Multi-objective distribution network reconstruction based on decimal coding

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Abstract. The distribution network reconfiguration problem is a highly complex mixed integer, nonlinear, multi-objective planning problem. According to the closed-loop design and open-loop operation of the distribution network, this paper proposes a loop-based decimal coding method to reduce the space of infeasible solutions. At the same time, combined with breadth-first search to form and test feasible solutions. The text takes the network loss and voltage deviation as the target, uses the NSGA-II algorithm for multi-objective optimization, and uses the Newton Raphson method to check and evaluate the reconstruction scheme. Finally, an IEEE-33 node test case is used to verify the algorithm. The results show that the algorithm can quickly calculate an approximate global optimal network reconstruction scheme.

1. Introduction
As a key infrastructure of a city, the distribution network is an important link between the grid and users. Since the beginning of the 21st century, with economic development and technological progress, the demand for electric energy has also expanded. The structure of the distribution network is becoming more and more complex, causing the loss of the distribution network to increase year by year. Relevant data show that the line loss rate of power grids in major western industrial countries is between 5% and 8%, while that of my country is about 9%, which is still far behind the developed countries. At the same time, there is a big gap between the construction of the distribution network and the requirements of social and economic development, and users' requirements for power supply reliability.

Therefore, quickly clarifying the structure of the medium-voltage distribution network will help deepen the application of distribution automation, further improve the self-healing and network reconfiguration capabilities of the distribution network, and continuously improve the power supply capacity and reliability of the distribution network.

Optimizing the operation of the distribution network can be achieved through the reconfiguration of the distribution network. Because the distribution network usually has the characteristics of closed loop design and open loop operation[2]. Therefore, a certain number of normally closed section switches are usually distributed along the feeder line, and normally open tie switches are installed between the feeders. The reconfiguration of the distribution network can reconstruct the operation structure of the distribution network by regularly adjusting the state of these switches according to changes in load demand. Make the load flow freely between the feeders to achieve the purpose of reducing network losses and improving power quality.
2. Multi-objective distribution network reconstruction based on decimal coding

The distribution network reconfiguration problem is a highly complex mixed integer, nonlinear, multi-objective planning problem. Take the IEEE-33 node power distribution system as an example, its possible switch states are as high as $2^{37}$. Even considering a series of constraints such as anti-islanding and radial operation, the number of possible network topologies is as high as 62,141. The traditional traversal search has a huge amount of calculation, and it is necessary to introduce intelligent algorithms including genetic algorithms to effectively solve the model. Genetic algorithm is suitable for solving high-dimensional space, complex and nonlinear problems, can obtain the global optimal solution, has high computational efficiency, and is easy to parallel calculation. It is widely used in the reconstruction of distribution network.

2.1. Loop-based decimal coding

Coding is the core of genetic algorithm and directly determines the scale of the solution space. The genetic algorithm interacts between the solution space and the coding space. In the coding space, genetic operations are performed on chromosomes, and the solution is evaluated and selected in the solution space. Using traditional binary coding, 0 and 1 are used to indicate the on-off state of the switch, and the chromosome length is the total number of network switches. This kind of coding is simple and easy to understand, but for ordinary distribution network wiring sets, the solution space increases exponentially, and there are a large number of infeasible solutions. Therefore, a decimal coding method based on the distribution network loop is proposed.

The reconfiguration process of the distribution network is the opening and closing process of the switch, but the opening and closing of the switch is not arbitrarily combined, which is limited by the distribution network maintaining a radial structure. If the tie switch is closed, a small loop is formed, and a section switch must be opened in this loop to keep the distribution network in a radial shape.

Therefore, a tie switch determines a ring network, and a coding rule based on the ring network is generated: First, the tie switches of the wiring group are numbered with natural numbers, and the switches are individually numbered in the ring network determined by each tie switch (from 1 to switch total). The genetic code uses the small ring network determined by the tie switch as the locus. The value of this bit is the number of the switch opened in the ring network. The value of the gene position is restricted, it must be a positive integer, and from 1 to the total number of switches in the ring. The length of the chromosome is equal to the number of rings.

At the same time, set the following strategies to reduce the solution space:

1. Switches on branches not in any loop must be closed, such as branches.
2. Generally, the switch connected to the power point should also be closed.

As shown in Figure 1, the figure is a simplified abstract diagram of the 17 nodes of the distribution network.

