AN EQUITABLE ACTIVE POWER CURTAILMENT METHOD FOR OVERVOLTAGE MITIGATION

A Thesis

by

Eihab Elgaily Elmukshfi Ahmed

Submitted to the
Graduate School of Sciences and Engineering
in Partial Fulfillment of the Requirements for
the Degree of

Master of Science

in the
Department of Electrical & Electronics Engineering

Özyeğin University
July 2024

AN EQUITABLE ACTIVE POWER CURTAILMENT METHOD FOR OVERVOLTAGE MITIGATION

Advisor: Asst. Prof. Göktürk Poyrazoğlu, Özyeğin University
Coadvisor: Asst. Prof. Alpaslan Demirci, Yıldız Technical University

Approved by:

Asst. Prof. Göktürk Poyrazoğlu, Advisor
Dept. of Electrical & Electronics Eng.
Özyeğin University

Asst. Prof. Ali Durusu
Dept. of Electrical Eng.
Yıldız Technical University

Asst. Prof. Said Mirza Tercan
Dept. of Electrical Eng.
Yıldız Technical University

Date Approved: May 13, 2024

To my beloved family

ABSTRACT

Distribution system operators pose various active power curtailment (APC) approaches to mitigate overvoltage. In contrast to general expectation, the overvoltage happens to be especially at the end of the distribution feeders in PV-rich networks. While APC helps keep the voltage within the stable operation limits, it causes renewable curtailment at each prosumer differently at increasing rates as the distance of the prosumer from the transformer increases. Hence, these approaches introduce unfairness among prosumers and fail to support the increased use of renewables locally. This study proposes an Equitable APC (EAPC) method based on the prosumer's self-consumption rate (SCR). The method calculates each prosumer's SCR during the overvoltage event, compares it with the precalculated critical SCR, and calculates a fair share of curtailment for each prosumer. Subsequently, leveraging the voltage sensitivity matrix, the new active power injection at the point of common coupling (PCC) is specified to ensure the overvoltage mitigation. To show the effectiveness of the proposed method, a comparison with three other methods, feed-in power limitation, inverter tripping, and dynamic APC, is presented under various PV penetration levels. The results show that EAPC significantly improves fairness among prosumers while providing comparable energy curtailment as dynamic APC. Furthermore, The proposed EAPC is less sensitive to the prosumer's location and improves fairness among prosumers.

ÖZETÇE

Dağıtım sistemi operatörleri aşırı gerilimi azaltmak için çeşitli aktif güç azaltma (APC) yaklaşımları ortaya koymaktadır. Genel beklentinin aksine, PV açısından zengin şebekelerde aşırı gerilim özellikle dağıtım fiderlerinin sonunda meydana gelmektedir. APC, gerilimi kararlı çalışma sınırları içinde tutmaya yardımcı olurken, tüketicinin trafodan uzaklığı arttıkça artan oranlarda her bir tüketicide farklı şekilde yenilenebilir enerji kullanımında kesintiye neden olmaktadır. Dolayısıyla, bu yaklaşımlar tüketiciler arasında adaletsizliğe yol açmakta ve yerel olarak yenilenebilir enerji kaynaklarının artışını desteklememektedir. Bu çalışma, tüketicinin öz tüketim oranına (SCR) dayalı bir Eşitlikçi APC (EAPC) yöntemi önermektedir. Yöntem, aşırı gerilim olayı sırasında her bir tüketicinin SCR'sini hesaplayıp, bunu önceden hesaplanmış kritik SCR ile karşılaştırır ve her bir tüketici için adil bir kesinti payı hesaplar. Daha sonra, gerilim duyarlılık matrisinden yararlanılarak, aşırı gerilimin azaltılmasını sağlamak için ortak bağlantı noktasında (PCC) yeni aktif güç enjeksiyon maiktarı belirlenir. Önerilen yöntemin etkinliğini göstermek için, çeşitli PV penetrasyon seviyeleri altında diğer üç yöntemle, besleme gücü sınırlaması, invertör açma ve dinamik APC ile bir karşılaştırma sunulmuştur. Sonuçlar, EAPC'nin dinamik APC ile benzer enerji kısıntısı sağladığını, üreticiler arasındaki adaleti önemli ölçüde geliştirdiğini göstermektedir. Ayrıca, önerilen EAPC, tüketicinin konumuna daha az duyarlıdır ve tüketiciler arasındaki adaleti geliştirmektedir.

ACKNOWLEDGEMENTS

First of all, I would like to express my deepest gratitude to my advisor, Asst. Prof. Gokturk Poyrazoglu, for his endless support and guidance throughout my master's degree journey. I am also thankful to my co-advisor, Asst. Prof. Alpaslan Demirci, whose passion for academia inspired me to embark on this path. I extend my sincere appreciation to my jury members, Asst. Prof. Said Mirza Tercan and Asst. Prof. Ali Durusu, for graciously accepting the role and providing valuable feedback that significantly enriched my work. I also extend my gratitude to my colleagues, Ahmad El-Sayed, Amin Alemdari, Sinem Kol, Eren Tekeler, Hilmi Namlı, and Ege Uğur for turning this stressful period into a joyful experience and creating a sense of family atmosphere that made it all the more enjoyable. I am forever grateful to my beloved family, whose belief in me has been a constant source of encouragement and motivation. Lastly, I deeply hope for a resolution to the ongoing conflict in my home country, Sudan, and an end to the tragic loss of innocent lives.

TABLE OF CONTENTS

DEDICATION . . . . **iii**

ABSTRACT . . . . **iv**

ÖZETÇE . . . . **v**

ACKNOWLEDGEMENTS . . . . **vi**

LIST OF TABLES . . . . **ix**

LIST OF FIGURES . . . . **x**

I INTRODUCTION **1**

1.1 Motivation and Background 1

1.2 Contribution of the thesis 3

1.3 Scope of the thesis 3

II LITERATURE REVIEW **4**

III ELECTRIC NETWORK MODELLING **8**

3.1 Electricity Supply Chain 8

3.1.1 Generation 9

3.1.1.1 Fossil Fuel-based Power Plants 9

3.1.1.2 Renewable Energy Based Power Plants 10

3.1.2 Transmission 11

3.1.3 Distribution 12

3.1.4 End-users 13

3.2 Distribution Network Modeling 14

3.2.1 Power flow calculation 14

3.2.2 Distributed energy resources modeling 16

3.2.3 Battery energy storage system 16

IV OVERVOLTAGE MITIGATION METHODS **18**

4.1 Inverter Tripping 18

4.2 Feed in Power Limitation 18
4.3 Active Power Curtailment 19
4.4 Proposed Equitable Active Power Curtailment 20
V PERFORMANCE EVALUATION OF OVERVOLTAGE MITIGATION METHODS 27
5.1 Energy curtailment considering overall PV generation 27
5.2 Nodal voltage fluctuations 27
5.3 Energy curtailment considering nodal PV generation 29
5.4 Energy curtailment considering location-sensitivity 30
5.5 Energy curtailment considering PV penetration 31
5.6 Energy curtailment considering location sensitivity and PV penetration 33
5.7 Energy curtailment considering BESS 34
VI DISCUSSION 36
VII CONCLUSION 38
REFERENCES 40
VITA 45

LIST OF TABLES

1 Energy curtailment rates by power curtailment methods 30

2 Energy curtailment rates considering location sensitivity. 31

3 Comparison of the power control methods 37

LIST OF FIGURES

1 Worldwide installed power capacity by sources in 2021 10

2 Cumulative RES capacity worldwide from 2010 to 2022 11

3 Break-even distance for HVAC and HVDC transmission lines, ... 12

4 RDN topology 13

5 Global electricity consumption by sector in 2019 14

6 Electric line model 14

7 Flow chart of the proposed EAPC. 22

8 Sensitivity of Energy curtailment to SCR. 23

9 Single-line diagram of the IEEE European LV distribution Test Feeder, green dots depict the examined nodes 25

10 PV installed capacity and SCR of the prosumers. 26

11 The amount of energy curtailment for a typical clear day 28

12 The voltage variation after applying control methods at (A) bus 34, (B) bus 248, (C) bus 406, and (D) bus 899. 29

13 Comparison of energy curtailment under different solar-to-demand ratios. 32

14 Voltage fluctuations for different solar-to-demand ratios under feed-in power limitation. 33

15 Energy curtailment under increasing penetration level for a) DAPC and B) EAPC methods. 34

16 Annual energy curtailment decrement when installing BESS. 35

CHAPTER I

INTRODUCTION

Electricity is considered indispensable for human survival. Sustainable access to electricity is a basic human right that should be guaranteed for everyone. Recently, the electricity demand has consistently accelerated due to the advancement in urbanization, transportation, and industrialization. As a response, the utilization of fossil fuel-based energy resources has grown dramatically, however, these resources are limited and considered a great threat to the environment due to carbon emissions. Recognizing these challenges, there's a growing urgency to shift towards more sustainable, cleaner, and infinite energy sources. Renewable energy sources (RES) such as solar, wind, and hydroelectric power are viable alternatives that can replace conventional energy sources (CES). RES are endless, sustainable, and eco-friendly. Making this transition not only mitigates the environmental impact of CES but also ensures a more sustainable, resilient and secure energy future for the upcoming generations.

1.1 Motivation and Background

In recent years, photovoltaic (PV) systems have emerged as a crucial component in global efforts to reduce dependence on fossil fuels and mitigate the adverse effects of climate change. By harnessing solar energy, PV systems offer a renewable and abundant source of electricity generation, thereby decreasing reliance on finite and environmentally harmful fossil fuel resources. The advantages of PV systems are manifold, ranging from their ability to generate electricity without emitting greenhouse gases or other pollutants to their scalability and modularity, making them suitable for diverse applications ranging from residential rooftops to large-scale utility installations. Additionally, PV systems can contribute to decentralized energy production, empowering communities to become more self-sufficient and resilient against disruptions in centralized power grids. However, despite their numerous benefits, integrating PV systems into existing power grids poses significant technical challenges. One of the foremost issues is the variability and intermittency of solar energy, which can lead to mismatches between supply and demand and exacerbate voltage fluctuations within LV distribution networks. Furthermore, the non-dispatchable nature of solar power presents operational challenges for grid operators, who must balance the intermittent generation from PV systems with the stable output of conventional power plants to ensure grid stability and reliability. Additionally, the spatial distribution of PV installations, often concentrated in areas with high solar irradiance, may exacerbate voltage rise issues in LV distribution networks with high PV penetration levels, necessitating careful planning and management strategies. Moreover, the integration of PV systems into power grids requires the deployment of advanced monitoring, control, and communication technologies to facilitate real-time management of generation and consumption patterns. Conventional power grids are designed to serve the end-users by using unidirectional power flow from the upstream grid to the downstream end-users. Nevertheless, the deployment of PV systems presents a power flow from the end-users to the upstream grid when the supply surpasses the demand, or when the demand is reduced to the point of overgeneration, resulting in reverse power flow, voltage rise, and increased power loss. Besides the supply-demand match, other factors trigger overvoltage especially at the end of the feeder, such as feeder impedance, and network configuration. In response to such conditions, inverters are programmed to disconnect from the grid temporarily and then reconnect after a specified time delay when the voltage at the point of common coupling (PCC) exceeds the maximum voltage limits. However, this process of frequent connection and disconnection can disrupt the smooth operation of the network and potentially compromise its stability.

1.2 Contribution of the thesis

The original contributions of this thesis include the following:

1) An SCR-based equitable framework for active power curtailment is proposed, which significantly improves the fairness of prosumers while observing the nodal voltage limits.

2) The proposed framework can fairly alleviate the location impact on energy curtailment leveraging SCR and the power-voltage sensitivity, even under high PV penetration levels.

3) The framework can achieve a comparable energy harvest per year as the dynamic active curtailment method without increasing BESS capacity.

1.3 Scope of the thesis

Within the scope, a thorough literature review of power control methods for overvoltage mitigation and their application opportunity and challenges are presented in Chapter II. Chapter III discusses electric network modeling including the electricity supply chain with its four stages, distribution network modeling, distributed energy resources modeling, and battery energy storage system modeling. The current and futuristic challenges associated with the massive deployment of PV systems in LV distribution networks are introduced in Chapter IV. Furthermore, the overvoltage mitigation methods including inverter tripping, feed-in power limitation, dynamic APC, and the proposed EAPC are discussed in detail in Chapter V. The simulation results and the comparison of these methods considering nodal voltage, location sensitivity, increasing PV penetration, and battery energy storage system integration is given in Chapter VI. Finally, a discussion on overvoltage mitigation methods performance from different perspectives is given in Chapter VII.

