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Novel Reactive Power Control Strategy for Mitigating Voltage Rise in the Malaysian Low Voltage Distribution Network with High PV Penetration

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ABSTRACT

Integrating renewable energy sources and distributed energy resources (DERs) in the Malaysian low voltage distribution network has introduced voltage stability challenges, particularly voltage rises, leading to detrimental impacts on network performance. This paper presents a novel reactive power control strategy for addressing these challenges. Unlike conventional methods with fixed reactive power references, the proposed technique dynamically adjusts the reactive power reference in real time, considering voltage and active power injection. It calculates the rate of change in reactive power reference (ΔQ) per second by analyzing Volt-VAR and Watt-VAR components and updates the reference accordingly. Simulations conducted on a low voltage distribution network in Taman Impian Putra, Malaysia, showcase the adverse effects of high photovoltaic (PV) penetration on voltage stability and highlight the success of the proposed strategy in mitigating voltage rise. The technique effectively reduces average voltage, maintains voltage regulation during high sun irradiance and low load demand periods, and surpasses the adaptability of existing methods dependent on PV active injection or network voltage alone. The proposed strategy ensures accurate control and efficiently addresses dynamic network changes by accounting for both PV active power injection and network voltage. This approach offers enhanced voltage regulation, adaptability to varying network

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conditions, and reduced losses, making it a promising solution for mitigating voltage rise in the Malaysian low voltage distribution network. The simulations, validated using MATLAB Simulation and OpenDSS, confirm the strategy's efficacy and potential for real-world implementation.

Keywords: Distributed energy resources, low voltage distribution network, network voltage, PV active power injection, reactive power control, renewable energy integration, voltage regulation, voltage stability

INTRODUCTION

The power distribution network in Malaysia has undergone a significant transformation in recent years, thanks to the integration of renewable energy sources and the increasing penetration of distributed energy resources (DERs) (Maghami et al., 2023)**.** It is mainly driven by the decreasing cost of renewable sources (Alwez et al., 2020). While these developments have brought numerous environmental and economic benefits, they have also introduced new challenges concerning voltage stability in the low-voltage distribution network. Voltage rises, in particular, have emerged as a critical issue that requires effective mitigation strategies to ensure a reliable and efficient power supply (Tie & Gan, 2013).

The voltage rises when the power injected from DERs exceeds the local load demand in the distribution network, resulting in an unacceptable increase in voltage levels (Haque et al., 2017). This phenomenon can adversely affect the network's performance, including increased energy losses, reduced power quality, equipment damage, and compromised system stability (Hasheminamin et al., 2015). Conventional voltage control methods, such as tap-changing transformers and voltage regulators, have limitations in addressing these voltage rise challenges, especially in dynamic and unpredictable DER integration. The reactive power control ability in the smart inverter of PV systems can be utilized to overcome these limitations. Reactive power control can be based on either PV active power injection, which offers good voltage regulation but high losses, or the voltage at the point of common coupling of PV systems in the distribution network, which provides poor voltage regulation but low losses.

Many studies have proposed utilizing Volt/Var reactive power control of PV smart inverters to mitigate voltage rise on distribution networks with high PV penetration (Inaolaji et al., 2022; Singh et al., 2021). However, it is important to note that techniques solely dependent on network voltage tend to result in poor voltage regulation, as network voltage relies on the network's sensitivity to both active and reactive power. Demirok et al. (2011) proposed a reactive power control technique to mitigate voltage rise on low voltage distribution networks by combining PV active power injection and network voltage. This technique, referred to as PF (P, V), balances the two approaches. The study's results demonstrated improved voltage regulation compared to the Q(V) technique and lower network losses compared to the PF(P) technique. However, it requires specific placement in areas with low voltage variations.

Kim and Song (2020) proposes a reactive power control technique to address voltage rise on low voltage distribution networks using PV active power injection (PF(P)) and network voltage (Q(V)). The weighting assigned to each technique varies based on the PV active power injection level. As a result, the proposed technique behaves like Q(V) when PV systems generate minimum power and acts like PF(P) when PV systems generate maximum power. However, this approach disregards load variations during high PV generation, potentially leading to unnecessary losses. Then, Inaolaji et al. (2022) present an algorithm for coordinating Volt-VAR and Watt-VAR control strategies. However, the initial algorithm failed to align peak load demand with peak PV generation. To resolve this issue, the author implemented an Energy Storage System. It is important to note that this solution has limitations, including high costs and potential impacts on network reliability.

