ADAPTIVE REACTIVE POWER CONTROL FOR MITIGATING VOLTAGE RISE IN DISTRIBUTION NETWORKS WITH HIGH PHOTOVOLTAIC PENETRATION

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By

ABO ALWEZ MUSTAFA HUSSEIN ABED

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

July 2024

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

ADAPTIVE REACTIVE POWER CONTROL FOR MITIGATING VOLTAGE RISE IN DISTRIBUTION NETWORKS WITH HIGH PHOTOVOLTAIC PENETRATION

By

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July 2024

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This thesis addresses the escalating challenge of voltage rise on electrical distribution networks, primarily attributed to high photovoltaic (PV) penetration. As the global shift towards renewable energy accelerates, the integration of PV systems in existing power grids has become increasingly prevalent, posing significant technical challenges. The primary focus of this research is the development, evaluation, and validate of an innovative adaptive reactive power control technique designed to mitigate voltage rise issues on these PV-intensive distribution networks. The study begins with a literature review, highlighting the limitations of traditional voltage regulation methods in mitigating the voltage rise and existing reactive power control strategies. It then introduces a novel adaptive reactive power control technique, distinguished by its dynamic approach that continuously updates reactive power references based on real-time network conditions. This technique depends on both Volt-Var and Watt-Var components, allowing for efficient

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voltage rise mitigation. Using MATLAB/Simulink and OpenDSS, the adaptive control technique is rigorously evaluated in two distinct scenarios: a small test distribution network and the Malaysian low voltage distribution network. The results demonstrate the technique's superior performance in maintaining voltage stability within acceptable limits under various PV penetration levels, outperforming existing reactive power control methods. The research contributes significantly to the field of power systems engineering by providing a practical solution for the sustainable integration of PV systems into existing distribution networks. It offers a pathway towards enhancing grid stability and reliability in the face of growing renewable energy adoption. The findings are particularly relevant for countries experiencing rapid growth in PV installations. In conclusion, this thesis not only addresses a pressing challenge in the modern power grid but also lays the groundwork for future research. It underscores the importance of innovative approaches in the ongoing evolution of power systems towards greater sustainability and resilience.

Keywords: High PV Penetration, Reactive Power Control, Voltage Rise

SDG: GOAL7: Affordable and Clean Energy

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Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KAWALAN KUASA REAKTIF ADAPTIF UNTUK MENGURANGKAN PENINGKATAN VOLTAN DALAM RANGKAIAN PENGEDARAN DENGAN PENEMBUSAN FOTOVOLTAIK YANG TINGGI

Oleh

ABO ALWEZ MUSTAFA HUSSEIN ABED

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Tesis ini membincangkan cabaran yang semakin meningkat berhubung dengan kenaikan voltan pada rangkaian pengedaran elektrik, yang terutamanya disebabkan oleh penembusan fotovoltaik (PV) yang tinggi. Dengan peralihan global ke arah tenaga boleh diperbaharui yang semakin pesat, integrasi sistem PV dalam grid elektrik sedia ada menjadi semakin meluas, membawa kepada cabaran teknikal yang ketara. Fokus utama penyelidikan ini adalah pembangunan, penilaian, dan pengesahan teknik kawalan kuasa reaktif adaptif yang inovatif, yang direka untuk mengurangkan masalah kenaikan voltan pada rangkaian pengedaran yang kaya dengan PV. Kajian ini bermula dengan ulasan literatur, yang menyorot kekangan kaedah pengawalan voltan tradisional dalam mengurangkan kenaikan voltan dan strategi kawalan kuasa reaktif sedia ada. Ia kemudian memperkenalkan teknik kawalan kuasa reaktif adaptif yang novel, yang dibezakan dengan pendekatan dinamik yang secara berterusan mengemas kini rujukan kuasa reaktif

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berdasarkan keadaan rangkaian masa nyata. Teknik ini bergantung pada kedua-dua komponen Volt-Var dan Watt-Var, yang membolehkan mitigasi kenaikan voltan dengan cekap. Menggunakan MATLAB/Simulink dan OpenDSS, teknik kawalan adaptif dinilai dengan teliti dalam dua senario berbeza: rangkaian pengedaran ujian kecil dan rangkaian pengedaran voltan rendah Malaysia. Hasil kajian menunjukkan prestasi cemerlang teknik ini dalam mengekalkan kestabilan voltan dalam had yang boleh diterima di bawah pelbagai tahap penembusan PV, mengatasi kaedah kawalan kuasa reaktif sedia ada. Penyelidikan ini memberikan sumbangan yang signifikan kepada bidang kejuruteraan sistem tenaga dengan menyediakan penyelesaian praktikal untuk integrasi mampan sistem PV ke dalam rangkaian pengedaran sedia ada. Ia menawarkan laluan untuk meningkatkan kestabilan dan kebolehpercayaan grid berdepan dengan peningkatan penggunaan tenaga boleh diperbaharui. Penemuan ini amat relevan bagi negara-negara yang mengalami pertumbuhan pesat dalam pemasangan PV. Sebagai kesimpulan, tesis ini bukan sahaja menangani cabaran penting dalam grid tenaga moden tetapi juga menyediakan asas untuk penyelidikan masa depan. Ia menekankan kepentingan pendekatan inovatif dalam evolusi berterusan sistem tenaga ke arah kelestarian dan ketahanan yang lebih besar.

Kata Kunci: Penembusan PV Tinggi, Kawalan Kuasa Reaktif, Kenaikan Voltan

SDG: MATLAMAT 7: Tenaga Bersih dan Berpatutan

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Date: 13 January 2025

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LIST OF ABBREVIATIONS

D	Distance
ESS	Energy Storage System
f	Frequency
FPF	Fixed Power Factor
GMRi	Geometric mean radius of conductor
IEA	Internation Energy Agency
P	Power
Pc	Charging power
Pd	Discharging power
PF	Power Factor
PV	Photovoltaic
Q	Reactive Power
r	Resistance
t	Time
UPM	Universiti Putra Malaysia
V	Voltage
W	Weight
ηc	Charging efficiencies
ηd	Discharging efficiency
ρ	Earth Resistivity
Ω	Ohm
UPM	Universiti Putra Malaysia

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CHAPTER 1

INTRODUCTION

This chapter highlights the current and existing reactive power control techniques to mitigate the voltage rise on distribution networks with high PV penetration. Then, this chapter presents the problem statement, the aim and the objectives of the thesis, the scope of the research, the contribution of the thesis finally, the outlines of the thesis are presented.

1.1 Background

Energy is a fundamental requirement for industries, agriculture, and daily lives. The energy demand continues to rise alongside the growing world population and increased electricity consumption in daily life. However, traditional power plants that rely on fossil fuels for electricity generation have a detrimental impact on the atmosphere, releasing CO_2 and NO_X emissions through the burning of fossil fuels. Furthermore, the availability of fossil fuels is limited, leading some countries to rely on imports, which adversely affects their economies (Wigley, 1991).

In light of these challenges, the utilization of photovoltaic cells (PVs) has experienced significant growth in the past decade (Hosenuzzaman et al., 2015). According to the International Energy Agency (IEA), solar energy is expected to emerge as a major energy source by 2050, contributing to approximately 11% of global power generation (Diner, 2011; Moosavian et al., 2013). The IEA also anticipates that the adoption of PV systems as distributed

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generation (DG) can achieve an unprecedented global penetration level exceeding 50%. The transition of a rapidly developing economy like China, which previously heavily relied on coal for electricity generation, towards renewable sources such as solar energy. As a result, PV-based electricity generation in China has increased from less than 20 TWh in 2012 to over 160 TWh in 2018. Similarly, countries like the United States of America and Australia have significantly enhanced their electricity generation reliability through PV systems, as depicted in Figure 1.1 rising from 2.08 TWh and 0.29 TWh to 97.12 TWh and 12 TWh respectively by 2018 (Renewables - Energy System - IEA, n.d.).

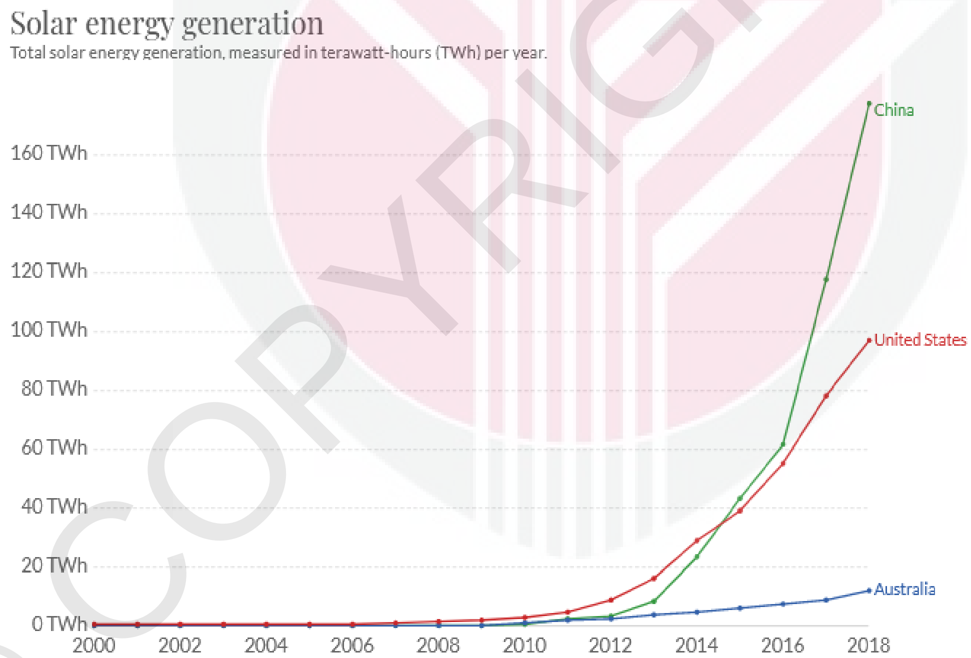

Figure 1.1 : Power Generation through PV (2000–2018)
(Renewables – Energy System – IEA, n.d.)

Among these increments in PV around the word, small-scale photovoltaic (PV) systems in grid-connected form are the most prevalent due to their affordability

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and ease of installation. The penetration of distributed generators has significantly increased on medium and low distribution networks over the past decade (Salimon et al., 2023). However, this rise in distributed generation penetration on the network has introduced several challenges to the network, including reverse power flow, voltage rise, and frequency issues. The voltage rise, in particular, has adversely affected the power quality of the network, resulting in increased losses and potential tripping of PV systems by protection systems. Consequently, these effects have limited the capacity of the network to accommodate distributed generators (Seuss et al., 2015).

This phenomenon occurs as a consequence of the excess power generated by PV systems being injected into the distribution grid. As more PV systems are connected to the network, the overall power injected into the grid increases. During peak sunlight hours, when PV systems produce the most energy which often occurs at mid-day and which happens to be the least load demanded because consumers are often out of the house, a surplus of power is fed into the distribution network, leading to an elevation in voltage levels (M. A. Mahmud et al., 2014).

1.2 Problem Statement

The increasing demand for energy and growing concerns about environmental pollution caused by fossil fuels has been a significant rise in the installation of photovoltaic (PV) systems (Wigley, 1991). PV installations harness solar energy and convert it into electrical energy, offering a cleaner and renewable alternative to conventional energy sources. However, the integration of a large

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number of PV systems into distribution networks that are not designed to accommodate that number of distributed generators can lead to several challenges, one of which is the voltage rise problem (M. A. Mahmud et al., 2014).

Traditional voltage regulation techniques, such as On-Load Tap Changers (OLTC), have been commonly used in distribution networks to maintain voltage levels within an acceptable range. However, these techniques may not be effective in mitigating the voltage rise caused by high PV penetration (Chamana et al., 2018). The intermittent nature of solar energy generation and the variability of PV system outputs make it challenging to regulate voltage levels using conventional methods (Petinrin & Shaabanb, 2016). Therefore, researchers proposed three methods to mitigate the voltage rise on distribution networks with high PV penetration. These methods can be categorized as follows.

1. Energy storage systems (ESS)
2. Active power curtailment
3. Reactive power control

Energy storage systems (ESS) have emerged as potential solutions for mitigating voltage rise in distribution networks with high PV penetration. ESS can absorb excess energy during periods of high PV generation and release it during low generation periods. By balancing the power flow, ESS can help regulate voltage levels (Alam et al., 2012; Zillmann et al., 2011). However, the deployment of ESS faces challenges such as high initial costs, limited storage

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capacity, and technological constraints, making it difficult to fully rely on energy storage for voltage rise mitigation (Faisal et al., 2018). Then, PV active power curtailment is an approach to mitigate the voltage rise problem. By reducing the power output of PV systems during periods of excessive generation, voltage levels can be controlled within acceptable limits (Gaudin et al., 2012; Stetz et al., 2013). However, active power curtailment may result in a loss of renewable energy potential and economic viability. Additionally, the curtailment strategy needs to be carefully designed to ensure fair distribution among PV systems and minimize the impact on system efficiency and grid stability (Pillai et al., 2017).

Then, Reactive power control is a very potential technique to overcome the voltage rise limitation of high PV penetration on distribution networks (Almeida et al., 2021a). This approach relies on smart inverters due to their ability to absorb/inject reactive powers (Seuss et al., 2015). The reactive power control of PV smart inverter can be categorized into two categories as follows:

1. Power-dependent reactive power control
2. Voltage-dependent reactive power control Q (V).

The power-dependent reactive power of PV smart inverter can be either fixed power factor or variable power factor. fixed power factor regulates the reactive power output based on a predetermined power factor reference. Only, during low solar irradiance conditions (i.e., low PV generation), resulting in a negligible risk of voltage rise in the distribution network. However, the absorption of reactive power during this period increases caused unnecessary

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network losses (Chaudhary & Rizwan, 2018). To address this limitation, the PF(P) is presented, which offers variable PF reference depending on the level of the PV active power injection. However, the techniques of reactive power control based on active power injection often overlook the variations in load demand. Consequently, in scenarios characterized by high load demand and substantial PV production, the risk of voltage rise is already quite low (S. Bin Kim & Song, 2020). In such cases, reactive power control relying solely on active power injection can lead to significant unnecessary losses due to high absorption of reactive power. This indicates that the reactive power control-based PV active power offers effective voltage regulation but at the expense of higher network losses (Almeida et al., 2021a). On the other hand, it is important to consider that the network's voltage sensitivity to both active and reactive power varies depending on the location. Consequently, employing the reactive power control technique based solely on the voltage at the point of common coupling Q(V), which is proportional to the network voltage, results in poor voltage regulation when implemented in a location with low network voltage sensitivity to active power. However, direct proportionality to the network voltage does offer the advantage of reducing unnecessary losses in such cases (S. Bin Kim & Song, 2020).

In conclusion, the increase in PV penetration in distribution networks that not originally designed to accommodate this level of PV integration has led to voltage rise problem. Then, the traditional voltage regulation devices, such as On-Load Tap Changers (OLTCs), are ineffective in mitigating this issue. Researchers have proposed using Energy Storage Systems to address this

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problem; however, this approach significantly increases the cost of PV systems. Alternatively, active power curtailment has been suggested, but this technique results in high losses in renewable power generation. Consequently, reactive power control through smart inverters is considered a more promising technique. However, power-dependent reactive power offers good voltage regulation but incurs high losses, while voltage-dependent reactive power results in lower losses but poorer voltage regulation. This research aims to address the gap by exploring a reactive power control strategy for PV smart inverters that simultaneously depend on PV active power and network voltage.

1.3 Aim and Objectives of the Thesis

The primary objective of this thesis is to investigate and present the effects of high PV penetration on distribution network voltage. Additionally, this research aims to propose a novel reactive power control strategy to effectively mitigate voltage rise in distribution networks with high PV penetration. The key aim of this thesis is to develop a adaptive reactive power control technique that achieves a better efficient voltage regulation. Then, the objectives of the thesis to meet the aims of the thesis are as follows:

1. To investigate the impact of high PV penetration on the voltage on a practical distribution network.
2. To develop an adaptive reactive power control to mitigate the voltage rise on the distribution network with high PV penetration.
3. To validate an adaptive reactive power control for voltage rise mitigation on the distribution network with high PV penetration.

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1.4 Scope of the Thesis

The scope of this thesis revolves around investigating the effect of high PV penetration on the distribution network in terms of voltage and proposing an adaptive reactive power control strategy to address the challenges posed by high PV penetration on the Malaysian distribution network. The research focuses on using MATLAB/Simulink and OpenDSS as the primary tools for analysis and evaluation. The specific aspects covered within the scope are as follows:

1. Investigation of High PV Penetration Effects: The thesis will analyze the effects of high PV penetration on the Malaysian distribution network in terms of voltage. Using MATLAB/Simulink and OpenDSS. Then, the research focuses on the strategies to mitigate the voltage rise that is mentioned in the literature.

2. Proposing and evaluating an adaptive Reactive Power Control: The scope includes proposing and evaluating a new and innovative reactive power control strategy to mitigate voltage rise on distribution networks facing high PV penetration. The proposed control approach aims to address the limitations of existing techniques, providing more efficient voltage regulation and loss mitigation.

3. Specific Focus on the Malaysian Distribution Network: The scope will emphasize the evaluation of the reactive power control technique on the Malaysian distribution network. By considering the unique characteristics and challenges of this specific network, the research aims to provide insights and recommendations tailored to the Malaysian context.

Overall, the thesis scope encompasses the investigation, proposal, development, and evaluation of an adaptive reactive power control strategy to

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tackle voltage rise in distribution networks with high PV penetration. The research will utilize the simulation tools and focus on the Malaysian distribution network as a case study, making it valuable for both academic understanding and practical applications in the field of power systems and renewable energy integration.

1.5 Significance of the Research

The significance of this thesis lies in addressing the increasing penetration of photovoltaic (PV) systems in distribution networks and the consequent impact on network voltage. As PV systems become more prevalent, it becomes crucial to understand and mitigate the effects of high PV penetration on voltage levels.

The thesis aims to investigate the effects of high PV penetration on the distribution network voltage, specifically in the context of the Malaysian distribution network. By utilizing MATLAB/Simulink and OpenDSS, the research provides an analysis of the voltage rise caused by high PV penetration in this specific network.

Moreover, the thesis proposes an adaptive reactive power control strategy to effectively mitigate voltage rise in distribution networks with high PV penetration. This research contributes to the field by developing a reactive power control technique that achieves efficient mitigating of voltage rise and voltage regulation. Then, the evaluation of the proposed reactive power control technique using MATLAB/Simulink provides valuable insights into its

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effectiveness in mitigating voltage rise on both the distribution network and specifically the Malaysian distribution network. The evaluation results will contribute to practical knowledge and inform decision-making processes for the adoption of reactive power control strategies in distribution networks with high PV penetration.

In summary, this thesis is significant because it contributes to the understanding of the effects of high PV penetration on distribution network voltage and proposes a novel reactive power control strategy to address this issue. The research findings and proposed technique have practical implications for the efficient integration of PV systems into distribution networks, ensuring stable voltage levels, minimizing losses, and optimizing network performance.

1.6 Contribution of the Thesis

In this thesis, significant effort has been made to address voltage rise problem on the distribution network with high PV penetration. The research builds upon existing literature while introducing novel approaches to enhance the reactive power control. The key contributions of this work are outlined as follows:

1. The reactive power control that not directly depend on active power injection or network voltage. Otherwise, the proposed control calculates the amount of change each second to provide more adaptiveness of the reactive power control with the network parameters variation.
2. Develop the reactive power control by MATLAB Simulink.

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3. Evaluation of the reactive power control to mitigate the voltage rise on the Malaysian distribution network with High PV penetration.

1.7 Outlines of the Thesis

Chapter one is the introductory chapter that provides an overview of the increasing presence of distributed generators, particularly photovoltaic (PV) systems, in the energy landscape. It addresses the issue of voltage rise accompanying the rise in PV penetration within distribution networks. The limitations of existing techniques and methods aimed at mitigating voltage rise in networks with high PV penetration are highlighted. Additionally, the chapter outlines the aims, objectives, significance, and scientific contributions of this thesis.

The second chapter is dedicated to an extensive review of the literature, delving into the structure and operation of low voltage distribution networks. It sheds light on the challenges posed by high PV penetration and the consequent voltage rise. Recent publications investigating the impact of high PV penetration on distribution network voltage are presented. Furthermore, this chapter provides an overview of methods to address voltage rise and summarizes the latest proposed techniques within this context.

In the methodology chapter, the proposed reactive power control technique designed to mitigate voltage rise in distribution networks is introduced. The components and operational principles of the technique are described. To evaluate its effectiveness, tests are conducted on a small-scale network

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comprising seven buses, illustrating the impact of the proposed reactive power control in comparison to existing methods. Furthermore, a real-world Malaysian distribution network located in Taman Impian Putra, Port Dickson, Malaysia, is utilized to validate the efficacy of the technique in mitigating voltage rise.

Chapter four is the chapter that presents the results and ensuing discussions from the evaluation and validation of the proposed reactive power control technique. Two distinct scenarios are considered, and the outcomes affirm the control's ability to maintain voltage within acceptable bounds while minimizing losses. Emphasis is placed on its effectiveness in managing voltage rise, particularly in low voltage distribution networks characterized by high PV penetration.

The fifth and final chapter serves as the conclusion of this thesis, offering a concise summary of key findings, research contributions, and their broader implications. Avenues for future research are discussed, highlighting research gaps that may pique the interest of readers in the field of study.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The electrical distribution network is currently experiencing a transformative phase, characterized by significant changes and the emergence of important challenges. At the forefront of these changes is the integration of distributed generators, which represents the most profound shift in the distribution network landscape. However, this integration brings forth a pressing concern in the form of voltage rise, particularly with the increasing penetration of photovoltaic (PV) distributed generators. As the distribution network embraces more PV distributed generators, the challenge of voltage rise becomes increasingly pronounced. This occurs when the generation from PV sources exceeds the actual load demand. The consequences of voltage rise can occur, leading to equipment damage, compromised power quality, and potential system failures. Thus, it is imperative to address this issue to ensure the optimal performance and stability of the distribution network.

This Chapter discussed the distribution network to demonstrate the distribution networks' elements, typologies, etc. This chapter aims to provide a comprehensive understanding of the voltage rise problem and its implications for the distribution network. It begins by offering an overview of the distribution network, highlighting its key characteristics. the chapter delves into a review of the existing literature, examining recent publications that delve into the effects of high PV penetration on the distribution network. In addition, this

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chapter explores the available methods to mitigate voltage rise in the distribution network. It presents a thorough review of relevant publications, evaluating the efficacy and limitations of these methods in addressing the voltage rise challenge.

In conclusion, this chapter presents the background of the thesis throw present and demonstrates the distribution network, the voltage rise problem and recent publications of the high PV penetration effects, and the existing method to mitigate the voltage rise on the distribution network with their limitations.

2.2 Low Voltage Distribution Networks

Low voltage distribution networks form a critical part of the overall electrical power system, delivering electricity from the medium voltage transmission lines to end consumers. These networks are designed to efficiently and reliably distribute electrical power to residential, commercial, and industrial customers at a lower voltage level. Low voltage distribution networks typically operate at voltage levels below 1000 volts, for Malaysian code 230 volts for single-phase systems and 400 volts for three-phase systems (TNB, 2023). The primary objective of these networks is to ensure the safe and reliable delivery of electricity to consumers, meeting their demand for electrical power while maintaining system stability. The components of low voltage distribution networks include (Sallam & Malik, 2018):

1. Distribution Substations: These substations receive power from the medium voltage transmission lines and step down the voltage to the appropriate level for distribution.

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2. Transformers: Transformers are used to step down the voltage from the distribution substations to the desired voltage level for consumer use.

3. Feeders: Feeders are the distribution lines that carry the electricity from the transformers to distribution transformers or directly to consumers.

4. Distribution Transformers: These transformers further step down the voltage to the appropriate level for consumer use, typically between 120 volts and 240 volts for residential customers.

5. Lines: lines connect the distribution transformers to individual consumer premises, delivering electricity to homes, businesses, and other facilities

Low voltage distribution networks are critical in ensuring the efficient and reliable delivery of electricity to consumers. Several key factors are essential to maintaining their performance. Load balancing is a primary concern, where the network works to evenly distribute electrical loads across different feeders and phases. This helps to prevent overloading and maintain the stability of the system. Voltage regulation is equally important, ensuring that voltage levels remain within acceptable limits. Proper voltage regulation prevents issues such as under-voltage or over-voltage, which can negatively impact the performance and longevity of electrical equipment (Kaur & Luthra, 2018). Fault detection and restoration are also vital components of low voltage distribution networks. Additionally, maintaining power quality is a priority. The network must minimize voltage fluctuations, harmonics, and other disturbances that could degrade the performance of connected equipment (Ponnaganti et al., 2018).

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These networks face significant challenges, including the growing demand for electricity driven by population growth, urbanization, and increased consumption (Kaur & Luthra, 2018). They must also manage the integration of distributed generation, particularly renewable energy sources like solar panels and wind turbines. This integration complicates power flow, voltage control, and system protection. Aging infrastructure, such as transformers, cables, and switchgear, requires regular maintenance and upgrades to ensure reliability (Chaudhary & Rizwan, 2018). Then, Future trends in low voltage distribution networks focus on technological advancements, including the deployment of smart grid technologies, energy storage systems, and microgrids. These innovations aim to enhance system efficiency, promote renewable energy integration, and improve grid resilience, helping these networks adapt to the evolving energy landscape (Pandiyan et al., 2023).

Finally, Low voltage distribution networks can be categorized into different typologies based on their design and operational characteristics. The typologies include (Sallam & Malik, 2018):

1. Radial Distribution Networks: Radial distribution networks are the most common and simplest type of low voltage distribution network. This topology was chosen for this research because of its widespread use and simplicity. Additionally, the topology does not affect the effectiveness of the reactive power control of the smart inverter proposed in this research. Radial networks operate in a configuration where power flows from the distribution substation to consumers along a single path. Each feeder is connected to a single source and serves a specific group of consumers. An example of radial distribution network shown in Figure 2.1.

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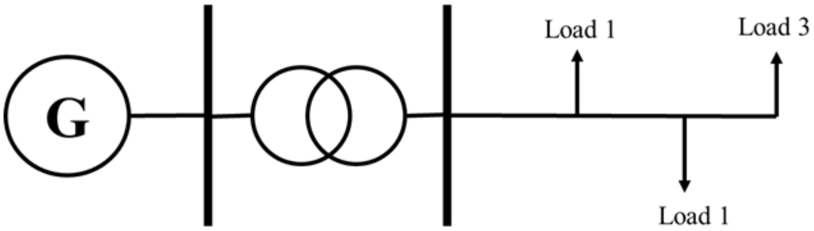

Figure 2.1 : Radial Topology Distribution Network
(Islam et al., 2017)

2. Loop Distribution Networks: Loop distribution networks introduce redundancy and enhanced reliability compared to radial networks. In a loop configuration, feeders are interconnected to create multiple paths for power flow. This arrangement allows for alternate supply routes, reducing the impact of faults or maintenance activities. Loop networks can be either open loop or closed loop. Open loop loops have multiple power supply points but do not form a complete loop, while closed loop loops provide multiple supply points that form a continuous loop. An example of ring distribution network topology shown in Figure 2.2.

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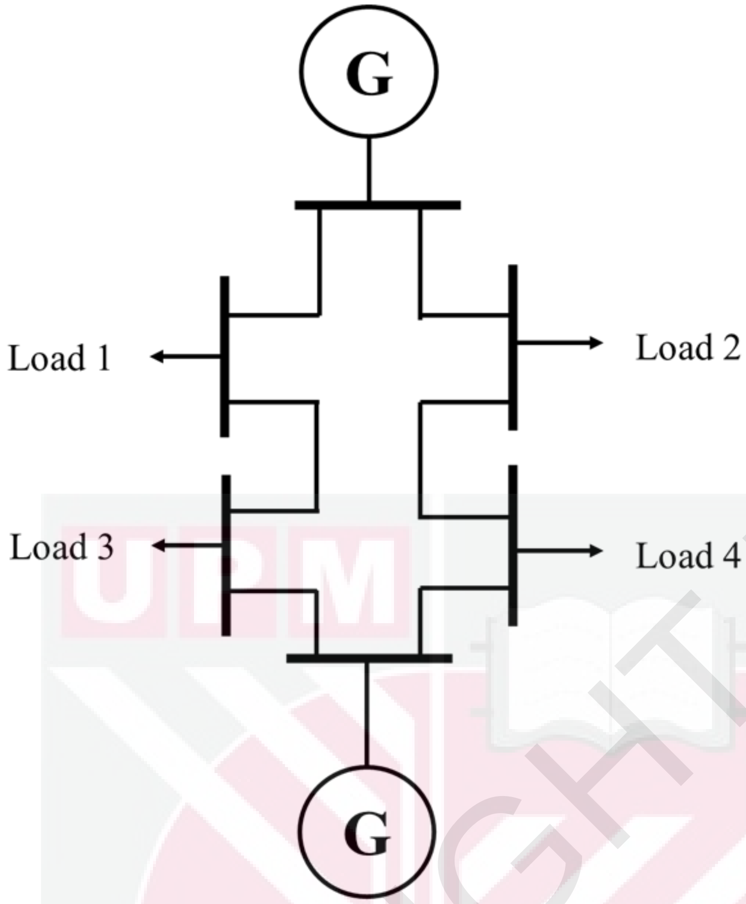

Figure 2.2 : Ring Topology Distribution Network
(Islam et al., 2017)

3. Network Distribution Networks: Network distribution networks, also known as grid distribution networks or meshed networks, are characterized by a high degree of interconnection between feeders. They offer the highest level of redundancy, flexibility, and reliability. In network networks, multiple paths exist for power flow, allowing for reconfiguration in case of faults or maintenance. This results in improved fault tolerance and shorter restoration times. Network networks are commonly found in urban areas or critical infrastructure settings. An example of network (Mesh) distribution network topology shown in Figure 2.3.

