	**-**	**66.43%**	**726.2**	**38.72%**	**-**	**57.56%**

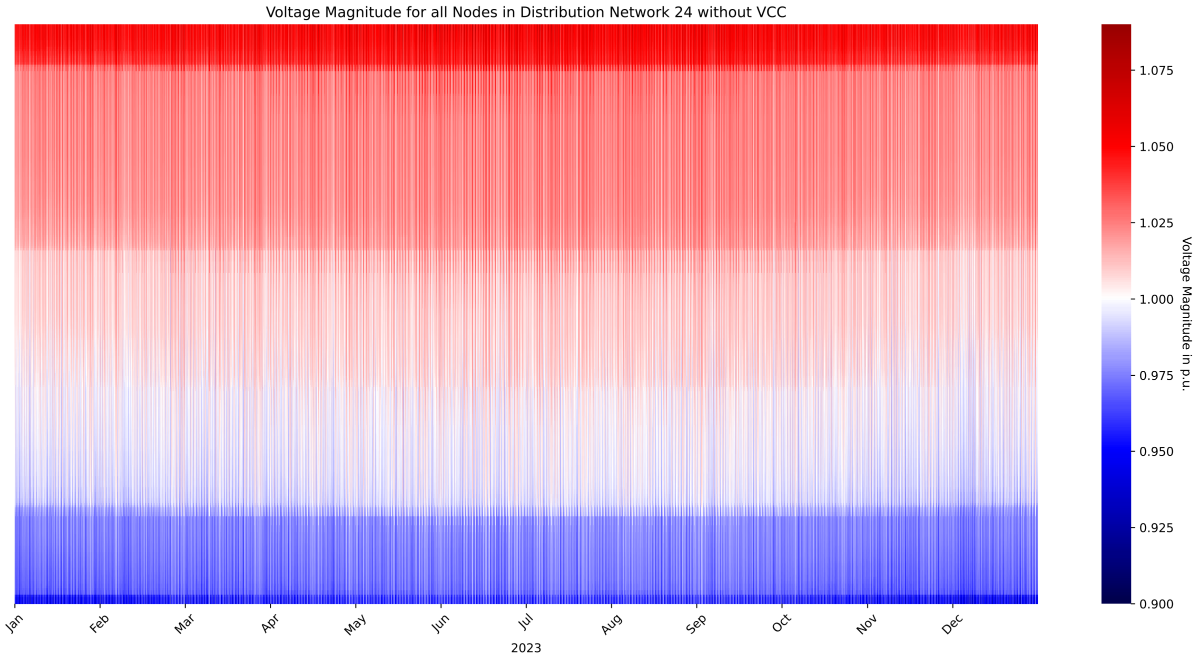


Figure A.3: Voltage magnitude for every hour of the year, (in p.u., descending) for all nodes in Distribution Network 24 with traditional voltage control and no VCC implemented. This visualization shows a substantial amount of voltage measurements have a too high (dark red) and too low (dark blue) voltage levels, concluding that a alternative voltage control method is necessary.

The data shown in Figure A.3 and A.4 is from Distribution Grid 24, which is a grid with 259 MV nodes and a total of 23 feeders (Table 4.1). To enhance the readability of the figures, the hourly measurements for all nodes have been arranged in descending order.

A break down of the content in Figure A.3 and A.4 will be provided to gain a clearer understanding of the contents. The figures depict a visualization of voltage magnitude data across distribution grid 24 over the year 2023. The temporal resolution is hourly, resulting in 8760 vertical lines representing each hour of the year. The y-axis displays the ranked voltage magnitudes for all 259 nodes in the grid at each specific hour. The color intensity corresponds to the voltage magnitude, with dark red indicating the highest values, blue representing the lowest and white being the optimal value.

