

Power Supply Unit Planning of Distribution Network Including Energy Storage based on N-1 Criterion

Zhan Zhang, Jin Yang*

College of Electrical Engineering and automation, Henan Polytechnic University, Jiaozuo, China

* Corresponding author: Jin Yang (Email: yj62082@163.com)

Abstract: In order to realize effective load transfer in medium voltage distribution network when $N-1$ fault occurs, a method of power supply unit division is proposed. Firstly, according to the content and characteristics of grid planning of distribution network, the principle of power supply unit division is proposed. Then, based on the grid planning of distribution network, the method of power supply unit division is established. Finally, the calculation results show that the division of power supply units based on the power supply grid and energy storage planning improves the line connection rate, meets the $N-1$ safety check, and improves the safety and reliability of the medium-voltage distribution network.

Keywords: Distribution network planning, Stored energy, Power supply unit, $N-1$ Security check.

1. Introduction

The division of power supply units is planned on the basis of the division of power supply grids in the medium voltage distribution network and the grid-connected capacity configuration of energy storage. It is composed of multiple power supply grids, which can be transferred by the connected power supply grids in the same power supply unit in case of failure. Each power supply unit operates independently to ensure the stable and reliable operation of the power grid. It is a very important content in meshing planning of medium voltage distribution network.

At present, some scholars have conducted research on the division of power supply units. Literature [1] defines the multi-level modular structure and functions at each level of the distribution network, and proposes the planning process and division method for each level. Based on the geographical boundary constraints and the quantity constraints of power supply units, literature [2] optimizes and combines the grids with high boundary coincidence degree, and proposes the evaluation index of grid boundary degree to divide power supply units. In literature [3], a mathematical model of project life cycle cost considering power failure loss factors was constructed, and a new distribution grid planning method based on capacity and power supply reliability, that is, double Q, was proposed. Literature [4] clarified the candidate channel layout in the supply area, and planned the power supply zone in the supply area based on the maximization of the " $N-1$ safety criterion" of the line channel and the minimization of the planned line cost. In literature [5], based on meeting the connectivity of trunk channels, and considering that load can be transferred between different lines and channels and reduce the comprehensive cost, a model was constructed, and the exhaustion method was adopted to solve it. In literature [6], the power supply units were divided based on the bipartite maximum weight algorithm^[7], considering the reliability of the power supply area and the improvement of load transfer capacity, while the distance between the power supply grids was minimized and the lines of the power supply units in the power supply area were not crossed. The above research uses different methods to divide the power supply unit, which has different degrees

of improvement in the performance of the power supply unit. However, in the future power grid construction, due to the change of the power grid structure, the influence of multiple factors should be considered in the division of the power supply unit, and the study on the participation of energy storage in the division of the power supply unit of the medium-voltage distribution network also plays an important role.

In view of this, the power supply unit division model and method are proposed to realize the effective load transfer when $N-1$ fault occurs in distribution network. Firstly, based on the planning results of power supply grid and energy storage capacity of medium voltage distribution network and the characteristics of power supply area, the principle of power supply unit division is established. Then, on this basis, the power supply unit division method is established. Finally, the validity of the power supply unit division method based on power grid and energy storage planning is verified by an example analysis.

2. Principles for Dividing Power Supply Units

2.1. Power supply unit definition

Power supply unit definition: consists of multiple grids with similar distances, and in the event of an $N-1$ fault, the interconnected grids within the power supply unit carry out belt transfer. The power supply unit operates independently, effectively reducing the impact range of faults between devices, and ensuring the safety and reliability of the medium-voltage distribution network.

Power supply units are divided into power supply units on the premise of considering load transfer capacity and improving power supply reliability after power grid planning. This paper considers the supporting role of energy storage on power supply units and carries out power supply unit planning, which will be detailed in the corresponding chapters. According to the "Technical Guidelines for Distribution Network Planning and Design" issued by the National Energy Administration^[8], the safety standards of medium voltage distribution network are shown in Table 1.

