Distribution network topology identification method based on matching loop power

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Abstract. The topology of the distribution network often changes during routine maintenance and expansion. In addition, the real-time measurement data and the number of configured sensors is limited, and the switch state lacks real-time telemetry, which causes the topology generator to often fail to obtain actual structure of distribution network. At present, the common topology identification methods are not well adapted to the above characteristics of the distribution network. Therefore, in order to avoid the state estimation distortion of the distribution network caused by serious errors in the distribution network topology, a new topology identification method is proposed. The method determines the possible topologies based on the matching loop power and performs state estimation on the possible topologies based on the common measured values. According to the state evaluation result and the measured value, thereby based on the highest matching degree, it is determined that the topology is a trusted topology, that is, an actual topology. The proposed method realizes the quantitative evaluation of the topology, simplifies the topology identification process, and reduces the computational complexity of the topology identification process. Finally, the effectiveness and practicality of the method are verified through related cases.

1. Introduction
The state estimation of the distribution system plays a vital role in the distribution automation management system (DMS) which controls the power output of the distribution network. The correct topology has an important impact on the rationality of the distribution system state estimation results. Due to the limited number of real-time measurements and sensors in the power distribution system, and the topology of the distribution network often change due to various factors such as reconstruction and expansion, the topology structure obtained by the topology generator has a large deviation from the actual structure. When the topology results in serious errors, it will affect the normal operation of DMS. Therefore, researches on the identification method of distribution network topology are getting more and more attention.

At present, there are various identification methods for distribution network topology, such as residual method [1], information loss minimum method [2], transfer power method [3], rule method [4], information chart method [5], etc. However, these methods have certain deficiencies, for example, the Bayesian formula iteration and empirical judgment based distribution network topology identification method [6] lacks of quantitative evaluation of the topology structure. The calculation process of topology identification method based on the branch current [7] is complicated, the amount of calculation data required is large, and the is not applicable for the case where the topology of the
distribution system is incorrect. The neural network-based topology identification method [8] has poor adaptability to distribution networks with large scale and frequent network structure changes. Based on the topology identification method of the rule method [9], when the structure of the distribution network changes dynamically, a complete rule base cannot be established effectively. It can be seen that the current common topology identification methods cannot adapt to the dynamic changes of the distribution network structure and the characteristics of insufficient measurement data of the distribution network [10].

Aiming at overcoming the shortcomings of the existing distribution network topology identification methods, according to the assumption that there is at least one branch power measurement device in each loop of the distribution system, a topology matching structure identification method based on optimal matching loop power and a method to quantify the trusted topology are proposed. The correctness and practicability of the method are proved by a case study.

2. Matching loop power and calculation model

2.1. Optimal matching loop

Figure 1 is a diagram of a single loop power distribution system with power measurement devices mounted on branches 2-9. The system runs in a ring shape under normal conditions. Assuming that the system adds a branch power of 10-11 in the opposite direction but the same value, the current and power of the 10-11 branch are reduced to zero, and the other nodes are subject to tidal current changes. After the power flow calculation, it is found that the value change of each node of the system is exactly the same as that of the 10-11 branch after increasing the power of the loop. Therefore, it can be concluded that when a branch in the loop is disconnected, the change in the power flow can be approximated by adding a corresponding branch power to the loops in the distribution network. Taking the branch 10-11 as an example, assume that the power of the branch 10-11 is \((P^0, Q^0)\) when the system is in the ring operation, and the power measurement value of the branch 2-9 is \((P^m, Q^m)\) when the branch 10-11 is disconnected, then the loop power can be taken as:

\[
\begin{align*}
\Delta P &= P^0 - P^m \\
\Delta Q &= Q^0 - Q^m
\end{align*}
\]  

(1)

When the distribution network is operated by a ring-shaped radiation structure, it is difficult to determine which branch is in an open state. The search can be based on the superposition principle of the loop power. The specific method is as follows: (1) The branch power is initialized. Through the power flow calculation, the power of each branch when the whole network switch is in the closed state is obtained, and this value becomes the initial power of the branch; (2) Calculate the residual power of the branch. Using the initial power of the branch to superimpose the different loop powers, find the loop power corresponding to the highest matching degree between the measured power and the iterative value, which is the optimal matching power. At this time, the power of each branch is the residual power of the branch; (3) Determining the fault Expenditure road. Selecting the branch residual power value minimum branch means that the branch is disconnected.

