

Article

Study of Synergetic Optimization Operation for Distribution Network Considering Multiple Reactive Power Output Modes of Photovoltaics and Different Port Numbers of Flexible Interconnection Devices

Yijin Li ¹, Jibo Wang ¹, Zihao Zhang ¹, Wenhao Xu ¹, Ming Wu ² and Geng Niu ^{2,*}

¹ School of Mechanical and Electrical Engineering, China University of Mining and Technology-Beijing, Haidian District, Beijing 100083, China; liyijin@cumtb.edu.cn (Y.L.); sqt2300403061@student.cumtb.edu.cn (J.W.); zqt2300403089@student.cumtb.edu.cn (Z.Z.); zqt2300403084@student.cumtb.edu.cn (W.X.)

² State Grid Shanghai Energy Interconnection Research Institute, China Electric Power Research Institute, Haidian District, Beijing 100192, China; wuming@epri.sgcc.com.cn

* Correspondence: niugeng@epri.sgcc.com.cn

Abstract: Due to the integration of distributed photovoltaic (PV) into distribution networks, significant challenges have affected voltage regulation and power quality maintenance. To improve the flexibility and stability of system operation, a synergetic optimization operation method based on PV and a flexible interconnection device (FID) is proposed. Both PV and FID hold the capability of controlling active power and reactive power. Besides the active power output of PV, three reactive power output schemes of power factor controlling, direct reactive power output, and night static var generator scheme are defined and analyzed. By adopting different schemes during the day or night, five reactive power output modes were built. FID with four-quadrant power control ability was used to coordinate with PV in system power balance. Different port numbers of FIDs are discussed. An optimization model with the aim of reducing voltage deviation, network loss, and the ratio of PV abandonment was constructed. Three algorithms were used for solving the multi-objective optimization model. Simulation results verify that the proposed synergetic optimization method can obviously improve power quality and decrease network loss. The optimal performance is obtained when PV operates in mode 5 and FID holds four ports. The proposed method shows potential in the coordinated operation of various resources and the flexible interconnection of the distribution network.



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Keywords: synergetic optimization; distribution network; photovoltaic (PV); reactive power output mode; flexible interconnection device (FID)

1. Introduction

Owing to the development of distributed generations (DGs) and the requirement of environment protection, more DGs are integrated into distribution networks [1,2]. Despite holding the advantages of being flexible, economic, and environmentally friendly, the integration of DGs bring significant challenges to the stable operation of distribution networks, resulting in the problems of bi-directional power flow, voltage out-of-limit, and line overload [3,4]. Traditional methods for voltage regulation includes on-load tap changer (OLTC) and capacitor bank (CB) [5,6]. However, utilizing OLTC requires abundant reactive power in a system. CB may cause harmonic amplification and significant impact current. Thus, new methods have to be explored for distribution networks to improve power quality.

A flexible interconnection device (FID) is a power electronic device. It can flexibly control power flow through voltage source converter (VSC) technology. Thus, it is used for feeder connection in distribution networks [7–9]. FID usually replaces the tie switches for the connection of two or more feeders [10]. FID can control active and reactive power flow separately. It shows the advantages of continuous adjustment and rapid response [11,12], which are applicable for operation optimization. Ehsanbakhsh M. et al. [13] constructed a stochastic scenario-based optimization model to simultaneously optimize the siting and sizing of soft open points (SOPs) and tie switches. The optimal operation strategy of these devices is obtained during the network reconfiguration process, thereby significantly improving the operational efficiency and system stability of the distribution network. Wang X. et al. [14] proposed a multi-objective robust optimization model based on various controllable devices as a flexible distribution switch and energy storage. The proposed method can obviously decrease network losses, increase the profit, and improve voltage profiles. Ali Z.M. et al. [15] introduced a novel mathematical optimization algorithm for maximizing hosting capacity (HC) through sequential network reconfiguration and SOP placement. A new SOP allocation index is proposed, which effectively improves distribution network performance and optimizes DG penetration. Deakin M. et al. [16] designed a hybrid multi-terminal soft open point (MT-SOP) to efficiently improve distribution system interconnection capacity. A case study showed that the hybrid MT-SOP increased the utilization of converters and reduced system loss. Shi M. et al. [17] presented a cooperative control strategy of a flexible interconnection device and energy storage. The proposed control strategy can achieve power mutual aid between feeders, leading to the stable operation of the power grid.

A photovoltaic (PV) system, as a typical DG, can selectively provide active power and reactive power based on inverter control [18]. The IEEE 1547-2018 standard indicates that inverter-based distributed energy resources can actively participate in voltage regulation by modulating the active and reactive power output [19]. Several studies have concentrated on the optimization of a PV inverter. Guo W. et al. [20] proposed a harmonic suppression and reactive power compensation strategy for a distribution network based on a photovoltaic multifunctional grid connected inverter. Except for the active power output of PV, the remaining capacity of the inverter was utilized to offer reactive power compensation for better power quality. Rahman M.M. et al. [21] propounded an advanced nonlinear control scheme based on adaptive integral back stepping for the optimization of a three-phase grid-connected photovoltaic inverter. The scheme aims to maximize the power output of the photovoltaic system, precisely control active and reactive power, and reduce harmonic injection. De Jesus V.M.R et al. [22] studied the PV inverter's capability to provide harmonic current compensation for nonlinear loads and proposed an algorithm to determine the capability curves of a multifunctional inverter during the harmonic current compensation process. Rossoni P. et al. [23] presented a hybrid approach considering both distribution network reconfiguration and the reactive power of a PV inverter. The PV inverter control of different power factors was discussed. The combination of PV inverter control and network reconfiguration can reduce active power loss by more than 37%. Alrashidi M. et al. [24] provided a voltage management strategy by the coordination of battery energy storage systems and smart PV inverters.

To comprehensively improve stability and economy of the distribution network operation, the aforementioned PV and FID are simultaneously used. Due to the high R/X ratio of distribution networks [25], both active power and reactive power will influence the voltage profile and power quality. The optimization of active power and reactive power is required. It is difficult to obtain satisfied performance when adjustment is carried out with a single device. Thus, synergetic optimization is proposed. Active power control can be achieved by

FID and PV. However, the curtailment of PV active power results in low a PV consumption rate and additional economical loss. To take the PV consumption rate into consideration, minimizing the ratio of PV abandonment is set as another optimization objective, except for power quality. The reactive power control can also be realized by FID and PV. However, the earlier reactive power optimization of PV mainly focuses on capacity constraint and power factor constraint. The specific analysis of PV reactive power output mode needs further study. In addition, different port numbers of FID and different solving algorithms of the optimal model can also impact the operation, which requires more analysis.

In this paper, a synergetic optimization operation method of PV and FID is proposed. Multiple scenarios are taken into consideration including different reactive power output modes of PV, different port numbers of FID, and different algorithms for the solution. The main contributions of this paper can be summarized as follows:

- (1) A synergetic optimization operation method of PV and FID is constructed. Three objectives of voltage deviation, network loss, and ratio of PV abandonment are selected. To flexibly control active power and reactive power, multiple reactive power output schemes of PV and multiple port numbers of FID are considered as constraints. The proposed method enhances power flow controlling, which provides better operation performance.
- (2) Five reactive power output modes of PV are analyzed and simulated. Three reactive power output schemes of power factor controlling, direct reactive power output, and night static var generator (SVG) scheme are considered. According to the adoption of different output schemes in different periods (day and night), five modes are built, simulated, compared, and discussed. By adopting a direct reactive power output scheme during daytime and the SVG scheme at night, PV is fully utilized in both active power consumption and reactive power compensation, which also improves the flexibility and stability of the system.
- (3) Multiple operation and optimization situations are analyzed and compared to verify the effectiveness of the proposed method. FIDs with different port numbers are taken into account. Three algorithms for solving the optimization model are compared. Cases with increasing permeability are simulated. Simulations show that the combination of FID with four ports, PV with operation mode 5, and the solving algorithm of NSGA-II gives the best result, which is the most suitable for optimization operation.