Table 1. Safety criteria of medium voltage distribution network

Power supply area type	Power supply safety criterion
A+, A, and B class	It should satisfy $N-1$
C class	The value must be $N-1$
D class	It satisfies $N-1$
E class	Do not make mandatory requirements

2.2. Division principle

According to the characteristics of the planned power supply area of the medium-voltage distribution network and the planning results of the meshing joint planning model of the medium-voltage distribution network based on the time series characteristics^[9], each power supply grid is reasonably matched to form a power supply unit to ensure the effective load transfer in the power supply unit when $N-1$ failure occurs. Therefore, the principle of power supply unit division is proposed to provide a theoretical basis for the division of power supply units.

According to the power supply grid planning results of distribution network and the definition of power supply unit in this paper, the power supply grid obtained after grid planning is combined into a power supply unit with uniform power supply radius, balanced load size and load balance according to geographical location. The division of power supply units should comply with the following principles.

Power supply radius balance: The power supply radius of each power supply unit and the power supply grid composed of the power supply unit should be balanced to facilitate management.

Load size balance: In order to improve the utilization of the equipment, the load of each power supply unit should be able to maintain a balance.

Load balancing: The load ratio of each power supply grid of the power supply unit should be balanced to minimize the peak-valley difference ratio of the power supply unit, improve the load ratio, and maintain the stability of the system.

3. Power Supply Unit Division Method

3.1. Partition index

After the meshing joint planning of medium voltage distribution network, in order to obtain the potential of each power supply grid, the differential matching of power supply grid is studied, so that each power supply grid can be reasonably matched to the corresponding power supply unit. In this paper, "full load difference coefficient" is proposed to quantify the matching degree between different power supply grids, and reasonable combination results are obtained through calculation, specifically:

$$X = \frac{1}{24} \sum_{i=1}^{24} \sqrt{(7 - f_{i,xy})^2} \quad (1)$$

Where: X is a positive indicator; $f_{i,xy}$ indicates the load value of the power supply unit at the i time.

3.2. Partition method

After obtaining the results of power supply grid division and energy storage capacity allocation through the mesh-oriented joint planning model of medium-voltage distribution network, based on the power supply grid obtained and the

proposed planning index, combined with graph theory knowledge^[10-11], the power supply unit planning method is proposed to meet the " $N-1$ safety criterion" and ensure the security and stability of the power grid. The specific process of power supply unit planning is shown in Figure 1.