The visual representation, encompassing 8760 x 291 data points, facilitates the analysis of several aspects of the grid's voltage behavior:

1. Voltage Magnitude Distribution: The overall color pattern across the hours reveals the distribution of voltage magnitudes within the grid throughout the year.
2. Temporal Voltage Variations: Examining any vertical line (representing a specific hour) allows for the observation of how voltage magnitudes vary across the nodes at that particular time.
3. Voltage Trends: Tracking a specific color intensity horizontally provides insight into the voltage fluctuations at a particular rank over the year.

The sorting of voltage magnitudes in descending order for each hour aids in visualizing the range of values and identifying potential outliers or extreme events. It is important to note that the y-axis represents the ranked voltage values, and no longer the number of the node Direct node-to-node comparisons at specific y-axis locations are not feasible in this figure. Additional figures are available in Appendix A, illustrating the data without descending order sorting. Figure A.5 and A.6 demonstrate the disorganized appearance of such figures when the data lacks sorting. However, these comprehensive visualizations provide a valuable tool for understanding the complex voltage dynamics within the power grid throughout a particular period, the year 2023 in this case.

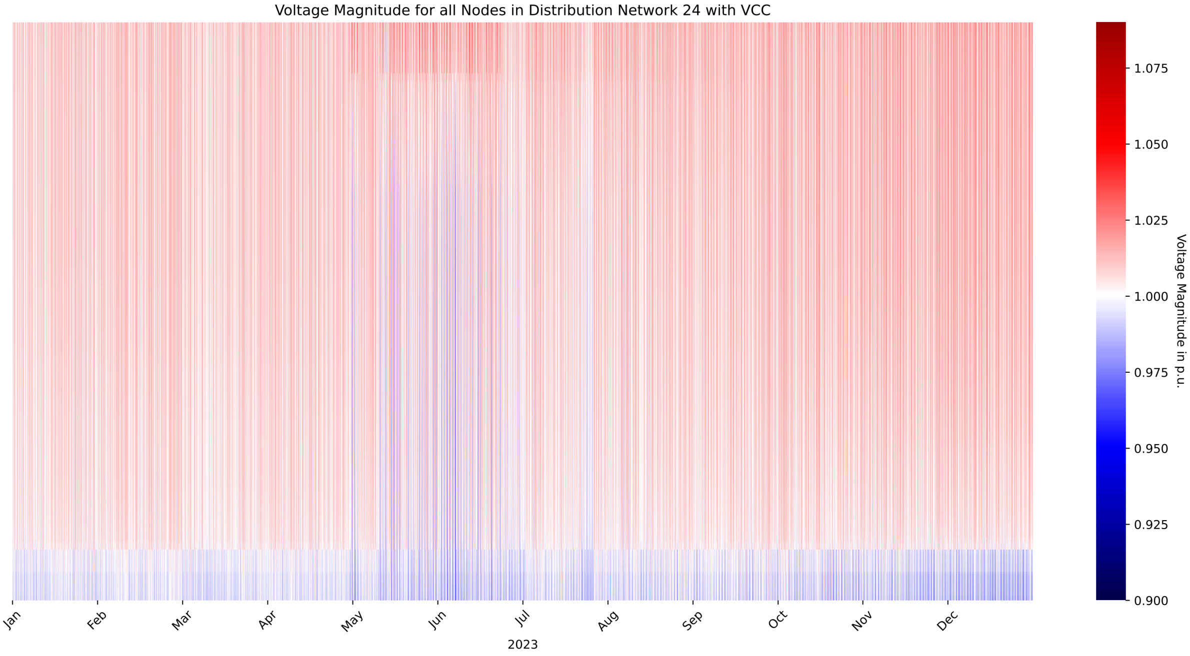


Figure A.4: Voltage magnitude for every hour of the year, (in p.u., descending) for all nodes in Distribution Network 24 with adaptive voltage control including a VCC. This visualization shows the tint of the graph has become more light due to the increased amount of lighter red and blue, indicating that the voltage levels are closer to $1.0\ p.u.$ and showing that the adaptive voltage control is improving the voltage levels.

