Practical Automatic Planning for MV Distribution Network Considering Complementation of Load Characteristic and Power Supply Unit Partitioning

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ABSTRACT A new practical automatic planning method for MV distribution network considering complementation of load characteristic and division of power supply is presented to solve the problems of large network size and low equipment utilization ratio caused by the lack of consideration of complementation of load characteristic in distribution network planning. First, based on the existing research results on load clustering and grid planning, the concepts of MV distribution network feeder block and power supply unit are redefined and the technical framework of MV distribution network planning considering division of power supply is designed. Then, the evaluation indexes of feeder block partitioning and power supply unit partitioning considering complementation of load characteristic are set up, and rotation center line distance weighting alternate location algorithm is proposed to divide the feeder block. Further, the MV distribution network planning model based on power supply unit partitioning is proposed, which takes the minimum value of the sum of interruption cost based on reliability index and line integrated cost of the planning year. Combining ant colony algorithm, automatic planning algorithm is proposed to get the combinatorial solution of trunk line and branch line. Finally, the scientificness and practicability of the model and method in this paper was verified through the case study.

INDEX TERMS Load characteristics, block partition, power supply unit, automatic planning.

I. INTRODUCTION

The distribution network planning is carried out on the basis of load forecasting and substation site selection and capacity, which has a direct and significant impact on the economics and reliability of distribution network construction and operation [1]–[3]. Distribution network planning, which requires the combination of geographic information to determine the spatial layout of the line, contact object selection, load division and other issues. Authors in [4] established a comprehensive planning model of line layout and switch setting, and obtained the economical optimal trunk line and switch setting scheme under the specified wiring mode. Authors in [5] optimized the grid structure of the distribution network based on the idea of maximizing the power supply capacity. However, the above documents are based on a simple topology, which do not reflect the geographical location of each device in the distribution network and the actual geographic elements and constraints between the devices. Therefore, in [6], an improved binary particle swarm optimization algorithm is used to obtain the solution set of distribution network reconfiguration, and the coordinates of invalid particles in the iterative process are modified randomly to improve the search efficiency. However, there are many planning objects for the distribution network planning, so it is difficult to consider the space and all planning objects. Most of the existing network planning studies select some of the planning objects in the network planning for research and discussion,
and make similar considerations for other parts, which is difficult to use for the actual complete network planning. These network planning schemes are mainly proposed by the experiences of the planners, which is likely to cause problems such as subjective and poor implementation. With the popularization of computer-aided decision-making technology, some researchers explored the problem of automatic planning, and also studied the main line and branch line layout and contact structure optimization [7]–[9]. And they proposed a solution based on heuristic algorithm and artificial intelligence algorithm [10]–[13]. Among them, the authors in [9] firstly constructed an optimization model including the main line and the trunk line according to the ant colony algorithm, and then used the simulated annealing algorithm to prevent premature convergence for the optimization model. And the branch line was considered during the planning process. In [13], considering the stochastic uncertainty of the load in the distribution system, a hybrid chance-constrained distribution grid planning model including both fuzzy variables and random variables is established on the basis of the theory of uncertain planning. And the paper solves it using a genetic algorithm.

However, due to the high complexity of the distribution network grid planning problem, the planning effect for large-scale networks is very limited. Therefore, the large-scale distribution network should be divided into several small modules, then plan for each module. Also, existing plans often predict the maximum load of power users and determine the simultaneous rate based on the experiences. This kind of planning method is inaccurate, and if the simultaneous rate is too large, which is easy to cause waste of resources. It increases the demand for network construction and investment scale. However, if the selection of the simultaneous rate is too small, which may cause problems such as low line capacity selection. Therefore it is necessary to accurately consider the load characteristics of power users, and then obtain the true and accurate maximum load value of the whole network.

In view of the above problems, this paper first constructs a modular planning idea system for power grid and power supply unit including substation interconnection structure. On this basis, this paper focuses on the planning level of the power supply unit. And the definition of the distribution network feeder block and power supply unit of the distribution network is revised by using the complementary characteristics of the load characteristics of the electric power district. Then propose the modularization-based grid layout planning steps. Secondly, the evaluation indexes of the feeder block partitioning and power supply unit partitioning considering complementation of load characteristic are set up, and rotation center line distance weighting alternate location algorithm is proposed to divide the feeder block. Thirdly, the MV distribution network planning model based on power supply unit partitioning is proposed, which takes the minimum value of the sum of interruption cost based on reliability index and line integrated cost of the planning year. Combining ant colony algorithm, automatic planning algorithm is proposed to get the combinatorial solution of trunk line and branch line. Finally, the scientificalness and practicability of the model and method in this paper was verified through the case study.

