Improved Fault Location Algorithm for Radial Distribution Network Based on PowerFailure Information

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Abstract. As the scale of the distribution network continues to increase, the importance of distribution network is getting higher and higher. Therefore, it is necessary to achieve fault location and restore it as soon as possible after the fault occurs. This paper proposes a new fault location algorithm for the radial distribution network, which is improved on the basis of traditional matrix algorithm. First, the power failure incidence matrix (PFIM) and power interruption information matrix (PIIM) is constructed based on the topological connection and fault information at each node. The fault location matrix (FLM) is then obtained through PFIM and PIIM to realize the fault location. Second, the accuracy of the proposed algorithm is verified by mathematical derivation. Finally, an 11-node radial distribution network is illustrated to testify the proposed algorithm. Results show that the improved fault location matrix algorithm proposed in this paper can effectively achieve fault location in radial distribution network.

1. Introduction
With the development of smart grid, the system needs to have the ability to quicker respond for the purpose of security[1]. Thus, it is necessary to fulfil fault location accurately, so that quick restoration can be achieved[2]. In recent years, many researches have been focused on fault location. The existing algorithm they use can be basically divided into three types: matrix algorithm, optimization algorithm and the combination of them. Reference [3] presents a unified matrix algorithm involving a describing matrix and a fault information matrix, with which the fault section can be detected and isolated correctly. Based on [3], a synthesis matrix algorithm is presented in [4], which makes full use of system's structural characteristics and sets two kinds of work patterns in FTU. Similarly, reference [5] proposes a modified matrix algorithm with the structure characteristics of distribution network, which has less computation without complex computing and good real-time performance. Reference [6] proposes a matrix algorithm on the basis of sub-network partition. Obviously, matrix algorithm is mainly used in reference[3-6]. Meanwhile, some of the works have been done through optimization algorithm. Reference [7] presents a new mathematical model of the fault sections identification and a refined genetic algorithm using the model as the fitness function is developed. Reference [8] proposes a novel complementarity constraints fault location model based on algebra relationship and complementary theory. Results shows it has high
fault tolerance performance, good numerical stability and high optimization efficiency. In [9], an absolute value model is presented on algebra descriptions-based approximation relationship approach. Three simulation examples validate this model. Besides, some literatures using the combination of matrix algorithm and optimization algorithm. Reference [10] proposes a comprehensive approach which combines the advantages of both methods. Reference [11] proposes a mathematical model of fault location involving auxiliary partition and discrete intelligent optimization algorithm. Although existing researches have attained certain achievements, short-circuit current information is mainly used to achieve fault location. In the actual operation of the distribution network, power interruption information is often available instead of short-circuit current information. Therefore, most of the previous achievement cannot be put in practice use. Based on the power interruption information, this paper improves the traditional matrix algorithm and establishes a new algorithm for fault location.

2. Improved Fault Location Matrix Algorithm

The improved fault location matrix algorithm (IFLM) can be specified as the following subsection.

2.1. Numbering principle of nodes and lines

First, nodes and lines should be numbered in the network for the sake of clarity. The numbering principle is quite simple. Start from the location of power supply and expand from small to large according to Arabic numerals until all nodes in the network are traversed. In addition, line numbers need to be corresponded to the node number at the end of each line (the node far from the location of power supply), as shown in Figure 1.

![Figure 1. Line and node number of a simple network](image)

In Figure 1, N represents the node, L represents the line, and the power supply locate at N0. Obviously, the number of each line corresponds to the number of the node at its end.

2.2. Power failure incidence matrix

The incidence matrix established in the existing literature is mostly based on the topological connection between nodes, which can only reflect the upper-lower relationship between nodes, failing to reflect the correlation of power interruption between nodes. Therefore, we improve the causal correlation matrix (CCM) established by reference [10] to form the PFIM. Unlike reference [10], power interruption information is used instead of short-circuit current. When line j fails, if node i loses power, \( A_{ij} \) is defined as 1. Otherwise, \( A_{ij} \) is defined as 0 as follows:

\[
A_{ij} = \begin{cases} 
1 & \text{When line j fails, node i loses power, } 0 < i, j \leq n \\
0 & \text{When line j fails, node i doesn't lose power, } 0 < i, j \leq n 
\end{cases}
\]  

(1)

It should be noted that in radial distribution network, since the power supply path of each line is unique, which stands for the number of lines is the same as the number of end nodes, that is, the power failure incidence matrix \( A \) is a square matrix of order \( n \). In addition, if a fault occurs on the line, the terminal node indeed occurs power interruption. Hence, the column of matrix \( A \) is full of rank, namely, matrix \( A \) is invertible. Furthermore, comparison between the power failure incidence matrix established by us and the causal correlation matrix established in [10] may reveal that the two matrices are transposed to each other. Interested readers can prove this for themselves.
2.3. Power interruption information matrix

Power failure information matrix (PIIM) is used to describe the state of nodes in the network, which can be represented by an n-dimensional column vector $B$. It is defined as follows:

$$B^{(i)}_j = \begin{cases} 1 & \text{When line } j \text{ fails, node } i \text{ loses power, } 0 < i, j \leq n \\ 0 & \text{When line } j \text{ fails, node } i \text{ doesn't lose power, } 0 < i, j \leq n \end{cases}$$

(2)

Where $i$ refers to the element in vector $B$, $j$ refers to the line. Each line $j$ corresponds to a vector $B_j$.