The remainder of this paper is organized as follows: Section 2 introduces the modeling of PV and FID. Multiple reactive power output modes of a PV inverter are considered. Section 3 develops a synergetic optimization operation model of PV and FID. Section 4 introduces three algorithms for solving the proposed multi-objective optimization model. Section 5 presents case studies. Section 6 gives the conclusion.

2. Modeling of PV and FID

2.1. Modeling of PV Considering Multiple Reactive Power Output Modes

A PV system mainly consists of the photovoltaic panel and the inverter. The photovoltaic panel transforms solar energy into electricity based on the photoelectric effect. The inverter controls the power output. Both active power and reactive power can be provided. The total output of active power and reactive power should not exceed the capacity of the inverter at any time. The constraint can be described as follows:

$$\sqrt{(P_{PV.m})^2 + (Q_{PV.n})^2} \leq S_{FV.n} \quad (1)$$

where $P_{PV.m}$ is the active power output of PV_m . $Q_{PV.n}$ is the reactive power output of PV_m . $S_{FV.n}$ is the capacity of PV_m . m is the number of PV.

The active power output is related to light intensity and environmental temperature. Generally, a PV is operated under the maximum power point tracking (MPPT) mode. Thus, maximum active power can be output, and a high consumption rate of PV is obtained. However, owing to the big resistance/inductance ratio (R/X) of a distribution network, the voltage is also sensitive to the change in active power. The injection of large amounts of active power can cause the voltage rise or even voltage out-of-limit. The intermittence and fluctuation of active power output also affect the power flow. Thus, the active power output of PV_m cannot exceed the active power of PV_m under MPPT mode ($P_{MPPT,m}$). To make full use of the PV and keep voltage within limits, the ratio of PV abandonment is set as an objective function to be minimized. The optimization will obtain an optimal solution for the whole system, instead of only for the PV.

According to the investigation of the product specifications of photovoltaic inverter manufacturers and the technical specifications established by some countries, the reactive power output by PV inverter holds three schemes. The first one is the power factor controlling scheme. The power factor of a PV inverter is restricted to the range of $-\cos \theta$ to $\cos \theta$. This scheme can only be used during daytime. The reactive power is limited as follows:

$$-\tan \theta \leq \frac{Q_{PV,m}}{P_{PV,m}} \leq \tan \theta \quad (2)$$

The second scheme is the direct reactive power output scheme. The reactive power output is no more than $\pm \tan \theta$ of the rated power. The constraint is as follows:

$$-\tan \theta \times S_{PV,m} \leq Q_{PV,m} \leq \tan \theta \times S_{PV,m} \quad (3)$$

The third scheme is the night SVG scheme. The reactive power output is only limited by the rated power. The following occurs:

$$-S_{PV,m} \leq Q_{PV,m} \leq S_{PV,m} \quad (4)$$

These last two schemes can be used during both daytime and nighttime. However, during daytime, the active power and reactive power output should also satisfy the capacity constraint.

The first two schemes are mainly used to satisfy the dispatching of reactive power. The third scheme is utilized to compensate the reactive power of the devices. To evaluate the performance of PV inverters' participation in reactive power optimization, different schemes are adopted at different time periods, such as during the day and night. Five reactive power output modes are built. The reactive power output ranges of the PV inverter in each mode are shown in Figure 1. The corresponding constraint equation selections are listed in Table 1. In the paper, $\cos \theta$ is set as 0.95.

Table 1. Constraint equations of five modes.

Mode	Day (PVs Output Active Power)	Night (PVs Do Not Output Active Power)
1	Equation (3)	Equation (3)
2	Equation (3)	Equation (4)
3	Equation (4)	Equation (4)
4	Equation (3)	Equation (5)
5	Equation (4)	Equation (5)

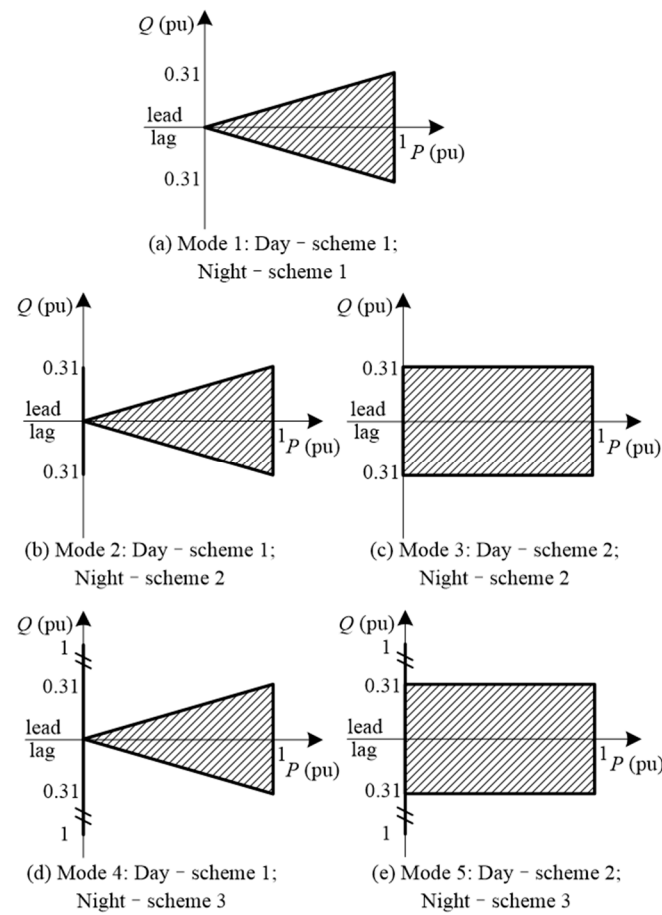


Figure 1. The reactive power output ranges of the PV inverter for five modes.

2.2. Modeling of FID

FID is a fully controlled power electronic device. Two or more VSCs connect at the DC side, forming a back-to-back structure. Each VSC forms a port. The port connects to the DC bus internally. The port connects to distribution feeders externally, achieving the interconnection of different feeders.

Generally, FID is operated in PQ- V_{dc} Q control mode. Both the voltage at the DC side and the active/reactive power are controlled. The active power satisfies the conservation law for all ports of an FID. It can be described as follows:

$$\sum_{i=1}^k P_{VSC,i} = 0 \quad (5)$$

Therein, $P_{VSC,i}$ is the active power of VSC_{*i*}. The *k* is the amount of FID ports.

The reactive power output is controlled independently for each port. The total active power output and reactive power output should not exceed the port capacity. The constraint is as follows:

$$P_{vsc,i}^2 + Q_{vsc,i}^2 \leq S_{vsc,i}^2 \quad (6)$$

where $Q_{vsc,i}$ is the reactive power of VSC_{*i*}. $S_{vsc,i}$ is the rated capacity of VSC_{*i*}.

3. Synergetic Optimization Operation Model of PV and FID

3.1. Objective Function

Multi-objective optimization can provide a comprehensive optimal solution for problems, which is adopted in this paper. The optimization objectives of distribution network

operation include reducing network loss and operation cost, improving power quality, balancing load, increasing the ratio of clean energy, and so on. Among them, three objective functions of voltage deviation (F_1), network loss (F_2), and the ratio of PV abandonment (F_3) are selected. The objective function is defined as follows:

$$\min f = (F_1, F_2, F_3) \quad (7)$$

- (1) Voltage is one of the most important quality indicators for a distribution network. The voltage quality is closely related to a network's safe operation, network loss, and consumers' electricity utilization. The line drop, the load fluctuation, and the connection of PV increase the difficulty in maintaining qualified voltage. Thus, minimizing voltage deviation is chosen as an objective function, representing the power quality. The voltage deviation is defined as follows:

$$F_1 = \sum_{i=1}^n \left| \frac{V_i - V_{iN}}{V_{iN}} \right| \quad (8)$$

where V_i is the actual voltage of node i . V_{iN} is the rated voltage of node i . n is the quantity of the nodes.

