

Impact of Reactive Power Compensation on Voltage Profile in Renewable-Integrated Distribution Network

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Received 11 January 2026, Revised 23 February 2026, Accepted 15 March 2026

ABSTRACT

The increasing integration of renewable energy sources, especially solar photovoltaic (PV) systems, poses challenges such as voltage fluctuations and power quality issues in modern power networks. Reactive power support has become an effective solution to enhance voltage stability and minimize system losses. This study investigates the impact of reactive power compensation on the IEEE 14-bus distribution system using ETAP software. The system is modified to include solar PV units at selected buses, and 150 kVAR capacitor banks are optimally placed to provide reactive power support. Load flow analysis and the Voltage Deviation Index (VDI) are used to assess performance improvements. Simulation results show that optimal capacitor placement significantly improves voltage profiles, with all bus voltages maintained within the acceptable range of 0.95 p.u. to 1.05 p.u., while reducing active power losses. The findings highlight the importance of reactive power management to ensure the reliable and efficient operation of distribution networks with high penetration of renewable energy sources, and they align with SDG 7 (Affordable and Clean Energy).

Keywords: Capacitor Banks, IEEE 14 bus, Reactive Power Compensation, Solar Photovoltaic Integration, Voltage Profile.

1. INTRODUCTION

The rapid growth of electricity demand and the global transition towards sustainable energy have accelerated the integration of renewable energy sources into power distribution networks. Among these sources, solar photovoltaic (PV) systems have gained significant attention due to their environmental benefits and scalability [1][2]. However, the intermittent and non-dispatchable nature of solar PV generation introduces technical challenges, particularly in maintaining voltage stability and power quality within distribution networks. Voltage fluctuations, undervoltage conditions, and increased system losses are commonly observed in networks with high renewable penetration, especially at buses located far from generation sources [3-5].

Reactive power plays a vital role in maintaining voltage stability and ensuring the efficient operation of power systems. Insufficient reactive power support can lead to voltage instability, increased line losses, and, in severe cases, system collapse [6][7]. Traditional power systems relied on centralized generation units to provide reactive power support; however, the increasing penetration of renewable energy sources has reduced the availability of inherent reactive power reserves. As a result, effective reactive power compensation strategies have become essential to support voltage regulation in modern distribution networks [8][9].

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Shunt capacitor banks are among the most widely adopted and cost-effective solutions for reactive power compensation [10-12]. When properly placed, capacitor banks can supply local reactive power demand, reduce reactive power flow through transmission lines, and improve overall voltage profiles. In renewable-integrated systems, capacitor banks complement solar PV installations by mitigating voltage deviations caused by fluctuating power generation [6]. Therefore, evaluating the impact of reactive power compensation in such networks is crucial for ensuring reliable and sustainable power system operation [13-15].

This study focuses on analyzing the impact of reactive power compensation on the improvement of the voltage profile in a renewable-integrated distribution network using ETAP software. An IEEE 14-bus system is employed as the test network, incorporating solar PV units and shunt capacitor banks. The system performance is assessed through load flow analysis under different operating scenarios, and voltage stability is validated using the Voltage Deviation Index (VDI). The findings of this study provide valuable insights into the effectiveness of reactive power compensation in enhancing voltage regulation and supporting the integration of renewable energy sources in distribution networks.

2. MATERIAL AND METHODS

This study evaluates the impact of reactive power compensation on the improvement of the voltage profile in a renewable-integrated distribution network using ETAP software. The methodology is designed to analyze system performance under different operating conditions systematically and to validate the effectiveness of reactive power support. The overall procedure includes system modeling, renewable energy integration, reactive power compensation, load flow analysis, and validation of voltage stability.

2.1 System Modeling and Data

The IEEE 14-bus distribution network is selected as the test system due to its widespread use as a benchmark model in power system analysis and research [16]. The system consists of buses, generators, transmission lines, transformers, and loads that represent a realistic medium-scale power network. The complete system is modeled in ETAP by accurately defining electrical parameters, including bus voltage levels, line impedances, transformer ratings, and load demands.

The base case model represents the original IEEE 14-bus system without renewable energy integration or reactive power compensation. This configuration serves as the reference case for evaluating the effects of solar PV integration and reactive power support on voltage profiles and system performance.