II. MODULAR DISTRIBUTION NETWORK PLANNING

Firstly, the modularization planning system of distribution network is introduced. Secondly, the concepts of feeder block and power supply unit are clarified. Finally, the solution steps of grid layout planning for medium voltage distribution network considering modular division are constructed.

A. DISTRIBUTION NETWORK MODULAR PLANNING SYSTEM

In the past, the layout of distribution network grids was often carried out on a global basis. The scope of the planning was carried out in pieces, and the network transition was relatively difficult. In the planning process, the differences in the regions were not taken into account, and the planning was not accurate. In order to reduce the need for planning and solving dimensions and improve the level of planning and the ease of transition of the grid, modular planning was widely used in distribution network planning in recent years. Modular planning no longer plans for a whole area, but divides the planning area into several appropriate planning units to differentiate the development goals of each planning unit.

The modular planning system is divided into two planning levels: the power grid and the power supply unit from top to bottom. A schematic diagram of the power supply grid is shown in Fig. 1.

![FIGURE 1. Schematic diagram of the power supply grid.](image-url)
B. DEFINITION OF FEEDER BLOCK AND POWER SUPPLY UNIT

Definition 1 feeder block: In the power supply range of a substation, considering the various factors such as road and river, load space distribution and complementary characteristics, the maximum load does not exceed the area of the residential area with the load of the 10kV outlet (outline group) under certain standard wiring. The lines within the feeder block need to be laid out along the street, and the problem of power supply crossover should be avoided as much as possible. The maximum value of the total load of the feeder block should be lower than the sum of the maximum load of each used power cell.

Definition 2 power supply unit: In the power supply range of multiple substations, considering the various factors such as administrative area, topography and load space distribution, a certain number of adjacent feeder blocks in the substation or between the substations will be combined according to the number of lines specified by the standard wiring. In this way the power supply unit is formed.

The power supply unit is an area based on a standard wiring mode, which is composed of a certain number of feeder blocks. Each power cell is powered by a substation to which the feeder block belongs, and is rotated by a line connected within the power supply unit during a fault. Independent planning and independent operation with other power supply units facilitates the standardization of wiring and makes the structure of the grid clear, which helps to reduce the impact of various equipment components. The schematic diagram of the feeder block and power supply unit is shown in Fig. 2.

C. STEPS FOR SOLVING GRID PLANNING BASED ON MODULAR PARTITIONING

Considering the modular division of the medium voltage distribution network grid planning framework, it is necessary to solve the two problems related to the division of the feeder block and the power supply unit and the automatic layout of the lines in the power supply unit. The solution steps proposed for this purpose are shown in Fig. 3.

In the power supply unit division method, firstly, according to the feeder block division algorithm, a feeder block division scheme in which multiple feeder block division evaluation indexes are better in each substation is determined. On this basis, the division schemes of the respective substations are combined. Further, a preliminary set of power supply unit division is formed. Then, according to the wiring mode and the geographically bound constraints and the optimal division principle of the evaluation degree of the boundary degree of the block, a certain number of candidate sets of power supply unit division schemes are selected from the primary selections.

For each power unit division scheme in the candidate set, establish a mathematical model of the grid plan with the goal of summing the line investment with the running cost and the power outage loss cost, and obtain the layout of the optimal trunk line, trunk line and the branch line according to the wiring mode. On this basis, the objective function of each scheme in the candidate set of the power supply unit partitioning scheme is compared, and the most optimal scheme is selected to achieve the best planning effect.

III. FEEDER BLOCK AND POWER SUPPLY UNIT DIVISION METHOD CONSIDERING LOAD CHARACTERISTIC COMPLEMENTATION

Considering the power supply unit division with complementary load characteristics, two technical problems need to be solved. One is the evaluation index for measuring the difference between the feeder block and the power supply unit, and the other is the block division algorithm using the evaluation index combined with the line power supply range division feature.
A. THE ADVANTAGES OF CONSIDERING THE LOAD CHARACTERISTICS

In the distribution network frame planning, the method of planning using the simultaneous rate is too extensive. If the simultaneous rate is too high, the maximum load of the whole network will be predicted to be large, which will cause waste of resources and lines during planning. The problem of low average asset utilization rate; if the simultaneous rate is too high, it will lead to the prediction that the maximum load of the whole network is too small, and it is easy to cause the selected line capacity to be low during planning. The load value of power users fluctuates all the time, and the load characteristics of users of different load types are different. When the load characteristics of power users are carefully considered, the maximum load of the whole network can be accurately obtained. Accurate overall network load maximum planning can improve the accuracy of planning.