![Figure 1. Simple distribution system diagram.](image)

2.2. Loop and branch relationship matrix

Before the power flow calculation of the power distribution system, the loop and branch relationship matrix B needs to be determined. Next, a brief introduction to the relationship between the loop and
the branch is given. The dimension of the loop and branch matrix \( B \) is determined by the distribution network structure. When there are \( m \) independent loops and \( n \) branches in the distribution network, the distribution network loop and the branch matrix \( B \) are \( m \times n \) dimensional matrices. The value of each element in the matrix is \( b_{ij} \), where \( i \) is the number of rows of matrix \( B \), that is, the independent loop value of the power distribution system, and \( j \) is the number of columns of matrix \( B \), which is the value of the branch of the power distribution system. The \( b_{ij} \) value is related to the branch and loop direction. When the branch \( j \) belongs to the independent loop \( i \) and the directions are the same, \( b_{ij} = 1 \), and if the branch \( j \) does not belong to the independent loop \( i \), \( b_{ij} = 0 \), otherwise, \( b_{ij} = -1 \). As shown in Figure 1, the system consists of 12 branches and 1 independent ring. The direction of the selected loop is counterclockwise, and the direction of the branch is the direction of numerical growth, that is, the current is assumed to flow from the node with the decimal value to the node with the large number. From this, the independent loop and branch relationship matrix of Figure 1 can be obtained as follows:

\[
B = \begin{bmatrix}
0 & 1 & 1 & 1 & 1 & 0 & -1 & -1 & -1 & -1 & -1 & -1
\end{bmatrix}
\]

2.3. Multi-loop matching loop power and objective function

To determine the topology, the following programming problem is proposed, where the topology with the smallest residual power of the all branches with sensors is solved:

\[
\min J = \sum_{j \in M} \omega_j \left[ \left( P_i^m - P_i^0 - \Delta P_i \right)^2 + \left( Q_i^m - Q_i^0 - \Delta Q_i \right)^2 \right]
\]

where \( \omega_j \) is the real-time measurement weight, \( \omega_j = 1/\delta_j^2 \), \( \delta_j^2 \) is the real-time measurement error; \( M \) is the set with the measuring device; \( P_i^m \) is the measured value with loop power; \( Q_i^m \) is the measured value without loop power; \( P_i^0 \) and \( Q_i^0 \) are the initial power of the \( j \) branch, that is, the power when all the switches in the power distribution network are in the closed state; \( \Delta P_i \) and \( \Delta Q_i \) are the superposition of the power of each loop in the branch \( j \); \( n \) is the number of loops; \( \Delta P_i \) and \( \Delta Q_i \) are The loop power of loop \( i \); \( b_{ij} \) is the element of the independent loop and branch relationship matrix.

The optimal loop power corresponds to the minimum value of \( J \), so the necessary conditions are:

\[
\begin{align*}
\frac{\partial J}{\partial \Delta P_i} &= 0 \\
\frac{\partial J}{\partial \Delta Q_i} &= 0
\end{align*}
\]

The optimal loop power calculation formula derived from Equation (4) is:

\[
\begin{align*}
\Delta P_{i,\text{opt}} &= \sum_{j \in M} \omega_j \left( P_i^m - P_i^0 \right) / \sum_{j \in M} \omega_j \\
\Delta Q_{i,\text{opt}} &= \sum_{j \in M} \omega_j \left( Q_i^m - Q_i^0 \right) / \sum_{j \in M} \omega_j
\end{align*}
\]

where \( \Delta P_{i,\text{opt}} \) and \( \Delta Q_{i,\text{opt}} \) are the average optimal loop power, and the value should be the optimal loop power of each branch, which always satisfies the following relationship:

\[
\begin{align*}
\Delta P_i &= \sum_{j \in M} b_{ij} \Delta P_{i,\text{opt}} \\
\Delta Q_i &= \sum_{j \in M} b_{ij} \Delta Q_{i,\text{opt}}
\end{align*}
\]

where \( \Delta P_{i,\text{opt}} \) and \( \Delta Q_{i,\text{opt}} \) are the optimum loop power for each branch.