CHAPTER II

LITERATURE REVIEW

To address these technical issues and ensure the seamless integration of PV systems into the power grid, it becomes imperative to implement control mechanisms for managing feed-in power. By regulating the amount of power injected into the grid from PV systems, operators can mitigate overvoltage occurrences and maintain grid stability. Such control strategies may involve reactive power control (such as volt-var) [1, 2, 3, 4], active power control (volt-watt) [5, 6, 7, 8], or a combination of them [9, 10, 11, 12, 13]. Furthermore, on-load tap changing transformers, voltage regulators, and grid reinforcement could be applied to address overvoltage problems [14, 15, 16]. Integration of Battery Energy Storage Systems (BESS) is also a common approach to deal with overvoltage in the distribution networks [17, 18, 19].

Unlike transmission networks, LV distribution networks have a relatively high resistance-to-reactance ratio due to the major use of underground cables, making the voltage more sensitive to active power variations. Hence using reactive power control is not effective [20, 21]. Rather, using active power curtailment (APC) is more attractive [10]. However, APC is not desirable economically due to the loss of valuable renewable energy, and reactive power control should be prioritized [22].

The literature is rich with APC methods, and these methods can be divided into distributed APC and centralized APC. Distributed APCs are generally droop-based and do not necessitate a communication infrastructure simplifying their implementation process significantly. In contrast, centralized APC involves communication links connecting to a central unit responsible for computing active and reactive power set-points for the inverters. Generally, centralized approaches demand more intricate and long-range communication connections [11, 23]. Although APC methods effectively mitigate overvoltage, they introduce a fairness issue among prosumers due to the radial layout of typical LV distribution networks, wherein, prosumers located farther from the substation encounter voltage rise during periods of reverse power flow when supply exceeds demand [24]. Consequently, APC applies varying degrees of power curtailment to prosumers, particularly impacting those situated at the end of the feeders. Conversely, methods employing fixed feed-in power limits offer a fairer alternative to APC. However, setting these limits too conservatively can result in underutilization of the full PV potential, while setting them too high can lead to voltage instability. In this study, fairness is defined as the capability of the PV curtailment method to treat prosumers equitably based on their power injection into the grid and self-consumption ratio (SCR), irrespective of their location within the network. In other words, unfairness arises if the prosumer is more penalized due to it is location. To ensure fairness, previous schemes outlined in [20, 25, 26, 27] have implemented a uniform generation limit for all PV systems, expressed as a percentage of their rated capacities. While this approach maintains fairness regarding PV harvesting, as all PV systems are subject to similar curtailment, it may not uphold fairness when assessing the prosumer's net demand. As a result, households with demands surpassing their local generation capacity could still face curtailment under these schemes, despite not contributing to overvoltage issue. The authors in [28] and [29] proposed optimization-based approaches to improve fairness among the prosumers. However, both approaches disregard PV coordination [30] and do not compare them with the other methods in the literature. The studies [22, 23, 31] utilize voltage sensitivity-matrix to determine the PV power curtailment at each bus. This approach allows more energy injection to the grid, compared to the droop-based approach. However, both approaches only consider the location, disregarding the prosumer's SCR and overlooking the reality that a prosumer who can effectively synchronize his electricity consumption with solar generation during peak sunlight hours will only contribute a minimal amount of power to the grid.

Few studies compare the sufficiency of the aforementioned overvoltage mitigation methods with each other. For example, in [23] the authors compare droop-based APC, sensitivity-based APC, and optimal power flow (OPF) based APC methods. In [32] reactive power control, APC, and grid reinforcement were compared from a financial perspective within a suburban grid in Germany. Another comprehensive study [33] evaluates the suitability of some strategies in dealing with overvoltage issues, including reactive power control, BESS, APC, grid reinforcement, and demand response. Meanwhile, the authors in [34] assess the potential of APC, BESS, and grid reinforcement in mitigating voltage fluctuations considering various PV penetration levels.

Despite the effectiveness of conventional electric distribution networks in supplying electricity to millions of end-users, they suffer from several challenges that must be addressed to serve global efforts in a sustainable energy future. These challenges range from operational difficulties to aging infrastructure and hosting the increased DER capacity, particularly PV systems.

Many components in distribution networks, like power lines and transformers, were designed decades ago when energy demand was lower, and the grid was less complex. As a result, these components are now reaching or surpassing their expected lifespan, necessitating replacement to maintain the quality of power distribution networks.

The change in load and intermittent renewable energy generations cause a variation in the voltage magnitude. This voltage fluctuation might cause equipment malfunctions, reducing its lifespan. In general distribution networks have a voltage variation tolerance within +/-5% [35]. Undervoltage occurs when the voltage drops below the acceptable limit due to the high demand or a sudden drop in the PV output power.

On the other hand, overvoltage occurs when the supply exceeds the demand, resulting in reverse power flow from the end-users to the substation. It happens at peak solar irradiance periods that often coincide with low demand. This situation can result in equipment damage and safety hazards in the network. Therefore, addressing the voltage fluctuations becomes essential to maintain the reliability of the network.

Furthermore, the mismatch in power balance between supply and demand due to the uncertainty of load and PV generation results in frequency deviation in LV distribution networks. System inertia; the resistance against frequency deviation; depends on the disturbance size. System inertia is negatively affected by the integration of non-synchronous generators such as PV systems due to the connect converters and other power electronic devices. Networks with high PV penetrations have less system inertia which causes voltage unbalance, increases frequency fluctuations, and disturbs active power flow.

When a fault occurs in a part of conventional distribution networks, it can be isolated from the main grid and safely recovered. However, when a part of the distribution networks is equipped with PV systems, isolation is not fully achieved because the PV systems continue to feed the separated part from the grid, causing a danger for maintenance workers.

Among all the aforementioned PV integration challenges in LV distribution networks, overvoltage issues are the most frequently reported problems. Therefore, addressing overvoltage stands as a primary challenge in PV-rich LV distribution networks. Reverse power flow also is a huge challenge; however, it leads to overvoltage eventually. Therefore, the focus of this thesis is mitigating the overvoltage.

CHAPTER III

ELECTRIC NETWORK MODELLING

This chapter presents a modeling of electric networks including the generation, transmission, distribution, and end-users. Moreover, it discusses the mathematical modeling of power flow calculations, battery energy storage systems, and distributed energy resources.

3.1 Electricity Supply Chain

In the contemporary world, the electricity demand is escalating, driven by technological advancements, exploding population growth, and expanding industrial sectors. As societies become increasingly dependent on electricity to power essential services, drive economic activities, and sustain modern lifestyles, the importance of robust electrical power networks cannot be neglected. The entire process from generating electricity to delivering to the end-users is called the electricity supply chain. It mainly comprises the following components:

1. Generation
2. Transmission
3. Distribution
4. End-users

The total generation capacity, and the length of transmission and distribution lines, coupled with the extensive coverage of national grids, serve as a tangible indicator of the welfare of communities. These networks are indispensable for modern civilization, enabling the smooth energy flow from the power plants to the end-users.

3.1.1 Generation

Electricity is generated in industrial facilities called Power Plants, where the primary energy is converted to electricity using a generator. The generators convert mechanical energy to electrical energy through the principle of magnetic induction. Power Plants can be categorized into two types according to the utilized fuel, which are fossil fuel-based Power Plants and renewable energy-based Power Plants. The selection of power plant location depends on various factors such as source availability, economic feasibility, environmental considerations, and network infrastructure. The diversification of the energy mix is essential for a reliable and sustainable electricity supply.

3.1.1.1 Fossil Fuel-based Power Plants

Fossil fuel, with its extensive infrastructure and high energy density, has historically held the highest capacity share among energy resources and has been used to supply the primary load worldwide, as shown in Figure 1 . Fossil-fuel-based power plants burn fossil fuels such as coal, natural gas, and oil to generate electricity. The principle of these power plants is generating heat by burning fossil fuels. Subsequently, the heat is used to generate the steam which is used to rotate the turbines which are connected to the generators, resulting in electricity generated.

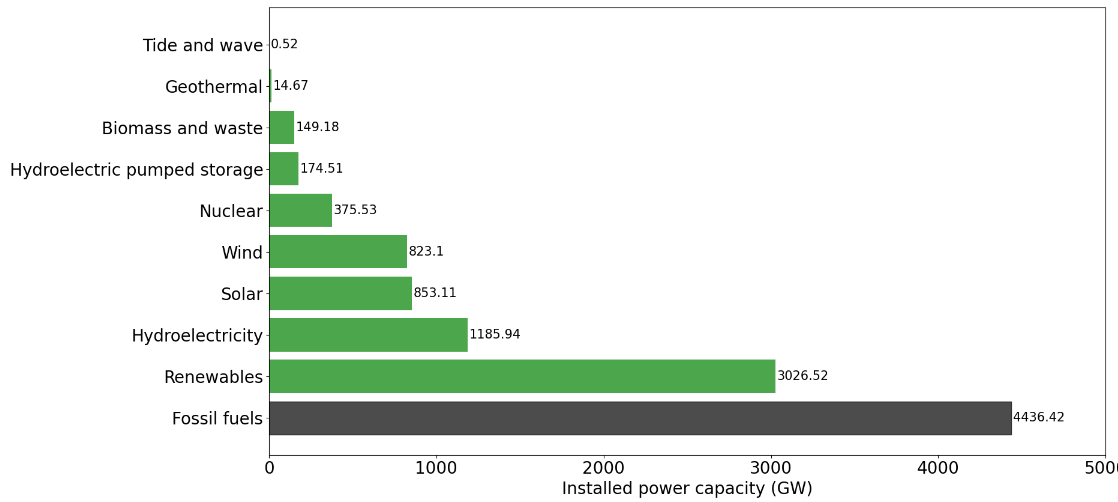

Figure 1: Worldwide installed power capacity by sources in 2021 [36]

These types of power plants are dispatchable and provide reliable and consistent electricity. Furthermore, they are relatively affordable and historically been more cost-effective compared to the other energy sources. Therefore, they are used to supply the primary load in many countries. However, these sources significantly pollute the environment by emitting greenhouse gases, contributing to climate change and global warming. The growing awareness about the drawbacks of these energy sources has accelerated the transition to alternative energy sources, such as renewable energy resources. Many countries have started reducing their dependency on these sources by setting targets for transitioning towards cleaner energy sources.

3.1.1.2 Renewable Energy Based Power Plants

Renewable Energy Resources (RES) are the most significant alternative to fossil fuels. The deployment of RES has increased dramatically, thanks to technological advancement, decreasing prices, and governmental incentives. Figure 2. Shows the global annual growth of RES as reported by the International Renewable Energy Agency

(IRENA).

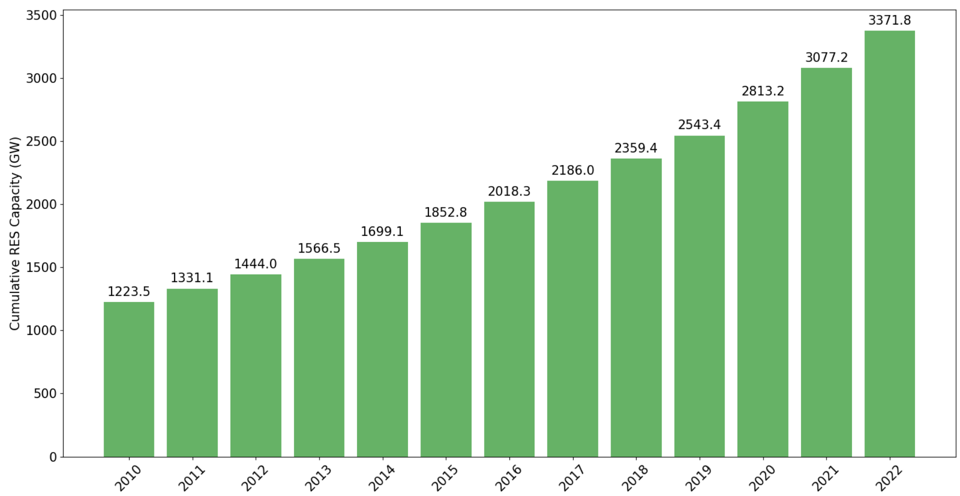

Figure 2: Cumulative RES capacity worldwide from 2010 to 2022 [37]

There are various types of RES, including solar energy, wind energy, hydropower energy, biomass, geothermal energy, and others. Among these resources, Photovoltaic systems representing solar energy and wind turbines representing wind energy have received significant research attention due to their abundance. PV systems convert sunlight to electricity using semiconductor materials. The output power of PV systems highly depends on weather conditions such as solar radiation, sunlight duration, and ambient temperature, such that a short-term cloud move can cause sudden power variations.

3.1.2 Transmission

Transmission networks are the backbone of the power systems which facilitate long-distance energy transmission from the production sources (power plants) to the substations and, subsequently to the distribution networks. The length of transmission lines varies from several hundred kilometres to thousand kilometres. High-voltage and long-distance mainly characterize the transmission lines. Generally, the voltage is produced at low levels at the power plants and then boosted by the transformers to high levels, particularly above 33 kV. The transmission lines can transfer the high voltage in AC voltage or DC voltage forms. Figure 3 shows the break-even point for the balance between AC and DC transmission lines according to the distance.

