SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V13I6P105

Volume 13 Issue 6, 64-77, June 2026

Original Article

Coordination and control of PV Energy and Voltage Regulating Devices in an Active Distribution Network under Uncertainty

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Received: 12 March 2026 Revised: 11 April 2026 Accepted: 10 May 2026 Published: 29 June 2026

Abstract - *The introduction of Distributed Energy Resources (DERs) into distribution networks leads to dynamics in power system operations, such as bidirectional flow of current in power system networks caused by the uncertainty of loading and PV power output. This has caused a lot of challenges, such as power flow imbalance, voltage fluctuation, and operation control of voltage regulation devices. The conventional voltage regulating techniques are unsuitable for adapting to the bidirectional power flow introduced by DERs. To address the aforementioned problem, this study presents an optimization-based approach that minimizes generation cost while enhancing voltage in active distribution networks with High Photovoltaic (PV) system penetration. A reactive power control strategy is embedded in the Optimal Power Flow (OPF) to dynamically regulate the reactive power within Grid-Connected Inverters (GCI) to avoid excessive import and exporting of reactive power. The approach also determines the optimal set points of On-Load Tap Changers (OLTC) and Distribution Static Synchronous Compensators (DSTATCOM) to ensure effective voltage control and reduction of active power losses. Simulation analysis of the proposed approach was tested on modified IEEE bus 69 networks with high penetration of PV energy. The simulation results demonstrate the effectiveness of the techniques in minimizing the cost of power generation, optimizing the reactive power of the GCI, determining the set points of OLTC and DSTATCOM, while ensuring an effective voltage profile for all the buses in the networks under the uncertainty of loading and PV power output. The techniques support grid operation with high penetration of DERs by leveraging inverter-based distributed energy resources and conventional voltage regulation devices to achieve technical and economic efficiency. It provides a scalable solution for distribution system operators managing networks with increasing renewable energy integration.*

Keywords - *Coordination control, Distributed energy resources, PV energy, Voltage regulating devices, Uncertainty.*

1. Introduction

Energy plays a fundamental role in driving the economic growth and development of any nation. In recent years, global commitments such as the United Nations-backed Paris Agreement have placed strong emphasis on reducing carbon emissions. As a result, countries that have traditionally relied on fossil fuels are increasingly transitioning to cleaner, more sustainable energy sources [1].

One widely adopted strategy for meeting these environmental targets is integrating Distributed Energy Resources (DERs) into existing power distribution networks. While this transition supports sustainability goals, it also introduces new operational challenges. In particular, the presence of DERs enables bidirectional power flow within the network, which significantly complicates the control and coordination of system parameters [2]. Conventional power system control devices were originally designed under the assumption of unidirectional power flow from generation to load. However, when DER generation at a specific node exceeds the local demand, reverse power flow can occur. This phenomenon can disrupt the normal operation of voltage regulation equipment, including devices such as On-Load Tap Changers (OLTCs) installed at substations. Consequently, maintaining stable voltage profiles and ensuring reliable system operation becomes more complex in modern distribution networks with high DER penetration.

The increase in the integration of DERs caused both technical and operational problems for power system operators [3] due to the uncertainty in the network loading conditions and the DERs' output. These developments place significant strain on conventional design and operational practices in electrical networks [4-7]. To address these challenges, Active Distribution Network Management (ANM) has gained prominence as a flexible and adaptive control approach [8]. ANM encompasses a range of strategies aimed at dynamically managing distribution systems with high penetration of distributed energy resources. Its primary objective is to ensure reliable operation by coordinating power flows, minimizing system losses, improving efficiency, and maintaining network parameters within acceptable operational limits.

A key aspect of ANM is the effective utilization of voltage regulation and reactive power compensation devices. Commonly deployed technologies include On-Load Tap Changers (OLTCs), Switched Capacitor Banks (SCBs), as well as Flexible AC Transmission Systems [9, 10]. These devices operate using different mechanisms to maintain voltage stability. For instance, OLTCs regulate voltage by modifying transformer tap positions, while SCBs and DSTATCOMs provide voltage support through reactive power injection or absorption.

However, SCB has delayed operational response characteristics and restricted switching capability, whereas FACT devices such as the Distribution Static Synchronous compensator DSTACOM has fast response time. Therefore, DSTATCOM is preferable to SCB for quick voltage control.

In modern Active Distribution Networks (ADN), the DERs, such as PV energy, are connected to the networks through a Grid-Connected Inverter (GCI), introducing challenges like uncertainty in the output power, affecting the voltage at the connection point, and leading to reverse power flow. When multiple DERs operate simultaneously, they may inject excess power into the grid, causing overvoltage in some areas and voltage dips elsewhere.

Additionally, the variability of DERs output, influenced by factors like wind speed and solar irradiance, complicates load balancing and network management. Moreover, excessive generation can also result in backward power flow, posing grid stability and equipment risks. To mitigate these challenges, advanced control techniques must be developed to coordinate the grid-connected inverter with voltage-regulating devices, ensuring a stable and reliable power system.

Several strategies for controlling DERs operation with traditional voltage-regulating devices have been investigated in the literature. A central active and reactive power control optimization for PV-based DERs was introduced by [11] using piecewise linear functions. However, the approach did not consider the cost of uncertainties in generation, especially from DERs. The authors in [12] introduced distributed adaptive robust control of Volt/VAR to minimize power losses in distribution networks.

However, this method requires multiple control centers to perform the voltage and reactive power optimization. Reference [13] introduced local voltage and reactive power control based on model-free extremum seeking to reduce network power losses. However, this method faced the challenge of high computational requirements. The hosting capacity of the distribution network sensitivity to ANM, such as OLTC, and the active and reactive power control capabilities of the PV smart inverter were studied by [14]. However, the control settings of the Volt/VAR and Volt/Watt operation modes of the smart inverter were not optimized. The author in [15] proposed probabilistic coordination of PV DERs with OLTC and Electrical Vehicles (EVs) to obtain maximum hosting capacity.

The probabilistic approach will face limitations due to the reliance on accurate probability distributions, which are challenging to obtain in dynamic and uncertain environments, and this will reduce the system’s reliability under unforeseen scenarios. In reference [16], a data-based distributional robust stochastic OPF methodology was proposed to mitigate overvoltage in distribution networks by controlling the setpoints of PV smart inverters and energy storage devices.