2.2 Solar Photovoltaics Integration

To represent a renewable-integrated distribution network, solar photovoltaic (PV) units are incorporated into the IEEE 14-bus system at selected buses, as shown in Figure 1. The PV systems are modeled in ETAP with appropriate inverter ratings, operating voltage levels, and power output characteristics. The integration of solar PV introduces variability in power injection, which affects voltage regulation, particularly at buses located far from the main generation sources [2] [17].

The PV-integrated system is analyzed using load flow simulations to observe changes in voltage magnitudes, power flow distribution, and reactive power demand. This scenario assesses how renewable energy sources affect voltage profiles and highlights the need for additional reactive power support.

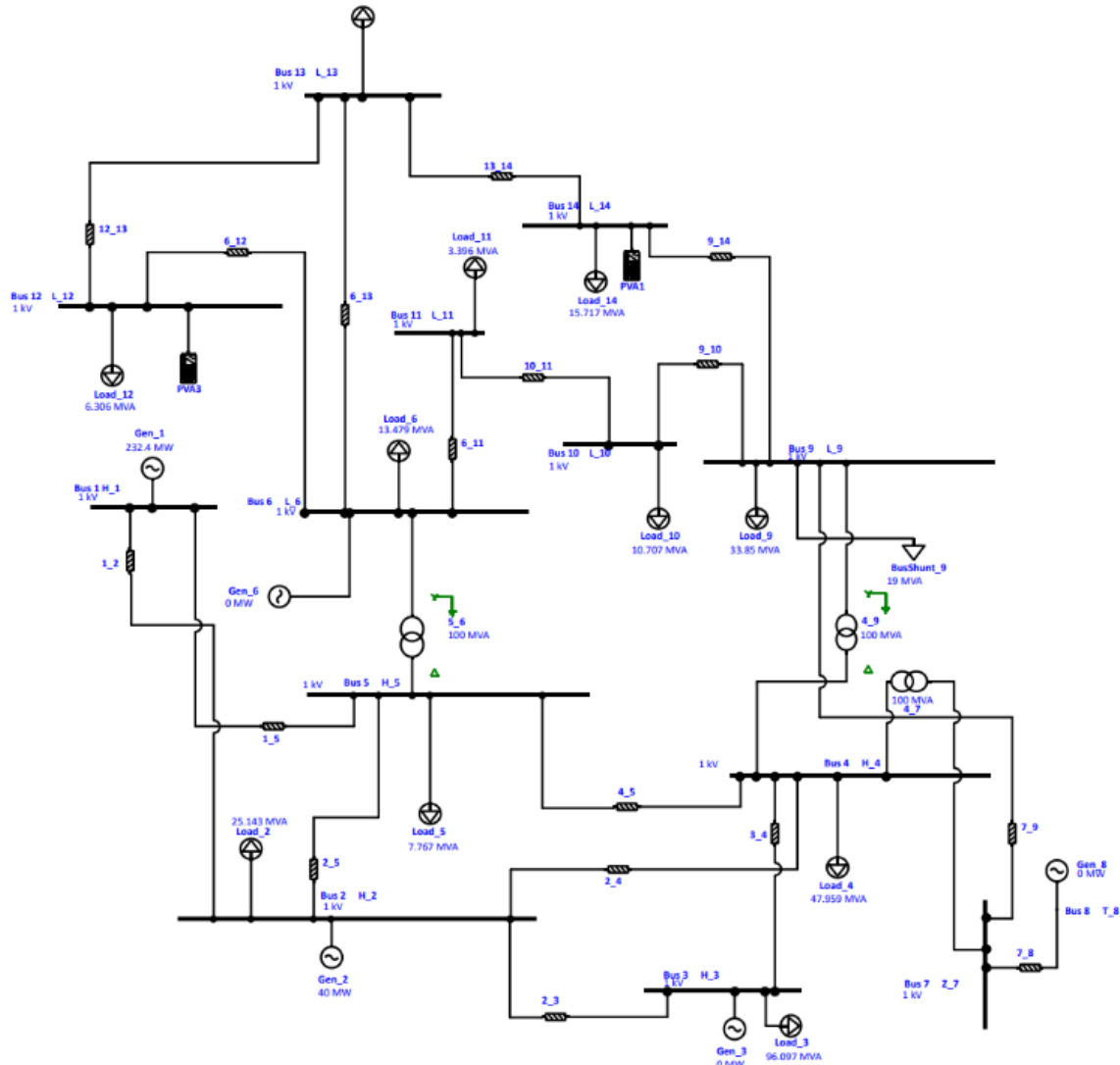


Figure 1: The single-line diagram voltage profile with solar PV Integration.

