

Grid Planning Method of Medium Voltage Distribution Network Including Distributed Power Sources based on Timing Characteristics

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ABSTRACT

Aiming at the problems of unbalanced load distribution of feeders and low utilization rate of system resources in existing medium voltage(MV) distribution network planning, it is difficult to meet the requirements of future grid construction, Propose a grid planning method of MV distribution network including distributed generator(DG) based on timing characteristics. Firstly, based on the existing grid planning achievements and temporal characteristics analysis, the grid structure and planning strategy of the MV distribution network are formed. Secondly, based on the network planning strategy, establish a dual level planning model for both internal and external distribution networks. The inner model uses comprehensive performance indicators as fitness functions to solve the optimal division of the distribution network grid, while the outer model calculates the distributed power capacity configuration of each grid with the goal of maximizing the consumption of DG. Then, based on the established dual layer planning model for the distribution network, genetic algorithms and self programming algorithms are used to solve the model by interconnecting the internal and external layers. Finally, the practicality and effectiveness of the proposed model and method were verified through practical examples combined with evaluation indicators.

KEYWORDS

Medium Voltage Distribution Network; Time Series Characteristics; Distributed Generator; Gridding; Bilevel Programming Model.

1. INTRODUCTION

With the continuous development of power system, grid planning of distribution network has built a relatively stable and reliable distribution network system with clear grid structure, standardized wiring, independent grid operation and mutual cooperation. However, with the increasing variety and quantity of power generation resources, especially the integration of DG and energy storage devices into the power grid, issues such as system security and stability, and power quality have been affected. At the same time, in the process of building a distribution network system, the load size and timing characteristics of various resources are not fully quantified, resulting in the failure to improve the power supply capacity of the distribution network, low system load rate and equipment utilization rate, and as the load in the power grid increases, the unsatisfactory situation of line peak-valley difference rate and load rate will become more and more obvious. Therefore, analyzing the timing characteristics of various loads, distributed power sources, and energy storage, as well as the carrying capacity of the power grid, and making fine-grained planning for the allocation of various resources can help the power grid achieve robust, reliable, and stable operation, and can maximize the utilization

of numerous resources, providing a planning solution for grid-based distribution networks with multiple resources.

Currently, research regarding grid planning for MV distribution networks has also achieved progress. Literature [15] proposes a practical automatic routing method for MV distribution networks that takes into account the complementary characteristics of loads and the division of power supply units. However, it fails to maximize the utilization of system resources because it does not consider the planning of distribution networks under the condition of DG grid connection. Literature [16] suggests a division method that considers the impact of several factors on power supply zones and utilizes pre- and post-processing techniques, yet it disregards the time-series characteristics of loads within those zones and is incapable of more appropriately matching various loads. Literature [17] proposes an optimization method for power supply zones based on the coupling characteristics of load peaks and valleys, but it still does not take into account the grid connection of DG. As a result, the low utilization rate of system resources cannot be effectively resolved. However, although the existing grid planning has improved the performance of the distribution network system, various resources in the distribution network cannot be reasonably and refined planned, and the indicators such as load rate, peak-valley difference rate, energy conservation and emission reduction rate in the system are at a low level, which cannot maximize the potential of system resource utilization.

To address the aforementioned issues, and building upon the existing grid planning for distribution networks achievements, we propose a grid planning model for MV distribution networks with DG, which is based on time-series characteristics. Firstly, a feeder grid planning model and a DG capacity planning model are constructed based on the time-series characteristics of load and DG. Using the genetic algorithm and self-programming algorithm interconnection method, the feeder grid and the DG capacity configuration of each grid are planned. Based on this consideration, a division method for power supply units is proposed, taking system safety and reliability into account. Finally, various evaluation indicators are constructed to compare and analyze the results before and after the planning of the example, in order to verify the practicality and effectiveness of the proposed model and method.