B. THE ADVANTAGES OF CONSIDERING THE COMPLEMENTARY LOAD CHARACTERISTICS

As mentioned above, the feeder block corresponds to the power supply range of a 10kV feeder. If the load with complementary characteristics is divided into a feeder block, the peak-to-valley difference of the load supplied by the feeder can be made smaller and effectively improved. In turn, the average annual asset utilization efficiency will be improved.

The above situation is an ideal situation considering the complementary load characteristics, but in the actual scenario, whether the load types in the power supply range of the substation are complementary, whether the loads with complementary load characteristics are similar in size, and the loads with complementary characteristics are geographically, whether the objective conditions such as bordering are limited, the planning effect considering the complementary load characteristics will be lower than the above effects, and the above ideal situation cannot be used to replace all possible situations.

In actual planning, loads of different types and sizes may be adjacent. Therefore, it is necessary to propose a general method to consider the effect of superposition of load characteristics under different conditions, in order to find the optimal solution of the complementary load characteristics in future planning.

C. FEEDER BLOCK DIVISION EVALUATION INDEX CONSIDERING LOAD CHARACTERISTICS COMPLEMENTATION

The evaluation of the feeder block partitioning scheme is based on the optimal overall load characteristics of each feeder block. Based on the consideration of the similar size of each block, avoiding the uneven distribution of load in each block, it is proposed to use the daily maximum load index to construct the block maximum load balance index $a_{lb}$. Based on the consideration of annual equipment utilization efficiency improvement of each line, it is proposed to use the daily load rate index to construct the block average daily load rate indicator $a_{f}$. Based on the mitigation of peak load tension, it is proposed to use the peak-to-valley difference to construct the block average peak-to-valley difference index $a_{pvr}$. Combine the above three indexes to obtain a comprehensive evaluation index of feeder block division $F_{feeder}$. The specific calculation formula of the index is shown in formula (1-4). Each value ranges from 0 to 1, and they are positive indexes.

$$a_{lb} = \frac{1}{N_{step}} \sum_{i=1}^{N_{step}} l_{ml,i}^{ml}$$  \hspace{1cm} (1)

$$a_{f} = \frac{1}{N_{step}} \sum_{i=1}^{N_{step}} l_{f,i}$$  \hspace{1cm} (2)

$$a_{pvr} = \frac{1}{N_{step}} \sum_{i=1}^{N_{step}} (1 - l_{pvr,i})$$  \hspace{1cm} (3)

$$F_{feeder} = \alpha a_{lb} + \beta a_{f} + \gamma a_{pvr}$$  \hspace{1cm} (4)

As previously described, $l_{ml,i}$ represents the maximum load of the $i$-th feeder block, $l_{max}$ represents the largest value of the maximum load of each feeder block, $l_{f,i}$ represents the daily load rate of the $i$-th feeder block, $l_{pvr,i}$ represents the daily peak-to-valley difference of the $i$-th feeder block, $\alpha$, $\beta$, and $\gamma$ are the weights of the three indicators, and the sum of the weights is 1, and the specific value is determined.
according to the importance of different grid regions for different indicators.

D. POWER SUPPLY UNIT DIVISION EVALUATION INDEX CONSIDERING LOAD CHARACTERISTICS COMPLEMENTARY

For each feeder block combination, there are many types of power supply unit divisions that satisfy the geographical boundary constraints and the demand of the number of the power supply units between the stations. Due to the large space optimization scheme of the power supply unit of the combination of the blocks with high boundary coincidence degree, it is more advantageous to find a more economical solution, so the two blocks of the power supply unit between the stations are at the substation boundary. The average degree of coincidence is defined as the block boundary assessment index $F_{\text{unit}}$. It is used as the selection of the power supply unit division scheme, and the specific calculation formula is shown in equations (5) and (6).

$$F_{\text{unit}} = \sum_{i=1}^{N_{\text{unit},0}} b_{\text{bor},i}$$

$$b_{\text{bor},i} = \frac{b_{\text{sec},i,1} \cap b_{\text{sec},i,2}}{b_{\text{sec},i,1} \cup b_{\text{sec},i,2}}$$

In the above, $N_{\text{unit},0}$ represents the number of divisions of power supply units between stations, $b_{\text{bor},i}$ represents the degree of coincidence of the two feeder blocks of the $i$-th power supply unit at the boundary, $b_{\text{sec},i,1}$ and $b_{\text{sec},i,2}$ represent the boundary line segments of each feeder block of the $i$-th power supply unit in the substation area.

