Distribution Network Planning Method Based on Hybrid Genetic Algorithm

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Abstract. Facing the discrete, multi-constrained, non-linear, multi-objective combination optimization problem of distribution network grid planning, some traditional heuristic algorithms such as genetic algorithms sometimes fall into local optimum. This paper proposes a distribution network planning method based on hybrid genetic algorithm. The algorithm consists of two stages. In the first stage, the genetic algorithm is used to obtain the initial planning scheme. In the second stage, the initial planning scheme obtained in the first stage is used to form the planned route set. The improved minimum spanning tree method is used to obtain the final planning scheme. In order to make full use of the effective information obtained in the first stage, this paper proposes a transmission line classification method to assess the importance of the transmission line, provide guidance for the second stage, and improve the search efficiency and accuracy. The algorithm solves the problem that heuristic algorithms such as genetic algorithm often fall into local optimization to a certain extent, and the problem of slow convergence when the minimum spanning tree algorithm has a large number of lines to be planned.

1. Introduction

The optimization planning of the distribution network structure is to determine the topological structure and conductor specifications of the distribution transmission line on the basis of the existing power supply substations and load points of the distribution network. While ensuring the quality and reliability of the power supply, the construction cost and operating cost of the power grid are minimize. Therefore, distribution network planning is a discrete, multi-constrained, nonlinear, and multi-objective combined optimization problem. It is difficult to obtain satisfactory planning results using general mathematical methods. A large number of excellent algorithms have been applied to solve the problem of distribution network planning. Such as genetic algorithm(GA), tabu search method(TS), particle swarm algorithm(PSO), ant colony algorithm(ACO) and other heuristic algorithms as well as minimum spanning tree algorithm combined with graph theory knowledge, and achieved good results [1-5]. However, when these algorithms are used directly or individually in distribution network planning, they can only obtain sub-optimal solutions. In order to further increase the probability of obtaining the optimal solution, more and more attempts have been made to improve the original algorithm, to mix multiple algorithms, and to use hierarchical and staged methods for distribution network planning, and they have achieved relatively satisfactory results [6-8]. Traditional GA usually take the construction of lines as the basis for individual coding, but due to the radial structure requirements of the distribution network, the use of this coding method will produce a large number of infeasible solutions in genetic operations, making the algorithm difficult to converge, slow and difficult to obtain Optimal solution. In order to solve the above problem, literature [9] proposed a GA
based on matrix coding to solve the problem of distribution network planning. But this method sacrifices the ability to search for optimal solutions in exchange for the ability to repair infeasible solutions, and the algorithm can easily fall into a local optimum.

In response to the above problems, the article combines GA with improved minimum spanning tree method, first uses the improved GA to obtain multiple planning schemes, selects the several schemes with the highest fitness value to combine the set of planned routes, and then uses the improved minimum spanning tree algorithm to get the optimal planning scheme. The GA is difficult to retain excellent genes in genetic operations, which makes it difficult for the algorithm to converge to the optimal solution, and the shortcomings of the minimum spanning tree algorithm for the initial set of routes are solved. The two algorithms learn from each other’s strengths, and finally obtain satisfactory results.

2. Mathematical Model of Distribution Network Planning

2.1. Objective Function

The objective function of the article is the annual comprehensive cost of the distribution network, that is, the construction cost plus the operating cost of the distribution network during the planning period, then convert it to the planning year and divided by the year. The objective function is [10]:

\[
\text{Min } W = \frac{r(1+r)^n}{(1+r)^n-1} \sum_{i} W_i
\]

\[
W_i = C_{f,i} + C_{p,i}
\]

\[
C_{f,i} = l_i z_i
\]

\[
C_{p,i} = \sum_{r=0}^{\lambda} \frac{M_0 I_i^2 R_i \tau}{(1+r)^{2r}}
\]

Where \(W_i\) is the total cost of the line \(i\), \(C_{f,i}\) is the annual capital construction cost of the line \(i\); \(C_{p,i}\) is the present value of the operation and maintenance costs of the line \(i\); \(l_i\) is the length of line \(i\) and \(z_i\) is the construction cost per unit length of the line; \(M_0\) is the power loss price; \(I_i\) is the current flowing through the line \(i\); \(R_i\) is the total resistance of the line \(i\); \(n\) is the service life of the line (years); \(\tau\) is the maximum load loss hour; \(r\) is the discount rate; \(\lambda\) is the load power factor. For existing lines, the construction investment cost is zero.

