Distribution Grid Hosting Capacity Improvement using Reactive Power Control Optimization Algorithm of Inverter-based Photovoltaic Generation System

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ABSTRACT

This paper uses a reactive power control optimization algorithm to present an inverter-based photovoltaic generation system for increasing the distribution grid host capacity. The main objective of this study is to regulate bus voltages by providing sufficient minimal reactive power consumption, which is obtained by a Particle Swarm Optimization-based optimization algorithm. A modeling study of the system network is developed using DIgSILENT PowerFactory, and the control algorithm is implemented in MATLAB. The proposed approach is efficient for various scenarios of the IEEE 13-bus test system and practical distribution network. The analysis results are compared with outcomes from other control methods, including technical and economic assessments. The performance of the proposed optimization-based power system has shown that the proposed algorithm method yielded significantly superior mitigated voltage rises and increased hosting capacity compared to those achieved by existing control methods of a specific distribution network.

Keywords: Optimization Algorithm, Reactive Power Control, Voltage Regulation, Grid Hosting Capacity, Inverter-based Photovoltaic Generation System, Smart Distribution Network

1. INTRODUCTION

Recent advancements in distributed energy resources (DER) have led to a rise in integrating and assessing renewable energy for utilization by utilities, consumers, and third-party entities. Generally, the primary sources of DER in distribution networks, such as photovoltaic and wind power generation systems, have peculiar characteristics that bring some technical challenges to the planning of distribution networks. Their widespread adoption could potentially be disrupted if not correctly designed, integrated, and managed [1-3]. Integrating high-capacity inverter-based DER motivates challenging problems that must be solved, such as power generation and demand mismatch, reverse power flow, voltage instability issues, complexity in protection coordination, power factor problems, harmonics, frequency instability, feeder losses, thermal limits of the grid, and security of supply in the distribution network [4-6]. Furthermore, the increase of DER penetration in the distribution network produces an uncontrolled reactive power flow associated with a transmission network or substation [7-14].

The power grid is transforming into an intelligent distribution network, seamlessly integrating various distributed energy resources to enhance reliability and power quality. However, excess DER penetration can adversely affect system performance and may result in severe overvoltage issues. Therefore, the inverter-based voltage control using a renewable energy system represents a potential solution to mitigate the voltage variation. In recent years, numerous research papers have focused on exploring voltage control methodologies necessitated by the increasing penetration of DERs, such as the fixed power factor (PF), fixed reactive power, active power-dependent PF, active power-dependent reactive power $Q(P)$, voltage-dependent reactive power $Q(V)$, and optimization algorithms [15-23].

Several research studies have proposed reactive power control methods to mitigate voltage violations in distribution networks. The voltage rise mitigation due to the reverse power flow via reactive power absorption from distributed photovoltaic inverters is presented in [22]. This paper proposes enhancing voltage regulation by implementing the $Q(V)$ control method coupled with the manage curve function of volt-var control based on the active power output of the photovoltaic system. The findings suggest that voltage control within standard limits is achievable. Nevertheless, it is observed that the reactive power output fails to adequately mitigate the low voltage variation caused by the specific installation locations of DERs within the distribution network. The study in [16] introduced an enhanced $Q(V)$ characteristic utilizing voltage-sensitive analysis to remedy voltage

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rise and reactive power contribution by photovoltaic systems. It employed a multi-objective approach to contrast with the equal reactive power sharing method, aiming to identify a voltage regulation technique capable of reducing reactive power consumption and line losses. However, it was found that the multi-objective method resulted in lower reactive power consumption compared to the equal reactive power-sharing method. The strategy addresses overvoltage issues and minimizes total line loss through a mutation fuzzy adaptive optimization algorithm for the distribution system connected with high penetration photovoltaic generation, as presented in [23]. Comparative analyses with other optimization algorithms validate the effectiveness of the proposed approach in mitigating overvoltage and reducing line loss. A limitation of the proposed approach was that it did not take into account the investment of PV inverter capacities and economic analysis.

This paper proposes the reactive power compensation capabilities of inverter-based photovoltaic generation systems. It also aims to increase the hosting capacity of the distribution network while improving the operational bus voltage level. The main contributions of this research are as follows:

- A topology-based approach is employed to adjust the inverter connection, enabling reactive power control conditions to integrate high-capacity photovoltaic generation systems seamlessly.
- Decentralized control of multiple inverters is implemented to facilitate voltage regulation, thereby enhancing overall system reliability.
- A chance constraint is employed to reduce the need for grid reinforcement significantly. An optimization algorithm for reactive power control has also been developed to improve grid voltage operations and promote economic efficiency.

The structure of this paper is as follows. Section 2 elaborates on the methodology to enhance distribution grid hosting capacity via the reactive power of photovoltaic generation systems. Section 3 outlines the problem formulation and solution algorithm to actively support reactive power management. Section 4 presents a comprehensive assessment of the grid capacity and economics. Section 5 delves into the analysis of case studies conducted on both the IEEE 13-bus distribution test network and real-world distribution networks. Finally, Section 6 synthesizes the key conclusions drawn from the study.

2. METHODOLOGY FOR IMPROVING DISTRIBUTION GRID HOSTING CAPACITY

This section explores the substantial impact of high levels of photovoltaic generation on distribution networks and the utilization of inverter-based photovoltaic generation systems to manage reactive power and regulate voltage. The following sections will discuss the problem description, power flow calculation, and the methodology for improving distribution grid hosting capacity using reactive power control.

