A Comprehensive Method for Fault Location of Active Distribution Network Based on Improved Matrix Algorithm and Optimization Algorithm

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The traditional fault location methods are not effective for the multisource active distribution network and are difficult to meet both requirements of timeliness and fault tolerance simultaneously. In this paper, a fault location method for active distribution networks which combines both improved matrix algorithm and optimization algorithm is proposed. The improved matrix algorithm is constructed to determine the fault section hypothesis by using the causal relationship between the alarm information and the fault section. Subsequently, network splitting is used for causal verification to check whether the alarm information is distorted. If the alarm information is normal, the fault sections can be quickly located by the above matrix algorithm. If the alarm information is distorted, the optimization model is constructed by using the fault section hypothesis selected by the matrix algorithm. The discrete particle swarm optimization (DPSO) algorithm is used to solve this optimization model, which can accurately locate the real fault sections. Hence, the advantages of both matrix algorithm and optimization algorithm are complementary. Simulation results show that the proposed method has the advantages of both high timeliness and fault tolerance in a complex active distribution network.

1. Introduction

When a short fault occurs in the distribution network, the breaker will be tripped off by the protective devices at the outlet of the feeder. The rapid and accurate location of fault sections is an effective premise for fault isolation and power supply recovery, which is of great significance to ensure both safe and stable operation of a system and therefore to improve the reliability of the power supply [1, 2]. Reclosers and sectionalizers are used to locate the fault in the traditional distribution network. However, a long delay is required in this method, and it may reclose to a fault again, which will impose an adverse influence on the power system. With the development of distribution automation systems and monitoring devices, DTU and FTU are gradually popularized, which can monitor the electrical status and alarm state during the operation of the distribution network and will timely upload the electrical information to the data center (SCADA) after fault detection. On this basis, some fault location methods are proposed for the active distribution network, such as expert system (ES) [3], artificial neural network (ANN) [4, 5], Petri nets [6], the rough set method [7], linked-list method [8, 9], matrix algorithm [10–15], and optimization algorithm [16–30]. Among them, the matrix algorithm and the optimization algorithm are widely used in the practical distribution network.

The matrix algorithm constructs the fault information matrix based on the alarm information uploaded by FTU. Matrix algorithm can quickly locate the fault section. In recent years, many improved matrix algorithms are studied. In [13], a matrix algorithm based on the network structure is constructed, which can simplify the solution process and improve the location efficiency. In [14], a matrix algorithm based on master-slave regional pilot protection is proposed,
which realizes fault section location by using the station area and wide area information. In [15], the fuzzy causal network (FCE-NETS) is used to express the causal relationship between fault location and alarm information, which has a certain inferential capability. The essence of the matrix algorithm is using the different alarm information on both sides of the fault section to realize fault identification. Thus, the implementation process of the matrix algorithm is relatively simple and the fault location speed is fast. However, the misjudgment of fault location may occur when the alarm information is distorted.

The optimization algorithm establishes the 0-1 integer optimization model based on the indicator state approximation and locates the fault section. In [16], the reason for multiple solutions in the optimization model is analyzed, and the constraint of "minimum set" is introduced into the objective function to improve the fault tolerance of the algorithm. In [17], the logical operation in the objective function is improved to the algebraic operation, and the complementary constraint programming model is constructed for fault location, which reduces the difficulty of solving the model. In [18], an analytical model for fault location in the case of alarm information distortion is established, which improves the fault-tolerant capability of the model. In [19], a layered fault location algorithm for the problem of low accuracy and efficiency in the case of multiple faults is designed, which improves the solving efficiency. In addition, genetic algorithm (GA) [20], pseudoelectromagnetism algorithm [21], particle swarm optimization (PSO) [22], imperial competition algorithm (ICA) [23], cuckoo search (CS) [24], harmony search (HS) [25], and many other artificial intelligence algorithms have been introduced into this field in recent years. The principle of the optimization algorithm is to construct the objective function based on the indicator states, which can fully excavate the redundant correlation between the alarm information and the fault section. Therefore, the optimization algorithm provides better fault tolerance compared to the matrix algorithm. However, the modeling of the optimization algorithm is complex, the solving speed of the optimization model is slow, and the solution may not converge or fall into local optimum in the large-scale distribution network.