2. PLANNING TECHNICAL FRAMEWORK

2.1. Grid Content and Structure

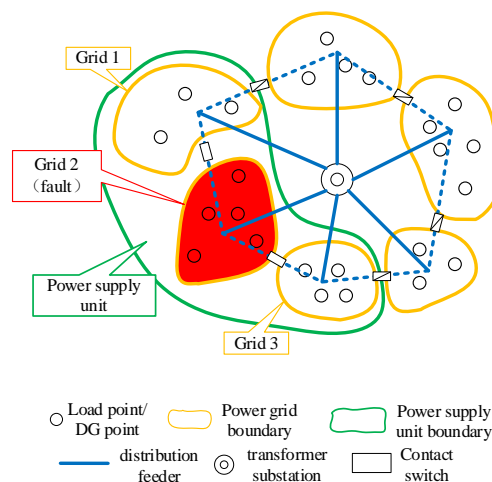


Figure 1. Schematic diagram of supply area planning structure

The grid division of the supply area is carried out based on the regulatory planning, the current grid situation, the penetration of distributed power sources, and the grid planning guidelines. The specific content is as follows:

The feeder power grid (hereinafter referred to as the grid) consists of load points with different timing characteristics. The total load of each load point within the same feeder power supply range should be lower than the line transmission capacity, and the load levels of each grid should be similar.

The power supply unit consists of multiple grids with close proximity. In the event of a failure, the grids within the power supply unit communicate with each other to transfer power. The power supply unit operates independently, effectively reducing the impact of failures between devices. The specific structural schematic diagram is shown in Figure 1.

2.2. Time Series Characteristic Planning Idea

In a power supply area, various loads exhibit different load characteristics in time series. DG sources such as distributed photovoltaic generation (DPV) exhibit daytime output characteristics in time series, while energy storage systems (ESS) exhibit flexible output characteristics according to demand. This article incorporates distributed power sources as "negative" load characteristics into distribution network planning, with a time series characteristics diagram shown in Figure 2.

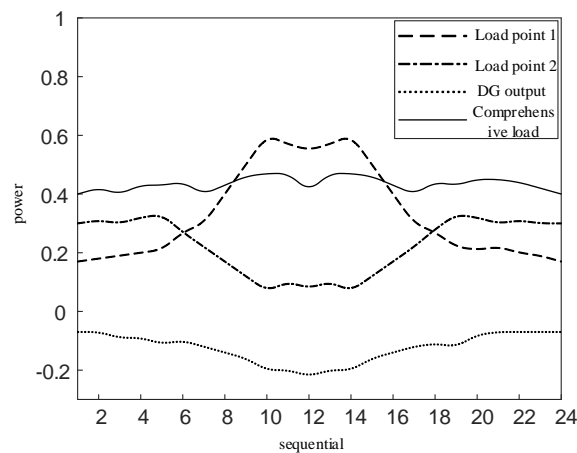


Figure 2. Schematic diagram of timing characteristics

As shown in Figure 2, by utilizing the time-series characteristics of different types of loads, peak loads and valley loads can be combined on the same time-series and planned into the same grid. The benefits that this planning idea can bring include: (i) In the same feeder, more load points can be loaded without exceeding the limit, which improves the utilization efficiency of the feeder and alleviates the pressure on the distribution network during peak power consumption; (ii) Within the power supply scope of the same substation, it can reduce the outgoing line spacing of the MV distribution network feeders, reduce the construction cost of the distribution network lines, and ensure the reliability of power supply.

3. PLANNING MODEL

3.1. Grid Planning Model

To optimize the power supply capacity in the area, it is crucial to match the loads based on the time-series characteristics. Therefore, a grid planning model is proposed, featuring the following planning indicators:

1) Considering that the feeder power supply distance should not be too long and to prevent the load point distribution from being dispersed, and to avoid the line crossing caused by the dispersion of

load locations, it is proposed to use the grid power supply range to construct the feeder grid power supply range planning index ρ_1 , and set the power supply range constraint to be no greater than 2km, as follows:

$$\rho_1 = \frac{1}{K} \sum_{j=1}^K \left(1 - \left| \frac{D_{j\max} - D_{\max}}{D_{\max}} \right| \right) \quad (1)$$

Where, $D_{j\max}$ is the maximum distance between load points in the j th grid; D_{\max} is the maximum value of the maximum distance between load points in each grid; K is the number of grids.