- (2) Network loss is one of the most important economic indicators for a distribution network. By active and reactive power optimization, network loss can be minimized. The network loss is defined as follows:

$$F_2 = \sum_{ij \in \Omega_0} \left(\frac{(P_{ij})^2 + (Q_{ij})^2}{(V_i)^2} R_{ij} \right) \quad (9)$$

Therein, P_{ij} and Q_{ij} are the active power and the reactive power flowing through branch ij , respectively. R_{ij} is the resistance of branch ij . Ω_0 is the set of all branches.

- (3) Environmental friendliness is an important requirement for sustainable development. PV belongs to clean energy and the permeability of PV continually increases. Large amounts of active power injections will cause voltage rise. Voltage regulation can be realized by the curtailment of PV active power output. However, the curtailment of PV active power will not only reduce the consumption rate of PV but also decrease the benefit of PV systems. To balance voltage quality and PV consumption rate, minimizing the ratio of PV abandonment is chosen as an objective function. The ratio of PV abandonment is defined as follows:

$$F_3 = \frac{\sum_{i=1}^m P_{MPPT,i} - \sum_{i=1}^m P_{PV,i}}{\sum_{i=1}^m P_{MPPT,i}} \quad (10)$$

Therein, $\sum_{i=1}^m P_{MPPT,i}$ is the sum of all PVs' active powers of MPPT. $\sum_{i=1}^m P_{PV,i}$ is the sum of all PVs' active power outputs.

3.2. Constraints

To ensure the safe and stable operation of the distribution network, four constraints should be satisfied.

- (1) Power flow constraint

For node i , there is the following:

$$\begin{cases} P_i = V_i \sum_{j \in \Omega_i} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \\ Q_i = V_i \sum_{j \in \Omega_i} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \end{cases} \quad (11)$$

Therein, P_i is the active power injected to node i . Q_i is the reactive power injected to node i . θ_{ij} is the phase angle difference between node i and node j . G_{ij} and B_{ij} are the conductance and susceptance of branch ij , respectively. Ω_i is the set of nodes adjacent to node i .

For each node, power conservation law must be satisfied. The power of PV, FID, and load are all taken into account. The following occurs:

$$\begin{cases} P_i = \eta (P_{PV}^i + P_{VSC}^i) - P_{Load}^i \\ Q_i = \eta (Q_{PV}^i + Q_{VSC}^i) - Q_{Load}^i \end{cases} \quad (12)$$

Therein, P_{PV}^i and Q_{PV}^i are the active power and reactive power of PV in node i , respectively. P_{VSC}^i and Q_{VSC}^i are the active power and reactive power of VSC in node i , respectively. P_{Load}^i and Q_{Load}^i are the active load and reactive load of node i , respectively. η is the efficiency. It is used to quantify the losses during energy conversion and transmission in the power system. The value is set as 0.9.

(2) Node voltage constraint

The node voltage cannot exceed the setting range to ensure safe and reliable operation. The following occurs:

$$V_{i,\min} \leq V_i \leq V_{i,\max} \quad (13)$$

where $V_{i,\min}$ and $V_{i,\max}$ are the allowed minimum voltage and the allowed maximum voltage of node i .

(3) Constraints of PV

The capacity constraint must be met as Equation (1). The active power output constraint must be met as follows:

$$P_{PV,m} \leq P_{MPPT,m} \quad (14)$$

For different reactive power output modes, the constraints should be met, as listed in Table 1.

(4) Constraints of FID

The active power conservation constraint and the port capacity constraint must be satisfied as Equations (5) and (6).

4. Solution Method for Optimization Model

The proposed optimization problem can be solved either by being transformed into a single-objective optimization problem or by utilizing multi-objective optimization algorithms. The former method is easily attained by adding weight for each objective. However, the weight value is difficult to determine. Thus, multi-objective optimization algorithms are adopted to find the Pareto solution set.

4.1. NSGA-II

NSGA-II (Non-dominated Sorting Genetic Algorithm-II) is a multi-objective evolutionary algorithm based on elitist strategy. Owing to non-dominated sorting, crossover, and mutation, the diversity of the population is maintained, improving the convergency and

searching efficiency. The application process of NSGA-II in solving the proposed model is illustrated in Figure 2. The procedures are listed as follows:

- (1) Initialization: Each individual (solution) is encoded as a real-valued vector, including daytime/night reactive power output mode of PV, p and Q set points of FID ports, and the active power curtailment ratio of PV. Randomly generate an initial population, ensuring that all solutions satisfy constraints. Set the parameters of population size as 100, maximum iterations as 200, crossover probability as 0.9, and the mutation probability as the reciprocal of the variable quantity.
- (2) Fitness evaluation: Make power flow calculations for each solution and further calculate the objective function. Use a penalty function to remove solutions that exceed constraints.
- (3) Non-dominated sorting: Sort the population into multiple Pareto fronts based on objective function values.
- (4) Crowding distance calculation: Calculate the crowding distance in the objective space to measure the distribution density of the solutions. Select solutions with larger crowding distances to maintain population diversity.
- (5) Selection, crossover, and mutation: Select parent individuals through binary tournament selection. Use simulated binary crossover (SBX) with a crossover distribution index of 20. Use polynomial mutation with a mutation distribution index of 20, ensuring variables remain within feasible bounds.
- (6) Iteration and termination: Combine parent and offspring populations. Perform non-dominated sorting and crowding distance calculation and retain the best N individuals. When the maximum number of iterations is reached or the convergence conditions are achieved, the iterations terminate.

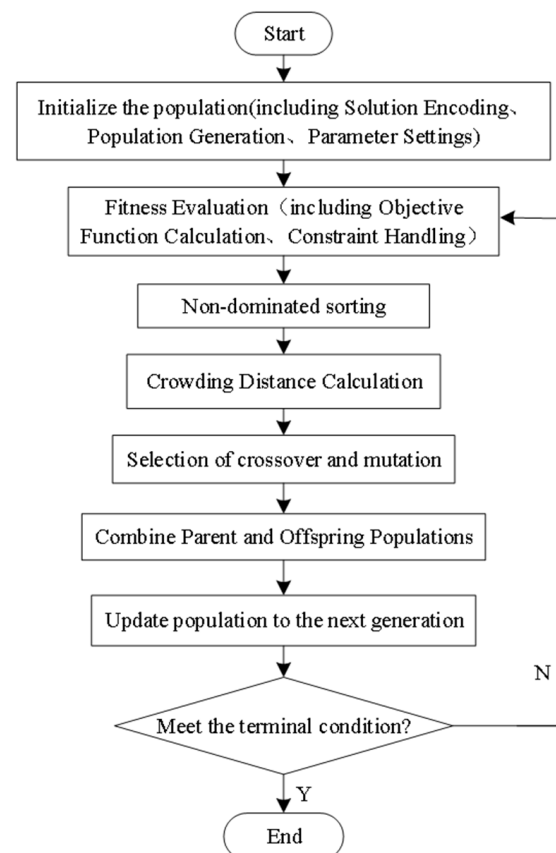


Figure 2. Flow chart of solving proposed model by NSGA-II.

4.2. NSGA-III

NSGA-III (Non-dominated Sorting Genetic Algorithm-III) is a modified algorithm of NSGA-II, which shows advantages in handling complex problems with high-dimensional objective spaces. Instead of sorting by crowded distance as NSGA-II, reference point set and hierarchical strategy are used in NSGA-III. The reference points are uniformly distributed in the normalized objective space, guiding the algorithm to preserve solutions that cover a broad and balanced range of the Pareto front. This approach enhances diversity, particularly in scenarios where objectives are numerous or conflicting, ensuring that the optimization process does not prematurely converge with the localized solutions. With the hierarchical strategy, the solutions within each front are associated with the nearest reference points. Individuals are selected to ensure the proportional representation of each reference region. This method effectively improves the convergence and solving efficiency.

