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The Intelligent Sizing Method for Renewable Energy Integrated Distribution Networks

Zhichun Yang [1,*], Fan Yang [1], Yu Liu [1], Huaidong Min [1], Zhiqiang Zhou [2], Bin Zhou [2], Yang Lei [1] and Wei Hu [1]

1 Electric Power Research Institute of State Grid Hubei Co., Ltd., Wuhan 430037, China; yangf81@hb.sgcc.com.cn (F.Y.); liuyu1795@gmail.com (Y.L.); minhuaidong@foxmail.com (H.M.); leiyang12@hb.sgcc.com.cn (Y.L.); huwei11@hb.sgcc.com.cn (W.H.)
2 State Grid HuBei Electric Power Co., Ltd., Wuhan 430037, China; zhouzq@hb.sgcc.com.cn (Z.Z.); zhoub@hb.sgcc.com.cn (B.Z.)
* Correspondence: yangzc@hb.sgcc.com.cn

Abstract: The selection of the optimal 35 kV network structure is crucial for modern distribution networks. To address the problem of balancing investment costs and reliability benefits, as well as to establish the target network structure, firstly, the investment cost of the distribution network is calculated based on the determined number of network structure units. Secondly, reliability benefits are measured by combining the comprehensive function of user outage losses with the System Average Interruption Duration Index (SAIDI). Then, a multi-objective planning model of the network structure is established, and the weighted coefficient transformation method is used to convert reliability benefits and investment costs into the total cost of power supply per unit load. Finally, by using the influencing factors of the network structure as the initial population and setting the minimum total cost of the unit load as the fitness function, the DE algorithm is employed to obtain the optimal grid structure under continuous load density intervals. Case studies demonstrate that different load densities correspond to different optimal network structures. For load densities ranging from 0 to 30, the selected optimal network structures from low to high are as follows: overhead single radial, overhead three-section with two ties, cable single ring network, and cable dual ring network.

Keywords: network structure; investment cost; differential evolution algorithm; network structure planning; reliability benefit

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1. Introduction

A distribution network is directly facing the users and is an important part of the power system [1,2]. The 35 kV network structure selection is important work of distribution network planning and transformation; on the one hand, it affects the investment and development of power supply enterprises, and on the other hand, it affects the level and quality of power supply to the users [3]. With the rapid development of the economy, people's living standards are improving, the demand for electricity is increasing, and the rational planning of distribution networks has been paid attention to [4]. However, at the current stage of China's distribution network, there are still problems with backward network framework and distribution network planning as well as unreasonable reliability target setting, which seriously affect the safe operation of the distribution network. The reliability index is an important criterion for the construction of distribution networks, and if the reliability of distribution networks is neglected, the reliability of normal electricity consumption will be seriously affected. Therefore, it is of great research value to construct a distribution network that considers reliability and economy. For this reason, a multi-objective planning method for distribution network framework design is proposed to determine the optimal network structure.

In order to rationally plan and formulate the 35 kV network structure of the distribution network, scholars at home and abroad have carried out various research and achieved more fruitful results and practical applications. Reference [5] combined with the operational characteristics of radial distribution networks, considering uncertainty factors, to establish the network frame interval planning model. Reference [6] establishes distribution network risk indicators and quantifies the network risk to assess the network risk level. References [7,8] consider the uncertainty of load and DG and adopt the fuzzy set method to construct a new method of grid planning. References [9–11] take the safety and adaptability of the network frame structure as the premise, propose a comprehensive assessment system for the distribution network frame structure in terms of economy and reliability, construct a theoretical analysis model, and evaluate various network frame structures. References [12,13] propose a comprehensive evaluation system for typical distribution network connection modes, focusing on aspects such as economy and reliability while meeting conditions of safety and adaptability. The studies establish a theoretical analysis model to evaluate various connection methods. References [14,15] consider the planning of distribution network connection modes under specific conditions from both technical and economic perspectives.

Considering the above problems, this paper firstly takes the typical 35 kV grid structure as the grid unit, calculates the number of grid units according to the power supply capacity of the grid unit and the load of the power supply area, combines the simultaneous coefficients, and determines the investment cost of the wiring unit; secondly, the reliability objective is transformed into reliability benefits after the reliability is translated by using the user's integrated outage loss; and then, the Pareto theory is used to establish the multi-objective function of the 35 kV wiring pattern. In order to find the optimal solution set, the Differential Evolution (DE) algorithm is employed. Key influencing factors of the grid structure, such as the number of sections, power supply radius, construction cost, and operation and maintenance costs, are used as the initial population. The investment cost and reliability of the grid structure are quantitatively calculated across the load density variation range. The total cost of power supply per unit load is used as the individual fitness function, and the Pareto optimal solution set under any load density condition is obtained. This provides a theoretical basis and investment reference for selecting the 35 kV medium-voltage wiring configuration in the distribution network. The rest of the paper is organized as follows: Section 2 presents the overall scheme design. Section 3 explains the investment cost and reliability benefits of the grid structure. Section 4 establishes a multi-objective planning model for the grid structure based on the DE algorithm. Section 5 presents an arithmetic example study. Finally, Section 6 gives the conclusion.

2. Overall Program Design

The formulation of the network structure is key to the transformation and planning of the distribution network. A reasonable formulation of the grid structure often needs to meet both economic efficiency and reliability, involving multi-objective planning. Existing theories mostly consider single factors or make comparisons under set conditions, and the algorithms have certain limitations and specificity. To reasonably select the target network structure, the overall program design is shown in Figure 1.

Firstly, based on the supply area and load density, the number of grid structure units is determined using a typical grid structure as the unit. By analyzing the influencing factors of the grid structure, an initial population is established. On one hand, the investment cost of the distribution network is calculated, and on the other hand, a reliability assessment of the grid structure is performed under the corresponding parameters. Using a comprehensive model for user outage losses, the total cost of power supply per unit load is calculated through the variable weight coefficient method. The DE algorithm is employed, with the lowest total supply cost per unit as the individual fitness criterion. By comparing the grid structures under different load density conditions, a Pareto curve of the grid structure and load density is constructed, thereby determining the optimal grid structure within the range of load density variations.