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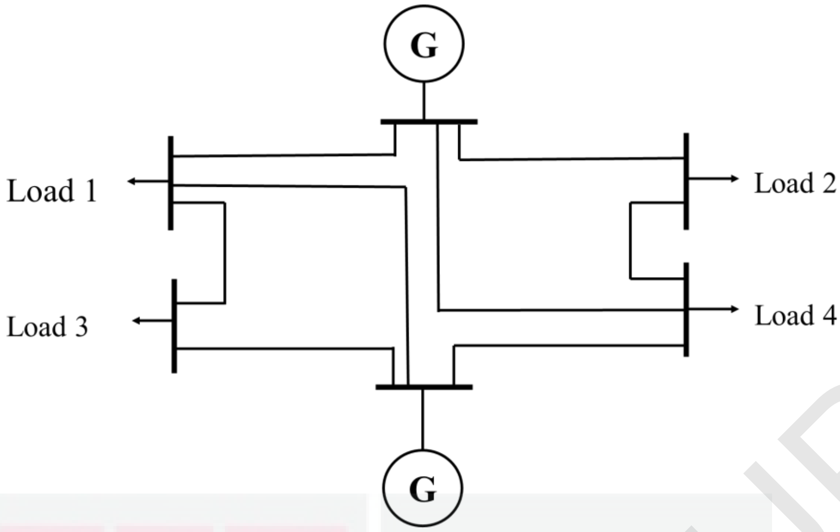

Figure 2.3 : Network (Mesh) Topology Distribution Network
(Islam et al., 2017)

4. Hybrid Distribution Networks: Hybrid distribution networks combine elements of both radial and network configurations. They leverage the advantages of both typologies to achieve a balance between cost-effectiveness and reliability. Hybrid networks often feature a combination of radial feeders in suburban or rural areas and networked sections in urban or critical load regions.

5. Ring Main Unit (RMU) Distribution Networks: RMU distribution networks are a specialized typology commonly used in compact urban areas. RMUs consist of a ring main unit, which serves as a compact substation, and multiple outgoing feeders connected to it in a ring configuration. This design allows for easy fault isolation and restoration, minimizing the impact on the power supply to individual consumers. An example of ring main unit distribution network topology shown in Figure 2.4.

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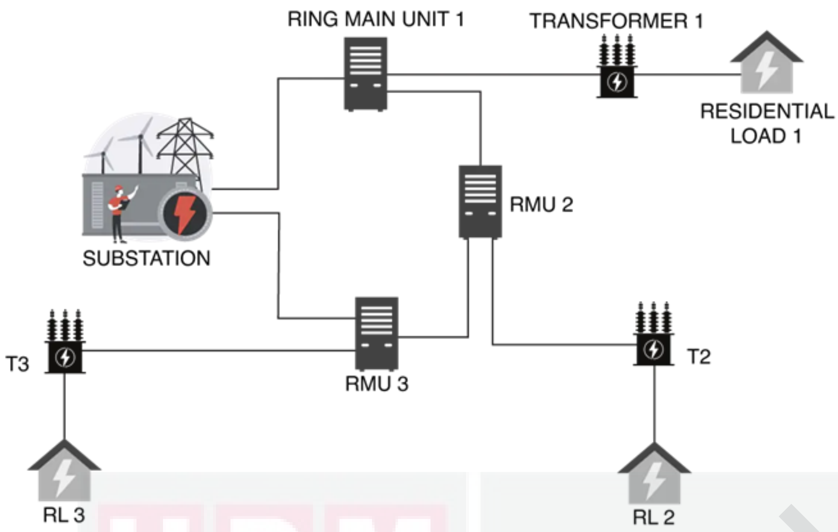

Figure 2.4 : Ring Main Unit Distribution Network
(Ring Main Unit in Electrical Distribution System, n.d.)

Each typology has its advantages and considerations, and the selection of a particular network typology depends on factors such as the size of the service area, load characteristics, reliability requirements, and cost considerations. Distribution network planners and operators carefully analyze these factors to determine the most suitable typology for a given area.

2.3 Voltage Rise Issue in Distribution Networks

Voltage rise refers to the increase in voltage above the nominal or expected level in an electrical power system. This can occur due to the generation of power from distributed generators (DGs), such as solar photovoltaic (PV) systems or wind turbines, which can feed power back into the grid, especially when the local load is low (Shivashankar et al., 2016). According to Malaysian distribution network standards, the acceptable voltage variation is (±5%) (TNB, 2023). Voltage rise is a significant challenge that distribution networks face

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with the increasing integration of distributed energy resources like solar photovoltaic systems. As renewable energy sources, such as PV, have an intermittent nature, they can generate excess power during periods of high production. This surplus power, if not managed effectively, can lead to an imbalance between supply and demand, causing voltage levels to rise beyond acceptable limits. This voltage rise issue poses a threat to the stability and reliability of the grid and can potentially damage equipment. The rise in distributed generation, particularly from PV systems, has transformed the traditional electricity distribution landscape. While it offers numerous benefits like reducing carbon emissions and promoting energy independence, it also presents unique operational challenges. The challenge of voltage rise arises due to the fundamental characteristic of PV systems, which generate electricity based on sunlight availability. During periods of high solar irradiance, PV systems can produce more power than the local demand, overwhelming the distribution network.

Shivashankar et al. conducted a comprehensive review addressing issues related to high PV penetration in distribution networks, along with proposing potential solutions. The study underscored the necessity for a thorough analysis to understand the behavior of distribution networks under high PV penetration. A tool was proposed for analyzing the behavior of a three-phase distribution network integrated with a single-phase PV system, aimed at addressing issues caused by PVs in such networks (Shivashankar et al., 2016). Haque et al. explored the effects of high PV penetration, highlighting specific characteristics of distribution networks such as their unbalanced

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nature and high resistance-to-reactance ratio. They noted that the imbalance in distribution networks arises from non-uniform load currents and untransposed feeder impedances, leading to uneven voltage levels across phases and compromised power and voltage quality (Haque et al., 2017).

Mahmud et al. categorized the effects of distributed PV generators on distribution networks into technical, commercial, and regulatory aspects (N. Mahmud & Zahedi, 2016). Alam et al. focused on technical solutions to mitigate or optimize voltage regulation effects. They developed an assessment tool to analyze the daily behavior of PV systems and their impact on distribution systems, verified using a single-phase PV system in a three-phase Australian distribution network (Alam et al., 2012). Baran et al. investigated operational and safety issues of PV generators in typical distribution networks, noting that the effects vary depending on the scale of PV penetration (Baran et al., 2012). Liu et al. examined the influence of distributed PV generators on voltage regulation and reactive power flow, emphasizing the importance of synchronized management of generator resources and utility infrastructure for enhanced operational efficiency (Y. Liu et al., 2008).

Demirok et al. reviewed techniques to increase the distribution capacity of distributed generation systems, considering voltage rise limitations and conducting simulations to evaluate these techniques (Demirok et al., 2009). Chen et al. studied the influence of varying levels of PV penetration on distribution network capacity estimation through extensive simulations (Chen et al., 2012). Ferreira et al. simulated unbalanced three-phase circuits,

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proposing a novel control strategy to prevent the cascading effects of distributed generators and improve their availability (Ferreira et al., 2013). Pourmousavi et al. analyzed the impact of different PV penetration levels (15% and 30%) on voltage and frequency, developing a PV model based on actual environmental data (Pourmousavi et al., 2012).

Punyachai et al. demonstrated the effects of high PV penetration on voltages in urban distribution networks, calculating the maximum allowable PV penetration per household (Punyachai et al., 2014). Aramizu and Vieira used OpenDSS software for simulation studies on the effects of high PV penetration (Aramizu & Vieira, 2013). Yaghoobi et al. analyzed the stability of dynamic voltage and the short-term voltage response in distribution networks with high PV penetration using an IEEE 37-bus test system (Yaghoobi et al., 2015).Cheng et al. discussed the implications of extremely high PV penetration on medium voltage distribution networks (Cheng et al., 2016), and Munkhchuluun et al. examined the long-term effects of large-scale PV generators, including control schemes and voltage stability (Munkhchuluun et al., 2020).

Iioka et al. investigated reverse power flow in distribution networks due to high PV penetration, focusing on the mathematical relationship between reverse power flow and voltage rise at the point of common coupling (Iioka et al., 2019). Gandhi et al. explored the implications of high PV penetration on power systems, reviewing its impact on various aspects including voltage, frequency, protection, and harmonics, as well as the observed limits of PV penetration in

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literature (Gandhi et al., 2020). This collective research emphasizes the multifaceted influences of high PV penetration on distribution networks and underscores the necessity of developing robust strategies and tools to mitigate these effects.

2.4 The Relationship between Incremental Reactive Power Absorption by Smart Inverters and Network Losses

In distribution networks with high penetration of photovoltaic (PV) systems, smart inverters play a critical role in maintaining voltage stability through reactive power control. One of the common strategies involves the absorption of reactive power to mitigate overvoltage issues (Chaudhary & Rizwan, 2018). However, an important consideration is the impact of increased reactive power absorption on network losses. The total power losses P_{Loss} in a distribution network can be expressed by the equation [2-1] (Glover et al., 2017):

$$P_{Loss} = I^2 R \qquad [2\text{-}1]$$

where I is the current through the network and R is the resistance of the line. The current consists of two components: the active current I_P and the reactive current I_Q, related to the active power (P) and reactive power (Q), respectively. The total current can be represented as in equation [2-2] (Glover et al., 2017):

$$I = \sqrt{I_P^2 + I_Q^2} \qquad [2\text{-}2]$$

where the active and reactive currents are as in equation [2-3] and [2-4] respectively:

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$$I_P = \frac{P}{V} \quad [2\text{-}3]$$

$$I_Q = \frac{Q}{V} \quad [2\text{-}4]$$

Substituting these into the total current equation in equation [2-5]:

$$I = \frac{\sqrt{P^2 + Q^2}}{V} \quad [2\text{-}5]$$

Subsequently, the power losses P_{loss} become as in equation [2-6]:

$$P_{Loss} = \frac{P^2 + Q^2}{V} R \quad [2\text{-}6]$$

While reactive power absorption helps to manage voltage levels, it doesn't mean that the actual amount of reactive power flowing in the network decreases. It means the inverter is absorbing reactive power locally to prevent voltage from rising too much. Both injecting and absorbing reactive power contributes to increasing the reactive power (Q). Whether the smart inverter is injecting or absorbing reactive power, it still adds to the overall magnitude of the reactive power flow within the network (Saadat, 1999).

Therefore, as equation [2-5] demonstrates that as the reactive power (Q) increases, the overall network losses also increase due to the proportional relationship between P^2+Q^2 and the losses. In scenarios where smart inverters increase their reactive power absorption to control voltage levels, this results in higher network losses.

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The quadratic relationship between network losses and the rise in both active and reactive power implies that while absorbing reactive power is beneficial for voltage regulation, it comes at the cost of increased losses within the distribution network. This trade-off highlights the need for a balance between maintaining voltage stability and minimizing network losses. Excessive reactive power absorption by smart inverters can lead to inefficient energy use and increased operational costs. Therefore, advanced control strategies must be implemented to optimize reactive power absorption, striking a balance between voltage regulation and loss minimization.

2.5 Existing Methods for Voltage Rise Mitigation

Several methods have been proposed in the literature to address voltage rise on distribution networks with high PV penetration. These techniques vary in complexity and effectiveness, depending on network conditions and the level of PV integration. While some solutions focus on energy storage systems, others focus on reactive power control.

2.5.1 Energy Storage System

Voltage rise is directly proportional to solar PV production, especially during mid-day when solar irradiance is at its peak and the load demand is lower (Chaudhary & Rizwan, 2018). To prevent such events, the high production rate should be reduced, or the surplus energy consumed. Energy storage systems are commonly used to address this issue by storing surplus energy during periods of high irradiance and feeding it back to the network during periods of high load demand. Various types of storage are available, including pumped

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hydro storage, supercapacitors, flywheels, and compressed energy storage. Among them, battery energy storage systems are the preferred choice for integrated PV systems (Rangel et al., 2018). Different types of batteries, such as lithium-ion, high-temperature, conventional, lead-acid, nickel-cadmium, and flow batteries, are utilized. The charging and discharging processes can be calculated using equations [2-7] and [2-8] (Shepherd, 1965).

$$E(t + \Delta t) = E(t) + \Delta t \ * \ P_c * \eta_c \qquad [2\text{-}7]$$

$$E(t + \Delta t) = E(t) - \ \Delta t * \ P_d * \eta_d \qquad [2\text{-}8]$$

where η_d and η_c are the discharging and charging efficiencies, respectively; E is the stored energy; t is the time taken by the battery to store energy E; and P_d and P_c are the discharging and charging powers, respectively.

A study by Zillmann et al. focused on voltage regulation in distribution networks, exploring the impact of various Energy Storage System (ESS) strategies. They identified potential limitations in ESS strategies, notably increased capital and operational costs (Zillmann et al., 2011). Tewari et al. proposed a coordinated control strategy for On-Load Tap Changers (OLTC) and Battery Energy Storage Systems (BESS) to enhance voltage regulation in distribution networks with high solar PV penetration. This strategy optimizes the use of OLTC and BESS to reduce voltage deviations and enhance system performance, though it requires a communication network, adding complexity and potential vulnerabilities (Tewari et al., 2021).

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Liu et al. discussed the utility of ESSs with step voltage regulation and OLTCs, aiming to reduce operational stress on OLTCs but introducing complexities in system design and maintenance (X. Liu et al., 2012). Sugihara et al. proposed using ESSs on the customer side to alleviate voltage rise on networks with high PV penetration, facing challenges such as limited space and end-user resistance (Sugihara et al., 2013). Yang et al. presented an approach for battery sizing in distribution networks that considers battery lifespan, balancing cost, and operational effectiveness. However, this approach is influenced by uncertainties in battery degradation and technology standards (Y. Yang et al., 2014).

Xie et al. proposed an optimal sizing strategy for ESS in smart microgrids with high PV penetration, incorporating a virtual energy storage system and a risk component, though it is complex in modeling and computational aspects (C. Xie et al., 2021). Babacan et al. used a Genetic Algorithm for multi-objective optimization of battery allocation in distribution systems, enhancing battery allocation but with computational complexity issues (Babacan et al., 2016). Marra et al. proposed various energy storage concepts for voltage regulation in networks with high PV penetration, facing deployment challenges due to regulatory and policy hurdles (Marra et al., 2012).

Ariyaratna et al. presented an algorithm for controlling the charging/discharging of ESSs, effectively mitigating voltage fluctuations. However, this approach relies on accurate modeling and real-time data (P. M. Ariyaratna et al., 2019). Xie et al. proposed a Model Predictive Control

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algorithm to regulate voltage in distribution networks with high PV penetration, facing challenges with computational burden in real-time scenarios (Y. Xie et al., 2020).

Ma et al. conducted a study on the effects of PV battery systems on distribution networks using Monte Carlo-based time series power flow analysis (Ma et al., 2019). Ariyaratna et al. suggested a hybrid energy storage system combining a supercapacitor and a battery for voltage fluctuations, adding complexity to system design and maintenance (P. Ariyaratna et al., 2018). Ranaweera et al. proposed a distributed control approach for customer battery storage units to reduce voltage rise, which enhances local autonomy but may lead to suboptimal performance due to a lack of global coordination (Ranaweera et al., 2017).

Marra et al. explored the use of electric vehicles to reduce voltage rise on networks with high PV penetration, facing infrastructure development and standardization challenges (Marra et al., 2012). Zeraati et al. developed a consensus algorithm for coordinating energy storage-based electric vehicles and active power curtailment, but it may face challenges in diverse stakeholder scenarios (Zeraati et al., 2019).

2.5.2 Active Power Curtailment

The relationship between the voltage of the distribution network and active power is significantly stronger compared to the relationship between the voltage of the distribution network and reactive power. This is due to the

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resistive characteristics of the distribution network. As mentioned earlier, the injection of reactive power can have several effects on the distribution network, including increased current losses and impact on power factor (Shivashankar et al., 2016). To address these issues, many authors have utilized active power curtailment as a technique to mitigate voltage rise and reverse power flow. However, it should be noted that the active power curtailment technique is not favored by renewable source owners due to the associated active power losses.

The active power curtailment technique, as shown in Figure 2.5, does not affect active power production as long as the line voltage remains below the threshold. However, when the voltage exceeds the limit, the active power is linearly curtailed towards the highest allowed line voltage. In (H. T. Yang et al., 2015), the authors proposed an active curtailment algorithm to mitigate voltage rise in low voltage distribution networks with high PV penetration. The algorithm reduces PV production in proportion to the line voltage and coordinates with the energy storage system and On-Load Tap Changer (OLTC). This allows the algorithm to balance PV production and load demand. Tonkoski et al. proposed coordinated active power curtailment to prevent voltage rise on a Canadian distribution network, tested over a 12-hour period. This approach's limitation is the lack of long-term performance data and its efficacy in diverse weather conditions (Tonkoski et al., 2011). Ku et al. suggested a hybrid approach combining active power curtailment and reactive power compensation to mitigate voltage rise during load exchange in low voltage systems, which could be less effective in systems with fluctuating load

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demands (Ku et al., 2016). Ghosh et al. proposed droop-based reactive power compensation with active power curtailment based on short-term PV power generation forecasting using the Kalman filter theory. The major drawback here is the reliance on accurate short-term forecasting, which can be challenging in unpredictable weather conditions (Ghosh et al., 2017).

Verma et al. presented a novel technique to mitigate voltage rise on distribution networks using a de-rating technique on the DC-DC converter to curtail the PV active power injection into the distribution network. However, this might lead to reduced efficiency and increased wear on the converters (Verma et al., 2022). Conti et al. introduced active power curtailment based on on/off control depending on the node voltage. A drawback of this method is its potential for abrupt changes in power output, which can stress the electrical grid (Conti et al., 2006). Finally, practical results of distribution networks with high PV penetration improved by active power curtailment were presented, but these studies may lack scalability and adaptability to different types of grid infrastructures (Gaudin et al., 2012; Stetz et al., 2013).

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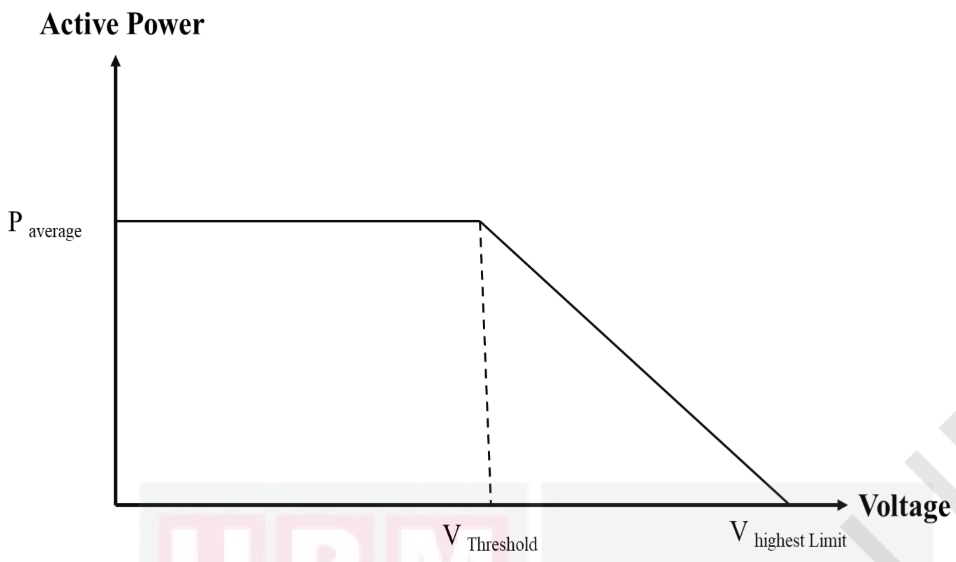

Figure 2.5 : Typical Graph of Active Power Curtailment
(Shivashankar et al., 2016)

2.5.3 Reactive Power Control

The reactive power control utilized in PV inverters for voltage regulation and voltage rise mitigation can be categorized into two approaches: those proportionate to active power injection, namely fixed power factor, maintained power factor, known as PF(P), and those proportionate to the voltage at the point of common coupling, known as Q(V). This section provides a description of these reactive power control techniques (Bernal A. et al., 2017; Ca et al., 2020; Darwish et al., 2018; Hasheminamin et al., 2018).

The fixed power factor and maintained power factor (PF(P)) are reactive power control techniques that rely on PV active power injection, assuming that voltage rise is directly proportional to PV active power injection alone. The fixed power factor (PF(P)) regulates the reactive power output based on a predetermined power factor reference, resulting in the calculation of the

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reactive power reference using equation [2-9] (Shivashankar et al., 2016).

$$Q_{ref} = \frac{\sqrt{1 - PF_{ref}^2}}{PF_{ref}} P \qquad [2\text{-}9]$$

Where Q_{ref} is the reference reactive power of the inverter, PF_{ref} is the reference power factor of the inverter, and P is the active power generated by the photovoltaic system (PV). However, it is important to note that the risk of voltage rise is significantly reduced when the PV system has low active power injection. Consequently, applying fixed power factor (PF(P)) control, which aims to maintain a constant power factor, may result in unnecessary increases in losses due to reactive power absorption. This limitation has been addressed by researchers through the introduction of an improved approach called maintained power factor (PF(P)) control. Unlike fixed PF, PF(P) offers flexibility by adjusting the power factor based on the active power injection range, as illustrated in equation [2-10] and described in Figure 2.6.

$$PF_{ref} = \begin{cases} 1, & P < P_1 \\ \frac{PF_{lim} - 1}{P_1 - P_2}(P - P_1), & P_1 \leq P \leq P_2 \\ PF_{lim}, & P_2 < P \end{cases} \qquad [2\text{-}10]$$

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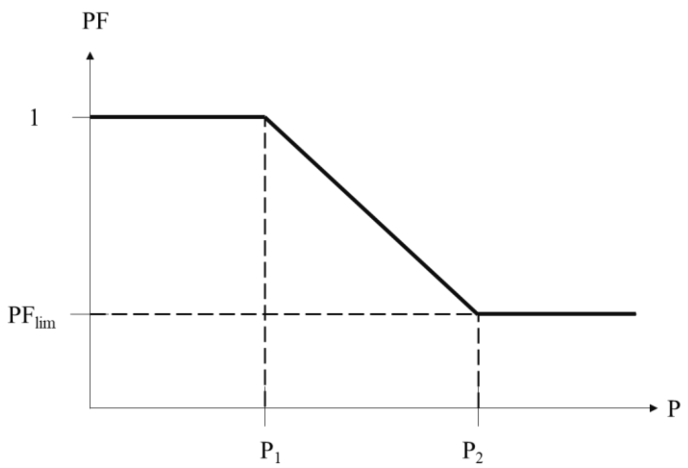

Figure 2.6 : Characteristics Graph of PF(P)
(Shivashankar et al., 2016)

Q (V) is a reactive power control strategy that relies on the voltage level at the point of common coupling. This approach selects the reactive power reference using equation [2-11] (Shivashankar et al., 2016), as illustrated in Figure 2.7, which presents the characteristic graph of Q(V).

$$Q_{ref} = \begin{cases} Q_{lim}, & V < V_1 \\ \dfrac{Q_{lim}}{(V_1 - V_2)}(V - V_1), & V_1 \le V < V_2 \\ 0, & V_2 \le V < V_3 \\ \dfrac{Q_{lim}}{(V_3 - V_4)}(V - V_3), & V_3 \le V < V_4 \\ -Q_{lim}, & V_4 \le V \end{cases} \quad [2\text{-}11]$$

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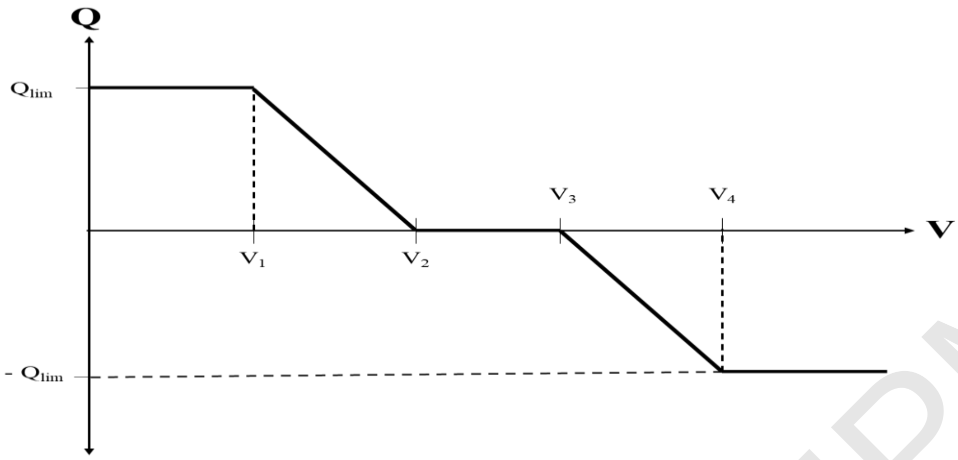

Figure 2.7 : Characteristic Graph of Q(V)
(Shivashankar et al., 2016)

Yan et al. modified the IEEE 13-bus system to analyze the effects of different PV penetration levels on voltage stability in residential networks. Their study highlights the potential for voltage instability due to high PV integration, an issue that has traditionally been underexplored at the distribution level. Although their findings suggest that voltage instability can be mitigated using PV inverter reactive power support, the solution depends on regulatory changes to permit such control. While effective, this approach requires further investigation into its practical implementation and long-term sustainability, particularly concerning inverter stress and financial viability (Yan & Saha, 2012). Kerber et al. identified significant voltage rise issues stemming from the integration of a high number of PV generators, particularly in low-voltage networks. To address these challenges, they proposed the use of modern voltage source converters (VSCs) with autonomous reactive power control. This solution effectively mitigates overvoltage without the need for costly infrastructure upgrades. However, while their approach reduces manual intervention by allowing VSCs to adapt automatically to grid changes, the effectiveness of this strategy depends heavily on grid characteristics, and challenges remain in ensuring consistent performance without excessive reactive power consumption, which can lead to energy losses (Kerber et al., 2009). Almeida et al. conducted a comparative analysis of four reactive power control techniques, evaluating them based on grid reinforcement needs, losses, and costs. While the study provides valuable insights into the strengths and weaknesses of each method, its findings may not be universally applicable across different distribution network configurations. For instance, variations in grid topology, load profiles, and regional regulatory standards could significantly affect the performance and feasibility of the proposed solutions. Therefore, further studies are needed to assess how these control techniques would perform in more diverse network scenarios (Almeida et al., 2021b).

Demirok et al. explored the limitations of traditional reactive power control techniques in addressing overvoltage in distributed solar inverters, particularly in low-voltage grids. Their study found that the efficiency of reactive power support significantly improves as the proximity between the inverter and the end customer increases. While this insight is valuable for optimizing local voltage control, their findings also highlight a key challenge: reliance on location-dependent performance may not offer a universal solution, as distribution networks vary in complexity and load profiles. Further research is needed to explore how scalable this approach is across different grid configurations (Demirok et al., 2011). Bletterie et al. conducted a comprehensive evaluation of various reactive power control approaches, focusing on their performance in terms of network losses, additional reactive

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power flows, and their effectiveness in mitigating voltage rise in low-voltage networks. While their analysis offers valuable insights into the potential of these methods, the practical implementation of the proposed solutions faces significant challenges. System compatibility and the coordination of reactive power control between distributed PV systems and grid operators are complex issues that require further research and development to ensure effective deployment across diverse network conditions (Bletterie et al., 2017). Kim et al. proposed a hybrid reactive power control method that combines the PF(P) and Q(V) approaches, using a weighted sum to determine the reactive power reference based on the active power output of Distributed Generators (DGs). Their method dynamically shifts between PF(P) control during periods of high active power output and Q(V) control when active power is low, effectively minimizing distribution network losses. However, while the approach demonstrates improved efficiency in certain scenarios, it may encounter limitations in networks with highly dynamic load profiles and high DG penetration, where rapid fluctuations could challenge the stability and responsiveness of the control method (S. Bin Kim & Song, 2020).

Cai et al. developed a local reactive power control approach with four operational modes to address the challenges posed by high PV penetration in low-voltage distribution networks, including voltage fluctuations, under-voltage, over-voltage, high losses, and low power factors. Their innovative PF(P) control approach, which accounts for both active and reactive power of loads, aims to prevent insufficient reactive power injection while reducing network losses and mitigating voltage fluctuations. However, while effective in

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isolated scenarios, this approach may encounter scalability and adaptability challenges when applied to more complex, dynamic network environments with varying conditions (Ca et al., 2020). Ghosh et al. enhanced the traditional droop-based reactive power control by integrating active power curtailment as a local voltage control method. While this approach improves local voltage regulation under high PV penetration scenarios, it introduces trade-offs in terms of system efficiency and economic viability. Active power curtailment, although effective in managing overvoltage, leads to a reduction in the overall energy output, potentially affecting the financial return of PV systems and overall grid efficiency (Ghosh et al., 2017).