In addition, most of the above studies are only applicable to the radiation distribution network. With the widespread use of distributed generation and energy storage, the traditional fault location methods cannot be applied in the active distribution networks directly. In [26], the adaptive objective function and corresponding optimization model with the consideration of the switching of the distributed generation are established, which can locate the correct faults yet the efficiency is low. In [27], a bat-difference hybrid algorithm is used to solve the optimization model of the complex multipower distribution network, which can improve the convergence of the algorithm. In [28], an optimization model of nonlogical operation is established, which can be directly solved by linear programming, but the method cannot solve the problem of multiple fault locations. In [29], the electricity information acquisition system is proposed as the second information source of fault location, proposed the multisource information fault auxiliary partition method, and then used the discrete intelligent optimization algorithm to solve it. In [30, 31], an efficient analytical method is proposed for optimally installing multiple distributed generation technologies to minimize reactive power loss in distribution systems. This method can optimize the access location of distributed generation according to the optimal power target, which changes the topology of the distribution network. At this time, the proposed fault location method should overcome the adverse effects of topology changes.

In general, the disadvantage of the existing fault location methods is that the fault tolerance and timeliness are difficult to be balanced. In particular, for complex multipower distribution networks, it is difficult for the existing methods to consider the interaction effect of multiple faults on the objective function, resulting in poor performance in the location of multiple complex faults.

Aiming at the above problems, a fault location method is proposed in this paper based on the combination of improved matrix algorithm and optimization algorithm for active distribution networks. Compared with the existing methods, the proposed method provides strong timeliness and fault tolerance and high adaptability due to the complementation of the advantages of the matrix algorithm and optimization algorithm. In the case of no alarm information distortion, only the matrix algorithm is used to locate the fault sections quickly. In the case of alarm information distortions, the suspicious fault section set is screened by the matrix algorithm first. Then, the optimization algorithm is used to further judge the fault position. The effectiveness of the proposed method has been verified by various simulation examples. These two algorithms not only solve the defect that the optimization algorithm is easy to fall into local optimum but also improve the solving speed and accuracy of the optimization algorithm, considering the timeliness and fault tolerance of fault section location.

2. Improved Matrix Algorithm

Most of the existing matrix algorithms build fault judgment matrix based on the connection relationship between nodes and devices only, and the covered information is relatively single. Therefore, the rules for fault section identification are generally complex, and the physical meaning of matrix description is not clear. In this paper, a matrix description of the distribution network is established based on the causal relationship between the fault assumption and indicator alarm information, and an improved matrix algorithm is proposed.

2.1. Radial Distribution Network with a Single Power Source.

For the single-source radial distribution network with m nodes and n sections, its causal association matrix \( A \) is of \( m \times n \) dimension, which is defined and shown in the following:
\[
A_{ij} = \begin{cases} 
1, & \text{in the event of a fault in section } j, \text{ indicator } i \text{ has an overcurrent alarm}, \\
0, & \text{in the event of a fault in section } j, \text{ indicator } i \text{ has no overcurrent alarm}.
\end{cases}
\]  \tag{1}

For the single power source radial distribution network \[32\], the power supply path of each section is unique, only one end of each section is connected to the power supply, and the number of sections is equal to the number of fault indicators, so the causal association matrix \( A \) is invertible. In addition, according to the definition of the causal association matrix, each column element of matrix \( A \) corresponds to the indicator overcurrent alarm sequence when the associated section of the column has a fault separately. Since the power supply circuit of each section is independent of each other, the causal association matrix must be a column full rank matrix. Therefore, it can be concluded that the causal association matrix \( A \) must be an invertible matrix for the single power source radial distribution network.

Corresponding to the causal association matrix, the \( n \times 1 \)-dimensional column vector matrix \( B \) is used to represent the indicator alarm information of the distribution network, and its elements are, respectively, corresponding to the indicator alarm state. If the FTU emits an overcurrent alarm, the state is 1; otherwise, it is 0. Similarly, the section state information of the distribution network is represented by the \( m \times 1 \)-dimensional column vector matrix \( C \) and its elements correspond to the fault state of the section, respectively. If a fault occurs in a section, the state is 1; otherwise, it is 0.