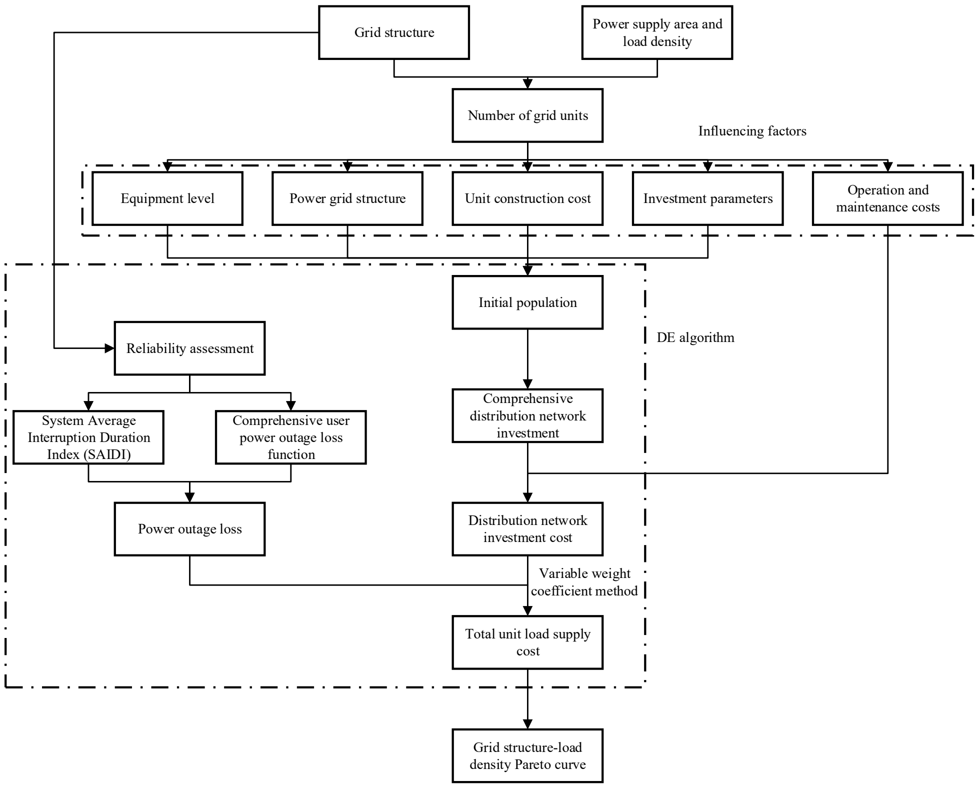

Figure 1. Overall program design.

3. Investment Costs and Reliability Benefits of Network Structures

3.1. Investment Impact Factors

There are many factors affecting the investment in the network structure, in addition to the supply area and load density, generally divided into the following categories:

(1) Equipment level categories: type of conductor, type of switch or circuit breaker, etc.;
(2) Network structure category: power supply radius, number of sections, number of contacts, etc.;
(3) Unit cost category: substation construction cost, cost per unit length of the line, cost per unit capacity, etc.;
(4) Operation and maintenance category: line loss rate, operation and maintenance costs, etc.;
(5) Investment category: examples are return on investment, payback period, etc.

Typically, factors such as equipment level, network structure, and unit cost directly affect the initial investment in the wiring configuration, while the operation and maintenance category influences the operation and maintenance costs. The return on investment and payback period impact the annual value of the investment.

3.2. Annualized Investment Cost

First, collect data on the equipment level, conductor type, and unit cost for the regional power grid structure. Then, calculate the initial investment cost for each network structure unit as Z_{unit}. Based on the annual operation and maintenance cost U_{unit} for each grid structure, the annualized investment cost for the grid structure unit can be calculated using the following formula:

$$C_{unit} = Z_{unit} \times [\frac{r_0(1+r_0)^n}{(1+r_0)^n - 1}] + U_{unit} \tag{1}$$

where r_0 is the return on investment; n is the payback period.

If the power supply area is A, the load density is ρ, and the power supply capacity of the wiring unit is S_{unit}; then, the required number of wiring units for the power supply area is calculated as

$$m = \frac{A \times \rho}{k \times S_{unit}} \tag{2}$$

where k is the simultaneous coefficient of each unit wiring; the value range is 0.8~0.95.

Therefore, the annual value of investment costs in the electricity supply area is

$$C = m(C_{unit} + U_{unit}) \tag{3}$$

3.3. Reliability Benefit Translation

Power outages directly affect the power sector's tariff revenue BE on the one hand, which is partly the direct reliability benefit; on the other hand, they result in customer outage losses due to power outages, which is partly the indirect reliability benefit, also known as customer outage losses or lack of power costs. In order to measure the customer outage losses due to the reliability of the wiring pattern, it is first necessary to establish a comprehensive customer outage loss function $f_{OC(t)}$, and then, using the power supply reliability indicator—the System Average Interruption Duration Index (SAIDI)—to determine the outage loss OC.

Therefore, the reliability benefit is

$$RB = RB_d + RB_{ind} = BE + OC \tag{4}$$

where RB_d is the direct benefit of reliability; RB_{ind} is the indirect benefit of reliability.

