Distribution Network Planning with Comprehensive Economy and Reliability

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Abstract: From the perspective of reliability and economy of distribution network, this paper combines the layout of network frame and the configuration of section switch and contact line, and obtains many plannings that coordinate economy and reliability. Firstly, considering the grid planning, a multi-objective optimization planning model of the distribution network frame with the lowest investment and operating costs and the best reliability index is established. When solving the model, the minimum spanning tree algorithm is used to avoid the generation of infeasible solutions and reduce the computational burden. This paper improves the minimum spanning tree algorithm, when algorithm iteratively generates a new solution, the sum of the reduction rate of economic index and the growth rate of reliability index is used to be the objective function in the iterative process, so that the multi-objective problem is transformed into a single objective problem. The preference factor of the decision-maker is given by weight assignment. And the algorithm is extended to multi-power planning. Secondly, considering the configuration of section switch and contact line, the nonlinear mixed integer programming model corresponding to the system is established, and the Pareto optimal solution set is generated by the NSGA-II algorithm. Then, the Pareto optimal solution set is converted into a series of corresponding planning schemes that the designer can select. Finally, the validity and correctness of the proposed method are verified by the analysis of single-source and multi-source distribution network examples.

1. Introduction
The statistical results of power system faults show that power distribution system faults account for the majority. The reason is that in the past, there was a significant phenomenon of "heavy power generation, light power supply and no power use" in China, resulting in a relatively backward distribution network, the vast majority of which is a single radiation network and basically no section switch. Therefore, the reliability is poor and power failure accidents occur frequently every year, resulting in huge economic losses. How to build economical and reliable distribution network has become a hot topic of current research [1].

In fact, the structure of the distribution network and the number and location of section switches and contact lines have a significant impact on the power supply reliability of the distribution network. Therefore, when considering such a multi-objective, nonlinear and high-latitude complex combinatorial optimization problem as distribution network planning including reliability and economy, it is necessary to take into account both network frame planning and the number and location of section switches and contact lines of distribution network.
Most scholars adopt heuristic algorithm to solve distribution network frame planning, such as genetic algorithm, particle swarm optimization [2], minimum spanning tree algorithm [3], etc., but most of them solve single-objective optimization problems from the perspective of economy, without considering the reliability of the grid. Or simply taking the loss of power shortage into account the economy, there is still a big gap between the solution obtained and the global optimal solution.

For the configuration of section switches and contact lines, reference [4] takes the sum of outage loss and construction cost as the objective function and uses dynamic programming method to solve the problem. The multi-objective optimization problem is transformed into a single-objective optimization problem, which is also the choice of most papers, so it is impossible to obtain a number of Pareto frontier solutions for designers to choose. Reference [5] uses a variety of heuristic algorithms to get results. Reference [6] takes into account the impact of distributed generation. But these references do not consider reliability.

Based on the above analysis, in this paper, when solving the planning problem that takes economy and reliability of distribution network into consideration, the network frame planning of distribution network and the number and location of section switches and contact lines are considered together. Two corresponding multi-objective models are established and Improved minimum spanning tree algorithm and NSGA - II algorithm are used to solve these models, so as to obtain several schemes of economy and reliability in different states for designers to choose together.

2. Improved minimum spanning tree algorithm

2.1 Network frame planning model for multi-objective distribution network

In this paper, a multi-objective optimization planning model for distribution network grid is established, which is based on the minimum investment and operating cost of distribution network and the best reliability index.

\[
\begin{align*}
\min & \quad f_1 = W_1(k) = W_{C1}(k) + W_{C2}(k) \\
\max & \quad f_2 = ASAI \\
\text{s.t.} & \quad P_i < P_{\max} \\
& \quad U_{\min} < U_i < U_{\max}
\end{align*}
\]

Where, \(W_{C1}(k)\) represents the construction investment cost of the iteration \(k\), \(W_{C2}(k)\) represents the operation investment cost of the iteration \(k\), \(P_i\) represents the active power on the line, \(P_{\max}\) represents the maximum allowable power on the line, \(U_i\) represents the node voltage, and \(U_{\min}, U_{\max}\) represents the upper and lower limits of node voltage.