Taking the simple distribution network in Figure 1 as an example, its network matrix is described as follows:

\[
A = \begin{bmatrix}
S_1 & L_1 & L_2 & L_3 & L_4 \\
S_2 & 1 & 1 & 1 & 0 \\
S_3 & 0 & 1 & 1 & 0 \\
S_4 & 0 & 0 & 1 & 0
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
B_{S_1} & B_{S_2} & B_{S_3} & B_{S_4}
\end{bmatrix}^T
\]

\[
C = \begin{bmatrix}
C_{L_1} & C_{L_2} & C_{L_3} & C_{L_4}
\end{bmatrix}^T
\]  \tag{2}

Since the above network matrices are all logical matrices, the logical operation \( "Y = [X]^T" \) is defined: \( X \) and \( Y \) are the logical real matrices of the same dimension; if \( X_{ij} > 0 \), then \( Y_{ij} = 1 \); otherwise, \( Y_{ij} = 0 \). On this basis, according to the definition of causal association matrix, each matrix must satisfy \( B = [AC] \). Therefore, this paper constructs the matrix criterion for fault location of distribution network as shown in (3), based on causal relationship and mathematical meaning:

\[
C^* = [A^{-1}B]. \tag{3}
\]

In Figure 1, when a fault occurs in section \( L_3 \), FTU at \( S_1 \), \( S_2 \), and \( S_3 \) issues the overcurrent alarms; i.e., \( B = [1 \ 0 \ 1 \ 1]^T \). Thus, \( C^* = [A^{-1}B] = [1 \ 0 \ 0 \ 1]^T \). It can be seen that the fault section can be located correctly by a simple matrix operation based on the causal relationship.

However, the \( ^{-1} \) operator defined above is not technically and strictly invertible. Therefore, it is necessary to conduct causal verification of the actual alarm information according to the criterion results. If \( B = [AC^*] \) is satisfied, it means that the criterion results can effectively explain the received indicator overcurrent alarm information, so that \( C = C^* \) and the fault section can be determined.

2.2. Active Distribution Network System with Distributed Generations. For the active distribution network with distributed generations, the current detected by FTU can flow in both directions due to multiple power sources in the system. Therefore, this paper firstly defines the direction of the main power supply pointing to the users as the positive direction and extends the definition of causal association matrix \( A \) as shown in the following:

\[
A_{ij} = \begin{cases} 
1, & \text{the overcurrent direction is same}, \\
-1, & \text{the overcurrent direction is different}, \\
0, & \text{no overcurrent alarm},
\end{cases}
\]  \tag{4}

where \( A_{ij} \) is the element in causal association matrix \( A \) and corresponds to the overcurrent information of indicator \( i \) when the fault occurs in section \( j \). If the overcurrent alarm occurs with the same direction as the reference direction, \( A_{ij} \) is 1. If the overcurrent alarm occurs with a different direction as the reference direction, \( A_{ij} = -1 \). If the indicator \( i \) has no overcurrent alarm, \( A_{ij} = 0 \).

Similarly, the direction attribute is introduced for the state matrix \( B \) of fault indicators according to the reference positive direction, and its matrix element is defined as

\[
B_{S_i} = \begin{cases} 
1, & \text{the overcurrent direction is same}, \\
-1, & \text{the overcurrent direction is different}, \\
0, & \text{no overcurrent alarm},
\end{cases}
\]  \tag{5}

where \( B_{S_i} \) is the element in state matrix \( B \) and corresponds to the state of indicator \( i \).

Taking the active distribution network shown in Figure 2 as an example, the direction of the dotted arrow in the figure is the positive direction of reference. According to (4) and (5), its network matrix is described as follows:
Figure 2: Active distribution network with distributed generations.

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

\[
B = \begin{bmatrix}
B_{S_1} & B_{S_2} & B_{S_3} & B_{S_4} & B_{S_5} \\
C_{L_1} & C_{L_2} & C_{L_3} & C_{L_4}
\end{bmatrix}^T
\]

2.3. Causal Verification Method for Multiple Faults Based on Network Splitting. When the result of fault location is multiple faults, the causal verification method in Section A is no longer applicable. The fundamental cause is the possibility of additional power supply between multiple fault sections.