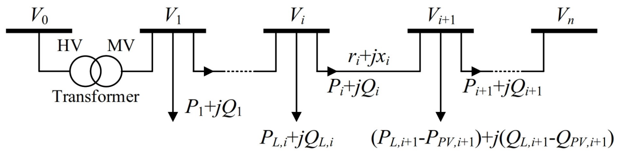


***Fig. 1**: Schematic diagram of a typical radial distribution network with a photovoltaic generation system for power flow analysis.*

2.1 Problem Description

The implementation of photovoltaic generation technology has significantly bolstered the integration of renewable energy systems. Nevertheless, the extensive adoption of photovoltaic generation significantly influences voltage deviation and the reversal of power flow within distribution networks. Therefore, in specific research endeavors, the reactive power supply capability of photovoltaic generation systems can be used to improve the voltage rise problem controlled by the reactive power. In this paper, the total hosting capacity percentage is characterized as a normalization factor for the spatial distribution of grid hosting capacity, achieved through reactive power management of an inverter-based photovoltaic generation system. As the grid capacity decreases, it signifies that the reactive power control method has been successfully implemented.

2.2 Power Flow Calculation in Distribution Network

The equivalent circuit model of a typical radial n-bus feeder in a distribution network for the power flow analysis is shown in Fig. 1. Based on this figure, the power flow calculation method in a radial distribution network with loads and photovoltaic generation systems can be calculated as follows [24], [25]:

$$P_{i+1} = P_i + \frac{r_i\left(P_i^2 + Q_i^2\right)}{V_i^2} - P_{L,i+1} + P_{PV,i+1} \tag{1}$$

$$Q_{i+1} = Q_i - \frac{x_i\left(P_i^2 + Q_i^2\right)}{V_i^2} - Q_{L,i+1} + Q_{PV,i+1} \tag{2}$$

$$V_{i+1}^2 = V_i^2 - 2\left(r_iP_i + x_iQ_i\right) + \frac{\left(r_i^2 + x_i^2\right)\left(P_i^2 + Q_i^2\right)}{V_i^2} \tag{3}$$

$$I_i = \frac{\sqrt{P_i^2 + Q_i^2}}{V_i} \tag{4}$$

where P and Q are the active and reactive power flows, respectively. P_L and Q_L are the active and reactive power of the loads. P_{PV} and Q_{PV} are the active and reactive power outputs from photovoltaic generation systems. r and x are the line resistance and line reactance, respectively. V is the bus voltage. I is the line current flowing through the impedance of the line. Finally, i is the bus number.

For low-voltage and medium-voltage distribution networks connected to distributed generations, the power flow analysis of the distribution network can be formulated from the above equations, which can be used in general cases for any radial distribution network.

Consider the distribution network in Fig. 1, where the photovoltaic generation system is connected. The voltage in the i-bus can be calculated as follows:

$$\begin{aligned} V_i &= V_{i+1} + I_i \left(r_i + jx_i\right) \\ &= \left[V_{i+1} + \left(\frac{r_i P_{i+1} + x_i Q_{i+1}}{V_{i+1}}\right)\right] + j\left[\frac{x_i P_{i+1} - P_{i+1} Q_{i+1}}{V_{i+1}}\right] \end{aligned} \tag{5}$$

where $I_i = \frac{P_{i+1} - jQ_{i+1}}{V_{i+1}}$.

Assuming the phase-angle deviation is very small, resulting in the imaginary term of the equation (5) can be neglected. Therefore, the voltage variation across each bus feeder in the distribution network can be approximated as:

$$\Delta V = \frac{r_i \left(P_{L,i+1} - P_{PV,i+1}\right) + x_i \left(Q_{L,i+1} - Q_{PV,i+1}\right)}{\left|V_{i+1}\right|} \tag{6}$$

where $\Delta V = V_i - V_{i+1}$.

As formulated in the above equation, the medium-voltage system has a high reactance value of the x/r ratio [1], [26]. The fluctuation in voltage along the distribution line is contingent upon the power factor of the line impedance and the characteristics of the connected load. In addition, the high penetration of photovoltaic generation systems affects grid performance, which causes a voltage rise and reverse power flows. Consequently, the problem of reactive power control in the distribution network is the focus of this paper to achieve minimal voltage deviation and minimal line loss simultaneously.

2.3 Reactive Power Control with Inverter-based Photovoltaic Generation Systems

The problem of voltage deviation can be mitigated by injecting reactive power with active power from photovoltaic generation into the distribution network, which is essential for regulating the voltage in the network. The reactive power of the inverter-based photovoltaic generation can be controlled independently of the active power and depends on the voltage on the bus voltage, which can be expressed as follows [4]:

$$Q_{PV,i}(s) = \alpha_{PV,i}\left[V_i(s) - V_0\right] \tag{7}$$

where α_{PV} is the rating of the photovoltaic generation, $V(s)$ is the voltage deviation, and V_0 is the nominal voltage.

As previously mentioned, there is a significant voltage rise due to massive photovoltaic system penetration, and reactive power control is insufficient to maintain efficient system operation, especially in distribution networks where the system capacity is low enough to give sufficient control.

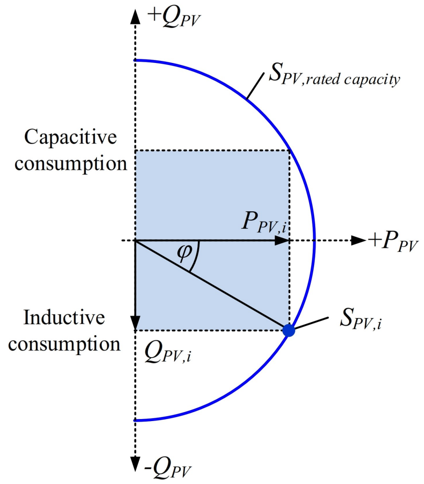


Fig. 2: *Active-reactive power control diagram of an inverter-based photovoltaic generation system.*

2.4 Inverter Capacity Limitations of Photovoltaic Generation Systems

In this study of inverter-based photovoltaic generation systems, the reactive power output can be utilized by restraining the active power output from the photovoltaic systems under the inverter, which is restricted by its capacity. Under the inverter capacity limitations, the active and reactive power outputs from the photovoltaic systems are expressed as follows:

$$P_{PV,i} = S_{PV,i}\cos(\varphi) \tag{8}$$

$$\begin{aligned} Q_{PV,i} &= \sqrt{\left(S_{PV,i}\right)^2 - \left(P_{PV,i}\right)^2} \\ &= \pm S_{PV,i}\sqrt{1 - \cos^2(\varphi)} \end{aligned} \tag{9}$$

where $S_{PV,i}$ is the system capacity of the photovoltaic generation inverter, and $\cos(\varphi)$ is the power factor of the inverter operated.