![Figure 1. 17-point abstract diagram of distribution network](image_url)

The branch circuit of the contact switch in the figure is aCLine17, aCLine18, aCLine19, aCLine20, aCLine21. According to the above simplification strategy, the ring network determined by the branch
circuit aCLine17 of the contact switch is composed of branches aCLine3, aCLLine12, aCLLine13, aCLLine15, aCLLine16, and aCLLine17, and is defined as the No. 1 ring network. In the ring network, all switches are numbered according to natural numbers, and the numbering sequence can be selected from a certain edge in the ring network as the starting point, and traverse each edge in the ring in order or reverse order. This kind of coding rule covers all switch combinations and meets the unique mapping requirements between chromosomes and solutions.

Take the example shown in Figure 1 as an example to initialize an individual, the specific steps are:
(1) Determine the length of individual chromosomes: 5 (number of ring nets).
(2) Determine the range of individual chromosomes: individually number the switches in the ring (from 1 to the total number of switches in the small ring), as the value range of each gene, record as shown in Table 1.

### Table 1. Chromosome gene value range

| Chromosome locus | Minimum chromosome locus | Maximum chromosome locus |
|------------------|--------------------------|--------------------------|
| Locus 1          | 1                        | 6                        |
| Locus 2          | 1                        | 9                        |
| Locus 3          | 1                        | 3                        |
| Locus 4          | 1                        | 6                        |
| Locus 5          | 1                        | 9                        |

2.2. Breadth first search

Distribution network reconstruction involves selecting an optimal network structure among multiple network structures to make the target network structure radial and connected. Therefore, ensuring the radiation and connectivity of the distribution network is an important part of the reconfiguration of the distribution network. The breadth-first search is used to judge the radial and connectivity of the solution generated by the algorithm.

For the chromosomes obtained by decimal encoding, there are still a large number of infeasible solutions, so we need to identify them. In fact, the radial operation constraint of the distribution network can be equivalent to the following two conditions:
(1) The number of branches = the number of nodes - 1;
(2) There are no island nodes in the topology.

For the decimal encoding method of the test case, as long as the positions of the selected 5 switches are not repeated, the number of branches in the topology can be guaranteed to be 16. Therefore, the difficulty of the problem is to ensure that there are no island nodes in the topology. Using breadth-first search, topology traversal starts from the substation nodes. If there are nodes that cannot be traversed, it means that the current topology is an infeasible solution and needs to be corrected.

2.3. NSGA-II: Fast non-dominated hierarchical sorting

In multi-objective planning, there are conflicts and incomparable phenomena between objectives. The specific manifestation is that one solution is the best for a certain objective, but may be poor for other objectives. Pareto proposed the concept of multi-objective non-dominated solutions in 1986: assuming that S1 and S2 are better than S2 for all objective functions of two solutions, then we call S1 dominates S2; if the solution of S1 is not controlled by other solutions Dominated, S1 is called non-dominated solutions, and the set of these non-dominated solutions is the so-called Pareto front.

The fast non-dominated hierarchical sorting algorithm first finds the solution at the Pareto front in all chromosomes. Separate them from the population and put them in the Pareto front (level 1). Subsequently, the remaining chromosomes in the population are compared. Separate the non-dominated optimal solution from the current population and put it into the second layer of Pareto front (level 2) [3]. This is repeated until the grade marking of all solutions in the population is completed.
Genetic algorithm has the property of automatic convergence. In order to ensure the diversity of solutions, it is hoped that the solutions in the same layer can be separated from each other. So the concept of congestion is set. It is considered that a solution with a large distance between solutions is better than a solution with a small distance between solutions. Crowding distance sorting is used to maintain the diversity of solutions. The crowded distance of each individual is obtained by calculating the sum of the distance difference between the two adjacent individuals on each sub-objective function[4].

\[ CD_i = \sum_k |f_k(x_{i+1}) - f_k(x_{i-1})| \]  

Where, \( f_k(.) \) is the \( k \)th objective function.

The purpose of this sorting is to make the solutions with more distinctive features in the same level higher. The relatively similar solutions are sorted later, which helps to ensure the diversity of the solutions and improve the convergence accuracy of the algorithm.