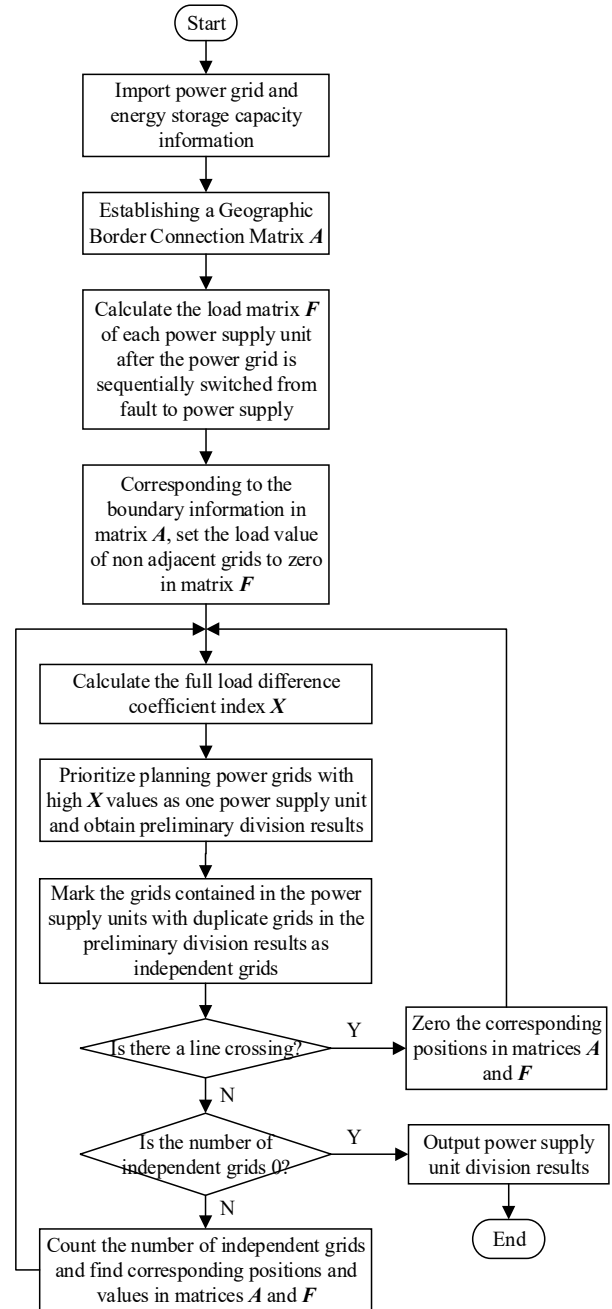


Figure 1. Power supply unit division flowchart

The specific steps are:

Step 1: Number the planned power supply grids and establish a geographic connectivity matrix $A = \{a_{xy}\}$, where $\forall x, y \in K$. Based on graph knowledge, when two power supply grids are adjacent, $a_{xy} = 1$, x and y are the numbers of the two adjacent power supply grids and $x \neq y$, otherwise they are denoted as 0.

Step 2: Using the load data of each power supply grid after planning, calculate the load matrix $F = \{f_{xy}\}$ aft

er the power supply grid switches to other power supply grids in case of successive faults, where x and y are the same as above.

Step 3: Corresponding to the grid boundary information in matrix A . If there is no boundary, assign the corresponding load value in matrix F to 0.

Step 4: Calculate the degree of load pressure on the power grid after the power supply is converted. The larger the X value, the lower the power grid pressure.

Step 5: Prioritize planning the power supply grid combination with the highest X value as one power supply unit, obtain the preliminary planning results of the power supply unit, determine whether there are duplicate power supply grids in each power supply unit. If there are, it cannot form a power supply unit and is temporarily marked as an independent power supply grid.

Step 6: Verify the planning results and determine if there are any line crossings between the main power supply lines of each power supply unit. If it exists, assign the corresponding values in matrices A and F to 0, return to step three, and if it does not exist, obtain the power supply unit planning result.

Step 7: Count the number of independent power supply grids, search for corresponding values in matrices A and F , return to step 3, rematch, and if there are no independent power supply grids, end and output the planning result.

4. Performance Evaluation System for Distribution Networks

After obtaining the results of power supply unit division, this article proposes corresponding evaluation indicators from multiple aspects to represent the degree of performance improvement after distribution network planning.

(1) Line connection rate (%): When a fault occurs in a line, the load of the faulty line can be quickly and effectively transferred through interconnected lines. The proportion of connected lines in the distribution network to all lines is called the line connection rate, which is specifically:

$$E_1 = \frac{L_{11}}{L} \times 100\% \quad (2)$$

In the formula: L_{11} represents the number of connected lines; L is the total number of lines.

(2) $N-1$ pass rate (%): When an " $N-1$ " fault occurs in the distribution network, in order to ensure the safe and reliable power supply of the system, the fault load is transferred to other lines. The proportion of lines that can achieve this transfer operation is the $N-1$ pass rate, specifically:

$$E_2 = \frac{S_{hp}}{L} \times 100\% \quad (3)$$

In the formula, S_{hp} represents the number of lines that have passed the $N-1$ safety criterion.