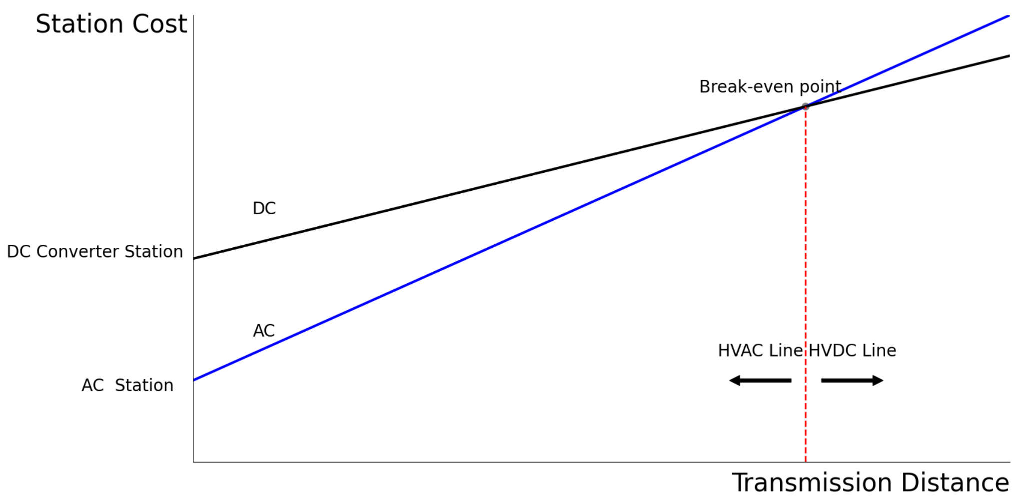

Figure 3: Break-even distance for HVAC and HVDC transmission lines, (adopted from [38])

3.1.3 Distribution

Distribution networks (DNs) distribute the power to the end-users. They have less line length compared to TNs. The voltage is decreased to lower levels by step-down transformers to make it suitable for end-users. such as ensuring high reliability and quality of power supply, integrating distributed energy resources (DERs), facilitating energy transactions among various customers, and providing flexible services to electric vehicles (EVs) are all fulfilled through DNs. Consequently, the DN has emerged as the most essential and dynamic component in the development of modern power systems. The topology of the DNs vary depending on various factors such as geographical location, system layout, and requirements, DNs mainly have three topologies, which are:

- Radial distribution networks (RDNs)
- Loop distribution networks (LDNs)
- Interconnected distribution networks (IDNs)

Radial distribution networks (RDNs) are the most common types of DNs. This topology carries the power through feeder lines from the distribution transformer to the end-users using unidirectional power flow. RDNs have relatively simple designs which make them cost-effective, which enhances cost-effectiveness. Yet, the absence of alternative paths for power flow means that a disrupted line can result in a complete blackout within the network. RDNs include load, voltage profile, reactance, and resistance of the lines. A sample RDN model is given in Figure 4. Where a distribution substation connects the external gird (transmission level) with two main feeders (distribution level).

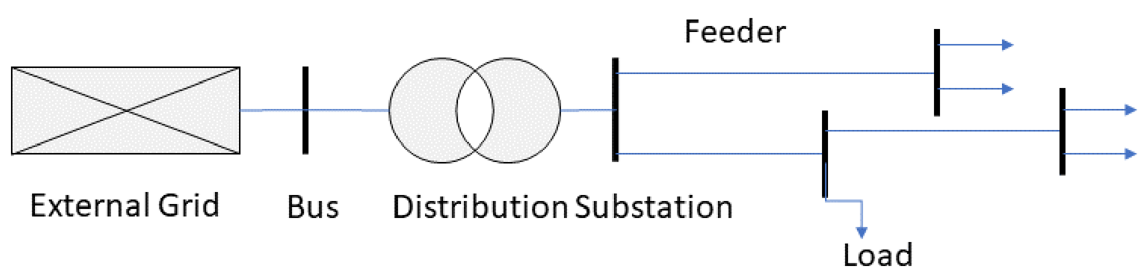

Figure 4: RDN topology

3.1.4 End-users

End-users including residential, commercial, and industrial customers are the last component of the electricity supply chain. End-users consume electricity for various purposes like lighting, heating, cooling, manufacturing, and transportation. Figure 5 shows the energy consumption by sector in 2019.

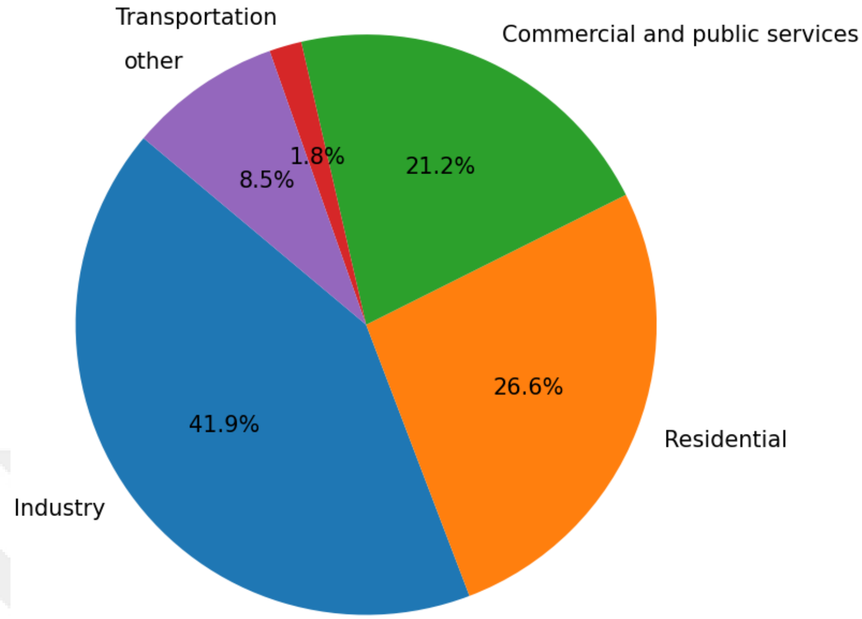

Figure 5: Global electricity consumption by sector in 2019 [39]

3.2 Distribution Network Modeling

3.2.1 Power flow calculation

Power flow modelling is an essential technique used to simulate the steady state behaviour of electric power system. It involves mathematical representations of power system components such as generators, demand, electric line, voltage, and current. Figure 6 shows the electric line model, including resistance, reactance, current, and voltage.

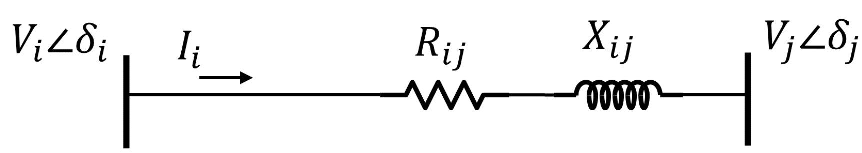

Figure 6: Electric line model

The impedance of the line is calculated as shown in equation (1).

$$Z_{ij} = R_{ij} + j.X_{ij}, \quad \forall i,j \tag{1}$$

where Z_{ij}, R_{ij}, X_{ij} are the impedance, resistance, and reactance of the line in Ω , respectively. Admittance matrix is the inverse of the impedance as shown in equation (2).

$$Y_{ij} = Z_{ij}^{-1} = G_{ij} + j.B_{ij}, \quad \forall i,j \tag{2}$$

where Y_{ij}, G_{ij}, B_{ij} are the admittance, conductance, and susceptance of the line in $\frac{1}{\Omega}$, respectively. The power flow equations can be derived as given in equations (3,4,5,6,7).

$$P_{G_i} - P_{D_i} = \sum_{j=1}^{N} V_i.V_j.Y_{ij}.\cos\left(\theta_{ij} + \delta_j - \delta_i\right), \quad \forall i,j \tag{3}$$

$$Q_{G_i} - Q_{D_i} = \sum_{j=1}^{N} V_i.V_j.Y_{ij}.\sin\left(\theta_{ij} + \delta_j - \delta_i\right), \quad \forall i,j \tag{4}$$

$$I_{ij} = |Y_{ij}| . \left[V_i^2 + V_j^2 - 2.V_i.V_j.\cos(\delta_j - \delta_i)\right]^{1/2}, \quad \forall i,j \tag{5}$$

$$P_{loss} = \sum_{j=1}^{N} I_{ij}^2.r_{ij}, \quad \forall\ i,j \tag{6}$$

$$V_{min} \leq V_i \leq V_{max}, \quad \forall\ i \tag{7}$$

The active power flow is described in equation (3), where P_{G_i} and P_{G_i} are the active supply and active demand in kW at bus i , respectively. Similarly, the reactive power flow is introduced in equation (4), where Q_{G_i} and Q_{D_i} are the reactive supply and reactive demand, Y_{ij} and θ_{ij} are the admittance matrix and the amplitude angle between bus i and bus j, respectively. The voltage angle at bus i and bus j are represented by δ_i, and δ_j, respectively. The current flow between bus i and bus j is given in equation (5). Meanwhile, the overall active power loss is calculated by equation (6), where r_{ij} is the resistance of the line connecting bus i and j. The voltage operation limits are given in equation (7), where V_{min}, and V_{max} are the voltage lower and upper boundaries, respectively.

3.2.2 Distributed energy resources modeling

Distributed energy resources (DER) include small scale power generation units like PV arrays and wind turbines; energy storage units and demand side management technologies that are located close to the end-users. Unlike the conventional power grid which depend on central power plants, DER are decentralized and generally connected to the grid, providing enhanced power quality and reduced grid dependency. The power generation units in DER are modelled as a negative demand, and the power balance equations (3,4) can be updated as shown in equations (8,9), where $\overline{P_{D_i}}, \overline{Q_{D_i}}$ are active and reactive power generation of renewables (negative load).

$$P_{G_i} - P_{D_i} - \overline{P_{D_i}} = \sum_{j=1}^{N} V_i.V_j.Y_{ij}.\cos\left(\theta_{ij} + \delta_j - \delta_i\right) \ , \quad \forall i, j \tag{8}$$

$$Q_{G_i} - Q_{D_i} - \overline{Q_{D_i}} = \sum_{j=1}^{N} V_i.V_j.Y_{ij}.\sin\left(\theta_{ij} + \delta_j - \delta_i\right) \ , \quad \forall i, j \tag{9}$$

3.2.3 Battery energy storage system

Battery Energy Storage Systems (BESS) play a crucial role in balancing supply and demand in electricity grids, especially in systems with high penetration of renewable energy sources. BESS charge when the supply of renewable energy sources (RES) like PV or wind exceeds the demand and discharge during the low supply and high demand periods. Moreover, BESS can be used for energy arbitrage to gain economic benefits by charging from the grid during low energy price periods and discharging during high energy price periods. In addition to balancing supply and demand, BESS enhances the resilience and reliability of fundamental services by providing backup power during grid outages. Furthermore, the integration of BESS into the electric grid improves the voltage profile and reduces the power loss significantly by mitigating the energy curtailment due to the variability nature of RES. BESS can be modeled in the distribution networks as illustrated in equations (10,11,12,13,14,15,16).

$$E_{i,t} = E_{i,t-1} + \Delta t.P_{ch_{i,t}}.\eta_{ch} - \Delta t.\frac{P_{disch_{i,t}}}{\eta_{disch}} \qquad \forall i,t \tag{10}$$

$$E_{i,t} = E_i^{init} \qquad \forall i,t \tag{11}$$

$$\underline{E_i} \leq E_{i,t} \leq \overline{E_i} \qquad \forall i,t \tag{12}$$

$$\underline{P_{ch_i}} \leq P_{ch_{i,t}} \leq \overline{P_{ch_{i,t}}} \qquad \forall i,t \tag{13}$$

$$\underline{P_{disch_i}} \leq P_{disch_{i,t}} \leq \overline{P_{disch_i}} \qquad \forall i,t \tag{14}$$

$$P_{ch_{i,t}} \leq U_{i,t}.M \qquad \forall i,t \tag{15}$$

$$P_{disch_{i,t}} \leq (1 - U_{i,t}).M \qquad \forall i,t \tag{16}$$

The energy of BESS- in kWh at bus i and time t ($E_{i,t}$) are defined by equation (10), where $P_{ch_{i,t}}$, $P_{disch_{i,t}}$ are the BESS charge and discharge powers in kW; η_{ch}, η_{disch} are the charging and discharging efficiency; and Δt is the time granularity. The initial energy of the BESS and the maximum and minimum operating range are given in equations (11,12). The upper and lower boundaries of the charge and discharge power are given in equations (13,14) respectively. The simultaneous charge and discharge are prevented by equations (15,16), where $U_{i,t}$ is a binary variable , and M is a big number.

