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Fault section location in urban distribution network based on fault marking

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Abstract. The goal is to propose an effective method for locating a fault segment in urban power distribution networks. Urban distribution networks have multiple outgoing lines, switches with multiple connections and have variable topology characteristics. It is found that the fault location method based on matrix algorithm has low adaptive capability and fault tolerance when dealing with complex and variable topology. Therefore, this paper proposes an efficient fault segment location method based on special fault indicators, which can significantly improve the accuracy and reliability of fault location. Accordingly, to improve the accuracy and reliability of fault location, a fault segment location method based on fault marking is proposed. The approach proposed in the paper relies on the analysis of the incident matrix, which describes the relationship between nodes and branches, and allows the use of graph theory. The branch state vector is added to obtain the adjacency matrix, which allows to describe the state of change in the dynamics of the distribution network topology. In the next step, a set of nodes and branches, which reflect the incoming and outgoing interconnections of the nodes, is established based on the selected direction of the network binding. According to the direction of the node fault current, the suspicious branches are identified and labeled to indicate the fault. By cumulative calculation and analysis of the labels, the target branches are screened out and the faulty sections of the city power supply network are identified. The results of the case study conducted in the paper show that the proposed method has good adaptability to the variable topology and increases the fault tolerance and accuracy of the developed matrix algorithm. The topological operating state of the network can be changed by controlling the switches to optimize the operation and improve the reliability of the power supply. Thus, the algorithm for fast and accurate fault location is of great importance for improving the safety and quality of urban power supply.
Keywords: fault section location, graph theory, matrix algorithm, urban distribution network, feeder terminal unit
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ЭНЕРГЕТИКА

УДК 62-50
Научная статья

Локализация поврежденного участка в городской распределительной сети на основе маркировки повреждения

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Резюме. Цель – предложить эффективный метод определения местоположения сегмента неисправности в распределительные сети городского электроснабжения. Городские распределительные сети имеют несколько исходящих линий, коммутаторы с несколькими соединениями и обладают характеристиками переменной топологии. Выявлено, что метод определения местоположения неисправности, основанный на матричном алгоритме, обладает низкой адаптивной способностью и способностью к отказоустойчивости при работе со сложной и изменяемой топологией. Поэтому в данной статье предлагается эффективный метод определения местоположения сегмента неисправности, основанный на специальных индикаторах неисправности, позволяющий существенно повысить точность и надежность определения местоположения неисправности. Соответственно, для повышения точности и надежности определения местоположения неисправности предлагается метод определения местоположения участка неисправности, основанный на маркировке неисправности. Предлагаемый в работе подход опирается на анализ матрицы инцидентности, описывающей связь между узлами и ветвями, и позволяющий использовать теорию графов. Вектор состояния ветвей добавляется для получения матрицы смежности, которая позволяет описывать состояние изменения динамики топологии распределительной сети. На следующем этапе набор узлов и ветвей, которые отражают входящие и исходящие взаимосвязи узлов, устанавливается на основе выбранного направления привязки сети. В соответствии с направлением тока неисправности узла определяются подозрительные ветви и маркируются для обозначения неисправности. Путем кумулятивного вычисления и анализа меток отсеиваются целевые ветви и определяются неисправные участки сети городского электроснабжения. Результаты проведенного в работе тематического исследования показывают, что предлагаемый метод обладает хорошей адаптивностью к переменной топологии и повышает отказоустойчивость и точность разработанного матричного алгоритма. Топологическое рабочее состояние сети может быть изменено путем управления переключателями для оптимизации работы и повышения надежности электроснабжения. Таким образом, алгоритм быстрого и точного определения места повреждения имеет большое значение для повышения безопасности и качества городского электроснабжения.

Ключевые слова: местоположение участка повреждения, теория графов, матричный алгоритм, городская распределительная сеть, фидерный терминальный узел

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INTRODUCTION

The urban distribution network (UDN) has the characteristics of high load density and high demand for power supply reliability. UDN generally adopts closed-loop, multi-outgoing lines design and open-loop operation mode. The topological operation state of UDN can be changed by controlling switches to optimize operation and improve power supply reliability. Thus, the quickly and accurately fault section location algorithm is of great significance to improve the safety and quality of power supply [1–3]. The feeder terminal unit (FTU) is popularized to provide real-time and complete fault information. The fault section location method of distribution network combined with FTU has become one of the research hotspots [4–6].

Presently, the fault location methods based on FTU mainly include matrix algorithm-based direct methods and intelligent optimization-based indirect methods [7]. The topology description matrix of distribution network needs to be established, and the detected information is used at both ends of the line section to determine the fault. This causes the fault tolerance of matrix algorithm quite weak [8, 9]. To solve the problems of low fault tolerance of matrix algorithm and slow solution speed of optimization algorithm, a distribution network fault location method combining these two algorithms is proposed to make complementary advantages in [5]. Ref. [10] takes matrix algorithm to describe the topology of distribution network, and implement fault section identification and fault isolation, according to multiple detection data provided by FTU. In [7], the location relationship between nodes and distributed generations is integrated into the description matrix, and the information uploaded by FTU is analyzed and corrected. Ref. [11] combines the advantages of matrix algorithm, exhaustive method and optimization algorithm, and then the suspected fault sections are screened by matrix algorithm.