E. THE ROTATION CENTER LINE DISTANCE WEIGHTING ALTERNATE LOCATION ALGORITHM OF DIVIDING THE FEEDER BLOCK

The essence of substation power supply range division is the space division with the substation position as the core, and the result is usually a circular area. However, the essence of the division of the power supply range of the medium voltage line is that the space division with several lines as the core should form a sector-like area. Obviously, the traditional substation power supply range division method is difficult to apply to such problems. Therefore, this paper combines the wiper sway search algorithm [15] with the characteristics of the line power supply range division problem. On the one hand, two weighting factors are introduced, taking into account the effects of block equalization and the characteristics of the load. On the other hand, this paper sets multiple sets of initial centerlines to obtain different partitioning schemes in order to improve the quality of the partitioning results. Finally, the rotation center line distance weighting alternate location algorithm is formed. The algorithm is shown in Fig. 5.

The algorithm mainly updates the weighting factor and the angles of the center line in the feeder block division. The specific process is as follows:

1) Identify multiple sets of initial centerlines. Fig.4 (a) shows the initial state of the power supply range of the substation. In each initial center line, the initial virtual centerline of the $N_{\text{feeder}}$ strip is distributed at an equal angle of $\Delta \theta 1$; and the angle of $\Delta \theta 2$ is rotated clockwise around the center to obtain different initial centerlines.

2) Set the initial values of $\omega_{1ij}$ and $\omega_{2ij}$ to 1, determine the initial load attribution center line according to the distance, and perform angle repositioning according to the load position to which the center line belongs.

3) In each alternate positioning, $\omega_{1ij}$ and $\omega_{2ij}$ are updated according to the maximum load of the total load of each block and the peak-to-valley difference. The weighting distance formula is given by formula (7-9). Each load is selected to be centered according to the weighting distance, and then the center lines are repositioned.

4) Determine whether the number of iterations is reached, then stop iteration, otherwise continue iteration.

5) Determine whether all group initial centerlines are calculated, and if so, end the algorithm, otherwise return to step 2 to calculate the next set of schemes.

$$\alpha_i = \text{atan} \left( \sum_{j \in F_i} \Delta y_j, \sum_{j \in F_i} \Delta x_j \right)$$

$$l_{ij} = l_{ij}' \omega_{1ij} \omega_{2ij}$$

$$\omega_{1ij} = \left( \sum_{j \in F_i} P_j \right)^k \left( P_i - P_j \right)^k$$

$$\omega_{2ij} = \left( \sum_{j \in F_i} e_{ij} \right)^k \left( \sum_i e_{ij} - e_{ij} \right)$$

As previously described, $l_{ij}'$ and $l_{ij}$ represent the vertical distance and weighting distance of the load point $j$ to the virtual center line $i$; $P_i$ represents the peak load of the block $i$ where the virtual center line $i$ is located. When $P_i$ becomes larger, the value of $\omega_{1ij}$ also becomes larger, so the weighting distance from each load to the virtual center line $i$ becomes larger. If the load $j$ originally does not belong to the block where the virtual center line $i$ is located, $e_{ij}$ represents the peak-to-valley difference of the block after the load point $j$ is added to the block where the virtual center line $i$ is located, otherwise $e_{ij}$ represents the peak-to-valley difference of the block where the virtual center line $i$ is located. If load $j$ is added to the block $i$, it is not conducive to improve the
peak-to-valley difference of the block, the value of \( e_{ij} \) will become larger, and the value of \( \omega_{2j} \) will also become larger. \( K \) represents the amplification factor of the weighting factor; the function of the \( \text{atan2}(x, y) \) represents the angle between the ray which is pointed to \((x, y)\) and the positive direction of the \(x\)-axis, and the value interval is at \((-\pi, \pi)\).

IV. NETWORK FRAME PLANNING METHOD BASED ON MODULAR PARTITION

Based on the candidate set of the modular partitioning scheme, an automatic routing model including the main line, the trunk line, and the branch line is first constructed for each power unit partitioning scheme. And find the optimal routing scheme under the partitioning scheme using the optimization of the algorithm. In this way, comparisons and preferences between the various partitioning schemes in the candidate set can be achieved.