CHAPTER IV

OVERVOLTAGE MITIGATION METHODS

There are several control techniques to address overvoltage mitigation such as inverter tripping, fixed feed-in power limitation, dynamic APC, and a new proposed EAPC as will be discussed in this chapter.

4.1 Inverter Tripping

This is the conventional protection method where the inverter disconnects from the grid if the voltage at the PCC exceeds the critical voltage limit and reconnects after a time delay [20]. Because overvoltage arises at nodes distant from the transformer, prosumers located at the end of the feeder are disadvantaged due to their placement [7]. Nonetheless, this control approach operates independently of communication infrastructure among prosumers, relying instead on local control. The inverter trips based on equation (17).

$$P_{inj} = \begin{cases} P_{exc}, & V_i < V_{cri} \\ 0, & V_i \geq V_{cri} \end{cases} \tag{17}$$

where P_{inj} is the injected power (kW), P_{exc} is the excess power (kW), V_i is the voltage at PCC (p.u), and V_{cri} is the critical voltage (p.u).

4.2 Feed in Power Limitation

The local PV generation impacts the demand patterns and might surpass the load several times during the peak generation periods. The conventional power grids were not planned to consider feed-in PV power. The main aim of feed-in power limitation is to increase the PV hosting capacity of the feeders and enhance the renewable energy mix within the overall energy landscape. However, the integration of PV can introduce technical challenges such as voltage fluctuations, transformer strain, and switcher malfunctions. Consequently, grid operators either restrict) or PV installation, such as in Thailand [40] (PV is limited by 15% of rating transformers), or implement maximum feed-in power limits as a preventative measure against these potential drawbacks. For instance, the utility in Germany restrict the power injection by 70% of the prosumer's nominal installed PV power [41]. It's important to note that feed-in limits do not consider grid dynamics like supply, demand, or voltage variations; instead, they solely restrict surplus power. Consequently, this approach may underutilize renewable energy during specific periods due to unnecessary curtailment, and it doesn't ensure operation within the voltage safety range. This study assumes that prosumers cannot feed more than 40% of their installed PV capacity into the grid [42].

$$P_{inj} = \begin{cases} P_{exc}, & P_{exc} < \alpha P_{PV\_nom} \\ \alpha P_{PV\_nom}, & P_{exc} \geq \alpha P_{PV\_nom} \end{cases} \tag{18}$$

The feed-in power is calculated according to equation (18), where $P_{PV_{nom}}$ is the nominal PV power (kW), and α is the feed-in coefficient, changing between zero and one.

4.3 Active Power Curtailment

The high R/X ratio is one of the main factors limiting the reactive power impact on voltage regulation in LV distribution networks. Rather, the APC is more effective in mitigating the overvoltage. There are two APC approaches, namely, droop-based APC and dynamic APC (DAPC).

Droop-based APC is desirable due to its simplicity because it does not demand shared information between prosumers. Instead, it depends on local control. This method does not require shared information among prosumers and can be controlled locally. The active power injection is limited based on the current state of the voltage (V_{pcc}) as given in equation (19).

$$P_{inj} = \begin{cases} P_{mppt} - m * max(0, V_i - V_{cri}), & V_{cri} \leq V_i \leq V_{max} \\ 0, & V_{cri} \geq V_{max} \end{cases} \tag{19}$$

DAPC adopts a varying droop-coefficient leveraging voltage sensitivity matrix. However, both methods are location-sensitive, causing unfair energy curtailment among the prosumers [43]. Further information about the two methods can be found in [44].

4.4 Proposed Equitable Active Power Curtailment

As discussed in the previous sections, the APC methods disregard the prosumer's SCR, resulting in an unfair energy curtailment among the prosumers. This study proposes an EAPC method that aims to enhance fairness among the prosumers by leveraging the voltage sensitivity while preserving the voltage under the critical voltage, V_{cri}. Prosumers will still adjust their active power at PCC, so their SCR should be greater than a predefined critical value, SCR_{cri}. The proposed method depends on the sensitivity matrix, which is the inverse of the power flow Jacobian matrix. The correlation between voltage and power changes can be derived from the power flow analysis results according to the Newton-Raphson technique as shown in equations (5,6,78,9) .

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = J \ . \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \tag{20}$$

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = J^{-1} \cdot \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} =$$

$$\begin{bmatrix} \underbrace{\begin{matrix} \frac{\partial\delta_2}{\partial P_2} & \cdots & \frac{\partial\delta_2}{\partial P_N} \\ \vdots & \ddots & \vdots \\ \frac{\partial\delta_N}{\partial P_2} & \cdots & \frac{\partial\delta_N}{\partial P_N} \\ \frac{\partial V_2}{\partial P_2} & \cdots & \frac{\partial V_2}{\partial P_N} \\ \vdots & \ddots & \vdots \\ \frac{\partial V_N}{\partial P_2} & \cdots & \frac{\partial V_N}{\partial P_N} \end{matrix}}_{V\ sen.\ at\ P} & \underbrace{\begin{matrix} \frac{\partial\delta_2}{\partial Q_2} & \cdots & \frac{\partial\delta_2}{\partial Q_N} \\ \vdots & \ddots & \vdots \\ \frac{\partial\delta_N}{\partial Q_2} & \cdots & \frac{\partial\delta_N}{\partial Q_N} \\ \frac{\partial V_2}{\partial Q_2} & \cdots & \frac{\partial V_2}{\partial Q_N} \\ \vdots & \ddots & \vdots \\ \frac{\partial V_N}{\partial Q_2} & \cdots & \frac{\partial V_N}{\partial Q_N} \end{matrix}}_{V\ sen.\ at\ Q} \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (21)$$

$$S_V = \begin{bmatrix} \frac{\Delta\delta}{dP} & \frac{\Delta\delta}{dQ} \\ \frac{\Delta V}{dP} & \frac{\Delta V}{dQ} \end{bmatrix} \quad (22)$$

The voltage sensitivity matrix quantifies how the changes in active and reactive power affect voltage magnitude $|V|$ and voltage angle δ. It is obtained by partial derivative of the power flow equations and taking the inverse of the Jacobian matrix, as given in equations (20,21,22). The sensitivity matrix S_V consists of 4 sub-matrices ($S_V^{m,n}$;m=1,2;n=1,2), however, EAPC method particularly utilizes the sub-matrix $\frac{\Delta V}{dP}$ because the voltage is more sensitive to active power variation in LV distribution network as discussed in the previous sections. Equation (23) calculates energy curtailment at each bus (ΔP_i) and equation (24) calculates the droop coefficient (m_i).

$$\Delta P_i = \frac{V_i - V_i^{cri}}{\sum_i^N S_{V,i}^{2,1}} \quad (23)$$

$$m_i = \frac{\Delta P_i}{V_i - V_i^{cri}} \quad (24)$$

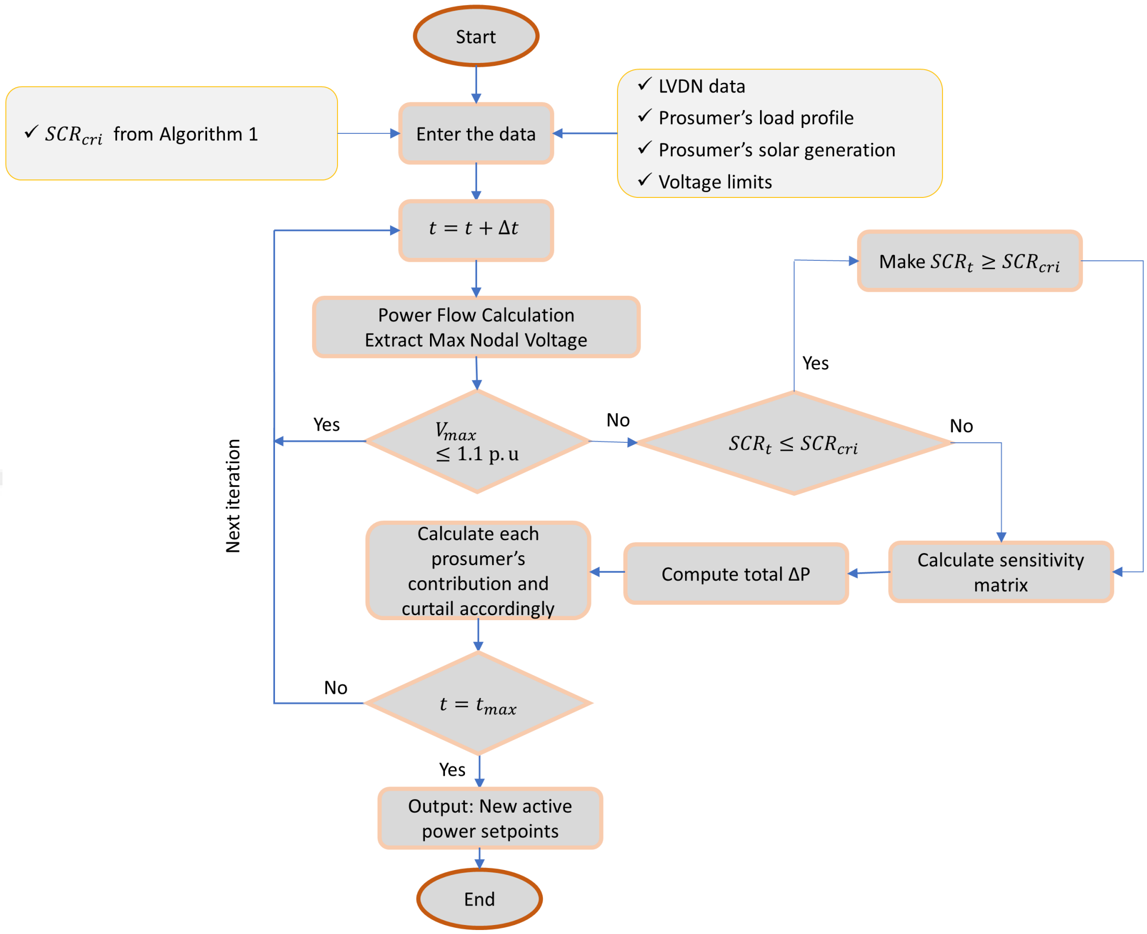

Figure 7: Flow chart of the proposed EAPC.

The flowchart of the proposed EAPC method is depicted in Figure 7. The method performs power flow calculation and computes the voltage sensitivity matrix as discussed in the previous section. In the scenario when the maximum voltage in the network $V_i^{max} > V_i^{cri}$, each prosumer's SCR_t is calculated and compared to SCR_{cri} which is computed according to the algorithm in the pseudo-code. Subsequently, the prosumers SCR_t is adjusted by curtailing the surplus energy. In this way, the prosumers are penalized based on their SCR, therefore, the prosumers close to the transformer may experience energy curtailment based on their SCR. After that, the voltage sensitivity matrix is calculated and ΔP_i is computed and extracted from the prosumer's energy.

The SCR_{cri} calculating algorithm consists of three functions: function 1 calculates the SCR of each prosumer, function 2 calculates the resulting energy curtailment by comparing the prosumer's SCR with a threshold, and function 3 determines SCR_{cri} by detecting the breakpoint from the energy curtailment. The breakpoint occurs at an SCR of 3%, and after the breaking point, the energy curtailment increases exponentially, as shown in Figure 8.

Energy curtailment resulting from the SCR constraint leads to an enhancement in voltage profile even before implementing the sensitivity-matrix-based curtailment. This is because the total energy injected into the system is decreased. Consequently, when the sensitivity matrix is applied, location-based penalties are reduced compared to the scenario where the SCR constraint is neglected.