Intelligent optimization algorithms finds the optimal solution through approximation and optimization theory. In [12–14], a global optimization search method for suspicious sections is proposed based on fitting degree. Ref. [15] uses the enumeration method of linear integer programming to solve the algebraic positioning model of FTU remote signaling data. In [16], the switch function of each section switch is introduced into the constructed fitness function, and finally genetic algorithm is used to screen and search the fitness function results. In [17], the upstream and downstream branches are marked according to the different states of fault indicators at different positions. The fault section is the one with the largest fault index value. In [18], the one-dimensional convolutional neural network is used to extract the fault features and locate the fault sections. In [19], fuzzy Petri algorithm is used to analyze multi-source heterogeneous data in the network, and the fault sections are determined through the minimum deviation index. The aforementioned researches improve the fault location algorithm in terms of fault tolerance, accuracy, applicability and operation speed. However, the amount of calculation is quite large and it is easy to fall into the suboptimal solution [20]. Moreover, the operation optimization of distribution network needs flexible topology management to improve power supply reliability [21]. Therefore, the impact of network topology changes on the effectiveness of fault location algorithm should be taken into consideration.

To fill the research gaps in the aforementioned research, a fault location method based on fault marking is proposed for UDN. The main contributions are summarized as follow:

1. The state of branch switches are introduced into the distribution network incidence matrix to enhance the adaptability of adjacency matrix, when the topology of distribution network is changed.

2. The suspicious branch set of nodes is established according to the fault current direction of nodes. Then, the fault indexes of branches are obtained by accumulative calculation of the mark value of suspicious branches. The target branches are screened according to the fault index of branches. The fault criterion is used to analyze the screened target branch and determine the fault branch.

3. A typical UDN with two outgoing lines and multiple interconnection switches is selected for example analysis to verify the accuracy and effectiveness of proposed fault section algorithm under different fault scenarios of single fault, multiple faults and FTU information distortion.

DYNAMIC DESCRIPTION OF DISTRIBUTION NETWORK TOPOLOGY

The distribution network can be described as an undirected graph according to the graph theory. If the distribution network has m nodes and n branches, the vertex set and edge set are respectively expressed as:

$$V=\{v_i \mid i=1,2,\cdots,m\}. \quad (1)$$

$$E=\{e_{ij}=(v_i,\ v_j) \mid j=1,2,\cdots,n\}. \quad (2)$$

The connection relationship between nodes and branches of distribution network can be described by the incidence matrix $\boldsymbol{A}=\left[a_{ij}\right]_{m\times n}$. The elements a_{ij} can be described as:

$$a_{ij}=\begin{cases}1, & v_i \in e_{ij}\\ 0, & v_i \notin e_{ij}\end{cases}. \quad (3)$$

The UDN adjusts the network topology through the control of switches to optimize operation, so that the connection relationship between nodes and branches has changed. In order to describe the real-time operation state of the network topology, a branch state vector of n dimensions $\beta=(t_{ij})$ is defined. t_{ij} represents the on-off state variable of branch:

$$t_{ij}=\begin{cases}1, & on\\ 0, & off\end{cases}. \quad (4)$$

The electrical incidence matrix ***B*** is describing the electrical connection relationship between branches and nodes. It can be obtained by the logical bit operation of the row vector of the incidence matrix ***A*** and the branch state vector *β*:

$$\boldsymbol{B}_{m\times n}=\left[diag(\beta)\boldsymbol{A}^{\mathrm{T}}\right]^{\mathrm{T}}. \quad (5)$$

The adjacency matrix ***D*** describing the topology of distribution network is calculated by equation (6):

$$\boldsymbol{D}_{m\times m}=\left(\boldsymbol{B}\boldsymbol{B}^{\mathrm{T}}\right)\cap\bar{\boldsymbol{I}}, \quad (6)$$

where, ***I*** is the unit Boolean matrix; the element d_{ij} of adjacency matrix ***D*** represents the connection relationship of each node. It has adaptive ability to the topology variability of distribution network. Meanwhile, it takes the power outflow direction of the main power supply as the reference positive direction. This direction has no physical significance and is only used as the position reference direction of the node.