2) Considering the need to reduce the pressure on the power grid during peak electricity consumption and ensure the stable operation of the distribution network, it is proposed to use the peak-to-valley ratio to construct a grid peak-to-valley ratio planning indicator ρ_2 , as follows:

$$\rho_2 = \frac{K}{\sum_{j=1}^K F_{jp}} \quad (2)$$

Where, F_{jp} is the peak-to-valley ratio of the j th grid, and the smaller the value, the lower the peak-to-valley ratio of the supply area, and the better the effect of alleviating the pressure on the power grid.

3) Considering the need to balance the load levels of each grid and maximize the utilization efficiency of each feeder, it is proposed to use the daily average load to construct a grid load balance planning indicator ρ_3 , as follows:

$$\rho_3 = \frac{1}{K} \sum_{j=1}^K \frac{f_{jm}}{f_{\max m}} \quad (3)$$

Where, f_{jm} is the average load of the j th grid; $f_{\max m}$ is the maximum value of the average load of each grid.

Based on the above planning indicators, a comprehensive index ρ_{all} for grid planning is proposed, specifically as follows:

$$\rho_{\text{all}} = \lambda_1 \rho_1 + \lambda_2 \rho_2 + \lambda_3 \rho_3 \quad (4)$$

Where, λ_1 , λ_2 , and λ_3 are the weight coefficients of the three indicators, and the grid planning indicator is a positive indicator. The larger the value, the better the planning effect.

3.2. DG Capacity Planning Model

3.2.1. DPV Output Modeling

The output power of DPV is constrained by local environmental conditions and equipment installation conditions, such as regional light intensity and equipment installation land. Therefore, there is a limit to the output power of DPV in a certain region. Due to the high power factor of photovoltaic power, the reactive power output of photovoltaic is ignored in this article. Based on the research results in literature [18], an hourly photovoltaic power model is constructed, specifically:

$$\begin{cases} P_{hPV} = P_S \frac{R(\varphi, m, d, h)}{1000} [1 + \alpha_T (T - 25)] \\ S_{HPV} = \sum_{h=1}^H P_{hPV} \end{cases} \quad (5)$$

Where, P_S is the rated power of DPV power; $R(\varphi, m, d, h)$ is the hourly mean value of surface solar irradiance at the m th month, d th day, h th hour in the φ th latitude area to be planned; α_T is the power temperature coefficient of photovoltaic panel; T is the operating temperature of photovoltaic module; H is taken as 24, with a time resolution of 1h; S_{HPV} is the power generation of DPV during the H period.

3.2.2. Calculation of ESS Capacity

To avoid excessive peak shaving of photovoltaic output at certain times during H period, resulting in a reverse increase in peak-to-valley difference, ESS is used to store the excess capacity of photovoltaic output, and the flexibility of ESS is utilized to peak-cut peak loads beyond the timing characteristics of photovoltaic output. The specific capacity of ESS is:

$$\begin{cases} S_{ESS} = \begin{cases} k \sum_{h=1}^H (P_{hPV} - P_{hL}), P_{hPV} \geq P_{hLF} \\ 0, P_{hPV} \leq P_{hLF} \end{cases} \\ P_{ESS} = \begin{cases} \max_{h=1,2,\dots,H} (P_{hPV} - P_{hLF}), P_{hPV} \geq P_{hLF} \\ 0, P_{hPV} \leq P_{hLF} \\ h \in H \end{cases} \end{cases} \quad (6)$$

Where, S_{ESS} is the total rated capacity of ESS; P_{ESS} is the rated power; P_{hPV} is the DPV output at h ; P_{hLF} is the peak load to be reduced at h ; k is the margin factor of energy storage capacity.

3.2.3. DG Capacity Planning Model

The DG capacity planning model calculates the capacity configuration of DG in the power supply area based on the grid planning scheme output by the grid planning model, with the objective function of minimizing the comprehensive cost, as follows:

$$\min C_{ZH} = C_1 + C_2 - C_3 + C_4 \quad (7)$$

Where, C_1 is the investment cost of the line and DG equipment; C_2 is the operation and maintenance cost of the distribution network system; C_3 is the subsidy for DPV; C_4 is the main grid electricity purchase cost; C_{ZH} is the comprehensive cost of the distribution network system. The specific costs in the function are as follows:

$$C_1 = c_{PV}C_{1PV}P_S + c_{ESS}(C_{1ESS}S_{ESS} + C_{1EP}P_{ESS}) \quad (8)$$

$$C_2 = C_{2PV}S_{HPV} + C_{2ESS}(P_{CESS} + P_{FESS}) \quad (9)$$

$$C_3 = \alpha S_{HPV} \quad (10)$$

$$C_4 = \sum_{h=1}^H C_{4P,h} P_{hP} \quad (11)$$

Where: c_{PV} and c_{ESS} are the investment coefficients of DPV and ESS respectively; C_{1PV} , C_{1ESS} , and C_{1EP} are the investment costs per unit capacity of DPV, ESS, and ESS per unit power respectively; C_{2PV} and C_{2ESS} are the operation and maintenance costs per unit generating capacity of DPV and ESS per unit charging and discharging capacity respectively; P_{CESS} and P_{FESS} are the charging and discharging power of ESS during the H period respectively; the annual value calculation formula for equipment investment is $D = r(1+r)^\tau / [(1+r)^\tau - 1]$, τ is the service life of the equipment, r is the discount rate; α is the subsidy per unit generating capacity of DPV; $C_{4P,h}$ is the unit electricity price of the main grid at time h; P_{hP} is the main grid power at time h.

The constraints include: 1) short-circuit current constraint; 2) voltage deviation constraint; 3) voltage fluctuation constraint; 4) feeder load capacity constraint; 5) power flow equation constraint; 6) DG capacity constraint.

$$I_D \leq I_{Dmax} \quad (12)$$

$$\begin{cases} \Delta U_+ \leq \varepsilon_+ \\ \Delta U_- \geq \varepsilon_- \end{cases} \quad (13)$$

$$d_j \leq d_{max} \quad (14)$$

$$|I_j| \leq I_{jmax} \quad (15)$$

$$\begin{cases} P_i = U_i \sum_{j \in i} U_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \\ Q_i = U_i \sum_{j \in i} U_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \end{cases} \quad (16)$$

$$0 \leq P_H \leq S_{PV \max} \quad (17)$$

Where, I_D is the short-circuit current of the system, and the short-circuit current provided by the converter-type DG supply is calculated at 1.5 times the rated current; $I_{D \max}$ is the maximum limit value of the short-circuit current, which is taken from the regulations on short-circuit current in the power industry standard "Technical Guidelines for Planning and Design of Distribution Network"; ΔU_+ and ΔU_- are the positive and negative voltage deviation rates caused by the addition of DG; ε_+ and ε_- are the upper and lower limits of voltage deviation specified in the national standard. The national standard "Power Quality - Supply Voltage Deviation" stipulates that the three-phase supply voltage deviation of 20 kV and below is $\pm 7\%$ of the nominal voltage; d_j is the voltage fluctuation value at feeder j; d_{\max} is the voltage fluctuation limit specified by the national standard. This article takes a value of 3% based on the provisions of the national standard "Power Quality - Voltage Fluctuation and Flicker"; I_j is the current flowing on the jth feeder; $I_{j \max}$ is the maximum current that can be loaded on the jth feeder; P_i and Q_i are the active and reactive power injections of node i, respectively; U_i and U_j are the voltage magnitudes of nodes i and j, respectively; G_{ij} and B_{ij} are the branch admittances; θ_{ij} is the phase difference between nodes; The National Grid Corporation enterprise standard "Design Code for Distributed Power Access to Distribution Network" recommends a single grid connection point capacity of 400kW~6MW at 10kV voltage level.