(3) Average load rate of the line (%): The average value of the load rate at each time point during a typical

daily time period, which can reflect the load situation of the line and determine whether the load is maximized to connect to each power grid considering the temporal characteristics, saving the distance between outgoing lines and avoiding waste. Specifically, it is:

$$E_3 = \frac{1}{K} \frac{1}{H} \sum_{j=1}^K \sum_{h=1}^H f_{j,h,lr} \times 100\% \quad (4)$$

In the formula, $f_{j,h,lr}$ represents the load rate at time h of the j th power grid.

(4) Average load rate (%): This indicator is the ratio of daily average load to maximum load value, which can reflect the utilization rate and redundancy degree of equipment in the power supply area. Specifically, it is:

$$E_4 = \frac{1}{K} \sum_{j=1}^K \frac{f_{j,avfh}}{f_{j,mfh}} \times 100\% \quad (5)$$

In the formula: $f_{j,avfh}$ is the average load of the j th power grid; $f_{j,mfh}$ is the maximum load of the j th power grid.

(5) Energy saving and emission reduction rate (%): The carbon dioxide emissions of typical daily power generation before and after grid planning are calculated. This indicator is the difference between the carbon dioxide emissions before and after planning compared to the carbon dioxide emissions before and after planning, reflecting the energy saving and emission reduction situation after planning. Specifically, it is:

$$E_5 = \frac{e_q - e_h}{e_q} \times 100\% \quad (6)$$

In the formula: e_q represents the pre planning carbon dioxide emissions; e_h is the planned carbon dioxide emissions, and according to the statistics of China Electric Power Union, the carbon dioxide emissions per kilowatt hour of thermal power are taken as 838 grams.

5. Example

5.1. Analysis of power supply unit division results

Taking the 85 node system as an example, the voltage level is 10kV, and the parameters are shown in reference[8]. The specific energy storage capacity information for supporting purposes in each power supply grid is shown in Table 2.

The power supply area is divided into 10 power supply grids, and a geographic adjacency matrix A is established to represent the adjacency of each power supply grid.

Table 2. Energy storage support capacity of each power grid

grid	1	2	3	4	5	6	7	8	9	10
Energy storage/MW	1.894	1.630	1.904	1.999	1.990	2.257	2.268	3.370	3.048	2.240

Establish a load matrix F for transferring power to other power grids in the event of a sequential failure in the power supply grid. Due to space limitations, this article selects matrices F_6 and F_{18} from two of the time points.

$$A = \begin{bmatrix} 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \end{bmatrix}$$

$$F_6 = \begin{bmatrix} 0 & 5.38 & 5.5 & 5.39 & 5.53 & 5.52 & 5.34 & 5.56 & 5.18 & 5.33 \\ 5.38 & 0 & 5.72 & 5.61 & 5.75 & 5.74 & 5.56 & 5.78 & 5.4 & 5.55 \\ 5.5 & 5.72 & 0 & 5.73 & 5.87 & 5.86 & 5.68 & 5.9 & 5.52 & 5.67 \\ 5.39 & 5.61 & 5.73 & 0 & 5.76 & 5.75 & 5.57 & 5.79 & 5.41 & 5.56 \\ 5.53 & 5.75 & 5.87 & 5.76 & 0 & 5.89 & 5.71 & 5.93 & 5.55 & 5.7 \\ 5.52 & 5.74 & 5.86 & 5.75 & 5.89 & 0 & 5.7 & 5.92 & 5.54 & 5.69 \\ 5.34 & 5.56 & 5.68 & 5.57 & 5.71 & 5.7 & 0 & 5.74 & 5.36 & 5.51 \\ 5.56 & 5.78 & 5.9 & 5.79 & 5.93 & 5.92 & 5.74 & 0 & 5.58 & 5.73 \\ 5.18 & 5.4 & 5.52 & 5.41 & 5.55 & 5.54 & 5.36 & 5.58 & 0 & 5.35 \\ 5.33 & 5.55 & 5.67 & 5.56 & 5.7 & 5.69 & 5.51 & 5.73 & 5.35 & 0 \end{bmatrix}$$