4. Multi-Objective Planning of Network Structure Based on DE Algorithm

4.1. Establishment of Multi-Objective Functions

The selection of 35 kV network structures is a multi-objective planning problem, which can be addressed using Pareto theory to establish objective functions. The Pareto curve provides planners with multiple optimal solutions. For the selection problem of medium-voltage wiring patterns, the Pareto optimal solution can be defined as

$$\min \boldsymbol{F} = [f_1(\boldsymbol{x}), f_2(\boldsymbol{x}), \cdots, f_n(\boldsymbol{x})]^T \tag{5}$$

$$\text{s.t}\begin{cases} h(\boldsymbol{x}) = 0 \\ g(\boldsymbol{x}) < 0 \end{cases} \tag{6}$$

In the equation, $\boldsymbol{x}$ represents the solution vector; $\boldsymbol{F}$ is the vector of objective functions. In the context of selecting medium-voltage wiring patterns, the elements of the vector typically include investment cost indicators, reliability indicators, and so on. Equation (6) represents the equality and inequality constraints, such as voltage, capacity, power, etc.

4.2. Basic Principles of the DE Algorithm

Multi-objective planning problems are often solved using algorithms such as genetic algorithms and particle swarm optimization [16,17]. However, due to the many factors affecting network structures and the high dimensionality, these algorithms tend to converge slowly or may even struggle to converge. In contrast, the DE algorithm converges quickly and with high precision. Additionally, the DE algorithm has fewer parameters to set, which minimally impacts the results. Therefore, the DE algorithm is more suitable. The algorithm steps are as follows [18,19]:

(1) Initialization of Population: Establish an initial population of size N_{p}, iterating for $G-1$ times. The individual i in the G-th generation is represented as $X_{i,G} (i = 1, 2, \cdots, N_{\text{p}})$, and the population is $\mathbf{X}_{i,G} = [x_{1.i.G}, x_{2.i.G}, \cdots, x_{n.i.G}]$. The initial population is generated randomly and can be represented as

$$X_{j.i.0} = l_j + \text{rand}(0,1)(u_j - l_j), j \in [1, n], i \in [1, N_\text{p}] \quad (7)$$

In the equation, rand(0, 1) represents a random number between 0 and 1; n is the number of variables; and u_j and l_j are the upper and lower bounds of the variables, respectively.

(2) Mutation Operation: Perform mutation by randomly selecting three different target individuals.

$$V_{i,G+1} = X_{r1.G} + F * (X_{r2.G} + X_{r3.G}),\ r_1 \neq r_2 \neq r_3 \neq i \quad (8)$$

In the equation, r_1, r_2, and r_3 are three randomly generated distinct integers, with values not exceeding N_p. F is the scaling factor, and $0 \leq F \leq 1$.

(3) Crossover Operation: A trial vector $\boldsymbol{U}_{i,G+1} = (u_{1.i.G+1}, u_{2.i.G+1}, \cdots, u_{n.i.G+1})$ is generated through crossover. To ensure the evolution of $\boldsymbol{X}_{i,G}$, at least one element of the individual target contributes to $\boldsymbol{U}_{i,G+1}$ through random selection, while the other elements undergo crossover according to Equation (9).

$$u_{j.i.G+1} = \begin{cases} v_{j.i.G+1},\ \text{rand}(j) \leq CR\ orj \neq rnb(i) \\ x_{j.i.G},\ \text{rand}(j) > CR\ orj \neq rnb(i) \end{cases} \quad (9)$$

In the equation, rand(j) is a uniformly distributed random number; rnb(i) is a random integer not greater than n; and CR is the crossover probability, with a range of [0, 1].

(4) Selection Operation

$$X_{.i.G+1} = \begin{cases} U_{i.G+1}, f(U_{i.G+1}) \leq X_{i.G} \\ X_{i.G}, f(U_{i.G+1}) > X_{i.G} \end{cases} \quad (10)$$

If the fitness function value of the trial individual meets the criteria, it replaces the current individual and becomes the new one; otherwise, the current individual is retained for the next generation.

4.3. Individual Fitness Function

To evaluate the Pareto optimal solution, the individual fitness function can be established using the weighted coefficient transformation method. If the objectives for wiring configuration in terms of economic efficiency and reliability are C_1 and C_2, with corresponding weight coefficients ω_1 and ω_2, then the linear weighting of the individual fitness function is

$$F = \omega_1 C_1 + \omega_2 C_2 \quad (11)$$

Typically, the weight coefficient ω_1 for the reliability objective depends on the power load within the supply area, while ω_2 depends not only on the power load but also on the comprehensive outage losses of the users, i.e., the shortage cost. The weight coefficients can be set as

$$\begin{cases} \omega_1 = 1/(A \times \rho) \\ \omega_1 = K/(A \times \rho) \end{cases} \quad (12)$$

Thus, the formula is transformed into

$$F = \frac{C_1 + E + OC}{A \times \rho} = TC \quad (13)$$

In the equation, TC represents the total cost of power supply per unit load, which is numerically equal to the ratio of the total power supply cost of the medium-voltage wiring configuration to the load it supplies.

Therefore, the individual fitness function of the DE algorithm is transformed as follows: under different load density conditions, the total cost of power supply per unit load for the 35 kV network structure is minimized.

4.4. Methodology Section

To solve for the Pareto optimal solution set, first, set the initial value of load density ρ_0. Based on the area of the power supply region, calculate the power load and determine the number of grid structure units based on the analysis of maximum power supply capacity. Then, select a specific grid structure and use the DE algorithm for optimization. The process is illustrated in Figure 2.