4. MODEL SOLVING METHOD

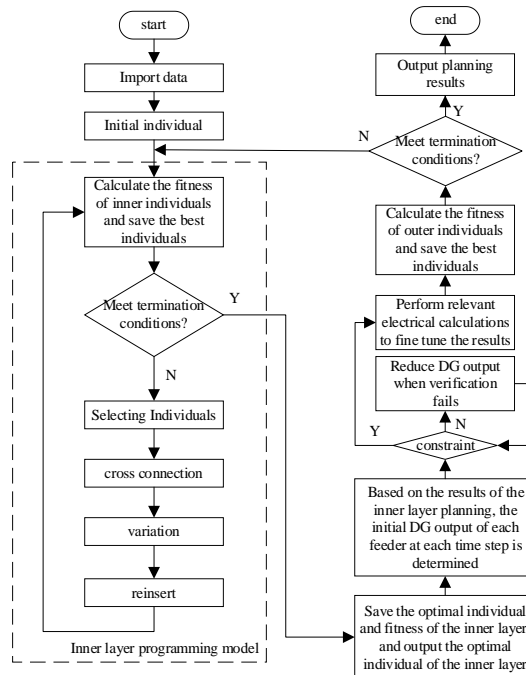


Figure 3. Algorithm flowchart of internal and external bilevel programming model

The grid planning model of the MV distribution network in this article uses a two-layer programming algorithm to solve the problem. The grid planning layer is used as the inner planning model to optimize the supply area to achieve the optimal grid load characteristics; the DG capacity planning layer is used as the outer planning model to calculate the DG capacity configuration at each time. The flow of the two-layer planning model solving method for the distribution network is shown in Figure 3.

The solution steps are as follows:

- 1) The input of raw data required for the calculation, calculate the distance between each load point, initialize the planning model population individuals.
- 2) Improve the calculation of the number of feeder grids to be planned in the literature [23].

$$K = \text{int} \left[\frac{P_Z - S_{\text{ESS}}^{\text{H}}}{S_{\text{k}} \cos \theta \mu} \right] \quad (18)$$

Where, P_Z is the total load of the system; S_{k} is the load capacity of a single feeder; $\cos \theta$ is the power factor of the feeder load; $S_{\text{ESS}}^{\text{H}}$ The configured energy storage capacity.

- 3) Take the feeder grid planning comprehensive index as the fitness function and calculate it, save the individual with the best fitness.
- 4) Judge whether the termination condition is met, if it is met, take the current best fitness and the best individual as the planning result and go to step 6); otherwise, go to step 5).
- 5) Perform selection, crossover, mutation, and reinsertion operations on the population to obtain a new population and recalculate individual fitness, save the best individual, and go to step 4).
- 6) Based on the results of the inner-layer planning, initialize the grid-connected capacity of DG at each time for each feeder.
- 7) Check the initialized grid-connected capacity based on the DG capacity planning model.
- 8) If the verification fails, reduce the DG grid-connected capacity by step size and return to step 7) for verification until it passes.
- 9) Fine-tune the capacity planning result, calculate fitness and save the best individual.
- 10) Judge whether the termination condition is met, if not, return to step 2); otherwise, output the planning result of the model.

5. EXAMPLE ANALYSIS

5.1. Introduction to the Example Case.

The specific data for the power supply area calculation example is as follows: the main transformer capacity of the 110kV substation is 2×50MVA, and the power supply area includes 13 feeders and 85 loads, including administrative, educational, residential, industrial, commercial, and other. The medium-voltage distribution network feeder model selected is LGJ-240, and the line load capacity is 7MW. The geographical locations and feeder grid division status of each load point, substation, and load area in the current power supply area are shown in Figure 4.

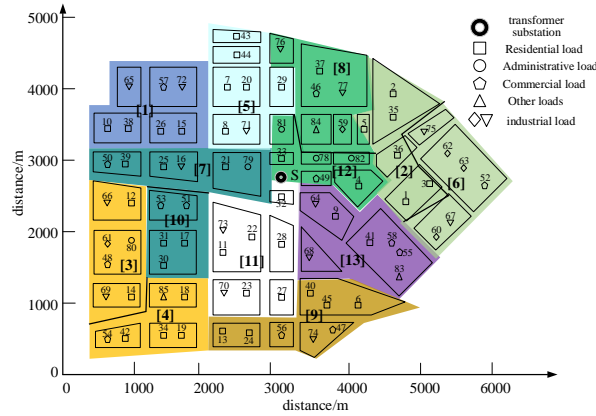


Figure 4. Current layout of distribution network

The power supply units in the figure are represented by blocks with different gray levels, and different grids in the power supply units are distinguished by line segments. The current grid's feeder connection rate, line N-1 pass rate, feeder load rate range, and peak-valley difference rate range are shown in Table 1.