The limitation of this method lies in its dependence on the quality and quantity of historical data, which may not capture rare events or dynamic changes accurately, leading to suboptimal control under highly uncertain or evolving conditions. In addition, since the approach relies on historical data and probability distributions, it may struggle to adapt quickly to sudden grid disturbances or unforeseen events. Reference [17] proposed a multi-mode data-driven method that coordinated conventional voltage control devices and PV inverters.

However, this method did not consider the effects of PV and load variation. Authors in [18] proposed a centralized constraint linear OPF to coordinate the action of PV energy OLTC and DSTATCOM in the presence of uncertainty regarding load and PV energy. The approach linearized the load flow equation, which tends not to give a real-life scenario for power system networks whose operations are nonlinear in nature. In addition, the cost of uncertainties in generation, especially from PV and wind sources, was not incorporated into the model’s objective function.

A multi-objective reactive power optimization strategy for distribution networks integrated with Photovoltaic (PV) generation was presented in [19] to mitigate power quality deterioration. The study formulated the optimization problem using the Non-dominated Sorting Genetic Algorithm III (NSGA-III), which was employed to obtain effective Pareto-optimal solutions. The findings revealed that the proposed NSGA-III approach achieved approximately 25% reduction in active power loss, whereas other comparative approaches resulted in less than 10% reduction in PV active power output.

Despite the improvement in loss reduction, conventional reactive power optimization approaches still exhibit limitations in computational efficiency and global search capability. In addition, these methods provide limited consideration of real-time operational cost variations associated with the intermittent and uncertain nature of renewable energy sources. In [20], a simulated annealing-based optimization approach was applied to mathematical models integrating photovoltaic generation, wind energy systems, and electric vehicles in active distribution networks.

The study reported considerable improvements in voltage profile regulation and reductions in total network power losses after optimization. Nevertheless, the model did not explicitly incorporate the impact of fluctuating generation costs associated with renewable energy intermittency, thereby limiting its effectiveness for economic operation under uncertain conditions. Reference [21] introduced an enhanced Particle Swarm Optimization (PSO) technique integrated with an ε-greedy search mechanism for solving a multi-objective reactive power optimization problem. The obtained simulation results indicated that the enhanced PSO approach outperformed conventional PSO and NSGA-II methods in minimizing active power losses and improving static voltage stability.

The incorporation of the ε-greedy strategy improved the exploration capability of the algorithm during the initial search stages while reducing premature convergence to local optima in later iterations. Consequently, the proposed method demonstrated improved robustness and effectiveness in identifying near-global optimal solutions. The techniques enhance reactive power optimization. However, the approach lacks mechanisms to track or minimize power generation cost variations in real-time as renewable availability changes. Authors in [22] proposed a multi-objective reactive power and voltage optimization model and introduced the grey wolf optimization algorithm to effectively improve the system node voltage quality and improve the stable operation level of the system. The approach improves voltage quality and system stability but lacks real-time adaptability to sudden fluctuations or unpredictable renewable energy behavior. In addition, the cost of uncertainties in generation, especially from PV and wind sources, was not incorporated into the model's objective function. The different optimization techniques focus on reactive power and voltage optimization; these approaches of reactive power may not really consider the cost optimization for active power generation under the uncertainty of the DERs and the loading condition. To this end, this research proposes an approach that focuses on cost optimization to coordinate and control Photovoltaic generation systems and voltage control equipment operating under uncertain solar power output and varying load demand conditions."

The significant contribution of the research is as follows:

1. The proposed approach helps to minimize the cost of power generation and maintain the voltage within acceptable limits by adjusting the reactive power output of the grid-connected inverter and determining the optimal set points of the voltage regulating devices in the active distribution network under the uncertainty of loading and PV output.
2. The approach improves power system efficiency in the presence of uncertainty by determining the optimal set points for voltage regulating devices by minimizing energy losses and improving overall system efficiency.
3. The control of the reactive power of the inverter embedded, along with the optimal dispatch of other system resources determined by OPF, ensures that reactive power is appropriately generated and consumed, which reduces the excessive reactive power that can result in active losses in the networks.
4. The proposed approach helps to dynamically adjust the reactive power output of the grid-connected inverter in response to real-time grid conditions, improving the integration of variable renewable Energy into the grid, and ensuring that renewable energy sources are better managed and their impact on grid stability is minimized.

2. Problem Formulation

The network topology of an active distribution network that integrates a Grid-Connected Inverter ($_{GCI}$) is presented in Figure 1.

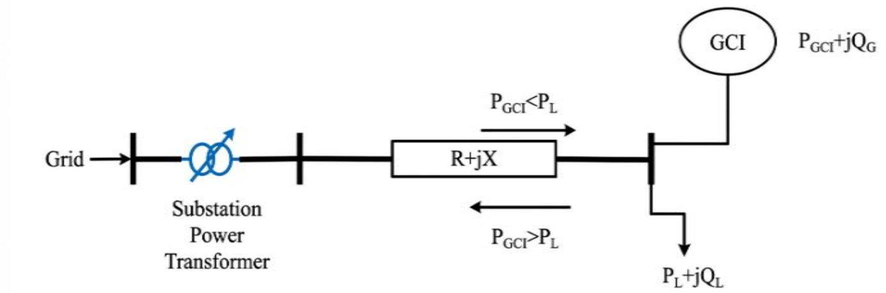


Fig. 1 Topology of active distribution networks with GCI

The behavior of the power flow and the voltage in the networks changes due to the presence of the GCI. The traditional real and reactive power flow equation when the power system is flowing in one direction is presented in first part of Equations (1) and (2) respectively, with the integration of GCI, the power flow equation is modified as in the second part of Equations (1) and (2) for active and reactive power flow respectively, the behavior of the GCI and the load at the point of connection determines the flow of current in the networks, when the active power of the GCI (P_{GCI}) is greater than the active power of the load at the point of connection there will be reverse power flow to the substation, this dynamics in the behavior of the GCI has affects the voltage regulating devices such as OLTC in the substation and other voltage regulation in the networks.

$$P_m = \begin{cases} P_{m-1} - P_L - P_{losses} & no\ GCI \\ P_{GCI} + P_{m-1} - P_L - P_{losses} & with\ GCI \end{cases} \quad (1)$$

$$Q_m = \begin{cases} Q_{m-1} - Q_L - Q_{losses} & no\ GCI \\ Q_{m-1} - Q_L - Q_{losses} \pm Q_{GCI} & with\ GCI \end{cases} \quad (2)$$

Where Pm_{-1} is the active power flow from bus m-1 connected to m, P_L at bus m, P_{losses} is the losses along the line, P_{GCI}, is the active power from the GCI, Q_{m-1} is the reactive power flow from bus $m-1$ connected to m, Q_L at bus m, Q_{losses} is the losses along the line, Q_{GCI}, is the reactive power that the GCI can import or export for voltage control.