2.2. Restrictions

According to the power system requirements and the actual operation characteristics of the distribution network, the distribution network should meet the following three constraints:

(1) Network connectivity and radiation.

All load points must be connected to the distribution network and have source points for power supply.

(2) Current constraint.

\[
|I_i| \leq |I_{i,\text{max}}|, i \in T
\]

Where \(I_i\) is the current value of line \(i\); \(I_{i,\text{max}}\) is the maximum allowable current capacity of the line; \(T\) is the line set.

(3) Voltage constraint.

\[
|V_j| \leq |V_{j,\text{max}}|, j \in N
\]

Where \(V_j\) is the voltage value of node \(j\); \(V_{j,\text{max}}\) are the lower limit and upper limit of each node voltage respectively;
3. Distribution Network Planning Model Based on Hybrid GA

The article first uses the improved GA to obtain the initial plan, and then uses the improved minimum spanning tree method to further optimize the initial plan to obtain the final planning plan. Modeling the GA and the minimum spanning tree method respectively.

3.1. GA Used in Distribution Network Planning

3.1.1. Encode and generate initial population The article uses the coding method of literature [9] for the coding of the distribution network, which can easily repair infeasible solutions. The chromosome has d bits, and each bit ranges from 1 to d, and is an integer, denoted as E. Rearrange the d-digit number from small to large, and the original number is transformed into a sequence of 1×(d+1) array S. From E, a (d+1)×d matrix can be generated. In the row i, the element in the E(q) column is 1, which means that the predecessor of the node q is the node S(E(q)), and the remaining elements in the matrix are all zeros. This matrix can uniquely correspond to a grid topology. The initial population can be obtained by random generation.

3.1.2. Fitness function and selection operation The fitness function is obtained by combining the objective function and constraint conditions:

\[
F(X) = \frac{1}{1.1^{p(X)}(1+1.1^{w(X)})} 
\]

\[
P(X) = \begin{cases} 
\sum_{i} I_{i} - I_{\text{lim}}, & I_{i} > I_{\text{lim}} \\
0, & I_{i} \leq I_{\text{lim}} 
\end{cases} 
\]

\[
\text{Where } P(X) \text{ is the penalty function; } W \text{ is the annual comprehensive cost of the grid planning scheme obtained by equation (1); } I_{i} \text{ is the current flowing through the line } i; I_{\text{lim}} \text{ is the current limit, which is set as 610A in the article; } \alpha, \beta \text{ are the constants set as 0.01 and 10-6 respectively in the article.}
\]

The proportional selection method is adopted, that is, the probability of each individual being selected is proportional to its fitness value.

3.1.3. Crossover and mutation The article uses adaptive crossover and mutation operators. That is, at the beginning of the iteration, the population fitness value is generally low. At this time, the probability of crossover and mutation should be increased. At the later stage of the iteration, the population fitness is generally high. At this time, the probability of crossover and mutation should be reduced to prevent the crossover and mutation operators from destroying excellent populations.

3.2. Application of Minimum Spanning Tree Method to Distribution Network Planning

In order to increase the probability of obtaining the optimal solution, the article uses the improved minimum spanning tree method to further optimize the initial plan obtained by the GA, and obtain the final planning plan. The specific planning steps are as follows:

**Step 1:** Among the multiple schemes obtained by the GA, select the scheme with the highest fitness value of m schemes, and put the non-duplicated edges contained in the m schemes into the set QM.

**Step 2:** According to the fitness value, classify the lines in QM to express the importance of the lines. The order of importance of lines from high to low is: lines included in all m schemes, lines included in m-1 schemes, ..., lines included in one scheme. The line classification can be adjusted according to the difference in the adaptation value of various schemes and the number of schemes.

**Step 3:** Set the initial value of the weight of each edge W_{i}^{0} and set the initial value of the number of iterations k=0.

\[
W_{i}^{0} = C_{f,i}^{0} + C_{p,i}^{0} 
\]
Where $W_i^0/C_{f,i}/C_{p,i}$ are the initial value of total cost, initial value of construction cost and initial value of operating cost of the line $i$, respectively. All lines use the same cross-section wire to determine $C_{f,i}, C_{p,i}$ can generally be set to 0.