A. MATHEMATICAL MODEL

The objective function of the modular planning model includes the planned annual investment of the main line, the running cost, and the sum of interruption cost, which is as followed.

\[
F = Z_1 + Z_2 + Z_3 + Z_4 \tag{11}
\]

\( Z_1 \) represents the investment cost and network loss cost of the main line, \( Z_2 \) represents the investment cost of the trunk line, \( Z_3 \) represents the investment cost of the branch line, ignoring the network loss of the branch line, and \( Z_4 \) represents the sum of interruption cost. Based on the expression of the traditional equal-year cost, the expressions of each part are proposed in combination with the power supply unit and the timing characteristics. The expression is shown in formula (12-15).

\[
Z_1 = \sum_{i=1}^{N_{\text{station}}} \sum_{j=1}^{N_{\text{step}}} \left[ \alpha \left( \frac{r_0 (1 + r_0)^m}{(1 + r_0)^m - 1} \right) L_{ij} + \frac{5}{7} \beta L_{ij} \sum_{i=1}^{96} P_{ij}^2 \right] + \frac{2}{7} \beta L_{ij} \sum_{i=97}^{192} P_{ij}^2, \beta = \frac{8760 \beta_1 \beta_2}{96 U^2 \cos^2 \varphi} \tag{12}
\]

\[
Z_2 = \alpha \left( \frac{r_0 (1 + r_0)^m}{(1 + r_0)^m - 1} \right) \times \sum_{k=1}^{N_{\text{unit}}} L_k \tag{13}
\]

\[
Z_3 = \gamma \left( \frac{r_0 (1 + r_0)^m}{(1 + r_0)^m - 1} \right) \times \sum_{i=1}^{N_{\text{station}}} \sum_{j=1}^{N_{\text{feeder}}} L_{ij} \tag{14}
\]

\[
Z_4 = \sum_{i=1}^{N_{\text{station}}} \sum_{j=1}^{N_{\text{feeder}}} \left( \sum_{i=1}^{n_{\text{ns}}} C_{\text{ns}(i,j)} (r_{j1}) L_{\text{av},i1} \lambda_{j1} \right) \tag{15}
\]

In the formulas above, \( \alpha \) represents the cost of the main line investment; \( r_0 \) represents the discount rate; \( m \) represents the line depreciation year; \( L_{ij} \) represents the length of the main line in the feeder block \( j \) of the substation \( i \); \( \beta \) represents the line network loss conversion coefficient; \( \beta_1 \) indicates the electricity price; \( \beta_2 \) indicates the line unit length resistance value; \( U \) indicates the voltage of the feeder line. \( L_q \) represents the length of the trunk line of the power supply unit \( k \); \( \gamma \) represents the cost of the main line investment in feeder block; \( L_j \) represents the sum of the branch line lengths of the feeder block \( j \) of the substation \( i \). \( F_{1,j} \) and \( n_{\text{ns}}(i,j) \) represent the load set and the number of failures that occur in the feeder block \( j \) of the substation \( i \). \( r_{j1} \) and \( \lambda_{j1} \) represent the power outage time and fault frequency of the \( j \)th fault. It can be obtained by the failure mode consequence analysis method; \( C_{\text{rns}(i,j)}(r_{j1}) \) represents the unit load power integration cost of the \( (l_{ij}) \)-th type of load when the power failure time is \( r_{j1} \). Based on the statistical average user power outage loss value of various users during different power outage durations, the unit load power outage loss cost function of different users can be obtained [16], [17].

In addition to the constraints of the number of feeder block and the number of power supply units, based on the requirements of the actual power grid planning, the following constraints are listed: the line load rate is at a reasonable level and meets the “N-1” check, the line meets the voltage drop constraint, the power supply does not cross each other, the line supply radius is not too long, and the wiring is routed on the line corridor.

B. THE STRATEGY OF SOLVING THE MODEL

In the grid planning based on the division of power supply units, each power supply unit is independently wired. The specific solution strategy is followed:

1) Select the street nodes around the boundary of each feeder block in the power supply unit as the set of candidate nodes at the end of the main line of the block, and the number of elements in the point set are respectively \( N_{\text{ser1}} \) and \( N_{\text{ser2}} \);

2) In each feeder block, the substation is taken as the start point, and the end candidate nodes are taken as the end point. The ant colony algorithm is used to obtain the better \( N_{\text{line}} \) candidate trunk lines. Then calculate the investment and running costs of each trunk line.