To evaluate the influence of active and reactive power injection from the Grid-Connected Inverter (GCI) on voltage behavior within the distribution network. The voltage changes in power system networks without GCI in (3) and (4) are revised when GCI is integrated into the network as described in (5). The imaginary term of (3) is small compared to the real term, and hence it is reduced to (4) [23, 24]. The introduction of $GCIs$ into the networks modified (4) to become (5)

$$\Delta V = \frac{RP_L + XQ_L}{V_L} + j\frac{XP_L + RQ_L}{V_L} \quad (3)$$

$$\Delta V \approx \frac{RP_L + XQ_L}{V_L} \quad (4)$$

$$\Delta V \approx \frac{R(P_L - P_{GCI}) + X(Q_L - Q_{GCI})}{V_{GCI}} \quad (5)$$

Where ΔV is the voltage deviation between the substation busbar and the GCI point of connection, P_{GCI} is the active power generated by the GCI, R and X are the resistance and reactance of the lines, respectively, V_G is the voltage where the GCI is connected on the power distribution line, and Q_{GCI} is the reactive power of GCI [23, 25, 26].

As demonstrated in (5), when the real power demand of the load P_L is higher than the active power generated by the GCI (P_{GCI}), and active power is flowing from the substation towards the load, the voltage change ΔV will be positive. A positive voltage variation, ΔV\Delta VΔV, signifies that the substation possesses the maximum voltage magnitude in the power system network, and voltage drops as the line length increases, starting from the substation.

However, when the active power demand P_L is smaller compared to the real power generated by the GCI (P_{GCI}), and there is a reverse flow of real power towards the substation, the voltage change ΔV will be negative. A negative voltage change ΔV indicates that the GCI voltage V_G is greater than the substation voltage, and the voltage is no longer dropping as the line length increases, but rising as the line length increases [23, 27].

The extent of voltage rise experienced as power flow reverses and starts flowing towards the substation will depend on the magnitude of active power flowing towards the substation. Furthermore, extreme reverse power flow will result in extreme over-voltages [23, 28]. Therefore, in a distribution network with integrated GCIs, low GCI power output causes active power to flow from the substation to the load, resulting in voltage reduction along the feeder. Conversely, high GCI generation drives active power toward the substation, leading to an increase in network voltage levels [28].

The conventional voltage regulation methods were only designed to control voltage when current drifts from the substation towards the load, and the voltage drops as the line length increases, starting from the substation. As a result, conventional voltage regulation methods will fail to regulate voltage issues caused by the uncertainties of PV energy, which lead to reverse power flow [23].

Moreover, $GCIs$ used nowadays can supply and absorb reactive power for regulating the voltage at the point of connection in the networks [18]. The conventional equation model to determine the reactive power operation of the GCIs is depicted in (6).

$$Q = \frac{V_{ref} - V_{GCI\_POC}}{K} \quad (6)$$

Where V_{ref} is the reference voltage of the power system grid networks, $V_{GCI\text{-}POC}$ is the voltage of the GCI at the point of connection, and K is the sensitivity index of the GCI to voltage change. The dynamics in the operation of the GCIs to import or export reactive power for voltage regulation tend to lead to voltage violations of other buses or nodes in the networks in the presence of multiple GCIs. Since the operation of the loading and PV energy behavior is uncertain, it is necessary to regulate the operation of GCIs and voltage control devices by minimizing the cost of power generation and optimize the reactive power flow for effective voltage profile and loss reduction in modern power system networks.

3. Research Methodology

The research overview framework is presented in Figure 2. We begin by setting the optimization power flow based on different operating constraints such as voltage, power flow, line rating, and the ratings of the voltage regulating devices. Data on loading conditions and PV power output variation at each time step is considered. The optimizer will determine the objective, minimising the cost of power generation by enforcing the network constraints. To optimize the reactive power of the GCI, a controller is modeled and embedded in the OPF to control the reactive power of the GCI under the uncertainty of loads and PV output. The optimizer will coordinate the operation of the voltage-regulating devices, OLTC, DSTATCOM, and the GCI's reactive power under different loading conditions and PV output levels.

The constraints consist of the GCI power flow, the GCI reactive power supply, the reactive power supply by the DSTATCOM, the tap position of the OLTC, the voltage profile in the networks, and the power capacity of the line.

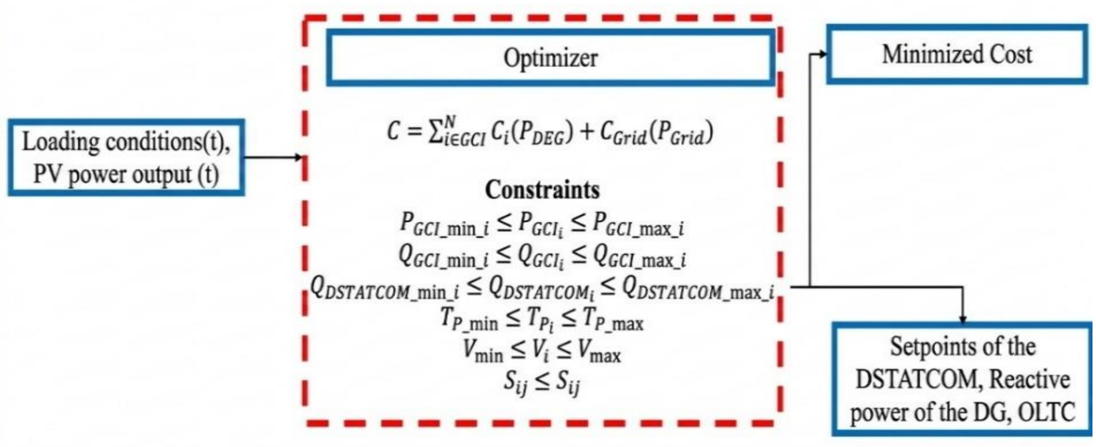


Fig. 2 Framework of the proposed approach

3.1. Objective Function

The optimization objective is to reduce the total expenditure related to active power generated by the GCI and the grid supply as depicted in Equation (7).