The overall application process of NSGA-III is similar with that of NSGA-II. Both of them hold the procedures of population initialization, fitness evaluation, non-dominated sorting, crossover, mutation, and iterative refinement. The distinction is that before population initialization, the reference point set is selected. During the solving process, the dominant individuals and the next generation are selected out based on the reference points.

4.3. MOPSO Algorithm

MOPSO (Multi-Objective Particle Swarm Optimization) is developed from PSO. The key strategy is using a non-dominated set to maintain and update the frontier solution. Thus, the problem of local optimum can be avoided. The application process of MOPSO in solving the proposed model is shown in Figure 3. The procedures are listed as follows.

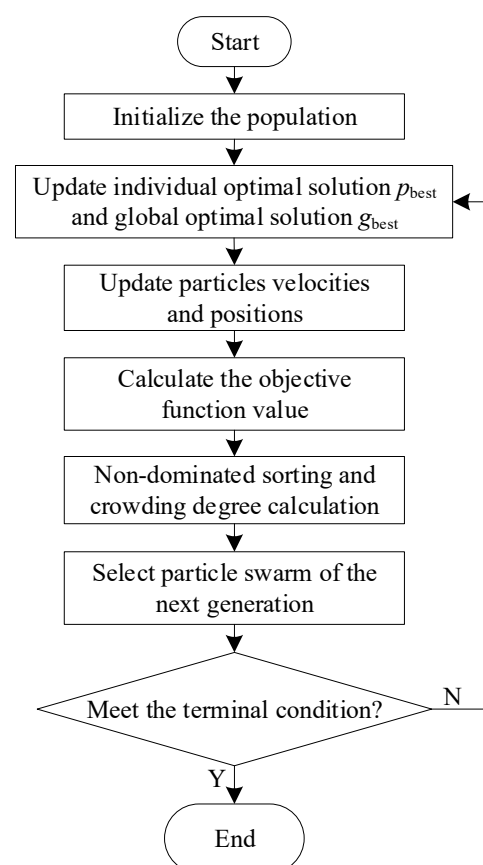


Figure 3. Flow chart of solving proposed model by MOPSO.

- (1) Initialize the population: Randomly generate N initial solutions as the population of the first generation. Randomly generate the velocity and position of the initial particle. N is set as 300. The maximum number of iterations is set as 100.
- (2) Update individual optimal solution p_{best} and global optimal solution g_{best} : The previous best position of a particle is p_{best} . If the p_{best} of the updating particle is non-dominated with the previous best position, make a selection between them with the probability of 0.5. Find the current best particle set by Pareto front. Select the least crowded particle as the best particle.
- (3) Update the particles' velocities and positions: Update the particles' velocities according to the current velocity, p_{best} and g_{best} . Update the particles' positions.
- (4) Calculate the objective function value: Calculate the power flow. Check the constraints. Make modifications for individuals not meeting the constraints. Calculate the objective function value.
- (5) Non-dominated sorting according to the individual fitness: Calculate the crowding degree.
- (6) Select the particle swarm of the next generation according to the results of step (5).
- (7) Judge the terminal condition. If the condition is met, end the solving process. If not, repeat step (2)–(6).

4.4. Comprehensive Evaluation of Solutions

In this paper, the promotion ratio and its weighted average are calculated out for obtaining a compromised optimal solution. The promotion ratio is defined as follows:

$$\mu = \frac{f_{\text{init}} - f_x}{f_{\text{init}}} \quad (15)$$

Therein, μ is the promotion ratio, which is used to evaluate the improvement degree of the objective functions before and after optimization. f_{init} and f_x are the objective function value before and after optimization, respectively. For each solution in the Pareto front and for each objective function, the promotion ratio is calculated and forms a promotion ratio matrix.

The normalized promotion ratio can be calculated as follows:

$$\mu_{\text{norm}} = \frac{\mu - \mu_{\min}}{\mu_{\max} - \mu_{\min}} \quad (16)$$

where μ_{norm} is the normalized promotion ratio. $\mu_{\max}$ and $\mu_{\min}$ are the maximum and minimum promotion ratios in the promotion ratio matrix, respectively.

For each objective function, all the normalized promotion ratios are summarized and averaged. By subjective decision or objective weighting methods, the weight of each objective function is given. The compromised optimal solution is obtained by the weighted calculation of the averaged promotion ratio.

5. Case Simulation

5.1. Setting of Cases

The simulation is conducted based on a modified IEEE 33-node system. The voltage level is 12.66 kV. The total active power and total reactive power are 3715 kW and 2300 kVar, respectively. PVs and FIDs with different port numbers are connected to the system. Seven cases are simulated and analyzed. The diagrams of the seven cases are shown in Figure 4. The parameter settings are listed in Table 2. The simulation is completed with MATLAB R2023b on a platform named PlatEMO [26].

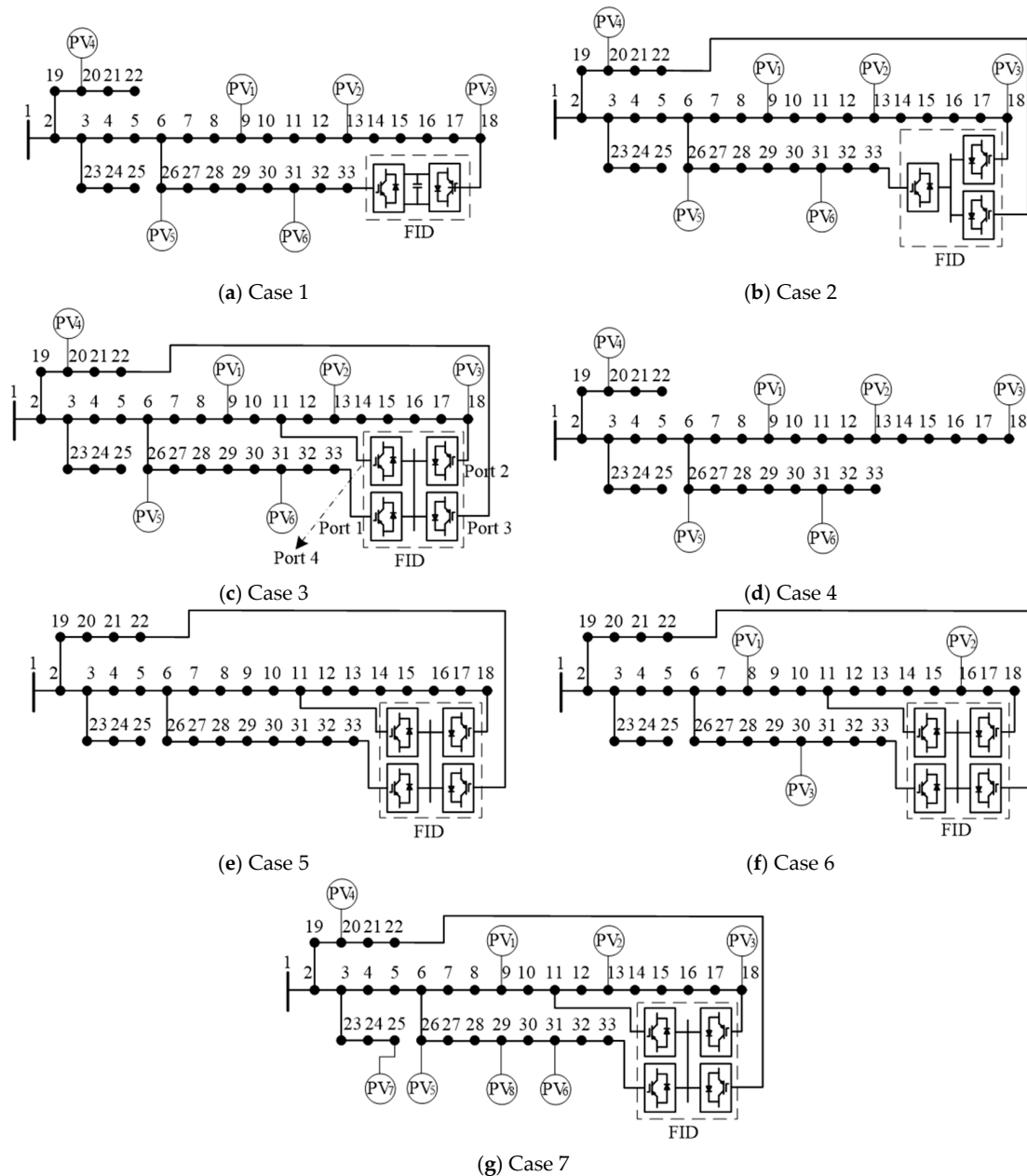


Figure 4. The diagrams of the simulation cases.