3) Based on the trace of each candidate main line, the branch line combination algorithm is used to obtain the branch line routing schemes which connect loads and main lines, and calculate the investment cost of each branch line \( Z_3 \).

4) Set each main line to three segments. Determine the position of the two segment switches based on the balance of the three segments, and calculate the reliability index and the power outage loss cost \( Z_4 \) through the failure mode consequence analysis method [18]. Combine step (3) to calculate and compare \( Z_3 + Z_4 \) of each branch line routing scheme, and determine the most optimal branch line routing scheme;

5) Combine step (2-4) to calculate and compare \( Z_1 + Z_3 + Z_4 \) of the \( N_{\text{line}} \) schemes, and select the most optimal scheme as the trace of this end candidate node;

6) Calculate the shortest distance between the candidate nodes between the two feeder blocks, that is, the length.
of the trunk line, and calculate the cost of the trunk line investment $Z_2$:

7) Compare the economical results of $Z_1 + Z_2 + Z_3 + Z_4$ of the “main line-trunk line-main line” single-contact wiring mode of $N_{set1} \times N_{set2}$ pairs of points, and select the most optimal point pair and the wiring scheme. This is the final model solution result.

![Diagram of combinatorial solution algorithm for branch line.](image)

**FIGURE 6.** Diagram of combinatorial solution algorithm for branch line.

**C. THE BRANCH LINE COMBINATION ALGORITHM**

In the case that the trunk line of the feeder block is determined, it is required to take the branch line connecting the load point and the main line. Since the number of load points carried by each main line is small and is adjacent to the main line, the branch line combination algorithm is proposed, and the schematic diagram is shown in Fig. 6.

1) Firstly, according to the position of each load point and the main line, determine the 2-4 candidate branch line schemes of the load point.

2) A branch line scheme for each load point is selected for combination, and the duplicate street segments are deleted to obtain the branch line traces under the combination. According to the principle of setting the segmentation switch position, the segmentation switch position is determined, and the failure mode consequence analysis method is used to solve the power failure time of each fault in each fault, and the sum of the branch line investment cost and the interruption cost under the branch line combination scheme are calculated;

3) Compare the branch line combination schemes of all load points, and save the scheme which the sum of branch line investment costs and the interruption costs are the lowest.

**V. CASE ANALYSIS**

**A. DATA OF THE CASE**

The example of a triangular single-contact power supply model is as follows: three substations which the capacity is $2 \times 31.5$ MVA. The power supply range has 80, 83, 80 loads, the size of the average load is 430 kW, the main load rate is about 60%, the model of the feeder is LGJ-185 and the transmission capacity is 7.8 MW.

The load has four types of loads: residential, commercial, industrial, and office. There are load curves of 8 typical days for each working day and weekend of spring, summer, autumn and winter. According to the power supply model [19], the constraint conditions of the contact line are: each substation has 10 feeders. 6 feeders are in contact with other substations, and 4 feeders are in contact at their own substation.

**B. THE RESULTS AND ANALYSIS OF THE FEEDER BLOCK PARTITION**

The weight of the feeder line block evaluation indicators is 1:1:1.

1) WHETHER TO CONSIDER THE COMPLEMENTARY FEATURES

Two strategies are used to divide the feeder block of substation S1 to compare whether the difference in load characteristics is considered. The two strategies are as follows:

(1) Consider the complementary of the load characteristics, the weighting factor $\omega_{1i}$ considers the equilibrium of the peaks of the sum of the block loads, $\omega_{2ij}$ considers the equilibrium of the peak-to-valley difference of each block;

(2) Without considering the complementary of the load characteristics, the weighting factor $\omega_{1i}$ considers the equilibrium of the sum of the load peaks of the blocks, and $\omega_{2ij}$ is not included in the calculation. The comparison results from the minimum number of outlets, the equipment utilization rate [20] for estimating the average annual load, and the peak-to-valley difference are shown in Table 1.

| complementation of load characteristic or not | Minimum feeder number | The mean of equipment utilization of each block/% | Average peak valley difference of each block % |
|-----------------------------------------------|-----------------------|-----------------------------------------------|---------------------------------------------|
| YES                                           | 10                    | 23.88                                         | 76.07                                       |
| NO                                            | 11                    | 21.71                                         | 76.23                                       |