2.3 Reactive Power Compensation Using Capacitor Banks

Reactive power compensation is implemented using shunt capacitor banks to improve voltage stability and reduce reactive power flow in the network [9]. Fixed-capacity capacitor banks rated at 150 kVAR are installed at selected buses identified as weak points based on voltage magnitude and reactive power demand from the load flow results. These buses typically experience undervoltage or significant voltage deviations during operation with renewable energy integration. The capacitor banks are modeled in ETAP to supply local reactive power, thereby supporting voltage regulation and reducing the burden on upstream generators. Multiple simulation cases are evaluated to ensure that capacitor placement effectively improves voltage profiles without causing overvoltage.

2.4 Load Flow Analysis

Load flow (or power flow) analysis is essential for determining the steady-state conditions of the power network [18]. In this study, ETAP's Newton-Raphson method is employed due to its high accuracy and fast convergence for large, interconnected systems. This analysis provides detailed information on bus voltage magnitudes, active and reactive power flows, and system losses under steady-state conditions [19].

$$P_i = \sum_{j=1}^n |V_i| |V_j| (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \quad (1)$$

$$Q_i = \sum_{j=1}^n |V_i| |V_j| (G_{ij} \sin \theta_{ij} + B_{ij} \cos \theta_{ij}) \quad (2)$$

where P_i and Q_i represent the active and reactive power injected at bus i , V_i and V_j are the voltage magnitudes at buses i and j , G_{ij} and B_{ij} are the conductance and susceptance elements of the bus admittance matrix, and θ_{ij} is the voltage angle difference between buses i and j .

The constraint of this project is:

$$0.95 \text{ p.u.} \leq V_i \leq 1.05 \text{ p.u.} \quad (3)$$

The load flow analysis is conducted under three operating scenarios:

1. Base case without solar PV and reactive power compensation,
2. System with solar PV integration only,
3. System with solar PV integration and reactive power compensation using capacitor banks.

The results from these scenarios are compared to evaluate the effectiveness of reactive power compensation in improving voltage profiles and overall system performance.

2.5 Voltage Stability Validation Using Voltage Deviation Index

The Voltage Deviation Index (VDI) is used to quantitatively assess voltage stability and validate the improvement achieved through reactive power compensation [20][21]. The VDI measures the deviation of bus voltage magnitudes from the nominal value of 1.0 p.u. and is expressed as a percentage. Lower VDI values indicate better voltage regulation and improved system stability. VDI calculations are carried out for all buses under each operating scenario. A comparative analysis of VDI values before and after reactive power compensation is conducted to demonstrate the effectiveness of capacitor banks in mitigating voltage deviations and enhancing voltage stability in the distribution network integrated with renewables.

$$VDI (\%) = \frac{V_{measured} - V_{nominal}}{V_{nominal}} \times 100 \quad (3)$$

where $V_{measured}$ represents the measured voltage magnitude at a particular bus obtained from the load flow analysis, and $V_{nominal}$ denotes the nominal bus voltage, which is taken as 1.0 p.u. in this study. A positive VDI value indicates an overvoltage condition, while a negative value indicates an undervoltage condition. Lower absolute VDI values signify better voltage regulation and improved system stability.

3. RESULTS AND DISCUSSION

This section presents and discusses the simulation results obtained from the IEEE 14-bus distribution network analyzed using ETAP. The system performance is evaluated under three operating scenarios:

- (i) base case without solar PV integration and reactive power compensation,
- (ii) system with solar PV integration, and
- (iii) system with solar PV integration and reactive power compensation via shunt capacitor banks.

The discussion focuses on voltage profile behavior and on improving voltage stability, supported by the Voltage Deviation Index (VDI).