THE DETERMINATION OF FAULT SECTIONS

The FTU equipped at each node is used to detect the fault current. The node fault current code is defined as follows:

$$F_i = \begin{cases} 1, & I_{if} \geq I_{set} \text{ and positive direction} \\ 0, & I_{if} = 0 \\ -1, & I_{if} \geq I_{set} \text{ and opposite direction} \end{cases}, \quad (7)$$

where $\boldsymbol{F_i}$ represents the code of node *i*, Iif represents the fault current of node *i*; Iset represents the setting current value. The fault information matrix $\boldsymbol{F}$ is generated from FTU detection information. The fault judgment matrix $\boldsymbol{P}$ can be obtained from the operation of matrix $\boldsymbol{F}$ and $\boldsymbol{D}$:

$$\boldsymbol{P} = \boldsymbol{D} + diag(\boldsymbol{F}). \quad (8)$$

The positional relationship between nodes, that is the upstream and downstream relationship, can be obtained through the directed adjacency matrix $\boldsymbol{D}$, and the definition is as follows:

$$\begin{cases} d_{ij} = (v_i, \ v_j) = 1, \ i \to j \\ d_{jx} = (v_j, \ v_x) = 1, \ j \to x \\ D_{i\text{-}down} = \{(v_j, \ v_x) | v_x \in V\} \\ D_{i\text{-}up} = D_C - D_{i\text{-}down} \end{cases}. \quad (9)$$

When d_{ij} equals to “1”, it indicates that the branch between node v_i and v_j is connected in the forward direction; d_{jx} represents other branch electrically connected with the node v_i. D_C is the set of network branches; $D_{i\text{-}down}$ is the set of downstream nodes; $D_{i\text{-}up}$ is the set of upstream nodes.

In case of single-phase grounding fault in distribution network, the flow direction of fault current will be consistent with or opposite to the reference positive direction, as shown in the fig. 1:

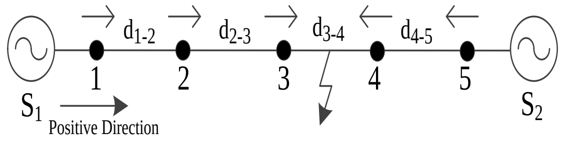

Fig. 1. Single-phase grounding fault of distribution network
Рис. 1. Однофазное замыкание на землю распределительной сети

In fig. 1, a single-phase grounding fault occurs between node 3 and 4. According to equation (7), F_1, F_2 and F_3 are coded as "1", indicating that the fault occurs in the downstream branch of node 1, 2 and 3. F_4 and F_5 are coded as "-1", indicating that the fault occurs in the upstream branch of node 4 and 5. Therefore, the suspicious branch set can be determined by the FTU coding value of the nodes. According to the definition of the nodes’ upstream and downstream relationship in equation (9), the suspicious branch set is defined as follows:

$$C_i = \begin{cases} \{d_{ij} | F_i = 1, d_{ij} = (v_i, v_j) \in D_{i\text{-}down}\} \\ \{d_{ij} | F_i = -1, d_{ij} = (v_i, v_j) \in D_{i\text{-}up}\} \\ \{\varnothing | F_i = 0\} \end{cases}. \quad (10)$$

The suspicious branches of node 1, 2 and 3 are located downstream, while those of node 4 and 5 are located upstream. The upstream and downstream suspicious branches will be marked, and the branch marking formula is as follows:

$$TagValue(d_{ij\text{-}x}) = \begin{cases} 1, & d_{ij} \in C_x \\ -1, & d_{ij} \notin C_x \\ 0, & C_x = \varnothing \end{cases}, \quad (11)$$

where *TagValue*($d_{ij\text{-}x}$) represents the mark of node *x* to branch d_{ij}, abbreviated as *T-V*. The total marking value *MarkValue*(d_{ij}), abbreviated as *M-V*, of all nodes to one branch is expressed as:

$$MarkValue(d_{ij}) = \sum_{x=1}^{m} TagValue(d_{ij\text{-}x}). \quad (12)$$

The fault mark values of each branch in fig. 1 are shown in tab. 1.

Table 1. Branch fault mark values
Таблица 1. Значения метки неисправности ответвления

Node code value		F_1	F_2	F_3	F_4	F_5	*M-V*
		1	1	1	-1	-1	
Suspicious branch set		C_1	C_2	C_3	C_4	C_5	
Branch	d_{12}	1	-1	-1	1	1	1
	d_{23}	1	1	-1	1	1	3
	d_{34}	1	1	1	1	1	5
	d_{45}	1	1	1	-1	1	3

Tab. 1 shows that the value of *M-V* tends to the maximum near the fault branch. And the larger the mark value of the suspicious branch is, the greater probability of failure of the branch is. Therefore, the fault index of each suspicious branch is calculated according to the normalized *M-V* value. The suspicious fault branch is screened from the suspicious branch. The fault index is defined as follows:

$$FaultIndex\left(d_{ij}\right)=\frac{M\text{-}V\left(d_{ij}\right)\text{-}\min\left\{M\text{-}V\right\}}{\max\left\{M\text{-}V\right\}\text{-}\min\left\{M\text{-}V\right\}}\geq\varepsilon, \tag{13}$$

where *ε* is the threshold value, ranging (0, 1). When *FaultIndex(dij)*, abbreviated as *F-I*, is greater than or equal to*ε*, the corresponding branch will be a suspicious fault branch for further fault analysis. The fault judgment formula is:

$$\left|F_i\text{-}F_j\right|>0, \tag{14}$$

where, *Fi* and F_j are the code values of FTUs at both ends of the suspicious fault branch respectively. Its physical meaning is that if the fault signals at both ends are different from each other, the fault is determined.