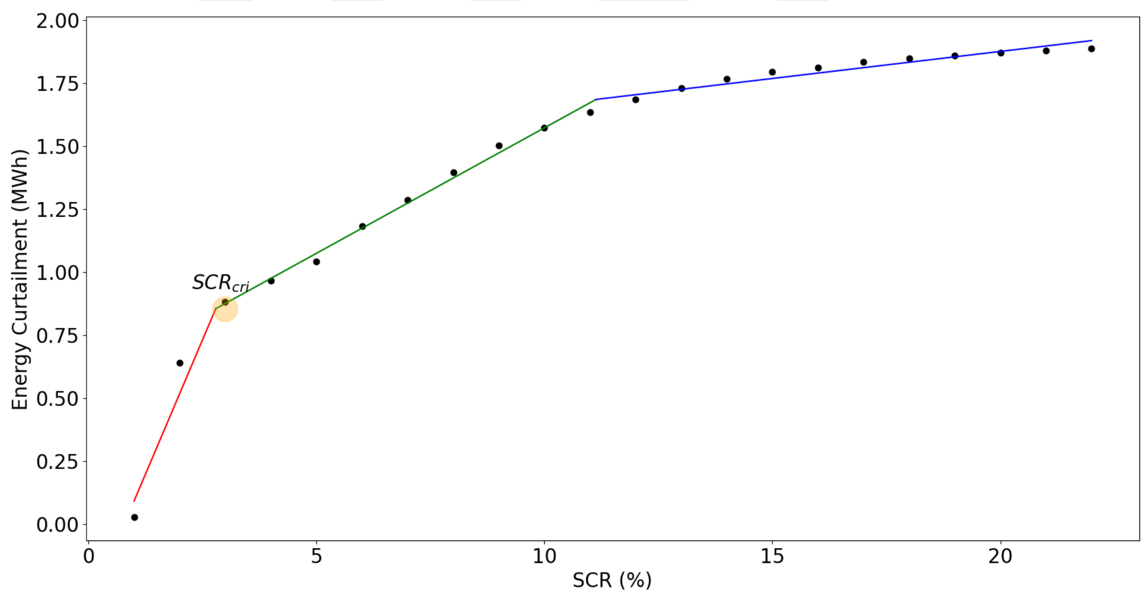

Figure 8: Sensitivity of Energy curtailment to SCR.

Algorithm 1 Proposed Algorithm for Calculating the Critical SCR.

$\boldsymbol{Function1: \ Calculate \ SCR}$

$\quad \boldsymbol{Input}: \ P_{G_{i,t}}, \ P_{D_{i,t}}, \ N, T$

$\quad For \ each \ (i,t) \ in \ (N,T)$

$\qquad \boldsymbol{Calculate} \ SCR_{i,t} \ based \ on \ (25)$

$\quad End \ For$

$\quad \boldsymbol{Output}: \ SCR_{i,t}$

$\boldsymbol{Function2}: Calculate \ Curtailment \ based \ on \ SCR$

$\quad \boldsymbol{Input}: S\check{C}R, \ P_{G_{i,t}}, \ P_{D_{i,t}}, \ N, T, SCR_{i,t}$

$\quad For \ each \ (i,t) \ in \ (N,T)$

$\qquad If \ SCR_{i,t} < S\check{C}R$

$\qquad\quad P^{new}_{G_{i,t}} = \frac{P_{D_{i,t}}}{1-SCR_{i,t}}$

$\qquad Else$

$\qquad\quad P^{new}_{G_{i,t}} = P_{G_{i,t}}$

$\qquad End \ If$

$\quad End \ For$

$\quad \boldsymbol{Compute} \ \overline{\in} = \sum_t^T \sum_i^N (P_{G_{i,t}} - P^{new}_{G_{i,t}})$

$\quad \boldsymbol{Output}: \ \overline{\in}$

$\boldsymbol{Function3: \ Determine \ \ SCR_{cri}}$

$\quad \boldsymbol{Input}: \widehat{SCR}, \ \overline{\ni}$

$\quad For \ S\check{C}R \ in \ \widehat{SCR}$

$\qquad \overline{\in} \ = Function2(S\check{C}R)$

$\qquad \boldsymbol{Append} \ \overline{\in} \ to \ \overline{\ni}$

$\quad End \ For$

$\quad \boldsymbol{Plot}(\widehat{SCR}, \overline{\in})$

$\quad \boldsymbol{Detect} \ SCR_{cri}$

$\quad \boldsymbol{Output}: \ \ SCR_{cri}$

$^*\check{SCR}$: Threshold of SCR; $\widehat{SCR}$: List of SCRs to be evaluated; $\overline{\in}$: Energy curtailment; $\overline{\ni}$: Empty list to store $\overline{\in}$.

The IEEE European Low Voltage Test Feeder [44] is considered a benchmark for the analysis. This is a typical distribution network in Europe developed by IEEE. The test feeder has 906 nodes with 55 active nodes, as illustrated in Figure 9. It is assumed

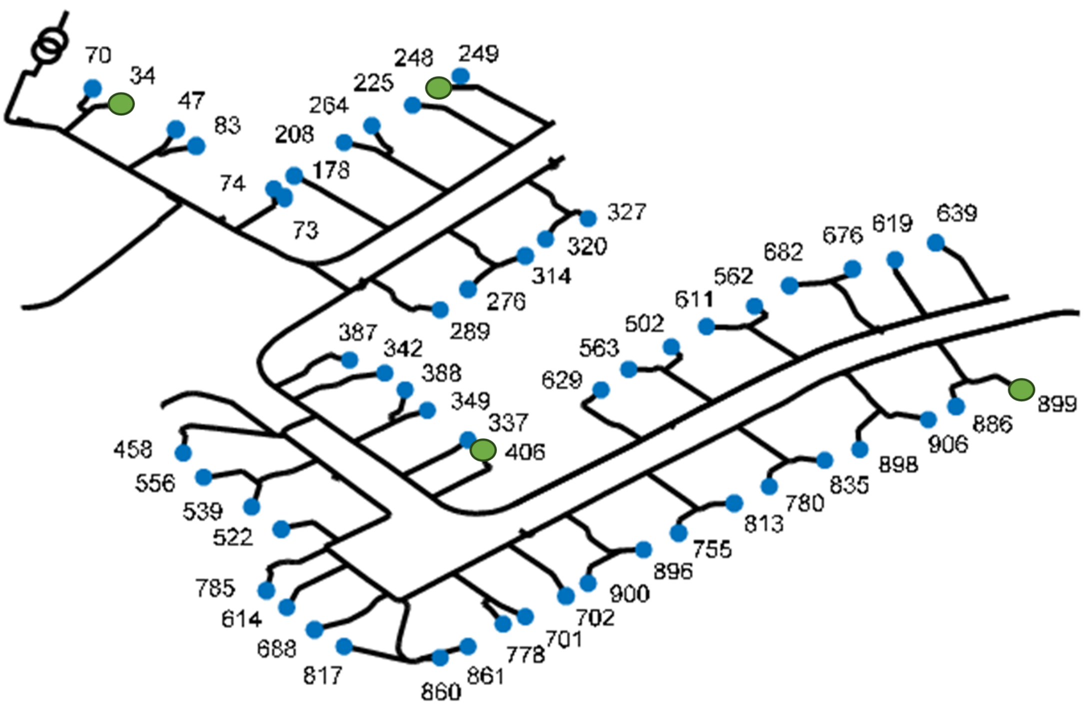

Figure 9: Single-line diagram of the IEEE European LV distribution Test Feeder, green dots depict the examined nodes

that all the customers in this LV distribution network are prosumers equipped with PV systems, and the total installed PV capacity is distributed among the prosumers based on their demand. The total installed PV capacity and SCR of each of the 55 prosumer is depicted in Figure 10. PV capacity varies from 1 kW up to 19.6 kW, and the SCR varies from 4.9% to 84.1%, with an average of 27.5%. The SCR is the ratio between the part of the PV generation directly transferred to the load and the total

PV generation, as stated in equation (25).

$$SCR = \frac{\int_{t=0}^{T} P_t^{pv \to load}}{\int_{t=0}^{T} P_t^{pv}} \tag{25}$$

where $P_t^{pv} = P_t^{pv \to load} + P_t^{pv \to grid} + P_t^{pv \to curtailed}$

Maximizing self-consumption is one of the main motivations behind PV installation for residential and industrial premises. High SCR levels are linked to technical and financial advantages. According to references [45, 46], a specific SCR threshold exists below which overvoltage issues arise in the LV distribution networks. Moreover, Reference [47] highlights the financial benefits of high SCR for residential end-users. Moreover, the secure voltage operational range of the LV distribution network is assumed to be between 0.94 and 1.10 p.u, and the transformer is configured at 1.05 p.u. A power flow simulation is performed using the time series demand and PV generation data with a 1-minute resolution by leveraging Pandapower [48].

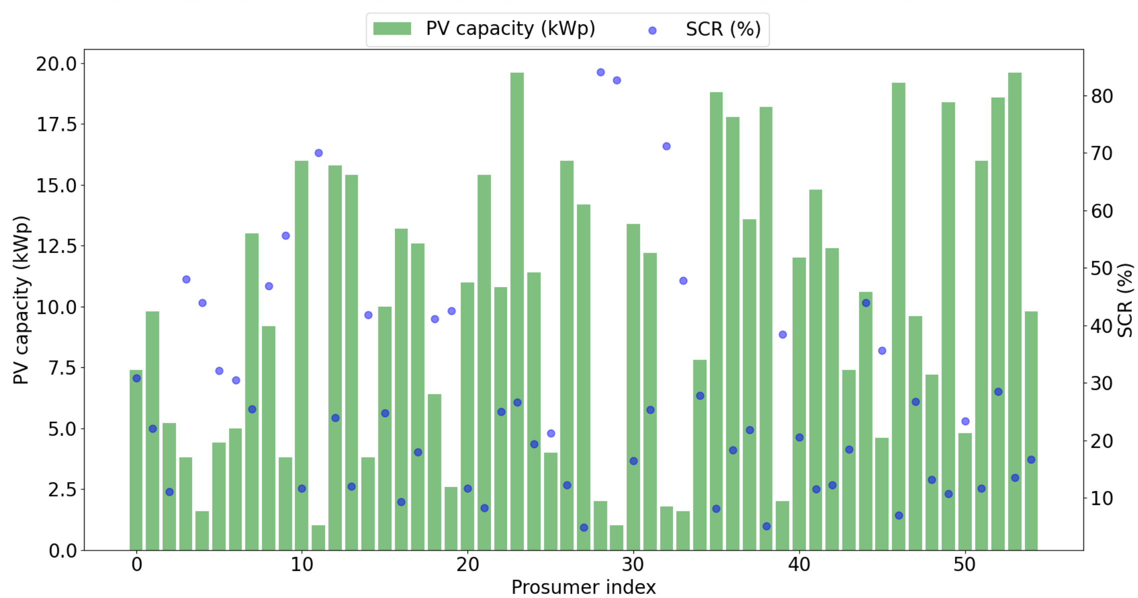

Figure 10: PV installed capacity and SCR of the prosumers.

CHAPTER V

PERFORMANCE EVALUATION OF OVERVOLTAGE MITIGATION METHODS

This chapter aims to validate the performance of the proposed EAPC by comparing it with the other over-voltage mitigation methods: DAPC, tripping, and feed-in power limitation. The technical comparison is conducted for a typical clear day, considering energy curtailment and nodal voltage variations under different PV penetrations.

5.1 Energy curtailment considering overall PV generation

A comparative analysis of four techniques for energy curtailment for a typical clear day is illustrated in Figure 11. The maximum energy curtailment of 1.7 MWh occurs under the tripping method because the inverter disconnects from the PCC when experiencing overvoltage cases; thereby, 56.6% of the total PV generation is curtailed. The proposed EAPC and DAPC energy curtailments are 1.05 MWh and 0.9 MWh, respectively, with a curtailment difference of less than 0.4% when considering the total surplus energy of 44 MWh. As we will discuss later, the feed-in power method has the minimum energy curtailment; however, this control method does not guarantee voltage stability for higher PV penetrations. Furthermore, EAPC and DAPC would achieve less energy curtailment if the feed-in power limit drops below 40%.