3.1 Voltage Profile Analysis for Base Case

In the base-case scenario, the IEEE 14-bus system is analyzed without any renewable energy integration or reactive power compensation. The load flow results indicate that several buses experience voltage magnitudes below the IEEE-recommended operational limit of 0.95 p.u., particularly those farther from the main generation source. These undervoltage conditions reflect insufficient reactive power support within the network and highlight the inherent weakness of the system under normal operating conditions.

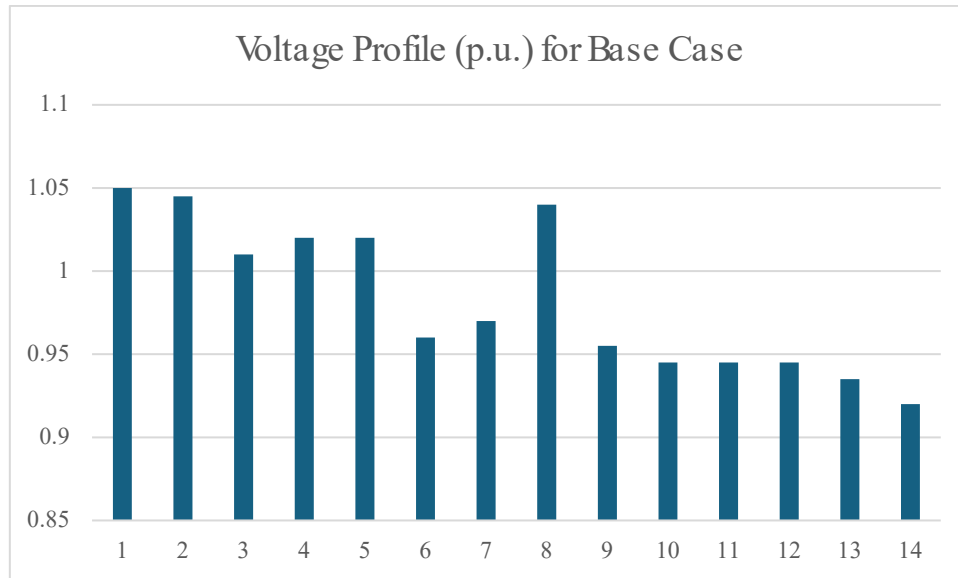


Figure 2: Voltage profile of the IEEE 14-bus system under base case operation without solar PV integration and reactive power compensation.

The voltage magnitude stability analysis indicates that not all buses in the system operate within the standard acceptable voltage range of 0.95 p.u. to 1.05 p.u., which is required to ensure reliable and stable power delivery. As illustrated in the voltage profile, Bus 1 and Bus 2 exhibit the highest voltage magnitudes, both operating close to 1.05 p.u., confirming that buses located near regulated generation sources maintain stable voltage conditions.

In contrast, several downstream buses experience significant voltage drops. Specifically, Bus 10 (0.942 p.u.), Bus 11 (0.943 p.u.), Bus 13 (0.935 p.u.), and Bus 14 (0.921 p.u.) operate below the minimum acceptable voltage limit of 0.95 p.u., indicating undervoltage conditions. Among these buses, Bus 14 records the lowest voltage magnitude, identifying it as the weakest bus in the network.

The observed undervoltage conditions are primarily due to increased reactive power demand and cumulative voltage losses along distribution lines as the distance from the generation source increases. These results clearly demonstrate that the base-case system lacks sufficient reactive power support, underscoring the need for reactive power compensation to enhance voltage regulation and improve overall system stability.

3.2 Impact of Solar Photovoltaic Integration on Voltage Profile

To improve the voltage profile of the IEEE 14-bus system, solar photovoltaic (PV) units were installed at Bus 12 and Bus 14, which were identified as weak buses with relatively low voltage

levels in the base case load flow analysis. The primary objective of this integration is to evaluate the capability of distributed generation (DG) in enhancing voltage stability through local power injection.

Table 1: Technical Specifications of PV systems and inverters.

Component	Parameter	Specification
PV Module	Manufacturer	Photo-watt
	PV Technology	Multi-crystalline
	Number of Cells	36
	PV Model	PW6-110
	Rated Power	110.3 W
	Operating Temperature	30 °C
Inverter	DC Power Rating	250 kW
	DC Voltage Rating	600 V
	AC Output Rating	0.4 kV, 225 kVA

The technical specifications of the installed PV systems are summarized in Table 1. The PV units are based on a Photo-watt PW6-110 multi-crystalline module, selected for its suitability in medium-scale applications and compatibility with distribution-level networks. Each module has a rated power output of 110.3 W and operates under standard ambient conditions.