**Step 4:** Set the solution with the highest fitness value as the initial solution $T^0$.

**Step 5:** Calculate the current flowing through each line $I_i$, determine the cross-sectional area of the wire used according to the current $\alpha_{ki}$, and calculate $C_{f,i}, C_{p,i}, W_k$ and the total cost $W_k$ from equations (1) to (4).

**Step 6:** Find subtrees from QM that meet the following conditions and put them into MN (these lines still exist in QM):

1. The lines in the subtree come from the same scheme.
2. The lines in the subtree are not connected to the power point.

**Step 7:** Restore the line weights other than $T_k$ to the initial value, and put them into the set QN from high to low according to the level, and put the lines of the same level from low to high according to the weight.

**Step 8:** Set the weight of the highest level line to zero, take a line from the head of QN and add it to $T_k$, and delete a non-newly added edge in the resulting loop, thereby obtaining a new scheme $T^N$. The specific deletion operation is:

- First, generate a random number $a$ between 0 and 1. $p$ can be adjusted accordingly based on the merits of the initial plan.
  1. If $a > p$, delete an edge with the lowest rank in the loop, and delete the edge with the highest weight if the rank is the same.
  2. If $a < p$, delete an edge with the largest weight in the loop.

Where $p$ is a constant between 0 and 1 set in advance. The article takes $p$ as 0.4.

**Step 9:** Following step 3, calculate the weight of each side of the new scheme and the total cost $W^N$.

1. If $W^k > W^N$
   \[ k = k + 1 \] \[ W^k = W^N \] \[ T^k = T^N \]

   Clear QN and skip to step 7.

2. If $W^k < W^N$, judge whether QN is empty, if yes, skip to step 10. If it is not empty, skip to step 8.

**Step 10:** Set the weight of the highest level line to zero, take a subtree from the head of the MN and add it to $T_k$, and delete multiple edges at the same time as step 8 until there is no loop, thereby obtaining a new tree $T^N$. Following step 3, calculate the weight of each side of the new scheme and the total cost $W^N$.

1. If $W^k > W^N$
   \[ k = k + 1 \] \[ W^k = W^N \] \[ T^k = T^N \]

   Go to step 10.

2. If $W^k < W^N$, judge whether QN is empty, if yes, end the planning, and the best solution is $T^k$. If it is not empty, skip to step 10.

### 4. Case Simulation and Analysis

The area to be planned includes 3 source points and 27 nodes with known loads. The geographical coordinates and loads of the source points and each load point are shown in table 1. Nodes 1 to 3 are source points, and nodes 4 to 27 are load nodes. The voltage level is 10kV. The planning parameters involved are: power loss price 0.4 yuan/(kW·h), planning cycle 10 years, annual average electricity
consumption 4000h, discount rate 6%, and power factor of each load is 0.85. The article uses MatlabR2019a software to simulate the above examples in windows10 environment.

Table 1. Node coordinates and load.

| number | X-axis (m) | Y-axis (m) | load (kw) | number | X-axis (m) | Y-axis (m) | load (kw) |
|--------|------------|------------|-----------|--------|------------|------------|-----------|
| 1      | 6000       | -4000      | 0         | 16     | 6000       | -4000      | 0         |
| 2      | -6000      | -4000      | 0         | 17     | 4872       | -6000      | 4608      |
| 3      | 0          | 5600       | 0         | 18     | -1120      | 0          | -2672     |
| 4      | 4256       | -1216      | 800       | 19     | -4608      | 800        | -2568     |
| 5      | 1872       | -344       | 300       | 20     | -9690      | -2672      | 800       |
| 6      | 8248       | -6592      | 1000      | 21     | -3704      | -6072      | 2400      |
| 7      | 6168       | -8392      | 800       | 22     | -2000      | -728       | 600       |
| 8      | 3256       | -2272      | 2300      | 23     | 2584       | 9600       | 300       |
| 9      | 632        | 7200       | 3100      | 24     | -400       | 8800       | 1100      |
| 10     | 6600       | -2560      | 2500      | 25     | 2216       | 4344       | 2200      |
| 11     | 1200       | -5872      | 2600      | 26     | -280       | 2072       | 600       |
| 12     | 9360       | -1096      | 1600      | 27     | 1880       | -5040      | 1000      |
| 13     | -5200      | 800        | 500       | 28     | -4368      | 7776       | 600       |
| 14     | -6400      | -2120      | 3000      | 29     | 3848       | 4608       | 1200      |
| 15     | -3512      | -9336      | 1000      | 30     | -3424      | 4920       | 1300      |