Carvalho et al. developed a voltage regulation approach that ensured active power injections did not exceed voltage limits in low-voltage distribution networks. While the approach was validated on a low-voltage single line with an On-Load Tap Changer (OLTC), the results indicated increased losses and stress on the tap changer. This added stress could lead to higher maintenance demands and potential equipment degradation, posing a challenge to the long-term sustainability of the method. Despite its efficacy in voltage regulation, the approach's practical implementation may require careful consideration of these operational trade-offs (Carvalho et al., 2008). Kabiri et al. proposed a combined strategy that integrates an electronic tap changer in the distribution transformer to provide voltage regulation, while leveraging local PV systems at each feeder bus for reactive power control to minimize losses. This approach effectively maintains voltage stability and reduces network losses, particularly in high PV penetration scenarios. However, the use of electronic

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tap changers introduces potential challenges, such as increased costs and maintenance demands. While the study demonstrates clear technical benefits, the economic feasibility and long-term operational sustainability of such systems remain important considerations (Kabiri et al., 2015).

Hu et al. introduced a novel method to mitigate voltage fluctuations caused by high PV penetration, using a two-level approach to coordinate the operation of on-load tap changers (OLTCs), capacitor banks (CBs), reactive power control, and active power curtailment. The approach combines a mixed integer nonlinear programming (MINP) model based on model predictive control (MPC) for planning, and a leader–follower consensus algorithm (LFCA) for real-time control. While this method significantly improves voltage regulation, it requires sophisticated mathematical modeling and robust communication systems for effective coordination, which may present challenges in terms of scalability and implementation in real-world networks (Hu et al., 2022). Hashemi et al. presented a voltage sensitivity-based approach to evaluate the impact of local reactive power control on the capacity requirements for energy storage units in preventing overvoltage in low-voltage grids. Their method, capable of modeling various levels of PV penetration and load conditions, demonstrated that reactive power management can reduce the energy storage capacity needed by approximately 30%. However, while this reduction is significant, the study highlighted that reliance on reactive power control might compromise the system's ability to handle unexpected fluctuations in PV output, especially in scenarios with high variability. Furthermore, challenges such as cost considerations and limited space availability for deploying energy

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storage systems remain potential barriers to widespread implementation (Hashemi et al., 2013).

Emarati et al. introduced a two-level voltage control method to manage over-voltage issues in distribution networks with high PV penetration. The first level focuses on day-ahead scheduling of battery energy storage systems and on-load tap changer (OLTC) adjustments, while the second level uses reactive power compensation through PV inverters for fine-tuning voltage profiles. This strategy enhances voltage stability by integrating both battery storage and inverter capabilities. However, the method's reliance on accurate day-ahead forecasting introduces uncertainties, particularly in highly variable grid conditions, which may reduce its effectiveness in dynamic environments. Additionally, the computational complexity of the approach could limit its scalability (Emarati et al., 2021). Adetokun et al. developed a reactive power-voltage (Q(V)) framework to assess voltage instability sensitivities in power systems with increasing renewable energy penetration. The study introduces two indices: the Critical Voltage Sensitivity Index (CVSI) and the Critical Reactive Power Sensitivity Index (CQSI), which measure the impact of renewable energy integration on voltage levels and reactive power intolerance in power system buses. While the indices provide valuable insights into optimal placements for reactive power compensation devices, the approach's reliance on detailed and accurate power system modeling poses challenges due to its complexity and time-intensive nature. Moreover, the indices' effectiveness in different power system configurations and under varying conditions requires further validation to ensure robustness and adaptability across diverse grid

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environments (Adetokun et al., 2020).

Takayama et al. proposed a novel voltage control approach based on reactive power control using PV inverters integrated with reinforcement learning, eliminating the need for information exchange between inverters. This method allows decentralized control, where each inverter independently optimizes its reactive power output based on local voltage conditions. While the approach reduces the need for communication infrastructure, its reliance on reinforcement learning introduces potential challenges, particularly in terms of computational complexity and the ability to adapt to dynamic network conditions. Furthermore, the method's effectiveness in large-scale implementations remains uncertain without further validation in diverse grid environments (Takayama & Ishigame, 2018). Howlader et al. conducted an experimental analysis of the Volt/Var control method's ability to regulate voltage using smart PV inverters in a distribution network. Their findings demonstrated that the injection of reactive power through Volt/Var control increases the voltage at the distribution level, while the absorption of reactive power decreases it. This approach allows utilities to manage voltage fluctuations effectively without the need for additional grid infrastructure. However, the study also highlights that the variability in reactive power absorption across the network may present challenges, particularly in highly dynamic or high-load conditions, where real-time adjustments may be needed (Howlader et al., 2018). Ghasemi et al. presented an adaptive droop-based control algorithm for regulating reactive and active power in a grid with high PV penetration, aimed at reducing losses, increasing grid capacity, and

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preventing overvoltage. Their algorithm, tested on a modified IEEE 33-bus system through computer simulations, demonstrated effective overvoltage control by balancing reactive and active power contributions. However, the adaptive nature of the algorithm may pose challenges in terms of system stability and predictability, particularly in highly dynamic grid environments where the interaction between multiple distributed generators can complicate control efforts (Ghasemi & Parniani, 2016).

Hasheminamin et al. proposed a single-point reactive power control (SPRPC) method to mitigate voltage rise due to reverse power flow in residential distribution networks with high PV penetration. By absorbing reactive power from a strategically selected point using an impedance-voltage rise index (IVRI), this approach effectively eliminates the need for widespread inverter upgrades and reduces voltage fluctuations. However, the method's reliance on detailed and precise mathematical modeling requires accurate network models, which may complicate implementation in less predictable environments. Additionally, deviations from assumed conditions could impact the accuracy and effectiveness of the control method, particularly in diverse network topologies (Hasheminamin et al., 2018). Bernal et al. proposed a fuzzy logic-based reactive power control technique for voltage regulation in low-voltage distribution systems with high PV penetration. This method utilizes local information from smart meters to adaptively adjust the reactive power output of PV inverters, resulting in reduced voltage rise and minimized power losses. While fuzzy logic-based control offers significant flexibility and robustness compared to traditional methods, its performance may be affected

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by uncertainties in network conditions and load variations. Additionally, the computational effort required for real-time implementation of fuzzy logic controllers may pose challenges in large-scale systems (Bernal A. et al., 2017). edawy et al. introduced a multi-agent reactive power control system utilizing a reactive power index (RPI) to assess the ability of each distributed generator (DG) to inject or absorb reactive power. This approach facilitates coordination between different voltage regulation devices and DGs, significantly improving voltage regulation in distribution networks. However, the reliance on coordination between multiple agents may introduce challenges related to communication delays and synchronization, which could affect the real-time performance of the control system, especially in highly dynamic network environments (Bedawy & Yorino, 2018).

Liu et al. developed a multi-level inverter system integrating partitioned energy storage units, incorporating a novel phase-locked loop (PLL) based on the discrete Fourier transform (DFT) technique for power distribution between segments and PV systems. This system successfully mitigated voltage rise issues through dynamic power regulation and provided substantial reactive power compensation. A reactive power allocation coefficient was also determined to prevent overmodulation and duty cycle saturation, ensuring high power quality. However, the use of multi-level inverters introduces potential complexities in control algorithms and increased maintenance requirements, particularly in large-scale implementations (L. Liu et al., 2011). Turitsyn et al. presented and compared several topologies for reactive power control in distribution networks with high PV penetration through detailed simulations.

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The study provides valuable insights into the performance of centralized versus decentralized control strategies, highlighting the potential benefits of local control in maintaining voltage stability and reducing power losses. However, while simulations offer significant theoretical understanding, the practical implementation of these topologies may face challenges, such as communication delays and hardware limitations, which require further real-world validation. (Turitsyn et al., 2011). Arshad et al. proposed a multi-level voltage control strategy for distribution networks with high PV penetration, integrating Flicker Control, Local Voltage Control, and Coordinated Voltage Control through PV inverters. The strategy effectively optimizes inverter set points to reduce curtailment and losses, while maintaining voltage stability. However, challenges such as communication latency and reliance on specific inverter capabilities may complicate real-time coordination under dynamic network conditions, potentially limiting the approach's scalability and robustness in diverse grid environments (Arshad & Lehtonen, 2019). Kim et al. introduced a voltage regulation method using a Volt/Var control approach, incorporating the positive-sequence sensitivity impedance matrix with power-factor constraints. This method, validated on the IEEE 34-bus test feeder, effectively maintained bus voltage within specific ranges while regulating reactive power. However, while the technique offers improved voltage control, its reliance on detailed feeder impedance sensitivity and power-factor constraints may complicate practical implementation, particularly in large and diverse grid environments where real-time performance and scalability are critical (I. Kim & Harley, 2020).

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2.5.4 Limitation of Existing Voltage Rise Mitigation Methods

The integration of energy storage systems (ESS) is a potential solution to mitigate voltage rise in distribution networks with high PV penetration. However, challenges exist in effectively utilizing ESS, including high costs, limited capacity, and optimal sizing requirements based on accurate PV generation forecasts (Abo Alwez et al., 2020). Additionally, efficient charging and discharging strategies must coordinate with PV generation, load demand, and system compatibility. Maintenance and lifecycle management, such as monitoring battery health and addressing degradation, are also critical for long-term performance. Despite these challenges, ongoing advancements in battery technology, control algorithms, and deployment strategies aim to enhance the role of ESS in stabilizing voltage levels and improving grid reliability (Singh et al., 2021).

Active power curtailment is another strategy for mitigating voltage rise in high PV penetration networks. However, it introduces potential energy loss, financial impacts for PV system owners, and technical challenges related to real-time control and coordination (Kyriakopoulos & Arabatzis, 2016). Furthermore, curtailment may affect grid stability and power quality due to abrupt generation changes. To manage these complexities, advanced control systems and forecasting are required. Addressing these challenges can help optimize active power curtailment, ensuring voltage stability and grid reliability while balancing economic considerations (Pan et al., 2022).

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2.5.5 Limitation of Existing Reactive Power Control to Mitigate the Voltage Rise

The primary cause of voltage rise in distribution networks with high photovoltaic (PV) penetration is the imbalance between PV generation and load demand. When PV generation exceeds local consumption, excess active power is injected into the grid, causing a rise in voltage levels (Turitsyn et al., 2011). Control strategies like fixed power factor and maintained power factor (PF(P)) focus solely on PV active power generation, overlooking fluctuations in load demand. This makes these control strategies open-loop systems that fail to dynamically adapt to changing grid conditions (L. Liu et al., 2011). For instance, during periods of both high PV generation and high load demand, the risk of voltage rise is minimal due to the balance between generation and consumption. However, under such conditions, the PF(P) strategy still absorbs unnecessary reactive power, increasing network losses and potentially causing the voltage to fall below the lower permissible limit of 0.95 per unit (I. Kim & Harley, 2020; Yan & Saha, 2012). These strategies are often inefficient in handling dynamic grid environments, as they fail to incorporate load variations into the control scheme (Arshad & Lehtonen, 2019). This limitation of PF and PF(P) control strategies highlights the need for more adaptive approaches that can balance both PV generation and load demand.

In contrast, the Q(V) strategy offers a more adaptive approach by basing reactive power control directly on the voltage measured at the point of common coupling (PCC) of the PV system. This method allows for more responsive voltage regulation, adjusting to real-time voltage levels rather than relying

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solely on PV power output (Kerber et al., 2009). However, the effectiveness of the Q(V) strategy is influenced by the PV system's location within the distribution network (Almeida et al., 2021b). Areas with high voltage sensitivity benefit the most from Q(V) control, as small changes in reactive power lead to significant voltage adjustments. Conversely, in areas with low voltage sensitivity, the Q(V) strategy may not be as effective, as larger reactive power adjustments are required to achieve the desired voltage regulation (Demirok et al., 2011). This highlights the importance of considering network topology and voltage sensitivity when deploying Q(V) control in distribution systems.

2.5.6 Summary

This section reviews existing methods for mitigating voltage rise on distribution networks with high photovoltaic (PV) penetration. Energy storage systems (ESS) store surplus energy during periods of high solar irradiance and release it during high demand. Batteries such as lithium-ion, lead-acid, and flow batteries are commonly used. Studies have proposed control strategies for ESS, including charge/discharge management, battery sizing optimization, and coordination with devices like on-load tap changers (OLTCs) to minimize voltage rise, reduce stress on OLTCs, and limit reverse power flow. However, the limited capacity of ESS requires accurate sizing based on PV forecasts and load profiles, along with careful coordination of charging and discharging strategies.

Active power curtailment reduces PV output when voltage exceeds set limits. Algorithms coordinating curtailment with ESS and OLTCs help balance PV

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production and load demand, with hybrid approaches combining curtailment and reactive power compensation to enhance voltage regulation. Although effective, curtailment can result in significant renewable energy losses.

Reactive power control techniques, such as fixed power factor (PF), maintained power factor (PF(P)), and Q(V) control, have been explored for PV inverters. These strategies depend on factors like active power injection and voltage levels but may result in high losses or insufficient voltage regulation.

Overall, while these methods show promise in mitigating voltage rise and improving network performance, challenges such as cost, control limitations, and coordination issues must be addressed for successful implementation in practical settings. scenarios.

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CHAPTER 3

METHODOLOGY

3.1 Introduction

As presented in the previous chapters, global pollution has shown a significant increase, resulting in countries adopting a trend of increasing their electricity generation through renewable sources, particularly photovoltaics. The majority of these PV installations are implemented as distributed generation. However, the existing power grid infrastructure was designed and installed prior to this surge in distributed generators, making it ill-prepared to accommodate the growing number of such generators. Consequently, this increase brings forth numerous issues for distribution networks, including voltage rise and reverse power flow, among others. Moreover, the earlier chapters highlight that conventional voltage regulation methods have proven ineffective in addressing this problem, while alternative voltage rise mitigation techniques also possess certain limitations.

Therefore, this chapter proposes an adaptive reactive power control technique to mitigate voltage rise on distribution networks with high PV penetration. Additionally, this chapter presents the components of the control, a flowchart outlining its operation, and modifications to the control using Matlab Simulink. To comprehensively understand the proposed control technique, it is necessary to test it on a distribution network. Thus, a small-scale distribution network consisting of 7 buses is introduced to evaluate the effectiveness of the proposed reactive power control and to assess its capabilities in mitigating

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the limitations of existing reactive power control techniques. However, while this network serves as a valuable tool for observing network behavior, it remains crucial to evaluate the proposed technique using real network data, including authentic load profile and sun irradiance data. Consequently, this chapter presents a distribution network that supplies power to the Taman Impian Putra residential area in Port Dickson, Malaysia, along with the corresponding load profile and sun irradiance data specific to Malaysia. Port Dickson was chosen due to the availability of reliable and comprehensive data, facilitating accurate analysis and comparison for the control technique. Figure 3.1 shows the flow chart of the thesis.

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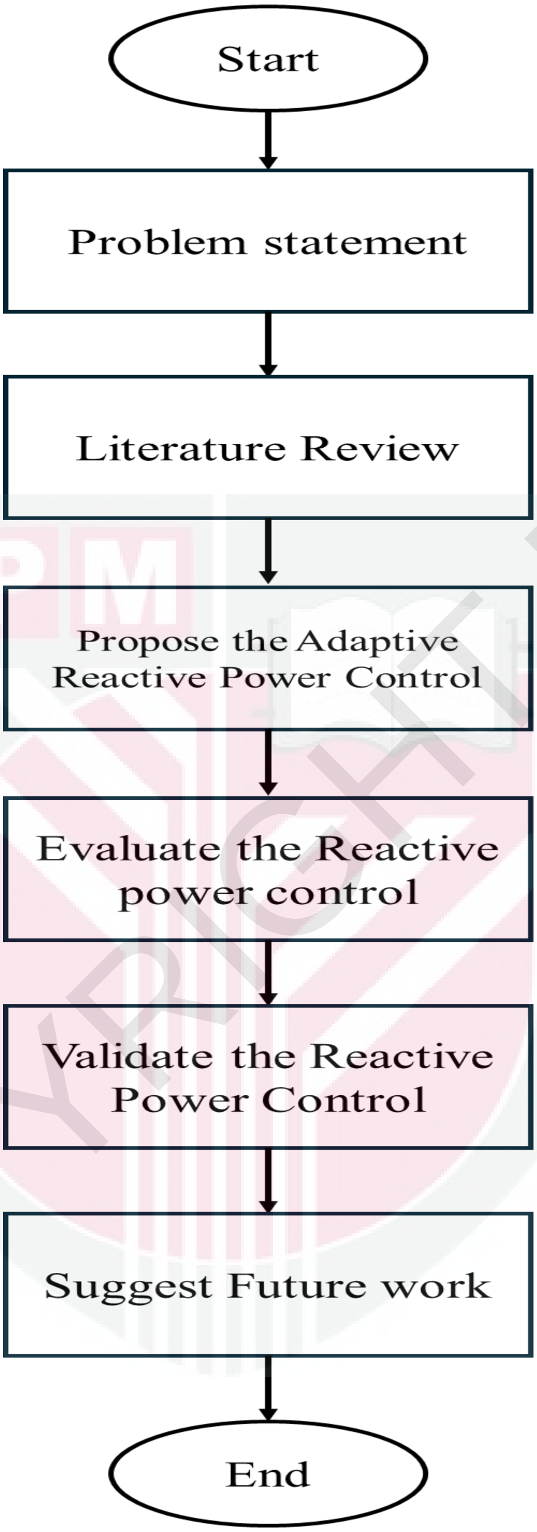

Figure 3.1 : Flow Chart of the Thesis

3.2 Proposed Reactive Power Control

The reactive power control method proposed in this study is distinct from traditional controls, which typically rely on fixed reactive power references based on either the PV system's active power injection or the voltage at the point of common coupling (PCC). These traditional controls use static values that do not adjust dynamically to the PV system's changing conditions, making them less responsive to fluctuations in voltage or power output. In contrast, the proposed adaptive reactive power control operates dynamically. Instead of using fixed references, it continuously updates the reactive power reference in real-time. Specifically, it calculates the rate of change in reactive power (ΔQ) every second. This change is calculated based on two factors: the voltage at the PCC and the active power being injected by the PV system. By continuously recalculating and adjusting the reactive power reference, the system can quickly respond to fluctuations in the grid, ensuring that voltage regulation is maintained more effectively. This approach enhances adaptability, as it can account for rapid changes in power generation or voltage, which are common in systems with high PV penetration. The ability to update every second ensures the system is responsive and adjusts to maintain stability, offering more reliable voltage regulation compared to static, predetermined methods.

This adaptive reactive power control represents a notable departure from conventional reactive power controls, which are often constrained by the static nature of their input parameters. As elucidated in the preceding section, reactive power control strategies predicated solely on network voltage exhibit

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commendable voltage regulation and minimal losses in locales characterized by high sensitivity to both active and reactive power fluctuations. However, in regions where voltage sensitivity is low, particularly in scenarios marked by significant PV active power generation juxtaposed with low load demand, the efficacy of voltage-based regulation diminishes. Despite the potential for voltage rise, such locations may not exhibit a commensurate increase in network voltage, thereby compromising voltage regulation. This discrepancy underscores the need for a more adaptive and context-aware reactive power control mechanism, prompting the introduction of the proposed technique.

The proposed methodology entails an initial assessment involving the computation of Volt-Var (Q(V)), which encapsulates the reactive power response to variations in network voltage, and Watt-Var (modified fixed power factor), which characterizes the reactive power response to PV active power injection. By judiciously weighing the influence of each component, ΔQ is determined using equation [3-1], thereby facilitating the calculation of the reactive power reference (Q) as outlined in equation [3-2]. To enhance the clarity of equations [3-1] and [3-2], Figure 3.3 provides a block diagram of the adaptive reactive power control for better understanding. Also, Figure 3.2 provides a visual representation of the procedural flow underlying the adaptive reactive power control, delineating the sequential steps involved in its implementation. It is important to note that the iterative process of adaptive reactive power control is continuous and will keep repeating indefinitely until the reactive power control of the smart controller is manually turned off. At that point, the iterative reactive power control will be interrupted and cease

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operation. This iterative process ensures that the reactive power control mechanism remains attuned to prevailing system dynamics, thereby enhancing its efficacy and adaptability.

To further elucidate the intricacies and merits of the proposed approach, it is imperative to delve deeper into the underlying principles and algorithms governing its operation. One key aspect deserving of scrutiny pertains to the computation of ΔQ, which serves as the linchpin of the dynamic reactive power control mechanism. By dynamically adjusting the reactive power reference in response to changes in both voltage and active power injection, the proposed method endeavors to optimize system performance while mitigating the risk of voltage instability and associated grid disturbances.

Moreover, the efficacy of the proposed technique hinges on its ability to strike a judicious balance between the competing demands of voltage regulation and reactive power support. Traditional reactive power control strategies often prioritize one aspect over the other, leading to suboptimal outcomes in certain operating conditions. In contrast, the proposed methodology adopts a holistic approach that takes into account the interplay between voltage dynamics, and active power injection, thereby enabling more nuanced and context-sensitive control decisions.

An in-depth analysis of the underlying mathematical formulations and control algorithms can offer valuable insights into the robustness and adaptability of the proposed approach. By dissecting the computational procedures involved

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in calculating ΔQ and determining the optimal reactive power reference. Furthermore, it is essential to consider the broader implications of the proposed reactive power control method within the context of emerging trends in power system operation and management. As renewable energy sources continue to proliferate and exert a growing influence on grid dynamics, the need for agile and responsive control mechanisms becomes increasingly pronounced. The proposed approach represents a step towards realizing the vision of a more dynamic and resilient power grid capable of accommodating diverse generation sources.

In conclusion, the proposed reactive power control methodology represents a significant departure from conventional approaches, offering a dynamic and adaptive framework for voltage regulation and reactive power support. By continuously updating the reactive power reference in response to changes in system conditions, the proposed method aims to enhance grid stability and efficiency while accommodating the complexities of modern power systems. Through further research and experimentation, it is hoped that this innovative approach will pave the way for more robust and resilient power grid operation in the face of evolving energy landscapes. Furthermore, Figure 3.7 serves to illustrate the practical instantiation of the adaptive reactive power control methodology within the MATLAB/Simulink environment, offering insights into its computational framework and operational dynamics.

$$\Delta Q(t) = (Volt - Var * w) + (Watt - Var * (1 - w)) \quad [3\text{-}1]$$

$$Q(t) = Q(t-1) + \Delta Q\ (t) \quad [3\text{-}2]$$

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Where∆Q: the amount of change in reactive power by a specific second

w: the weight

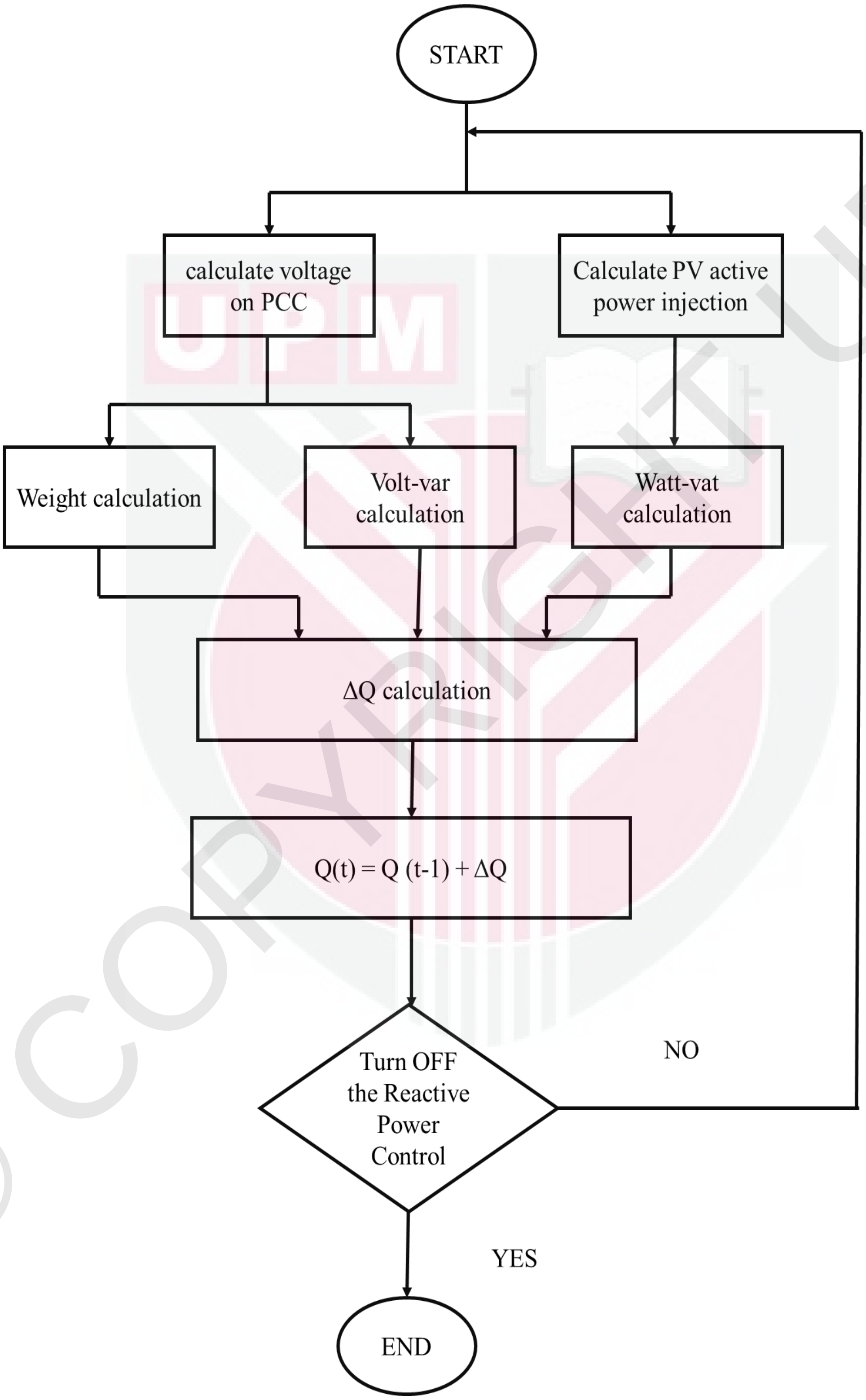

Figure 3.2 : Flow Chart of the Adaptive Reactive Power Control

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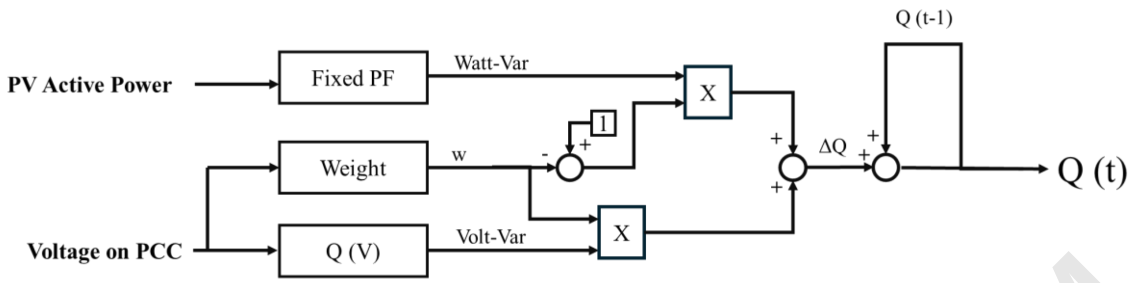

Figure 3.3 : Block Diagram of the Adaptive Reactive Power Control

3.2.1 Watt-Var

The role of the Watt-Var component in determining the reactive power reference based on PV active power cannot be overstated. In the adaptive reactive power control technique, a modified fixed power factor method is introduced to enhance control efficacy. This modification entails fine-tuning the reactive power response to accommodate minimal PV active power generation (0 W) within a narrow range from 0 to 0.1. The primary objective of this adjustment is to curtail the absorption of reactive power during periods of decreased PV generation, thereby mitigating losses associated with reactive power control operations.

The calculation of the Watt-Var output is facilitated by equation [3-3], which encapsulates the functional relationship between the reactive power reference and PV active power. To gain a visual understanding of this relationship, reference Figure 3.4, which provides a graphical depiction of the Watt-Var output. This graphical representation offers insights into how changes in PV active power influence the reactive power reference, thereby facilitating informed decision-making in reactive power control operations. Moreover, By integrating the modified fixed power factor approach into the reactive power

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control framework, the adaptive reactive power control endeavors to improve control performance under varying operating conditions. The ability to adjust the reactive power dynamically in response to fluctuations in PV generation levels enhances the adaptability and responsiveness of the control system.