This paper aims to study the effectiveness of a novel reactive power control technique in mitigating voltage rise on the Malaysian distribution network. The proposed reactive power control is based on simultaneous PV active power injection and network voltage. Unlike conventional methods, the proposed reactive power control does not directly correlate with PV active power injection or network voltage. Instead, it calculates the amount of reactive power change based on PV active power injection and network voltage, repeating this process every second. This control technique offers greater flexibility in managing reactive power to accommodate variations in network parameters. Furthermore, since it depends on both PV active power generation and voltage simultaneously, it ensures precise control over reactive power output. The proposed control technique is examined on the low voltage distribution network supplying a residential neighborhood in Taman Impian Putra PD, Malaysia. This study utilizes MATLAB simulation and OpenDSS simulation to simulate and evaluate the effectiveness of the proposed technique.

METHODOLOGY

Low Voltage Network Modelling

As presented by Tie and Gan (2013), the network used in this study 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 residential area and the distribution network are depicted in Figures 1 and 2, respectively. Furthermore, the network data is summarized in Table 1. The radial network comprises a 4 × 500 mm^2 PVC/PVC Aluminum (Al) cable that connects the transformer to the feeder pillar. The feeder pillar serves a total of five feeders. The cable between the feeder pillar and the poles is 185 mm^2 4C Al XLPE. An Aerial Bundle Cable (ABC) with 3 × 185 mm^2 + 120 mm^2 is employed to distribute power from the poles to the houses. 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 terrace houses, assuming an average maximum demand of 2 kW per consumer, accounting for diversity. Mutual impedance and self-impedance are calculated using Equations 1 and 2, respectively (Ebrahimi et al., 2011).

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

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

where D_{ij} = Distance between conductor i and j; r_i = Resistance of conductor (Ω/km); f = System frequency 50 Hz; GMR_i = Geometric mean radius of conductor (cm); and ρ = earth resistivity (Ω-100).

Then, the subsequence and sequence impedance are calculated by Equations 3 and 4 (Kersting, 2020).

$$Z_o = Z_s + 2Z_m \quad [3]$$

$$Z_1 = Z_2 = Z_s - Z_m \quad [4]$$

Where Zm and Zs Can be calculated based on Equations 5 and 6 respectively (Kersting, 2020).

$$Z_m = \frac{Z_{ab} + Z_{ac} + Z_{ba} + Z_{bc} + Z_{ca} + Z_{cb}}{6} \quad [5]$$

$$Z_S = \frac{Z_{aa} + Z_{bb} + Z_{cc}}{3} \quad [6]$$

Table 1
Summary of the network data

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

Figure 1. The residential area in Taman Impian Putra PD, Malaysia (https://www.google.com/maps)

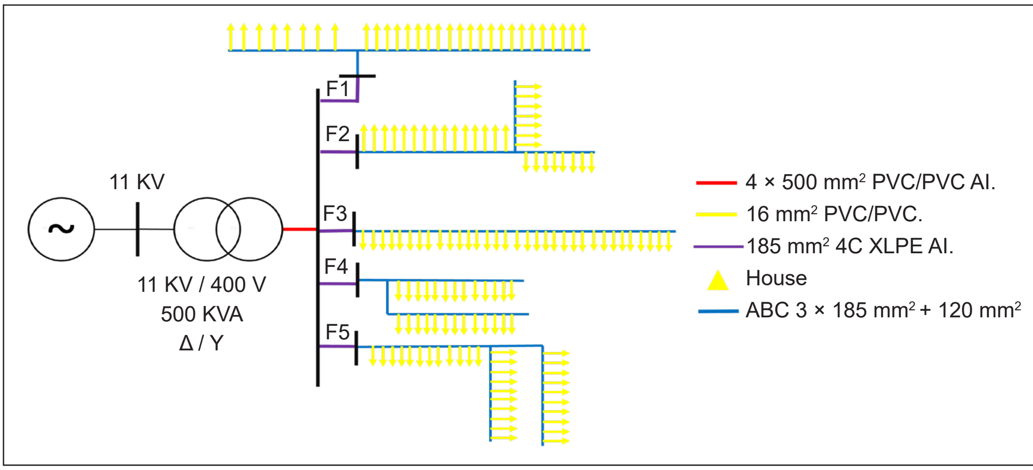

Figure 2. Low voltage distribution network of Taman Impian Putra (Tie & Gan, 2013)

Load Demand and PV Generation

Figure 3 illustrates Malaysia's aggregate load demand profile (Ebrahimi et al., 2011). It can be observed that the load demand experiences an increase at 5 p.m., reaching its peak at 8 p.m. This surge in demand is primarily attributed to the prevalent hot weather in Malaysia, leading to most customers' higher usage of air conditioning systems. Conversely, the load demand is at its minimum between 7 a.m. and 5 p.m., as most customers are outdoors during this period. This load profile serves as a representative shape for all houses within the distribution network.