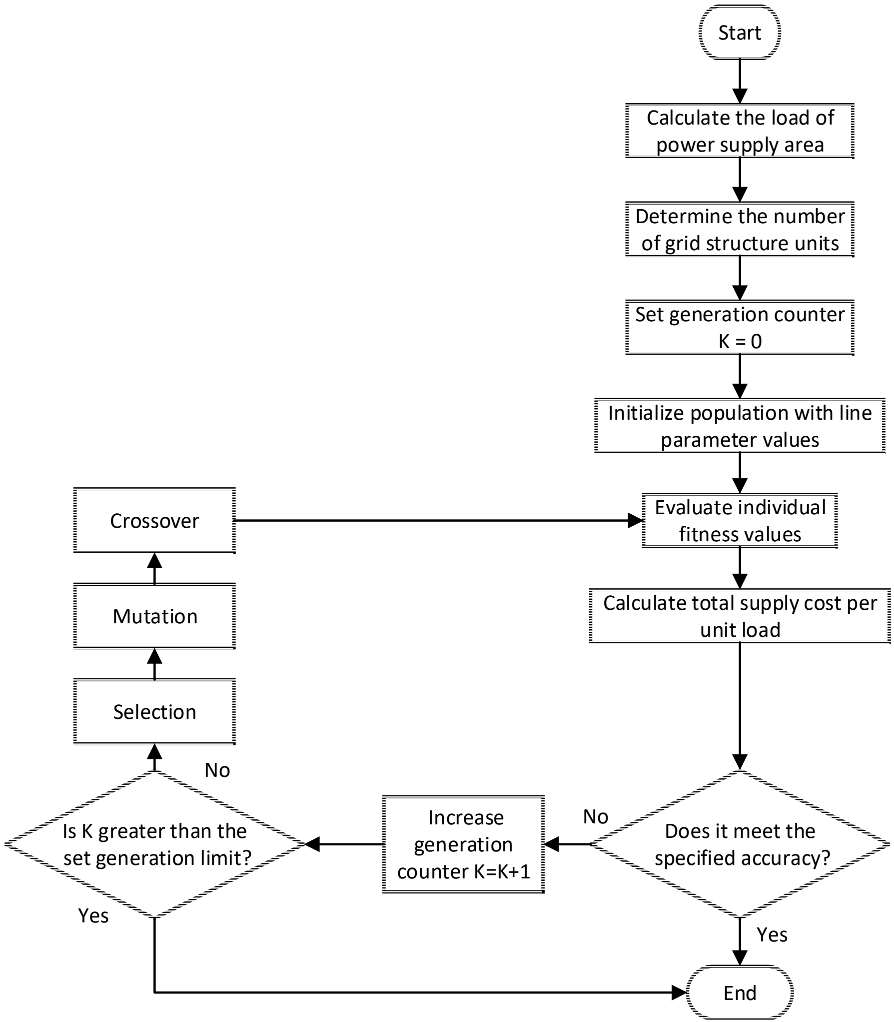

Figure 2. Flowchart for solving multi-objective planning of grid structure based on DE evolutionary algorithm.

The steps of multi-objective planning for grid structure based on the DE evolutionary algorithm are as follows:

Step 1: Calculate the load of the power supply area. This step involves determining the total load requirement of the area that needs to be served by the grid structure.

Step 2: Determine the number of grid structure units. Based on the load calculation and area size, identify how many grid units are necessary to ensure adequate coverage and service.

Step 3: Set the generation counter K = 0. Initialize the algorithm by setting the iteration counter to zero.

Step 4: Initialize the population with line parameter values. Randomly generate initial candidate solutions (population) based on the grid structure's line parameters.

Step 5: Evaluate individual fitness values. Assess each candidate solution's effectiveness by calculating the fitness values, where lower costs lead to better fitness scores.

Step 6: Calculate the total cost of power supply per unit load. For each solution, compute the total cost of power supply per unit load.

Step 7: Check if the solution meets the specified accuracy. Verify whether the obtained solution has reached the desired level of precision or fitness. If yes, the algorithm ends. If no, continue to the next step by increasing the generation counter.

Step 8: Check if the generation counter K is greater than the preset generation limit. Determine whether the current generation count exceeds the predefined limit for the number of iterations. If yes, the algorithm ends. If no, proceed to the selection, mutation, and crossover, and return to step 5.

Establish the initial population based on factors such as the number of segments, power supply radius, and unit construction cost. Use the total cost of power supply per unit load as the fitness function to calculate the fitness of each individual in the population across generations. Perform mutation and crossover operations to generate a new population. By comparing the total cost of power supply per unit load for various wiring configurations, the Pareto optimal solutions under the load density ρ_0 can be obtained.

Set the load density step size as $\Delta\rho$. Select a new load density and, following the previously described steps, use the DE algorithm to analyze the total cost of power supply per unit load for various wiring configurations. Through iterative comparison, find the wiring configuration with the lowest total cost of power supply per unit load. Continue increasing the load density step size until reaching the maximum load density, obtaining the Pareto optimal solution set under each load density condition. This will determine the Pareto optimal solution set for different wiring configurations within the load density variation range.

5. Example Calculation

5.1. Case 1

The model is applied to a city in eastern China to facilitate the rational selection of the 35 kV distribution network structure in that city. The central urban area of the city covers a power supply area of 2397 km^2, with an average load density of 1.59 MW/km^2 in 2024. The connection modes of overhead systems include single radial, overhead single tie, multiple sections with multiple ties, and multiple sections with complex ties. The connection modes of cable systems include a cable single radial and single ring network. The basic parameters of the power grid are shown in Table 1 [20]. Table 1 is a table of basic grid parameters for the city, including parameters such as the fault rate of 35 kV overhead lines/cable lines, fault rate of 35 kV circuit breakers/switches, fault rate of busbars, recovery time for a 35 kV line/switch faults, investment return rate/period, grid loss rate, annual maintenance cost proportion, and unit price of a 35 kV circuit breaker/integrated automation switchgear, along with their corresponding values. These parameters reflect the operational characteristics of the power grid, equipment reliability, and economic-related indicators from different aspects.

Table 1. Case 1 basic parameters of the power grid.