The way to calculate \(f_2\) is in the previous section. The ASAI is used for the corresponding reliability index of \(f_2\). And the minimum path method is used for calculating \(f_2\), which can be found in references [7-8].

2.2 Multi-objective improved minimum spanning tree algorithm for distribution network planning

The minimum spanning tree algorithm is a connected tree with the smallest weight when the weights of each edge are known. It has been applied in distribution network planning, and can be seen in reference [3]. However, the traditional minimum spanning tree algorithm can only solve the economic single-objective model.

To solve the multi-objective optimization model, it is necessary to improve the spanning tree algorithm. In this paper, the solution of the update condition was improved. The paper calculates the economic index of decrement rate and reliability index of the increase, respectively multiply by the corresponding weights, and then sum is used for improved minimum spanning tree algorithm update condition of iteration solution. This method can be convenient to multi-objective problem is transformed into single objective problem.
Set $f_1$ as the value of the total cost of distribution network investment and operation after the end of the last iteration, Set $g_1$ as the value of the reliability index of the grid frame after the end of the last iteration process, set $f_2$ as the value of the total investment and operation cost of distribution network after the end of this iteration process, Set $g_2$ as the value of the reliability index of the grid frame after the end of the last iteration process.

Under the condition that only economy is considered, the conditional criterion in the iterative process is:

$$f_1 - f_2 > 0$$

(2)

When considering the economy and reliability of distribution network comprehensively, the above criterion is changed to:

$$-\alpha_1 \frac{f_1 - f_2}{f_1} + \alpha_2 \frac{g_1 - g_2}{g_1} < 0$$

(3)

Where, $\alpha_1$ is the weight of economic index, $\alpha_2$ is the weight of reliability index, $\frac{f_1 - f_2}{f_1}$ is the growth proportion of economic index, and $\frac{g_1 - g_2}{g_1}$ is the growth proportion of reliability index.

$$-\alpha_1 \frac{f_1 - f_2}{f_1} + \alpha_2 \frac{g_1 - g_2}{g_1}$$

represents the change trend of and the overall, if the sum of proportion is less than 0, it may be the following three cases:

1) If the economy $f_1$ decreases and the reliability $g_1$ increases, this is the optimal situation.

2) If the economy $f_1$ increases, the reliability $g_1$ increases, but the increasing proportion is not as good as the increasing proportion.

3) If the economy $f_1$ decreases, the reliability $g_1$ decreases, but the decreasing proportion is not as good as the decreasing proportion.

At this time, the sum of the system is superior to the results of the previous iteration in general, and achieve the optimization purpose of making the economy as small as possible and the reliability as large as possible is achieved.

2.3 Application of improved minimum spanning tree algorithm in multi-power network planning

In view of the multi-power distribution network frame planning, the improved algorithm cannot be directly applied. Multi-power grid frame planning can be regarded as the optimization planning of multi-group single-power radial grid frame. To achieve the above state, the planning area of multi-power grid frame planning should be partitioned.

In this paper, because the path constraint in the planning should be taken into account in the load partition, the Dijkstra's Algorithm was first adopted to determine the shortest distance between different load points and put it into the weight matrix to prepare for the load partition.

Then, the k-means clustering algorithm is adopted to set the clustering center according to the number of substation nodes. At the same time, each substation node is designated as the clustering center point. Then, the weight matrix is input into the k-means clustering algorithm to obtain the partitioning results of each region. Then the districts are planned separately.