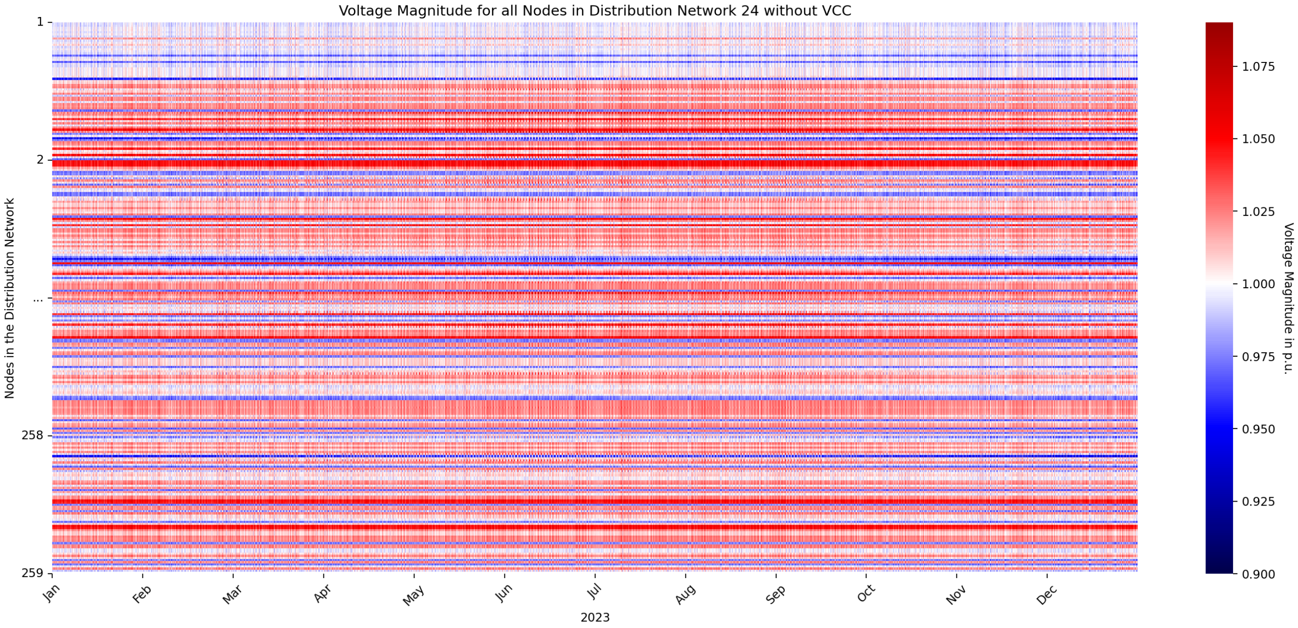


Figure A.5: Voltage Magnitude (in p.u., per Node) for all nodes in Distribution Network 24 with traditional voltage control and no VCC implemented. This visualization shows a substantial amount of voltage measurements have a too high (dark red) and too low (dark blue) voltage levels, concluding that a alternative voltage control method is necessary. The purpose of this figure is to illustrate the disarray of voltage levels throughout an entire distribution network, highlighting the necessity for sorted voltage magnitudes on the y-axis.