$$C = \sum_{i \in GCI}^{N} C_i(P_{GCI}) + C_{Grid}(P_{Grid}) \tag{7}$$

3.2. Constraints

There are several constraint sets in this research work, which include real and reactive power constraints for the GCI, described by Equations (8) and (9), respectively. The DSTATCOM and OLTC constraints are presented in Equations (10) and (11), respectively. Likewise, the voltage and line capacity constraints are presented in Equations (12) and (13), respectively.

$$P_{GCI\_\mathrm{min}} \le P_{GCI\_t} \le P_{GCI\_\mathrm{max}} \tag{8}$$

$$Q_{GCI\_\mathrm{min}} \le Q_{GCI\_t} \le Q_{GCI\_\mathrm{max}} \tag{9}$$

$$Q_{DSTATCOM\_\mathrm{min}} \le Q_{DSTATCOM\_t} \le Q_{DSTATCOM\_\mathrm{max}} \tag{10}$$

$$T_{P\_\mathrm{min}} \le T_{P\_t} \le T_{P\_\mathrm{max}} \tag{11}$$

$$V_{\mathrm{min}} \le V_{i\_t} \le V_{\mathrm{max}} \tag{12}$$

$$S_{ij\_t} \le S_{ij\_max} \tag{13}$$

Where P_{GCI_min} and P_{GCI_max} are the minimum and maximum active power that the GCI can provide, P_{GCI_t} is the active power supplied by the GCI at any time t, due to the variation in the PV power output. Q_{GCI_min} and Q_{GCI_max} are the reactive power capacity of the GCI, and Q_{GCI_t} is the reactive power that can be imported or exported by the GCI for voltage regulation support.

T_{p_min} and T_{p_max} are the minimum and maximum capacity ratings of the OLTC, respectively, and T_{p_t}, is the tap position at any time t, for voltage regulation. V_{min} and V_{max} are the minimum and maximum voltages that can be experienced at any bus in the network, and V_{i_t} is the voltage experienced by bus i at any time t.

S_{ij_t} is the maximum power that flows across the distribution line connecting bus *i* and *j* at any time *t*, and *Sij_max* is the maximum power that can flow across the distribution line connecting bus i and *j*

3.3. Modelling of a Controller for GCI

In practical distribution systems, several Grid-Connected Inverters (GCIs) are equipped with volt–var control functionality for voltage regulation at their respective points of interconnection. Nevertheless, the Optimal Power Flow (OPF) framework determines the inverter reactive power output according to the specified network objectives and operational constraints. Although this approach satisfies system constraints, it may not always yield the most effective optimization outcome. To enhance system performance, a dedicated controller is incorporated within the OPF formulation to dynamically compute the inverter reactive power requirement based on the measured voltage at the connection point. The mathematical representation of the controller is provided in Equation (14).

$$Q_{GCI} = \begin{cases} Q_{max} & u \le u_1 \\ \frac{Q_{max}}{(u_2 - u_1)} \times (u - u_1) & u_1 \le u \le u_2 \\ 0 & u_2 \le u \le u_3 \\ \frac{-Q_{max}}{(u_4 - u_3)} \times (u - u_3) & u_3 \le u \le u_4 \\ -Q_{max} & u \ge u_4 \end{cases} \quad (14)$$

When Qmax is the peak VAR power, the GCI can import or export. u_1, u_2, u_3, and u_4 are the voltage set points for the inverter to regulate reactive power. u is the operating voltage at the point of connection. The use of the controller will allow a smooth transition of reactive power that will mitigate unnecessary oscillation. The u_1, u_2, u_3, and u_4 are the functions of the grid reference voltage u_r, voltage width D, and the deadband d as depicted in Equations (15)-(18) [18]. The quantity of reactive power injected or absorbed by the Grid-Connected Inverter (GCI) for maintaining the operating voltage near the reference value u_r depends on the selected voltage deviation parameter D and the inverter's reactive power capability limits. In this study, the voltage deviation threshold D was set to 5% of the nominal system voltage, and the deadband region was specified at 2% of the nominal voltage. The reference voltage u_r was fixed at 1 per-unit (p.u.), representing the desired nominal operating condition.

$$u_1 = v_r - D \quad (15)$$

$$u_2 = v_r - d \quad (16)$$

$$u_3 = v_r + d \quad (17)$$

$$u_4 = v_r + D \quad (18)$$

Since the optimization problem is nonlinear, the equations were modeled in MATLAB and solved using a real-time solver, which enables real-time optimization of nonlinear equations.

4. Test Case

The proposed method was evaluated using a modified IEEE 69-bus test system, whose network configuration is illustrated in Figure 3.