5.2 Nodal voltage fluctuations

The nodal voltage fluctuations are analysed considering the base case (no power control) and the other four power control techniques as shown in Figure 12. Four buses are selected to display the results while considering their electrical distance from the substation: Bus 34, Bus 248, Bus 406, and Bus 899. The smaller the

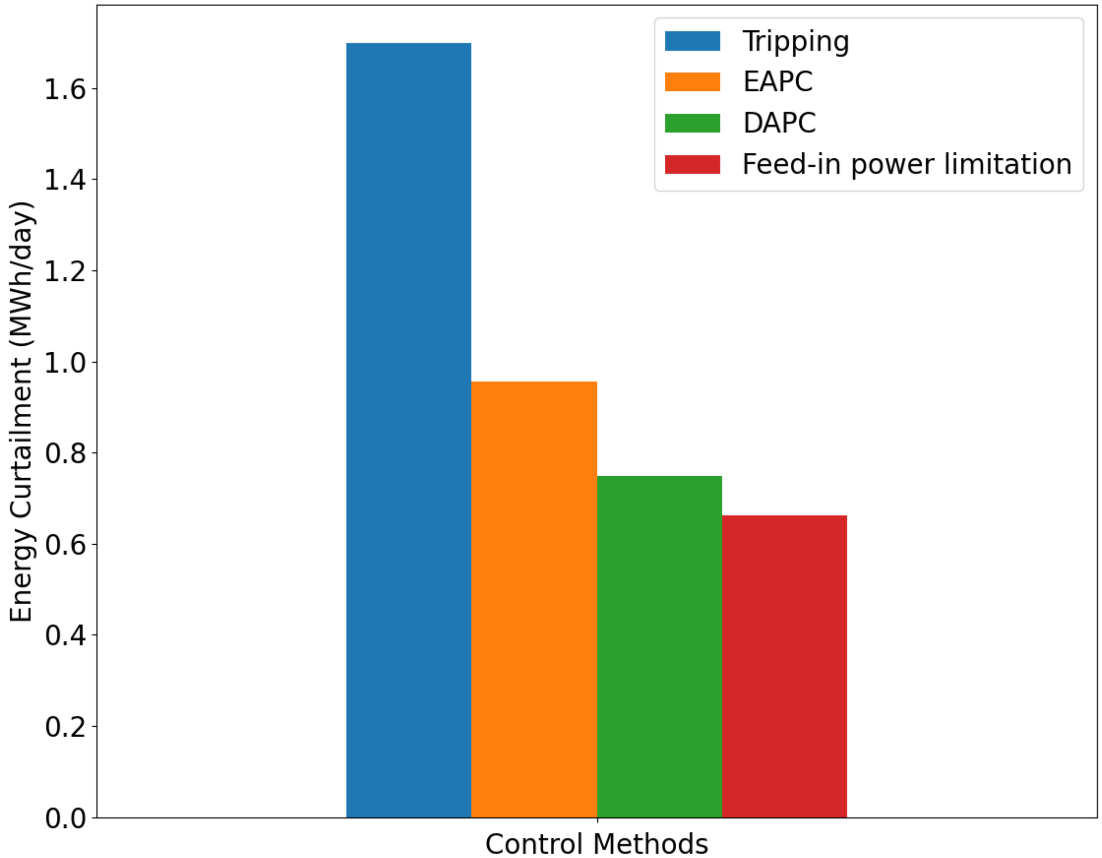

Figure 11: The amount of energy curtailment for a typical clear day

bus number, the closer to the substation. At Bus 34 (Figure 12. A), the voltage doesn't exceed the extreme operation condition (1.1 pu). Thus, the inverter remains connected to the PCC. However, the voltage drops at bus 34 due to the inverter tripping at different buses, especially the ones at the end of the feeder. Furthermore, the maximum voltage at buses 248, 406, and 899 occurs at noon, and the highest power injection is associated with Feed-in power, DAPC, EAPC, and tripping, respectively. Consequently, the rise in voltage corresponds proportionally to the increase in power injection. Therefore, it can be inferred that the method exhibiting the highest power injection will also undergo the most substantial voltage rise. It is worth mentioning that the voltage rises as the distance from the substation increases. Therefore, the maximum voltage in the system (1.16 pu) is recorded at the end of the feeder at bus

899.

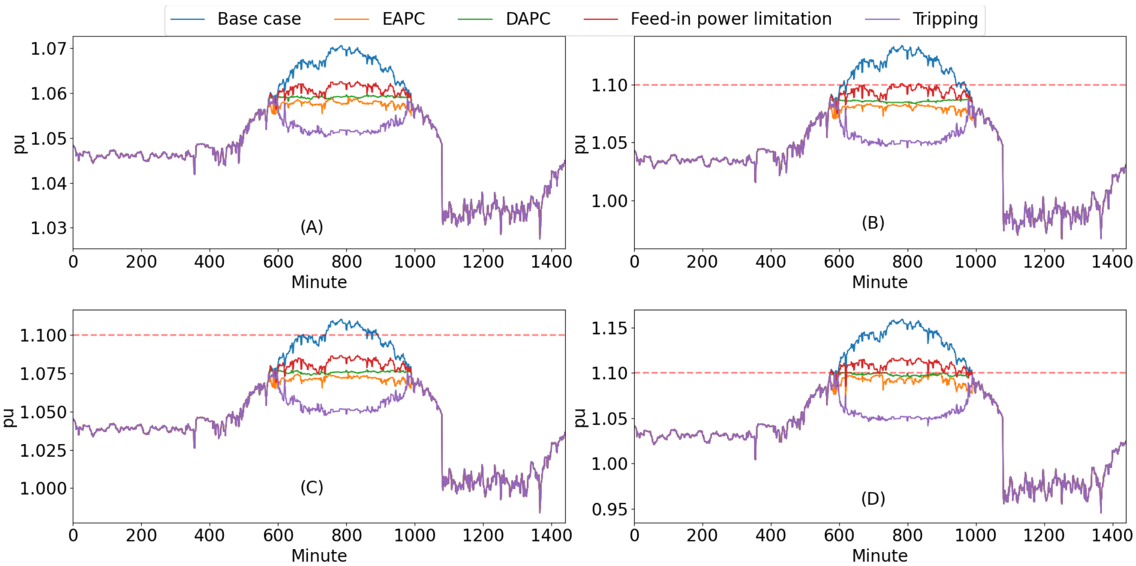

Figure 12: The voltage variation after applying control methods at (A) bus 34, (B) bus 248, (C) bus 406, and (D) bus 899.

5.3 Energy curtailment considering nodal PV generation

The energy curtailment at the selected buses after applying power control methods is given in Table 1. The total solar generation at Bus 34 is 40 kWh. After implementing DAPC, EAPC, feed-in power, and tripping methods, the usable solar generation has dropped to 36.8 kWh, 28.1 kWh, 32.6 kWh, and 40 kWh. It can be observed from Figure 12 that the voltage at bus 34 is below V_i^{max}; thus, the inverter remains connected to the grid. This case leads to the solar generation at bus 34 being the same as the base case under the ripping method, without energy curtailment. At buses 248, 406, and 899; the total generation is 20.4 kWh, 58.2 kWh, and 100 kWh, respectively. The curtailed energy at these buses due to DAPC is 58.8%, 31.5%, and 24.3%. When considering the feed-in power limit, the energy curtailment rates are 18.6%, 6%, 17.7%, and 22.4%, corresponding to total utilizable solar energy of 32.4 kWh, 39 kWh, and 36.4 kWh at bus 248, 406, and 899, respectively. Furthermore, the usable solar energy used in the tripping method for the same buses is 16 kWh, 25.4 kWh, and 37.8 kWh, respectively. The prosumer at Bus 248 and 406 maintain a satisfactory SCR value, consistently exceeding the SCR_{cri} threshold. Consequently, the EAPC method demonstrates minimal energy curtailments (16% and 12% of total PV generation) compared to other power control approaches, with most of the curtailment attributable to the location.

Table 1: Energy curtailment rates by power curtailment methods

Method	**Bus 34**	**Bus 248**	**Bus 406**	**Bus 899**
DAPC	8%	58.8%	31.5%	24.3%
EAPC	29.7%	16%	12%	18.3%
Feed-in power	18.6%	6%	17.7%	22.4%
Tripping	0%	21.9%	56.4%	62.2%

5.4 Energy curtailment considering location-sensitivity

As the prosumer moves farther from the distribution substation, more energy is curtailed under DAPC because prosumers at the end of the feeder are more vulnerable to overvoltage problems. This phenomenon is observed when changing the prosumer's location from near to the substation toward the end of the feeder, as seen in Table 2. The energy curtailment increases from 8% at the beginning of the feeder to 56.7% at the end of the feeder. Thus, the usable solar generation starts from 100% under no control method and declines gradually to a minimum value of 43.3%. This means that moving Prosumer 1 from bus 34 to bus 899 leads to losing 22.7 kWh of its energy. On the contrary, energy curtailment rates change within a tiny range from 29.7% to 30.8% under EAPC. Hence, it could be stated that the EAPC method is less sensitive to the prosumer's site and is more affected by the SCR.

Table 2: Energy curtailment rates considering location sensitivity.

Method	**Bus 34**	**Bus 248**	**Bus 406**	**Bus 682**	**Bus 899**
DAPC	8%	32%	35.6%	52.6%	56.7%
EAPC	29.7%	29.9%	30.7%	30.8%	30.5%

5.5 Energy curtailment considering PV penetration

The impact of increasing PV penetrations on energy curtailment is analysed in Figure 13. The Figure has been obtained by increasing the total installed PV capacity in the distribution network, running power flow, and calculating the respective energy curtailment for each method. In area (A), DAPC, EAPC, and tripping achieved the least energy curtailment. The tripping method is the simplest and needs no information shared between participants, so it is recommended that it be applied for solar-to-demand ratios (PV penetrations) less than 60%. Nonetheless, in area (B), DAPC was associated with the least energy curtailment; however, the feed-in power limitation method achieved better energy savings than the tripping method for penetration levels greater than 70%. Feed-in power limitation outperformed other methods for penetration levels greater than 100%, as illustrated by area (C). Nevertheless, this method does not consider voltage stability and might lead to overvoltage problems in high PV penetrations, as shown in Fig 14. Additionally, there is a slight difference between DAPC and EAPC in area (C); however, the merit of EAPC lies in its fairness compared to DAPC, rendering it more suitable for implementation in this region. These results will assist the grid operators in making a wise decision when selecting the curtailment method. Figure 14 shows the voltage rise in response to increased PV penetration when implementing the feed-in power limitation method. Bus 34 does not experience overvoltage problems despite the high PV penetration levels. On the other hand, as we move further from the substation, overvoltage occurs at lower penetration levels. For example, overvoltage occurs for penetration levels

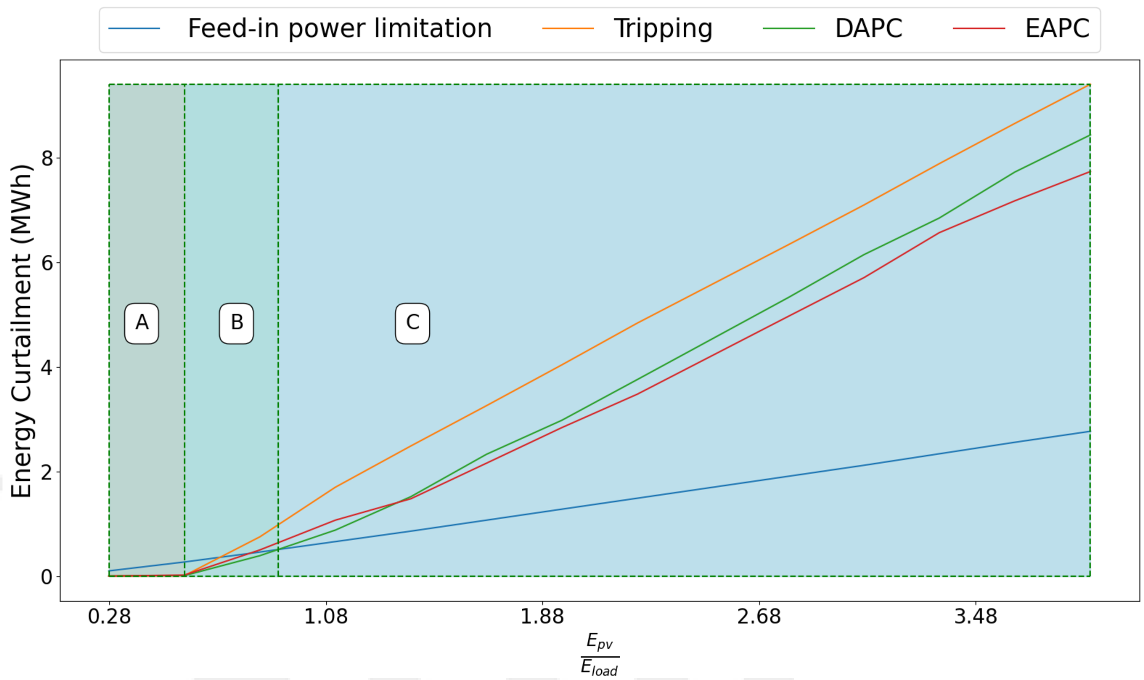

Figure 13: Comparison of energy curtailment under different solar-to-demand ratios.

greater than 140%, 110%, and 80% at Bus 248, 406, and 899, respectively. Hence, it can be deduced that this approach becomes invalid as a power control mechanism beyond a specific penetration threshold. Instead, it is advisable to adapt the feed-in power limit according to the fluctuations in supply and demand.