For grid interfacing, a compatible inverter is employed to convert DC power to AC power. The inverter is rated at 250 kW DC and 600 V, with an AC output of 225 kVA at 0.4 kV, ensuring proper integration with the IEEE 14-bus system. The selected PV and inverter configuration provides adequate local power support at the targeted buses, contributing to improved voltage conditions and enhanced overall system stability.

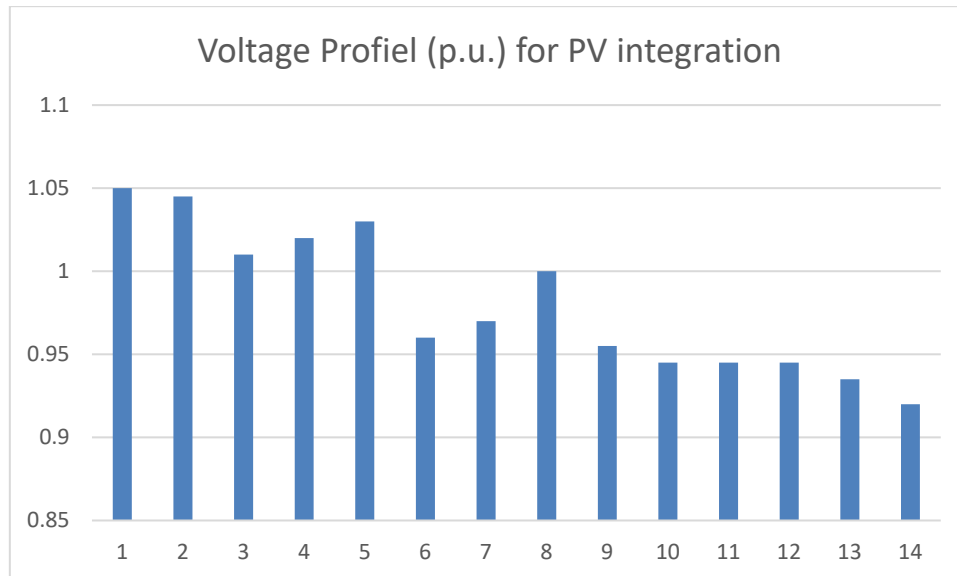


Figure 3: Voltage profile of the IEEE 14-bus system with solar PV integration.

Following the integration of solar photovoltaic (PV) systems at Bus 12 and Bus 14, a moderate improvement in voltage magnitude is observed across several buses compared to the base case (Figure 3). Buses near the PV installation points exhibit noticeable voltage increases due to local active power injection, indicating the positive contribution of distributed generation to voltage support.

However, despite this improvement, undervoltage conditions persist at downstream buses, particularly Bus 10, Bus 11, Bus 12, Bus 13, and Bus 14, with voltage magnitudes remaining below

the minimum acceptable limit of 0.95 p.u. Notably, Bus 14 continues to exhibit the lowest voltage level, suggesting that solar PV integration alone is insufficient to fully mitigate voltage instability. This is mainly because the PV units primarily supply active power, while reactive power support remains limited. These findings highlight the need for additional reactive power compensation to further improve voltage regulation and system stability.

3.3 Impact of Reactive Power Compensation Using Capacitor Banks

To address the remaining undervoltage issues, reactive power compensation is implemented through the installation of shunt capacitor banks at selected buses identified as weak points in the system. Capacitor banks are placed at Bus 5, Bus 9, Bus 10, Bus 11, and Bus 13, each rated at 150 kVAr, to provide localized reactive power support and improve voltage regulation.

The implementation of capacitor banks results in significant voltage improvement at the compensated buses (Figure 4). For instance, Bus 11, which previously experienced undervoltage conditions, achieves a voltage magnitude of 0.998 p.u. after installing 25 capacitor banks, restoring its operation within the acceptable voltage range. Overall, the use of shunt capacitor banks effectively mitigates undervoltage issues and enhances network voltage stability.