It can be seen from the above table that the most minimum numbers of the substation feeders calculated by the strategy of considering the complementary of the load characteristics is lesser. The annual equipment utilization ratio of each block is higher, and the average peak-to-valley difference is lower. Therefore, when the feeder block is divided from the range of the substation power supply, on the one hand, consider the strategy of complementary load characteristics can reduce the number of substation outlets. That is beneficial to improve the annual equipment utilization rate of the line and save the economic cost of planning. On the other hand, the peak-to-valley difference of each block is small, which is conducive to the stable operation of the power grid.
2) THE RESULTS OF THE FEEDER BLOCK PARTITION WHEN THE COMPLEMENTATION OF THE LOAD CHARACTERISTICS IS CONSIDERED

According to the feeder block partitioned algorithm considering the complementary of the load characteristics, a better feeder block partitioned scheme for each substation is obtained. The number of feeders is 10; each substation retains three feeder partitioned schemes with better evaluation criteria. The corresponding indicators of the three schemes with better evaluation indicators for each substation are shown in Table 2.

| Substation | Scheme | Load rate of each block, % | Comprehensive assessment indicator |
|------------|--------|---------------------------|-----------------------------------|
| S1         | Scheme1 | [40.37,46.86]             | 0.574 0                          |
|            | Scheme2 | [40.46,48.41]             | 0.564 6                          |
|            | Scheme3 | [40.46,49.73]             | 0.557 1                          |
| S2         | Scheme1 | [40.27,45.88]             | 0.537 3                          |
|            | Scheme2 | [40.85,48.81]             | 0.518 7                          |
|            | Scheme3 | [40.02,48.72]             | 0.517 8                          |
| S3         | Scheme1 | [39.52,45.59]             | 0.549 5                          |
|            | Scheme2 | [39.42,46.89]             | 0.538 9                          |
|            | Scheme3 | [36.33,46.67]             | 0.534 7                          |

The comprehensive evaluation index mainly consists of load balance, average daily load rate and average peak-to-valley difference. It can be seen from the above table that the load ratio of each block in the most optimal solution of the three substations is relatively balanced. The reason is that the residential load and the administrative load are more complementary. In the most optimal scheme, the residential load and the administrative load are preferentially divided into the same feeder block, which reduces the maximum load of the total load of the block. And it is beneficial to increase the block load rate and reduce the peak-to-valley difference of the block.

C. THE RESULTS AND ANALYSIS OF THE POWER SUPPLY UNIT PARTITION

According to the combination of each substation feeder block, the corresponding primary selection schemes can be obtained. Using the previously mentioned method, three power supply unit division schemes with better boundary degree evaluation indicators can be obtained. 27 power supply unit division schemes constitute the candidate set of the power supply unit division schemes.

Since the process of obtaining the each power supply unit division scheme is the same, the solution of the power supply unit division scheme is explained only by obtaining the most optimal planning scheme. The feeder block combination is composed of the third optimal scheme of the feeder block partition in S1, the first optimal scheme of the feeder block partition in S2, and the second optimal scheme of the feeder block partition in S3.

The following explains in detail why the feeder block partition combination in the optimal planning scheme is the third best feeder block partition scheme of substation S1, the first best feeder block partition scheme of S2, and the second best feeder block partition scheme of S3. As mentioned above, each substation contains three feeder block partition evaluation schemes that are better. There are a total of 27 feeder block partition combination schemes. For each feeder block partition combination scheme, there are several types of power supply unit schemes, choosing the three supply unit partitioin plans with the better boundary degree evaluation indicators, then you can get a total of 81 power supply unit partition plans. For each type of power supply unit partition plan, using the method of the network planning algorithm to solve, you can get the most optimal results for each group of power supply unit partition schemes. A total of 81 economic results can be obtained. Comparing these 81 economic results, you can find that the most optimal scheme is composed of the third best feeder block partition scheme of substation S1, the first best feeder block partition scheme of S2, and the second best feeder block partition scheme of S3.
TABLE 3. Primary schemes of power supply unit portioning for 20th feeder block combination.