On the other hand, Figure 3 also presents the solar panel generation profile (Ebrahimi et al., 2011). Notably, the solar panels do not generate electricity during the night period from 8 p.m. to 8 a.m. due to the absence of sun irradiance. Subsequently, the PV generation gradually increases, reaching its maximum output at 1 p.m. It is important to highlight that this PV generation profile applies to all PV systems within the network.

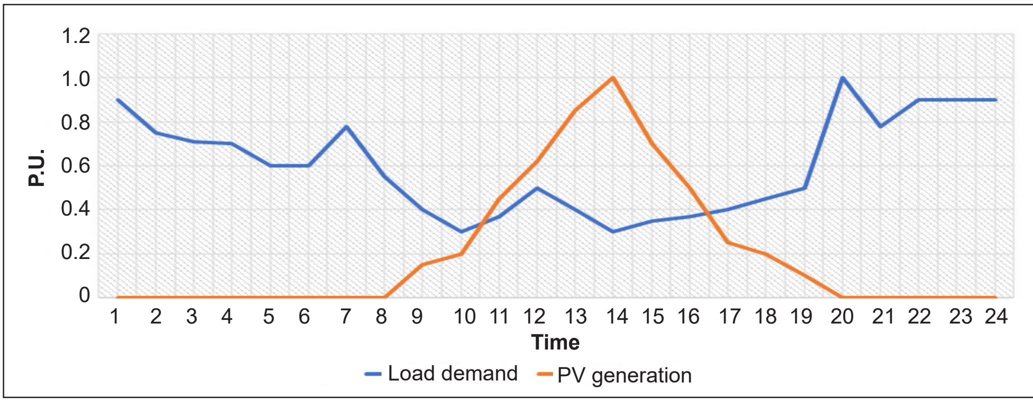

Figure 3. PV generation and load demand profile

The Proposed Reactive Power Controls

The reactive power control algorithm alleviates voltage rise in distribution networks with high photovoltaic (PV) penetration. The algorithm relies on the smart inverter's capacity to absorb or inject reactive power. Smart inverters that link PV systems to the national grid can regulate real power to meet national grid requirements and control reactive power through Iq and Id for active power management. Additionally, voltage control is implemented to adhere to the voltage requirements of the national grid.

This study's proposed reactive power control algorithm considers both PV active injection and the voltage simultaneously at the point of common coupling. In contrast to conventional approaches, the reactive power reference is not solely determined based on PV active injection or network voltage alone. Instead, this technique calculates the delta-reactive power and recalculates every second using Equation 7. This delta-reactive power is then utilized to determine the reactive power reference at a specific time using Equation 8. Consequently, the proposed reactive power control demonstrates enhanced adaptability to varying network parameters, continuously updating in real-time.

$$\Delta Q(t) = (VV * W) + (WV + (1 - W)) \qquad [7]$$

$$Q(t) = Q(t-1) + \Delta Q\ (t) \qquad [8]$$

The proposed technique commences by calculating the influence of PV active power injection on reactive power change (Watt-VAR). A modified fixed power factor method is employed, with the modification setting the starting point at 0.1 instead of 0. This adjustment implies that when there is no PV active power injection, the Watt-VAR aims to increase the reactive power reference by 0.1 per second towards the capacitive mode based on Equation 9. For a visual representation, please refer to Figure 4. Simultaneously, the proposed technique evaluates the impact of the voltage at the point of common coupling on reactive power change (Volt-VAR) in conjunction with Watt-VAR. Volt-VAR is computed using the conventional Q(V) technique, as illustrated in Figure 5 and Equation 10.