Table 2. Parameter settings of seven cases.

Case Number	Parameter Settings	
	FID	PV
1	Two ports: between node 33 and node 18 Capacity of each port: 500 kW	Six PVs PV1: at node 9, 400 kW PV2: at node 13, 600 kW PV3: at node 18, 500 kW PV4: at node 20, 300 kW PV5: at node 26, 300 kW PV6: at node 31, 400 kW
2	Three ports: among node 33, node 18, and node 22 Capacity of each port: 500 kW	
3	Four ports: among node 33 (port 1), node 18 (port 2), node 22 (port 3), and node 11 (port 4) Capacity of each port: 500 kW	
4	None	

Table 2. Cont.

Case Number	Parameter Settings	
	FID	PV
5		None
6	Four ports: among node 33 (port 1), node 18 (port 2), node 22 (port 3), and node 11 (port 4) Capacity of each port: 500 kW	Three PVs PV1: at node 8, 400 kW PV2: at node 16, 500 kW PV3: at node 30, 300 kW
7		Eight PVs PV1–6: the same as case 1 PV7: at node 25, 400 kW PV8: at node 29, 300 kW

5.2. Comparison of Different Algorithms

Taking PV reactive power output mode 1 as an example, optimization results at different time periods, by different algorithms, with different reactive power optimization conditions and for different FID port numbers are compared and displayed in Figure 5. The daytime corresponds to 8:00–18:00, as shown in Figure 1, during which the PVs output active power. The night refers to 0:00–7:00 and 19:00–24:00, during which the active power output of the PVs is 0. Three algorithms of MOPSO, NSGA-II, and NSGA-III were compared. The “Yes” in the horizontal axis represents that the reactive power of PV is optimized. The “No” in the horizontal axis represents that the reactive power of the PV is not optimized. The FID of two ports, three ports, and four ports are also compared. The voltage deviation and network loss are displayed. The ratio of PV abandonment is very low for all the cases, which is not shown in Figure 5.

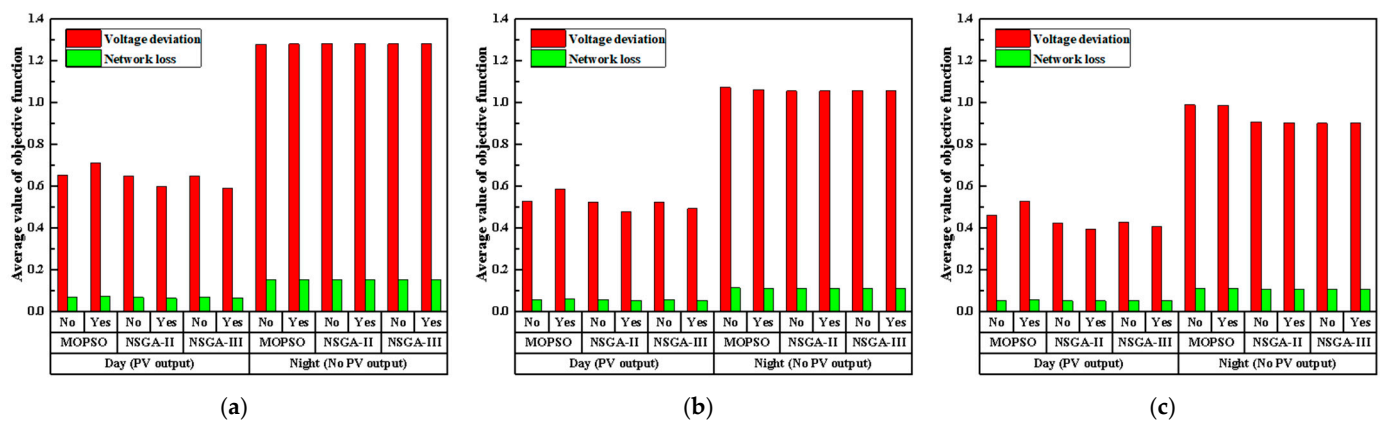


Figure 5. Optimization results obtained by different algorithms for FID with different number of ports. “No” in horizontal axis means that reactive power of PVs is not optimized. “Yes” in horizontal axis means that reactive power of PVs is optimized. (a) FID of two ports. (b) FID of three ports. (c) FID of four ports.

By comparing the results of day and night, it can be seen that the voltage deviation and network loss are both lower during daytime than during night. It indicates that the active power and reactive power adjustment of PV improves power quality. The effect of synergetic optimization is better than that of FID optimization alone.

During the night, the active power output of PV is 0. The reactive power output is also 0 in reactive power output mode 1. Thus, optimizing PV output does not have an impact on optimization results. The optimization results of the three algorithms are basically consistent. However, during the daytime, PVs can output both active power

and reactive power, leading to the difference in PV optimization. If there are m PVs, the dimension of searching space increases by $2m$ when the PV is optimized. The global searching ability of MOPSO is limited. The voltage deviation and network loss increase when the PV is optimized. The optimization performance of NSGA-II and NSGA-III shows the same changing trend. The power quality is better by synergetic optimization of the FID and PV than by FID optimization only. In further comparison, the searching ability of NSGA-II is better in dealing with problems of multi-port FID. The voltage deviation and network loss are lower. Thus, NSGA-II is chosen for later simulations.

In addition, by comparing the results in Figure 5a–c, the increase in FID port number also reduce voltage deviation and network loss. Owing to the increase in FID port number, active power can be transformed among the ports flexibly. The reactive power output of the ports provides a more reactive power adjustment for the network. The distribution network is more flexible. It is beneficial to improve the power quality of the system.

5.3. Discussion of Reactive Power Output Ratio by PV Inverter

The influence of the reactive power output ratio restriction by the PV inverter is discussed. The active power output of the PV operates at the rated power before optimization. It can be optimized together with reactive power, under the circumstance of satisfying the capacity constraint. The reactive power output ratio restriction of the PV can be adjusted from 0.01 to 0.31 by an increment of 0.01, composing 31 scenarios. Each scenario is simulated five times. The results are the average value of the five simulations. NSGA-II is used for solving problems. FIDs with different port numbers are also simulated. The simulation results are shown in Figure 6. The reference value used in Figure 6 is the voltage deviation and network loss without PV reactive power optimization.

