Topology identification method of distribution network based on branch active power

Biqi Liu1*, Danni Wang1, Yunpeng Li1, Lin Qiao1, Shuo Chen1

1State Grid Liaoning Information and Communication Company, Shenyang, Liaoning 110006, China
*1142101056@ncepu.edu.cn

Abstract: Because of low measurement redundancy and frequent switch changes, it is difficult to identify the correct topology structure. In this paper, a topology recognition method of distribution network based on branch active power is proposed. Firstly, branch active power residual algorithm is used to identify the topological structure. The topology obtained by this method has the highest matching degree with the real-time measured data. Then genetic algorithm is used to optimize the inverse recognition of power grid topology. The numerical example shows that the method is reasonable, effective, rapid and simple. It also has good adaptability with a large number of measurement errors.

1. Introduction
Topological structure analysis is the basis of all kinds of advanced analysis functions of the distribution system. Therefore, the accuracy of topology structure has an important influence on the rationality of power flow calculation and state estimation[1]. In order to achieve the goal of flexible operation and reliable power supply, power distribution network is usually installed a large number of switches, and switch opening and closing statement will change according to different needs. In addition, measurement redundancy of the distribution network is very low, which leads to the unreliable topology of the distribution network, thus affecting the application of other advanced analysis functions of the distribution network[2]. Therefore, it is necessary to find a topology identification method which can adapt to the dynamic change of the distribution network structure.

In this paper, a distribution network topology identification method based on branch active power is proposed. Compared with the existing analytical methods, this method has better adaptability to the dynamic changes of the distribution network structure, and makes reasonable use of the load data in the distribution network metering system and the real-time measurement data of each branch[3]. The numerical example shows that the method is reasonable, effective, quick and simple, and has good practicability.

2. Residual value of branch activity power

2.1. Concept of branch activity power residual value
Distribution networks mostly operate in a radial ring structure. If a branch in a certain ring network is arbitrarily broken, the power flow change caused by the change of topology structure can be simulated by introducing a specific circuit power into the ring network. The active power of the branch of the distribution network can reflect the operation state of the switch to some extent. For example, when the switch is in the disconnected state, the true value of the active power of the branch is 0. Therefore,
the branch with the greatest possibility of interruption of the distribution network can be found by superposition of the circuit power. The specific methods are as follows. Firstly, the whole network switch is closed to form several ring networks, and the initial power of each branch is obtained by power flow calculation. Then adjust the loop power of each ring network. Superposition the initial power of each branch and the loop power of each ring network, so that the active power of the branch equipped with measuring device is closest to the real-time measurement data of the active power of the branch. The active power of the branch is called the residual value of the active power of the branch. Finally, by comparing the residual value of active power of each branch to determine the branch interrupted by each ring network (take the minimum residual value), the topology structure obtained by this method has the highest matching degree with the current real-time measurement data.

2.2. Branch active power residual value algorithm

It is necessary to calculate the optimal solution of the active power of each circuit, so that the matching degree between the actual measured value of the branch active power and the residual value of the branch active power is the highest. Therefore, it should satisfy the following relation:

$$\text{min } S = \sum_{j \in M} w_j \left( P_{m,j} - P_j \right)^2$$

where $S$ is the objective function; $W_j$ is the weight of real-time measurement of branch power, $w_j = 1 / \delta^2$; $m$ is the branch set for setting the power measuring device; $P_{m,j}$ is the actual measured value of branch active power; $P_j$ is the active power residual value of the branch. To minimize $S$, take the partial derivative of (1):

$$\frac{\partial S}{\partial P_j} = 0$$

Through mathematical derivation, the residual value of active power of each branch at this time can be written as:

$$P_{\text{opt},j} = \sum_{j \in M} w_j P_{m,j} / \sum_{j \in M} w_j$$

where $P_{\text{opt},j}$ is the residual value of the branch active power after the superposition of the active power of each circuit and the initial active power of each branch. Therefore, (4) is always satisfied:

$$P_{\text{opt},j} = P_{0,j} + \sum_{i} \Delta P_{\text{opt},Li} b_{ij}$$

where $P_{0,j}$ is the initial active power of the branch, that is, the power obtained by power flow calculation after closing the whole network switch; $\Delta P_{\text{opt},Li}$ is the optimal solution of active power of each ring network; $b_{ij}$ is an element in the relationship matrix between branch and independent circuit in the distribution network (1 when branch $j$ belongs to independent circuit $i$ and both directions are the same; -1 when branch $j$ belongs to independent circuit $i$ and both directions are opposite; 0 when branch $j$ does not belong to independent circuit $i$).