$$X_{\%} = \begin{bmatrix} 0 & 0.2413 & 0.2323 & 0.2399 & 0.2357 & 0.2170 & 0.2234 & 0.2143 & 0.2158 & 0.2189 \\ 0.2413 & 0 & 0.2418 & 0.2493 & 0.2451 & 0.2264 & 0.2328 & 0.2237 & 0.2252 & 0.2283 \\ 0.2323 & 0.2418 & 0 & 0.2403 & 0.2362 & 0.2175 & 0.2239 & 0.2148 & 0.2163 & 0.2194 \\ 0.2399 & 0.2493 & 0.2403 & 0 & 0.2437 & 0.2250 & 0.2314 & 0.2223 & 0.2238 & 0.2269 \\ 0.2357 & 0.2451 & 0.2362 & 0.2437 & 0 & 0.2208 & 0.2272 & 0.2181 & 0.2196 & 0.2227 \\ 0.2170 & 0.2264 & 0.2170 & 0.2250 & 0.2208 & 0 & 0.2085 & 0.1994 & 0.2009 & 0.2040 \\ 0.2234 & 0.2328 & 0.2239 & 0.2314 & 0.2272 & 0.2085 & 0 & 0.2058 & 0.2073 & 0.2104 \\ 0.2143 & 0.2237 & 0.2148 & 0.2223 & 0.2181 & 0.1994 & 0.2058 & 0 & 0.1982 & 0.2013 \\ 0.2158 & 0.2252 & 0.2163 & 0.2238 & 0.2196 & 0.2009 & 0.2073 & 0.1982 & 0 & 0.2028 \\ 0.2189 & 0.2283 & 0.2194 & 0.2269 & 0.2227 & 0.2040 & 0.2104 & 0.2013 & 0.2028 & 0 \end{bmatrix}$$

After filtering through the adjacency matrix of the power grid, matrix $X_{\%}$ is used to obtain a matching degree map of the power supply units, as shown in Figure 2.

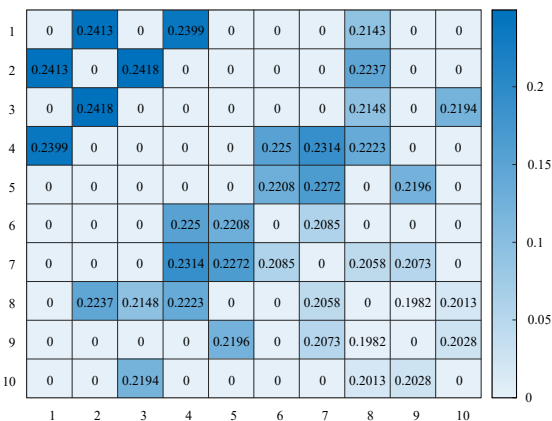


Figure 2. Matching degree diagram between power supply grids

$$F_{18} = \begin{bmatrix} 0 & 5.73 & 5.8 & 5.74 & 5.68 & 5.96 & 5.82 & 5.76 & 5.84 & 5.96 \\ 5.73 & 0 & 5.66 & 5.6 & 5.55 & 5.82 & 5.69 & 5.63 & 5.7 & 5.83 \\ 5.8 & 5.66 & 0 & 5.67 & 5.61 & 5.89 & 5.75 & 5.69 & 5.77 & 5.89 \\ 5.74 & 5.6 & 5.67 & 0 & 5.55 & 5.83 & 5.69 & 5.63 & 5.71 & 5.83 \\ 5.68 & 5.55 & 5.61 & 5.55 & 0 & 5.77 & 5.64 & 5.58 & 5.65 & 5.78 \\ 5.96 & 5.82 & 5.89 & 5.83 & 5.77 & 0 & 5.91 & 5.85 & 5.93 & 6.05 \\ 5.82 & 5.69 & 5.75 & 5.69 & 5.64 & 5.9 & 0 & 5.72 & 5.79 & 5.92 \\ 5.76 & 5.63 & 5.69 & 5.63 & 5.58 & 5.85 & 5.72 & 0 & 5.73 & 5.86 \\ 5.84 & 5.7 & 5.77 & 5.71 & 5.65 & 5.93 & 5.79 & 5.73 & 0 & 5.93 \\ 5.96 & 5.83 & 5.89 & 5.83 & 5.78 & 6.05 & 5.92 & 5.86 & 5.93 & 0 \end{bmatrix}$$