Basic Parameters of the Power Grid	Values
Fault rate of 35 kV overhead lines/cable lines (times/100 km·year)	7.31/0.151
Fault rate of 35 kV circuit breakers/switches (times/unit·year)	0.05/2.03
Fault rate of busbars (times/unit·year)	0.012
Recovery time for 35 kV line/switch faults (h)	5.61/2.98
Investment return rate/period (%)	12/18
Grid loss rate (%)	6.7
Annual maintenance cost proportion (%)	12%
Unit price of 35 kV circuit breaker/integrated automation switchgear (CNY 10,000)	10/240

The values in Table 1 have the following meanings. The fault rate of 35 kV overhead lines/cable lines refers to the number of times that 35 kV overhead lines and cable lines fail and are out of service per 100 km per year, with 7.31 times per 100 km per year for overhead lines and 0.151 times per 100 km per year for cable lines. The fault rate of 35 kV circuit breakers/switches indicates the number of times that 35 kV circuit breakers and switches fail and are out of service per unit per year, with 0.05 times per unit per year for circuit breakers and 2.03 times per unit per year for switches. The fault rate of busbars represents the number of times that the busbar fails and is out of service per unit per year, which is 0.012 times per unit per year. The recovery time for the 35 kV line/switch faults refers to the time required to repair 35 kV lines and switches after a failure, with 5.61 h for lines and 2.98 h for switches. The investment return rate/period shows an investment return rate of 12% and an investment return period of 18 years. The grid loss rate is the percentage of electrical energy loss in the power grid operation process to the total electrical energy, which is 6.7%. The annual maintenance cost proportion is the percentage of annual maintenance costs to the total investment or total cost, which is 12%. The 35 kV circuit breaker/integrated automation switchgear unit price indicates that the unit price of 35 kV circuit breakers is CNY 100,000 per unit and the unit price of the integrated automation switchgear is CNY 2,400,000 per unit.

Let the comprehensive outage loss model for users in the city be as follows [21]:

$$y = -59.5x^2 + 759.6x - 156.9 \tag{14}$$

where y represents the total outage loss (in CNY), and x denotes the duration of the power outage (in hours). This model was developed through a regression analysis based on empirical data collected from past outages in the region.

5.2. Case 2

The method is applied to a city in central China to optimize the structure of the 35 kV distribution network. In 2023, the load density in the central urban area of this city was 0.52 MW/km^2. The available 35 kV wiring configurations included the following: overhead single radial, overhead single tie, multiple sections with multiple ties, cable single radial, and single ring network. The basic parameters of the distribution network are shown in Table 2.

Table 2. Case 2 basic parameters of the power grid.

Basic Parameters of the Power Grid	Values
Fault rate of 35 kV overhead lines/cable lines (times/100 km·year)	7.85/0.128
Fault rate of 35 kV circuit breakers/switches (times/unit·year)	0.1/2.24
Fault rate of busbars (times/unit·year)	0.02
Recovery time for 35 kV line/switch faults (h)	6.35/3.02
Investment return rate/period (%)	12/19
Grid loss rate (%)	6.1
Annual maintenance cost proportion (%)	11%
Unit price of 35 kV circuit breaker/integrated automation switchgear (CNY 10,000)	6/260

Through investigation, the comprehensive outage loss model for users in this city is

$$y = \begin{cases} -0.0263x^2 + 10.991x + 497.27 & x \le 120 \text{ min} \\ -0.0003t^2 + 0.61t + 1367.1 & x > 120 \text{ min} \end{cases} \tag{15}$$

5.3. Existing Grid Structure Planning Methods

According to the Technical Guidelines for Distribution Network Planning and Design, while it is possible to determine the network structure for a certain load density, such as selecting an overhead multi-section structure with moderate interconnection or a single ring network for Class C supply areas, it is difficult to quantitatively compare the advantages and disadvantages of these two connection schemes. Using existing theories, several load density conditions are typically selected, and after assuming parameters such as the number of sections, interconnections, and supply radius, the total unit power supply cost for different connection schemes is compared, as shown in Figure 3. However, due to the dynamic nature of load density, if the load density takes a value within a certain range, such as 8 MW/km^2, recalculations are required; otherwise, it is impossible to compare the two connection schemes. Moreover, due to the many influencing factors, each grid structure can have several configurations, such as the number of sections, conductor cross-section, etc., making the selection of grid structures both unique and limited in scope.

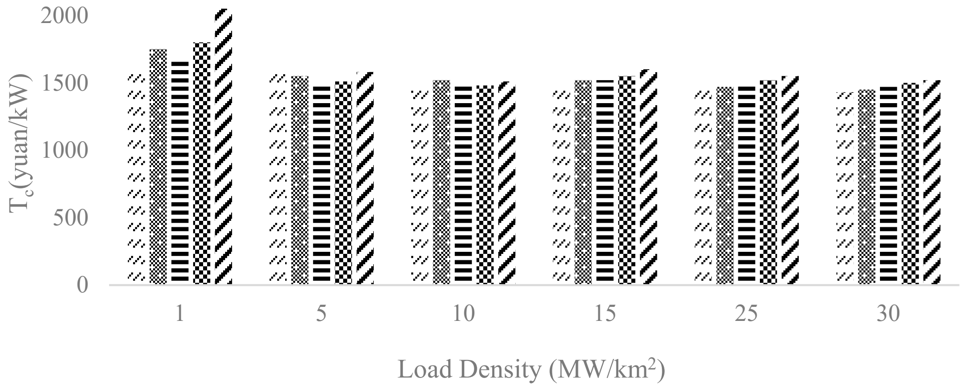

Figure 3. The comparison of the network structure under the condition of fixed load density.

5.4. DE Algorithm Solution

Based on the actual grid conditions in case 1, the initial load density is set to 0.1 MW/km^2, with a step size of 0.1 MW/km^2 and an upper limit of 30 MW/km^2. The number of sections, supply radius, number of interconnections, conductor cross-section, and operation and maintenance costs are set as control variables to establish the initial population. The maximum number of generations is set to 100, and the process is terminated if the optimal solution set remains unchanged for three consecutive iterations. The scaling factor is set to 0.5, and the crossover probability is set to 0.1. The network structure modes are an overhead single radial, a single tie, multiple sections with multiple ties, a cable single radial, and a single ring network. Through calculation, the SAIDI–load density curve for the distribution network structures in case 1 is shown in Figure 4.