The Equations (5)(6) are composed and converted into the least squares method (7). The objective function \( S \) of the optimal matching loop is mathematically derived:
3. Determination of topological relationship

Distribution network load measurement is generally obtained by load prediction method, called load pseudo-measurement. The branch initial power \((P_0, Q_0)\) can be obtained from the load pseudo-measurement calculation. The optional matching loop power for each individual loop is then calculated according to the method described in Section 1. In determining the distribution network after the matching loop power is optional, the residual power of each branch can be solved by matrix operation. The specific solution method is as follows:

\[
\begin{align*}
\{ P &= P_0 + B^T \Delta P^{opt} \\
Q &= Q_0 + B^T \Delta Q^{opt}
\end{align*}
\]

After determining the residual power of each branch, the possible topology results of the distribution network can be selected according to the pair value, and the trusted topology is used as the Real distribution network topology.

3.1. Possible topology

With the improvement of the automation level of the power distribution system and the application of more advanced load forecasting algorithms such as Advanced metering infrastructure (AMI), the accuracy of the load pseudo-measurement is improved. In order to reduce the calculation error caused by the load pseudo-measurement error and the network loss, in the calculation, according to the actual situation, several branches with the smallest residual power in each loop are selected as the selection target of the disconnected branches. For loops with more branches and poor pseudo-measurement accuracy, several branches can be selected as an alternative. For loops with fewer branches and less false measurement errors, fewer options can be selected. Considering the calculation rate, it is recommended to select 2 to 4 branches as an alternative. When \(n\) branches are selected, that possible topology can be determined.

For the distribution system of the common branch in the middle of different loops, the following three special conditions are selected when the branch is disconnected:

1. Select the same branch as an open circuit in different circuits;
2. Different branches are selected as disconnects in different circuits, but the two branches belong to the common branch of different circuits;
3. Among the different disconnects selected in different circuits, one is a common branch and the other is not a public branch.

The topology determined by case (1) and case (2) does not meet the assumption of radial operation of the distribution network, so such topology needs to be excluded. The topology determined by case (3) can be calculated as a possible topology. When there is a real-time measuring device in the branch, this branch can no longer be used as a candidate for the disconnected branch. After this processing, the useless topology can be effectively reduced.

3.2. Determination of trusted topology

According to the above expression, there are \(n\) possible topologies for a particular power distribution system. Then you can find a trusted topology by the following methods. First define the topology matching objective function:

\[
\min J' = \sum_{i \in H} \omega_i \left| z_{meas} - z_{esti} \right|
\]

where \(z_{meas}\) is the real-time measurement value; \(z_{esti}\) is the real-time measurement estimation value; \(H\) is the real-time measurement set; \(\omega_i\) is the real-time measurement weight, \(\omega_i = 1/\delta^2\), and \(\delta\) is the real-time measurement error.
5

$J'$ is calculated from the common measured values in each possible topology. And the correct topology has the highest matching and the smallest $J'$ value. Therefore, the topology with the smallest $J'$ value is chosen as the correct topology.

4. Case studies

To verify the proposed topology identification method, we select the 69-bus power distribution system shown in Figure 2 to be tested. The measurement configuration position is shown in Table 1. The system has a reference value of 1 000 kV·A and a line voltage reference of 10 kV.