An example is given for the convenience of illustration. In Figure 2, when the faults occur simultaneously in sections \(L_3\) and \(L_4\), the alarm information is correct. The actual alarm of each indicator is \(B = \begin{bmatrix} 1 & 1 & 1 & -1 & -1 & -1 \end{bmatrix}^T\). Substitute the state matrix of the indicator into (7), and the following equation can be obtained:

\[
C^* = [\left(A^T A\right)^{-1} A^T B] = \begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix}^T.
\]  

The location result of the fault section is accurate. However, when the causal verification is carried out,

\[
[AC^*] = \begin{bmatrix} 1 & 1 & 0 & -1 & 0 & 1 \end{bmatrix}^T \neq B.
\]

Indicators \(S_3\) and \(S_5\) have different verification results from expected values, and the causal verification fails. New operator \(\neq\) is introduced because the alarm direction of the indicator may be negative, and the calculation result needs to be processed. The logical operation \(\text{"Y = [X]" is defined: X and Y are the logical real matrices of the same dimension; if X}_{ij} > 0\), then \(Y_{ij} = 1\); if \(X_{ij} < 0\), then \(Y_{ij} = 1\); otherwise, \(Y_{ij} = 0\).

The reason for the failure of causal verification is that the fault sections \(L_3\) and \(L_4\) are located in the upstream and downstream of indicators \(S_3\) and \(S_5\), respectively. In this case, the expected alarm states of indicators \(S_3\) and \(S_5\) show "positive and negative cancellation," which is resolved to 0. However, due to the extra Source 1 between the fault sections \(L_3\) and \(L_4\), indicators \(S_3\) and \(S_5\) show positive overcurrent alarm information, resulting in the wrong causal verification result. Therefore, this paper proposes a causal verification method for multiple faults based on network splitting.

When a fault occurs in a distribution network, the fault current provided by each power source flows from the power source to the fault points. Therefore, taking each fault section as the boundary, the distribution network system can be divided into several subnets, and the causal verification results of each subnet are analyzed separately.

Taking simultaneous faults in sections \(L_3\) and \(L_4\) as an example, the distribution network can be divided into three subnets, as shown in Figure 3. Subnet 1 is composed of Source 1, sections \([L_1, L_2, L_3, L_4]\), and indicators \([S_1, S_2, S_3, S_5]\). Subnet 2 is composed of Source 2, section \([L_3]\), and indicator \([S_4]\); Subnet 3 is composed of Source 3, section \([L_4]\), and indicator \([S_6]\).

In Subnet 1, the block matrix corresponding to indicators \([S_1, S_2, S_3, S_5]\) and sections \([L_1, L_2, L_3, L_4]\) is extracted from the complete causal association matrix \(A\). On this basis, consider that Source 1 provides positive current to the indicators \([S_1, S_2, S_3, S_5]\), then, the causal association matrix \(A_1\) of Subnet 1 can be obtained by retaining only the element “1” in the block matrix. The result is shown as follows:

\[
A_1 = \begin{bmatrix}
1 & 1 & 1 & 1 \\
0 & 1 & 1 & 1 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

Subnet 1 contains sections \([L_1, L_2, L_3, L_4]\), so the state matrix of the sections is \(C^* = \begin{bmatrix} 0 & 0 & 1 & 1 \end{bmatrix}^T\). The causal verification result of fault indicators \([S_1, S_2, S_3, S_5]\) is
breakers since all fault sections are at the “end” of the faults in the subnet after the distribution network is split.

After a similar analysis to Subnet 2 and Subnet 3, the causal verification result of indicator $S_4$ in Subnet 2 is $B_2^* = [A_4C_4^*] = [-1]^T$. Similarly, the causal verification result of indicator $S_4$ in Subnet 3 is $B_4^* = [A_4C_4^*] = [-1]^T$. The causal verification results of the whole system can be obtained by merging the causal verification results of each subnet: $B^* = [B_1^*, B_2^*, B_3^*, B_4^*]^T = [1 1 1 -1 1 -1];$ the causal verification result is correct.

$$B^*[A_1C_1^*], [A_2C_2^*], [A_3C_3^*], [A_4C_4^*]^T.$$  \hspace{1cm} (12)

It can be seen that the network splitting for multiple faults can effectively realize causal verification. In addition, the breadth-first search method is used to realize the network splitting. The basic process is illustrated as follows: start the search from the source access node of the system and stop the downward search if the search reaches the terminal section or the fault section until all the power sources are searched. The result of distribution network splitting is then obtained.