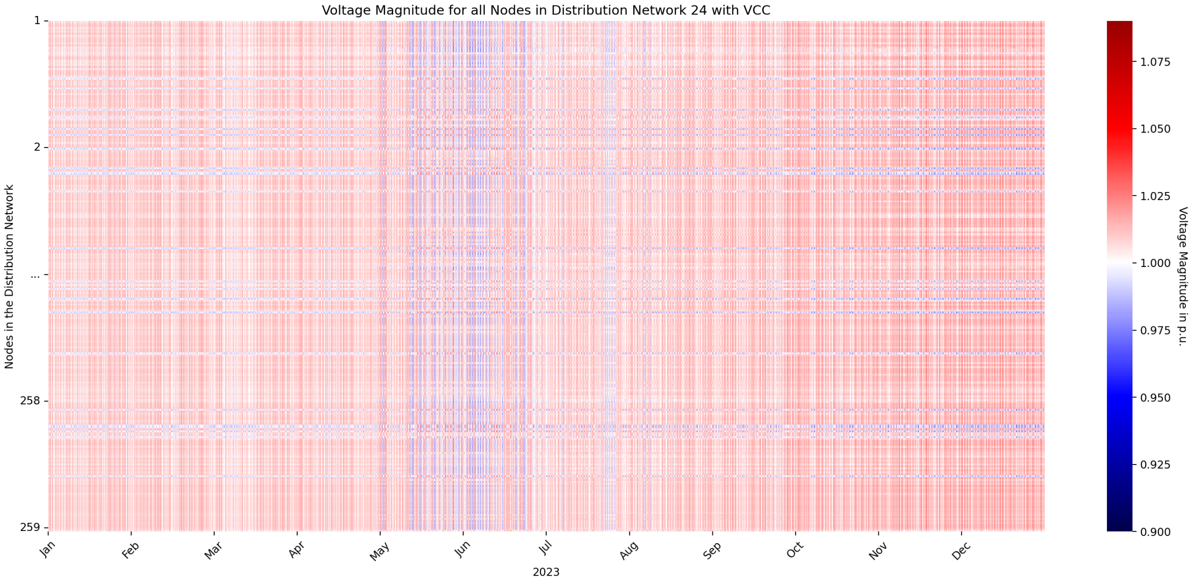


Figure A.6: Voltage magnitude for every hour of the year, (in p.u., per node) for all nodes in Distribution Network 24 with adaptive voltage control including a VCC. This visualization shows the tint of the graph has become more light due to the increased amount of light red and blue, indicating that the voltage levels are closer to $1.0\ p.u.$ and showing that the adaptive voltage control is improving the voltage levels. However, the figure is still chaotic and the purpose of this figure remains to illustrate the disarray of voltage levels throughout an entire distribution network, highlighting the necessity for sorted voltage magnitudes on the y-axis.