As shown in Eq. (9), the reactive power generation depends on the rated capacity of the photovoltaic generation inverter and the power factor of the inverter operated. Fig. 2 shows an active-reactive power control diagram of the inverter-based photovoltaic generation system. The rated capacity of the photovoltaic generation inverter is given as a constant. The active power output is a varied operating parameter depending on the irradiation conditions for the photovoltaic generation system. Moreover, this study focuses on a reactive power provision with an inverter-based photovoltaic generation system.

3. PROBLEM FORMULATION AND SOLUTION ALGORITHM

To improve the hosting capacity in the distribution network, the high penetration of the photovoltaic generation system may affect the high occurrence of reverse power flow and overvoltage. For this reason, the design of the proposed optimization algorithm, which consists of the constraint of distribution networks, is an optimal design problem for formulating the optimal reactive power. The objective function and constraints are present in this section to evaluate the minimum reactive power and hosting capacity.

3.1 Objective Function

For the optimal value of the reactive power injection of the compensates at the bus voltage, the objective function is considered to be the minimization of the reactive power demand and the reactive power at the bus voltage. The proposed formulation for the objective function can be expressed as:

$$\text{Min} \sum_{i=1}^{N} \left(Q_{L,i+1} + Q_{i+1}\right) \tag{10}$$

where N is the number of bus networks connected by i bus.

From Eq. (10), the function of the reactive power is various alternatives to consider and minimize the bus voltage into a single objective function.

3.2 Nonequality Constraints

For the problem formulation of the proposed optimal reactive power injection at the bus voltage, nonequality constraints are detailed as follows:

- **Voltage limits**

The values of the bus voltage should be within the desired range of $\pm 5\%$ of the nominal voltage value. Therefore, the voltage constraint is given as

$$0.95V_{i+1}^{\min} \leq V_{i+1} \leq 1.05V_{i+1}^{\max} \tag{11}$$

- **Reactive power generation limits**

The reactive power of the photovoltaic inverter can be considered the range of power generation. Accordingly, the reactive power generation at the bus is bounded by upper and lower limits as

$$Q_{PV,i+1}^{\min} \leq Q_{PV,i+1} \leq Q_{PV,i+1}^{\max} \tag{12}$$

Although this study focuses on medium-voltage networks, the above voltage and reactive power constraints are applied to all distribution networks. The receiving voltage is determined by regulating the distribution network interconnection code.

3.3 Optimization Algorithm for Reactive Power Management

According to the aims of the objective and constraint conditions in the optimization algorithm, this paper applies the PSO algorithm in solving optimization problems [27], [28]. This algorithm technique is a heuristic global optimization method. It shares the best position in every generation and simultaneously moves toward its best-known position and the entire best-known position in the search space. The numerical explanation of the PSO algorithm is updated according to the following:

$$v_i^{t+1} = \omega v_i^t + c_1 r_1 \left(p_i^t - Q_{PVi}^t\right) + c_2 r_2 \left(g_i^t - Q_{PVi}^t\right) \tag{13}$$

$$Q_{PVi}^{t+1} = Q_{PVi}^t + \left(v_i^{t+1} \times C\right) \tag{14}$$

where v_i^t is the velocity of particle i during cycle t, Q_{PVi}^t is the reactive power of the photovoltaic generation system on bus i during cycle t, c_1, c_2 are acceleration factors, $r_1, r_2$are random variables, varying in the range [0,1], p_i^t is the best position of particle i up to cycle t, g_i^t is the best global position to each of all particles up to cycle t, ω is the inertia weight, and C is the convergence of the solution algorithm.

This study introduces a constriction factor to improve the proposed solution algorithm.

$$C = \frac{2}{\left|2 - \varphi - \sqrt{\varphi^2 - 4}\right|} \tag{15}$$

where φ the variable that makes the constriction factor faster or slower, affecting population diversity, varies in the range [4.1, 4.2]. In this algorithm, the constriction factor is 0.352 for fast convergence.

All through the reactive power management in the distribution network with photovoltaic generation system, the pseudo-code of the reactive power optimization algorithm as applied by the distribution system operator in terms of nominal voltage deviation and total reactive power of distribution grid optimization is illustrated in Algorithm 1.

Algorithm 1: The solving optimization algorithm

Input:
- N – population size
- D – Problem dimensionality
- c_1, c_2 – Personal and global learning coefficient
- T – Maximum number of iterations
- UB, LB – Domain (upper and lower bounds)

Output: Solution with the best fitness value

Start
  Initialize the swarm randomly;
  for i = 1 to N **do**
    Initialize particles' velocity and positions
    Initialize the best position to its initial position
  end for
  $t \leftarrow 1$;
  while $t \leq T$ **do**
    for i = 1 to N **do**
      set r_1, r_2, $\omega \in [0,1]$
      Apply Equation (10);
      Apply Equations (13) and (14);
      if $f\left(Q_i^t\right) \leq f\left(p_{best,i}^{t-1}\right)$ **then**
        $f\left(p_{best,i}^t\right) = Q_i^t$;
      end if
    end for
    Update the global best;
    $t \leftarrow t+1$;
  end while
End

4. QUANTITATIVE ASSESSMENT

This section explores the grid capacity and economic assessments related to managing reactive power within the distribution network.