Table 1. Current supply area indicator data

index	data
Number of feeder grids/unit	13
Feeder connection rate/%	76.92
Line N-1 pass rate/%	61.54
Average load rate/%	33.06
Average peak valley difference rate/%	36.84
Average load rate/%	81.18

5.2. Analysis of Planning Results and Indicators

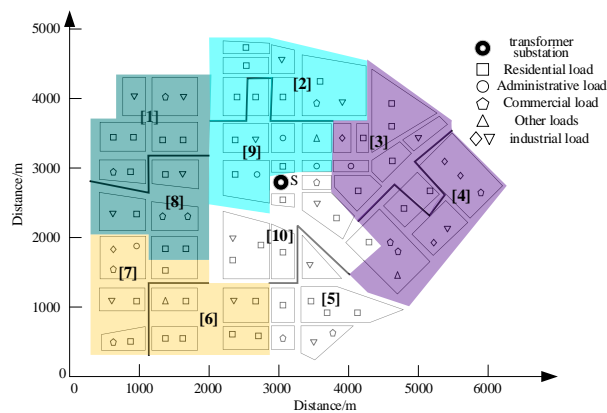


Figure 5. Layout after distribution network planning

The planning area is gridded according to the planning ideas and methods in this article, and the indicator data is calculated within a typical daily time period with a time resolution of 1h. The

planning results and analysis are as follows: Figure 5 shows the grid planning map of the supply area obtained by the planning method proposed in this article.

As shown in Figure 5, the number of feeder grids in the planned supply area is 10, and the number of power supply units is 5. The specific data of various indicators in the planned supply area are shown in Table 2.

Table 2. Planned supply area indicator data

index	data
Number of feeder grids/unit	10
Average load rate/%	42.98
Average peak valley difference rate/%	29.03
Average load rate/%	83.59
PV configuration total capacity/MW · h	79.28
Total ESS Configuration Capacity/MW · h	21.55

As can be seen from the data in the table, the number of feeder outgoing lines in the supply area has been reduced by 3 after planning, and the peak-valley difference rate has been significantly reduced compared to before planning. At the same time, the system has also increased the output of distributed power, which is conducive to reducing the burden on the power grid during peak load. The system after planning has made better improvements in many aspects compared to before.

In terms of distributed power consumption, as shown in Figure 6, it displays the capacity configuration of PV and ESS in each feeder grid and the consumption rate of distributed power at each moment. Due to the differences in time sequence matching between DPV output and load, DPV may not be fully absorbed. This article achieves storage by configuring energy storage devices to store excess power generation. When there is less or no power generation, it outputs. This improves the matching degree between DG output and load and also enhances the consumption rate.

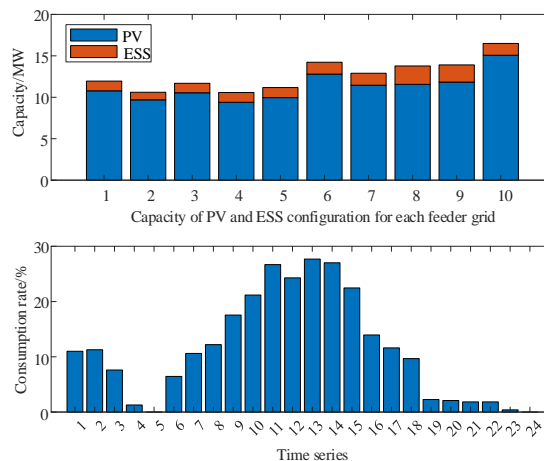


Figure 6. Figure of DG capacity configuration results after planning

After the planning of the supply area, it is necessary to perform an analysis of the planning results using indicators to evaluate the planning effectiveness. This article proposes the feeder connection rate indicator and energy conservation and emission reduction rate indicator, as well as improved line

N-1 pass rate indicators, daily average load rate indicators for each feeder grid, and average peak-valley difference rate indicators to evaluate and analyze the performance of the medium-voltage distribution network.

1) Feeder Connection Rate Indicator E_1 : Evaluate the load supply capability of the power grid in the supply area.

2) Energy Conservation and Emission Reduction Rate Indicator E_2 : Evaluate the energy carbon emission reduction level of the gridded power distribution network planned.

3) Line N-1 Criterion Pass Rate Indicator E_3 : Evaluate the reliability of the power distribution network.