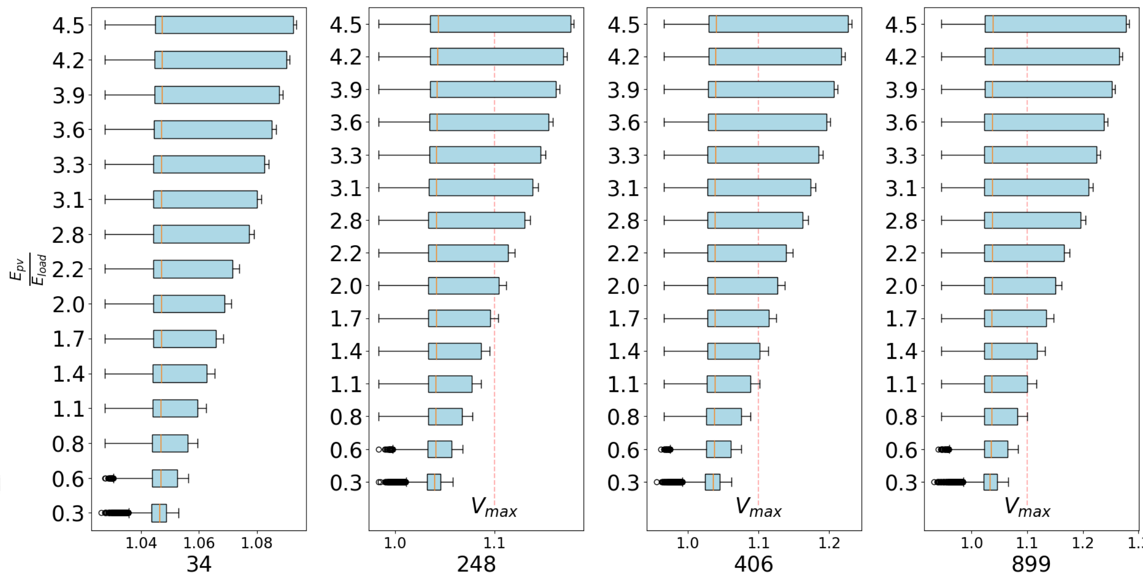

Figure 14: Voltage fluctuations for different solar-to-demand ratios under feed-in power limitation.

5.6 Energy curtailment considering location sensitivity and PV penetration

To reveal the correlation between energy curtailment and the prosumer's location, Prosumer 1 has been relocated from the vicinity of the substation (Bus 34) towards the terminus of the feeder (Bus 899) as shown in Figure 15. As mentioned before, DAPC is highly sensitive to the prosumer's location in the network. It can be noticed that despite the massive increase in the penetration level, the energy curtailment at Bus 34 slightly increases compared to the energy curtailment at buses further from the substation, where the energy curtailment increases dramatically. For instance, if the penetration level equals 207%, the difference between energy curtailment at Bus 34 and 899 is more than 100 kWh. On the other hand, this difference (illustrated by Δ) is only 18 kWh in the case of EAPC, as shown in Figure 15.B. Since EAPC is based on SCR, the energy curtailment at bus 34 when applying EAPC is much higher than it when applying DAPC. However, the overall energy curtailment in EAPC is less than that of DAPC. This graph illustrates the superiority of EAPC over DAPC in terms of fairness and energy curtailment.

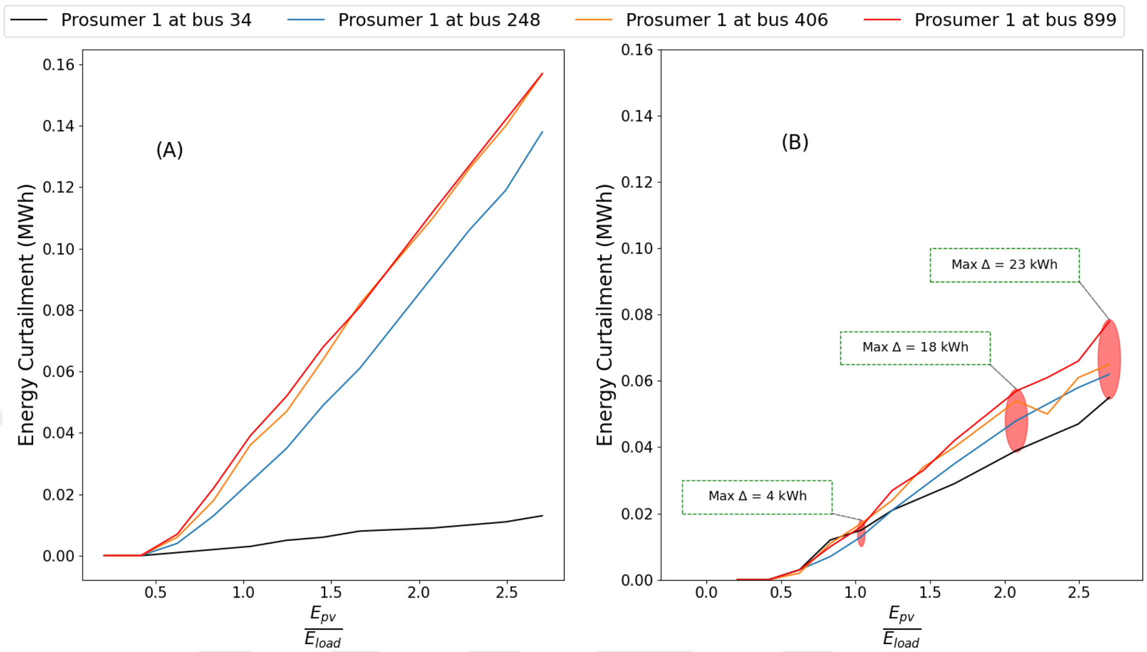

Figure 15: Energy curtailment under increasing penetration level for a) DAPC and B) EAPC methods.

5.7 Energy curtailment considering BESS

As the BESS capacity increases, there is a notable decrease in energy curtailment till a certain point. Figure 16 illustrates this consistent trend across all four methods. This phenomenon can be attributed to the capability of BESS to store surplus energy and subsequently release it during peak demand periods. Doing so diminishes the need to curtail energy production, resulting in a more efficient utilization of resources and reduced wastage. The difference in energy curtailment between DAPC and EAPC can be further reduced using BESS, as shown in the graph. For example, for a BESS capacity of 2.5 MWh, there is about 1.6% energy curtailment decrease when applying EAPC compared to DAPC. Noteworthy, the capacity of the Battery Energy Storage System (BESS) is determined by assessing both annual demand and supply. In the region under examination, where cloudy or partially cloudy weather conditions characterize 131 days, the total energy curtailment experiences a notable decrease.

Furthermore, this reduction in curtailment will be even more pronounced in regions with greater cloud cover.

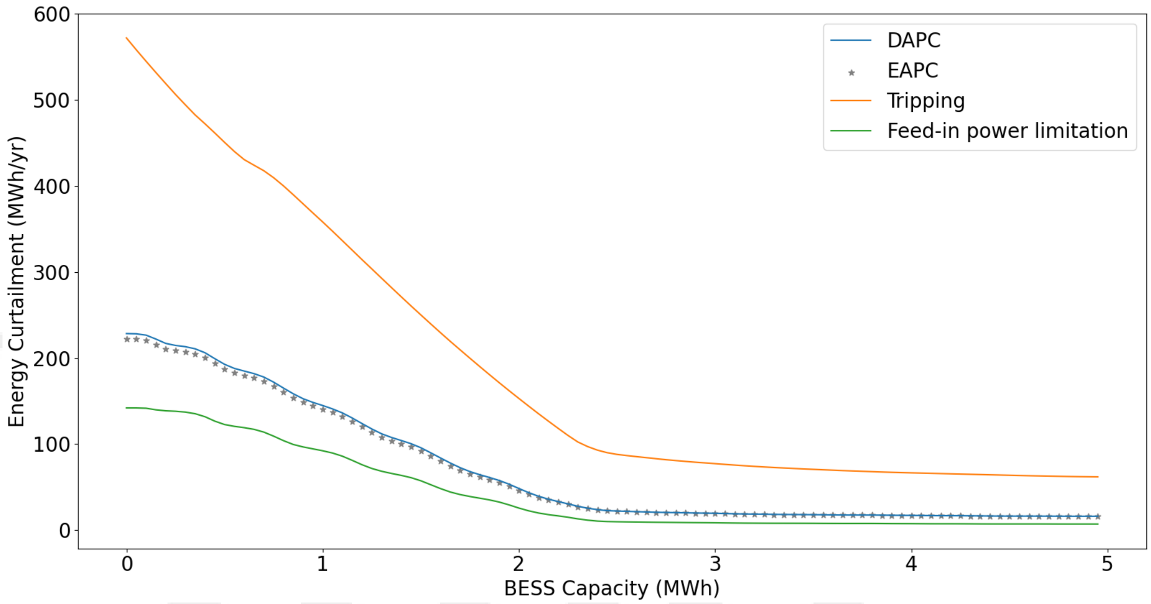

Figure 16: Annual energy curtailment decrement when installing BESS.

CHAPTER VI

DISCUSSION

The efficacy of the four active power control techniques outlined in this paper is technically apparent in alleviating voltage surges. Nevertheless, each approach comes with its own limitations.

Feed-in power limitation methods curtails the surplus power considering the predefined feed-in threshold, without observing voltage operation limits. Therefore, voltage constraint violation might occur in high PV pnentration levels as shown in the section VI. Moreover, the energy curtailment amount highly dependent on the feed-in limit, such as high limit allows more power injection to the grid, however, this might cause overvoltage issues. Meanwhile, conservative limit enables less energy injection and more energy curtailment, but ensure voltage stability. Thus, the feed-in power threshold must be determined after conducting careful analyses considering the available solar potential, estimated demand growth, and calculated feeder' solar hosting capacity.

Inverter tripping considers the voltage at PCC, such that the inverter trips when detecting overvoltage at the node and connects after a time delay. Despite the effectiveness of this method in successfully addressing the overvoltage problem, it introduces unfairness between participants. Due to the radial layout of LV distribution networks, the voltage rises as we move further from the transformer, such that overvoltage happens to occur at the end of the feeders. Thus, the prosumers located there experiences frequent overvoltage, event that they might not have major contribution to it. In they way, they are more penalized compared to prosumers near to the substation. This situation extremely impact their financial benefits and limit their revenue.

Active power curtailment methods like Droop-based APC and DAPC are also promising methods in addressing the overvoltage issue. Droop-based APC, whcich consider both critical and maximum voltage band, results in higher energy curtailment compared to DAPC. However, this method ensures voltage safety operation limits without any violation hazard. DAPC, on the other hand, leverages the voltage sensitivity matrix to calculate each prosumer's contribution to voltage rise. This methods, unlike, the previous ones, curtails energy from each prosumer with surplus power. However, even though it seems to be fairer than tripping and Droop-based APC, it fails to count the impact of the radical nature of the distribution grid, resulting in high curtailment at end nodes, and less curtailment at closer nodes from the substation.

All these methods, fails the count the prosumer's self-consumption and the interactive of supply and demand, hence, unfairness is appear between two prosumers due to their location even if they have similar load demand. The proposed EAPC successfully alleviate the impact of radial network on voltage profile by prioritizing self-consumption, such that it is highly sensitive to location even in extremely high PV penetrations. Despite this method introduces slight increase in curtailed energy compared to DAPC, the usage of BESS can overcome this issue. Table 3 illustrates a comparison of these methods from different perspectives.

Table 3: Comparison of the power control methods

Methods	**Voltage Stability**	**Communication Link**	**Fairness**	**Energy Curtailment**
Feed-in power	No	No	Moderate	Low
Droop-based APC	Yes	No	Poor	High
Tripping	Yes	No	Poor	High
DAPC	Yes	Yes	Poor	Low
EAPC	Yes	Yes	High	Low

CHAPTER VII

CONCLUSION

While generally, the voltage drop at the end of the LV distribution networks is expected traditionally; overvoltage issues arise with the widespread adoption of distributed resources. Especially in PV-rich distribution networks, conventional solutions to mitigate overvoltage problems introduce unfairness in the amount of energy curtailment for the prosumers located at the end of the feeders. However, this paper proposes a more equitable approach for active power curtailment to mitigate overvoltage while considering the interaction between prosumers and the grid. The proposed approach penalizes the prosumers who fail to satisfy a certain SCR level to support raising self-consumption locally to lower the impact on the grid. The proposed method curtails energy based on the voltage sensitivity matrix that reflects the relation between the power injection and the bus voltage. A comparative analysis of the proposed EAPC and three prevalent methods, feed-in power limitation, inverter tripping, and DAPC, shows that slightly less energy curtailment occurs for penetration levels below 60%; thus, the tripping method is desired because of its simplicity. The feed-in power limitation method does not preserve voltage safety for PV penetration above 80% because it does not consider demand and supply interaction. However, EAPC exhibits reduced sensitivity to the prosumer's location within the feeders while effectively alleviating overvoltage incidents. Additionally, the location sensitivity of EAPC and DAPC is evaluated by moving one prosumer from the feeder's beginning to the end, and the results indicate that only a 4 kWh energy curtailment difference occurred under EAPC. Meanwhile, this value is 36 kWh under DAPC, resulting in a four times higher curtailment due to the location of the prosumer, proving that EAPC treats prosumers more equitably than DAPC. The opportunity of leveraging BESS to reduce energy loss is also examined. The energy curtailment difference between DAPC and EAPC can be decreased to less than 1.6% annually, without the need to increase the capacity of the BESS. The proposed method would help the prosumers manage their active power and encourage them to achieve high self-consumption.