4.1 Distribution Network Grid Capacity

Grid capacity is effectively the power in the network that can reliably deliver, whether it is the hosting capacity or the load service capacity [29]. In this study, the grid capacity can be the maximum power generation available for reactive power management. The percentage of the grid capacity equation can be expressed as follows:

$$Grid\ capacity\,(\%) = \frac{\sum_{i=1}^{N} S_{used,i} \times \Delta t}{S_{tr,rated} \times 24hr} \times 100\% \qquad (16)$$

where $S_{used,i}$ is the apparent power of the distribution network usage, $S_{tr,rated}$ is the rated apparent power of the transformer, and $\Delta t$is the time step of 15/60 hr.

4.2 Approach for Economic Evaluation

In order to evaluate the economic advantages of reactive power control methods, it's essential to consider both investment costs and operational expenses [30].

The annual total costs of the control method can be divided between expenses for the distribution system operator and those for the photovoltaic generation system operators. The distribution system operator costs include annual expenses for compensating grid losses and compensating reactive power. The photovoltaic generation system operators are responsible for covering costs associated with reduced active power feed-in. Therefore, the annual total costs can be expressed as follows:

$$C_{total} = C_{losses} + C_{PV} + C_{QF} \qquad (17)$$

where C_{losses} is the cost of line loss compensation, C_{PV} is the cost of the reduced active power feed-in, and C_{QF} is the cost of the reactive power compensation.

In Eq. (17), the annual total costs of the proposed control methods can be divided between the costs for the distribution system operator and the photovoltaic generation system operators, where the costs for the distribution system operator encompass the power line losses and reactive power compensations, which can be calculated by:

$$C_{losses} = \left(\sum_{y=1}^{n} P_{losses,y} \right) \times \Delta t \times c_{losses} \qquad (18)$$

$$C_{QF} = \left(\sum_{y=1}^{n} \left| Q_{flow,y} \right| \right) \times \Delta t \times c_{QF} \qquad (19)$$

where $P_{losses,y}$ is the power line losses, $Q_{flow,y}$ is the reactive power exchange in the network, c_{losses} is the compensation of network losses, c_{QF} is the compensation of reactive power, and y is the calculated time step $y = 1,\ldots,n$.

***Table 1**: Costs for the Economic Assessment [24].*

Details	Costs	
Network losses compensation (c_{losses})	0.0087	€/kVArh
Reactive power compensation (c_{QF})	0.0790	€/kWh
Photovoltaic feed-in tariff (c_{PV})	0.2874	€/kWh

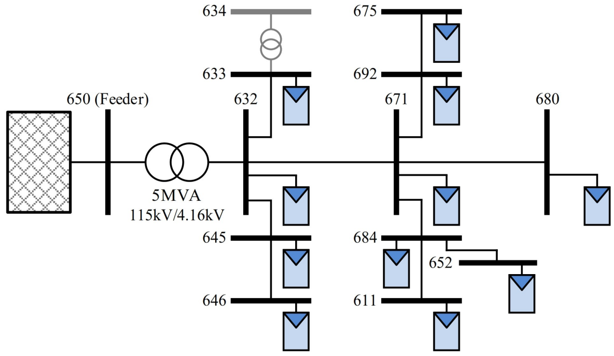


***Fig. 3**: Single line diagram of IEEE 13-bus distribution test network incorporating photovoltaic generation system.*

The photovoltaic generation system operators must carry the costs for a reduced active power output, which are calculated by the difference between the photovoltaic energy that could be fed in without using control methods (E_{PV}) and the photovoltaic energy while applying control methods (E_{PVC}). Therefore, the reduced active power feed-in cost can be calculated as follows:

$$C_{PV,reduced} = \left(E_{PV} - E_{PV,C} \right) \times c_{PV} \qquad (20)$$

where c_{PV} is the photovoltaic feed-in tariff.

The all-cost assumptions for calculating the economic assessment in this study are shown in Table 1:

5. ANALYSIS AND DISCUSSION OF RESULTS

The proposed PSO-based optimization algorithm was implemented through MATLAB and the DIgSILENT Power Factory software program. The effectiveness of the proposed algorithm approach is to demonstrate two distribution systems, namely the IEEE 13-bus test system and the practical distribution network. The optimization problem is applied to a case study, and the following section outlines the scenarios that were considered in the paper.

5.1 Modified IEEE 13-Bus Distribution Network

The topology of the IEEE 13-bus distribution test network shown in Fig. 3 is considered. It includes a swing bus (bus 650) connected to a distribution network via a 5-MVA 115kV/4.16kV distribution transformer, which converts voltage levels to supply the power to the different loads. For this purpose, each bus test system is employed considering photovoltaic generation and variable demand profile during a day period.

This study aims to assess the effectiveness of the reactive power optimization method for regulating voltage