It is worth mentioning that when the location of the fault section obtained by the matrix criterion is a single fault, there is no need to split the network, and the causal verification can be carried out directly. In addition, there is also no need to partition the network for the distribution network without distributed generations (traditional radial distribution network); that is, there is no need to consider the overlapping effects of multiple faults alone. This is because, in the radial distribution network, each fault can only form a fault current in the same direction at the switch, and there is no additional power supply (distributed generations). The expected alarm signal of the switch can be retained in the model after superposition, and there is no positive and negative cancellation of the alarm signals.

### 2.4. Influence of Alarm Information Distortion on Improved Matrix Algorithm

In this paper, the improved matrix algorithm is established based on the causal association relationship with simple rules. The calculation speed of this method is fast because the factor matrix $(A^TA)^{-1}A^T$ can be calculated and stored offline in advance according to the association matrix $A$. However, this method has the same disadvantage of poor fault tolerance as the existing matrix algorithms. When there is distorted alarm information, it tends to misjudge.

For example, in Figure 2, when a fault occurs in section $L_1$, the indicator at $S_1$ shall issue a positive overcurrent alarm and the indicators at $S_2$ and $S_3$ shall issue negative overcurrent alarms. However, if the alarm information at $S_3$ is lost, its alarm signal changes from $+1$ to $0$; i.e., the state matrix of the indicators is $B = [1 -1 1 -1 -1 -1]^T$. The result of fault location is

$$C^* = [(A^TA)^{-1}A^TB] = [1 0 1 0]^T.$$  \hspace{1cm} (13)

Thus, the fault sections are $L_1$ and $L_3$. The method in Section C is used for causal verification:

$$[AC^*] = [1 0 0 -1 -1]^T \neq B.$$  \hspace{1cm} (14)

The causal verification relationship is not satisfied; i.e., the location result is wrong. The correlation matrix $A$ contains causal association constraints between the section and the alarm information, and the fault section is associated with the overcurrent alarm of all indicators between itself and the power supply. Although the distortion of individual alarm information may affect the result, it cannot subvert the ability of the matrix algorithm of indicating the fault section. The true fault section must be contained in a set of extents whose matrix criterion results in “1.”

Therefore, when the causal verification is not satisfied, this paper defines the judgment result of the matrix algorithm as the suspicious section set of the system. In the above case, its suspicious sections set is $\{L_1, L_3\}$, and other nonsuspicious sections can be directly determined as normal sections. There are four fault hypotheses in this set, namely, $\{L_1, L_3\}, [L_i], [L_i]$, and no fault. The dimension of the solution space is 4, and fault-tolerant judgment can be further achieved by the optimization algorithm.

### 3. Fault-Tolerant Judgment Based on the Optimization Algorithm

To further distinguish the suspicious sections, this paper refers to the ideas of existing optimization algorithms and establishes the optimization objective function as shown in the following equation based on the principle of "fault indicators approximation" [33] and "minimum set" [17]:

$$\min f(X) = \sum (B \rightarrow B^*(X)) + \omega \times \sum C(X),$$  \hspace{1cm} (15)
where the objective function is the unconstrained 0-1 integer programming model. The first item represents the approximation between the expected alarm information of indicators and the actual alarm information, and the solution of the set of fault sections that can best explain the alarm information is selected. \( B^* (X) \) is the expected alarm state of each indicator. The second item represents the system’s minimum set constraint, the solution with the minimum number of fault sections is selected, \( \omega \) is the minimum set coefficient, and the value is 0.8. \( X \) is the state hypothesis of each suspicious section of the system. If its element is 1, it means that the corresponding section includes a fault; on the contrary, if it is 0, it means that there is no fault in the section. \( \sum \) operator realizes the sum operation after taking the absolute value of matrix elements. The comparison operation \( Z = X \leftrightarrow Y \) is defined as follows: \( X, Y, \) and \( Z \) are the logical real matrix with the same dimension, respectively, if \( X_{ij} = Y_{ij} \), then, \( Z_{ij} = 0 \); otherwise, \( Z_{ij} = 1 \). According to the physical meaning of the causal association matrix, it is known that the smaller the objectives function is, the more the hypothesis can explain the received alarm information and the greater the probability of the real fault is.