In the field of electrical engineering, the relationship between variables can be fitted according to the known data, and the method with better fitting effect is the least square fitting. The fitting method is as follows.

Assume that there is a linear relationship between $n$ variables $x$ and variable $y$. To make the linear fitting of them, as showed in (5), then the key point of fitting is to find out $a_j (j = 0,1...n)$.

$$y = a_0 + \sum_{j=1}^{n} a_j x_j y = a_0 + \sum_{j=1}^{n} a_j x_j$$

Let $x_j$ be the $i$th measured value of variable $x_j$, and its corresponding function value is $y_i (i = 0,1...m)$, then the sum of squares of residuals is:

$$s(a_0, a_1, \cdots, a_n) = \sum_{i=1}^{m} (y_i - y)^2 = \sum_{i=1}^{m} \left( y_i - a_0 - \sum_{j=1}^{n} a_j x_j \right)^2$$

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In order to minimize the square sum of residual difference between the variable \( y \) and the actual value \( y_i \), the partial derivative of (6) is obtained, and the measurement data \((x_{ij}, y_i)\) is substituted into it to obtain the unknown parameter \( a_j(j=0,1,\ldots,n)\).

According to (4), \( P_{opt,j} \) and \( n+1 \) variables \((P_{0,j}, b_{1j}, \ldots, b_{nj})\), the objective function of the branch active power residual value based on the least square method can be established by linear fitting:

\[
\text{min } J = \sum_{j=0}^{n} w_j \left[ p_{opt,j} - \left( p_{0,j} + \sum_{i=1}^{n} \Delta p_{opt,Li} b_{ij} \right) \right]^2 \tag{7}
\]

In order to minimize \( J \), the partial derivative of (7) is taken and the known data is substituted into it. The optimal solution of active power of each circuit can be obtained as \( \Delta P_{opt,L1}, \ldots, \Delta P_{opt,Ln} \), and after fitting, the active power residual value equation of each branch can be obtained as:

\[
P = P_0 + \sum_{i=1}^{n} b_i \Delta p_{opt,Li} \tag{8}
\]

3. Genetic algorithm for inverse topology identification of power network

3.1. Overview of genetic algorithm
Due to the large scale of the power network and the high requirement of real-time performance, all possible solutions should not be exhaustive in the process of solving branch correlation matrix[4]. The initial solution can only be evolved continuously under the constraint conditions, and the global optimization search can be carried out to gradually and quickly find the optimal solution to meet the online identification requirements[5]. Therefore, the algorithm's evolution ability and global optimization search ability are required to solve the grid topology reverse identification.

Genetic Algorithm (GA) is a parallel, efficient and global search method that simulates the genetic and evolutionary process of biology. Inheritance can make the good traits of the population continuously passed to the next generation, maintain the characteristics of the population. Variation can change the characteristics of the population and make the population develop towards the direction of adapting to the new environment. Under certain constraints, a series of genetic operations such as selection, crossover and mutation of the current population can generate a new generation of the population, and the fitness calculation can be carried out to judge the adaptability of the population to the environment. Solving process of this algorithm is consistent with the solving requirements of the reverse identification problem of grid topology structure, and GA can be chosen to better realize the solution of the reverse identification problem of grid topology structure.

3.2. Initial population generation
The initial solution of grid topology reverse identification is the branch correlation matrix \( C=(C_{ij}) \). When incoming line \( i \) and outgoing line \( j \) are combined, \( C_{ij}=1 \), otherwise \( C_{ij}=0 \).

However, the solution of the initial branch correlation matrix formed according to the above ideas is not necessarily the real topological correlation matrix of the power network. That is, the loss \( d_{i,ki} \) corresponding to the combination of incoming line \( i \) and outgoing line \( ki \) is not necessarily the line loss corresponding to incoming line \( i \) of the real power network. At some point, \( d_{i,ki} \) may be less than the actual line loss of grid incoming line \( i \). That is, the combination of line 1 and line 1 outbound is not a real branch of the grid, and may lead to interlocking combination errors in the loss calculation of line \( i+1 \) and later in the incoming line matrix. In other words, there is no guarantee that the global optimal solution can be obtained.

3.3. Fitness calculation
After the initial branch correlation matrix population is generated, the fitness \( f_C \) of each branch correlation matrix \( C' \) in the population is calculated to evaluate the fitness degree between the correlation matrix and the real grid topology structure. The correlation matrix with the highest fitness
in the population $R$ is selected as the optimal solution at the current moment. In order to facilitate comparison, the fitness of the association matrix in the population is normalized, as showed below:

$$f_{C_r} = 1 - \frac{F'(C_r) - F_{\min}(R)}{F_{\max}(R) - F_{\min}(R)}$$

(9)

where $F'(C_r)$ is the objective function value of the branch correlation matrix $C_r$; $F'_{\min}(R)$ is the minimum fitness of the branch correlation matrix in the population; $F'_{\max}(R)$ is the maximum fitness of the branch correlation matrix in the population.