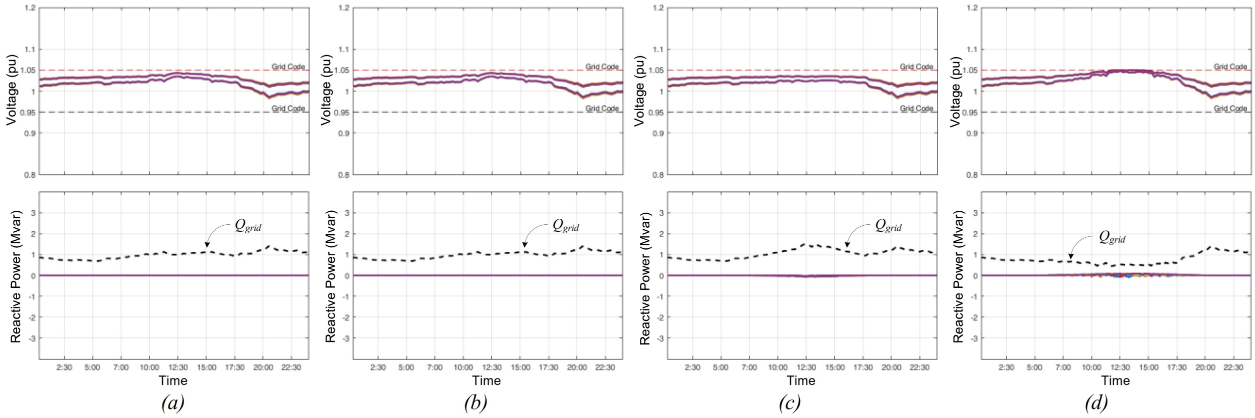


Fig. 4*: Voltage profile and reactive power compensation of modified IEEE 13-bus distribution network in Case 1. (a) Fixed PF method. (b)* $\cos\phi(P)$ *method. (c)* $Q(V)$ *method. (d) Proposed optimization method.*

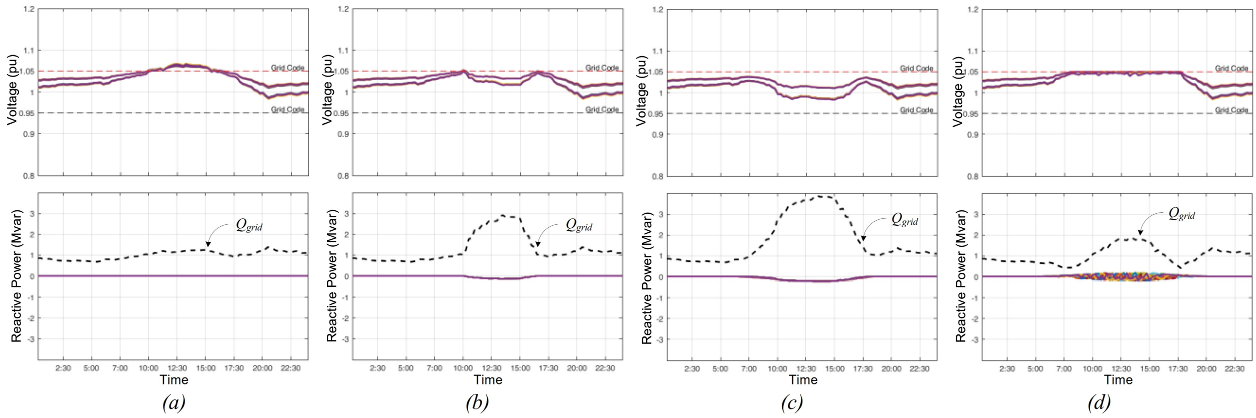


Fig. 5*: Voltage profile and reactive power compensation of modified IEEE 13-bus distribution network in Case 2. (a) Fixed PF method. (b)* $\cos\phi(P)$ *method. (c)* $Q(V)$ *method. (d) Proposed optimization method.*

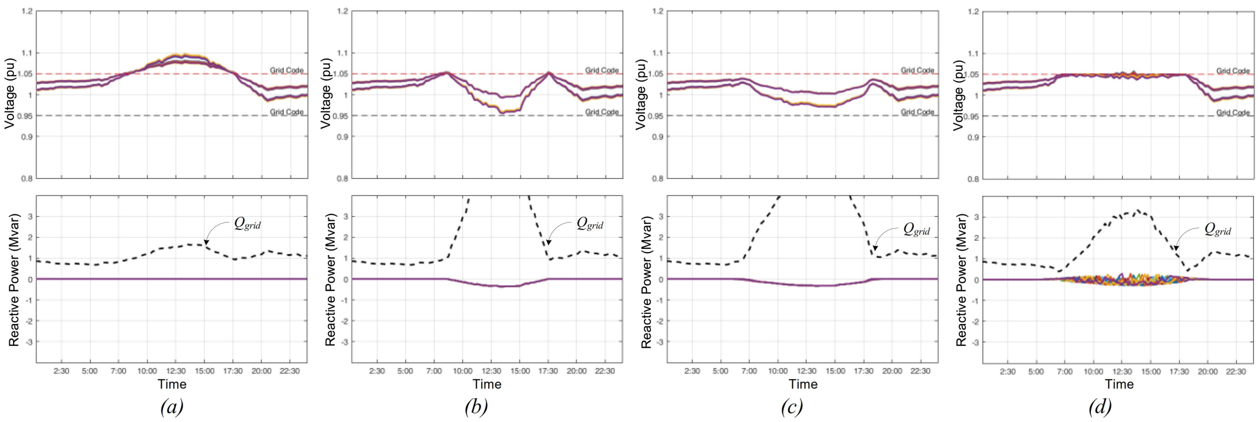
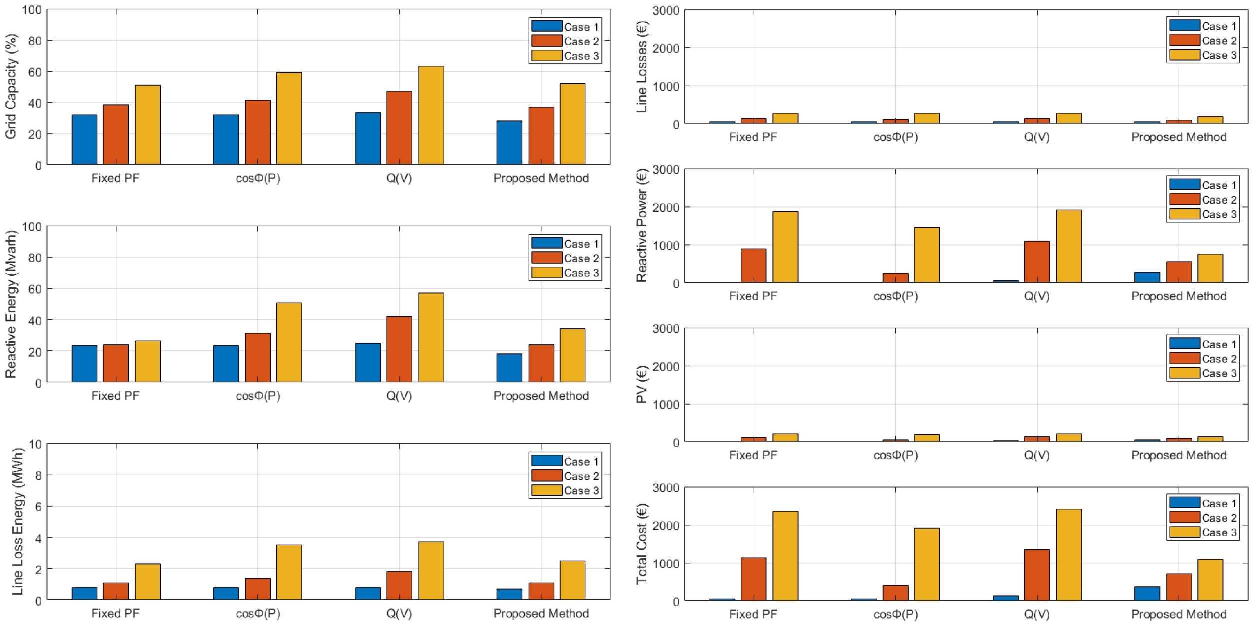