In summary, the incorporation of the modified fixed power factor method within the reactive power control framework represents a significant advancement in control strategy design. Through careful calibration of the reactive power response to accommodate minimal PV generation, the proposed adaptive reactive power control offers a more robust and resilient control solution. The graphical representation of the Watt-Var output serves as a valuable tool for understanding the dynamic interplay between PV active power and reactive power reference, thereby facilitating optimal control decision-making.

$$Watt - Var = \begin{cases} -1, & P \geq P_{max} \\ \frac{1.1 * P}{-P_{Max}} + 0.1, & 0 \leq P < P_{Max} \end{cases} \quad [3\text{-}3]$$

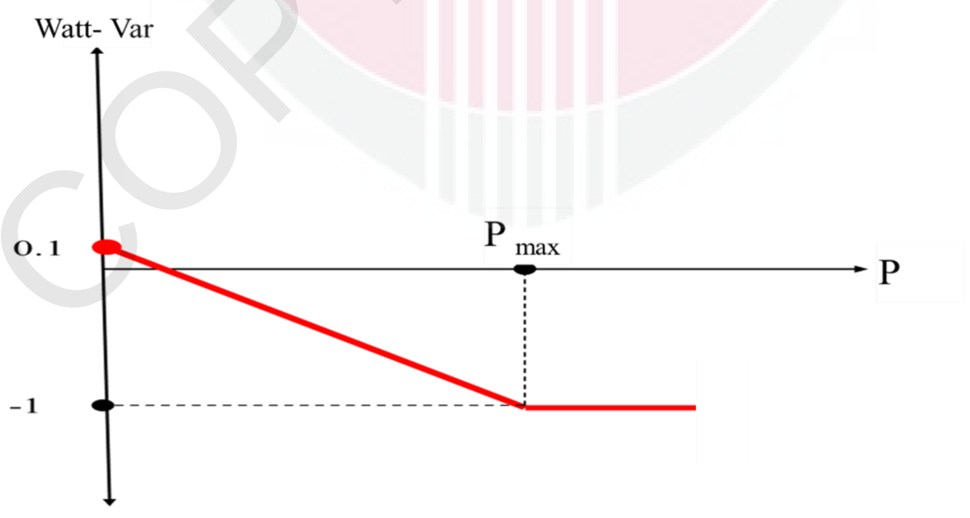

Figure 3.4 : Graph of Watt-Var Output

3.2.2 Volt-Var

The significance of the Volt-Var component in shaping the reactive power response to voltage variations at the point of common coupling cannot be overstated, particularly in the context of PV systems integrated into distribution networks. The proposed technique capitalizes on the established Q(V) methodology, as detailed in section (2.4.3), to quantify this relationship. By leveraging equation [3-4] (Shivashankar et al., 2016), the reactive power output is computed based on the prevailing network voltage conditions, thereby enabling the control system to adapt dynamically to voltage fluctuations. A graphical representation of the relationship between reactive power output and network voltage is provided in Figure 3.5, offering a visual insight into the Volt-Var characteristic. This graph elucidates how changes in network voltage influence the reactive power response, thereby facilitating a nuanced understanding of the control dynamics. By aligning reactive power output with voltage variations, the proposed technique enhances voltage regulation capabilities, thereby bolstering grid stability and performance. The utilization of the Q(V) technique within the reactive power control framework underscores the method's reliance on established principles and methodologies. By drawing upon well-established techniques, the proposed approach inherits the strengths and advantages of existing methodologies while introducing refinements tailored to the specific requirements of PV integration. This strategic integration of proven methodologies with innovative enhancements underscores the pragmatic and forward-thinking nature of the proposed technique.

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$$Volt-Var = \begin{cases} 1\ , & V < 0.95\ p.u. \\ \frac{1}{(V_1 - V_2)}(V - V_1), & 0.95\ p.u. \leq V < 0.99\ p.u. \\ 0, & 0.99\ p.u. \leq V < 1.01\ p.u. \\ \frac{1}{(V_3 - V_4)}(V - V_3), & 1.01\ p.u. \leq V < 1.05\ p.u. \\ -1\ , & 1.05\ p.u. \leq V \end{cases} \quad [3\text{-}4]$$

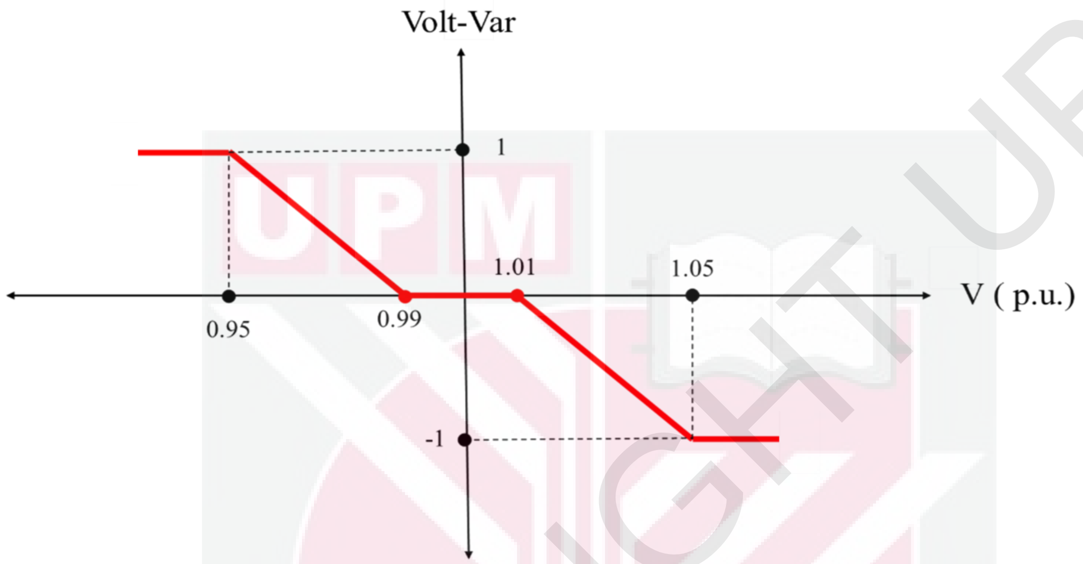

Figure 3.5 : Graph Volt-Var Output

3.2.3 Weight

The weight calculation component of the proposed algorithm plays a pivotal role in determining the relative importance of the Watt-Var and Volt-Var components in reactive power control. This weighting mechanism, governed by equation [3-5], dynamically adjusts the significance attributed to each component based on the voltage at the point of common coupling. As voltage levels fluctuate, the weight assigned to the Volt-Var component is modulated accordingly, amplifying its influence during periods of elevated voltage and attenuating it during voltage dips, and vice versa for the Watt-Var component.

The reason for assigning weights is to prioritize inputs based on their impact on the voltage rise mitigation. When voltage levels increase, indicating high weight or importance to the voltage at the point of common coupling, the algorithm focuses on reducing the voltage rise. Although the lower weight given to Watt-Var during voltage rise that is not caused by significant PV power might seem like a drawback, because the Watt-Var will aim to reduce the reactive power absorption. it is important to remember that reactive power still helps address the issue. Therefore, this limitation is considered minor, given the main goal of regulating voltage.

Conversely, when voltage decreases, indicating either low voltage sensitivity or minimal PV active power injection, the algorithm reallocates importance to the Watt-Var component. This shift in weight allocation ensures that the control strategy remains responsive to changing system conditions, thereby optimizing performance under diverse operating scenarios. The graphical depiction of weight calculation, showcased in Figure 3.6, provides a visual representation of this dynamic adjustment process, elucidating how the weighting mechanism adapts to varying voltage conditions. The figure illustrates that when the voltage reaches its maximum (1.2 p.u.), all the weight (1) is assigned to Volt-Var to reduce the voltage rise as quickly as possible. As the voltage decreases, the weight gradually shifts, giving more emphasis to Watt-Var. Once the voltage reaches its minimum (0.6 p.u.), all the weight is transferred to Watt-Var to prevent unnecessary reactive power control absorption and help increase the network voltage by injecting reactive power. It’s important to note that the voltage values were selected based on extensive

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empirical methods.

By dynamically adjusting the relative importance of Watt-Var and Volt-Var components, the proposed algorithm achieves a balanced and adaptive approach to reactive power control. This dynamic weighting mechanism ensures that the control strategy remains responsive to evolving system dynamics, thereby enhancing grid stability and performance. While certain limitations may exist, such as the lower weight assigned to Watt-Var during voltage rise events, the overall efficacy and adaptability of the control strategy remain uncompromised. In essence, the weight calculation component serves as a crucial cog in the reactive power control framework, enabling nuanced and context-sensitive decision-making to optimize grid operation.

$$W = \begin{cases} 1\ , & V \geq 1.2 \\ \dfrac{1}{(V_{Max} - V_{min})}(V - V_{min}), & 0.6 < V < 1.2 \\ 0, & 0.6 \leq V \end{cases} \qquad [3\text{-}5]$$

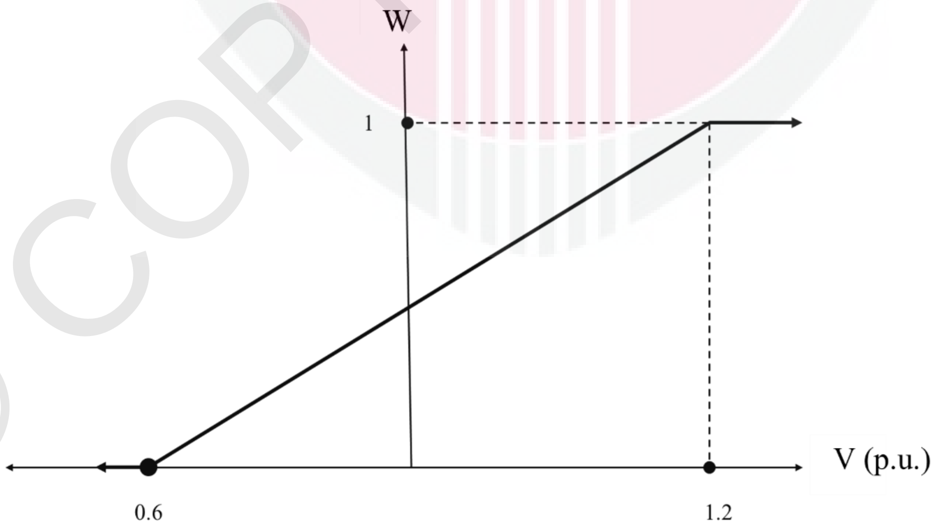

Figure 3.6 : Graph of Weight

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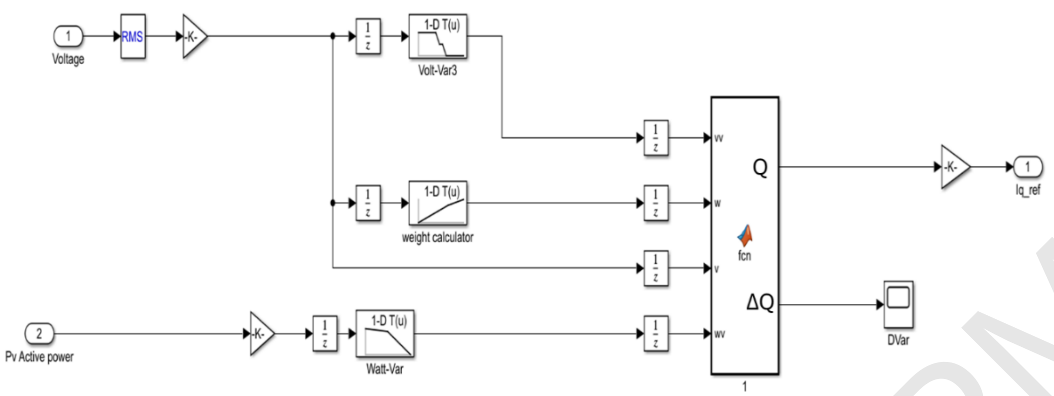

Figure 3.7 : The Proposed Reactive Power Control in MATLAB/Simulink

3.3 Smart Inverter

The smart inverter plays a pivotal role in the conversion of direct current (DC) power generated by PV panels into alternating current (AC) power, which can be utilized by the national grid (Makdisie et al., 2018). Within the smart inverter, three distinct control mechanisms are in place to ensure the efficient conversion and transmission of power to the grid (Zhong & Hornik, 2012).

Firstly, the smart inverter governs the voltage levels, maintaining them within specified limits to ensure compatibility with the grid. This voltage control mechanism is crucial for preventing overvoltage or undervoltage conditions, which could damage grid infrastructure or disrupt power supply (Demirok et al., 2011). Secondly, the smart inverter oversees the direct current component (I_d) and the quadrature current component (I_q). These two components represent the current flowing through the inverter and are essential for managing the active and reactive power components of the generated electricity. I_q, in particular, plays a vital role as it is orthogonal, meaning it is 90 degrees out of phase with the voltage waveform (M. Ebrahimi et al., 2016).

I_q is primarily responsible for the management of reactive power in the system. Reactive power, denoted as "Q" is vital for maintaining the voltage levels and stability of the grid. By adjusting the magnitude of I_q, the smart inverter can effectively control the amount of reactive power it either generates or absorbs (Varma & Siavashi, 2018). When the smart inverter increases the magnitude of I_q, it supplies more reactive power to the grid. This is particularly useful in situations where the grid requires additional reactive power to stabilize voltage levels. Conversely, when the smart inverter decreases the magnitude of I_q, it absorbs reactive power from the grid, which can be valuable in situations where excess reactive power needs to be mitigated to maintain grid stability (Kusters & Moore, 1980).

In summary, the smart inverter is a critical component in photovoltaic systems, responsible for converting DC power into AC power suitable for the national grid. Its advanced control mechanisms ensure the proper management of voltage levels and the precise adjustment of reactive power through the manipulation of I_q, thereby enhancing grid stability and overall system efficiency. This technology represents a crucial step towards the integration of renewable energy sources into the existing power infrastructure. Finally, Figure 3.8 shows the controller of the smart inverter that been modified by MATLAB Simulink.

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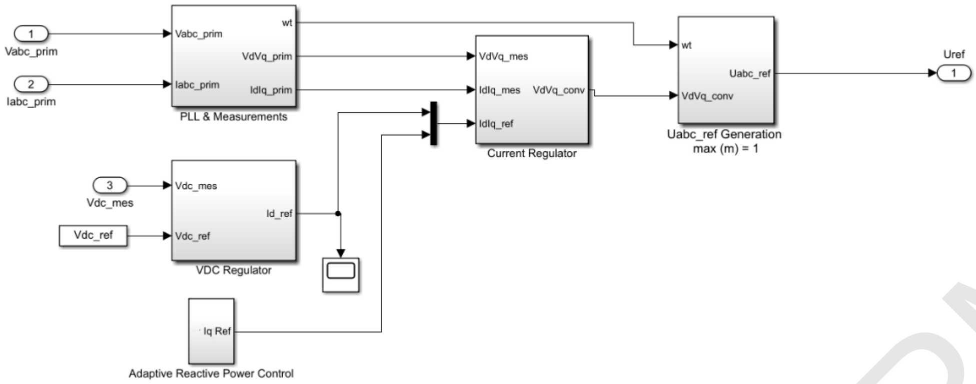

Figure 3.8 : The Control of Smart Inverter by MATLAB Simulink

3.4 Distribution Network

This section presents two distribution networks: a small test network and a Malaysian low voltage network. These networks help illustrate the impact of voltage rise and how reactive power control techniques perform under different conditions.

3.4.1 Small Test Distribution Network

A small radial distribution network consisting of 7 buses, as described in Table 3.1 and depicted in Figure 3.9, is presented to illustrate the voltage rise during high PV generation and the limitations of available reactive power control techniques in mitigating voltage rise. This small-scale network is chosen due to its manageable size, allowing for the exploration of various scenarios and the examination of both the limitations and successes of the proposed reactive power control techniques. The network incorporates PV systems as distributed generators. The network has been penetrated by PVs as distribution generators. The active power output of the PV systems within the network is visualized in Figure 3.10, providing valuable insights into the behavior of the network. Additionally, Table 3.2 presents the parameters of the existing reactive power technique integrated with the PV system. This facilitates a comprehensive analysis of their performance.

A voltage sensitivity analysis was performed on the distribution network, with the results depicted in Figure 3.11. Voltage sensitivity refers to how the voltage at a specific point in an electrical network change in response to variations in active power and reactive power. In power distribution networks, particularly those with distributed generation like solar PV systems, the injection or absorption of active and reactive power can significantly influence voltage levels. The analysis assessed the voltage sensitivity in response to both reactive power and active power injections, represented by red triangles and blue circles, respectively. The findings indicate that the sensitivity to active power injections are higher compared to those of reactive power injections. This observation can be attributed to the high R/X ratio typically encountered in low voltage distribution networks, along with the low short circuit ratio (SCR). Intriguingly, the analysis also revealed that the sensitivity to both active and reactive power injections increase as the buses are located farther from the substation transformers. As a result, injecting reactive power at bus 7 will exert the most significant impact on the network voltage.

The network was tested under two scenarios: no load and full load. The no-load scenario simulates conditions where all generated PV power is injected into the grid, highlighting potential voltage rise during low demand. In contrast,

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the full-load scenario examines the effect when the generated PV power is entirely consumed by the load. These scenarios were selected to evaluate the network's performance under different demand conditions and to assess the effectiveness of the adaptive reactive power control technique. Subsequently, the existing reactive power control technique is individually applied in both scenarios to assess the extent of losses and its efficacy in mitigating voltage rise. Finally, the proposed control technique is employed in the same scenarios to evaluate the losses attributable to this new control technique and its effectiveness in addressing voltage rise. This enables a comparative analysis between the proposed control technique and the existing reactive power control techniques, highlighting the advantages of the proposed approach.

Table 3.1 : Parameters of Test Feeder Model

Parameters	Value	Description
S_{base}	10 KVA	Base power
V_{base}	0.4 KV	Base Voltage
V_{limit}	0.4 ± 0.02 KV	Voltage limit V_{base} ± 5%
P_{PV}	10 KW	Nominal active power of PV
Z_{OHL}	0.004 + j 0.0027 p.u.	Overhead line (OHL) impedance
Z_{Grid}	0.0001+ j 0.0001 p.u.	Medium Voltage grid impedance
Z_{TR}	0.0009 + j 0.002 p.u.	Transformer impedance
V_{Slack}	1.02 p.u.	Slack bus voltage

(Huang et al., 2021)

Table 3.2 : Reactive Power Control Strategies Parameters
(TNB, 2023)

Method	Parameters	Value	Unit
Fixed PF	PF reference	-	0.95
PF (P)	X lookup of PF(P)	p.u.	[0.0, 0.4, 1.0, 1.20]
	Y lookup of PF(P)	-	[1.0, 1.0, 0.95, 0.95]
Q(V)	X lookup of Q(V)	p.u.	[0.90, 0.95, 0.99, 1.01 1.05, 1.10]
	Y lookup of Q(V)	p.u.	[0.45, 0.45, 0.0, 0.0, -0.45, -0.45]

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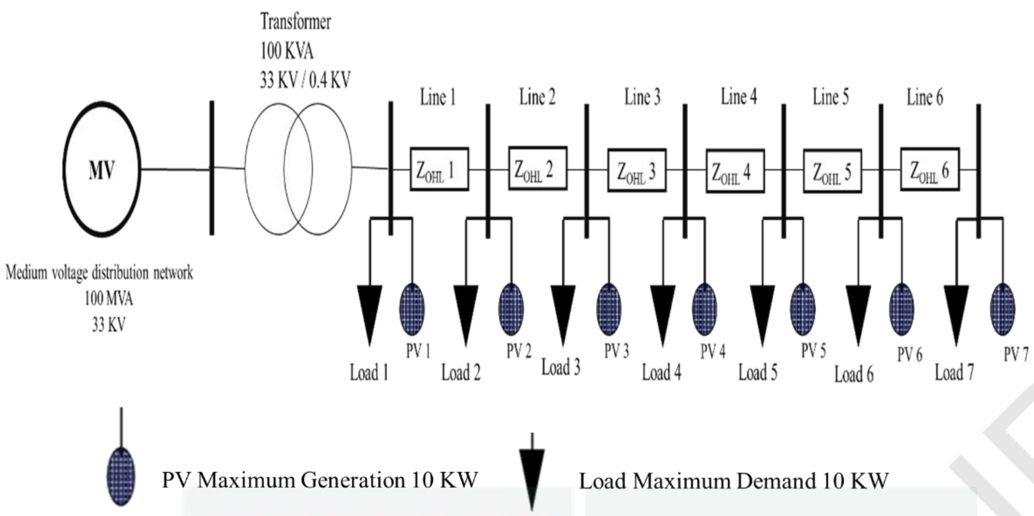

Figure 3.9 : Small Test Distribution Network Feeder Diagram

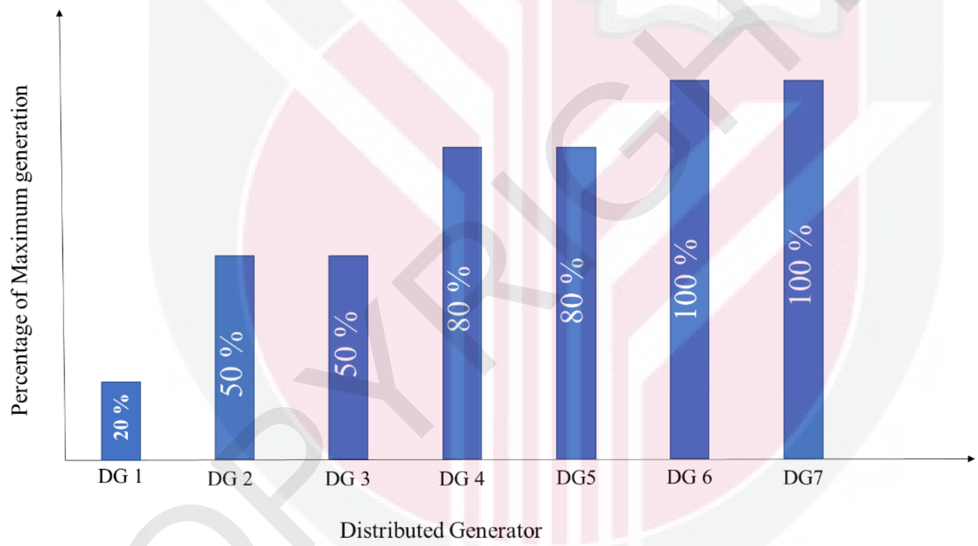

Figure 3.10 : Active Power Output of PV Distributed Generation That Penetrated Small Test Distribution Network

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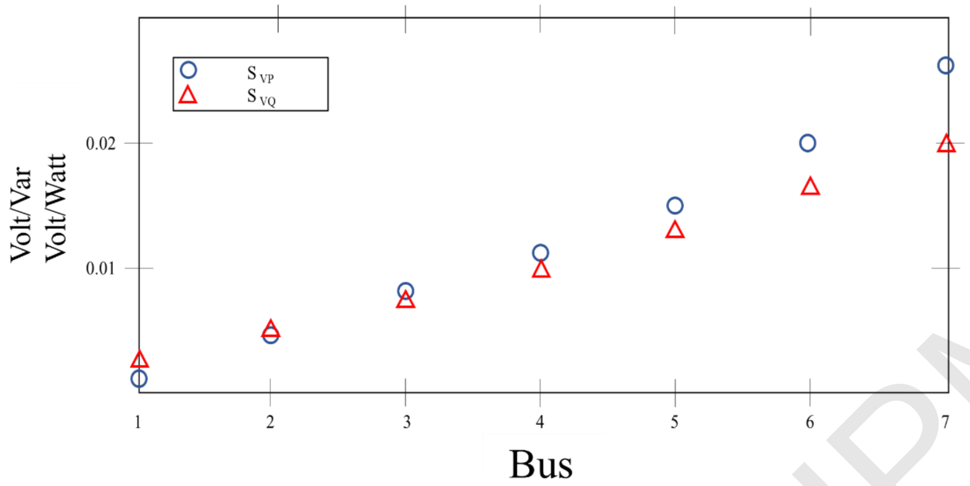

Figure 3.11 : Voltage Sensitivity to Active and Reactive Power Variations on the Small Test Distribution Network

3.4.2 Malaysian Low Voltage Distribution Network

The Malaysian low voltage distribution network that has been utilized in this thesis presented by the authors in (Tie & Gan, 2013), is a low voltage distribution network that supplies electricity to a residential area called Taman Impian Putra in Malaysia. The network data was collected from TNB, the company responsible for the transmission and distribution of electricity in Malaysia. The distribution network is depicted in Figure 3.12. Furthermore, the network data is summarized in Table 3.3. The radial network comprises a 4 X 500 mm^2 PVC/PVC Aluminum (Al) cable that connects the transformer to the feeder pillar. The feeder pillar serves a total of 5 feeders. The cable used between the feeder pillar and the poles is 185 mm^2 4C Al. XLPE cable. For distributing power from the poles to the houses, an Aerial Bundle Cable (ABC) with 3 x 185 mm^2 + 120 mm^2 is employed. Among the feeders, feeder 5 is the longest, spanning 332 meters, while feeder 4 is the shortest at 186 meters. Each feeder serves approximately 27 to 33 houses, assuming an average

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maximum demand of 2 kW per consumer, accounting for diversity. The self-impedance and mutual-Impedance are calculated by equations [3-5] and [3-6] respectively(R. Ebrahimi et al., 2011).

$$Z_{ii} = r_i + 9.8696 * 10^{-4}.f + j1.2566 * 10^{-3}.f.\left(ln\frac{1}{GMR_i} + 6.4905 + \frac{1}{2}ln\frac{\rho}{f}\right) \ \Omega/\text{Km} \qquad [3\text{-}5]$$

$$Z_{ij} = 9.8696 * 10^{-4}.f + j1.2566 * 10^{-3}.f.\left(ln\frac{1}{D_{ij}} + 6.4905 + \frac{1}{2}ln\frac{\rho}{f}\right) \ \Omega/\text{Km} \qquad [3\text{-}6]$$

r_i = Resistance of conductor (Ω/Km).

D_{ij} = Distance between conductor i and j.

GMR_i = Geometric mean radius of conductor (cm).

f = System frequency 50 Hz.

ρ = earth resistivity (Ω-100).

Then, the positive and zeros sequence impedance calculated by equation [3-7] and [3-8] (Kersting, 2020).

$$Z_1 = Z_2 = Z_s - Z_m \qquad [3\text{-}7]$$

$$Z_o = Z_s + 2Z_m \qquad [3\text{-}8]$$

Where Z_S and Z_m which refer to Mutual and self Impedance respectively are calculated by equations [3-9] and [3-10] respectively ,

$$Z_S = \frac{Z_{aa} + Z_{bb} + Z_{cc}}{3} \qquad [3\text{-}9]$$

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$$Z_m = \frac{Z_{ab} + Z_{ac} + Z_{ba} + Z_{bc} + Z_{ca} + Z_{cb}}{6} \quad [3\text{-}10]$$

Figure 3.13 illustrates the aggregate load demand profile in Malaysia (R. Ebrahimi et al., 2011). The load represents the average aggregate load of the area during the working days. It is expressed in per-unit form, obtained by normalizing the maximum load value from the curve. It can be observed that the load demand experiences an increase at 5 PM, reaching its peak at 8 PM. This surge in demand is primarily attributed to the hot weather prevalent in Malaysia, leading to higher usage of air conditioning systems by the majority of customers. Conversely, the load demand is at its minimum between 7 AM and 5 PM, as most customers tend to be outdoors during this period. This profile serves as a representative shape for all houses within the distribution network.

On the other hand, Figure 3.13 also presents the solar panel generation profile (R. Ebrahimi et al., 2011). It is expressed in per-unit form, obtained by normalizing the maximum value from the curve, to facilitate easy comparison between the load and the solar panel generation. Notably, solar panels do not generate electricity during the night time period from 8 PM to 8 AM due to the absence of sun irradiance. Subsequently, the PV generation gradually increases, reaching its maximum output at 1 PM. It is important to highlight that this PV generation profile is applicable to all PV systems within the network.

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This network has been operated at various levels of PV penetration to illustrate the issue of voltage rise within the Malaysian low voltage distribution network, particularly under conditions of high PV penetration. Subsequently, a proposed reactive power control technique was implemented on the distribution network to validate its effectiveness in mitigating voltage rise while minimizing unnecessary losses.

Table 3.3 : Data of Distribution Network

Characteristics	Amount
Area (Km^2)	0.75
Number of customers	149
Power demand (KW)	298
Energy consumption (MWh / Year)	1572
Load density (MW / Km^2)	4
Total network length (Km)	1.5
Transformer rating (KVA)	500

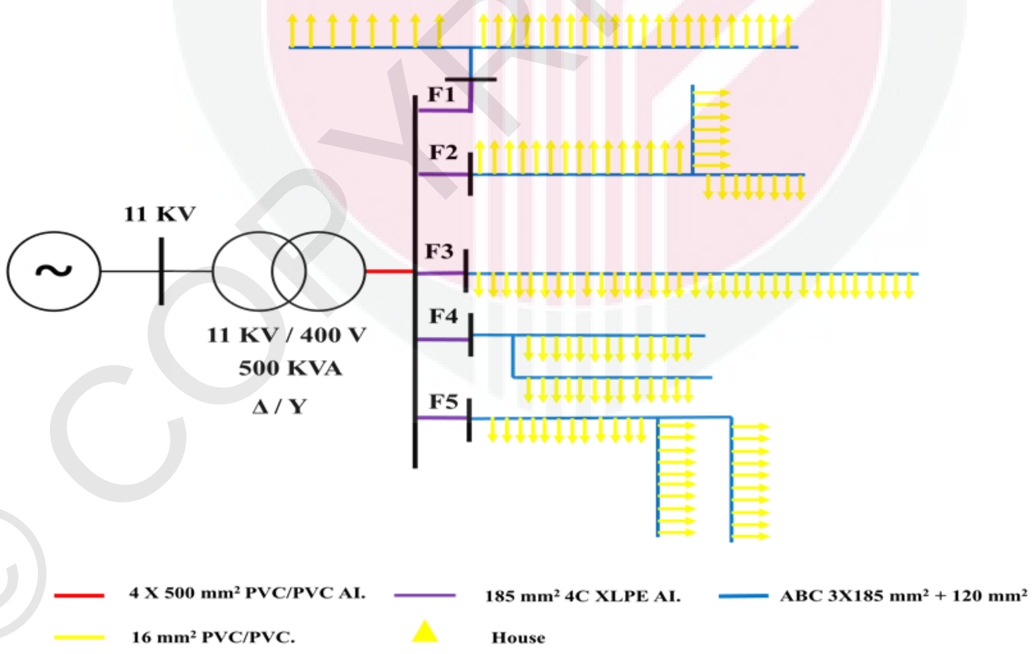

Figure 3.12 : Low Voltage Distribution Network of Taman Impian Putra
(Tie & Gan, 2013)

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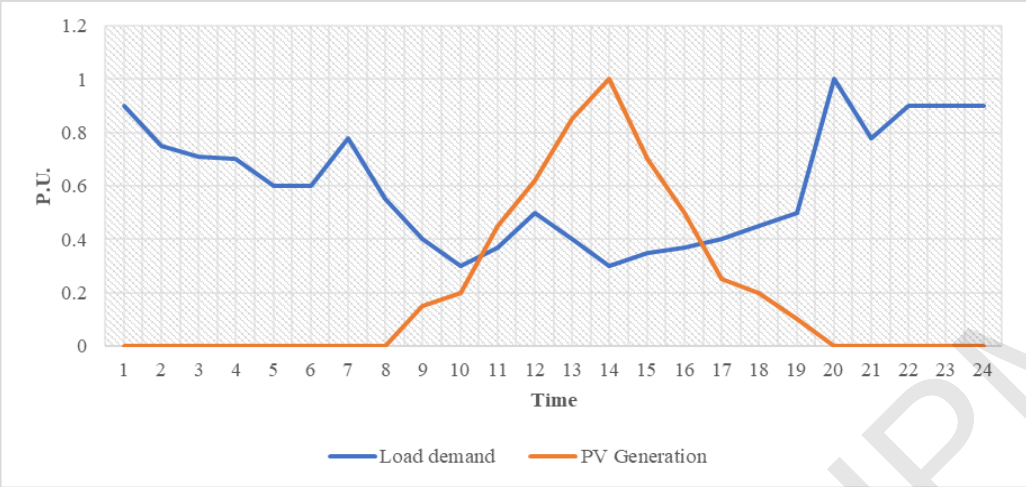

Figure 3.13 : Load Demand and PV Generation Profile

3.5 Summary

This chapter presented an innovative approach to reactive power control, addressing voltage rise challenges in distribution networks with high PV penetration. By continuously updating reactive power reference based on real-time voltage and active power data, the proposed technique offers a balanced solution for voltage regulation and reactive power support. The chapter introduces a computational framework incorporating Volt-Var and Watt-Var methods, dynamically adjusting reactive power to changing system conditions. Validation using small-scale and real-world networks demonstrates the effectiveness of the approach in mitigating voltage rise while minimizing losses. Additionally, the role of smart inverters in PV systems is discussed, highlighting their contribution to voltage control and reactive power management.