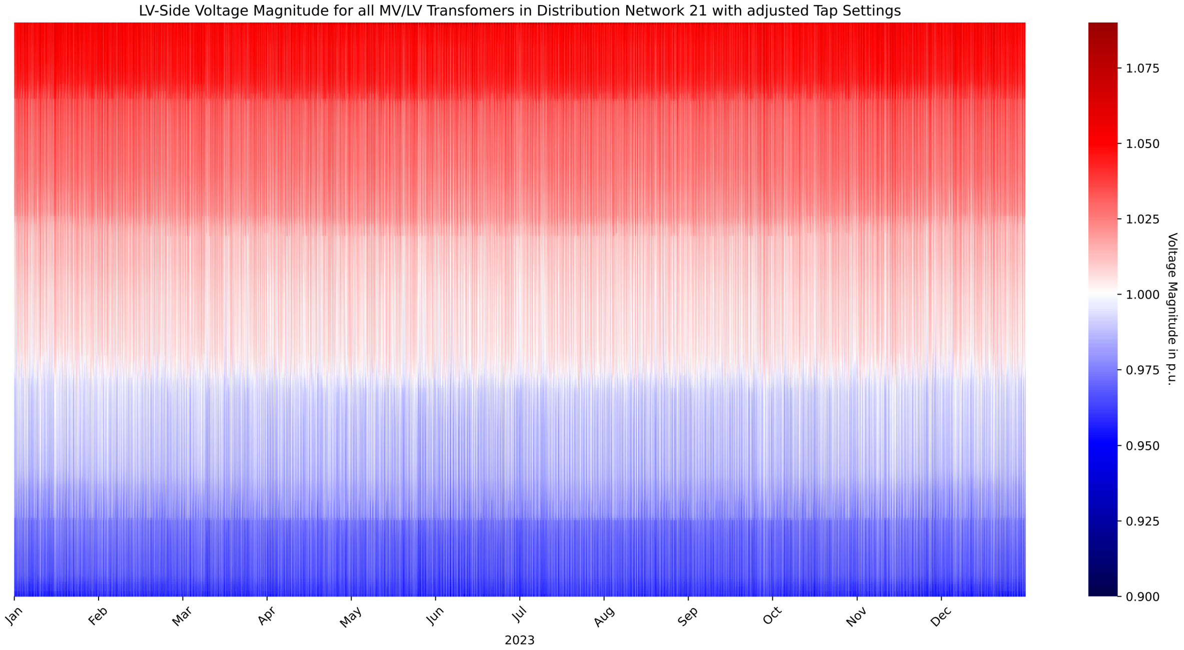


Figure A.7: LV-side voltage magnitude for all MV/LV transformers in Distribution Network 21 with adjusted tap settings, meaning the real-life tap settings of the transformers are applied (ranging form 1 to 5). In this figure, adaptive voltage control is already applied. This visualization shows a clear deviation between a few levels of voltage magnitude, ranging from dark red to dark blue indicating diverse voltage levels throughout the distribution network.

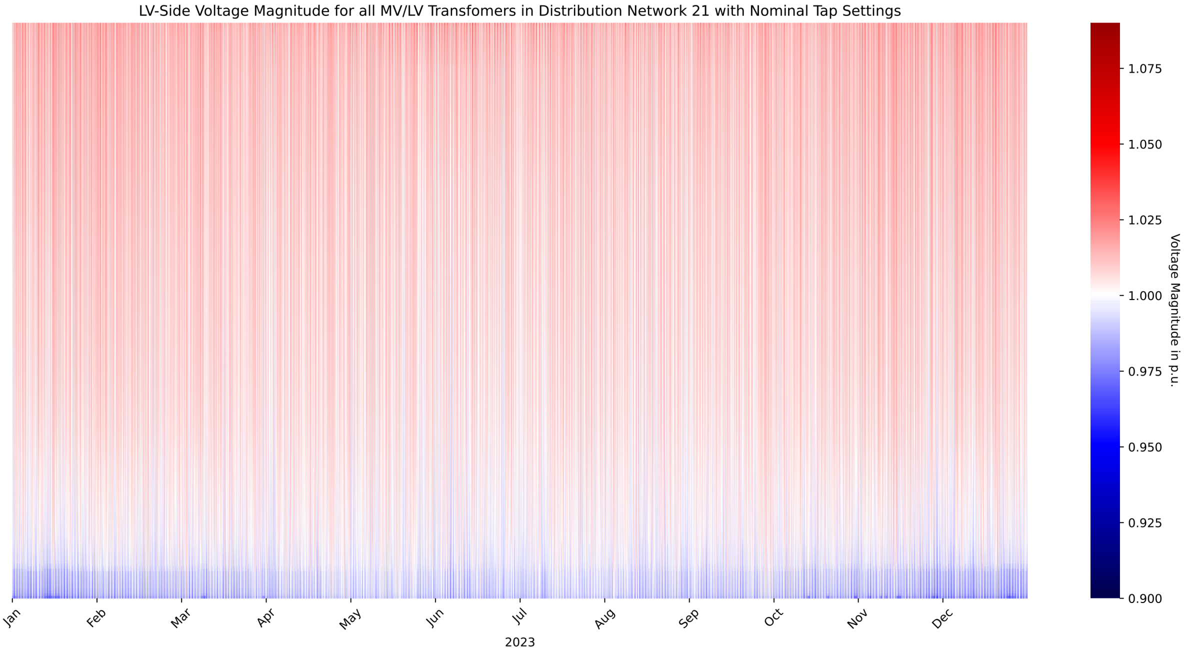


Figure A.8: LV-side voltage magnitude for all MV/LV Transformers in Distribution Network 21 with neutral tap settings, meaning all transformers are set to the neutral tap setting (3). In this figure, adaptive voltage control is already applied. This visualization shows the tint of the graph has become more light due to the increased amount of light red and blue, indicating that the voltage levels are closer to $1.0\ p.u.$ and suggesting the tap settings should be set to neutral.

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