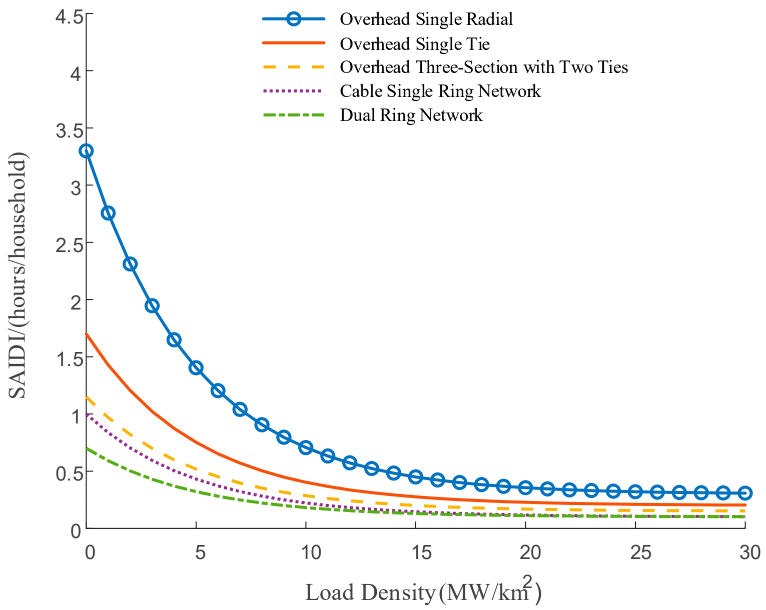

Figure 4. The curve of SAIDI versus load density for case 1.

Similarly, based on the actual conditions of the power grid in case 2, the initial load density is set to 0.5 MW/km^2, with a step size of 1 MW/km^2 and an upper load density limit of 30 MW/km^2. The network structure modes are an overhead single radial, a single tie, multiple sections with multiple ties, a cable single radial, and a single ring network. The number of segments, supply radius, and average number of users per segment per line are set as control variables. An initial population of 30 is chosen, with the number of iterations not exceeding 100. The process is terminated if the optimal solution set remains unchanged for three consecutive iterations. The crossover and mutation probabilities are set to 0.5 and 0.01, respectively. Through calculation, the SAIDI–load density curve for the distribution network structures in case 2 is shown in Figure 5.

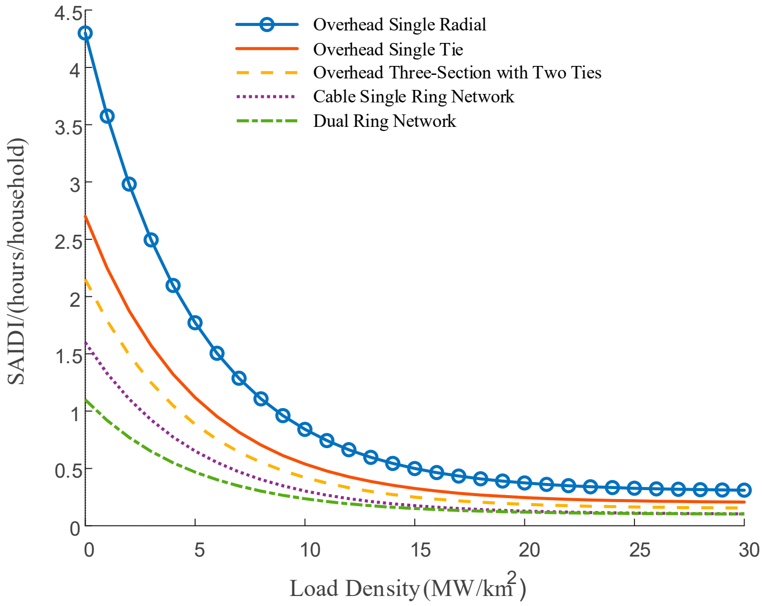

Figure 5. The curve of SAIDI versus load density for case 2.

Based on the SAIDI and user comprehensive power outage loss model function, the Pareto solution set for the network structure patterns is determined, and the Pareto optimal curves for case 1 and case 2 are plotted, as shown in Figures 6 and 7, respectively.

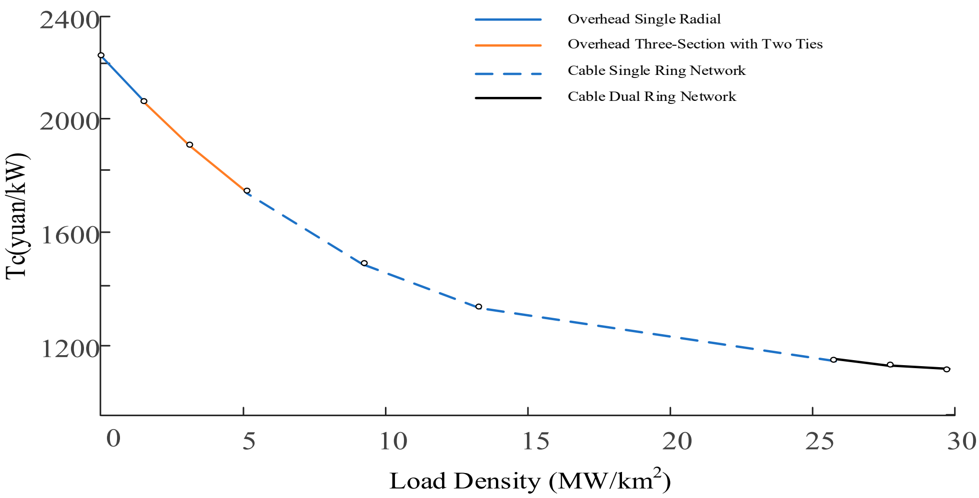

Figure 6. The optimal network structure curve under the condition of the continuous load density interval for case 1.