| Option number | The inter-station power supply unit of the solution | Block boundary assessment index | Target function cost |
|---------------|-----------------------------------------------|---------------------------------|---------------------|
| 1             | 9-17,10-16,1-25,2-24,12-27,13-26              | 0.3635                          | 411.27             |
| 2             | 9-17,10-16,1-25,2-24,12-29,13-28              | 0.3618                          | 411.95             |
| 3             | 9-17,10-16,1-26,2-25,12-28,13-27              | 0.3727                          | 409.96             |
| 4             | 9-17,10-16,1-25,2-24,12-29,13-26              | 0.3635                          | 411.49             |
| 5             | 9-17,10-16,1-25,2-24,14-27,15-26              | 0.4330                          | 405.46             |
| 6             | 9-17,10-16,1-26,2-25,14-28,15-27              | 0.4310                          | 410.95             |
| 7             | 9-17,10-16,1-25,2-24,12-27,15-26              | 0.4166                          | 409.72             |
| 8             | 9-17,10-16,1-26,2-25,12-28,15-27              | 0.3881                          | 412.22             |
| 9             | 9-17,10-16,1-25,2-24,12-29,15-26              | 0.4166                          | 410.39             |

Each power supply unit has a large degree of bordering, and the available optimization space of the line is larger, and it is more likely to find a better solution. Among them, the scheme 5, scheme 6 and scheme 7 have the best evaluation indicators. They are selected into the last candidate set of power supply unit division schemes.

D. THE RESULTS AND ANALYSIS OF THE AUTOMATED PLANNING

For the 81 power supply unit division schemes, automatic planning is performed according to the ant colony algorithm and the branch line combination solving algorithm. Because the process of the automatic planning is the same, the result is only described by the power supply unit partition scheme corresponding to the most optimal planning scheme.

Economic calculation data: The main line model is LGJ-185, the transmission capacity is 7.8MW, the cost is 100,000 yuan/km, the resistance per unit length is 0.17Ω/km, and the line load rate is specified between 35% and 50%. The branch line model is LGJ-95, the cost is 70,000 yuan/km; the electricity price is 0.5 yuan/(kW·h); the discount rate $r_0$ is 0.08; the line depreciation year $m$ is 20 years. Reliability calculation data: the fault frequency of the circuit breaker is 0.0078 times/year, the fault repairing time is 2.62 hours; the fault frequency of the feeder section is 0.047 times/(year·km), the fault repairing time is 3.73 hours; the fault frequency of the isolation switch is 0.0119 times/year, the fault repairing time is 3.96 hours; the fault isolation time is 0.5 hours; the transfer operation time is 1 hour.

According to the Fig. 8, the horizontal comparison shows that the most optimal solution is 5.6% lower than the worst solution, indicating that reasonable power supply unit portioning can improve the economics of the planning. The most optimal power supply unit partition scheme is scheme 58. It takes the investment of the line and operating cost and power outage loss into account. Other schemes have lower investment and operating cost but higher interruption cost, such as scheme 4 and scheme 73. Some schemes have better reliability indicators and lower interruption cost, but the investment of the line and operating cost are higher, such as scheme 63 and scheme 68.

In terms of vertical comparison, the proportion of the interruption cost in each scheme is about 60%, which highlights the guiding role of reliability indicator in grid planning.

The wiring results of the main lines and the trunk lines in the most optimal power supply unit partitioning is shown in Fig.9. Due to the space limitation, the complete wiring results of internal and back-up power supply units in the optimal power supply unit partitioning scheme are shown in Fig.10.
It can be seen from the above figure that the lines do not cross each other, which is in line with the requirements of the actual distribution network planning; The objective function adds the interruption cost to the cost of the traditional line investment and the operation investment. It avoids some of the problems that the branch lines have too many loads, and the main line is too short to affect the reliability.

VI. CONCLUSION
This paper proposes a practical automatic planning for distribution network considering the complementation of load characteristic and module partitioning. The main contributions are as follows:

1) In this section, the definition of feeder block and power supply unit is improved by using the complementation of load characteristic, and the technical framework of medium voltage distribution network practical planning based on modular partitioning is constructed.

2) Propose the indicators of feeder block and power supply unit partition, and propose the method of dividing the feeder block and power supply unit.

3) The objective function is that the investment and operating cost of the line and the integration cost considering reliability is the lowest. And the individual power supply units are separately wired. The solution can balance the economics and reliability of the construction and operation of the distribution network.

4) The original distribution network planning method was usually performed for large-scale areas, and there are few planning researches about dividing large-scale complex network into small power supply units. Therefore, this paper proposed a method for planning the distribution network considering the partition of power supply unit and firstly gave the integrated distribution network planning method.

The result of the triangular single-contact power supply model study is a good proof of the scientific and practical nature of the model and method. Future work will focus on the common power supply unit partition method for interconnected multi-substation areas.

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