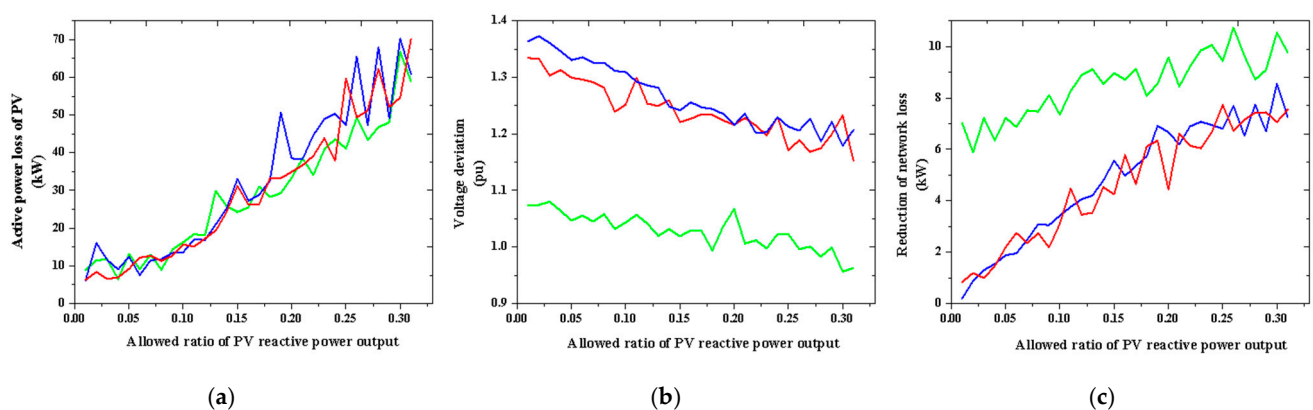


Figure 6. Optimization result comparison by setting allowed ratio of PV reactive power output. Blue line—FID with two ports; red line—FID with three ports; green line—FID with four ports. (a) Active power loss of PV. (b) Voltage deviation. (c) Reduction in network loss.

As seen from Figure 6, with the increase in PV reactive power output ratio restriction, the active power loss of the PV increases. Owing to the objective function of minimizing PV abandonment ratio, the active power loss of the PV cannot increase without limit. The active power loss does not exceed 70 kW. The whole PV rated capacity is 2500 kW. The ratio of PV abandonment is lower than 2.8%. Because the promotion ratio of the PV abandonment ratio is relatively small, the compromised optimal solution tends to the minimization of voltage deviation and network loss.

The reduction in network loss increases with the increase in reactive power output ratio restriction. However, it is less than 10 kW. It indicates that the optimization performance for network loss is limited due to the injection point of PV.

The voltage deviation is reduced when the reactive power output ratio restriction increases. The injection of reactive power improves the power factor of the distribution line. The voltage loss is reduced, and better power quality is obtained.

The optimization results are also compared for different FID port numbers. When the FID port number increases, the active power loss of the PV is substantially unchanged. The reduction in network loss slightly increases. The voltage deviation is obviously reduced, representing better power quality.

5.4. Comparison of Optimization Operation Results Under Different Reactive Power Output Modes of PV Inverter

The synergetic optimization of FID and PV under five PV reactive power output modes is simulated. The results are listed in Table 3 and shown in Figure 7. Because the ratio of PV abandonment was analyzed above, it is not listed. It can be seen that the network loss of the different modes is nearly the same. The range of network loss is 0.0043, which is very small. The difference focuses on the voltage deviation. The range of voltage deviation is 0.1217.

Table 3. Simulation results of five reactive power output modes.

Mode	Voltage Deviation (Ranking)	Network Loss (Ranking)
Mode 1	0.8355 (5)	0.0945 (3)
Mode 2	0.7976 (4)	0.0933 (2)
Mode 3	0.7883 (3)	0.0927 (1)
Mode 4	0.7253 (2)	0.0970 (5)
Mode 5	0.7138 (1)	0.0963 (4)

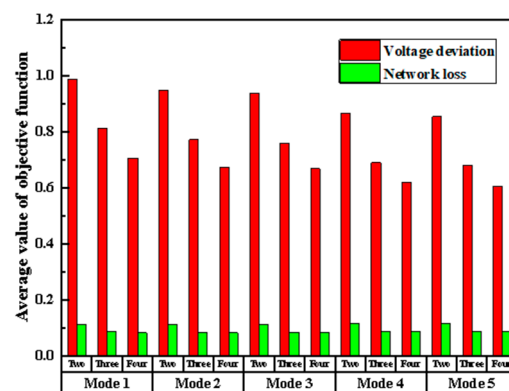


Figure 7. Optimization results under five modes and with different FID port numbers.

Different from mode 1, mode 2 can provide reactive power of no more than 0.31 pu during the night. The injection of reactive power during the night reduces both voltage deviation and network loss.

Different from mode 2, mode 3 canceled the power factor limitation of the PV inverter during the daytime. The adjustment range of reactive power output is 0.31 pu during the daytime. The voltage deviation and network loss are further reduced.

Compared with mode 2, mode 4 utilizes the night SVG scheme for PV inverters. The adjustment range of reactive power output increases to 1 pu. The voltage deviation is reduced from 0.7976 to 0.7253. The drop proportion is 9.06%. The voltage quality is obviously improved. However, due to the injection of reactive power, the network loss is slightly increased from 0.0933 to 0.0970. The overall level of power quality is ameliorated.

Compared with mode 3, mode 5 also utilizes the night SVG scheme for PV inverters. The conclusions are similar. The voltage deviation dropped by 9.45%. Though network loss is slightly increased, the overall level of power quality is improved.

As seen from Figure 8, the increase in FID port numbers improves the flexibility of power control, leading to higher power quality. The conclusion is suitable for all five modes. However, an FID with more ports is more expensive. Thus, in actual analysis, many aspects including network flexibility, power quality, and cost of investment and operation have to be comprehensively considered.

5.5. Performance of Proposed Optimization Operation Method

As analyzed above, the proposed optimization method obtains the best power quality when an FID holds four ports and a PV operates in mode 5. Thus, under the best operation conditions, the voltage distribution of all nodes, the PV output, and the FID power control are specifically discussed. The optimization results are displayed in Figures 8–10.

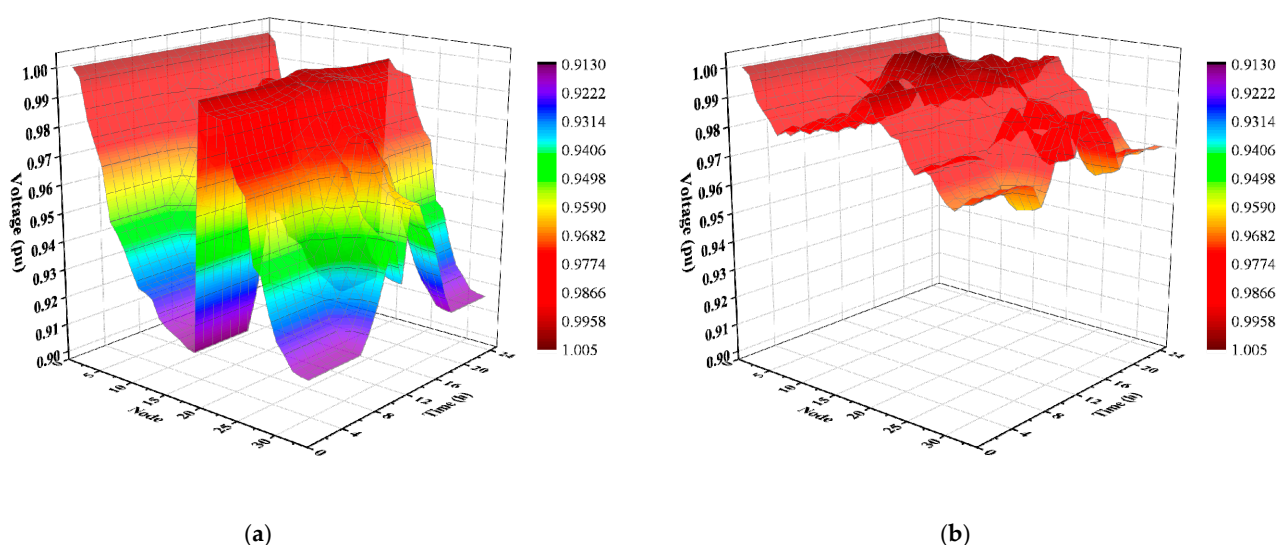


Figure 8. Voltage distribution with (a) and without (b) synergetic optimization of PV and FID.