$$Watt - Var = \begin{cases} -1, & P \geq P_{max} \\ \dfrac{1.1 * P}{-P_{Max}} + 0.1, & 0 \leq P < P_{Max} \end{cases} \qquad [9]$$

$$Q_{ref} = \begin{cases} Q_{lim}, & V < V_1 \\ \dfrac{Q_{lim}}{(V_1 - V_2)}(V - V_1), & V_1 \leq V < V_2 \\ 0, & V_2 \leq V < V_3 \\ \dfrac{Q_{lim}}{(V_3 - V_4)}(V - V_3), & V_3 \leq V < V_4 \\ -Q_{lim}, & V_4 \leq V \end{cases} \qquad [10]$$

Furthermore, the technique determines the weight, signifying the relative significance of Volt-VAR and Watt-VAR in influencing reactive power change based on the voltage at the point of common coupling. As the voltage increases, the weight also increases, exerting more influence on the Volt-VAR algorithm to adjust reactive power, either increasing or decreasing it. This relationship is depicted in Figure 6 and defined in Equation 11. At 1.2 V (p.u.), the weight is 1, indicating that reactive power change depends entirely on Volt-VAR. Subsequently, the weight gradually decreases until it reaches 0 at 0.6 V (p.u.), signifying that reactive power change relies solely on Watt-VAR. Refer to Figure 6 for the weight calculation. Finally, Figure 7 illustrates the proposed reactive power control flow chart.

$$Weight = \begin{cases} 1\ , & V \geq V_{Max} \\ \frac{1}{(V_{Max} - V_{min})}(V - V_{min}), & V_{Min} < V < V_{Max} \\ 0, & V \leq_{Min} \end{cases} \quad [11]$$

By considering both PV active injection and network voltage in the control strategy, the proposed approach ensures effective interaction with the dynamic changes in the network. This real-time updating capability enhances the system's performance and stability, facilitating efficient reactive power control.

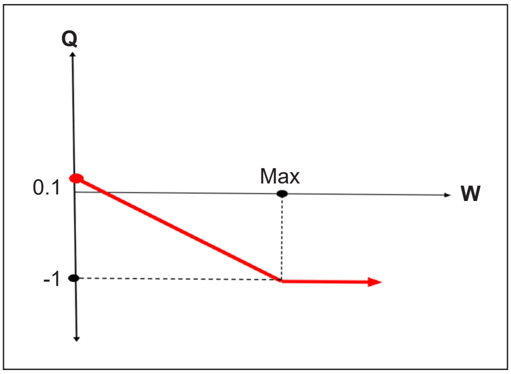

Figure 4. Proposed technique response to PV active power injection

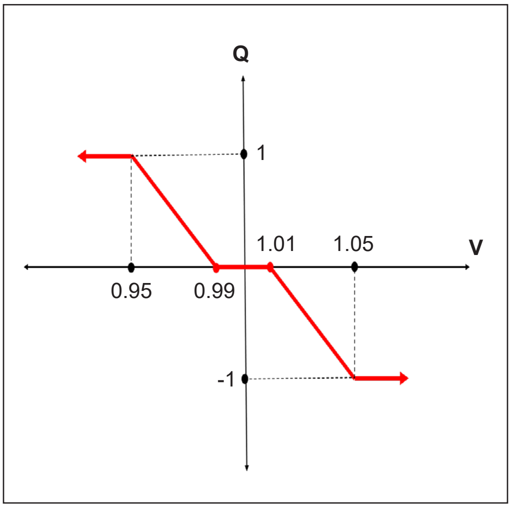

Figure 5. Proposed technique response to the voltage on the point of common coupling