CASE STUDIES

Dynamic description of distribution network topology. This paper modifies the distribution network topology in [17] and takes it for case studies, as shown in fig. 2. Node N_1~$N1_2$ are equipped with FTUs. S_1 and S_2 represent the power supply from different bus lines. S_1 is set as the main power supply and S_2 as the auxiliary power supply, which are connected to power grid through circuit breakers K_1 and K_2 respectively. The interconnection switches t_{12} and t_{13} are equipped to improve power supply reliability. The interconnection switches are taken equivalently as virtual branches.

There are nodes connected to the distribution network with secondary voltage level, such as node N_4 is connected to the low-voltage distribution network through the section switch t_{L1}. The low-voltage network is not considered in the fault location analysis. Fig. 2 is transformed into a directed topology diagram with the power outflow direction of the main power supply S_1 as the reference positive direction, as shown in fig. 3.

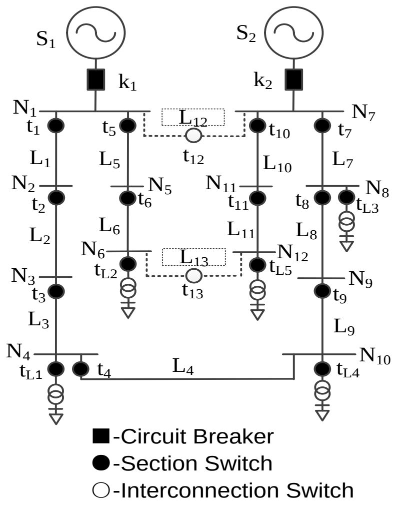

Fig. 2. Schematic diagram of distribution network topology
Рис. 2. Принципиальная схема топологии распределительной сети

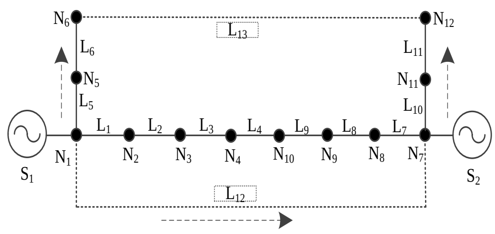

Fig. 3. Directed topology of distribution network
Рис. 3. Направленная топология распределительной сети

The incidence matrix ***A*** in fig. 3 is expressed as:

$$A=\begin{bmatrix}1&0&0&0&1&0&0&0&0&0&0&1&0\\1&1&0&0&0&0&0&0&0&0&0&0&0\\0&1&1&0&0&0&0&0&0&0&0&0&0\\0&0&1&1&0&0&0&0&0&0&0&0&0\\0&0&0&0&1&1&0&0&0&0&0&0&0\\0&0&0&0&0&1&0&0&0&0&0&0&1\\0&0&0&0&0&0&1&0&0&1&0&1&0\\0&0&0&0&0&0&1&1&0&0&0&0&0\\0&0&0&0&0&0&0&1&1&0&0&0&0\\0&0&0&1&0&0&0&0&1&0&0&0&0\\0&0&0&0&0&0&0&0&0&1&1&0&0\\0&0&0&0&0&0&0&0&0&0&1&0&1\end{bmatrix}. \tag{15}$$

In equation (15), the line number represents the network node number (N_1 ~ N_{12}), and the column number represents the branch number (L_1 ~ L_{18}). The state of each branch can be represented by the on-off state of branch switches (t_1~t_{13}), so the branch state vector *β* is:

$$\beta = [t_1 \quad t_2 \quad \dots \quad t_{13}]^{\mathrm{T}} . \qquad (16)$$

This paper takes switches $t_{12} = t_{13} = 0$ and other switch states as "1" for the first topology state of distribution network. And the second state of distribution network topology is taking switches $t_{13} = 1$, $t_4 = t_{12} = 0$ and other switch states as "1". The accuracy and reliability of dynamic description matrix are analyzed respectively. The branch state vector β_1 in the first state and the branch state vector β_2 in the second state of distribution network topology are as follows:

$$\beta_1 = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 \end{bmatrix}^{\mathrm{T}} . \qquad (17)$$

$$\beta_2 = \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \end{bmatrix}^{\mathrm{T}} . \qquad (18)$$