Based on the established geographical adjacency matrix A and the results of the load matrix F after the power grid is sequentially converted to other power grids in case of faults, the full load difference coefficient index X is calculated to evaluate the matching degree of each power grid, and then differentiated power grid combination matching is carried out to achieve the optimal score of the power supply unit. After calculating the full load difference coefficient index X , it is converted into a percentage based matching degree matrix to represent the matching degree of the power supply units composed of each power grid. Specifically:

From Figure 2, it can be seen that each power supply unit has a corresponding best match. When dividing power supply units, the combination with the highest X value should be prioritized to be matched within the same power supply unit. However, in the actual planning and construction process, due to geographical location or environmental constraints, it may have a certain impact on the final planning results. Therefore, it is necessary to consider the combination of the top 2 to top 3 X values between power supply grids as candidate combinations to ensure that the maximum potential for regulation between power supply grids and loads can be explored, and the goal of maximizing equipment utilization within a single power supply unit can be achieved.

According to the power supply unit division method proposed in this article, the optimization division of the distribution network planning supply area was carried out, and the results of the distribution network power supply unit division are shown in Figure 3. In the figure, different grids in the power supply unit are distinguished by black line segments.

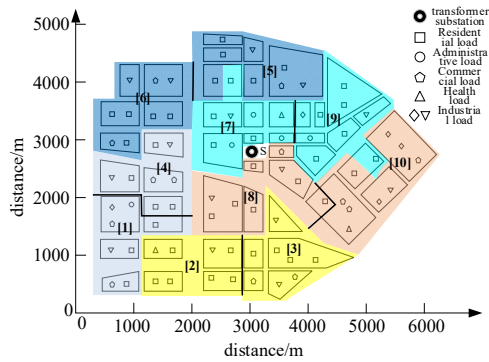


Figure 3. Power supply unit division result diagram

After planning, the indicator data of each power supply unit are shown in Table 3.

Table 3. Power supply unit division index parameters

Power supply unit	Indicator value
1—4	0.2399
2—3	0.2418
5—6	0.2208
7—9	0.2073
8—10	0.2013

From Figure 3 and Table 3, it can be seen that the planned area of the medium voltage distribution network is divided into 10 power supply grids and 5 power supply units. Analysis shows that after considering the temporal characteristics of load and energy storage, the number of power supply grids in the planned supply area is reduced, and the power supply units can meet the $N-1$ safety criterion. The equipment utilization rate is also significantly improved, and the overall performance of the distribution network system is improved.

5.2. Analysis of performance improvement in distribution network

In order to further demonstrate the efficiency improvement of the power supply area optimization method proposed in this article on the medium voltage distribution network, after dividing the power supply units in the planning area, this paper proposes to quantitatively evaluate the degree of load side efficiency improvement of the medium voltage distribution network from five aspects: line connection rate E_1 , $N-1$ pass rate E_2 , line average load rate E_3 , average load rate E_4 , and energy conservation and emission reduction rate E_5 . The specific improvement effects are shown in Table 4.