In this paper, discrete particle swarm optimization (DPSO) [34] is used to solve the 0-1 integer optimization model as shown in (15). The relevant parameters are set as follows: the total number of particles is 50; the particle dimension is determined by the number of fault hypotheses provided by the matrix algorithm; the upper limit of particle velocity is 50; the inertia weight decreases linearly, from 0.6 to 0.1, with the number of iterations. Since the dimension of the fault hypothesis is generally small after screening by the matrix algorithm, it can converge to the optimal solution after a few iterations, so the maximum number of iterations of the algorithm is set to 50, and the algorithm terminates when the number of optimization iterations exceeds 50.

The complete process diagram of the active distribution network fault location method is shown in Figure 4. The specific implementation steps are as follows:

1. According to the connection and causality of the distribution network, the causal correlation matrix \( A \), the switching state matrix \( B \), and the section state matrix \( C \) are established to describe the network matrix. Among them, the causal correlation matrix \( A \) can be determined by simulating the alarm situation of individual faults in each section.

2. The overcurrent alarm information of each switch in the distribution network is obtained in real time, and the fault section is preliminarily judged by the matrix criterion. The criterion factor matrix \( A^{-1} \) can be calculated and stored offline according to the causal correlation matrix in advance, thus speeding up the calculation efficiency of online fault diagnosis.

3. According to \( C^* \), the distribution network is divided into several subnets, and the expected alarm state is analyzed and compared with the actual alarm information for causal verification. The location results of the matrix algorithm and the alarm information sequence of the system are compared. If the two are matched, it indicates that the location result is accurate and there is no alarm information distortion. The judgment result of the fault section is directly output. If the two are not matched, it indicates that there is a distortion of the alarm information and the set of suspicious sections is determined by the results of the matrix algorithm.

4. The fault hypothesis is established according to the set of suspicious sections, and the 0-1 integer optimization model is established according to (15). The optimization algorithm is used to solve the model, and the optimal solution is the section state combination that can best explain the alarm information.

5. According to the “1” element in the optimal solution, the real fault section is determined and the location results are output. On this basis, the expected alarm sequence can be analyzed and the distorted alarm information can be evaluated.

![Figure 4: Improved matrix algorithm combined with the optimization algorithm for fault location of active distribution network.](image-url)
The proposed method is mainly used for the emergency disposal of distribution network faults in the power dispatching department. For dispatching emergency response, the short circuit fault of the distribution network line is concerned. The basic goal is to locate the specific fault section according to the alarm information monitored at each switch, which is convenient for dispatching operators to accurately isolate the fault section, reduce the power outage range, and shorten the power outage time. When the topology of the system is changed by reconfiguration, system expansion, or installing other distributed generator types, it is necessary for the power dispatching department to update the causal association matrix $A$ in time according to the changed topological structure to ensure the normal use of the proposed method.

4. Performance Evaluation

To verify the effectiveness of the proposed algorithm, the multi-T wiring radiation distribution network shown in Figure 5 is the local power grid in the county of Wuhan City in China as a reference for modeling. There are 6 breakers, 29 disconnectors, 1 contact switch, and 31 sections. DG1, DG2, DG3, and DG4 represent the distributed generation accesses. The inverter-interfaced distributed generation is used in the simulation, and its basic parameters are shown in Table 1. The control system includes active/reactive power separation outer loop control, low voltage ride through (LVRT) control and protection, and positive and negative sequence double current inner loop control. S1 and S2 represent the system power access points, connected by the main transformer and 110 kV transmission network; the main transformer capacity is 20 MVA. The installed capacity of the distributed generations is 8 MVA, and the proportion of new energy is more than 20%.