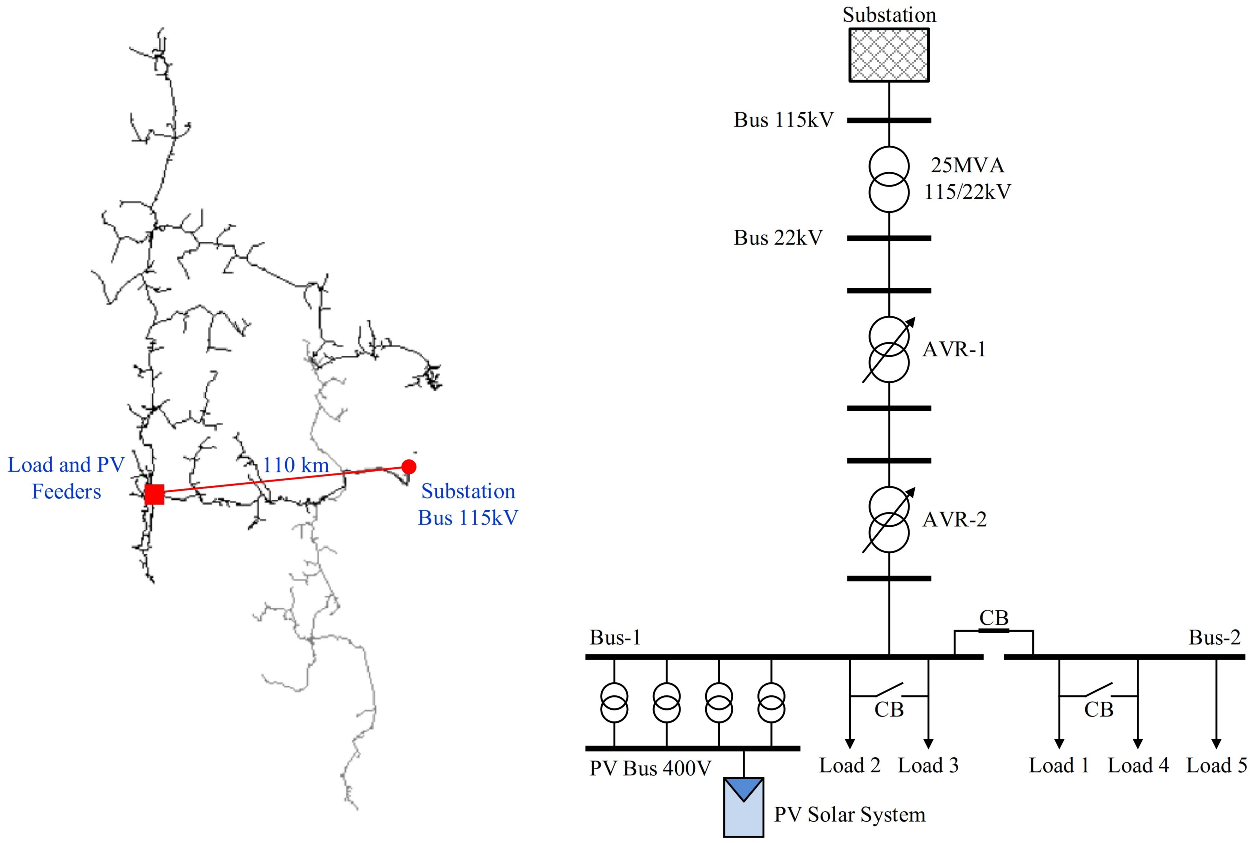
Fig. 6*: Voltage profile and reactive power compensation of modified IEEE 13-bus distribution network in Case 3. (a) Fixed PF method. (b)* $\cos\phi(P)$ *method. (c)* $Q(V)$ *method. (d) Proposed optimization method.*

and reducing system line losses in the high penetration of photovoltaic generation conditions. In order to analyze the performance of the proposed optimization method compared to the fixed power factor (PF), $\cos\phi(P)$, and $Q(V)$ methods. The bus voltages are kept within ±5% of the nominal voltage value under the IEEE 1547 standard [31]. Under operating conditions, the installed photovoltaic capacity can be described as *Case 1*: 2.5 MWp (Base case), *Case 2*: 5 MWp, and *Case 3*: 7.5 MWp. All simulation-based case studies define the total system network load demand as 2.5 MW and the total system reactive power load as 1.0 Mvar.