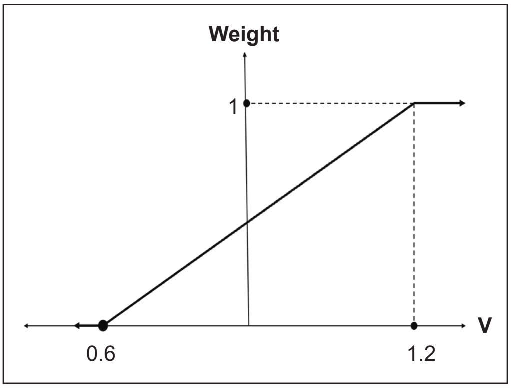

Figure 6. Weight calculation characteristic graph

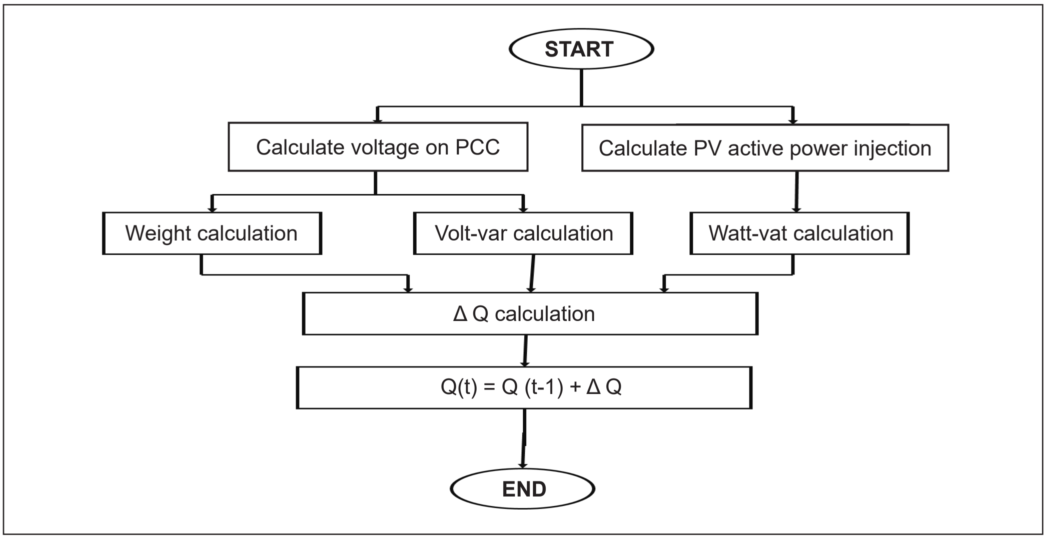

Figure 7. Proposed reactive power control technique flow chart

SIMULATION AND RESULTS

The low voltage distribution network in the residential area of Taman Impian Putra PD in Malaysia, depicted in Figures 1 and 2, was not originally designed to accommodate the high number of distributed generation (DG) sources. Consequently, the increased penetration of PV systems brings numerous challenges to the network. One such challenge is voltage rise, discussed previously.

Simulations were conducted using MATLAB Simulation and OpenDSS on the network with varying levels of PV penetrations to analyze the impact of PV penetration. Figure 8 illustrates the voltages at the point of common coupling for a random house (the last householder of Feeder 3) without any reactive power control. It can be observed that the voltage starts to increase at 10 p.m. due to an increase in sun irradiance and a decrease in load demand. Subsequently, the voltage reaches its maximum at 1 p.m. The voltage declines as the sun irradiance decreases and householders return to their houses. Notably, the figure demonstrates that the level of PV penetration directly influences the maximum voltage increase.

Furthermore, Figure 9 provides insight into the highest and lowest average voltages observed on the distribution network at different penetration levels, all without any reactive power control implemented.

These simulation results highlight the adverse effects of high PV penetration on the network voltage. Without effective reactive power control measures, the voltage levels experience significant daily fluctuations influenced by sun irradiance and load demand variations. It is imperative to address these voltage issues to ensure the reliability and stability of the distribution network.

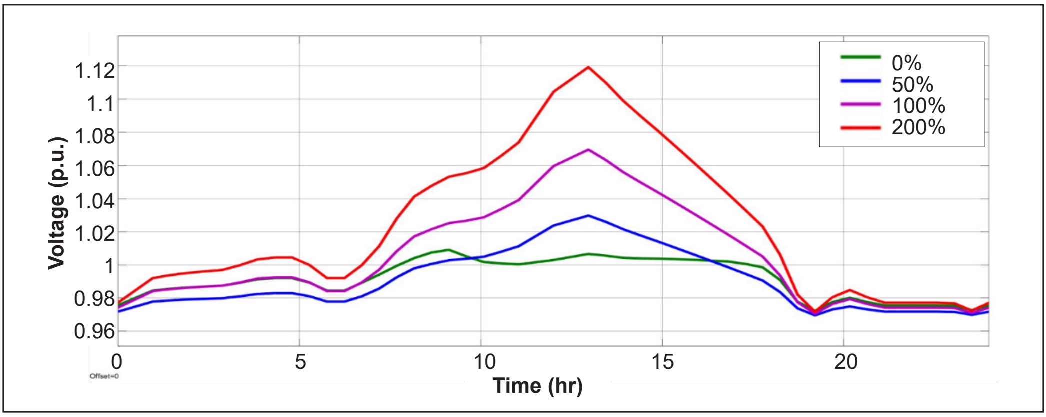

Figure 8. The voltage graph on the point of common coupling of the last customer on Feeder 3 for 24 h without reactive power control for a different level of penetration (0%, 50%, 100%, and 200%)