Nevertheless, this chapter presented a small-scale distribution network illustrates voltage rise during high PV generation and evaluates existing and proposed control techniques. Additionally, a Malaysian network offers insights into load demand and PV generation profiles, facilitating testing of the proposed control technique's efficacy in mitigating voltage rise. These networks serve as valuable tools for assessing the proposed methodology and its application in real-world scenarios.

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CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results of the evaluation and validation of the proposed reactive power control. The small distribution network presented in the previous chapter was simulated using MATLAB Simulink. The simulated distribution network was subjected to the high level of penetration. In the case of high PV penetration, the load was set to consume 0% and 100% in two different load demand scenarios. Additionally, different reactive power controls, including Q(V), fixed Power Factor (PF), and maintained Power factor as a function (PF(P)), were connected to the network alongside the proposed technique control. The results of the proposed reactive power control were compared to existing reactive power control methods to validate the effectiveness of the proposed technique.

Furthermore, this chapter investigates the impact of different levels of PV penetration on the voltage of the Malaysian low voltage distribution network presented in the previous chapter. Therefore, the Malaysian low voltage distribution network with various levels of penetration was simulated using MATLAB Simulink and OpenDSS. Finally, the effectiveness of the proposed reactive power control in mitigating voltage rise on the Malaysian network was evaluated. This was achieved by applying the proposed reactive power technique to mitigate voltage rise and monitoring the voltage at random points of common coupling for 24 hours at different penetration levels.

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4.2 Small Low Voltage Distribution Network

This section presents the evaluation of the proposed reactive power control to mitigate voltage rise on a small network consisting of 7 buses, that been demonstrated in the previous chapter in section (3.3.1) and depicted in Figure 3.9. The network underwent a voltage sensitivity analysis for active and reactive power, and the results are illustrated and described in Figure 3.11. In summary, the results indicate that the network's voltage sensitivity to active and reactive power increases as the distance to the distribution transformer increases. The proposed network was evaluated under two scenarios as follows:

4.2.1 No Load Scenario

This section presents a scenario involving a small 7 buses network described in the previous chapter in section (3.3.1) and depicted in Figure 3.9, which is penetrated by PV distributed generators. Figure 4.1 displays the amount of PV active power generation, revealing an increase as the distance to the distributed transformer decrease. Importantly, in this scenario, the load consumes 0% of the PV active power generation. Consequently, the risk of voltage rise under the given circumstances is very high. The chosen amount of PV generation was specifically selected to highlight the weaknesses of existing reactive power control methods and demonstrate the effectiveness of the adaptive reactive power control. This level of PV generation was deliberately set to create conditions where the limitations of current methods, which is the failure to mitigate the voltage rise, would become evident. By

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selecting this specific generation level, it becomes easier to observe how the adaptive reactive power control method addresses these challenges, ensuring better voltage regulation. Figure 4.2 illustrates the voltage at the points of common coupling without any reactive power control. The Figure indicates that the voltage on buses 4-7 exceeds the allowed limit of 0.95 to 1.05 per unit (p.u.). This phenomenon occurs as a result of a high cumulative PV generation and minimal load consumption. Voltage rises are observed on buses 4-7, even though the highest PV generation occurs on buses 1-3, primarily due to the heightened voltage sensitivity of buses 4-7 to active power. Then, the proposed adaptive reactive power control and the existing reactive power control strategies were implemented on the mentioned network to assess their effectiveness in mitigating the voltage rise under the same conditions.

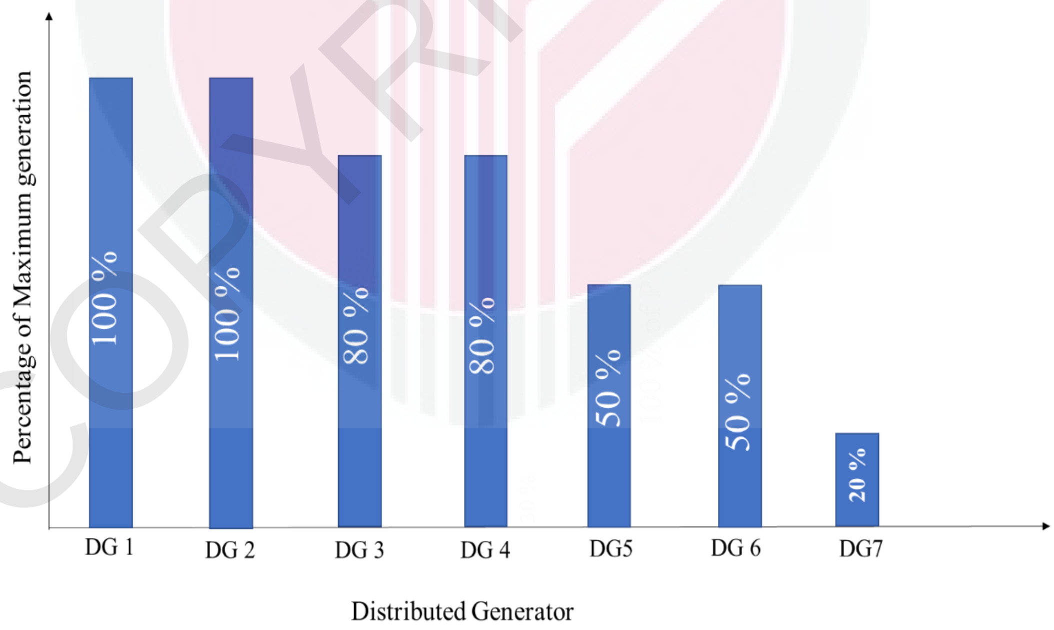

Figure 4.1 : Active Power Output of PVs

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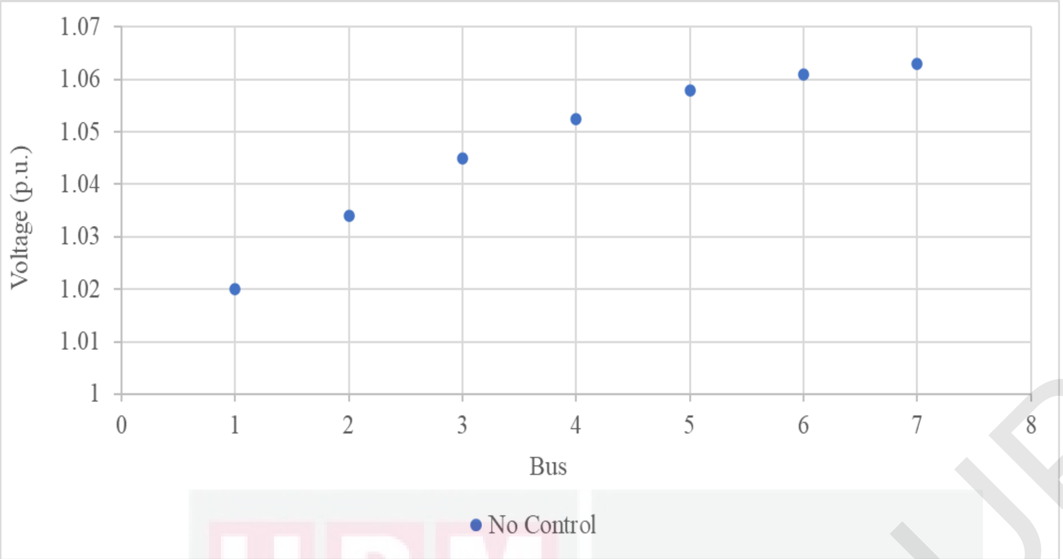

Figure 4.2 : The Voltage on the Buses of the Small Test Distribution Network under the No-Load Scenario, with No Reactive Power Control Applied

4.2.1.1 Applying Q (V) Reactive Power Control

The Q(V) reactive power control technique was implemented in the specified network and conditions. This approach relies on the network's voltage rather than the active power generation from PV sources. As illustrated in Figure 4.3, the technique absorbs a considerable amount of reactive power on DGs 4-7 due to the elevated high network voltage on those buses, due to its high sensitivity to active power. However, it absorbs minimal reactive power on DG1 and DG2, despite their high active power generation. This results in a voltage rise event, but these buses exhibit low voltage sensitivity to active power. Unfortunately, this technique fails to maintain voltage within acceptable limits, as demonstrated in Figure 4.4, where the voltage exceeds the specified limits on buses 6 and 7.

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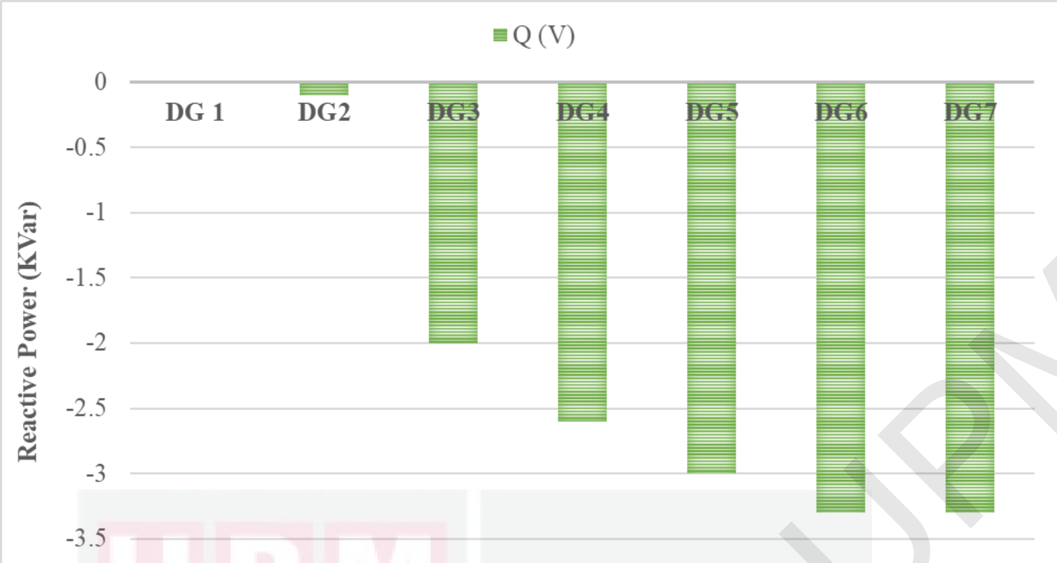

Figure 4.3 : Reactive Power Absorption by Smart Inverter with Q (V) Reactive Power Control of PVs on the Small Test Distribution Network under No-Load Scenario

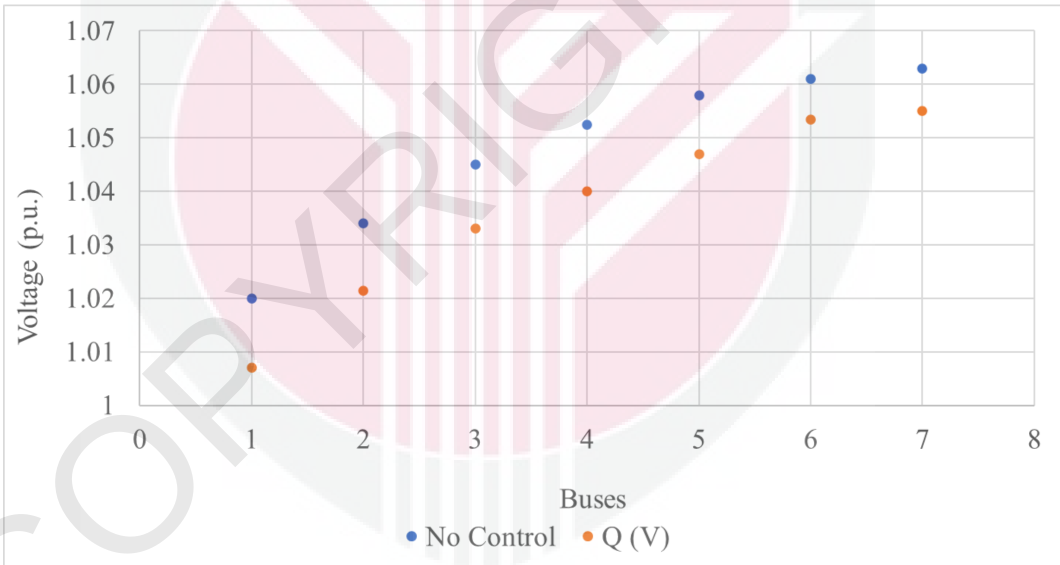

Figure 4.4 : The Voltage on the Buses of the Small Test Distribution Network under the No-Load Scenario, with No Reactive Power Control Applied and Q (V) Reactive Power Control Applied

4.2.1.2 Applying Fixed PF Reactive Power Control

The Fixed Power Factor (PF) reactive power control technique was implemented to mitigate voltage rise on the specified network under specific

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conditions. Figure 4.5 presents the reactive power absorption under these circumstances. The primary objective of this technique is to maintain a fixed power factor in proportion to the active power injection from the photovoltaic (PV) sources. It is observed that the fixed PF control absorbs a significant amount of reactive power from DGs 1-4 due to their high active power generation. Conversely, it absorbs a smaller amount of reactive power from the remaining DGs. The technique is largely successful in maintaining the voltage within acceptable limits, as depicted in Figure 4.6. All voltages are within acceptable limits, except for bus 7, which reaches the maximum acceptable limit of 1.05 per unit (p.u.). This is because the fixed PF control absorbs a minimal amount of reactive power from buses 6 and 7, primarily because of the low PV generation, despite the high voltages on this bus.

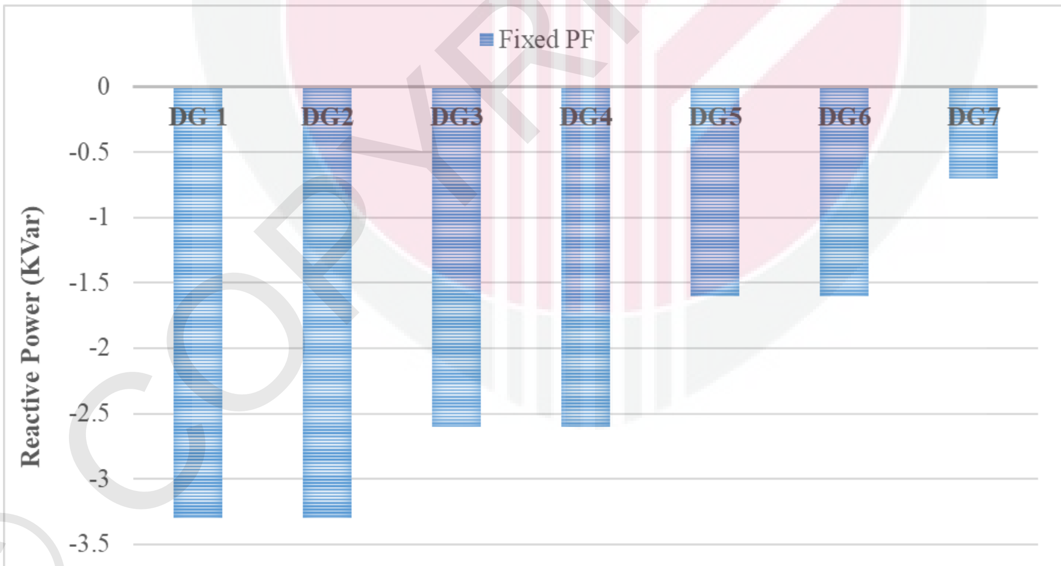

Figure 4.5 : Reactive Power Absorption by Smart Inverter with Fixed PF Reactive Power Control of PVs on the Small Test Distribution Network under No-Load Scenario

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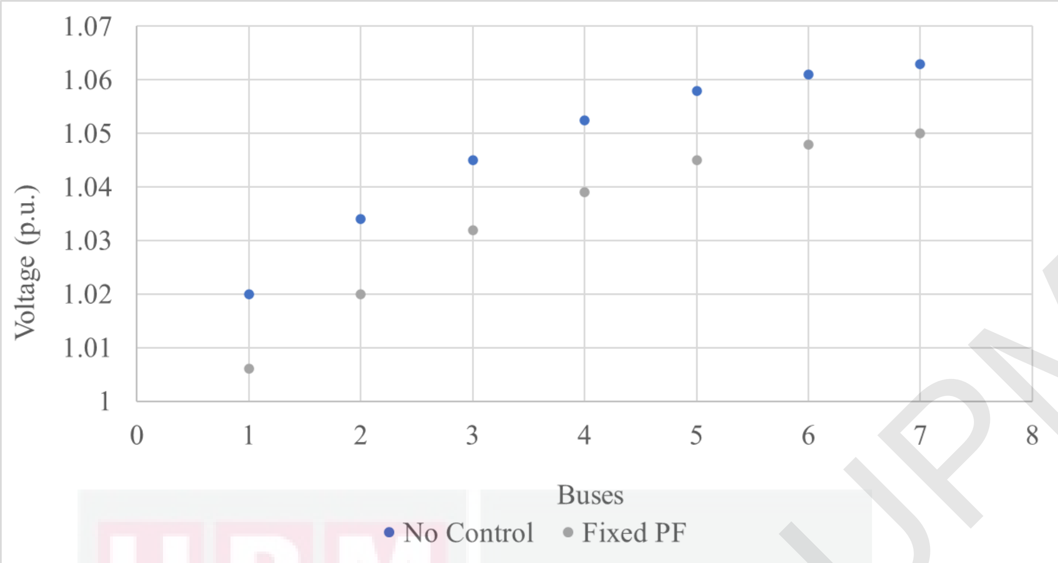

Figure 4.6 : The Voltage on the Buses of the Small Test Distribution Network under the No-Load Scenario, with No Reactive Power Control Applied and Fixed PF Reactive Power Control Applied

4.2.1.3 Applying PF (P) Reactive Power Control

The PF (P) technique, which is proportional to PV active power injection and maintains the power factor, was employed. The power factor increases as the PV active power injection decreases. Reactive power control absorbs a high amount of reactive power into DGs 1-4, while almost no reactive power is absorbed into the remaining DGs, as illustrated in Figure 4.7. However, despite these efforts, this technique fails to keep the voltages within the acceptable limit, because this technique absorbs no reactive power on DG 7 and a very low amount on DGs 5 and 6, as depicted in Figure 4.8. The Figure shows that voltages exceed the allowed limit on buses 6 and 7.

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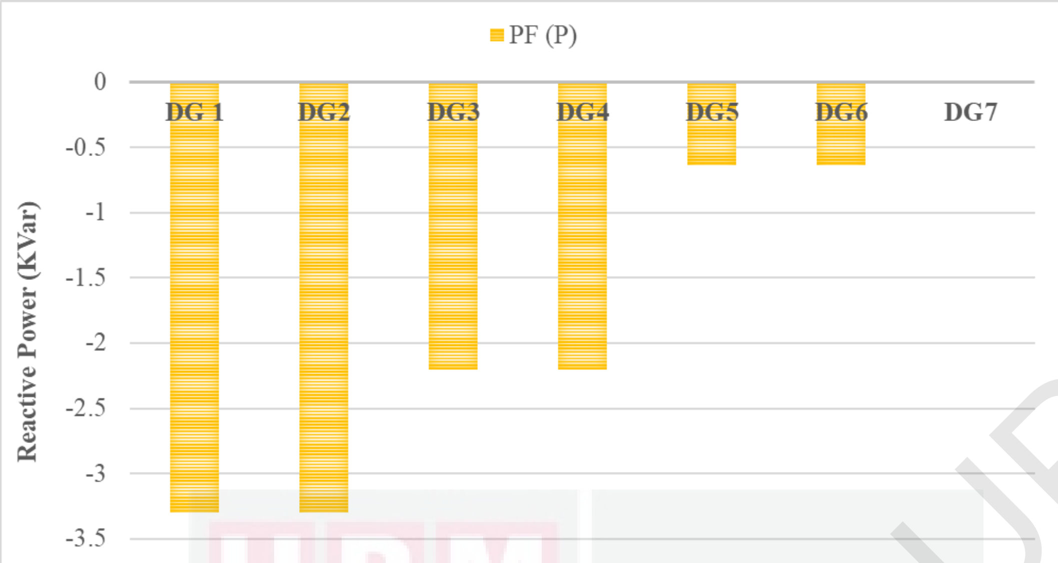

Figure 4.7 : Reactive Power Absorption by Smart Inverter with PF (P) Reactive Power Control of PVs on the Small Test Distribution Network under No-Load Scenario

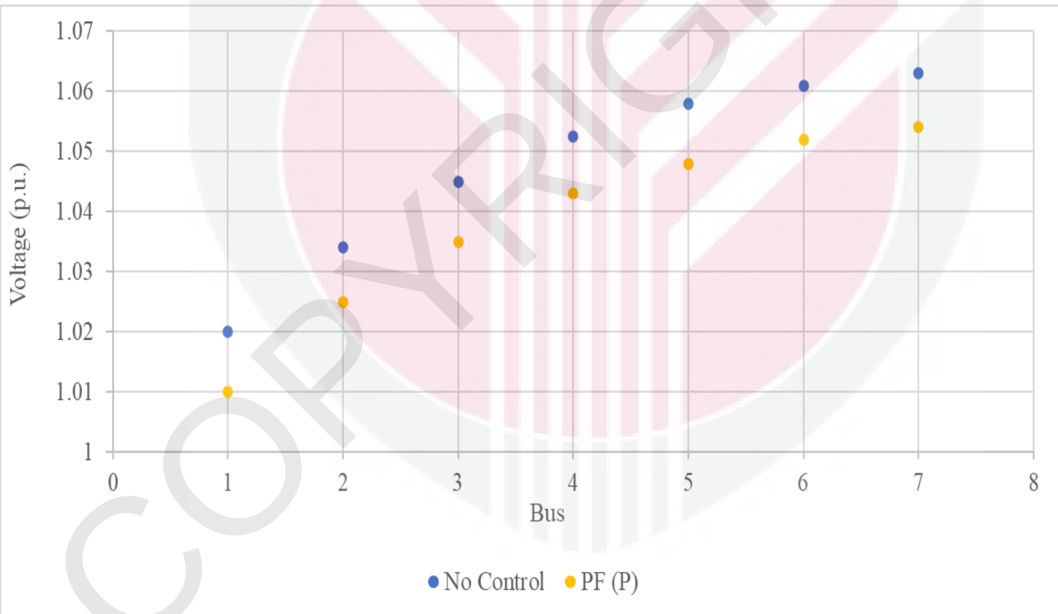

Figure 4.8 : The Voltage on the Buses of the Small Test Distribution Network under the No-Load Scenario, with No Reactive Power Control Applied and PF (P) Reactive Power Control Applied

4.2.1.4 Applying Adaptive Reactive Power Control

The adaptive reactive power control technique, as described in the previous chapter, relies on factors which are the network voltage, PV active power injection, and weight. The weight is based on the network voltage. For the given circumstances, the network's voltage increases as the distance from the transformer increases, while the PV active power increases as the distance decreases. In accordance with this approach, the adaptive reactive power control technique absorbs a moderate level of reactive power into DGs 1-3 due to their high PV injection, while the remaining DGs witness a higher level of reactive power absorption due to the elevated voltage levels because of the high voltage sensitivity. This is illustrated in Figure 4.9. Importantly, the adaptive reactive power technique successfully keeps the voltages within acceptable limits, as demonstrated in Figure 4.10. The proposed reactive power control succeeds in keeping the voltage within acceptable limits by absorbing the right amount of reactive power at the right location.

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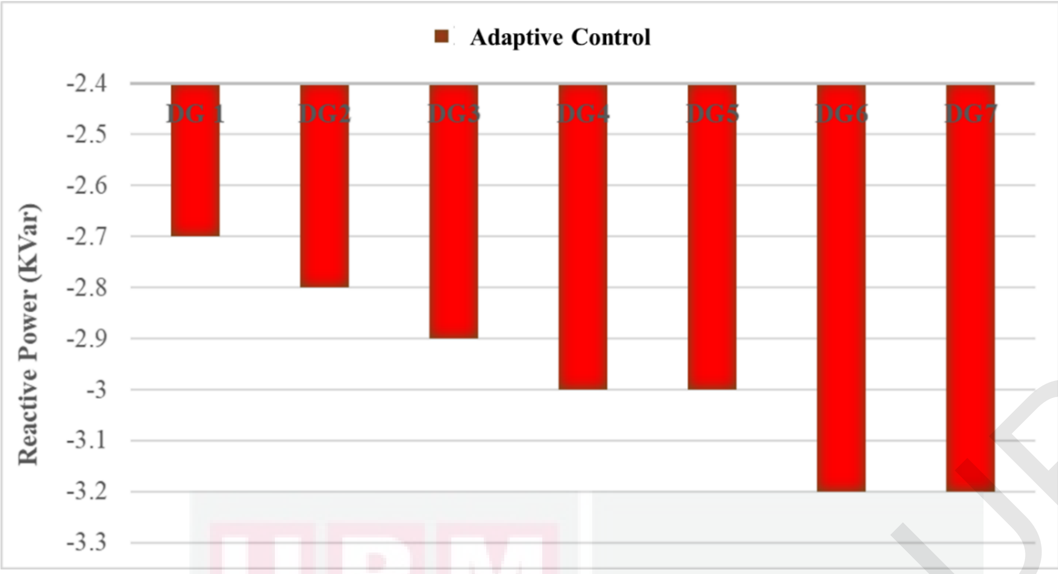

Figure 4.9 : Reactive Power Absorption by Smart Inverter with Adaptive Reactive Power Control of PVs on the Small Test Distribution Network under No-Load Scenario

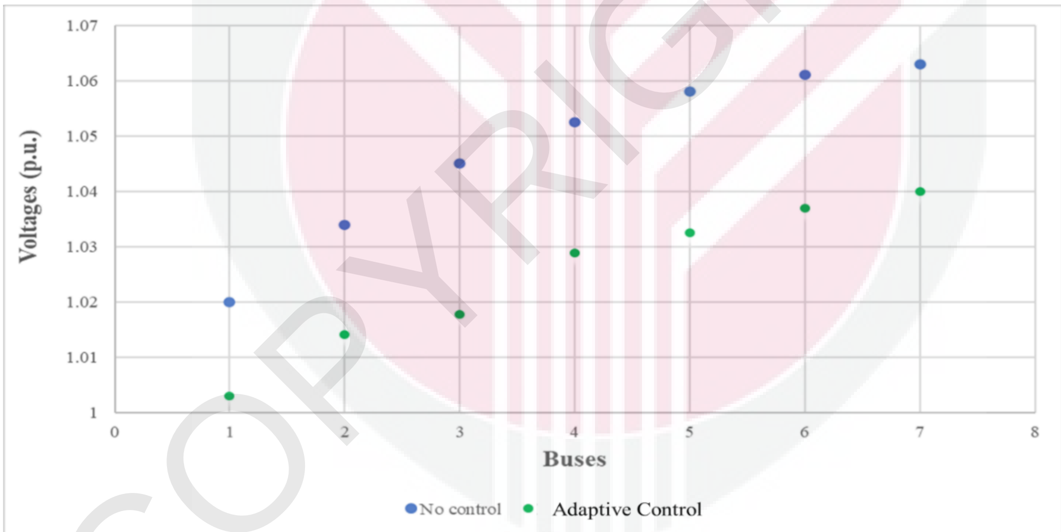

Figure 4.10 : The Voltage on the Buses of the Small Test Distribution Network under The No-Load Scenario, with No Reactive Power Control Applied and PF (P) Reactive Power Control Applied

4.2.1.5 Existing Reactive Power Controls on Small Test Distribution Network under No Load Scenario

Figure 4.12 provides a comprehensive visualization of voltage levels across the network under varying reactive power control scenarios, shedding light on the efficacy of different control techniques in maintaining voltages within acceptable limits. In the absence of any reactive power control measures, the depicted voltages exceed permissible thresholds, underscoring the critical role of reactive power management in grid stability. The subsequent implementation of existing reactive power controls, including the Q(V) technique, reveals limitations in voltage regulation, as these methods struggle to keep voltages within prescribed bounds given the prevailing conditions.