Through the calculation of equation (5), multiply the "0" elements in β_1 and β_2 is multiplied by the corresponding elements in the matrix ***A***, t and the connection relation between nodes and branches is changed to obtain the electrical correlation matrix ***B₁*** and ***B₂***. Through the calculation of equation (6), the adjacency matrixes in two topological states of distribution network are obtained:

$$\boldsymbol{D}_1 = \begin{bmatrix}
0 & 1 & 0 & 0 & 1 & 0 & \underline{0} & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & \underline{0} \\
\underline{0} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & \underline{0} & 0 & 0 & 0 & 0 & 1 & 0
\end{bmatrix} . \qquad (19)$$

$$\boldsymbol{D}_2 = \begin{bmatrix}
0 & 1 & 0 & 0 & 1 & 0 & \underline{0} & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & \underline{0} & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & \underline{1} \\
\underline{0} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & \underline{0} & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & \underline{1} & 0 & 0 & 0 & 0 & 1 & 0
\end{bmatrix} . \qquad (20)$$

In equation (19), $d_{1\text{-}7}$ and $d_{6\text{-}12}$ are "0", indicating that the switches t_{17} and t_{13} are disconnected. In equation (20), $d_{6\text{-}12}$ is "1" and $d_{4\text{-}10}$ is "0", showing that the switch t13 is on and the switch t_4 is off. The above calculation results are consistent with the two distribution network topology states. The adjacency matrix describing topological structure has the ability to adapt to topological change.

Fault section location of distribution network. Fig. 4 is the schematic diagram of single-phase grounding fault of distribution network based on fig. 3. f_1 and f_2 are the single-phase grounding faults on branch L_3 and L_8 respectively. The accuracy and reliability of the algorithm are verified under two fault scenarios of single fault and multiple faults.

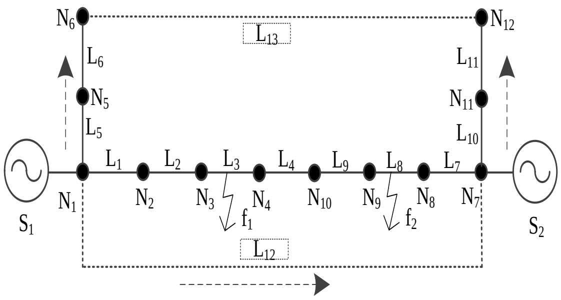

Fig. 4. Single-phase grounding faults of distribution network
Рис. 4. Однофазные замыкания на землю распределительной сети

(1) Fault section determination in the scenario of single fault. When fault f_1 occurs in the distribution network, the fault information matrix ***F*** and fault judgment matrix ***P*** obtained from equation (7) and (8) are as follows:

$$diag(\boldsymbol{F}) = \begin{bmatrix} 1 & 1 & 1 & -1 & 0 & 0 & -1 & -1 & -1 & -1 & 0 & 0 \end{bmatrix} . \qquad (21)$$

$$\boldsymbol{P} = \boldsymbol{D}_1 + \boldsymbol{F} = \begin{bmatrix}
1 & 1 & 0 & 0 & 1 & 0 & \underline{0} & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & \underline{0} \\
\underline{0} & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & \underline{0} & 0 & 0 & 0 & 0 & 1 & 0
\end{bmatrix} . \qquad (22)$$

The suspicious branch sets of nodes are analyzed in the fault decision matrix ***P*** according to equation (9) and (10):

$$\begin{cases} d_{11}=1, C_{1\text{-down}}=\begin{Bmatrix} d_{12}, d_{15}, d_{23}, d_{34}, \\ d_{56}, d_{98}, d_{87}, d_{4\text{-}10}, \\ d_{10\text{-}9}, d_{7\text{-}11}, d_{7\text{-}12}, \end{Bmatrix} \\ d_{22}=1, C_{2\text{-down}}=\begin{Bmatrix} d_{23}, d_{34}, d_{4\text{-}10}, d_{10\text{-}9}, \\ d_{98}, d_{87}, d_{7\text{-}11}, d_{11\text{-}12} \end{Bmatrix} \\ d_{33}=1, C_{3\text{-down}}=\begin{Bmatrix} d_{34}, d_{10\text{-}9}, d_{87}, d_{98}, \\ d_{4\text{-}10}, d_{7\text{-}11}, d_{11\text{-}12} \end{Bmatrix} \\ d_{44}=-1, C_{4\text{-up}}=\{d_{12}, d_{15}, d_{23}, d_{34}, d_{56}\} \\ d_{55}=0, C_{5}=\{\varnothing\} \\ d_{66}=0, C_{6}=\{\varnothing\} \\ d_{77}=-1, C_{7\text{-up}}=\begin{Bmatrix} d_{12}, d_{15}, d_{23}, d_{34}, \\ d_{98}, d_{87}, d_{56}, \\ d_{4\text{-}10}, d_{10\text{-}9}, \end{Bmatrix} \\ d_{88}=-1, C_{8\text{-up}}=\begin{Bmatrix} d_{12}, d_{15}, d_{23}, d_{34}, \\ d_{98}, d_{56}, d_{4\text{-}10}, d_{10\text{-}9}, \end{Bmatrix} \\ d_{99}=-1, C_{9\text{-up}}=\begin{Bmatrix} d_{12}, d_{15}, d_{23}, d_{34}, \\ d_{4\text{-}10}, d_{10\text{-}9}, d_{56} \end{Bmatrix} \\ d_{10\text{-}10}=-1, C_{10\text{-up}}=\begin{Bmatrix} d_{12}, d_{15}, d_{23}, \\ d_{34}, d_{4\text{-}10}, d_{56} \end{Bmatrix} \\ d_{11\text{-}11}=0, C_{11}=\{\varnothing\} \\ d_{12\text{-}12}=0, C_{12}=\{\varnothing\} \end{cases} . \quad (23)$$