2.4. Fault location matrix

Fault location matrix is used to identify the specific line where the fault occurred. Based on the power failure incidence matrix $A$ and the power interruption information matrix $B$, the fault location matrix $C$ is defined as the product of the inverse of $A$ and $B$ as follows:

$$C_j = A^{-1}B_j$$

(3)

Obviously, $C$ is a n-dimensional vector (the same as $B$) whose element composed of 0 and 1. In particular, the number of 0 element is (n-1) and the number of 1 element is 1. And this will be proved in the 3rd section. Furthermore, it should be noted that the row in $C$ where element 1 located refer to the line where fault occur.

2.5. Algorithm flow

Based on 2.1-2.4, the process of the improved fault location matrix algorithm can be expressed as follows:

| Algorithm | Start |
|-----------|-------|
| Step 1 | Number nodes and transmission lines in distribution network |
| Step 2 | Form power failure incidence matrix $A$ according to 2.2 |
| Step 3 | Obtain power interruption information matrix $B$ in terms of 2.3 |
| Step 4 | Let fault location matrix $C = A^{-1}B$ according to 2.4 |
| Step 5 | Output fault location result |

End

3. Mathematical Derivation

According to the definition of the power failure incidence matrix $A$, it is not difficult to see that the element in the jth column of $A$ represents whether there is a power interruption appears at node $i$ when line $j$ fails. meanwhile, power failure information matrix $B_j$ refer to the state at node $i$ when line $j$ fails. Hence, when line $j$ fails, the jth column of matrix $A$ equals $B_j$. Then we get $A = (B_1, B_2, \cdots B_n)$, let

$$D = A^A = A^{-1}(B_1, \cdots B_n) = E = \begin{pmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{pmatrix} = (C_1, \cdots C_N) \Rightarrow \begin{pmatrix} A^{-1}B_1 = C_1 \\ \vdots \\ A^{-1}B_N = C_N \end{pmatrix}$$

(4)

Obviously, a unit matrix can be obtained after the product of $A^{-1}$ and $A$, where $C_j$ is the jth column of that unit matrix. Hence, $C_j$ is a unit vector involving only one element is 1, the row of which is j. Besides, when line $j$ fails, let
\[ C_j = A^{-1}B_j = (0 \cdots 1 \cdots 0)^T \Rightarrow \text{line } j \text{ fails} \]  

Hence achieving the fault location and validating the accuracy of IFLM algorithm.

4. Case Study
Take a relatively complex radial distribution network as an example to achieve fault location. All the experiments are implemented in the MATLAB R2019a on a computer with Intel(R) Core(TM) i7-10710U CPU @1.10Ghz and 16GB memory. The network has 11 lines and 11 nodes with the power supply locating at left, as shown in Figure 2.

First, number the network according to the principles presented in Section 2.1. Result is shown in Figure 3. It is obvious that all the line numbers are the same as the numbers of the end nodes. Then obtain the power failure incidence matrix \( A_{11 \times 11} \), which can be visualized in Figure 4.

The position where element 1 located is marked in red while the position of element 0 is not marked. It can be seen that \( A_{11 \times 11} \) is a column full-rank matrix, which is consistent with the discussion in Section 2.2. Besides, \( \text{nz}=33 \) refer to the number of non-zero elements in the matrix are 33.

Supposing that the faults occur on L2, L6 and L9 respectively, FLM can be obtained through PFIM and PIIM. Visualize them as previous, we can get the vector shown in Figure 5, Figure 6 and Figure 7 respectively. The position where line fails is marked in blue. Results validate again the improved fault location algorithm proposed in this paper.

5. Conclusion and Future Work
A new fault location algorithm is proposed in this paper based on the traditional matrix algorithm. The power failure incidence matrix and power interruption information matrix are established using power cut-off information instead of short-circuit current. The accuracy of the proposed method is verified
from two levels of mathematical derivation and case study on a 11-nodes, 11-lines topological network. However, this method can only work in radial distribution network, where there are no current flow direction changes. As the penetration of distributed generators is getting higher and higher in the distribution network, the operating mode of the distribution network has undergone great changes. It means that there is no longer a traditional single current flow direction. Therefore, subsequent research will focus on the fault location of distribution network with high proportion distributed power sources, namely active distribution network. Meanwhile, new algorithm adapted to it should be studied.

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