Notably, the Watt-Var techniques, specifically the fixed power factor, emerge as more effective alternatives to the Q(V) approach in this scenario. Their ability to modulate reactive power absorption in response to active power injection demonstrates superior performance in maintaining voltage stability. However, it is the adaptive reactive power control technique that stands out as the most potent solution for voltage regulation. By leveraging a dynamic framework that integrates both active power injection and network voltages, this technique achieves unparalleled success in curbing voltage rise and ensuring compliance with regulatory standards.

Figure 4.11 complements these findings by elucidating the levels of reactive power absorption associated with each control technique. The data reveal a clear correlation between reactive power absorption and active power injection for the fixed power factor and PF(P) methods, highlighting their suitability for the given conditions. Conversely, the Q(V) technique's dependence solely on network voltage and sensitivity proves inadequate for mitigating voltage rise, further emphasizing the need for a more holistic approach.

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In contrast, the adaptive reactive power control technique exhibits a nuanced understanding of system dynamics, effectively balancing reactive power absorption across PV units based on both active power generation and network voltages. This targeted approach ensures optimal reactive power absorption at critical points within the distribution network, thereby mitigating voltage rise similar scenarios.

Overall, the comparative analysis presented in the figures underscores the superiority of the adaptive reactive power control technique in mitigating voltage rise across low-voltage distribution networks with high PV penetration. By considering both active power injection and network voltages, this technique offers a robust and effective solution for voltage regulation under diverse operating conditions. Thus, it emerges as the preferred approach for mitigating voltage rise and ensuring grid stability across all scenarios, reaffirming its status as the most effective reactive power control strategy.

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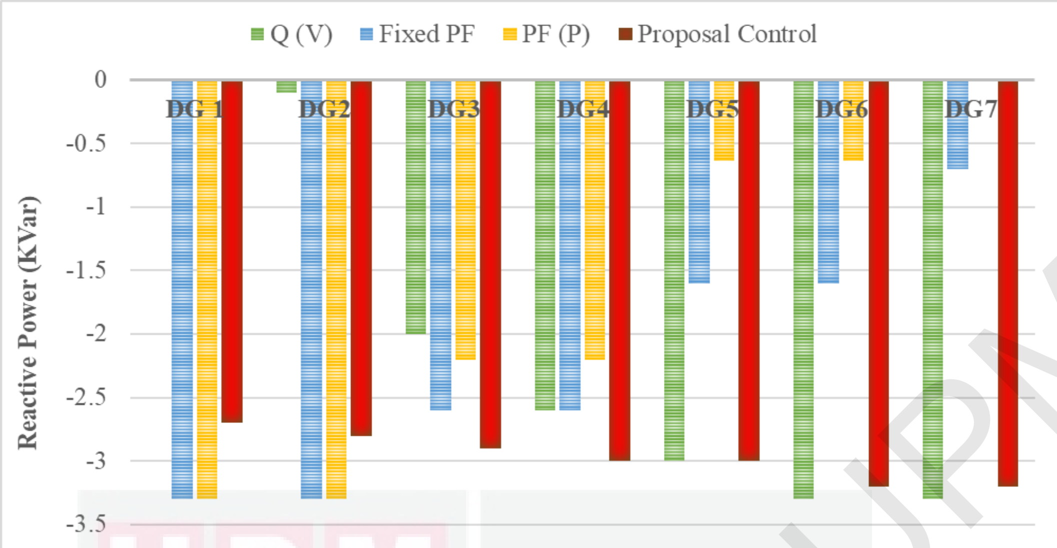

Figure 4.11 : Reactive Power Absorption by Smart Inverter with Different Reactive Power Controls of PVs on the Small Test Distribution Network under No-Load Scenario

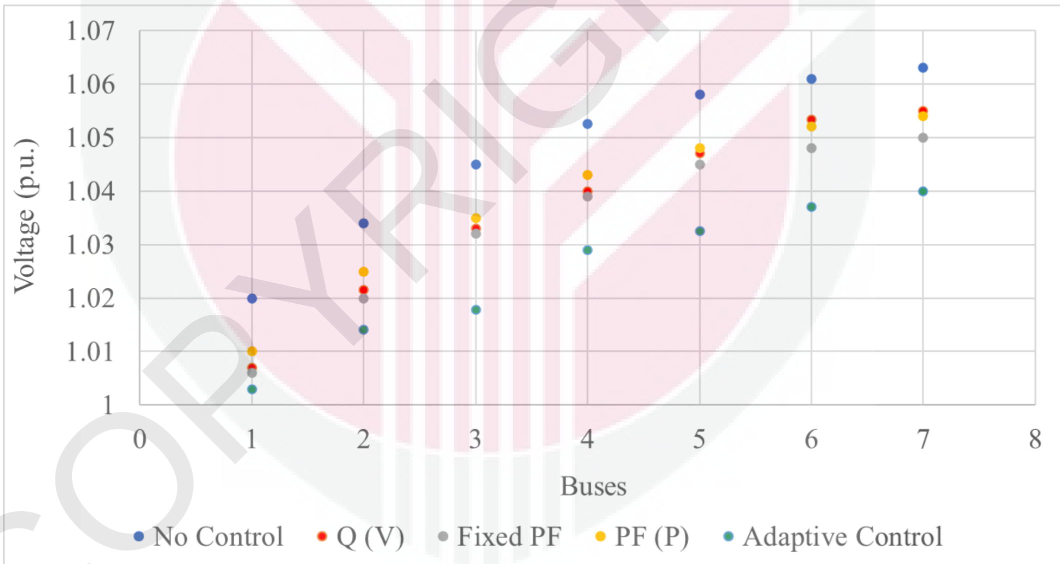

Figure 4.12 : The Voltage on the Buses of the Small Test Distribution Network under the No-Load Scenario, with No Reactive Power Control Applied and with Different Reactive Power Control Applied

4.2.2 Full Load Scenario

In this scenario, the existing network is being impacted by the integration of PV distributed generators. Figure 3.10 in the previous chapter displays the

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amount of PV generation, revealing an increase as the distance from the distributed transformer increases. The load consumes 100% of the power generated by the PVs. Since the load utilizes all the power generated by the PVs, the risk of voltage rise is very low. Figure 4.13 depicts the voltage levels at the points of common coupling for the given scenario without any reactive power control. The Figure indicates that all the voltage values remain within acceptable limits and are in a satisfactory range. Therefore, as shown in Figure 4.13, the voltage risk is negligible.

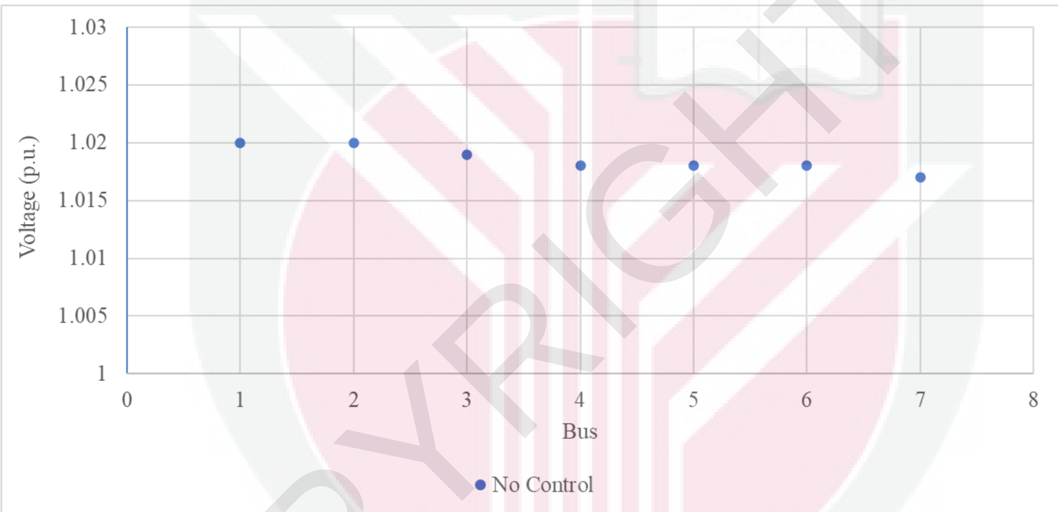

Figure 4.13 : The Voltage on the Buses of the Small Test Distribution Network under the Full-Load Scenario, with No Reactive Power Control Applied

4.2.2.1 Applying Q (V) Reactive Power Control

In this section, the application of the Q (V) reactive power control technique on the given network under the specified circumstances is demonstrated. The reactive power absorption resulting from this technique is depicted in Figure 4.14. As explained in the previous chapter, Q (V) depends on the voltage at the points of common coupling, and these voltages are within acceptable

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levels even without any reactive power control. Consequently, the reactive power absorption via this technique, under the given circumstances, is minimal. This indicates that Q (V) reduces losses of utilizing reactive power control when the risk of voltage rise is low. Figure 4.15 illustrates that the voltage under this technique remains close to the voltage without reactive power control.

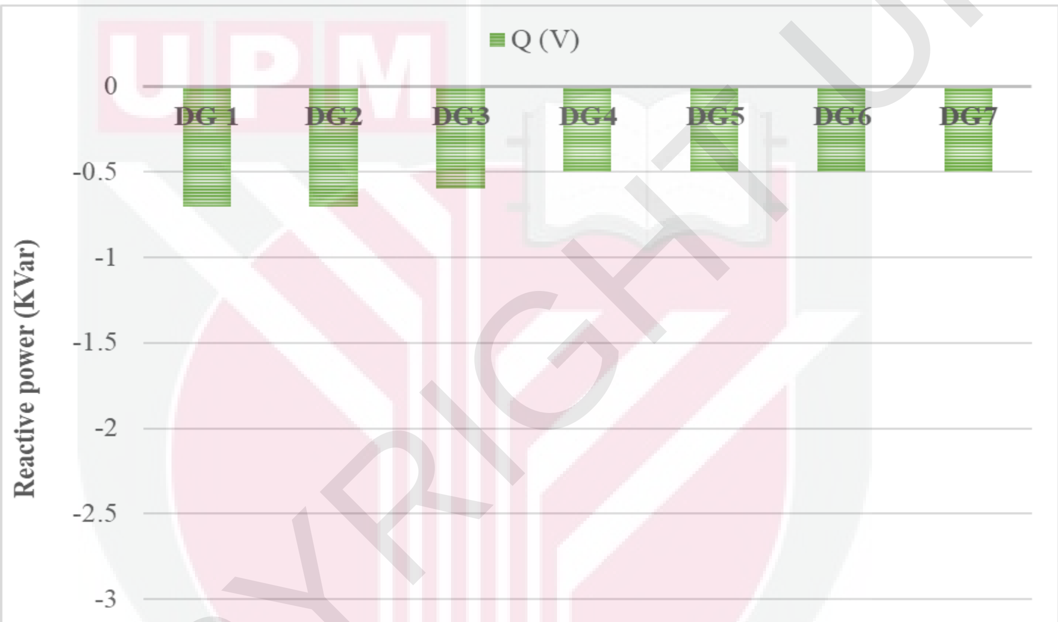

Figure 4.14 : Reactive Power Absorption by Smart Inverter with Q (V) Reactive Power Control of PVs on the Small Test Distribution Network Under Full-Load Scenario

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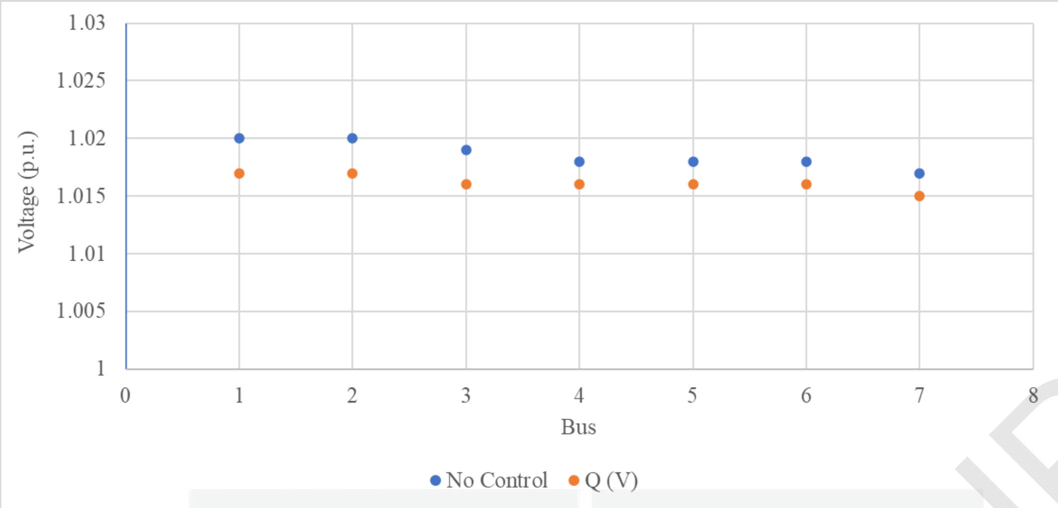

Figure 4.15 : The Voltage on the Buses of the Small Test Distribution Network Under the Full-Load Scenario, with No Reactive Power Control Applied and Q (V) Reactive Power Control Applied

4.2.2.2 Applying Fixed PF Reactive Power Control

The Fixed PF technique, as explained in the previous chapter, relies on maintaining a constant power factor. Consequently, the absorption of reactive power is proportional to the injection of active power. For the given circumstances, the Fixed PF technique absorbs reactive power, as shown in Figure 4.16. The Figure reveals that the technique absorbs a high amount of reactive power, particularly from DGs, as these DGs inject a substantial amount of active power. Since the risk of voltage rise is very low due to the load consuming 100% of the power generated by DGs, these absorptions result in significant losses that are unnecessary. This highlights how the technique's disregard for load variance leads to increase the unnecessary losses. Furthermore, the Figure demonstrates that there is a high absorption of reactive power, even though the DG1 generation is only 0.2 p.u. Thus, the risk of voltage rise remains very low, regardless of whether the load consumes

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this PV generation or not. In Figure 4.17, the voltages under the Fixed PF technique and without reactive power control are compared, revealing that this technique decreases the voltage while still maintaining it within acceptable limits.

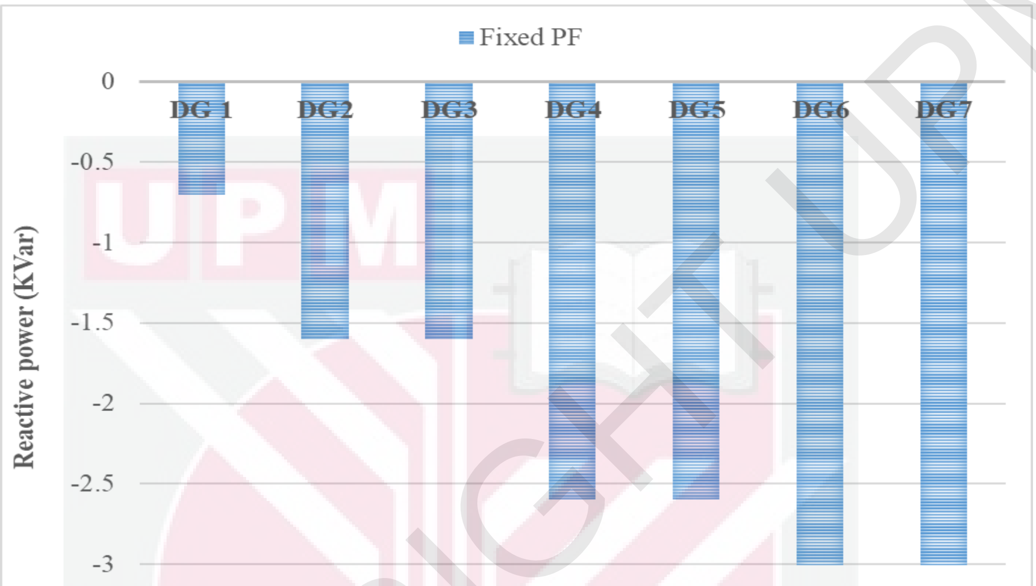

Figure 4.16 : Reactive Power Absorption by Smart Inverter with Fixed PF Reactive Power Control of PVs on the Small Test Distribution Network under Full-Load Scenario

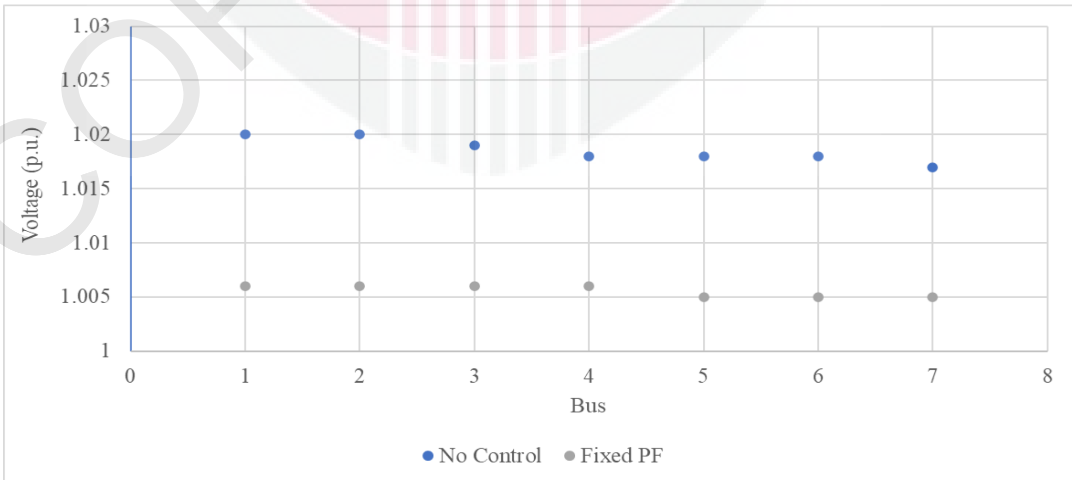

Figure 4.17 : The Voltage on the Buses of the Small Test Distribution Network under the Full-Load Scenario, with No Reactive Power Control Applied and Fixed PF Reactive Power Control Applied

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4.2.2.3 Applying PF (P) Reactive Power Control

The PF (P) reactive power control technique, which was described in the previous chapter, aims to overcome the limitations of the fixed PF technique. This technique maintains a PF reference, ensuring that the DG1 does not absorb any reactive power, as depicted in Figure 4.18. This is because PV1 generates a very low amount of active power, and the technique sets the PF to 1. However, the technique still disregards load variation and relies entirely on PV active power generation. Consequently, DG 4-7 continues to absorb a high amount of reactive power, resulting in unnecessary losses. Figure 4.19 illustrates the voltages at the points of common coupling, revealing that the technique reduces the voltages, although the decrease is less significant compared to the fixed PF technique.

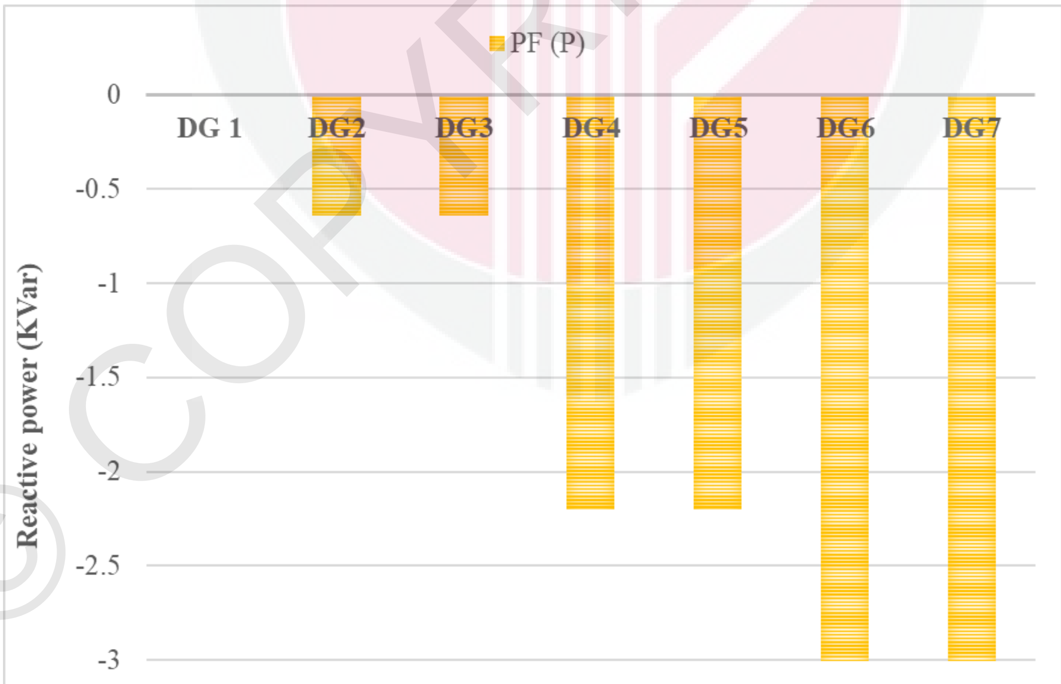

Figure 4.18 : Reactive Power Absorption by Smart Inverter with PF (P) Reactive Power Control of PVs on the Small Test Distribution Network under Full-Load Scenario

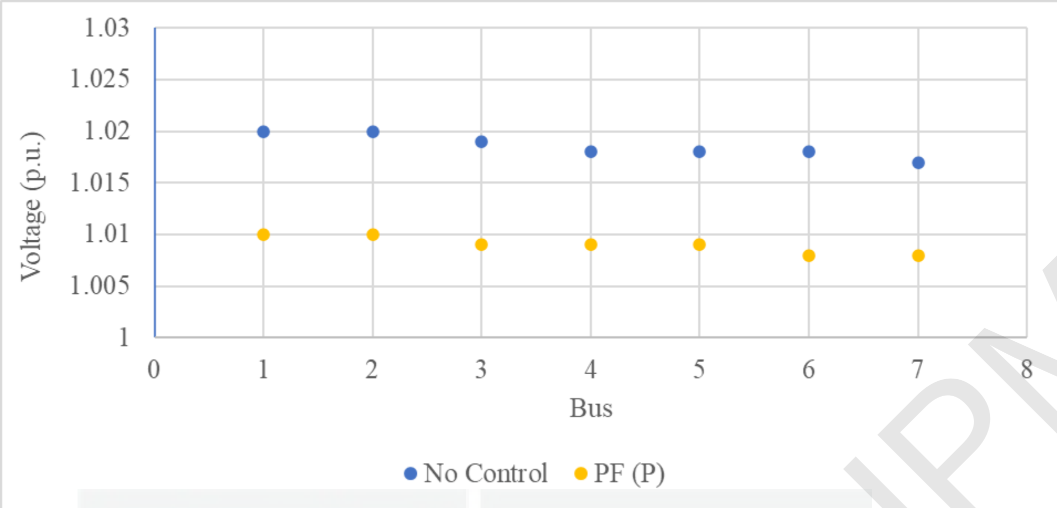

Figure 4.19 : The Voltage on the Buses of the Small Test Distribution Network under the Full-Load Scenario, with No Reactive Power Control Applied and PF (P) Reactive Power Control Applied

4.2.2.4 Applying Adaptive Reactive Power Control

The proposed adaptive reactive power control technique that demonstrated in the previous chapter has been implemented in the network under the specified scenario, which is characterized by a low risk of voltage rise. Figure 4.20 displays the reactive power absorption of the adaptive reactive power control technique. The Figure illustrates that adaptive control absorbs a moderate amount of reactive power, lower than both PF (P) and Fixed PF techniques. Furthermore, it is significantly lower than the reactive power absorbed by the Fixed PF technique. therefore, the unnecessary loss of the adaptive reactive power control technique is very low.

Figure 4.21 presents the voltages at the points of common coupling with and without reactive power control in the given network under the specified circumstances. The Figure demonstrates that the adaptive control successfully maintains the network voltages within the desired range of 0.99

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to 1.01 per unit (p.u.), which is considered a strength point for the proposed control to keep the voltage within the desired range by less reactive power absorption than the reactive power control that solely depending on the active power injection.

Figure 4.20 : Reactive Power Absorption by Smart Inverter with Adaptive Reactive Power Control of PVs on the Small Test Distribution Network under Full-Load Scenario

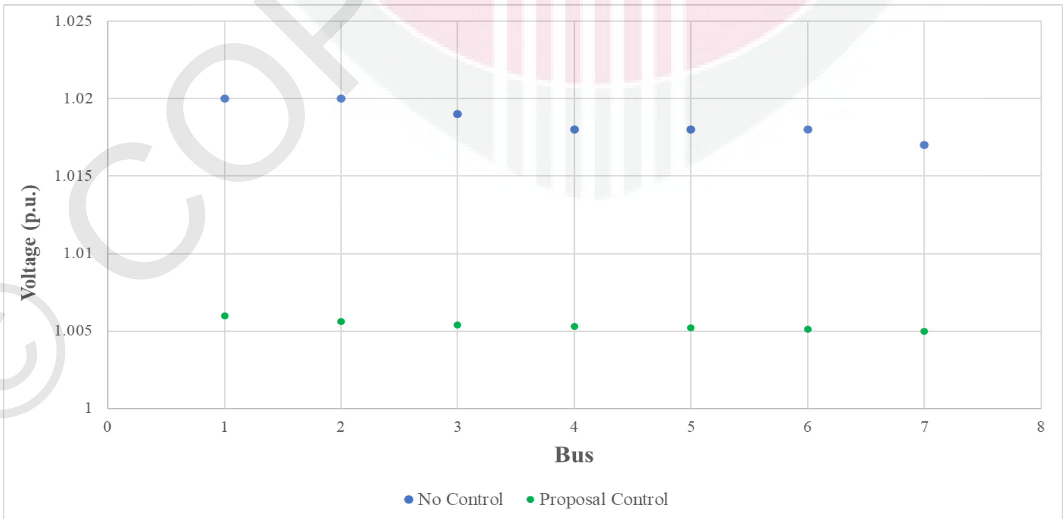

Figure 4.21 : The Voltage on the Buses of the Small Test Distribution Network under the Full-Load Scenario, with No Reactive Power Control Applied and Adaptive Reactive Power Control Applied

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4.2.2.5 Existing Reactive Power Control on Small Test Distribution Control under Full Load scenario

Figure 4.23 serves as a comprehensive illustration of voltage dynamics across various reactive power control techniques, providing valuable insights into their respective impacts on grid stability. In scenarios where no reactive power control is implemented, voltage levels remain well within permissible limits, attributed to the consumption of all active power generated by the PV system. This effectively mitigates the risk of voltage rise, underscoring the role of load consumption in maintaining grid stability.

The Q(V) control technique, while demonstrating minimal voltage reduction, fails to offer substantial improvements in voltage regulation. Similarly, the adaptive control technique, alongside the fixed power factor (PF) and PF(P) techniques, achieves modest voltage reduction within the range of 1.01-1. Despite this reduction, the effectiveness of these methods in addressing voltage rise remains limited.

Figure 4.22 delves specifically into the reactive power injection profiles of different techniques under the specified circumstances, reaffirming the findings from the previous analysis. The Q(V) technique's notable absorption of reactive power can be attributed to its reliance on voltage interaction within an acceptable range. Conversely, the fixed PF and PF(P) techniques exhibit significant reactive power absorption in distributed generation units (DGs) 7-4, primarily due to their high injection of active power, leading to unwarranted losses.

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In contrast, the adaptive control technique strikes a balance by absorbing a higher amount of reactive power compared to Q(V) but significantly less than PF(P) and fixed PF methods. This nuanced approach results in lower unnecessary losses compared to the PF(P) and fixed PF techniques, thereby enhancing overall grid efficiency.

Through the juxtaposition of Figure 4.23 and Figure 4.22, it becomes evident that while certain reactive power control techniques offer marginal improvements in voltage regulation, they may inadvertently contribute to unnecessary losses. In contrast, the proposed technique stands out for its ability to optimize reactive power absorption, striking a balance between voltage regulation and operational efficiency.

Thus, the comparative analysis presented in these figures underscores the efficacy of the adaptive reactive power control technique in enhancing grid stability while minimizing losses that occur due to unnecessary absorption of reactive power, positioning it as a preferred solution for voltage regulation in distributed generation systems.