3. Multi-objective distribution network planning model of section switch and contact line

3.1 Mathematical model

In the configuration of section switch and contact line of distribution network, both economy and reliability should be considered, so it is also a multi-objective optimization problem. The corresponding mathematical model in this paper is shown as follows.
\[ \begin{align*}
\min \ f_1(X_1, X_2) & = g_1 + g_2 + g_3 \\
\max \ f_2(X_1, X_2) & = \text{ASAI} - \text{ASAI}_{\text{penalty}} \\
\text{s.t.} \sum(X_i) & \leq n_i \\
\sum(X_2) & \leq n_2 \\
X_i & = [x_1, x_2, \ldots, x_i] \\
X_2 & = [x_{i+1}, \ldots, x_N] \\
x_i & = 0 \text{ or } 1 \quad i = 1, 2, \ldots, N 
\end{align*} \] (4)

Where, \( f_1 \) is the configuration cost of the section switch. \( f_2 \) is the corresponding distribution network reliability at this time. \( \text{ASAI} \) represents the reliability of distribution network. \( \text{ASAI}_{\text{penalty}} \) represents the penalty item after violating the limit of the number of segment contacts.

\( n \) is the number of lines included in the network frame already planned in one stage, and \( N \) represents the number of potential lines subject to GIS constraints. \( n_i \) represents the upper limit of the number of sectional switches specified by the planner, and \( n_2 \) represents the upper limit of the number of contact lines specified by the planner.

The binary variable \( X_1 \) represents whether the section switch is installed on the corresponding planning line, and the binary variable \( X_2 \) represents whether the contact line is planned.

Inequality constraint \( \sum(X_i) \leq n_i \) represents that the section switch of the program cannot exceed upper bound \( n_i \), and inequality constraint \( \sum(X_2) \leq n_2 \) represents that the number of contact lines of the program cannot exceed upper bound \( n_2 \).

3.2 Objective Function

\[ \begin{align*}
g_1 & = \sum_{j=1}^{n} x_j \times \text{price}_\text{fendaran,j} \\
g_2 & = \sum_{j=n+1}^{N} \delta_j \times \text{price}_\text{lianluoxian,j} \\
g_3 & = [n_i - \sum(X_i)] \times \text{penalty}_\text{fendaran} \\
& + [n_2 - \sum(X_2)] \times \text{penalty}_\text{lianluoxian}
\end{align*} \] (5)

Where, \( \text{price}_\text{fendaran,j} \) represents the construction cost of section switches on the line \( i \), \( \text{price}_\text{lianluoxian,j} \) represents the unit cost of the contact line in line \( i \), \( \text{penalty}_\text{fendaran} \) and \( \text{penalty}_\text{lianluoxian} \) represent the penalty item when the construction quantity exceeds the constraint, and \( \delta_j \) represents the length of the line in section \( i \).

3.3 Based on the NSGA-II algorithm of network section switches and contact lines planning

The core of multi-objective genetic algorithm is to coordinate the relationship between various objective functions and find out the optimal solution set which can make each objective function as large as possible (or as small as possible). The NSGA algorithm born on the basis of the fitness sharing technology proposed by Goldberg is to classify individuals in the population based on the principle of non-dominant sequencing, so as to obtain the Pareto optimal solution or non-inferior solution with uniform distribution. However, this algorithm has many disadvantages, such as high computational complexity and artificial parameter sharing. On the basis of the extension of the NSGA algorithm, there is NSGA-II algorithm, which to overcome the above shortcomings. By the choice using crowded distance instead of fitness, and introducing the elite retention mechanism, NSGA-II algorithm reduces the computational complexity. The algorithm flow are as follows:

1) Line coding. Count the number of lines that have been built and may be tie lines \( n \) and \( N \), and encode the lines at the same time.
2) The creation of an initial population. Random generation of \( n+N \) bit binary chromosome, set the appropriate population number and random generation of initial population, where each individual corresponds to a planning scheme. Determine the maximum evolutionary algebra \( k_{max} \), current algebra \( k=1 \).