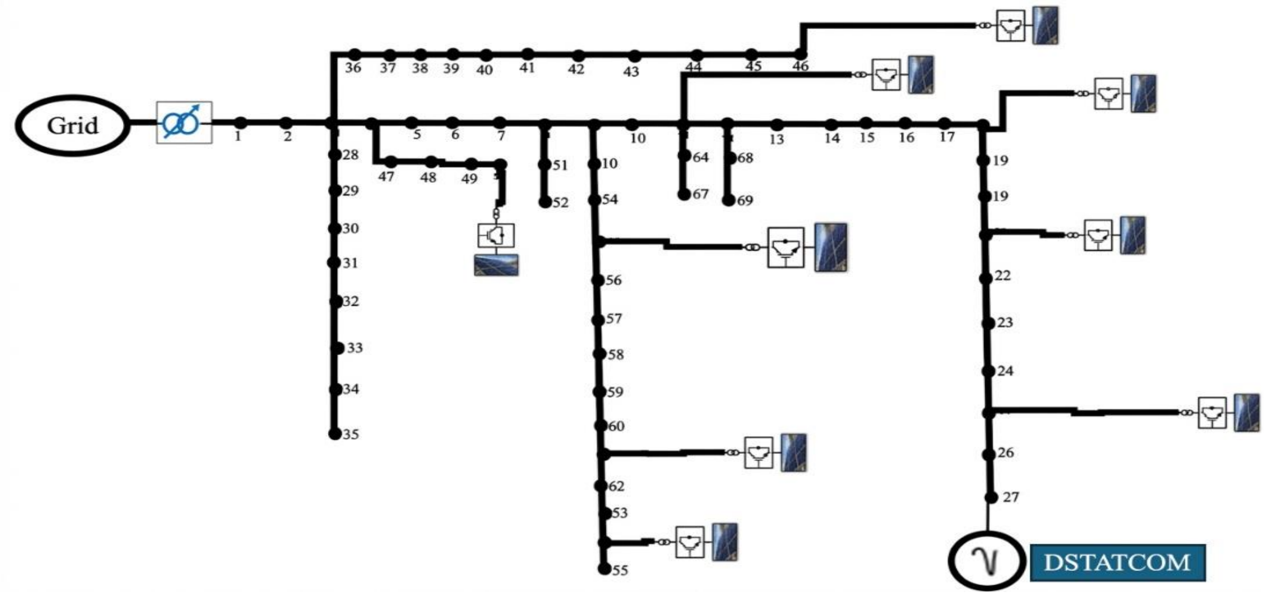


Fig. 3 Modified IEEE bus 69 network

The network consists of nine (9) GCI that operate under the same solar irradiance at the optimal point, and a DSTATCOM of 0.3 Mvar is connected at the bus that experiences the lowest voltage. The OLTC is installed in the transformer at the substation with tap limits of -8 to 8, and constraints were embedded with the OLTC to avoid two consecutive tap changes in order to reduce the frequent operation of the OLTC. The maximum capacity of the PV inverter is 4.5 MVA, and the maximum reactive power that can be imported or exported by the controller is 1.5 MVAR at a power factor of 0.94. The power factor of the inverter is used to determine the reactive capacity of the PV inverter according to IEEE Standard 1574 [29]. The GCI has the capacity for voltage regulation when the PV energy is zero. To validate the performance of the proposed approach, two scenarios were created: Scenario 1 represents the operating condition in which the inverter's reactive power output remained uncontrolled, whereas Scenario 2 corresponds to the case where the reactive power was optimally managed using a controller integrated within the OPF framework. The optimizer will coordinate and control the voltage control devices by determining the minimum power generation cost and the operating set points of the voltage control devices under the uncertainty of loads and the PV power output. The load profile and the PV power output profile used are presented in reference [30].

5. Results and Discussion

This session discusses the simulation results for the two scenarios. The results include the voltage profiles in the network, the reactive power imported and exported by the grid-connected inverter, the active power of the grid-connected inverter, the set points of the OLTC and DSTATCOM at different loading conditions, and PV power output discussed in Subsections 5.1. Subsection 5.2 presents and discusses the sensitivity analysis results of the two scenarios.

5.1. Simulation Results

To validate the importance of the proposed approach. The base case simulation results of the voltage profile are presented in Figure 4, without the coordination of the PV inverter under the dynamic loading and the PV power output.

The results indicate that the voltage of the buses in the networks is outside the acceptable limits in the networks, as the voltage is greater than 1.05 PU and less than 0.95 PU.

In addition, the base case total active power loss is 375.567 kW. The result is consistent with existing literature that the integration of PV into the power system without coordination causes voltage violation issues and increases losses in the network. The proposed approach was used to address the problem under two scenarios.

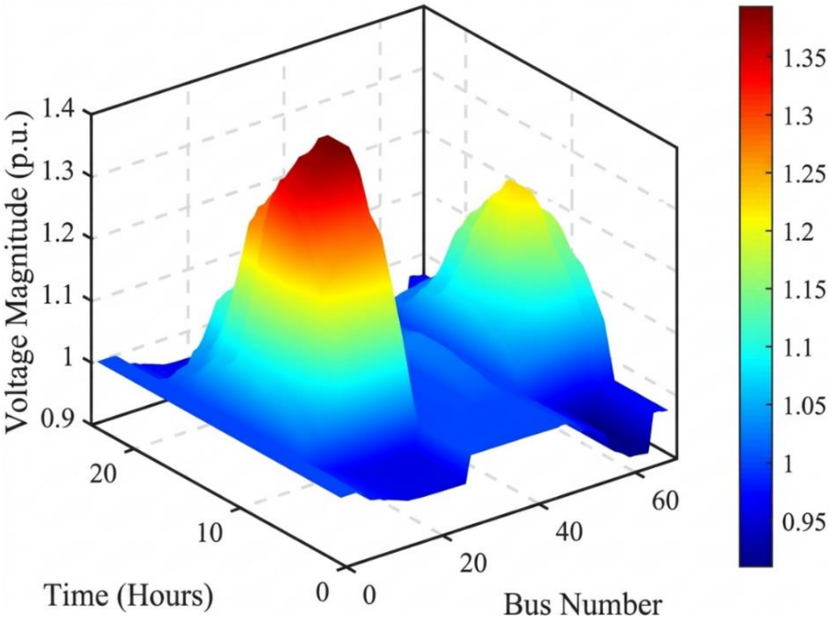


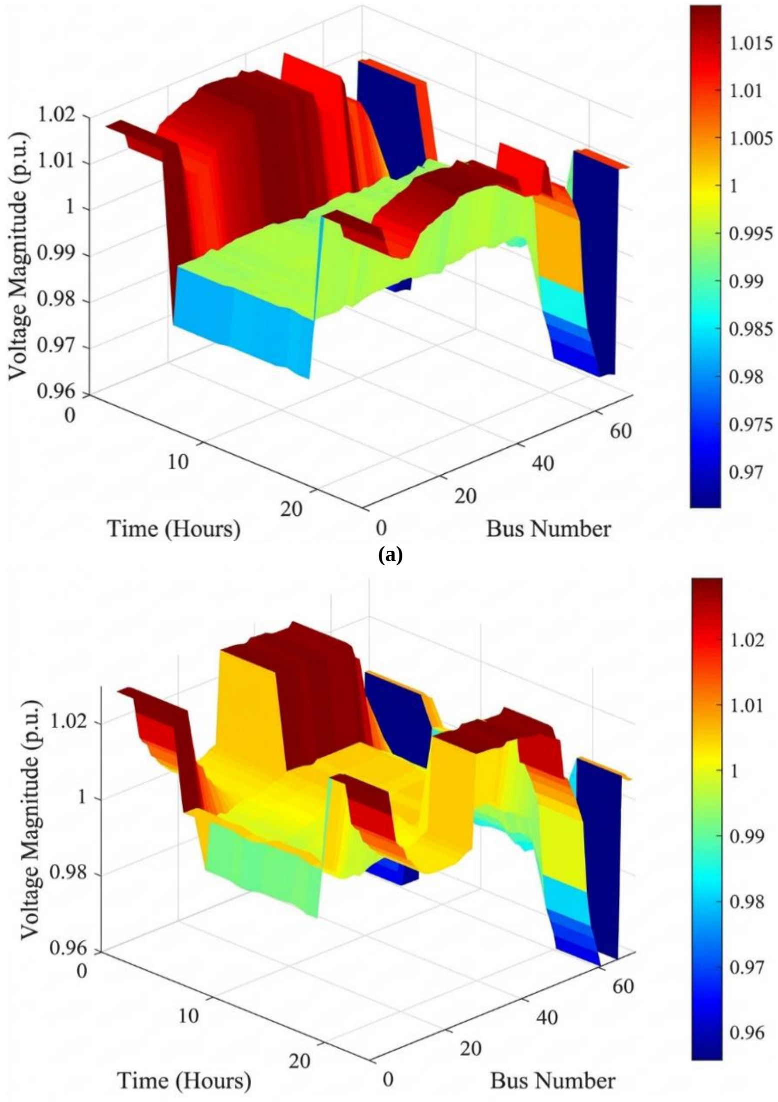
Fig. 4 Voltage profile of the buses in the networks for the base case