The marking value of each node to the branch by using equation (11) and (12), are shown in tab. 2.

Tab. 2 shows that the larger the value is, the greater failure probability there is. When the value of a branch is less than 0, it is indicated that no failure occurred in the branch. Therefore, when analyze the failure probability of a suspected branch, it is necessary to add a constraint $M\text{-}V(d_{ij})\geq 0$ to equation (13). The fault index of each suspicious branch in тab. 2 are depicted in tab. 3.

When ε is set to 0.8, branch L_3 (d_{34}) is screened out. According to equation (14), it can be obtained that $|F_3 - F_4| = 2 > 0.$ Then, branch L_3 occurs fault, which is consistent with the assumed fault scenario.

(2) Fault section location in the scenario of FTU information distortion

When F_5 took "1" by mistake and F_7 took "0" by omission, the fault index of branches are obtained as follows.

Tab. 4 shows that the branch with fault index greater than or equal to 0.8 is still L_3, and the fault determination result is correct. Since the fault index is determined by the nodes' judgment to all the branches, the influence of the FTU information distortion is diluted. It does not affect the correctness of the fault determination result. (3) Fault section location in the scenario of multiple faults. When faults f_1 and f_2 occurred simultaneously, the fault information matrix ***F*** is:

$$diag(\boldsymbol{F})=\begin{bmatrix}1 & 1 & 1 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0\end{bmatrix}. \quad (24)$$

The corresponding fault index of branches are shown in tab. 5.

Table 2. Marking values of suspicious branches
Таблица 2. Значения маркировки подозрительных ветвей

Node code		**F_1**	**F_2**	**F_3**	**F_4**	**F_5**	**F_6**	**F_7**	**F_8**	**F_9**	**F_{10}**	**F_{11}**	**F_{12}**	*M-V*
		1	1	1	-1	0	0	-1	-1	-1	-1	0	0	
Suspicious branch set		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	
Branch	$L_1(d_{12})$	1	-1	-1	1	0	0	1	1	1	1	0	0	4
	$L_2(d_{23})$	1	1	-1	1	0	0	1	1	1	1	0	0	6
	$L_3(d_{34})$	1	1	1	1	0	0	1	1	1	1	0	0	8
	$L_4(d_{4\text{-}10})$	1	1	1	-1	0	0	1	1	1	1	0	0	6
	$L_5(d_{15})$	1	-1	-1	1	0	0	1	1	1	1	0	0	4
	$L_6(d_{56})$	1	-1	-1	1	0	0	1	1	1	1	0	0	4
	$L_7(d_{87})$	1	1	1	-1	0	0	1	-1	-1	-1	0	0	0
	$L_8(d_{98})$	1	1	1	-1	0	0	1	1	-1	-1	0	0	2
	$L_9(d_{10\text{-}9})$	1	1	1	-1	0	0	1	1	1	-1	0	0	4
	$L_{10}(d_{7\text{-}11})$	1	1	1	-1	0	0	-1	-1	-1	-1	0	0	-2
	$L_{11}(d_{11\text{-}12})$	1	1	1	-1	0	0	-1	-1	-1	-1	0	0	-2

Table 3. Branch fault indexes in the scenario of single fault
Таблица 3. Индексы отказов ветвей в сценарии единичной неисправности

Suspicious branches	*M-V*	*F- I*
L_1	4	0.5
L_2	6	0.75
L_3	8	1
L_4	6	0.75
L_5	4	0.5
L_6	4	0.5
L_7	0	0
L_8	2	0.25
L_9	4	0.5

Table 4. Branch fault indexes in the scenario of Feeder terminal unit information distortion
Таблица 4. Индексы отказов ветвей в сценарии искажения информации о фидерном терминале