3.4. **Algorithm process**

Solving process of power network branch correlation matrix based on the genetic algorithm is shown in Fig.1.

![Fig.1 Flowchart of genetic algorithm](image)

The specific implementation steps are as follows:
1) According to the idea of Section 2.2, an initial branch correlation matrix population $R$ of $N_P$ size is generated according to the principle of minimum branch loss;
2) Calculate the total network loss $F(C)$ corresponding to each branch correlation matrix $C^r$ in population R, the improved objective function $F'(C)$, and the fitness $f^c$;

3) If the objective function $F(C)$ of the correlation matrix in the initial population is equal to the total network loss $F_s$, and the solution is unique, then the optimal correlation matrix is output;

4) Judge whether the maximum number of iterations has been reached, if so, calculate the voltage difference rate $\Delta U$, if $\Delta U=0$, output the optimal correlation matrix, otherwise go to Step 5);

5) Determine whether the loss $F(C)$ corresponding to the branch correlation matrix is equal to the grid measurement calculation loss $F_s$. If not, select, cross, immunize and other operations are carried out, and then go to Step 2). If equality into step 6);

6) Calculate the voltage difference rate $\Delta U$, if $\Delta U=0$, it means that the correct grid topology solution has been obtained, otherwise go to Step 5) until the solution is unique;

7) Output the correlation matrix and end it.

4. Analysis of the example

4.1. Example of actual distribution network

In order to verify the practicality of the proposed topology identification method to the actual distribution network, three feeders R1, R2 and R3 at the voltage level of 10 kV in a certain area were selected for analysis. Their network structure can be referred to [6].

In the calculation example, the measurement data of phase A at 8:00 a.m. on a certain day is selected as real-time measurement and pseudo-load measurement, the load data collected by the electricity charging system is taken as load measurement, and the power measurement updated every 15 minutes by the medium voltage load collected by the metering system is taken as real-time measurement. There are six possible topologies, as showing in Table 1. The objective function values of the six topologies are calculated respectively, and the calculation results are shown in Fig. 2.

| Topological number | R1 and R2 | R1 and R3 |
|--------------------|-----------|-----------|
| 1                  | LN R1-21-R2-2 | LN R1-13-R3-12 |
| 2                  | LN R1-21-R2-2 | LN R1-2-R1-13 |
| 3                  | LN R1-21-R2-2 | LN R3-2-R3-12 |
| 4                  | LN R1-16-R1-21 | LN R1-13-R3-12 |
| 5                  | LN R1-16-R1-21 | LN R1-2-R1-13 |
| 6                  | LN R1-16-R1-21 | LN R3-2-R3-12 |

Fig.2 Objective function values of different topologies

It can be seen from Fig. 2 that the objective function value of No. 1 topology is the smallest, which is the same as the assumed benchmark network topology, proving that the method can accurately identify topology in the actual distribution network.
4.2. Comparison of global optimization efficiency of intelligent algorithms

In order to verify the superiority of the algorithm presented in this paper in global optimization, the immune algorithm, a commonly used optimization algorithm, was selected to invert and identify the topological structures of the IEEE 39-node system and the IEEE 118-node system by using the combinatorial optimization mathematical model proposed in the text, and the time needed to obtain the final inversion topological structures was recorded, as shown in Table 2.

Table 2 Comparisons of search efficiency of each algorithm

| The system category | Immune algorithm | GA |
|---------------------|------------------|----|
| IEEE 39             | 20               | 0.30 |
| IEEE 118            | 35               | 0.33 |

It can be seen from Table 2 that the global optimization time of the genetic algorithm used in this paper on the IEEE39-node system and the IEEE118-node system is 0.3 and 0.33s respectively, which is far lower than the optimization time required by the immune algorithm. The superiority of genetic algorithms in solving the global optimal combination problem in this paper is verified. The method presented in this paper can realize the online identification of grid topology structure and has a wide range of engineering application value.

5. Conclusion

Aiming at the current situation of topology error detection difficulty of distribution network, this paper proposes a distribution network topology identification method based on branch active power. A topology recognition method of distribution network based on combined branch active power and GA is proposed. The branch active power residual algorithm is used to identify the topological structure. The topology obtained by this method has the highest matching degree with the real-time measured data. Numerical examples show that this method can effectively identify the accurate topology structure of the distribution network, and have good adaptability in the case of a large number of measurement errors. It is simple and fast to realize, especially suitable for a small scale distribution network.

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