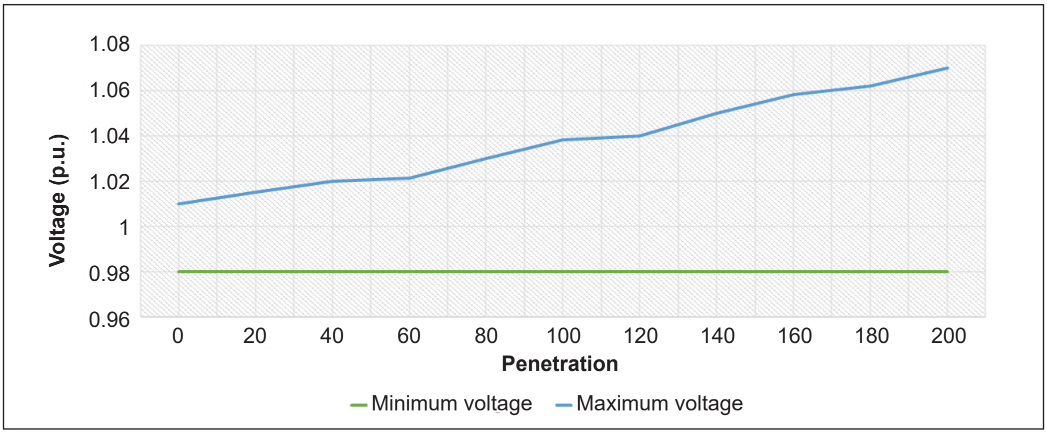

Figure 9. Highest and lowest voltage of distribution network for different levels of PV penetration without reactive power control

As a result, it is crucial to employ a voltage rise mitigation technique on the distribution network to address the challenges posed by high PV penetration. Fortunately, the proposed reactive power control technique demonstrates promising results in mitigating voltage rise and maintaining voltage within the permissible limits of 0.95 to 1.05 per unit (p.u.). Figure 10 presents the distribution network's maximum and minimum average voltages when utilizing the proposed reactive power control at different levels of PV penetration. It is evident from the figure that the proposed technique effectively reduces the average voltage to a highly acceptable level.

The proposed reactive power control achieves this by mitigating the voltage during the mid-day period, characterized by maximum sun irradiance and minimum load demand, as depicted in Figure 11. The figure illustrates the voltage at the point of common coupling of the last customer on Feeder 3 over 24 hours, employing the proposed reactive power control at different penetration levels. The control technique successfully mitigates voltage rise while minimizing losses. It accomplishes this by utilizing a novel control approach that does not rely directly on PV active injection or network voltage. Instead, the instantaneous values of PV active power injection and network voltage are used to calculate the required change in reactive power reference. This approach provides greater flexibility in adapting to variations in network parameters.

Moreover, this technique overcomes the limitations of other methods that solely depend on PV active injection and network voltage, which tend to overlook load variations and rely heavily on network voltage sensitivity. The proposed technique effectively addresses these limitations, improving voltage regulation and reducing losses.

Finally, Figure 12 illustrates the reactive power injection of the reactive power control at the last customer on Feeder 3, highlighting the effectiveness of the proposed control strategy.