3) Calculate the rank and the crowding distance. The population was stratified rapidly by using the fast non-dominant ranking method, and the population individuals' rank \( i_{rank} \) were obtained. The crowding distance \( i_{distance} \) was calculated for the same \( i_{rank} \).

4) Select operation. When \( k=1 \), it does not participate in the selection. When \( k>1 \), it makes the selection based on the \( i_{rank} \) and \( i_{distance} \) of each individual. Each time I randomly pick two individuals \( i \) and \( j \) from the parent population.

If \((i_{rank} = j_{rank} \text{ and } i_{distance} > j_{distance}) \) OR \( i_{rank} > j_{rank} \) then individual \( i \) is better than individual \( j \), put individual \( i \) into the offspring, otherwise choose another to put into the offspring. All individuals of the population were screened according to the rotation system selection operator.

5) Crossover and variation.

6) Elite strategy. The population recombined by the parent generation and the offspring generation is calculated by rapid non-dominant sequencing stratification and crowding degree, and then the population is pruned to select the optimal \( N \) as the new parent population, so as to promote the evolution of the population in the specified direction and prevent the loss of elites. At the same time, the population whose rank of successive dynasties is 1, 2 or 3, will be stored to prevent the planners from not being able to choose the scheme due to the small number of solutions.

7) Output results. After 1) -- 6) step until the specified generation is satisfied, the Pareto optimal solution set of each iteration is obtained. All previous dynasties optimal solution set are rapidly non-dominated sorted to obtain the final Pareto optimal solution set, and then transformed into a series of planning corresponding schemes for designers to choose.

4. Example analysis

4.1 Examples of network frame planning based on improved minimum spanning tree algorithm

As an example shown in the figure, there are 29 streets and 21 load points, the solid line is the existing line, the dotted line is the line to be planned, and the power node is located at 6 points. Part of the parameters are as follows: set LGJ-120, LGJ-150, LGJ-180, LGJ-240 four lines, take LGJ-120 as the initial line. The number of users at each point is 100, and the failure rate per unit length line is 0.09 \( kM\cdot a^{-1} \), and the maintenance rate is the same. Other data can be found in Reference [9-10]. The results are shown in figure 1 and table 1.

![Figure 1. Single power planning](image)

(a) The planning area (b) Scheme 1 considering economic (c) Scheme 2 considering reliability (d) Scheme 3 comprehensive result

| Scheme | Construction costs / \( 10^5 \text{yuan} \) | Network loss / MW | operating cost/ \( 10^5 \text{yuan} \) | total cost/ \( 10^5 \text{yuan} \) | ASA1% |
|--------|------------------------------------------|-----------------|----------------------------|----------------------|-------|
| 1      | 46.49                                    | 334.0767        | 2.67                       | 49.16                | 99.9809 |
| 2      | 47.94                                    | 360.3521        | 2.88                       | 50.82                | 99.9855 |
| 3      | 47.12                                    | 337.83009       | 2.70                       | 49.82                | 99.9826 |
When the above algorithm is applied to multi-power network planning, the weight of economy and reliability is 1. The example data are shown in references [6], and the calculation example load in literature is modified appropriately. The grid frame planning of the distribution network as shown in figure 2 can be obtained. The points of the same partition after partition are the same color.

**Figure 2.** multiple power planning area

**Figure 3.** multiple power planning result

### 4.2 An Example of Section switch and Contact Line Planning

Based on the calculation results of the above multi-power grid frame planning, it is stipulated that the sectional switch is set at 100,000 yuan/unit, the contact line is set at LGJ-400, and the investment cost is 503,325 yuan/kM, including the investment of the contact switch. The load of each node and the number of users are the same as the above calculation example. The maximum number of sectional switches is 25, and the maximum number of tie lines is 4. After the quantity crosses the boundary, the economic penalty item is 100 million/item, and the reliability penalty item is 0.1/ item.

The final pareto frontier and partial solutions can be saw in figure 3. In figure a, red is the first frontier, yellow is the second frontier, and blue is the third frontier. In figure c and b, red indicates that there is a switch on the line and green is the contact line.