2.4. NSGA-II: selection, crossover, mutation

The traditional single-objective genetic algorithm adopts the "roulette" method to select operations according to the fitness value of the individual. But for NSGA-II multi-objective planning, the fitness includes multiple objective functions, and traditional methods cannot be used for selection. For this reason, the "dual tournament" selection method is introduced. For two individuals randomly selected from the population, the optimization is performed according to the idea of fast non-dominated hierarchical sorting, that is: if the two individuals are of different levels, select the individual with a lower level. If two individuals have the same level, select the individual with a high degree of "crowding". In the population, the above selection is continued (selected and replaced) until the number of selected individuals reaches the required scale.

The crossover and mutation operators of NSGA-II are consistent with traditional genetic algorithms. The process of biological evolution by simulating the natural selection and genetic mechanism of Darwin's biological evolution theory. And with the help of genetic operators of natural genetics to combine crossover and mutation, a population representing a new solution set is generated. Among them, the crossover operation refers to randomly selecting two individuals from the population, and randomly selecting two genes on each individual, and performing crossover according to the crossover probability and the corresponding crossover algorithm. Mutation operation refers to randomly selecting a certain gene of an individual from the population, and mutating according to the mutation probability and the corresponding mutation algorithm.

There may be a certain number of infeasible solutions in the new population after the operation of the genetic operator, and the radial inspection and the anti-islanding inspection need to be carried out according to the breadth-first search idea. For the infeasible solutions among them, the method of regenerating new feasible solutions is adopted to modify.

2.5. NSGA-II: Elite Choice

Elite selection is a major improvement of NSGA-II over NSGA. The offspring are no longer directly generated by the parents through genetic operators, but instead adopt the elite selection strategy. Specifically, the parent population A first generates the offspring population B through genetic operators, and then obtains the new parent population \( A = A \cup B \) by taking and combining, that is, the new population A includes both parents and offspring. On this basis, a fast non-dominant hierarchical sorting is performed on the population A, and chromosomes are selected according to the level and "crowding degree", and participate in the next iteration as the true offspring.

The elite selection strategy ensures that the excellent individuals in the parent can directly enter the offspring, preventing the Pareto optimal solution that has been obtained from being lost through the genetic operator. On the other hand, the elite selection strategy chooses between the parent and the offspring at the same time to improve the overall optimal degree of understanding, and has the characteristics of fast convergence.
2.6. Newton Raphson method power flow calculation
The polar coordinate Newton Raphson method is used to calculate the objective function of the generated initial scheme and the scheme after the distribution network reconstruction, and the voltage limit and line capacity overload are considered in the calculation process.

The process of multi-objective distribution network reconstruction based on decimal coding is shown in Figure 2.

3. Case analysis
Taking the IEEE-33 node as a test example, the whole system contains 33 nodes, 37 branches, the rated voltage is 12.66kV, and the total system load is 3715kW+j2300kvar, as shown in Figure 3. The population size is set to 100, the crossover probability is 0.8, the mutation probability is 0.6, and the final optimal index weight of the scheme is 0.5.

Figure 2. Flow chart of multi-objective distribution network reconstruction based on decimal coding.

Figure 3. IEEE-33 node system diagram

The reconstructed and optimized distribution network structure is shown in Figure 4.
Figure 4. Reconstructed and optimized IEEE-33 node system

The comparison of network loss and voltage deviation before and after reconstruction is as follows:

| Evaluation index                  | Network loss (p.u.) | Voltage deviation rate (p.u.) | Comprehensive index |
|-----------------------------------|---------------------|--------------------------------|---------------------|
| IEEE-33 system before reconstruction | 0.054358            | 0.053788                      | 0.054073            |
| IEEE-33 system after reconstruction | 0.056192            | 0.043318                      | 0.049755            |

According to the analysis of the above table, the comprehensive index of the network after reconstruction is lower than the comprehensive index before reconstruction. That is, the network loss and voltage deviation rate have been optimized, and an approximate global optimal solution has been found to make the network loss and voltage deviation rate more excellent.

4. Conclusion
The distribution network reconfiguration problem is a highly complex mixed integer, nonlinear, multi-objective planning problem. This paper takes the network loss and voltage deviation as the objective function, and combines the loop-based decimal code with the NSGA-II algorithm. Through rapid non-dominated sorting and crossover mutation, the generated population individuals are genetically evolved, and then the best individuals are selected through elite selection. Finally, an IEEE33-node system example is used to verify that the algorithm can quickly calculate an approximate global optimal network reconstruction scheme.

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