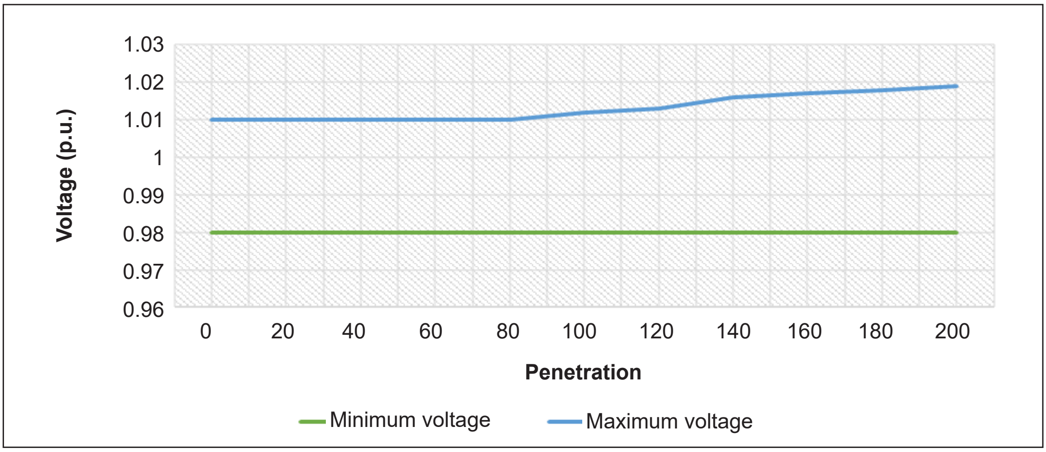

Figure 10. The highest and lowest voltage of the distribution network for different levels of PV penetration with the proposal reactive power control

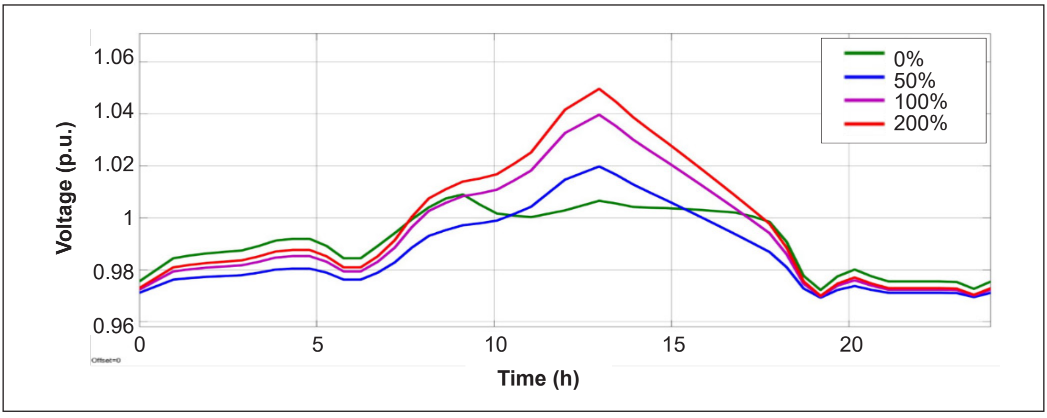

Figure 11. The voltage graph on the point of common coupling of the last customer on Feeder 3 for 24 hours with the proposal reactive power control for a different level of penetration (0%, 50%, 100%, 200%)

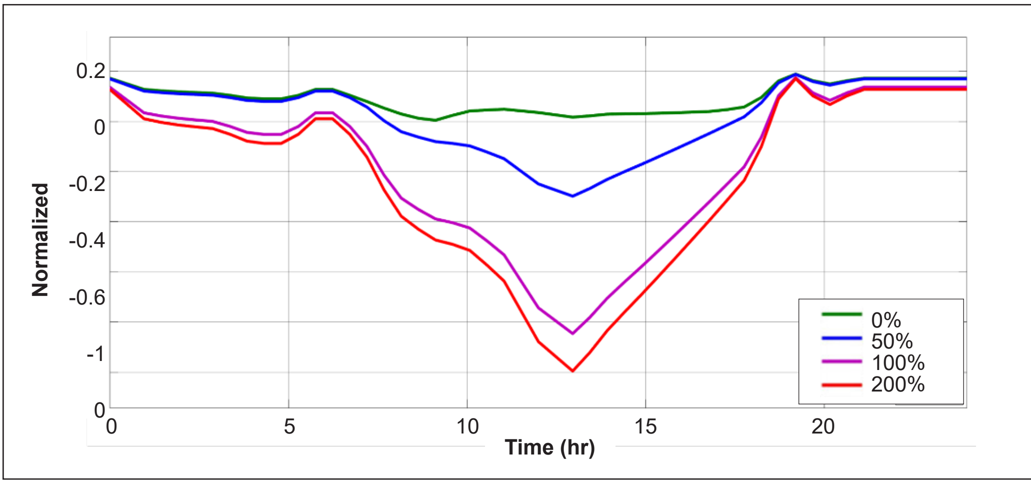

Figure 12. Reactive power injection of the proposal reactive power control for the last customer on Feeder 3 during 24 hours for different level of penetration (0%, 50%, 100%, 200%)

DISCUSSION

This paper's proposed reactive power control technique combines both PV active power injection and the voltage at the point of common coupling. By considering these parameters and a weight determined by the network voltage, the technique calculates the necessary change in reactive power reference. This calculation is repeated every second to provide the control strategy with greater flexibility in adapting to changes in network parameters.