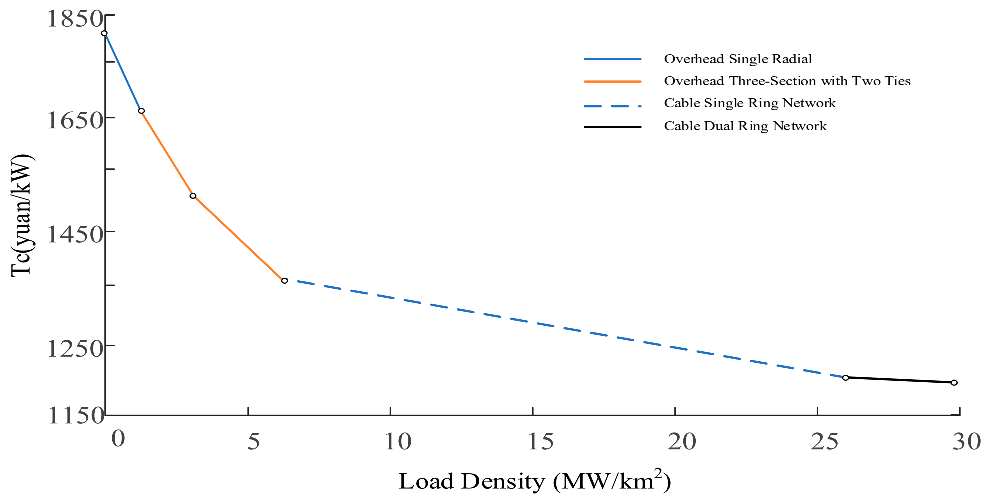

Figure 7. The optimal network structure curve under the condition of the continuous load density interval for case 2.

As shown in Figure 6, the load density-optimal network structure curve is not a smooth curve, due to the reflection of various grid configurations' investment costs and reliability benefits. Additionally, as the unit power supply cost of the network structure varies with load density, the optimal grid structure and its key indicators also change accordingly. When the load density is below 1.7, the optimal grid structure is an overhead single radial configuration. When the load density is between 1.7 and 4.9, the optimal grid structure shifts to the configuration of an overhead three-section with two ties. When the load density ranges from 4.9 to 26.8, the optimal structure becomes a cable single ring network, and for load densities between 26.8 and 30, the optimal structure is a cable dual ring network.

The data presented in Figure 7 show that the total cost of power supply per unit load of the network structure varies depending on different load densities. Therefore, the optimal network structure and its key indicators should be adjusted accordingly. When the load density is below 2.3, the optimal grid structure is an overhead single radial configuration. When the load density is between 2.3 and 7, the optimal grid structure shifts to the configuration of an overhead three-section with two ties. When the load density ranges from 7 to 26, the optimal structure becomes a cable single ring network, and for load densities between 26 and 30, the optimal structure is a cable dual ring network. The optimal network structures and their main performance indicators for each load density interval in case 2 are presented in Table 3.

Table 3. Main performance indicators of the optimal network structures for case 2.

Load Density /(MW/km^2)	**≤2.3**	**2.3~7**	**7~26**	**26~30**
Optimal network structure	overhead single radial	overhead three-section with two ties	cable single ring network	cable dual ring network
Supply radius/km	10	5	4	3

Therefore, within the range of load density variations, by employing the DE algorithm and comparing the total cost of power supply per unit load of different connection schemes, while comprehensively considering the factors affecting both reliability and economic efficiency, the optimal solution set for multi-objective planning across any load density interval can be obtained. This effectively overcomes the limitations and specificity of the connection scheme comparison method under specified load density conditions and also addresses the challenges posed by high-dimensionality and convergence difficulties due to the numerous influencing factors.

6. Conclusions

The selection of the target network structure for a 35 kV distribution network is influenced by multiple factors, making it a multi-objective planning problem. To comprehensively consider both the reliability and economic efficiency of the network structure, this paper establishes an objective function based on Pareto theory and uses the variable weighting coefficient method to convert the reliability and economic objectives into the total unit power supply cost. To mitigate the issues of high dimensionality and slow convergence caused by multiple influencing factors, the DE algorithm is employed. An initial population is generated based on the influencing factors, and the lowest total unit power supply cost is set as the fitness objective. Through mutation, crossover, and selection, a continuous optimal network structure curve within the load density range is eventually drawn, providing theoretical support and reference for the rational selection of the 35 kV distribution network grid structure.

The results of this study demonstrated the efficiency of the DE algorithm in converging quickly and achieving high precision, even when faced with multiple influencing factors such as the number of sections, power supply radius, and operation costs. The graphical results and logical analysis, as presented in Figure 7 and Table 3, illustrate that the optimal network structure evolves with changing load density, providing valuable insights for practical grid planning. When the load density is below 2.3, the optimal grid structure is an overhead single radial configuration. When the load density is between 2.3 and 7, the optimal grid structure shifts to the configuration of an overhead three-section with two ties. When the load density ranges from 7 to 26, the optimal structure becomes a cable single ring network, and for load densities between 26 and 30, the optimal structure is a cable dual ring network. Case studies demonstrate that different load densities correspond to different optimal network structures. For load densities ranging from 0 to 30, the selected optimal network structures from low to high are as follows: overhead single radial, overhead three-section with two ties, cable single ring network, and cable dual ring network.

Moreover, this approach offers a significant improvement over traditional methods by allowing for continuous adjustment of load density, thereby offering more flexibility and accuracy in grid structure selection. The case study results confirm the effectiveness of the method in reducing the total cost of power supply while ensuring a high level of reliability, which is critical for establishing the target network structure.