The improvement is attributed to the ability of capacitor banks to supply reactive power locally, thereby reducing reactive power flow through transmission lines and minimizing voltage drops. This local compensation mechanism effectively strengthens weak buses and improves overall voltage regulation. The results confirm that reactive power compensation with shunt capacitors is an effective and practical solution for improving the voltage profile in renewable-integrated distribution networks.

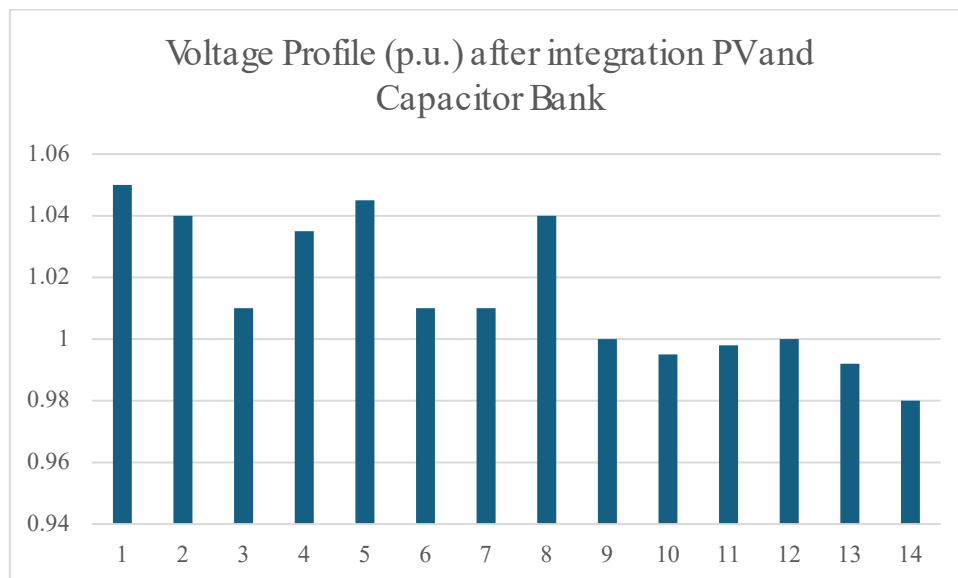


Figure 4: Voltage profile of the IEEE 14-bus system with solar PV integration and reactive power compensation.

3.4 Voltage Deviation Index

The Voltage Deviation Index (VDI) is used to quantitatively assess the improvement in the voltage profile achieved through reactive power compensation. In the base case, several buses exhibit high negative VDI values, indicating poor voltage regulation and significant deviation from the nominal voltage. After solar PV integration, the VDI values decrease slightly, reflecting partial improvement in voltage stability.