Suspicious branches	*M-V*	*F- I*
L_1	4	0.5
L_2	6	0.75
L_3	8	1
L_4	6	0.75
L_5	5	0.625
L_6	2	0.25
L_7	0	0
L_8	1	0.125
L_9	4	0.5
L_{10}	0	0
L_{11}	0	0

Table 5. Branch fault indexes in the scenario of multiple faults
Таблица 5. Индексы отказа ветвей в сценарии множественных отказах

Suspicious branches	*M-V*	*F-I*
L_1	1	0
L_2	3	0.5
L_3	5	1
L_4	5	1
L_5	1	0
L_6	1	0
L_7	3	0.5
L_8	5	1
L_9	5	1
L_{10}	1	0
L_{11}	1	0

According to equation (13), the target branches are screened out as follows: L_3 (d_{34}), L_4 ($d_{4\text{-}10}$), L_8 (d_{98}) and L_9 ($d_{10\text{-}9}$). And these target branches are calculated respectively by the fault criterion:

$$\begin{cases} |F_3 - F_4| = |1 - 0| = 1 > 0 \\ |F_4 - F_{10}| = |0 - 0| = 0 \\ |F_9 - F_8| = |0 + 1| = 1 > 0 \\ |F_{10} - F_9| = |0 - 0| = 0 \end{cases}. \quad (25)$$

According to equation (25), the faults occur in branches L_3 and L_8, and the determination result is consistent with the assumed fault scenario.

From the results analysis of the above examples, the fault section location algorithm proposed in this paper can accurately determine the fault section and has good fault tolerance. It can adapt to the characteristics of UDN.

CONCLUSION

In order to improve the accuracy and reliability of fault location of UDN, a fault section location method based on fault marking is proposed in this paper. It solves the problems of low adaptive ability and fault tolerance of matrix algorithm in UDN. The conclusions are drawn through the case studies:

1. By adding the branch state vector into the adjacency matrix, the connection relation between nodes and branches in the adjacent matrix changes with the operation state of branches. The adaptive ability of adjacency matrix to describe topology changes is enhanced.

2. By calculating the mark value of the branch, we can get the number of times that the branch appears in the suspicious branch sets of all nodes. The larger the fault index of the branch is, the more times it appears in the suspicious branch sets, and the greater the probability of the branch failure. In addition, the influence of node information distortion on fault determination results is diluted in the process of mark value calculation. Therefore, the fault tolerance of matrix algorithm is enhanced.

3. The fault criterion is used to analyze and judge the screened target branches, which can accurately identify multiple fault branches. It can be used to locate faults in multiple fault scenarios.

References

1. Salehi M., Namdari F. Fault location on branched networks using mathematical morphology. *IET Generation, Transmission & Distribution*. 2018;12(1):207-216. https://doi.org/10.1049/iet-gtd.2017.0598.

2. Teng Jen-Hao, Huang Wei-Hao, Luan Shang-Wen. Automatic and fast faulted line-section location method for distribution systems based on fault indicators. *IEEE Transactions on Power Systems*. 2014;29(4):1653-1662. https://doi.org/10.1109/TPWRS.2013.2294338.

3. Jiang Yazhou, Liu Chen-Ching, Diedesch M., Lee Erik, Srivastava A. K. Outage management of distribution systems incorporating information from smart meters. *IEEE Transactions Power System.* 2016;31(5):4144-4154. https://doi.org/10.1109/TPWRS.2015.2503341.

4. Gu Jyh-Cherng, Huang Zih-Jhe, Wang Jing-Min, Hsu Lin-Chen, Yang Ming-Ta. High impedance fault detection in overhead distribution feeders using a DSP-based feeder terminal unit. *IEEE Transactions on Industry Applications*. 2021;57(1):179-186. https://doi.org/10.1109/TIA.2020.3029760.

5. Xu Biao, Yin Xianggen, Zhang Zhe, Pang Shuai, Li Xusheng. Fault location for distribution network based on matrix algorithm and optimization algorithm. *Automation of Electric Power System*. 2019;43(5):152-158. https://doi.org/10.7500/AEPS20180115002.

6. Sun Kongming, Chen Qing, Gao Zhanjun. An automatic faulted line section location method for electric power distribution systems based on multisource information. *IEEE Transactions on Power Delivery*. 2016;31(4):1542-1551. https://doi.org/10.1109/TPWRD.2015.2473681.

7. Kong Pei, Liu Jianfeng, Zhou Jian, Zhou Yongliang, Song Ziheng. Fault-tolerant algorithm for fault location in distribution network based on integer linear programming. *Power System Protection and Control*. 2020;48(24):27-35. https://doi.org/10.19783/j.cnki.pspc.200073.

8. Zheng Tao, Ma Wenlong, li Wenbo. Fault section location of active distribution network based on feeder terminal unit information distortion correction. *Power System.* 2021;45(10):3926-3935. https://doi.org/10.13335/j.1000-3673.pst.2020.1991.