(a) (b)

***Fig. 7**: Charts displaying various results of simulated modified IEEE 13-Bus distribution network. (a) Grid capacity, reactive energy, and line loss energy. (b) Comparison of economic assessment of reactive power management methods under different case studies.*



(a) (b)

***Fig. 8**: Practical distribution network with substation including load and photovoltaic generation location. (a) Geographical diagram for the distribution network. (b) 2-bus aggregated feeder diagram.*

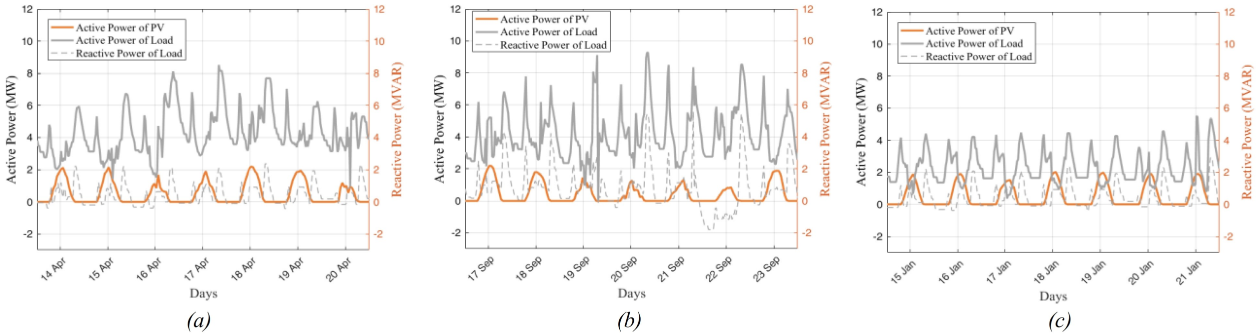


***Fig. 9**: Active and reactive powers of the load and photovoltaic generation profiles in different seasons. (a) Summer season. (b) Rainy season. (c) Winter season.*

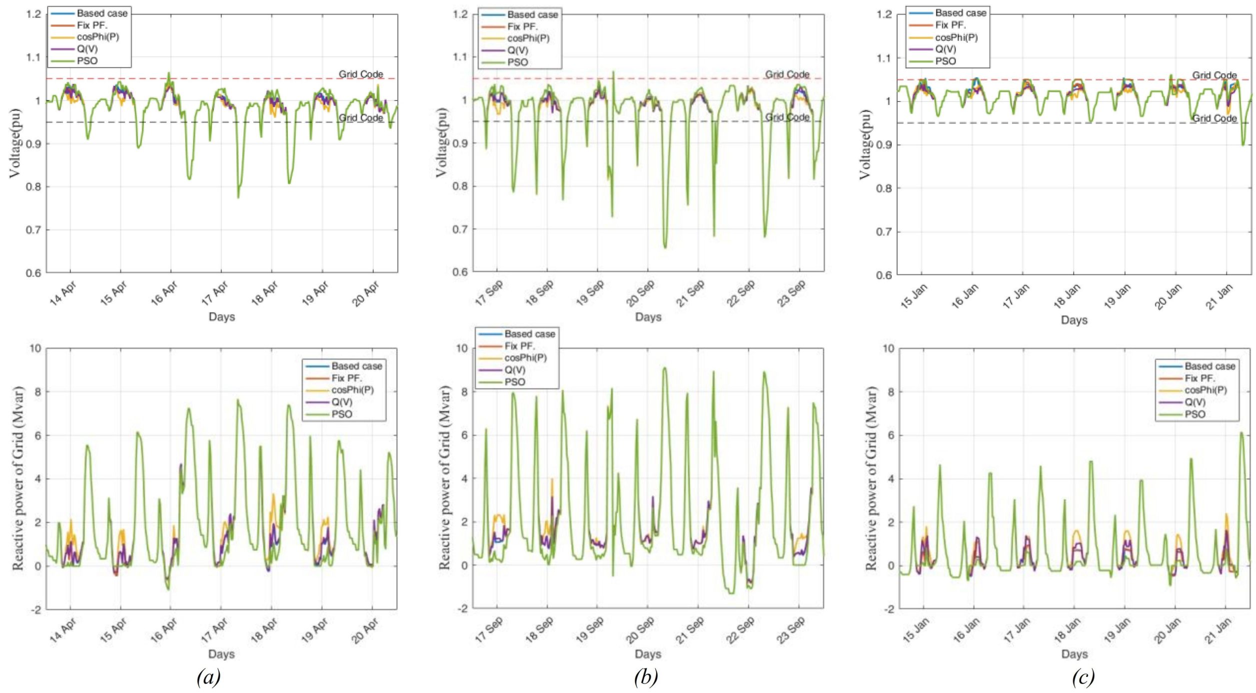


***Fig. 10**: Voltage profile and reactive power compensation of the reactive power control methods for practical distribution networks in different seasons. (a) Summer season. (b) Rainy season. (c) Winter season.*

The voltage variation and reactive power profiles resulting from implementing reactive power control methods in *Case 1-3* are depicted in Figs. 4-6, respectively. In *Case 1* (Base case), as shown in Fig. 4, the voltage variation at each bus can be effectively managed to ensure stability and minimize voltage levels across all reactive power control methods. Furthermore, the findings illustrated in Fig. 4 (*d*) demonstrate that the proposed optimization method outperforms other control methods in supporting reactive power on a distribution network. It is evident that the proportion of grid reactive power consumption is lower compared to other methods.

To mitigate the overvoltage issue resulting from the high penetration of photovoltaic generation in the distribution network, Figs. 5 and 6 (*Case 2* and *Case 3*) illustrate that the proposed method effectively utilizes reactive power from photovoltaic generation to bolster the distribution network, surpassing other methods in efficiency.