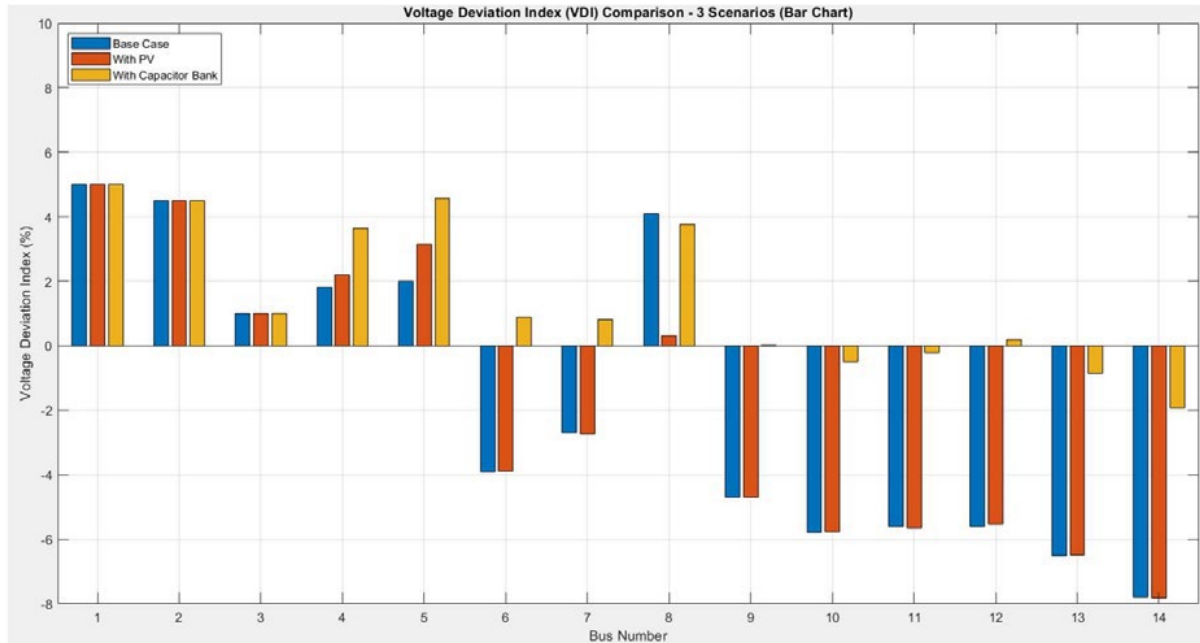


Figure 5: Voltage profile of the IEEE 14-bus system with Solar PV integration and Reactive Power Compensation.

Figure 5 presents the comparison of the Voltage Deviation Index (VDI) for the IEEE 14-bus system under three operating scenarios: base case, with solar PV integration, and with combined solar PV and reactive power compensation using capacitor banks. In the base case, several buses exhibit large negative VDI values, particularly at downstream locations, indicating significant undervoltage conditions and poor voltage regulation.

With the integration of solar PV, a slight improvement in VDI values is observed at buses located near the PV installation points. However, substantial negative deviations persist at downstream buses, demonstrating that solar PV integration alone is insufficient to fully mitigate voltage instability across the network. The most pronounced deviations remain at buses near the end of the feeder, where voltage sensitivity to reactive power demand is highest.

Following the installation of shunt capacitor banks, the VDI values are significantly reduced across all buses and approach zero, indicating effective voltage regulation. Notably, buses that previously experienced severe undervoltage conditions, such as Bus 10 to Bus 14, show substantial improvement, confirming the effectiveness of reactive power compensation in stabilizing voltage levels and enhancing overall system performance.

4. CONCLUSION

This study investigated the impact of reactive power compensation on the improvement of the voltage profile in a renewable-integrated distribution network using ETAP software. An IEEE 14-bus system was analyzed under three operating scenarios, namely the base case, system with solar photovoltaic (PV) integration, and system with both PV integration and shunt capacitor banks.

The simulation results show that the base case system experiences undervoltage conditions at several buses due to insufficient reactive power support. The integration of solar PV slightly improves the voltage profile by injecting active power closer to the load; however, this improvement is insufficient to maintain all bus voltages within acceptable operational limits. The addition of shunt capacitor banks provides effective reactive power support, resulting in a

significant improvement in the voltage profile, with all buses operating within the IEEE-recommended range of 0.95 p.u. to 1.05 p.u.

Furthermore, the Voltage Deviation Index (VDI) validation confirms that reactive power compensation significantly enhances voltage regulation by reducing voltage deviations across the network. The findings highlight the importance of integrating renewable energy with appropriate reactive power compensation strategies to ensure the stable and reliable operation of modern distribution networks. Future work may consider the application of advanced reactive power devices or optimization techniques to further enhance system performance under varying load and generation conditions.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support from the Faculty of Electrical Engineering & Technology, Universiti Malaysia Perlis (UniMAP), which facilitated this research. Appreciation is also extended to all individuals who contributed directly or indirectly to the completion of this study.

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Conflict of interest statement: The authors declare no conflict of interest.

Author contributions statement: Conceptualization, Aminudin Anuar; Methodology, Aminudin Anuar and W. M. Afnan; Software, W. M. Afnan; Validation, Aminudin Anuar and Chin-Leong Wooi; Formal Analysis, W. M. Afnan; Investigation, W. M. Afnan; Resources, Aminudin Anuar; Data Curation, W. M. Afnan and Chin-Leong Wooi; Writing – Original Draft Preparation, W. M. Afnan; Writing – Review & Editing, Aminudin Anuar and Chin-Leong Wooi; Visualization, W. M. Afnan; Supervision, Aminudin Anuar; Project Administration, Aminudin Anuar.

Data Availability Statement: All data generated or analyzed during this study are included in this published article.