The results of the proposed approach used in coordinating and control the PV inverters and the voltage regulating devices is presented in Figures 5 to 9. The voltage profile of all the buses in the networks under the uncertainty of the PV power output and the loading conditions for scenario 1 and scenario 2 is presented in Figures 5(a) and (b), respectively.

Figure 5(a) depicts that the voltage profile for scenario 1 varies from 0.96 to 1.018 PU, and in Figure 5(b), the voltage profile varies from 0.96 to 1.029 PU. The results show that the optimizer in the two scenarios enforces the voltage constraints of all the buses in the networks within the acceptable values of 0.95 to 1.05 PU, under the uncertainty of the PV power and loading conditions.

This implies that the optimizer is sensitive to the voltage constraints in the networks. Furthermore, the results of the optimizer in regulating the reactive power of the GCI for effective voltage regulation in the networks are presented in Figures 6(a) and 6(b), respectively, for the two scenarios.

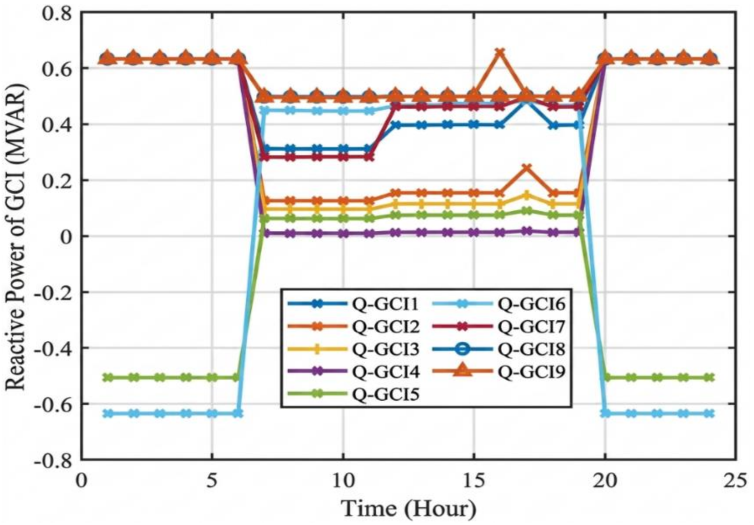
In Figure 6(a) for scenario 1, the optimizer imports and exports reactive power to regulate the voltage at the point of connection of the inverter under the variation in the loading and the PV power output. Furthermore, in Figure 6(b), for Scenario 2, the use of the controller embedded in the OPF optimized the operation of the GCI in importing and exporting reactive power. This will reduce the active losses in the networks.



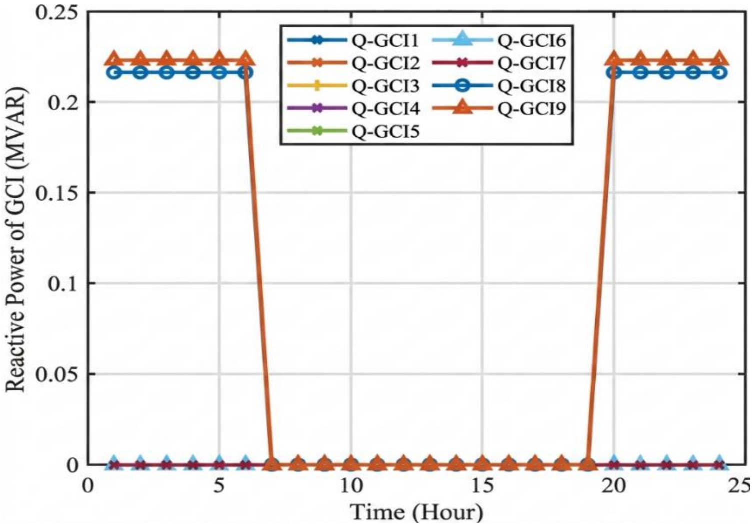
(a)

(b)