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References

1. Huang, N.; Zhao, X.; Guo, Y.; Cai, G.; Wang, R. Distribution Network Expansion Planning Considering a Distributed Hydrogen-Thermal Storage System Based on Photovoltaic Development of the Whole County of China. *Energy* **2023**, *278*, 127761. [CrossRef]
2. Xiang, Y.; Yao, H.; Yang, J.; Dai, J.; Liu, J. Optimal Planning of Distribution Network with Transactive Energy: Review and Framework. *IET Smart Grid* **2024**, *7*, 120–129. [CrossRef]
3. Xiang, Y.; Liu, J.; Li, F.; Liu, Y.; Liu, Y.; Xu, R.; Su, Y.; Ding, L. Optimal Active Distribution Network Planning: A Review. *Electr. Power Compon. Syst.* **2016**, *44*, 1075–1094. [CrossRef]
4. Ehsan, A.; Yang, Q. State-of-the-Art Techniques for Modelling of Uncertainties in Active Distribution Network Planning: A Review. *Appl. Energy* **2019**, *239*, 1509–1523. [CrossRef]

5. Zdraveski, V.; Vuletic, J.; Angelov, J.; Todorovski, M. Radial Distribution Network Planning under Uncertainty by Implementing Robust Optimization. *Int. J. Electr. Power Energy Syst.* **2023**, *149*, 109043. [CrossRef]
6. Zhou, J.; Jin, X.; Ye, X.; Ning, X.; Zhu, J. Research on Data Classification and Risk Level Perception of Weak Distribution Network. In Proceedings of the 2023 8th Asia Conference on Power and Electrical Engineering (ACPEE), Taijin, China, 14–16 April 2023; pp. 1803–1807.
7. Zubo, R.H.A.; Mokryani, G.; Rajamani, H.-S.; Aghaei, J.; Niknam, T.; Pillai, P. Operation and Planning of Distribution Networks with Integration of Renewable Distributed Generators Considering Uncertainties: A Review. *Renew. Sustain. Energy Rev.* **2017**, *72*, 1177–1198. [CrossRef]
8. Martins, V.F.; Borges, C.L.T. Active Distribution Network Integrated Planning Incorporating Distributed Generation and Load Response Uncertainties. *IEEE Trans. Power Syst.* **2011**, *26*, 2164–2172. [CrossRef]
9. Yuanhong, L.; Tao, W.; Wei, L.; Wei, Z.; Yuanpeng, T.; Quanzhi, C.; Bo, Y.; Xueqian, Z. Big Data Based Analysis Between Power Distribution Network Reliability Parameters and Economic and Social External Environment. In Proceedings of the 2021 IEEE International Conference on Power Electronics, Computer Applications (ICPECA), Shenyang, China, 22–24 January 2021; pp. 528–531.
10. Du, W.; Lu, M.; Li, D. Distribution Network Planning with Comprehensive Economy and Reliability. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *486*, 012016. [CrossRef]
11. Xie, L.; Xiang, Y.; Xu, X.; Wang, S.; Li, Q.; Liu, F.; Liu, J. Optimal Planning of Energy Storage in Distribution Feeders Considering Economy and Reliability. *Energy Technol.* **2024**, *12*, 2400200. [CrossRef]
12. Xie, C.-F.; Xu, L.; Xu, L.-X. The Reliability and Economic Analysis on System Connection Mode. In Proceedings of The 3rd Multidisciplinary International Social Networks Conference on SocialInformatics 2016, Data Science 2016, Union, NJ, USA, 15–17 August 2016; Association for Computing Machinery: New York, NY, USA, 2016; pp. 1–5.
13. Zhang, P.; Li, W. Boundary Analysis of Distribution Reliability and Economic Assessment. *IEEE Trans. Power Syst.* **2010**, *25*, 714–721. [CrossRef]
14. Ghadi, M.J.; Ghavidel, S.; Rajabi, A.; Azizivahed, A.; Li, L.; Zhang, J. A Review on Economic and Technical Operation of Active Distribution Systems. *Renew. Sustain. Energy Rev.* **2019**, *104*, 38–53. [CrossRef]
15. Ahmadi, M.; Lotfy, M.E.; Howlader, A.M.; Yona, A.; Senjyu, T. Centralised Multi-Objective Integration of Wind Farm and Battery Energy Storage System in Real-Distribution Network Considering Environmental, Technical and Economic Perspective. *IET Gener. Transm. Distrib.* **2019**, *13*, 5207–5217. [CrossRef]
16. Ma, X.; Liu, R.-L. Reactive Power Optimization in Power System Based on Improved Niche Genetic Algorithm. In Proceedings of the 2010 International Conference On Computer Design and Applications, Qinhuangdao, China, 25–27 June 2010; Volume 3, pp. V3-413–V3-416.
17. Mourtzis, D.; Angelopoulos, J. Reactive Power Optimization Based on the Application of an Improved Particle Swarm Optimization Algorithm. *Machines* **2023**, *11*, 724. [CrossRef]
18. Van Sickel, J.H.; Lee, K.Y.; Heo, J.S. Differential Evolution and Its Applications to Power Plant Control. In Proceedings of the 2007 International Conference on Intelligent Systems Applications to Power Systems, Kaohsiung, Taiwan, 5–8 November 2007.
19. Mayer, D.G.; Kinghorn, B.P.; Archer, A.A. Differential Evolution—An Easy and Efficient Evolutionary Algorithm for Model Optimisation. *Agric. Syst.* **2005**, *83*, 315–328. [CrossRef]
20. Hu, J.; Sun, G.; Guo, M. Research on Target Planning Method of Urban Distribution Network Considering Investment Benefit and Reliability. In Proceedings of the 2022 4th International Academic Exchange Conference on Science and Technology Innovation (IAECST), Guangzhou, China, 9–11 December 2022; pp. 361–364.
21. Ilie, I.-S.; Hernando-Gil, I.; Djokic, S.Z. Theoretical Interruption Model for Reliability Assessment of Power Supply Systems. *IET Gener. Transm. Distrib.* **2014**, *8*, 670–681. [CrossRef]