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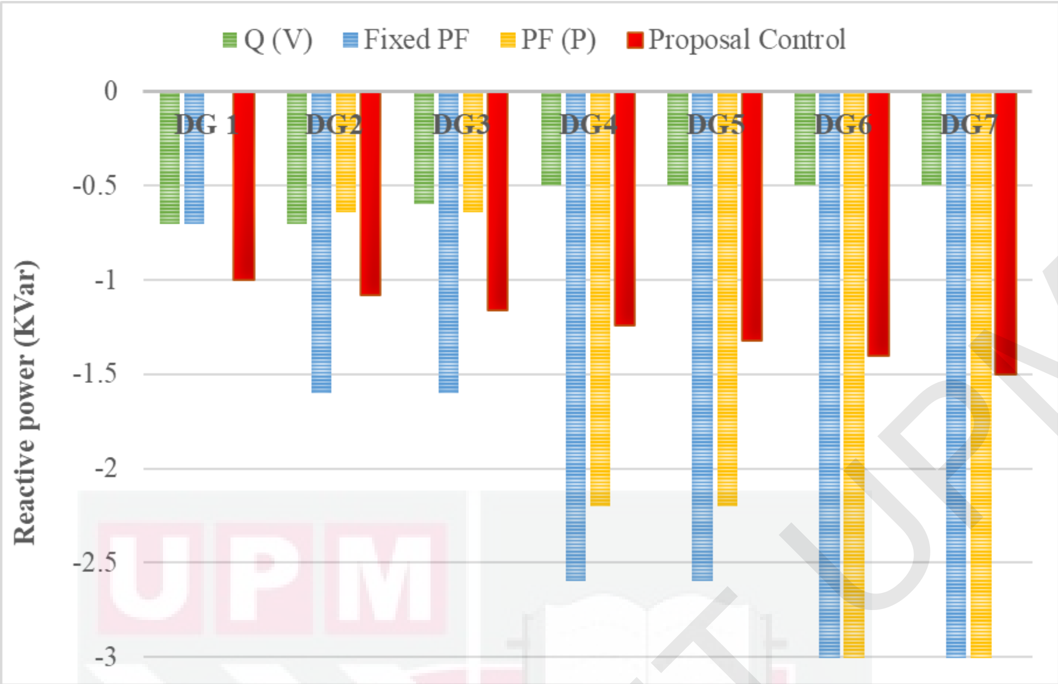

Figure 4.22 : Reactive Power Absorption by Smart Inverter with Different Reactive Power Controls of PVs on the Small Test Distribution Network under Full-Load Scenario

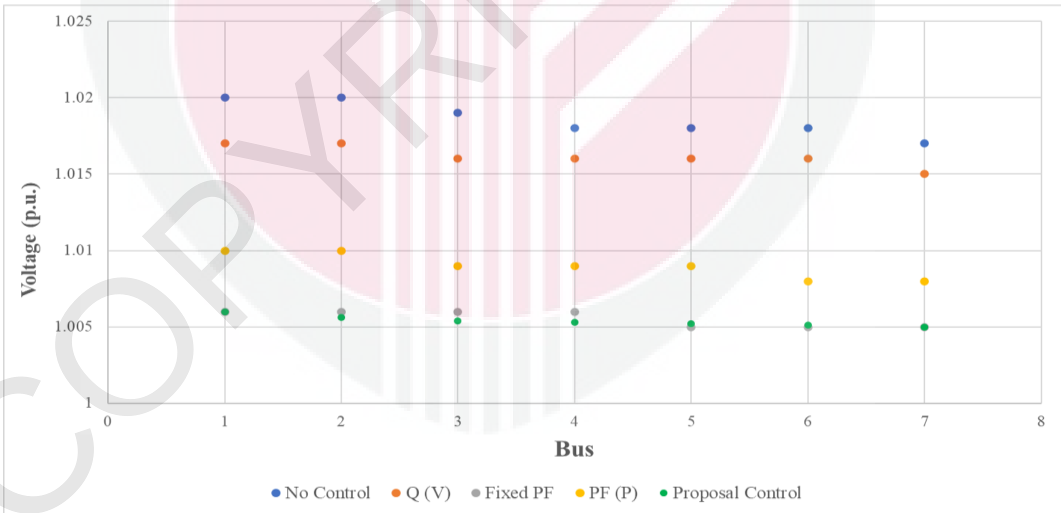

Figure 4.23 : The Voltage on the Buses of the Small Test Distribution Network under the Full-Load Scenario, with No Reactive Power Control Applied and with Different Reactive Power Controls Applied

4.2.3 Discussion

The Q (V) technique, being based on network voltage, exhibits very low losses on the network, as demonstrated in the full load scenario characterized by low voltage rise risk. This technique absorbs minimal reactive power, resulting in low network losses, due to its reliance on network voltage. However, this dependence on network voltage has limitations in cases of high voltage rise risk, particularly when connected in locations with low voltage sensitivity to active power, as illustrated in the no load scenario. On the other hand, the fixed PF technique demonstrates acceptable voltage regulation and voltage rise mitigation in situations of high voltage rise risk because it depends on PV active power injection, as shown in the no load scenario. However, this technique has its own limitations. The key limitation is obvious in scenarios of low voltage rise risk and high PV generation; high network losses occur because of high reactive power absorption. This occurs due to the technique's complete disregard for the current voltage level on point of common coupling. The full load scenario addresses the limitation of the fixed PF. The PF(P) technique, which stabilizes reactive power absorption during periods of low active power generation, addresses the second major limitation of fixed PF—excessive reactive power absorption despite low PV activity. However, it still retains the primary limitation associated with the fixed reactive power approach.

In contrast, the adaptive reactive power control relies on both the voltage at the point of the common coupling and the DG active power generation. It does not have a fixed output for a specific input. Instead, it continuously updates the

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reactive power reference until reaching a stable situation ($\Delta Q = 0$). The full load scenario, characterized by low voltage risk rise, demonstrates that adaptive control absorbs significantly less reactive power compared to PF (P) and Fixed PF, resulting in lower losses. The no load scenario showcases the second contribution of the adaptive control technique, which is its superior voltage regulation capability. By continuously updating the reactive power reference, the adaptive reactive power control technique ensures that PV systems, whether generating a high amount of active power in areas with low voltage sensitivity or experiencing high voltage due to their location in areas with high voltage sensitivity, effectively participate in mitigating voltage rise. As a result, adaptive control successfully maintains the network voltage within the acceptable limit, even when PVs generate high active power and there is no load demand.

4.3 Malaysian Low Voltage Distribution Network

This section focuses on assessing the impact of high PV penetration on the low distribution network in Malaysia, which was previously introduced in the chapter. The goal is to validate the effectiveness of the proposed reactive power control technique in mitigating voltage rise on the distribution network under various levels of PV penetration.

4.3.1 PV Penetration Effect

In order to investigate the impact of PV penetration on the Malaysian distribution network, the PV penetration level has been calculated using equation [4-1]. To establish a baseline, it is important to understand the voltage

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profile under normal conditions, with 0% PV penetration. Figure 4.24 illustrates the voltages at a random point (we chose the last customer of feeder 3) over a 24-hour period, considering the load demand as depicted in Figure (3.11) in the previous chapter. The Figure demonstrates a slight increase in voltage during the period from 9 AM to 5 PM, attributed to a decrease in load demand. In the remaining periods, the voltage experiences a minor decrease as the load demand reaches its maximum.

$$\text{PV Penetration} = \frac{\text{Maximum PV generation}}{\text{Maximum Load demand}} \times 100\% \qquad [4\text{-}1]$$

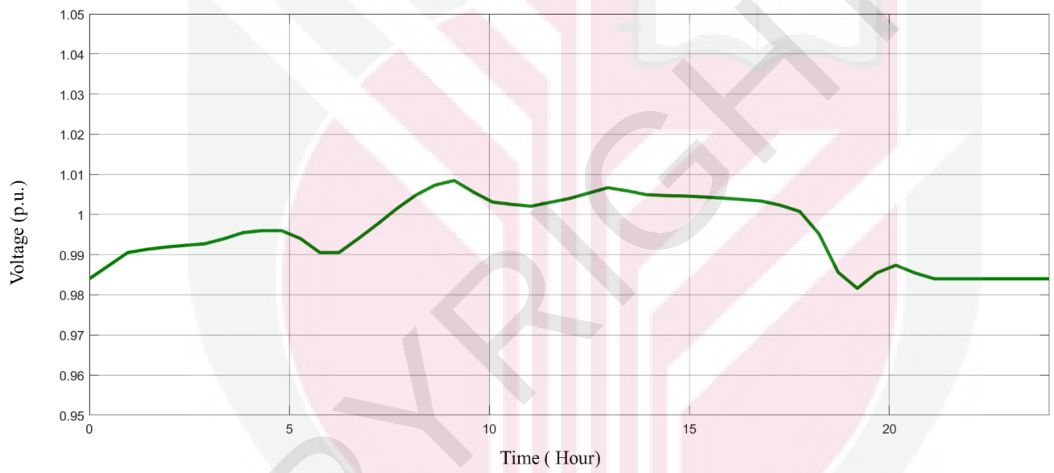

Figure 4.24 : The Voltage on the Last Customer of Feeder 3 For 24 Hours without PV Penetration

The Malaysian low voltage distribution network has been subjected to different levels of PV penetration (50%, 100%, 200%). The levels of PV penetration selected for this study—50%, 100%, and 200%—were strategically chosen to provide a clear and comprehensive analysis of the network's behavior under varying degrees of renewable integration. The 50% penetration level represents a significant yet manageable increase, allowing us to observe the initial effects of PV integration on voltage stability and grid dynamics. The

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100% level equates to full equivalent generation capacity of the network's base load, serving as a critical threshold to evaluate the network's capability to handle energy equivalent to its existing demand without reliance on traditional power sources. Lastly, the 200% penetration level was chosen to stress test the network under extreme conditions, where renewable generation far exceeds the demand, highlighting potential regulatory and technical challenges that could arise with high levels of PV generation. These distinct levels are not arbitrary but are intended to simulate realistic scenarios that could emerge as renewable penetration increases, providing valuable insights into both incremental and radical shifts in energy dynamics. Those penetration levels have been inserted into the network without any reactive power control. Figure 4.25 illustrates the voltage at the last customer of feeder 3 under these various penetration levels. The results indicate that when PV penetration exceeds 70%, the risk of voltage rise becomes very high. For a 50% PV penetration, there is a voltage rise during mid-day hours, but the voltage remains within the acceptable limit (1.05 p.u. (TNB, 2023)). However, with 100% and 200% PV penetration, a significant voltage rise occurs during mid-day, surpassing the allowed limit. This voltage rise is attributed to the increase in solar irradiance and the decrease in load demand as occupants are away from their homes, as shown in Figure 3.13 in the previous chapter. Hence, when PV penetration exceeds 70%, it becomes crucial to implement voltage rise mitigation techniques. Figure 4.26 displays the average voltage of the Malaysian low voltage distribution network for different penetration levels without any voltage rise mitigation techniques. The Figure confirms that when the PV penetration exceeds 50%, it becomes necessary to employ voltage rise

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mitigation techniques.

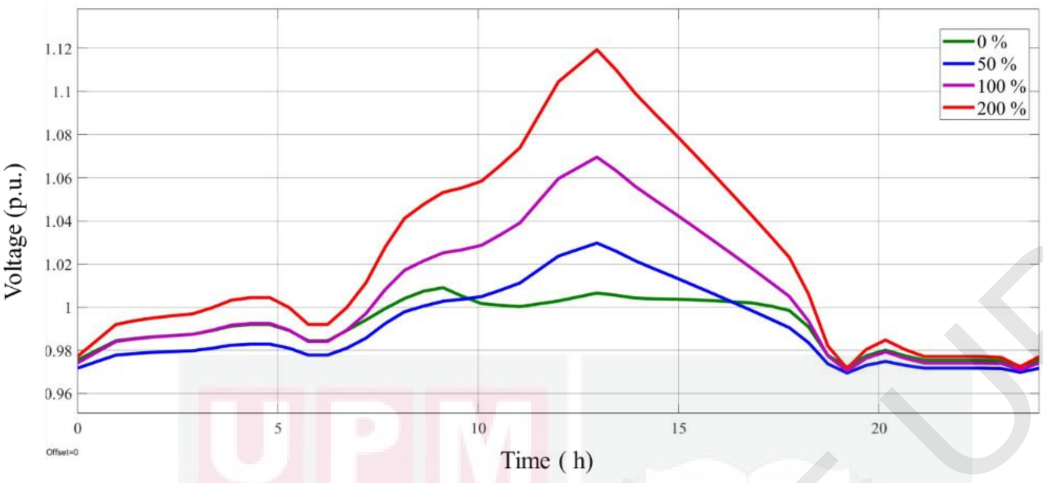

Figure 4.25 : The Voltage Graph on the Point of Common Coupling of the Last Customer on Feeder 3 For 24 Hours without Reactive Power Control for Different Levels of Penetration (0%, 50%, 100%, and 200%)

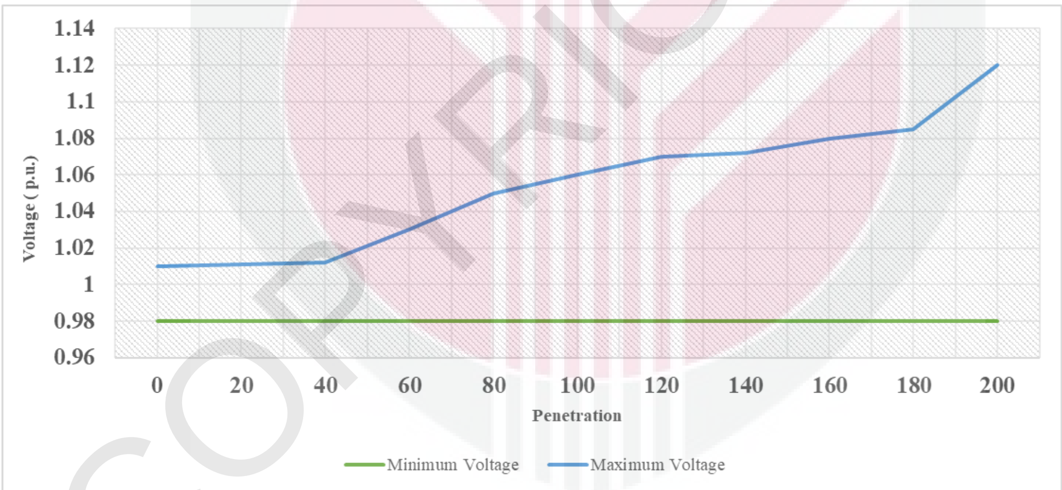

Figure 4.26 : Highest and Lowest Voltage of Distribution Network for Different Level of PV Penetration without Reactive Power Control

4.3.2 Adaptive Reactive Power Control to Mitigate the Voltage Rise

In this section, the adaptive reactive power control technique has been employed to validate its effectiveness in mitigating voltage rise on the

Malaysian low voltage distribution network under different levels of PV penetration (50%, 100%, and 200%). The validation takes into account the circumstances of load demand and sun irradiance, as depicted in Figure 3.12 in the previous chapter. For a 50% PV penetration, the voltage rise risk is very low. Consequently, the voltage exhibits a slight decrease, as shown in Figure 4.27, due to the low PV generation. The proposed reactive power control technique, which relies on voltage and PV generation, successfully mitigates the voltage rise in this scenario. As the PV penetration increases to 100%, the voltage rise risk becomes very high. Figure 4.28 demonstrates a voltage rise occurring during mid-day. However, the proposed reactive power control technique proves effective in mitigating this voltage rise, keeping the voltage within the acceptable limit. The same applies to a 200% PV penetration, as illustrated in Figure 4.29, where the adaptive reactive power control successfully maintains the voltage within the acceptable range. Consequently, it can be concluded that the proposed reactive power control technique ensures the voltage remains within acceptable limits for the entire distribution network, even with a PV penetration of up to 200%, as shown in Figure 4.30, which displays the average maximum and minimum voltage across the entire network. This highlights the efficacy of the proposed reactive power control technique.

Furthermore, Figure 4.31 depicts the reactive power injection by the reactive power control technique at the last customers of feeder 3 under different levels of PV penetration (0%, 50%, 100%, and 200%). During 0% PV penetration, the reactive power injection follows a capacitive mode, increasing the voltage

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at the start and end of the day to compensate for the voltage decrease caused by high demand. At 50% PV penetration, the adaptive control technique maintains a similar behavior at the start and end of the day but absorbs a small amount of reactive power due to PV generation and slight voltage rise. However, during 100% and 200% PV penetration, the proposed control technique exhibits maximum reactive power absorption during mid-day due to voltage rise and high PV generation.

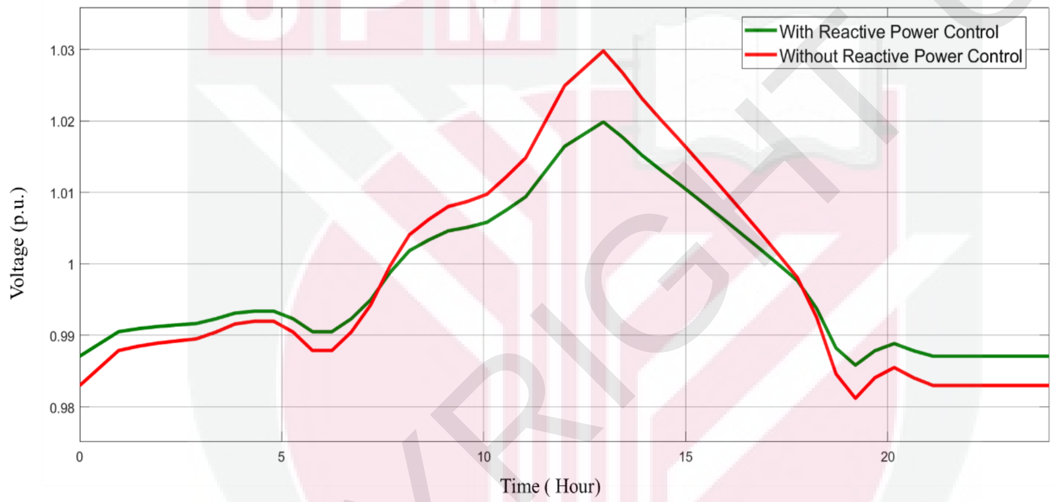

Figure 4.27 : The Voltage on the Last Customer on Feeder 3 for 24 Hours with 50% PV Penetration on Low Voltage Distribution Network with and without Adaptive Reactive Power Control

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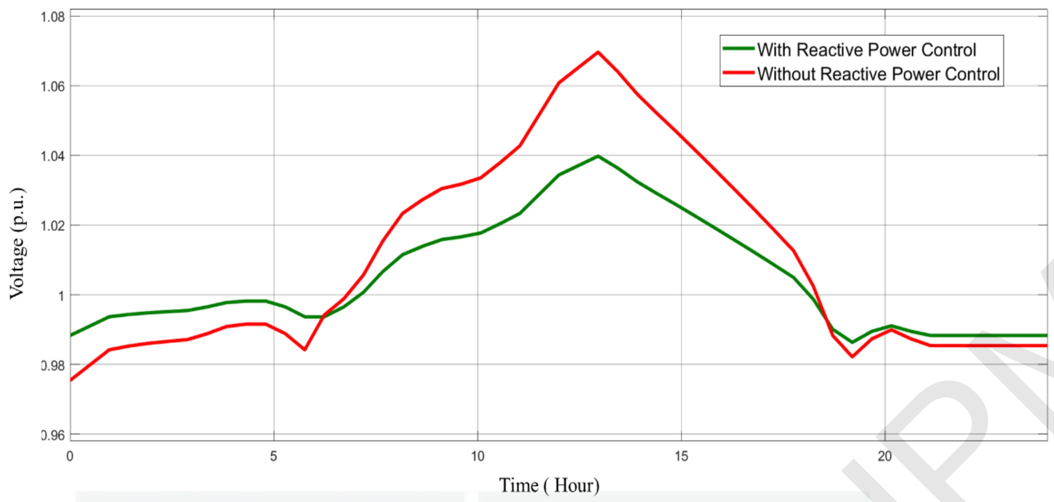

Figure 4.28 : The Voltage on the Last Customer on Feeder 3 for 24 Hours with 100% PV Penetration on Low Voltage Distribution Network with and without Adaptive Reactive Power Control

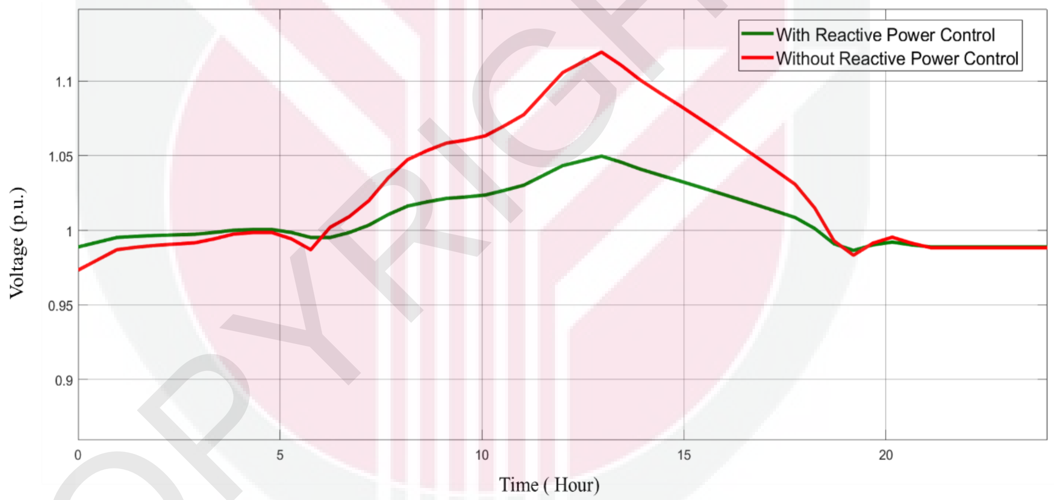

Figure 4.29 : The Voltage on the Last Customer on Feeder 3 for 24 Hours with 50% PV Penetration on Low Voltage Distribution Network with and without Adaptive Reactive Power Control

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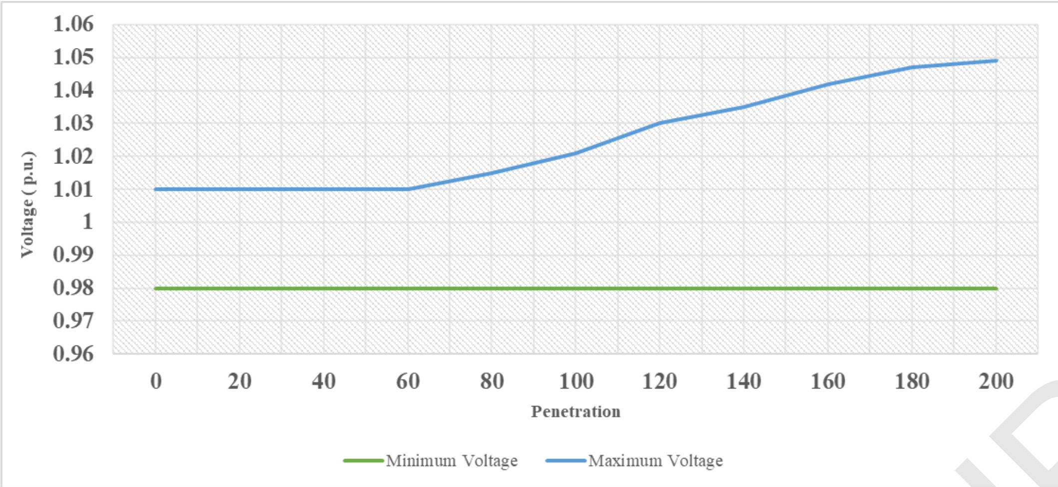

Figure 4.30 : Highest and Lowest Voltage of Distribution Network for Different Levels of PV Penetration with the Proposal Reactive Power Control

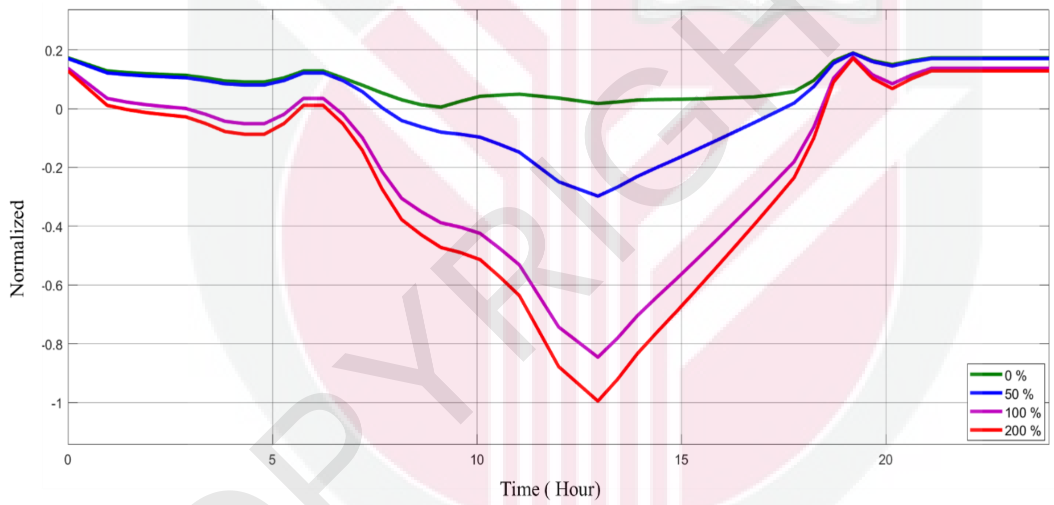

Figure 4.31 : Reactive Power Injection of the Proposal Reactive Power Control for Last Customer on Feeder 3 during 24 Hours for Different Level of Penetration (0%, 50%, 100%, 200%)

4.4 Summary

In conclusion, this chapter presented the results and discussion of the evaluation and validation of the adaptive reactive power control technique. The study focused on a small low voltage distribution network and the Malaysian low voltage distribution network to assess the impact of high PV penetration

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and validate the effectiveness of the adaptive reactive power control technique in mitigating voltage rise.

For the small distribution network, it was observed that the adaptive reactive power control technique successfully maintained the voltages within acceptable limits, even under scenarios of high PV penetration. Compared to existing techniques such as Q(V), Fixed PF, and PF(P), the adaptive technique demonstrated acceptable voltage regulation and minimized losses. It considered both the voltage at the points of common coupling and the PV active power generation, leading to optimized reactive power injection.

In the case of the Malaysian low voltage distribution network, the study revealed that as the PV penetration level increased, the risk of voltage rise became significant. However, the adaptive reactive power control technique effectively mitigated voltage rise and ensured the voltage remained within acceptable limits. The technique adapted its reactive power injection based on the network voltage and PV generation, providing optimal voltage regulation.

The results emphasized the importance of employing voltage rise mitigation techniques when PV penetration exceeds a certain threshold, highlighting the effectiveness of the adaptive reactive power control technique in addressing this issue. The adaptive reactive power control technique exhibited superior performance compared to other techniques, maintaining voltage stability and minimizing losses.

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Overall, the findings of this chapter validate the effectiveness of the adaptive reactive power control technique in mitigating voltage rise on low voltage distribution networks with high PV penetration. The adaptive technique provides a reliable and efficient approach to ensure voltage stability and minimize losses, contributing to the successful integration of PV distributed generators in the distribution network.

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CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

The primary focus of this thesis was to address the significant challenge of voltage rise on distribution networks due to high photovoltaic (PV) penetration. This issue is increasingly prevalent as the global shift towards renewable energy sources accelerates. The thesis introduced an adaptive reactive power control technique, designed to dynamically manage the injection and absorption of reactive power within distribution network parameters—voltage at the point of common coupling, and PV active power injection to effectively mitigate voltage rise. This adaptive technique marks a significant advancement in the field of electrical power systems, offering a real-time solution that adapts reactive power to varying network conditions, thus improving the mitigation of voltage rise by keeping voltage within acceptable limits and minimizing losses.

The effectiveness of this adaptive reactive power control technique was rigorously tested through simulations in MATLAB/Simulink and OpenDSS, across various scenarios in both small-scale and real-world Malaysian distribution networks. The key findings demonstrate that this technique not only maintains voltage stability across a wide range of PV penetration levels but also outperforms existing reactive power control methods, especially in high PV penetration scenarios where traditional methods often fail. Moreover, the technique enhances operational efficiency by reducing unnecessary

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reactive power absorption, thereby minimizing power losses across the distribution network. Its adaptability to different network conditions and scalability across various network sizes and configurations was clearly demonstrated, making it a versatile tool for grid operators globally. These findings are significant as they facilitate the stable integration of PV systems into existing distribution networks, supporting the broader adoption of renewable energy and addressing a critical barrier—voltage instability—that has impeded the scalability of solar energy deployment globally. By providing a practical tool to manage the complexities introduced by renewable energy sources, this technique ensures that the transition towards a greener energy portfolio does not compromise grid performance.

The objectives of this thesis were fully met through the development and validation of the adaptive reactive power control technique. By investigating the impact of high PV penetration on distribution network voltage through extensive simulations, designing a dynamic control strategy that effectively manages voltage levels, and validating this strategy in both simulated environments and a real-world scenario, this research substantiates its contributions to power systems engineering. It offers a viable solution for integrating substantial renewable energy resources into existing power grids without compromising grid stability and efficiency.

Looking to the future, the field of power systems management is poised for further innovations. The successful implementation of the adaptive reactive control technique can contribute significantly to sustainability goals, such as

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reducing carbon emissions and enhancing reliance on clean energy. Future research directions include integrating this control technique with other renewable energy sources like wind or hydro, enhancing voltage fluctuation prediction accuracy through advanced grid analytics, and conducting economic and regulatory assessments to fully understand the impacts of widespread adoption of such adaptive controls. Longitudinal studies to assess the durability and reliability of the technique will be crucial in ensuring its long-term effectiveness and sustainability in modern power grids. This ongoing evolution of power systems emphasizes the necessity for innovative approaches to accommodate increasing renewable energy integration, aiming for greater system sustainability, resilience, and efficiency.

5.2 Future Work

Several areas warrant further exploration to build on the findings of this research.

1. Integration with Other Renewable Energy Sources: Future studies could explore the integration of the proposed control technique with other types of renewable energy sources, such as wind or hydro, to create a more resilient and flexible energy system.

2. Advanced Grid Analytics: Investigating the use of advanced predictive analytics and machine learning algorithms to enhance the prediction accuracy of voltage fluctuations and the corresponding control actions.

3. Economic Analysis: Conducting a detailed cost-benefit analysis to determine the economic impacts of implementing the adaptive reactive power control technique, including potential savings in operational and capital expenditures.

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4. Regulatory and Policy Assessment: Examining the regulatory challenges and policy implications of widespread adoption of adaptive reactive power controls in national grids.