It can be analyzed that the state of the contact switch will not change the essential characteristics of the distribution network operation. For the system shown in Figure 5, when the contact switch is closed, the causal association matrix $A$ can be established according to the topology of the distribution network, as shown in Figure 6 (since the matrix dimension is high, circles of different colors represent the values of the association matrix elements for the convenience of typesetting and intuition); when the contact switch is disconnected, the system divides the distribution network into two independent subnets with the boundary of the contact switch. The causal association matrix consisted of the submatrices $A_{N1}$ and $A_{N2}$, as shown in Figure 6. To be more specific, it is the fault location of two isolated systems, which exerts no essential influence on the proposed method.

In this paper, the fault location test is carried out for the typical fault scenarios, only considering the closure of the contact switch. Table 2 shows the results of fault section location in some scenarios. In the table, examples $N1 \sim N2$ and $N5 \sim N9$ are the location results under the normal condition of alarm information, while examples $N3 \sim N4$ and $N10 \sim N13$ are the location results under the condition of 1–3 alarm information distortion.

From the perspective of the location effect in Table 2, the method in this paper fully combines the advantages of the matrix algorithm and optimization algorithm; the
Figure 6: The causal association matrix of a distribution system.

Table 2: Results of fault location.

| Num | Fault section | Distortion | Matrix algorithm results | Optimization algorithm results | Fault location result | Evaluation |
|-----|---------------|------------|--------------------------|--------------------------------|-----------------------|------------|
|     |               |            | Suspicious section | Correct check? | Value | Optimal solution |                         |            |
| N1  | 2             | —          | 2                        | Yes               | —     | —               | 2                      | Correct    |
| N2  | 17            | —          | 17                       | Yes               | —     | —               | 17                     | Correct    |
| N3  | 8             | 19°, 14°, 23°, 6°, 23°, 24° | 8, 13, 16, 21 | No                | 3.8   | 8               | 8                      | Correct    |
| N4  | 27            | 5°, 10°, 23°, 24° | 6, 22, 27 | No                | 4.8   | 27              | Correct                |
| N5  | 5, 8          | —          | 5, 8                     | Yes               | —     | —               | 5, 8                   | Correct    |
| N6  | 2, 17         | —          | 2, 17                    | Yes               | —     | —               | 2, 17                  | Correct    |
| N7  | 2, 20         | —          | 2, 20                    | Yes               | —     | —               | 2, 20                  | Correct    |
| N8  | 2, 8, 24      | —          | 2, 8, 24                 | Yes               | —     | —               | 2, 8, 24               | Correct    |
| N9  | 2, 17, 21, 27 | —          | 2, 17, 21, 27            | Yes               | —     | —               | 2, 17, 21, 27         | Correct    |
| N10 | 2, 17         | 5°, 17°, 35° | 2, 5, 8, 17, 31         | No                | 4.6   | 2, 17           | Correct                |
| N11 | 2, 20         | 10°, 11°, 25° | 2, 11, 20, 23            | No                | 4.6   | 2, 20           | Correct                |
| N12 | 2, 8, 24      | 19°, 14°, 23° | 2, 8, 13, 17, 21, 24     | No                | 5.4   | 2, 8, 24       | Correct                |
| N13 | 2, 17, 21, 27 | 5°, 7°, 25°, 28° | 2, 5, 6, 17, 21, 23, 24, 27 | No                | 7.2   | 2, 17, 21, 27  | Correct                |

Note. “+” indicates that the alarm information is distorted by 1, “−” indicates that the alarm information is distorted by −1, and “0” indicates that an alarm message is missing.
complementation of both algorithms’ advantages improves the performance of the fault location. When there is no alarm information distortion, the improved matrix algorithm can quickly and effectively determine the real fault section without using the optimization link. Whilst there are several alarm information distortions, the result of the sole matrix algorithm is unable to meet the causal verification. However, the suspicious sections can be screened rapidly through matrix criterion, and then DPSO is used to make the fault-tolerant judgment for obtaining the real fault sections. All the examples in Table 2 can converge to the optimal solution in the first 50 iterations, and the convergence time is less than 0.1 s. It can be seen that this method can meet the real-time requirements of distribution network online fault location. It is worth mentioning that the location performance of the proposed method is related to the number of alarm information distortions but is not positive. The location performance is mainly related to the position of the alarm information. How much distortion information the proposed method can withstand is also greatly affected by the size of the distribution network. When a fault occurs at section L500, and the alarm information distortion, the improved matrix algorithm is unable to meet the causal verification. However, the suspicious sections can be screened rapidly through matrix criterion, and then DPSO is used to make the fault-tolerant judgment for obtaining the real fault sections. All the examples in Table 2 can converge to the optimal solution in the first 50 iterations, and the convergence time is less than 0.1 s. It can be seen that this method can meet the real-time requirements of distribution network online fault location. It is worth mentioning that the location performance of the proposed method is related to the number of alarm information distortions but is not positive. The location performance is mainly related to the position of the alarm information. How much distortion information the proposed method can withstand is also greatly affected by the size of the distribution network. The larger the network scale is, the better the location performance can be maintained when more alarm information is distorted.