Fig. 5 Voltage profile of the buses in the networks

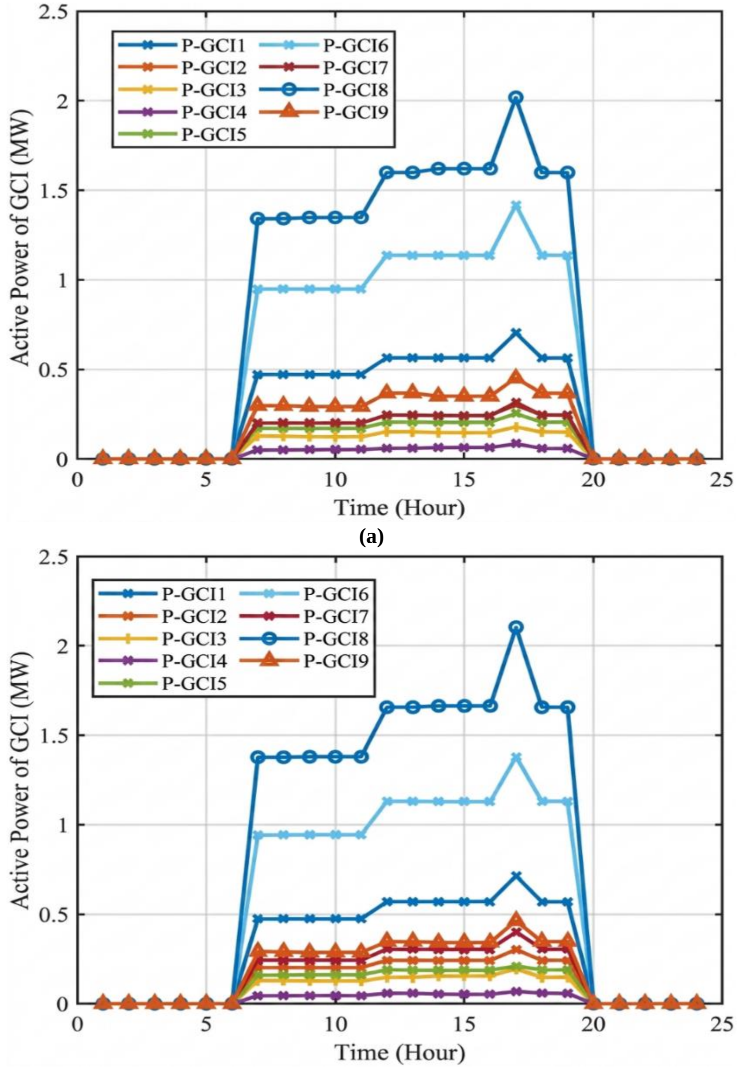


(a)



(b)

Fig. 6 Reactive power of the Grid Connected Inverter (GCI)

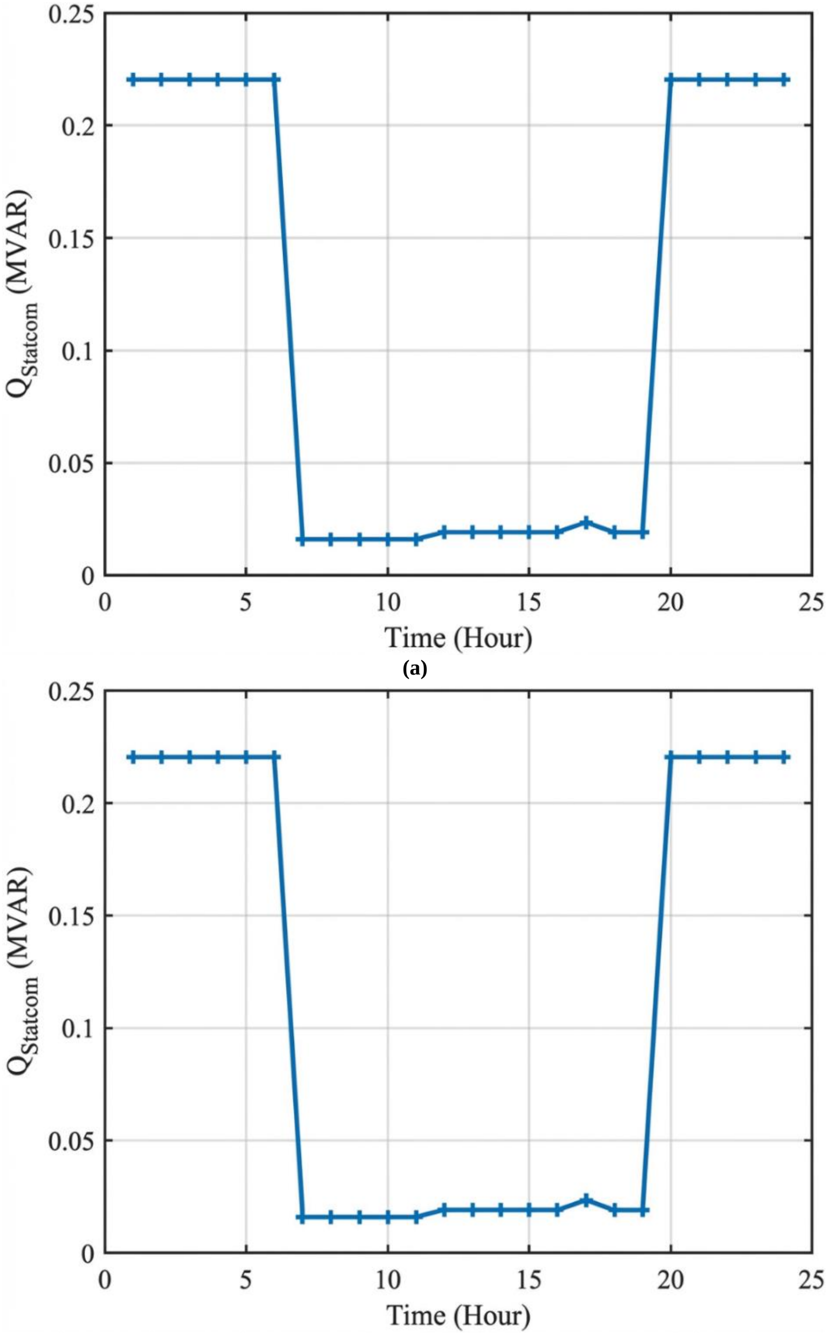


(a)

(b)

Fig. 7 Active power of the GCI

The results of the active power generated by the GCI for the two scenarios are presented in Figures 7(a) and 7(b) for Scenarios 1 and 2, respectively. The results depicted that the active power generated by the GCI under the uncertainty of the PV power output and loading conditions shows that the GCI maximized the output power when the PV power output is available, and it reduces to zero when there is no power supply from the PV for the two scenarios 1 and 2. This is due to the dependence of the PV on solar irradiance, which varies as the solar irradiance changes throughout the time step. Furthermore, the results of the setpoints of the DSTATCOM under variations in the loading and the PV power output are presented in Figures 8(a) and 8(b) for scenarios 1 and 2, respectively. The results indicate that the optimizer enforces DSTATCOM to operate within the limits under the variation of loads in all the buses and PV power output. Additionally, the optimizer minimized the operation of the DSTATCOM in exporting reactive power to the network for voltage regulation. This reduces the excessive reactive power in the network, which can lead to active power losses.