As shown in Fig. 7, the performance of quantitative assessments for reactive power control methods is primarily defined in terms of the percentage of grid capacity, grid reactive energy, line losses energy, and economics. As anticipated in Fig. 7 (*a*), the proposed optimization algorithm effectively reduces reactive energy and line losses within the distribution network, leading to the grid capacity being diminished. Fig. 7(*b*) presents a comparative analysis of the economic assessment of reactive power management methods across various case studies. It can be seen that with high penetration of photovoltaic generation and effective reactive power control strategies, the total costs can be reduced.

5.2 Practical Distribution Network

As shown in Fig. 8, a real distribution network is located in the Microgrid Development Project in Mae-Sariang district, Mae Hong Son province, Thailand, to design and test the optimization algorithm.

The modeling of the system network was developed using the DIgSILENT Power Factory software program, which controls the algorithm with MATLAB. The geographical diagram of the distribution network shown in Fig. 8 (*a*) is a practical medium-voltage 22 kV distribution feeder with a long overhead power line from the substation about 110 km. Fig. 8 (*b*) shows the 2-bus aggregated model of the described distribution network used to analyze the performance of the proposed algorithm. A feeder diagram consists of a 25-MVA and 115kV/22kV power transformer to supply residential consumers (Load 1-5), which is the neglected operation of the on-load tap change of the power transformer. The distribution lines employed are Space Aerial Cables (SAC), sized at 120 and 185 sq.mm., spanning a length of 110 km each. Additionally, a 4-MW photovoltaic generation system has been integrated at Bus 1. This feeder experiences load fluctuations, ranging from a minimum of 4 MW to a maximum of 8 MW.

Fig. 9 shows the active and reactive powers of the load and photovoltaic generation profiles in the three season case studies: summer, rainy, and winter. The study investigates seasonal variations, analyzing how load and photovoltaic generation power output shift throughout the year. It noticed that weather conditions directly influence solar energy production; it rises during sunny weather and declines during cloudy conditions due to its dependence on solar radiation. Typically, the load demand tends to be greater during summer than winter, with peak demands in summer surpassing those in winter. In addition, electricity demand also varies throughout the day, driven by human activities and behaviors.

Fig. 10 shows the voltage variation and reactive power support from the grid of the reactive power control methods for practical distribution networks in different seasons. Figs. 10 (*a*) and (*b*) show that the voltage experiences a drop within the constraints of the lower grid code with IEEE 1547 standard due to increased electrical load demand during periods of low solar irradiance. It indicates that the reactive power compensations of photovoltaic generation and the distribution grid are insufficiently supported due to constraints imposed by the rated power of the transformer and photovoltaic generation limitations. However, the voltage variation and grid reactive power compensation in winter are shown in Fig. 10 (*c*). Reactive power control methods can effectively regulate stability by managing voltage variation. It also consumes minimal reactive power from the grid.

Finally, Fig. 11 illustrates the resulting bar charts comparing the grid capacity and economic assessments across various seasons alongside reactive power control methods. As seen in Fig. 11 (*a*), the proposed optimization algorithm method can achieve a reduced percentage of grid capacity utilization compared to alternative control methods. On the one hand, the reactive power support from photovoltaic generation can substantially decrease grid reactive power and power line losses, as shown in Fig. 11 (*b*) and (*c*), respectively. As a result, in Fig. 11 (*d*), the proposed method can lead to significant total cost savings if reactive power management is invested in photovoltaic generation systems in distribution networks.

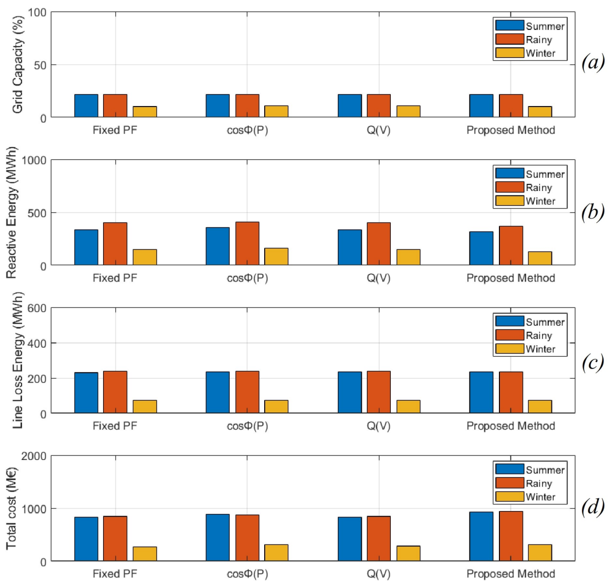


Fig. 11: Economic assessment comparison for practical distribution network in different seasons. (a) Grid capacity. (b)Reactive energy. (c) Line loss energy. (d) Total cost.

6. CONCLUSIONS

This paper presented an optimization algorithm for reactive power control aimed at voltage regulation and minimized reactive power utilization, employing an inverter-based photovoltaic generation system to enhance the hosting capacity of the distribution grid. The effectiveness of the proposed optimization algorithm has been assessed on the IEEE 13-bus test system and a practical distribution network, offering a comparison with a fixed power factor (PF), $\cos f(P)$, and $Q(V)$ methods to evaluate the capability of photovoltaic generation systems under various operational scenarios. The effectiveness of the proposed control method was demonstrated in efficiently maintaining the bus voltage, managing grid reactive power, reducing distribution line losses, and optimizing the grid capacity of the distribution network, with a specific focus on minimizing reactive power flow through the connection point at the substation. The comprehensive technical and economic assessments presented provide the test systems invaluable. They enable a substantial reduction in grid reinforcement measures by leveraging additional reactive power support from photovoltaic generation systems rather than solely supplying active power.

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