Table 1. Installation meter distribution table.

| Branch number | Power measurement device | Current measurement device |
|---------------|--------------------------|---------------------------|
| 1-2           | √                        |                           |
| 14-15         | √                        |                           |
| 63-64         | √                        |                           |
| 4-36          | √                        |                           |
| 3-4           |                          | √                         |
| 5-6           |                          | √                         |
| 7-8           |                          | √                         |
| 15-16         |                          | √                         |
| 17-18         |                          | √                         |
| 19-20         |                          | √                         |
| 22-23         |                          | √                         |
| 3-28          |                          | √                         |
| 30-31         |                          | √                         |
| 33-34         |                          | √                         |
| 3-59          |                          | √                         |
| 61-62         |                          | √                         |
| 65-66         |                          | √                         |
| 67-68         |                          | √                         |
| 36-37         |                          | √                         |
| 8-40          |                          | √                         |
| 9-42          |                          | √                         |
| 44-45         |                          | √                         |
| 47-48         |                          | √                         |
| 49-50         |                          | √                         |
| 51-52         |                          | √                         |
| 11-55         |                          | √                         |
| 12-57         |                          | √                         |

![Figure 2. 69-bus wiring diagram of distribution network.](image)
The branch 11-66, 13-21, and 39-48 are disconnected to form the reference topology of the distribution network, and the power flow calculation is performed under the reference topology. All the measured values in the example are obtained by adding the error to the calculated value of the power flow, and the measurement errors are subject to the Gaussian distribution. The measured value is calculated according to Equation (10).

\[ z = h_{\text{flow}} \left( 1 + \delta_{\text{err}} \right) \]  

(10)

where \( \delta_{\text{err}} \) is the random error of the Gaussian distribution; \( h_{\text{flow}} \) is the measured true value; \( z \) is the measured value.

The programming calculation is performed by MATLAB, and the calculation is carried out under two cases with different errors. The carrying error value is set as shown in Table 2.

| Case number | Power measuring error | Current measuring error | Load pseudo-measuring error |
|-------------|------------------------|-------------------------|-----------------------------|
| 1           | 0                      | 0                       | 20                          |
| 2           | 0                      | 0                       | 40                          |
| 3           | 0                      | 0                       | 80                          |
| 4           | 10                     | 0                       | 80                          |
| 5           | 20                     | 0                       | 80                          |

Table 2. Measurements with different errors.

| Case number | L1          | L2          | L3          |
|-------------|-------------|-------------|-------------|
| 1           | 11-66       | 13-21       | 39-48       |
| 2           | 65-66       | 20-21       | 38-39       |
|             | 64-65       | 19-20       | 37-38       |
|             | 11-66       | 13-21       | 39-48       |
| 3           | 65-66       | 20-21       | 38-39       |
|             | 64-65       | 19-20       | 37-38       |
|             | 11-66       | 13-21       | 39-48       |
| 4           | 65-66       | 20-21       | 38-39       |
|             | 64-65       | 19-20       | 37-38       |
|             | 11-66       | 13-21       | 39-48       |
| 5           | 65-66       | 20-21       | 38-39       |
|             | 64-65       | 19-20       | 37-38       |

Table 3. The first 3 branches with the smallest residual power in each ring network.

| Topological relationship | Disconnected branch |
|--------------------------|---------------------|
| 1                        | 11-66               |
| 2                        | 11-66               |
| 3                        | 11-66               |
| 4                        | 11-66               |
| 5                        | 65-66               |
| 6                        | 65-66               |
| 7                        | 65-66               |
| 8                        | 65-66               |
In the case of different measurement errors, assuming that all switches are in the closed state, the residual power of each branch is calculated by the power flow calculation, and the three branches (L1, L2, L3) with the smallest residual power are taken as the branches that may be disconnected. According to the calculation result, the branches that may be disconnected are summarized to obtain Table 3. It can be seen from Table 2 that the calculations with different measurement errors are performed, and the possible disconnected branches are identical. And since the branches 64-65, 19-20 and 33-38 are equipped with current measuring devices, thereby eliminating three branches, finally eight possible topologies are obtained and summarized in Table 4.

5. Conclusions
Through analysis, the following conclusions are obtained:

(1) The proposed topology identification method based on matching loop power is more effective for case where there are the dynamic changes of distribution network structure and the shortage of measurement data of distribution network;

(2) It is found that in the test cases the method can effectively identify the topology of the distribution network and quickly determine the disconnected branches based on the residual power of the branch;

(3) The proposed topology identification method is not susceptible to the measurement errors, and its practicality and reliability are higher in the actual application process.

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