4) Daily Average Load Rate Indicator E_4 for each feeder grid: Evaluate the level of equipment utilization and equipment redundancy.

5) Average Peak Valley Difference Rate Indicator E_5 : Evaluate the ability to "peak shaving and valley filling" and the safe and stable operation of the power system.

$$E_1 = \frac{L_{\eta}}{L} \times 100\% \quad (19)$$

$$E_2 = \frac{C_{jp}}{C_{njp}} \times 100\% \quad (20)$$

$$E_3 = \frac{S_{hp}}{L} \times 100\% \quad (21)$$

$$E_4 = \frac{1}{L} \sum_{j=1}^L F_j \quad (22)$$

$$E_5 = \frac{1}{L} \sum_{j=1}^L (1 - F_{jp}) \quad (23)$$

Where, L_{η} is the number of contacted grids; L is the total number of grids; C_{jp} is the carbon emission reduction; C_{njp} is the carbon emission before energy carbon emission reduction; S_{hp} is the number of grids that have passed the N-1 safety criteria; F_j is the daily load rate of the j th feeder grid.

The evaluation indicators for the supply area are equally weighted, and the calculation results before and after planning are shown in Table 3.

Table 3. Comparison of evaluation indicators before and after supply area planning

index	Before planning	After planning
Feeder connection rate	0.62	1
Carbon reduction rate	0	0.11
Line N-1 criterion pass rate	0.31	1
Daily average load rate	0.79	0.99
Average peak valley difference	0.62	0.96

From the data in Table 3, it can be seen that after the planning of the supply area, all indicators have improved compared to before. The pass rate of the line N-1 safety criteria has increased to 1, and the feeder connection rate has also increased from 0.62 to 1, showing significant improvement. Then the average daily load rate and average peak-valley difference rate of the supply area have increased by 25% and 55% respectively, indicating that the utilization rate and redundancy of the distribution network have been significantly improved after the planning. Due to the consideration of DG integration into the grid in the planning, the energy conservation and emission reduction rate indicator in this article has reached 0.11. It can be seen that after the planning of the supply area, the distribution network has been improved in various aspects such as stability, reliability, energy conservation and emission reduction, which also proves that the replacement of traditional thermal power by renewable energy is an effective way to achieve the goal of carbon neutrality.

5.3. Economic Analysis

After planning, a comparative analysis of the economic efficiency of the medium-voltage distribution network before and after planning was conducted, with reference to cost parameters in reference [19]. The calculation results are shown in Table 4. From the analysis of economic indicators, it can be seen that the comprehensive cost after planning is significantly lower than that before planning. The main reason is that the combination configuration of DPV and ESS compensates for the timing mismatch between DPV output and load demand, increases the access capacity of DPV, and DG offsets part of the load demand of the distribution network, reducing the purchase cost of the main grid. Overall, the economic efficiency after planning is better.

Table 4. Economic indicator data before and after planning

cost	Before	After
Investment cost/yuan	0	21705
Operation and maintenance costs/yuan	0	33385
Electricity generation subsidy/yuan	0	41527
electricity purchase cost/yuan	397111	342731
Comprehensive cost/yuan	397111	356294

6. CONCLUSION

This article takes a practical power supply area as an example and proposes a MV grid distribution system based on time-series characteristics that includes DG. This system can effectively solve the problems of low resource utilization and weak energy conservation and emission reduction capabilities in the distribution network, and draws the following conclusions:

- 1) When grid planning is carried out for MV, the time-series characteristics of load are analyzed to more rationally match and divide the load within the supply area, resulting in a distribution network system with balanced load rates and high load rates.
- 2) In the double-layer grid planning model for the distribution network, the outer layer model takes the minimum comprehensive cost as the objective function, and combines with the inner layer feeder grid planning model to achieve the linkage between the inner and outer layers, which helps to alleviate the mismatch between the timing characteristics of DG and load, increases the absorption capacity of DG, and thus improves the energy-saving and emission-reduction capabilities of the system.
- 3) The comparison of the results before and after planning based on the evaluation indicators proposed in this article has verified that the proposed planning method can effectively improve the system's economy and overall performance.
- 4) The next step will be to consider more types of DG, and further study the grid planning of distribution networks with multiple types of DG based on the model in this article.

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