Choose LGJ-50, LGJ-120, LGJ-150, LGJ-180 and LGJ-240 for the newly-built line. First, use the previously established GA distribution network planning model for preliminary planning. The maximum genetic algebra is 500 and the population size is 4000. The individual codes and comprehensive costs of the top 3 fitness values obtained through multiple experiments are shown in table 2, and the routes and classifications included in each plan are shown in table 3. The variation curve of the highest fitness value of the 3 GA population with the genetic algebra (see figure 1).

Observing figure 1, it can be seen that the improvement of the fitness of the population in the three trials was mainly in the first 200 generations. When the genetic generation number is between 300 and 500, the fitness of the population has almost no improvement. At this time, the GA may have fallen into a local optimum. At this time, it is difficult to get a better solution in a short time only by increasing the genetic algebra.

Table 2. Program code and cost.

| Program | code | Comprehensive annual cost (10^4 yuan) |
|---------|------|-------------------------------------|
| 1       | 1,1,1,6,6,7,2,4,2,2,2,10,3,12,3,3,3,10,3,4,18,4,4,4,2,4,4,4 | 330 |
| 2       | 1,1,1,6,2,8,2,4,2,2,2,4,3,3,3,12,3,13,3,4,4,4,4,4,4,6,4,21,4 | 348 |
| 3       | 1,1,1,2,5,6,2,4,2,2,8,3,3,13,3,3,20,3,12,3,4,17,4,4,4,3,4,4,4 | 344 |

Table 3. Route and grade to be planned.

| Feeder level | feeders to be planned |
|--------------|-----------------------|
| 1            | 1-8,3-9,1-10,1-11,2-14,2-16,2-17,2-19,2-21,3-22,3-24,3-25,3-26,3-28,3-30 |
| 2            | 4-10,7-11,1-12,15-17,3-29 |
| 3            | 5-10,6-11,13-14,2-18,14-20,23-24,1-27,5-8,1-6,3-13,2-15,16-18,17-20,3-23,8-27,25-29,1-4,4-5,6-7,1-7,10-12,2-13,18-25,16-20,9-23,2-27 |

The first, second, and third-level lines in the table refer to the set of lines included in three, two, and one schemes respectively;

The lines are represented by the beginning and the end, for example, 0-1 means the lines with nodes 0 and 1 as the end points;
The lines included in the three plans are formed into a distribution network planning area containing 49 lines to be planned (see figure 2). Finally, the final planning scheme obtained from the second stage is shown in figure 3(a).

The optimal planning result of genetic algorithm is shown in the figure 3(d). If the GA is used to obtain the area to be planned as shown in figure 2, and then the basic minimum spanning tree method is used, the resulting planning scheme is shown in figure 3(c). If the improved minimum spanning tree algorithm is used, the resulting planning scheme is shown in figure 3(b). Using the method proposed in the article, the solution obtained is shown in figure 3(a).
The annual comprehensive cost and comparison of each algorithm are shown in the table 4. Considering the total cost in 10-year planning period, this algorithm saves 2 million yuan compared to the improved minimum spanning tree method, 5.2 million yuan compared to the basic minimum spanning tree method, and 2.5 million yuan compared to the GA.

**Table 4. Comparison of various algorithms.**

| Algorithm                | Stage 2                     | Annual cost ($10^4$ yuan) | Cost compared with stage 1 ($10^4$ yuan) |
|--------------------------|-----------------------------|----------------------------|----------------------------------------|
| GA                       | no                          | 330                        | 0                                      |
| GA                       | Minimum spanning tree       | 357                        | +27                                    |
| GA                       | Literature [12]Algorithm    | 325                        | -5                                     |
| GA                       | stage 2 of the article algorithm | 305                      | -25                                    |

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