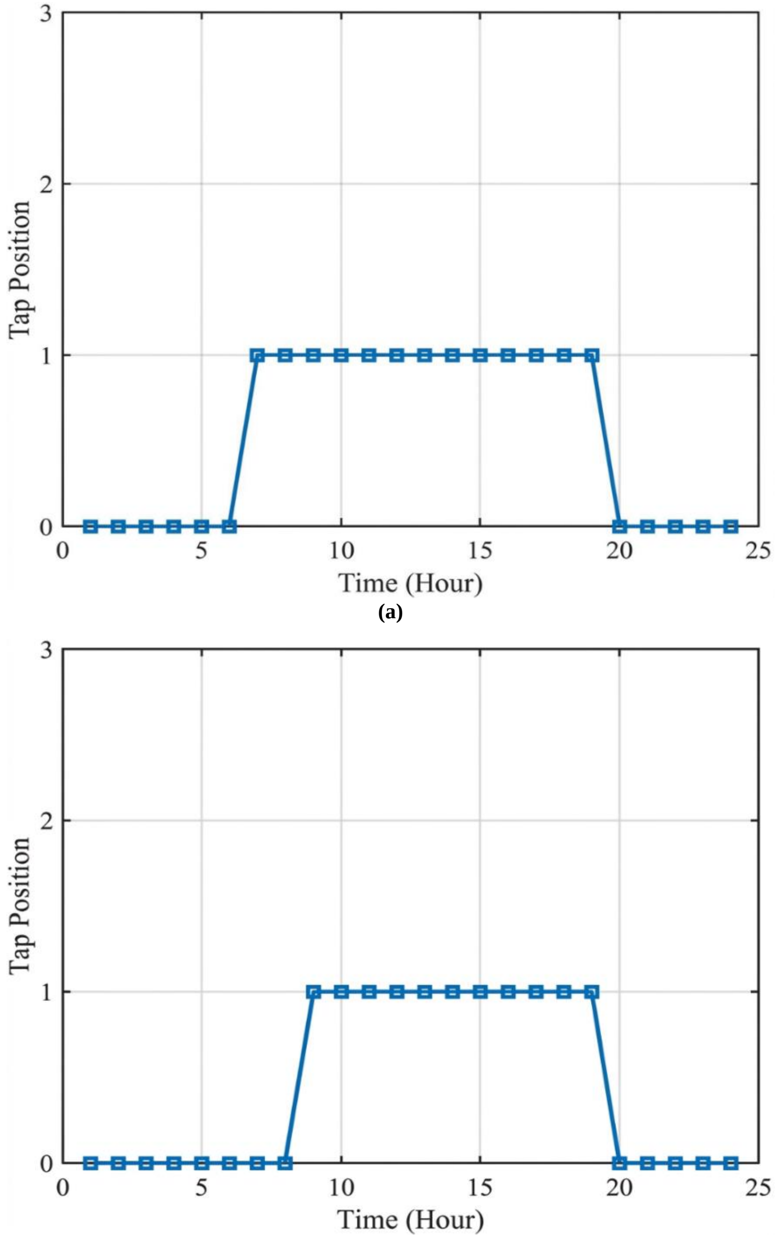


(a)

(b)

Fig. 8 Reactive power of the DSTATCOM

Furthermore, the setpoints of the OLTC under varying loading and PV power output are determined by the optimizer for the two scenarios, as depicted in Figures 9(a) and 9(b), respectively. The results show that the optimizer minimized the operation of the OLTC as the loading and the PV power changed for the two scenarios. The OLTC stall change is 3 for the two scenarios under the 24-hour time span variation in loading and PV power output. This implies that the optimizer does not allow frequent operation of the OLTC, which can reduce its lifespan. To show the superiority of embedding control in an optimizer, a sensitivity analysis is performed as presented in Subsection 5.2.



(a)

(b)

Fig. 9 OLTC tap position for scenarios 1 and 2

5.2. Sensitivity Analysis

The sensitivity of the two approaches to active power losses and the cost of power generated under the variation of the loading and the PV power output is presented in Table 1. The results show that the optimizer minimizes the active power losses in scenario 2 by 15.9 % when a controller is embedded to regulate the action of the reactive power of the GCIs under the variation of the PV and the loading conditions, compared to scenario 1. In addition, the cost of Energy generated is reduced in scenario 2. This is because the controller embedded in the optimizer minimized the importing and exporting of reactive power of GCI in the networks, reducing the active power losses and energy cost in scenario 2. Although the absolute cost reduction of $0.1125 appears small, it is accompanied by a significant 15.9 % reduction in system losses (276.39 kW to 232.56 kW). When scaled over long-term operation in large power systems, even small per-interval savings accumulate to substantial economic benefits, while simultaneously improving efficiency and system reliability. This implies that a controller embedded in an OPF ensures a better optimal solution for the reactive power of the GCI that increases the efficiency of the GCI inverter.

Table 1. Sensitivity analysis

Scenarios	Active Power Losses (kW)	Cost of Energy ($)
1	276.39	12.3497
2	232.56	12.2372

6. Conclusion

The use of renewable energy-based generation through GCIs in active distribution networks has caused a lot of challenges, such as imbalanced power flow and voltage fluctuation in active distribution networks. To address the issues mentioned, an advanced technique that coordinates the operation of the voltage regulating devices is required. In this research, we proposed an optimization technique that coordinates the operation of OLTC and DSTATCOM in the presence of GCIs under the uncertainty of PV output and the loading condition. The optimization approach integrates a cost-minimizing strategy with a reactive power control scheme embedded in the OPF to regulate the reactive power of the grid-connected inverters to minimize the importing and exporting of reactive power. By dynamically regulating the reactive power output of the inverters, the approach effectively minimizes real power losses while improving voltage profiles, even under fluctuating Photovoltaic (PV) output and variable loading conditions. In addition, the optimizer determines the optimal setpoints of the OLTC and DSTATCOM at any point in the networks to ensure an effective voltage profile that enhances stability in the networks. The techniques proposed not only improved voltage regulation but also optimal use of control resources, leading to enhanced cost-effectiveness and reduced operational strain on equipment. The optimization process considers technical and economic aspects, producing a solution that balances energy cost, power losses, and voltage stability under real-world uncertainty conditions. In practice, the proposed techniques in coordinating the PV energy and voltage regulating devices can support distribution system operators in transitioning to active network management strategies where high penetration of renewables introduces unpredictability.

Furthermore, the adequacy of the approach to coordinate inverter-based resources with conventional voltage regulation devices presents a scalable and flexible solution for modern power systems. Moreover, the proposed approach reduces dependence on costly infrastructure upgrades by using existing assets more effectively and supports increased renewable energy integration without compromising network stability. To increase the power delivery of the PV inverter, the dynamic line rating can be considered in future research.

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