REFERENCES

[1] Z. Wang, X. Yu, Y. Mu, and H. Jia, “A distributed peer-to-peer energy transaction method for diversified prosumers in urban community microgrid system,” *Applied Energy*, vol. 260, 2020.

[2] C. Yin and F. Li, “Reactive power control strategy for inhibiting transient overvoltage caused by commutation failure,” *IEEE Trans. Power Syst.*, vol. 36, no. 5, pp. 4764–4777, 2021.

[3] E. E. Pompodakis, I. A. Drougakis, I. S. Lelis, and M. C. Alexiadis, “Photovoltaic systems in low-voltage networks and overvoltage correction with reactive power control,” *IET Renew. Power Gener.*, vol. 10, no. 3, pp. 410–417, 2016.

[4] A. Safayet, P. Fajri, and I. Husain, “Reactive power management for overvoltage prevention at high pv penetration in a low-voltage distribution system,” *IEEE Trans. Ind. Appl.*, vol. 53, no. 6, pp. 5786–5794, 2017.

[5] A. M. Howlader, S. Sadoyama, L. R. Roose, and Y. Chen, “Active power control to mitigate voltage and frequency deviations for the smart grid using smart pv inverters,” *Appl. Energy*, vol. 258, no. April 2019, p. 114000, 2020.

[6] R. Tonkoski, L. A. C. Lopes, and T. H. M. El-Fouly, “Coordinated active power curtailment of grid connected pv inverters for overvoltage prevention,” *IEEE Trans. Sustain. Energy*, vol. 2, no. 2, pp. 139–147, 2011.

[7] A. I. Nousdilis, G. C. Christoforidis, and G. K. Papagiannis, “Active power management in low voltage networks with high photovoltaics penetration based on prosumers’ self-consumption,” *Appl. Energy*, vol. 229, pp. 614–624, Nov. 2018.

[8] G. C. Kryonidis, E. O. Kontis, A. I. Chrysochos, C. S. Demoulias, and G. K. Papagiannis, “A coordinated droop control strategy for overvoltage mitigation in active distribution networks,” *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 5260–5270, 2018.

[9] A. M. S. Alonso, L. D. O. De Oro Arenas, D. I. Brandao, E. Tedeschi, and F. P. Marafao, “Integrated local and coordinated overvoltage control to increase energy feed-in and expand der participation in low-voltage networks,” *IEEE Trans. Sustain. Energy*, vol. 13, no. 2, pp. 1049–1061, 2022.

[10] R. Wagle, P. Sharma, C. Sharma, and M. Amin, “Optimal power flow based coordinated reactive and active power control to mitigate voltage violations in smart inverter enriched distribution network,” *Int. J. Green Energy*, vol. 21, no. 2, pp. 359–375, 2024.

[11] Y. Z. Gerdroodbari, R. Razzaghi, and F. Shahnia, “Decentralized control strategy to improve fairness in active power curtailment of pv inverters in low-voltage

distribution networks," *IEEE Trans. Sustain. Energy*, vol. 12, no. 4, pp. 2282–2292, 2021.

[12] L. Collins and J. K. Ward, "Real and reactive power control of distributed pv inverters for overvoltage prevention and increased renewable generation hosting capacity," *Renew. Energy*, vol. 81, pp. 464–471, 2015.

[13] T. T. Mai, N. A. N. M. M. Haque, H. T. Vo, and P. H. Nguyen, "Coordinated active and reactive power control for overvoltage mitigation in physical lv microgrids," *J. Eng.*, vol. 2019, no. 18, pp. 5007–5011, 2019.

[14] L. Cheng, Y. Chang, and R. Huang, "Mitigating voltage problem in distribution system with distributed solar generation using electric vehicles," *IEEE Trans. Sustain. Energy*, vol. 6, no. 4, pp. 1475–1484, 2015.

[15] C. L. Masters, "Voltage rise the big issue when connecting embedded generation to long 11 kv overhead lines," *Power Eng. J.*, vol. 16, no. 1, pp. 5–12, 2002.

[16] J. Lazo and D. Watts, "Stochastic model for active distribution networks planning: An analysis of the combination of active network management schemes," *Renew. Sustain. Energy Rev.*, vol. 191, no. December 2023, p. 114156, 2024.

[17] A. I. Nousdilis, G. C. Kryonidis, E. O. Kontis, G. C. Christoforidis, and G. K. Papagiannis, "An exponential droop control strategy for distributed energy storage systems integrated with photovoltaics," *IEEE Trans. Power Syst.*, vol. 36, no. 4, pp. 3317–3328, 2021.

[18] M. R. Jannesar, A. Sedighi, M. Savaghebi, and J. M. Guerrero, "Optimal placement, sizing, and daily charge/discharge of battery energy storage in low voltage distribution network with high photovoltaic penetration," *Appl. Energy*, vol. 226, no. March, pp. 957–966, 2018.

[19] R. Luthander, D. Lingfors, and J. Widén, "Large-scale integration of photovoltaic power in a distribution grid using power curtailment and energy storage," *Sol. Energy*, vol. 155, pp. 1319–1325, 2017.

[20] M. M. V. M. Ali, P. H. Nguyen, W. L. Kling, A. I. Chrysochos, T. A. Papadopoulos, and G. K. Papagiannis, "Fair power curtailment of distributed renewable energy sources to mitigate overvoltages in low-voltage networks," in *2015 IEEE Eindhoven PowerTech, PowerTech 2015*, no. 608998, 2015.

[21] S. M. Alizadeh, C. Ozansoy, and T. Alpcan, "The impact of x/r ratio on voltage stability in a distribution network penetrated by wind farms," in *2016 Australas. Univ. Power Eng. Conf.*, pp. 1–6, 2016.

[22] A. Samadi, R. Eriksson, L. Söder, B. G. Rawn, and J. C. Boemer, "Coordinated active power-dependent voltage regulation in distribution grids with pv systems," *IEEE Trans. Power Deliv.*, vol. 29, no. 3, pp. 1454–1464, 2014.

[23] S. Paudyal, B. P. Bhattarai, R. Tonkoski, S. Dahal, and O. Ceylan, "Comparative study of active power curtailment methods of pvs for preventing overvoltage on distribution feeders," in *IEEE Power Energy Soc. Gen. Meet.*, vol. 2018-Augus, pp. 1–5, 2018.

[24] A. T. Procopiou, K. Petrou, L. F. Ochoa, T. Langstaff, and J. Theunissen, "Adaptive decentralized control of residential storage in pv-rich mv-lv networks," *IEEE Trans. Power Syst.*, vol. 34, no. 3, pp. 2378–2389, 2019.

[25] S. Weckx, C. Gonzalez, and J. Driesen, "Combined central and local active and reactive power control of pv inverters," *IEEE Trans. Sustain. Energy*, vol. 5, no. 3, pp. 776–784, 2014.

[26] S. Alyami, Y. Wang, C. Wang, J. Zhao, and B. Zhao, "Adaptive real power capping method for fair overvoltage regulation of distribution networks with high penetration of pv systems," *IEEE Trans. Smart Grid*, vol. 5, no. 6, pp. 2729–2738, 2014.

[27] F. Olivier, P. Aristidou, D. Ernst, and T. Van Cutsem, "Active management of low-voltage networks for mitigating overvoltages due to photovoltaic units," *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 926–936, 2016.

[28] P. Lusis, L. L. H. Andrew, A. Liebman, G. Tack, and S. Chakraborty, "Reducing the unfairness of coordinated inverter dispatch in pv-rich distribution networks," in *2019 IEEE Milan PowerTech, PowerTech 2019*, vol. 675318, pp. 1–6, 2019.

[29] M. Z. Liu and et al., "On the fairness of pv curtailment schemes in residential distribution networks," *IEEE Trans. Smart Grid*, vol. 11, no. 5, pp. 4502–4512, 2020.

[30] D. Gebbran, S. Mhanna, Y. Ma, A. C. Chapman, and G. Verbič, "Fair coordination of distributed energy resources with volt-var control and pv curtailment," *Appl. Energy*, vol. 286, no. January, 2021.

[31] A. Latif, W. Gawlik, and P. Palensky, "Quantification and mitigation of unfairness in active power curtailment of rooftop photovoltaic systems using sensitivity based coordinated control," *Energies*, vol. 9, no. 6, 2016.

[32] J. Von Appen, M. Braun, T. Stetz, K. Diwold, and D. Geibel, "Time in the sun: The challenge of high pv penetration in the german electric grid," *IEEE Power Energy Mag.*, vol. 11, no. 2, pp. 55–64, 2013.

[33] S. Hashemi and J. Østergaard, "Methods and strategies for overvoltage prevention in low voltage distribution systems with pv," *IET Renew. Power Gener.*, vol. 11, no. 2, pp. 205–214, 2017.

[34] L. R. Visser, E. M. B. Schuurmans, T. A. AlSkaif, H. A. Fidder, A. M. van Voorden, and W. G. J. H. M. van Sark, "Regulation strategies for mitigating voltage

fluctuations induced by photovoltaic solar systems in an urban low voltage grid," *Int. J. Electr. Power Energy Syst.*, vol. 137, no. December 2020, p. 107695, 2022.

[35] E. Stewart, J. MacPherson, S. Vasilic, D. Nakafuji, and T. Aukai, "Analysis of high-penetration levels of photovoltaics into the distribution grid on oahu, hawaii: detailed analysis of heco feeder wf1," 2013. Available online: `http://www.osti.gov/bridge%0Ahttps://www.nrel.gov/docs/fy13osti/54494.pdf`.

[36] U.S. Energy Information Administration, "Electricity capacity," 2021.

[37] International Renewable Energy Agency, "Renewable capacity statistics 2023," 2023.

[38] P. Schavemaker and L. Van der Sluis, *Electrical power system essentials*. John Wiley & Sons, 2017.

[39] IEA, "Key world energy statistics 2021 statistics report," tech. rep., IEA Publications, 2021.

[40] K. Chatchairungruang and S. Suwankawin, "Peak-shaving of feed-in pv power for residential pv-battery system with added feedback-adjustment scheme," in *ECTI-CON 2021 - 2021 18th Int. Conf. Electr. Eng. Comput. Telecommun. Inf. Technol. Smart Electr. Syst. Technol. Proc.*, pp. 192–195, 2021.

[41] H. Ruf, "Limitations for the feed-in power of residential photovoltaic systems in germany – an overview of the regulatory framework," *Sol. Energy*, vol. 159, no. October 2017, pp. 588–600, 2018.

[42] S. M. Tercan, A. Demirci, E. Gokalp, and U. Cali, "Maximizing self-consumption rates and power quality towards two-stage evaluation for solar energy and shared energy storage empowered microgrids," *J. Energy Storage*, vol. 51, no. June 2021, p. 104561, 2022.

[43] R. Tonkoski, L. A. C. Lopes, and T. H. M. EL-Fouly, "Droop-based active power curtailment for overvoltage prevention in grid connected pv inverters," in *IEEE Int. Symp. Ind. Electron.*, pp. 2388–2393, 2010.

[44] F. G. Gause, "Coordinated active power curtailment of grid connected pv inverters for overvoltage prevention," *Middle East Policy*, vol. 14, no. 2, pp. 119–124, 2007.

[45] E. E. E. Ahmed and A. Demirci, "Assessment of overvoltage and power losses in low voltage distribution networks with high photovoltaics penetration based on prosumers' self-consumption," in *HORA 2022 - 4th International Congress on Human-Computer Interaction, Optimization and Robotic Applications, Proceedings*, pp. 1–4, 2022.

[46] A. I. Nousdilis, A. I. Chrysochos, G. K. Papagiannis, and G. C. Christoforidis, "The impact of photovoltaic self-consumption rate on voltage levels in lv distribution grids," in *2017 11th IEEE Int. Conf. Compat. Power Electron. Power Eng. CPE-POWERENG 2017*, pp. 650–655, 2017.

[47] S. van der Stelt, T. AlSkaif, and W. van Sark, "Techno-economic analysis of household and community energy storage for residential prosumers with smart appliances," *Appl. Energy*, vol. 209, no. August 2017, pp. 266–276, 2018.

[48] L. Thurner and et al., "Pandapower - an open-source python tool for convenient modeling, analysis, and optimization of electric power systems," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 6510–6521, 2018.

VITA

EIHAB E. E. AHMED received the B.Sc. from the Department of Electrical Engineering, Yildiz Technical University, Istanbul, Turkey, in 2022. He is currently pursuing his master's program in the Department of Electrical and Electronics Engineering at Ozyegin University. Furthermore, he was a Teaching Assistant in Energy Systems courses and a Research Assistant in Grid Operations and Planning Laboratory at Ozyegin University during his graduate studies. His research interest includes power system optimization, distributed renewable energy systems, electricity markets, electric vehicles, and energy storage systems. He published several papers related to his research areas.