In contrast, existing reactive power control techniques typically depend on PV active power injection or network voltage at specific times. When relying solely on PV active power injection, the control technique is highly influenced by load variations. While this approach can achieve good voltage regulation, it may result in significant unnecessary losses when both PV injection and load demand are high. Moreover, this technique is based on a typical load shape assumption, which may not accurately represent the actual conditions.

On the other hand, network voltage-based reactive power techniques are directly proportional to the network voltage. However, the proponents of this technique overlooked that the network voltage in a specific location reacts differently to changes in active and reactive power, depending on the voltage-active/reactive sensitivity. This sensitivity increases as the distance from the feeder transformer increases. Consequently, this technique may demonstrate good voltage regulation only in high-sensitivity locations. This technique may result in poor voltage regulation for large-scale networks like the one presented in this paper.

However, the proposed technique incorporates active power injection and network voltage, allowing for a more accurate reactive power reference. The two parameters work together to correct each other, albeit at a slower rate compared to other techniques. Unlike these techniques, which have predetermined reactive power references for specific PV active power or network voltage values, the proposed technique adjusts the reactive power reference every second based on the active power injection and network voltage until reaching a stability mode where the change in reference becomes zero. As variations in load demand and sun irradiance are typically not rapid, this technique yields better results compared to existing reactive power control techniques.

Hence, the presented simulation results offer a comprehensive analysis of the impact of photovoltaic (PV) penetration on distribution network voltage and the potential solutions to mitigate associated challenges. In Figure 8, the voltage variations at the point of common coupling for a random house show that increased sun irradiance and reduced load demand during the day result in voltage rise directly influenced by the level of PV penetration. These findings underscore the pressing need to mitigate voltage rise, as the proposed reactive power control technique addresses. The subsequent analysis in Figure 10 reveals that the proposed technique effectively reduces the average voltage to acceptable levels. This control strategy, illustrated in Figure 11, successfully combats voltage rise during peak sun irradiance, demonstrating adaptability to varying network parameters. Notably, this approach outperforms methods reliant solely on PV active injection and network voltage, as it considers load variations and reduces reliance on network voltage sensitivity. Figure 12 confirms the effectiveness of this strategy by showcasing the reactive power injection. In summary, these results emphasize the necessity of implementing innovative reactive power control measures to ensure the reliability and stability of distribution networks amidst high PV penetration, offering valuable insights for future grid management and renewable energy integration.

In summary, the proposed reactive power control technique uses both PV active power injection and network voltage, providing a more accurate reactive power reference. Although slower than other techniques, it achieves better results due to its adaptive nature. This approach surpasses the limitations of existing techniques by considering the dynamic changes in active power injection and network voltage, leading to improved voltage regulation in the distribution network.

CONCLUSION

This paper addresses the pressing issue of voltage rise in low voltage distribution networks in Malaysia, driven by the increasing integration of renewable energy sources and distributed energy resources (DERs). While these developments offer substantial environmental and economic benefits, they bring new challenges, particularly regarding voltage stability. Voltage rises, triggered by the excessive power injection from DERs, can lead to increased energy losses, reduced power quality, equipment damage, and system instability. Conventional voltage control methods have limitations in effectively addressing these challenges, especially in dynamic DER integration.

This paper introduces a novel reactive power control strategy that simultaneously considers PV active power injection and network voltage to overcome these limitations. Unlike traditional approaches, this technique continuously updates its reactive power reference based on real-time changes in PV power generation and network voltage, offering greater flexibility to adapt to varying network parameters. Simulation results on a representative distribution network in Malaysia demonstrate the effectiveness of this technique in mitigating voltage rise and maintaining voltage within permissible limits under different penetration levels.

The proposed technique strikes the drawbacks of existing methods, which primarily rely on PV active injection or network voltage. Considering both parameters provides more precise control over reactive power output, ensuring improved voltage regulation and reduced losses. The technique's adaptability to variations in load demand and sun irradiance positions it as a promising solution for the challenges posed by high PV penetration in distribution networks. Overall, this research offers valuable insights into enhancing the reliability and stability of distribution networks in the face of increasing renewable energy integration and sets the stage for further developments in grid management and clean energy adoption.

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