In addition, the system in Figure 1 is extended to a radial distribution network with 500 switching points and 500 sections. At this point, the line sections are extended to L1, L2, ..., L500, the switching points are extended to S1, S2,..., S500. When a fault occurs at section L500, and the alarm information of switches S100, S200, S300, and S400 are distorted, matrix algorithm reduces the range of suspicious sections to {L99, L199, L299, L399, L500} only 1 ms. On this basis, the variable dimension of the optimization model is established to be 5, which is further optimized by the particle swarm optimization algorithm and can converge to the optimal solution after a few iterations. After the screening of suspicious sections by matrix algorithm, the dimension of optimization variables can be greatly reduced. Therefore, the diagnostic performance of the proposed method in this chapter is not affected by the network size but is mainly determined by the complexity of the system fault (multiple faults, false alarms, etc.). However, the existing fault location methods based on optimization algorithms need to establish fault hypotheses for all 500 sections. Even if the maximum number of iterations is adjusted to 200, the particle swarm optimization algorithm cannot converge to the optimal solution. It can be seen that this method has great advantages for high fault tolerance fault location of large-scale distribution network.

Finally, the proposed method is compared with several existing distribution network fault location methods. Under the same algorithm parameter settings, the simulation tests are carried out for the distribution network with DG shown in Figure 5 according to the fault conditions set in Table 3. It can be seen from Table 3 that the traditional matrix method cannot accurately locate the fault section of multiple faults when the warning information is distorted and the optimization algorithm also has a certain error rate. This is because the optimization algorithm has the problem of local convergence and is easy to fall into local optimum in the process of iteration, so when meeting the requirements of iteration stops, the possible nonoptimal solution will affect the accuracy of the algorithm. However, the proposed method first uses the location results of the matrix algorithm to determine the suspicious fault section hypothesis and then substitutes it into the evaluation function of the optimization algorithm for the solution, which greatly reduces the search range of the optimization algorithm, solves the defect that the optimization algorithm is easy to fall into local optimum, and improves the solution speed and accuracy of the optimization algorithm.

The proposed method is compared with the existing methods from the aspects of the modeling model, main calculation, positioning efficiency, multiple positioning performance, and fault tolerance. The results are shown in Table 4; the tolerance in Table 4 corresponds to the accuracy in Table 3. The computer configuration for simulation includes processor i7-11700, memory 16.0 GB.

In summary, this method can meet the requirements of the timeliness and accuracy of fault location, and it has good adaptability to a complex distribution network with multi-T branches multidistributed generation. Furthermore, the
proposed method can effectively locate fault sections when either single or multiple faults occur, which demonstrates strong fault tolerance.

5. Conclusion

A fault location method used for the emergency disposal of distribution network faults in the power dispatching department is proposed based on the improved matrix algorithm and optimization algorithm, which has the following characteristics:

(1) Based on the characteristics of causal association, the improved matrix algorithm is proposed to locate the fault sections for the active distribution network when the alarm information is complete and correct.

(2) When there are alarm information distortions, the suspicious fault sections can be determined by the improved matrix algorithm. Then, the DPSO algorithm is used to make the fault-tolerant judgment obtain the real fault sections. The optimization algorithm has strong fault tolerance.

(3) According to the complementary advantages of matrix algorithm and optimization algorithm, the method improves the fault location performance with high adaptability to both single fault and multiple faults. Simulation results show that the proposed method has the advantages of both high timeliness and fault tolerance.

Data Availability

The data used are explained in this paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors’ Contributions

The authors contributed equally to the development of this research. All authors read and approved the final manuscript.

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