**Figure 4.** Configuration scheme.

Twenty-four schemes that meet the requirements are obtained, some of which are shown in Figure 4. The results are stored in table 2. Yellow indicates that this section of the line has section switches, and green indicates that it is planned as a contact line.

**Table 2 Results of typical program**

| Scheme | Construction costs/ yuan | Reliability index | ASA1% |
|--------|--------------------------|-------------------|-------|
| 19     | 1496130.153              | 99.997836%        |       |
| 24     | 2998221.056              | 99.9989132%       |       |
5. Conclusion

1) For the two planning problems of distribution network frame planning and sectional switch contact line configuration planning, considering their economy and reliability at the same time, two corresponding multi-objective planning models are established.

2) In view of the large number of infeasible solutions in the process of solving the comprehensive economic and reliability network planning model, this paper uses the minimum spanning tree algorithm to avoid the generation of infeasible solutions, and improves the calculation speed. And by improving the update condition of the solution of the minimum spanning tree algorithm, it can solve the corresponding multi-objective programming model in this paper. And the weight assignment of reliable and economy be given by planner enables algorithm to determine which side the solution is biased when solving multi-objective optimization planning model.

3) For multi-power grid frame planning, simple partitioning algorithm is used to partition, and each region is divided into single-power multi-target grid frame planning. In this way, the single power planning algorithm can be extended to multi-power planning.

4) In view of the section switches and contact lines planning, establishing multi-objective nonlinear mixed integer programming model, which is corresponded by system, with a penalty function method is joined to the NSGA-II planning algorithm to automatically generate Pareto optimal solution set of corresponding solutions, which can convert into a series of planning.

References

[1] XIAO Jun, ZHANG Ting, ZHANG Yue, et al. TSC-based planning idea and method for distribution networks[J]. Proceedings of the CSEE, 2013, 33(10): 106-113.

[2] SU Haifeng, ZHANG Jianhua, LIANG Zhirui, et al. Multi-stage planning optimization for power distribution network based on LCC and improved[J]. Proceedings of the CSEE, 2013, 33(4): 118-125.

[3] LIU Jian, YANG Wenyu, YU Jianming, et al. An improved minimum-cost spanning tree based optimal planning of distribution networks[J]. Proceedings of the CSEE, 2004, 24(10): 103-108.

[4] WANG Yansong, SUN Guilong, CAO Mingzhi. Research on the optimization of the tie lines based on dynamic programming for distribution network[J]. Power System Protection and Control, 2016, 44(10): 30-36.

[5] Aghaei J, Muttaqi K M, Azizivahed A, et al. Distribution expansion planning considering reliability and security of energy using modified PSO (Particle Swarm Optimization) algorithm[J]. Energy, 2014, 65:398-411.

[6] Li ZhenWen, Cheng Hong, Xiong Shangfeng et al. Expansion planning for distribution network considering DG and tie-lines [J]. Proceedings of the CSU-EPSA, 2016, 28(1):63-67.

[7] Xiong X, Yang L, Li N, et al. Reliability Analysis of Distribution Network with Distributed Generators Based on Affine Minimal Path Method[J]. Automation of Electric Power Systems, 2017, 41(17):43-50.

[8] Jane C C, Laith Y W. Distribution and Reliability Evaluation of Max-Flow in Dynamic Multi-State Flow Networks[J]. European Journal of Operational Research, 2016, 259(3):1045-1053.

[9] WU Shuang, WEI Zhinong, SUN Guojiang, et al. Multi-Objective planning of distribution network considering network survivability[J]. Automation of Electric Power Systems, 2014, 38(3):137-142.

[10] Xu Hang, Dong Shufeng, Zhu Jiaqi, et al. Path Description Based Planning Method for Power Corridor of Distribution Network[J]. Automation of Electric Power Systems, 2018, 42(16):80-86.