Table 4. Comparison of indicators before and after planning

index	Before planning	After planning
Line connection rate/%	76.92	100
$N-1$ pass rate/%	61.54	100
Average load rate of the line/%	33.06	37.09
Average load rate/%	81.18	96.38
Energy saving and emission reduction rate/%	0	13.69

According to Table 4, the line connection rate and various evaluation indicators after optimizing the supply

area have all been improved compared to before. The $N-1$ pass rate has the most significant improvement effect, reaching 62.50%, followed by the line connection rate and average load rate, with improvement rates of 30.01% and 18.72% respectively, followed by the average load rate of the line, with an improvement rate of 12.19%, and the energy conservation and emission reduction rate has also increased from 0 to 13.69%. It can be seen that the power supply area optimization method proposed in this article has improved the load transfer capacity, safety, and economy of the medium voltage distribution network to varying degrees, reduced the redundancy of the distribution network, improved equipment utilization and economy, and greatly improved the overall performance of the distribution network.

6. Conclusion

This article takes an 85 node system as an example and proposes a power supply unit division method. This method can effectively solve the problem of effective load transfer when $N-1$ faults occur in the distribution network, and the following conclusions are drawn:

1) The definition of power supply units has been improved by utilizing the content and characteristics of grid based planning for medium voltage distribution networks, and the principles for dividing power supply units have been constructed.

2) Consider the evaluation indicators for power grid planning, energy storage capacity configuration, and power supply unit division, and propose a method for dividing power supply units.

3) Based on the evaluation indicators proposed in this article, the results before and after the case planning were compared, and the comparison results verified that the proposed planning method can effectively improve the security and economy of the system.

4) The next step will be to consider more types of distributed power sources, and further study the division of power supply units in distribution networks containing multiple types of distributed power sources based on the model in this paper.

References

- [1] Liu Weisheng, Liu Hong, Liu Zhiqing et al, "Modular Planning System and Method for Distribution Networks," Journal of Power Systems and Automation.J., vol. 31, no. 11, 2019,pp. 139-144.
- [2] W Liu, H Liu, F Wang, et al, "Practical Automatic Planning for MV Distribution Network Considering Complementation of Load Characteristic and Power Supply Unit Partitioning," IEEE Access.J., vol. 8, no. 4, 2020,pp. 91807-91817.
- [3] Hou Jia, Wu Zhili, Cui Kai, "A New Grid Planning Method for Distribution Networks Based on Double Q," Guangdong Electric Power.J., vol. 32, no. 04, 2019,pp. 17-25.
- [4] Ren Hongyu, Wang Zhuding, Zhang Chao, et al, "Optimization Model and Method for Grid Planning of High Voltage Distribution Networks," Power System Automation.J., vol. 43, no. 14, 2019,pp. 151-158.
- [5] Zhang Man, Wang Zhuding, Li Qiang, et al, "Optimization model and method for power supply zoning in medium voltage target network planning," Power System Automation.J., vol. 43, no. 16, 2019,pp. 125-135.

- [6] Tang Bo, Yang Peng, Yu Guangzheng, et al, "Optimization method for medium voltage distribution network supply area based on load peak valley coupling characteristics," Chinese Journal of Electrical Engineering.J., vol. 42, no. 19, 2022,pp. 7051-7063.
- [7] Wang Haiying, Huang Qiang, Li Chuantao, et al, "Graph theory algorithms and their MATLAB implementation," Beijing: Beihang University Press.M.,2010,pp. 101-105.
- [8] Technical Guidelines for Distribution Network Planning and Design: DL/T 5729-2016, National Energy Administration.S. 2016.
- [9] Zhang Z, Yang J, "Grid Planning Method of Medium Voltage Distribution Network Including Distributed Power Sources Based on Timing Characteristics," IJEPES.J., vol. 2, no. 1, 2024,pp. 11-24.
- [10] Yao Yongfeng, Wang Qizhe, Wang Huiping, et al, "Fault section localization method for low-voltage distribution networks based on adjacency matrix," China Electric Power.J., vol. 54, no. 11, 2021,pp. 91-96114.
- [11] Xu Jingyou, Ding Jianyong, Yang Dongjun, et al, "A reliability evaluation method for distribution networks based on graph theory and network equivalence," Journal of Electrical Engineering.J., vol. 16, no. 03, 2021,pp. 92-98.