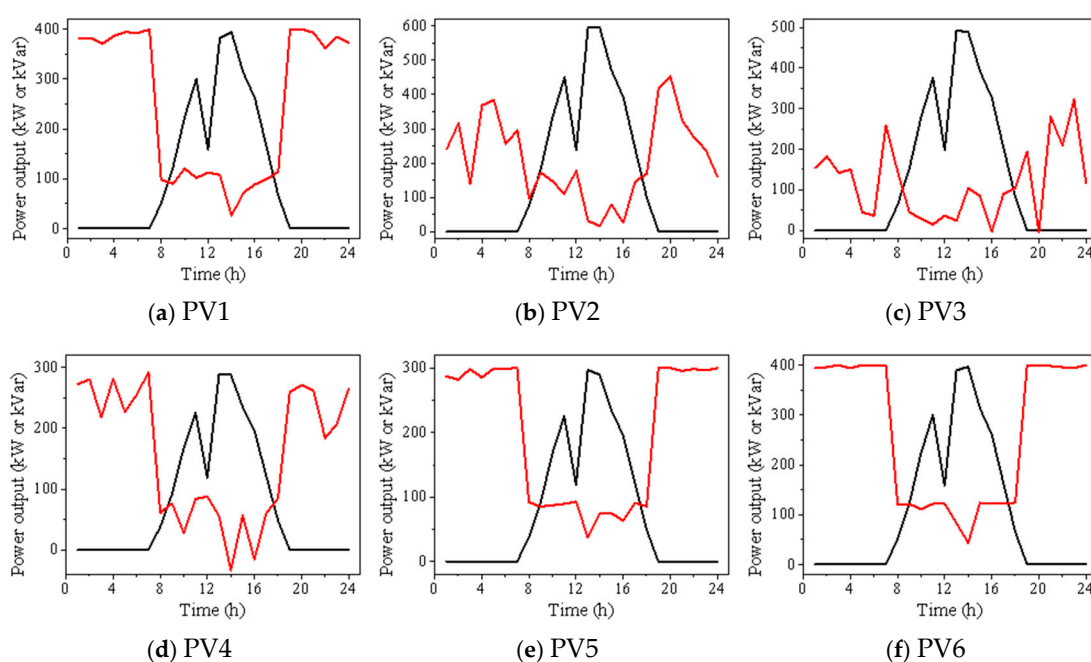


Figure 9. Active power (black) and reactive power (red) output curves of PVs.

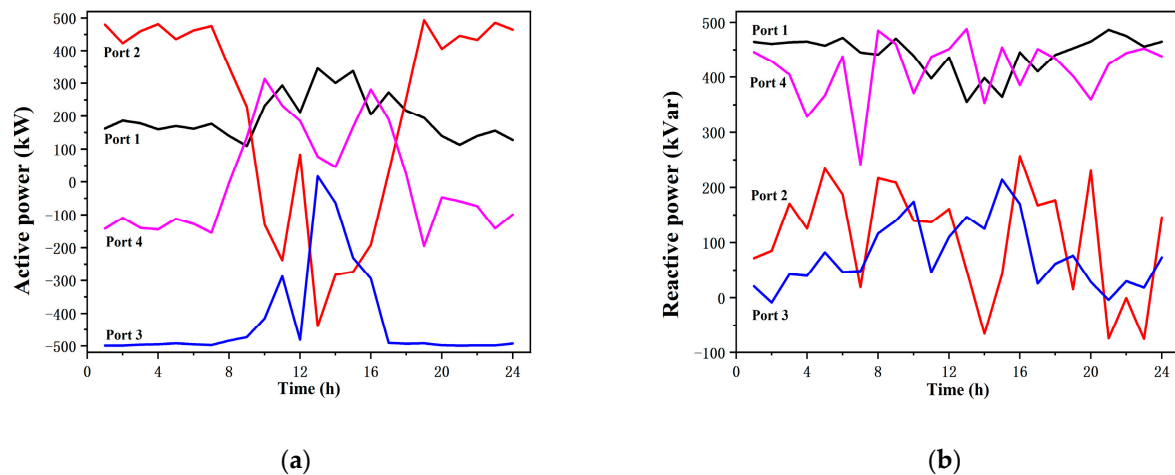


Figure 10. Optimal scheme of FID. In (a), positive value means active power flow from port; negative value means active power flow into port. (a) Active power flows among ports. (b) Reactive power output of ports.

Simulations are carried out for case 4 (before optimization) and case 3 (after optimization). As seen from Figure 8a, the voltage reduces to 0.9130 pu at some nodes and some moments. Due to the injection and fluctuation of PVs, voltage is occasionally out-of-limit. The power quality turns bad, which further impedes the consumption of the PV. When the synergetic optimization of the PV and FID is utilized, the voltage amplitude is stabilized. The minimum voltage is 0.9615 pu. The voltage deviation is 0.2004 pu and the network loss is 0.0289 MW. It indicates that the power quality is improved.

The optimization results of PVs are shown in Figure 9. The active power output approximately equals the value of MPPT for all the PVs, as shown by the black line in Figure 9. Owing to the setting of the PV abandonment ratio as an objective function, the active power output of the PV is optimized to minimize the PV abandonment ratio. The PV abandonment ratio does not exceed 3%.

The reactive power output is displayed with a red line in Figure 9. During the daytime, the reactive power output is mainly limited by capacity constraints. Due to the injection of the PV active power, reactive power compensation is required to stabilize the voltage. During the night, the active power of the PV is 0. The reactive power output of the PV is used to compensate the reactive power of the devices. The reactive power output is related to the position of the PV, the position of the FID, and the distribution of the load.

The optimization result of the FID is also analyzed. The active power flow is shown in Figure 10a. Owing to the four ports of the FID, the active power flows more flexibly. The active power flows among the four ports according to the PV access position, output, and the load. Port 1 and port 2 connect to the terminal nodes of two feeders. Thus, during the night, active power is transformed from port 3/port 4 to port 1/port 2, ensuring the effective utilization of active power. During the daytime, the PVs output active power. The access position of PV₃ and PV₄ is close to port 2 and port 3. Active power flows from port 2/port 3 to port 1/port 4 for active power balance.

The reactive power flow is shown in Figure 10b. During most time periods, the FIDs output reactive power. The reactive power output is limited by the port capacity. It is also influenced by the output of the PVs and the distribution of the load. Due to the close connection of the PVs to port 2 and port 3, the reactive power output of port 2/port 3 is lower than that of port 1/port 4.

With the development of the PV and the requirement of environmental friendliness, more PVs are connected to the distribution network. PV permeability grows quickly. To

testify the applicability of the proposed method, the optimization under the conditions of different PV permeabilities is simulated. Simulations of cases 3, 5, 6, and 7 are compared. The results are listed in Table 4.

Table 4. Optimization result comparison of different PV permeability.

PV Permeability	Voltage Deviation	Network Loss	Ratio of PV Abandonment
0	0.9010	0.1071	-
32.3%	0.3719	0.0475	0.0082
67.3%	0.2004	0.0289	0.0250
86.1%	0.1138	0.0169	0.0251

With the increase in PV permeability, the voltage deviation and the network loss are both reduced. When the PV permeability reaches 86.1%, the reduction ratio of voltage deviation and network loss is 87.4% and 84.2%, respectively. The power quality is obviously improved. When the PV permeability increases, the ratio of PV abandonment increases slightly. However, the ratio of PV abandonment does not exceed 2.51%. The consumption rate of the PVs can be kept at a high level. Thus, the proposed method is applicable for cases with high PV permeability, which shows the potential in operation optimization in the future.

6. Conclusions

In this paper, a synergistic optimization operation method for a distribution network is proposed. Owing to the multi-mode output of PVs and the flexible power control capability of FIDs, PVs and FIDs are simultaneously optimized for active power and reactive power output. Taking power quality, economy, and environmental friendliness into consideration, minimizing voltage deviation, network loss, and the ratio of PV abandonment are selected as the objective functions. The constraints of power flow, voltage, and device operation are set in the optimal model. Different reactive power output modes of PVs and different port numbers of FIDs were analyzed and compared. NSGA-II, NSGA-III, and MOPSO were adopted for solving the proposed model. Simulations indicate that the proposed synergetic optimization operation method can provide satisfied results in decreasing voltage deviation and network loss. The best performance is obtained by the PV operating in reactive power output mode 5, the FID with four ports, and utilizing NSGA-II. Due to the participation of the PV in active and reactive power optimization, the proposed method shows better optimization results with the increase in PV permeability. The proposed method indicates the potential of application in the dispatching center and also provides an effective means for the integration of more renewable energy resources. It is applicable for modern and smart grids.