5. Longitudinal Studies: Long-term studies to assess the durability and reliability of the proposed technique under prolonged operational conditions and its impact on grid aging.

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REFERENCES

Abo Alwez, M., Jasni, J., Mohd Radzi, M. A., & Azis, N. (2020). PV system sizing to cover the electricity shortage in a residential quarter in Iraq. PECon 2020 - 2020 IEEE International Conference on Power and Energy, 214–218. https://doi.org/10.1109/PECON48942.2020.9314441

Adetokun, B. B., Ojo, J. O., & Muriithi, C. M. (2020). Reactive Power-Voltage-Based Voltage Instability Sensitivity Indices for Power Grid with Increasing Renewable Energy Penetration. IEEE Access, 8, 85401–85410. https://doi.org/10.1109/ACCESS.2020.2992194

Alam, M., Muttaqi, K., & Sutanto, D. (2012). A comprehensive assessment tool for solar PV impacts on low voltage three phase distribution networks. 2nd International Conference on the Developments in Renewable Energy Technology (ICDRET 2012).

Almeida, D., Pasupuleti, J., & Ekanayake, J. (2021a). Comparison of Reactive Power Control Techniques for Solar PV Inverters to Mitigate Voltage Rise in Low-Voltage Grids. Electronics 2021, Vol. 10, Page 1569, 10(13), 1569. https://doi.org/10.3390/ELECTRONICS10131569

Almeida, D., Pasupuleti, J., & Ekanayake, J. (2021b). Comparison of Reactive Power Control Techniques for Solar PV Inverters to Mitigate Voltage Rise in Low-Voltage Grids. Electronics 2021, Vol. 10, Page 1569, 10(13), 1569. https://doi.org/10.3390/ELECTRONICS10131569

Aramizu, J., & Vieira, J. C. M. (2013). Analysis of PV generation impacts on voltage imbalance and on voltage regulation in distribution networks. IEEE Power and Energy Society General Meeting, 1–5. https://doi.org/10.1109/PESMG.2013.6672822

Ariyaratna, P. M., Muttaqi, K. M., & Sutanto, D. (2019). The simultaneous mitigation of slow and fast voltage fluctuations caused by rooftop solar PV by controlling the charging/discharging of an integrated battery energy storage system. Journal of Energy Storage, 26(March), 100971. https://doi.org/10.1016/j.est.2019.100971

Ariyaratna, P., Muttaqi, K. M., & Sutanto, D. (2018). A novel control strategy to mitigate slow and fast fluctuations of the voltage profile at common coupling Point of rooftop solar PV unit with an integrated hybrid energy storage system. Journal of Energy Storage, 20(July), 409–417. https://doi.org/10.1016/j.est.2018.10.016

Arshad, A., & Lehtonen, M. (2019). A comprehensive voltage control strategy with voltage flicker compensation for highly PV penetrated distribution networks. Electric Power Systems Research, 172, 105–113. https://doi.org/10.1016/J.EPSR.2019.02.019

© COPYRIGHT UPM

Babacan, O., Torre, W., & Kleissl, J. (2016). Optimal allocation of battery energy storage systems in distribution networks considering high PV penetration. IEEE Power and Energy Society General Meeting, 2016-Novem, 1–5. https://doi.org/10.1109/PESGM.2016.7741191

Baran, M. E., Hooshyar, H., Shen, Z., & Huang, A. (2012). Accommodating high PV penetration on distribution feeders. IEEE Transactions on Smart Grid, 3(2), 1039–1046. https://doi.org/10.1109/TSG.2012.2190759

Bedawy, A., & Yorino, N. (2018). Reactive Power Control of DGs for Distribution Network Voltage Regulation Using Multi-Agent System. IFAC-PapersOnLine, 51(28), 528–533. https://doi.org/10.1016/j.ifacol.2018.11.757

Bernal A., E., Bueno-López, M., & Salazar-Caceres, F. (2017). Fuzzy-Based Reactive Power Control for Smart PV Inverters in LV Distribution Systems. IFAC-PapersOnLine, 50(1), 7705–7710. https://doi.org/10.1016/J.IFACOL.2017.08.1147

Bletterie, B., Kadam, S., Bolgaryn, R., & Zegers, A. (2017). Voltage Control with PV Inverters in Low Voltage Networks-In Depth Analysis of Different Concepts and Parameterization Criteria. IEEE Transactions on Power Systems, 32(1), 177–185. https://doi.org/10.1109/TPWRS.2016.2554099

Ca, Y., Tang, W., Li, L., Zhang, B., Zhan, L., & Wang, Y. (2020). Multi-mode adaptive local reactive power control method based on pv inverters in low voltage distribution networks. IET Generation, Transmission and Distribution, 14(4), 542–551. https://doi.org/10.1049/IET-GTD.2018.6955/CITE/REFWORKS

Carvalho, P. M. S., Correia, P. F., & Ferreira, L. A. F. M. (2008). Distributed reactive power generation control for voltage rise mitigation in distribution networks. IEEE Transactions on Power Systems, 23(2), 766–772. https://doi.org/10.1109/TPWRS.2008.919203

Chamana, M., Chowdhury, B. H., & Jahanbakhsh, F. (2018). Distributed control of voltage regulating devices in the presence of high PV penetration to mitigate ramp-rate issues. IEEE Transactions on Smart Grid, 9(2), 1086–1095. https://doi.org/10.1109/TSG.2016.2576405

Chaudhary, P., & Rizwan, M. (2018). Voltage regulation mitigation techniques in distribution system with high PV penetration: A review. Renewable and Sustainable Energy Reviews, 82, 3279–3287. https://doi.org/10.1016/J.RSER.2017.10.017

Chen, P. C., Salcedo, R., Zhu, Q., De Leon, F., Czarkowski, D., Jiang, Z. P., Spitsa, V., Zabar, Z., & Uosef, R. E. (2012). Analysis of voltage profile problems due to the penetration of distributed generation in low-voltage secondary distribution networks. IEEE Transactions on Power Delivery, 27(4), 2020–2028. https://doi.org/10.1109/TPWRD.2012.2209684

Cheng, D., Mather, B. A., Seguin, R., Hambrick, J., & Broadwater, R. P. (2016). Photovoltaic (PV) impact assessment for very high penetration levels. IEEE Journal of Photovoltaics, 6(1), 295–300. https://doi.org/10.1109/JPHOTOV.2015.2481605

Conti, S., Greco, A., Messina, N., & Raiti, S. (2006). Local voltage regulation in LV distribution networks with PV distributed generation. International Symposium on Power Electronics, Electrical Drives, Automation and Motion, 2006. SPEEDAM 2006, 2006, 519–524. https://doi.org/10.1109/SPEEDAM.2006.1649827

Darwish, E. M., Hasanien, H. M., Atallah, A., & El-Debeiky, S. (2018). Reactive power control of three-phase low voltage system based on voltage to increase PV penetration levels. Ain Shams Engineering Journal, 9(4), 1831–1837. https://doi.org/10.1016/J.ASEJ.2017.01.006

Demirok, E., González, P. C., Frederiksen, K. H. B., Sera, D., Rodriguez, P., & Teodorescu, R. (2011). Local reactive power control methods for overvoltage prevention of distributed solar inverters in low-voltage grids. IEEE Journal of Photovoltaics, 1(2), 174–182. https://doi.org/10.1109/JPHOTOV.2011.2174821

Demirok, E., Sera, D., Teodorescu, R., Rodriguez, P., & Borup, U. (2009). Clustered PV inverters in LV networks: An overview of impacts and comparison of voltage control strategies. 2009 IEEE Electrical Power and Energy Conference, EPEC 2009. https://doi.org/10.1109/EPEC.2009.5420366

Diner, F. (2011). The analysis on photovoltaic electricity generation status, potential and policies of the leading countries in solar energy. Renewable and Sustainable Energy Reviews, 15(1), 713–720. https://doi.org/10.1016/J.RSER.2010.09.026

Ebrahimi, M., Khajehoddin, S. A., & Karimi-Ghartemani, M. (2016). Fast and Robust Single-Phase DQ Current Controller for Smart Inverter Applications. IEEE Transactions on Power Electronics, 31(5), 3968–3976. https://doi.org/10.1109/TPEL.2015.2474696

Ebrahimi, R., Branch, B., Babaee, A., & Hoseynpoor, M. (2011). Evaluation and Calculation of Overhead Line Impedance in Distribution Networks. Australian Journal of Basic and Applied Sciences, 5(8), 1278–1284.

Emarati, M., Barani, M., Farahmand, H., Aghaei, J., & del Granado, P. C. (2021). A two-level over-voltage control strategy in distribution networks with high PV penetration. International Journal of Electrical Power & Energy Systems, 130, 106763. https://doi.org/10.1016/J.IJEPES.2021.106763

© COPYRIGHT UPM

Faisal, M. ;, Hannan, M. A., Ker, P. J., Hussain, A. ;, Mansor, M. B., & Blaabjerg, F. (2018). Review of Energy Storage System Technologies in Microgrid Applications: Issues and Challenges. IEEE Access, 6, 35143–35164. https://doi.org/10.1109/ACCESS.2018.2841407

Ferreira, P. D. F., Carvalho, P. M. S., Ferreira, L. A. F. M., & Ilic, M. D. (2013). Distributed energy resources integration challenges in low-voltage networks: Voltage control limitations and risk of cascading. IEEE Transactions on Sustainable Energy, 4(1), 82–88. https://doi.org/10.1109/TSTE.2012.2201512

Gandhi, O., Kumar, D. S., Rodríguez-Gallegos, C. D., & Srinivasan, D. (2020). Review of power system impacts at high PV penetration Part I: Factors limiting PV penetration. Solar Energy, 210, 181–201. https://doi.org/10.1016/j.solener.2020.06.097

Gaudin, C., Ballanti, A., & Lejay, E. (2012). Evaluation of PV curtailment option to optimize PV integration in Distribution Network. 50–50. https://doi.org/10.1049/CP.2012.0733

Ghasemi, M. A., & Parniani, M. (2016). Prevention of distribution network overvoltage by adaptive droop-based active and reactive power control of PV systems. Electric Power Systems Research, 133, 313–327. https://doi.org/10.1016/j.epsr.2015.12.030

Ghosh, S., Rahman, S., & Pipattanasomporn, M. (2017). Distribution Voltage Regulation Through Active Power Curtailment With PV Inverters and Solar Generation Forecasts. IEEE Transactions on Sustainable Energy, 8(1), 13–22. https://doi.org/10.1109/TSTE.2016.2577559

Glover, J. Duncan., Overbye, T. J. ., & Sarma, M. S. . (2017). Power system analysis & design. 942. https://thuvienso.hoasen.edu.vn/handle/123456789/11192

Haque, A. N. M. M., Nguyen, P. H., Vo, T. H., & Bliek, F. W. (2017). Agent-based unified approach for thermal and voltage constraint management in LV distribution network. Electric Power Systems Research, 143, 462–473. https://doi.org/10.1016/J.EPSR.2016.11.007

Hashemi, S., Ostergaard, J., & Yang, G. (2013). Effect of reactive power management of PV inverters on need for energy storage. Conference Record of the IEEE Photovoltaic Specialists Conference, 2304–2308. https://doi.org/10.1109/PVSC.2013.6744938

Hasheminamin, M., Agelidis, V. G., Ahmadi, A., Siano, P., & Teodorescu, R. (2018). Single-point reactive power control method on voltage rise mitigation in residential networks with high PV penetration. Renewable Energy, 119, 504–512. https://doi.org/10.1016/J.RENENE.2017.12.029

Hosenuzzaman, M., Rahim, N. A., Selvaraj, J., Hasanuzzaman, M., Malek, A. B. M. A., & Nahar, A. (2015). Global prospects, progress, policies, and environmental impact of solar photovoltaic power generation. Renewable and Sustainable Energy Reviews, 41, 284–297. https://doi.org/10.1016/J.RSER.2014.08.046

Howlader, A. M., Sadoyama, S., Roose, L. R., & Sepasi, S. (2018). Distributed voltage regulation using Volt-Var controls of a smart PV inverter in a smart grid: An experimental study. Renewable Energy, 127, 145–157. https://doi.org/10.1016/j.renene.2018.04.058

Hu, R., Wang, W., Wu, X., Chen, Z., Jing, L., Ma, W., & Zeng, G. (2022). Coordinated active and reactive power control for distribution networks with high penetrations of photovoltaic systems. Solar Energy, 231, 809–827. https://doi.org/10.1016/j.solener.2021.12.025

Huang, L., Wu, C., Zhou, D., & Blaabjerg, F. (2021). Impact of Grid Strength and Impedance Characteristics on the Maximum Power Transfer Capability of Grid-Connected Inverters. Applied Sciences 2021, Vol. 11, Page 4288, 11(9), 4288. https://doi.org/10.3390/APP11094288

Iioka, D., Fujii, T., Orihara, D., Tanaka, T., Harimoto, T., Shimada, A., Goto, T., & Kubuki, M. (2019). Voltage reduction due to reverse power flow in distribution feeder with photovoltaic system. International Journal of Electrical Power and Energy Systems, 113(April), 411–418. https://doi.org/10.1016/j.ijepes.2019.05.059

Islam, F. R., Prakash, K., Mamun, K. A., Lallu, A., & Pota, H. R. (2017). Aromatic network: A novel structure for power distribution system. IEEE Access, 5, 25236–25257. https://doi.org/10.1109/ACCESS.2017.2767037

Kabiri, R., Holmes, D. G., McGrath, B. P., & Meegahapola, L. G. (2015). LV Grid Voltage Regulation Using Transformer Electronic Tap Changing, with PV Inverter Reactive Power Injection. IEEE Journal of Emerging and Selected Topics in Power Electronics, 3(4), 1182–1192. https://doi.org/10.1109/JESTPE.2015.2443839

Kaur, R. R., & Luthra, A. (2018). Population growth, urbanization and electricity - Challenges and initiatives in the state of Punjab, India. Energy Strategy Reviews, 21, 50–61. https://doi.org/10.1016/J.ESR.2018.04.005

Kerber, G., Witzmann, R., & Sappl, H. (2009). Voltage limitation by autonomous reactive power control of grid connected photovoltaic inverters. CPE 2009 - 6th International Conference-Workshop - Compatability and Power Electronics, 129–133. https://doi.org/10.1109/CPE.2009.5156024

Kersting, W. H. (2020). Series Impedance of Overhead and Underground Lines. Distribution System Modeling and Analysis, 91–122.

© COPYRIGHT UPM

https://doi.org/10.1201/9781420041736-6/SERIES-IMPEDANCE-OVERHEAD-UNDERGROUND-LINES-WILLIAM-KERSTING

Kim, S. Bin, & Song, S. H. (2020). A hybrid reactive power control method of distributed generation to mitigate voltage rise in low-voltage grid. Energies, 13(8). https://doi.org/10.3390/en13082078

Kim, I., & Harley, R. G. (2020). Examination of the effect of the reactive power control of photovoltaic systems on electric power grids and the development of a voltage-regulation method that considers feeder impedance sensitivity. Electric Power Systems Research, 180. https://doi.org/10.1016/j.epsr.2019.106130

Ku, T. T., Lin, C. H., Chen, C. S., Hsu, C. T., Hsieh, W. L., & Hsieh, S. C. (2016). Coordination of PV Inverters to Mitigate Voltage Violation for Load Transfer between Distribution Feeders with High Penetration of PV Installation. IEEE Transactions on Industry Applications, 52(2), 1167–1174. https://doi.org/10.1109/TIA.2015.2491268

Kusters, N. L., & Moore, W. J. M. (1980). On the definition of reactive power under non-sinusoidal conditions. IEEE Transactions on Power Apparatus and Systems, PAS-99(5), 1845–1854. https://doi.org/10.1109/TPAS.1980.319833

Kyriakopoulos, G. L., & Arabatzis, G. (2016). Electrical energy storage systems in electricity generation: Energy policies, innovative technologies, and regulatory regimes. Renewable and Sustainable Energy Reviews, 56, 1044–1067. https://doi.org/10.1016/J.RSER.2015.12.046

Liu, L., Li, H., Wu, Z., & Zhou, Y. (2011). A cascaded photovoltaic system integrating segmented energy storages with self-regulating power allocation control and wide range reactive power compensation. IEEE Transactions on Power Electronics, 26(12), 3545–3559. https://doi.org/10.1109/TPEL.2011.2168544

Liu, X., Aichhorn, A., Liu, L., & Li, H. (2012). Coordinated control of distributed energy storage system with tap changer transformers for voltage rise mitigation under high photovoltaic penetration. IEEE Transactions on Smart Grid, 3(2), 897–906. https://doi.org/10.1109/TSG.2011.2177501

Liu, Y., Bebic, J., Kroposki, B., De Bedout, J., & Ren, W. (2008). Distribution system voltage performance analysis for high-penetration PV. 2008 IEEE Energy 2030 Conference, ENERGY 2008. https://doi.org/10.1109/ENERGY.2008.4781069

Ma, Y., Azuatalam, D., Power, T., Chapman, A. C., & Verbič, G. (2019). A novel probabilistic framework to study the impact of photovoltaic-battery systems on low-voltage distribution networks. Applied Energy, 254(July), 113669. https://doi.org/10.1016/j.apenergy.2019.113669

© COPYRIGHT UPM

Mahmud, M. A., Hossain, M. J., & Pota, H. R. (2014). Voltage variation on distribution networks with distributed generation: Worst case scenario. IEEE Systems Journal, 8(4), 1096–1103. https://doi.org/10.1109/JSYST.2013.2265176

Mahmud, N., & Zahedi, A. (2016). Review of control strategies for voltage regulation of the smart distribution network with high penetration of renewable distributed generation. Renewable and Sustainable Energy Reviews, 64, 582–595. https://doi.org/10.1016/J.RSER.2016.06.030

Makdisie, C., Haidar, B., & Alhelou, H. H. (2018). An Optimal Photovoltaic Conversion System for Future Smart Grids. IGI Global, 601–657. https://doi.org/10.4018/978-1-5225-3935-3.CH018

Marra, F., Fawzy, Y. T., Bulo, T., & Blažič, B. (2012). Energy storage options for voltage support in low-voltage grids with high penetration of photovoltaic. IEEE PES Innovative Smart Grid Technologies Conference Europe, 1–7. https://doi.org/10.1109/ISGTEurope.2012.6465690

Moosavian, S. M., Rahim, N. A., Selvaraj, J., & Solangi, K. H. (2013). Energy policy to promote photovoltaic generation. Renewable and Sustainable Energy Reviews, 25, 44–58. https://doi.org/10.1016/J.RSER.2013.03.030

Munkhchuluun, E., Meegahapola, L., & Vahidnia, A. (2020). Long-term voltage stability with large-scale solar-photovoltaic (PV) generation. International Journal of Electrical Power and Energy Systems, 117(October 2019), 105663. https://doi.org/10.1016/j.ijepes.2019.105663

Pan, Y., Sangwongwanich, A., Yang, Y., Liu, X., Liserre, M., & Blaabjerg, F. (2022). Flexible Active Power Control of Distributed Photovoltaic Systems with Integrated Battery Using Series Converter Configurations. IEEE Journal of Emerging and Selected Topics in Power Electronics, 10(6), 6891–6909. https://doi.org/10.1109/JESTPE.2021.3134203

Pandiyan, P., Saravanan, S., Usha, K., Kannadasan, R., Alsharif, M. H., & Kim, M. K. (2023). Technological advancements toward smart energy management in smart cities. Energy Reports, 10, 648–677. https://doi.org/10.1016/J.EGYR.2023.07.021

Petinrin, J. O., & Shaabanb, M. (2016). Impact of renewable generation on voltage control in distribution systems. Renewable and Sustainable Energy Reviews, 65, 770–783. https://doi.org/10.1016/J.RSER.2016.06.073

Pillai, G., Putrus, G., Pearsall, N., & Georgitsioti, T. (2017). The effect of distribution network on the annual energy yield and economic performance of residential PV systems under high penetration.

Renewable Energy, 108, 144–155. https://doi.org/10.1016/J.RENENE.2017.02.047

Ponnaganti, P., Pillai, J. R., & Bak-Jensen, B. (2018). Opportunities and challenges of demand response in active distribution networks. Wiley Interdisciplinary Reviews: Energy and Environment, 7(1), e271. https://doi.org/10.1002/WENE.271

Pourmousavi, S. A., Cifala, A. S., & Nehrir, M. H. (2012). Impact of high penetration of PV generation on frequency and voltage in a distribution feeder. 2012 North American Power Symposium, NAPS 2012. https://doi.org/10.1109/NAPS.2012.6336320

Punyachai, R., Ongsakul, W., & Schmidt, U. (2014). Impact of high solar rooftop PV penetration on voltage profiles in distribution systems. Proceedings of the 2014 International Conference and Utility Exhibition on Green Energy for Sustainable Development, ICUE 2014, March, 1–7.

Ranaweera, I., Midtgård, O. M., & Korpås, M. (2017). Distributed control scheme for residential battery energy storage units coupled with PV systems. Renewable Energy, 113, 1099–1110. https://doi.org/10.1016/j.renene.2017.06.084

Rangel, C. A. S., Canha, L., Sperandio, M., & Severiano, R. (2018). Methodology for ESS-type selection and optimal energy management in distribution system with DG considering reverse flow limitations and cost penalties. IET Generation, Transmission and Distribution, 12(5), 1164–1170. https://doi.org/10.1049/iet-gtd.2017.1027

Renewables - Energy System - IEA. (n.d.). Retrieved August 18, 2024, from https://www.iea.org/energy-system/renewables

Ring Main Unit in Electrical Distribution System. (n.d.). Retrieved August 27, 2024, from https://www.allumiax.com/blog/ring-main-unit-in-electrical-distribution-system

Saadat, H. (1999). Power system analysis. https://www.uvic.ca/ecs/ece/assets/docs/current/undergraduate/201901/ece488.pdf

Salimon, S. A., Adepoju, G. A., Adebayo, I. G., Howlader, H. O. R., Ayanlade, S. O., & Adewuyi, O. B. (2023). Impact of Distributed Generators Penetration Level on the Power Loss and Voltage Profile of Radial Distribution Networks. Energies, 16(4). https://doi.org/10.3390/EN16041943

Sallam, A., & Malik, O. (2018). Distribution System Structure. Electric Distribution Systems, Second Edition, 9–22. https://doi.org/10.1002/9781119509332.CH2

Seuss, J., Reno, M. J., Broderick, R. J., & Grijalva, S. (2015). Improving distribution network PV hosting capacity via smart inverter reactive power support. IEEE Power and Energy Society General Meeting, 2015-September. https://doi.org/10.1109/PESGM.2015.7286523

Shepherd, C. M. (1965). Design of Primary and Secondary Cells. Journal of The Electrochemical Society, 112(7), 657. https://doi.org/10.1149/1.2423659

Shivashankar, S., Mekhilef, S., Mokhlis, H., & Karimi, M. (2016). Mitigating methods of power fluctuation of photovoltaic (PV) sources – A review. Renewable and Sustainable Energy Reviews, 59, 1170–1184. https://doi.org/10.1016/J.RSER.2016.01.059

Singh, S., Veda, S., Singh, S. P., Jain, R., & Baggu, M. (2021). Event-Driven Predictive Approach for Real-Time Volt/VAR Control with CVR in Solar PV Rich Active Distribution Network. IEEE Transactions on Power Systems, 36(5), 3849–3864. https://doi.org/10.1109/TPWRS.2021.3057656

Stetz, T., Marten, F., & Braun, M. (2013). Improved low voltage grid-integration of photovoltaic systems in Germany. IEEE Transactions on Sustainable Energy, 4(2), 534–542. https://doi.org/10.1109/TSTE.2012.2198925

Sugihara, H., Yokoyama, K., Saeki, O., Tsuji, K., & Funaki, T. (2013). Economic and efficient voltage management using customer-owned energy storage systems in a distribution network with high penetration of photovoltaic systems. IEEE Transactions on Power Systems, 28(1), 102–111. https://doi.org/10.1109/TPWRS.2012.2196529

Takayama, S., & Ishigame, A. (2018). Autonomous Decentralized Control of Distribution Network Voltage using Reinforcement Learning. IFAC-PapersOnLine, 51(28), 209–214. https://doi.org/10.1016/j.ifacol.2018.11.703

Tewari, T., Mohapatra, A., & Anand, S. (2021). Coordinated control of OLTC and energy storage for voltage regulation in distribution network with high PV penetration. IEEE Transactions on Sustainable Energy, 12(1), 262–272. https://doi.org/10.1109/TSTE.2020.2991017

Tie, C. H., & Gan, C. K. (2013). Impact of grid-connected residential PV systems on the malaysia low voltage distribution network. Proceedings of the 2013 IEEE 7th International Power Engineering and Optimization Conference, PEOCO 2013, 670–675. https://doi.org/10.1109/PEOCO.2013.6564631

TNB. (2023). ELECTRICITY SUPPLY APPLICATION HANDBOOK (3.1).

Tonkoski, R., Lopes, L. A. C., & El-Fouly, T. H. M. (2011). Coordinated active power curtailment of grid connected PV inverters for overvoltage prevention. IEEE Transactions on Sustainable Energy, 2(2), 139–147. https://doi.org/10.1109/TSTE.2010.2098483

Turitsyn, K., Šulc, P., Backhaus, S., & Chertkov, M. (2011). Options for control of reactive power by distributed photovoltaic generators. Proceedings of the IEEE, 99(6), 1063–1073. https://doi.org/10.1109/JPROC.2011.2116750

Varma, R. K., & Siavashi, E. M. (2018). PV-STATCOM: A New Smart Inverter for Voltage Control in Distribution Systems. IEEE Transactions on Sustainable Energy, 9(4), 1681–1691. https://doi.org/10.1109/TSTE.2018.2808601

Verma, P., Katal, N., Sharma, B., Chowdhury, S., Mehbodniya, A., Webber, J. L., & Bostani, A. (2022). Voltage Rise Mitigation in PV Rich LV Distribution Networks Using DC/DC Converter Level Active Power Curtailment Method. Energies, 15(16), 5901. https://doi.org/10.3390/en15165901

Wigley, T. M. L. (1991). Could reducing fossil-fuel emissions cause global warming? Nature 1991 349:6309, 349(6309), 503–506. https://doi.org/10.1038/349503a0

Xie, C., Wang, D., Lai, C. S., Wu, R., Wu, X., & Lai, L. L. (2021). Optimal sizing of battery energy storage system in smart microgrid considering virtual energy storage system and high photovoltaic penetration. Journal of Cleaner Production, 281. https://doi.org/10.1016/j.jclepro.2020.125308

Xie, Y., Liu, L., Wu, Q., & Zhou, Q. (2020). Robust model predictive control based voltage regulation method for a distribution system with renewable energy sources and energy storage systems. International Journal of Electrical Power and Energy Systems, 118(September 2019). https://doi.org/10.1016/j.ijepes.2019.105749

Yaghoobi, J., Mithulananthan, N., & Saha, T. K. (2015). Dynamic voltage stability of distribution system with a high penetration of rooftop PV units. IEEE Power and Energy Society General Meeting, 2015-Septe, 1–5. https://doi.org/10.1109/PESGM.2015.7286608

Yan, R., & Saha, T. K. (2012). Investigation of voltage stability for residential customers due to high photovoltaic penetrations. IEEE Transactions on Power Systems, 27(2), 651–662. https://doi.org/10.1109/TPWRS.2011.2180741

Yang, H. T., Chen, Y. T., Liao, J. T., & Yang, C. T. (2015, November 10). Over-voltage mitigation control strategies for distribution system with high PV penetration. 2015 18th International Conference on Intelligent System Application to Power Systems, ISAP 2015. https://doi.org/10.1109/ISAP.2015.7325529

© COPYRIGHT UPM

Yang, Y., Li, H., Aichhorn, A., Zheng, J., & Greenleaf, M. (2014). Sizing strategy of distributed battery storage system with high penetration of photovoltaic for voltage regulation and peak load shaving. IEEE Transactions on Smart Grid, 5(2), 982–991. https://doi.org/10.1109/TSG.2013.2282504

Zeraati, M., Hamedani Golshan, M. E., & Guerrero, J. M. (2019). A Consensus-Based Cooperative Control of PEV Battery and PV Active Power Curtailment for Voltage Regulation in Distribution Networks. IEEE Transactions on Smart Grid, 10(1), 670–680. https://doi.org/10.1109/TSG.2017.2749623

Zhong, Q., & Hornik, T. (2012). Control of power inverters in renewable energy and smart grid integration. John Wiley & Sons.

Zillmann, M., Yan, R., & Saha, T. K. (2011). Regulation of distribution network voltage using dispersed battery storage systems: A case study of a rural network. 2011 IEEE Power and Energy Society General Meeting. https://doi.org/10.1109/PES.2011.6039094

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LIST OF PUBLICATIONS

Abo Alwez, M., Jasni, J., Mohd Radzi, M. A., & Azis, N. (2020). PV system sizing to cover the electricity shortage in a residential quarter in Iraq. PECon 2020 - 2020 IEEE International Conference on Power and Energy, 214–218. https://doi.org/10.1109/PECON48942.2020.9314441

Abo Alwez, M., Jasni, J., Wahab, R., Amran, M., Radzi, M., & Azis, N. (2024). Novel Reactive Power Control Strategy for Mitigating Voltage Rise in the Malaysian Low Voltage Distribution Network with High PV Penetration. Pertanika J. Sci. & Technol, 32(4), 1651–1664. https://doi.org/10.47836/pjst.32.4.11

alwez, M. A., Jasni, J., MohdRadzi, M. A., & Azis, N. (2025). Adaptive reactive power control for voltage rise mitigation on distribution network with high photovoltaic penetration. Renewable and Sustainable Energy Reviews, 207, 114948. https://doi.org/10.1016/J.RSER.2024.114948

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