Though the coordination of PVs and FIDs is simulated and verified, the intermittence and uncertainty of PVs and load are not considered. This paper focuses on the improvement of power quality and PV consumption, without considering the cost of FID investment and system operation. In subsequent research, the influence of source-load uncertainty will be discussed. The objective function will be adjusted for practical applications. More flexible resources will be integrated into the grid to enhance the flexibility and stability of the system.

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References

1. Zhang, L.; Shen, C.; Chen, Y.; Huang, S.; Tang, W. Coordinated allocation of distributed generation, capacitor banks and soft open points in active distribution networks considering dispatching results. *Appl. Energy* **2018**, *231*, 1122–1131. [\[CrossRef\]](#)
2. Yang, W.; Chen, L.; Deng, Z.; Xu, X.; Zhou, C. A multi-period scheduling strategy for ADN considering the reactive power adjustment ability of DES. *Int. J. Electr. Power Energy Syst.* **2020**, *121*, 106095. [\[CrossRef\]](#)
3. Khasanov, M.; Kamel, S.; Rahmann, C.; Hasanien, H.M.; Al-Durra, A. Optimal distributed generation and battery energy storage units integration in distribution systems considering power generation uncertainty. *IET Gener. Transm. Distrib.* **2021**, *15*, 3400–3422. [\[CrossRef\]](#)
4. Wu, T.; Zheng, Y.; Wu, H.; Dong, H.; Wang, X. Power transfer and multi-control mode of a distribution network based on a flexible interconnected device. *IEEE Access* **2019**, *7*, 148326–148335. [\[CrossRef\]](#)
5. Dzafic, I.; Jabr, R.A.; Halilovic, E.; Pal, B.C. A sensitivity approach to model local voltage controllers in distribution networks. *IEEE Trans. Power Syst.* **2014**, *29*, 1419–1428. [\[CrossRef\]](#)
6. Lachovicz, F.J.; Fernandes, T.S.P.; Vilela Junior, J.A. Impacts of PV-STATCOM reactive power dispatch in the allocation of capacitors bank and voltage regulators on active distribution networks. *J. Control Autom. Electr. Syst.* **2023**, *34*, 796–807. [\[CrossRef\]](#)
7. Qi, Q.; Jiang, Q.; Xu, Y. Research status and development prospect of flexible interconnection for smart distribution networks. *Power Syst. Technol.* **2020**, *44*, 4664–4676.
8. Ji, H.; Wang, C.; Li, P.; Ding, F.; Wu, J. Robust operation of soft open points in active distribution networks with high penetration of photovoltaic integration. *IEEE Trans. Sustain. Energy* **2019**, *10*, 280–289. [\[CrossRef\]](#)
9. Alamri, B.; Hossain, M.A.; Asghar, M.J. Electric power network interconnection: A review on current status, future prospects and research direction. *Electronics* **2021**, *10*, 2179. [\[CrossRef\]](#)
10. Rezaeian-Marjani, S.; Galvani, S.; Talavat, V. A generalized probabilistic multi-objective method for optimal allocation of soft open point (SOP) in distribution networks. *IET Renew. Power Gener.* **2022**, *16*, 1046–1072. [\[CrossRef\]](#)
11. Cao, W.; Wu, J.; Jenkins, N.; Wang, C.; Green, T. Benefits analysis of soft open points for electrical distribution network operation. *Appl. Energy* **2016**, *165*, 36–47. [\[CrossRef\]](#)
12. Yu, W.; Li, M.; Zhang, Z.; You, R. Research on distribution network optimal operation with a novel medium voltage photovoltaic power generation device with the soft open point function. *Energy Rep.* **2023**, *9*, 1751–1763. [\[CrossRef\]](#)
13. Ehsanbakhsh, M.; Sepasian, M.S. Simultaneous siting and sizing of Soft Open Points and the allocation of tie switches in active distribution network considering network reconfiguration. *IET Gener. Transm. Distrib.* **2023**, *17*, 263–280. [\[CrossRef\]](#)
14. Wang, X.; Yang, W.; Liang, D. Multi-objective robust optimization of hybrid AC/DC distribution networks considering flexible interconnection devices. *IEEE Access* **2021**, *9*, 166048–166057. [\[CrossRef\]](#)
15. Ali, Z.M.; Diaaeldin, I.M.; El-Rafei, A.; Hasanien, H.M.; Aleem, S.H.A.; Abdelaziz, A.Y. A novel distributed generation planning algorithm via graphically-based network reconfiguration and soft open points placement using Archimedes optimization algorithm. *Ain Shams Eng. J.* **2021**, *12*, 1923–1941. [\[CrossRef\]](#)
16. Deakin, M.; Taylor, P.C.; Bialek, J.; Ming, W. Design and operation of hybrid multi-terminal soft open points using feeder selector switches for flexible distribution system interconnection. *Electr. Pow. Syst. Res.* **2022**, *212*, 108516. [\[CrossRef\]](#)
17. Shi, M.; Zhang, J.; Ge, X.; Fei, J.; Tan, J. Power optimization cooperative control strategy for flexible fast interconnection device with energy storage. *Energy Eng.* **2023**, *120*, 1885–1897. [\[CrossRef\]](#)
18. Rezaei, F.; Esmaeili, S. Decentralized reactive power control of distributed PV and wind power generation units using an optimized fuzzy-based method. *Int. J. Electr. Power Energy Syst.* **2017**, *87*, 27–42. [\[CrossRef\]](#)
19. *IEEE Standard 1547–2018*; IEEE, for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces. IEEE: Piscataway, NJ, USA, 2018; pp. 1–138. [\[CrossRef\]](#)

20. Guo, W.; Xu, W. Research on optimization strategy of harmonic suppression and reactive power compensation of photovoltaic multifunctional grid connected inverter. *Int. J. Electr. Power Energy Syst.* **2023**, *145*, 108649. [[CrossRef](#)]
21. Rahman, M.M.; Biswas, S.P.; Islam, M.R.; Rahman, M.A.; Muttaqi, K.M. An advanced nonlinear controller for the LCL-type three-phase grid-connected solar photovoltaic system with a DC–DC converter. *IEEE Syst. J.* **2021**, *16*, 3203–3214. [[CrossRef](#)]
22. De Jesus, V.M.R.; Cupertino, A.F.; Xavier, L.S.; Pereira, H.A.; Mendes, V.F. Operation limits of grid-tied photovoltaic inverters with harmonic current compensation based on capability curves. *IEEE Trans. Energy Conver.* **2021**, *36*, 2088–2098. [[CrossRef](#)]
23. Rossoni, P.; Belati, E.A.; Benedito, R.S. A hybrid approach for optimization of electric power distributed networks with photovoltaic sources. *Electr. Power Syst. Res.* **2022**, *211*, 108183. [[CrossRef](#)]
24. Alrashidi, M.; Rahman, S. A bi-level optimization method for voltage control in distribution networks using batteries and smart inverters with high wind and photovoltaic penetrations. *Int. J. Electr. Power Energy Syst.* **2023**, *151*, 109217. [[CrossRef](#)]
25. Niknam, T. A new HBMO algorithm for multiobjective daily Volt/Var control in distribution systems considering distributed generators. *Appl. Energy* **2011**, *88*, 778–788. [[CrossRef](#)]
26. Tian, Y.; Cheng, R.; Zhang, X.; Jin, Y. PlatEMO: A MATLAB platform for evolutionary multi-objective optimization [educational forum]. *IEEE Comput. Intell. Mag.* **2017**, *12*, 73–87. [[CrossRef](#)]

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