9. Li Wenbo, Su Jianjun, Wang Xin, Li Jiamei, Ai Qian. Fault location of distribution networks based on multi-source information. *Global Energy Interconnection*. 2020;3(1):77-85. https://doi.org/10.14171/j.2096-5117.gei.2020.01.009.

10. Sun Kongming, Chen Qing, Zhao Pu. Automatic faulted feeder section location and isolation method for power distribution systems considering the change of topology. *Energies*. 2017;10(8):1081. https://doi.org/10.3390/en10081081.

11. Zheng Tao, Ma Long, Zhang Bo. Fault tolerant fast fault section location method for active distribution network. *Journal of North China Electric Power University*. 2022;49(1):12-21.

12. Ding Yi, Zhang Xin, Wang Xudong. A New Method for Fault Section Location of Feeder Based on Peak-Combination. *Proceedings of the CSU-EPSA*. 2021;33(9):26-31. https://doi.org/10.19635/j.cnki.csu-epsa.000789.

13. Jiang Yazhou. Toward detection of distribution system faulted line sections in real time: a mixed integer linear programming approach. *IEEE Transactions on Power Delivery*. 2019;34(3):1039-1048. https://doi.org/10.1109/TPWRD.2019.2893315.

14. Ji Xingquan, Zhang Shuo, Zhang Yumin, Han Xueshan, Xiao Yundong, Zeng Ruomei. Fault section location for distribution network based on improved electromagnetism-like mechanism algorithm. *Automation of Electric Power Systems*. 2021;45(22):157-166. https://doi.org/10.7500/AEPS20210121007.

15. Guo Zhuangzhi, Xu Qixing, Hong Junjie, Mao Xiaoming. Integer linear programming based fault section diagnosis method with high fault-tolerance and fast performance for distribution network. *Proceedings of the CSEE*. 2017;37(3):786-794. https://doi.org/10.13334/j.0258-8013.pcsee.152361.

16. Gong Xuan, Ren Xinxu, Wang Qiujie, Chen Ting, Wang Ling. A section location method with high fault tolerance stability for distribution network with distributed generation. *High Voltage Engineering*. 2021;47(11):3992-4006. https://doi.org/10.13336/j.1003-6520.hve.20201665.

17. Liu Pengcheng, Li Xinli. Fault-section location of distribution network containing distributed generation based on the multiple-population genetic algorithm. *Power System Protection and Control*. 2016;44(2):36-41.

18. Džafić R. A. Jabr S. Henselmeyer, Đonlagić. T. Fault location in distribution networks through graph marking. *IEEE Transactions on Smart Grid*. 2018;9(2):1345-1353. https://doi.org/10.1109/TSG.2016.2587583.

19. Guo Mou-Fa, Gao Jian-Hong, Shao Xiang, Chen Duan-Yu. Location of single-line-to-ground fault using 1-d convolutional neural network and waveform concatenation in resonant grounding distribution systems. *IEEE Transactions on Instrumentation and Measurement*. 2021;70. https://doi.org/10.1109/TIM.2020.3014006.

20. Kiaei I., Lotfifard S. Fault section identification in smart distribution systems using multi-source data based on fuzzy Petri nets. *IEEE Transactions on Smart Grid*. 2020;11(1):74-83. https://doi.org/10.1109/TSG.2019.2917506.

21. Zhang Guangxiao, Tong Xiaoyang, Hong Qiteng, Lu Xuemin, Booth C. D. A novel fault isolation scheme in power system with dynamic topology using wide-area information. *IEEE Transactions on Industrial Informatics*. 2022;18(4):2399-2410. https://doi.org/10.1109/TII.2021.3095254.

Список источников

1. Salehi M., Namdari F. Fault location on branched networks using mathematical morphology // IET Generation, Transmission & Distribution. 2018. Vol. 12. Iss. 1. P. 207–216. https://doi.org/10.1049/iet-gtd.2017.0598.
2. Teng Jen-Hao, Huang Wei-Hao, Luan Shang-Wen. Automatic and fast faulted line-section location method for distribution systems based on fault indicators // IEEE Transactions on Power Systems. 2014. Vol. 29. Iss. 4. P. 1653–1662. https://doi.org/10.1109/ TPWRS.2013.2294338.
3. Jiang Yazhou, Liu Chen-Ching, Diedesch M., Lee Erik, Srivastava A. K. Outage management of distribution systems incorporating information from smart meters // IEEE Transactions Power System. 2016. Vol. 31. Iss. 5. P. 4144–4154. https://doi.org/10.1109/TPWRS.2015. 2503341.
4. Gu Jyh-Cherng, Huang Zih-Jhe, Wang Jing-Min, Hsu Lin-Chen, Yang Ming-Ta. High impedance fault detection in overhead distribution feeders using a DSP-based feeder terminal unit // IEEE Transactions on Industry Applications. 2021. Vol. 57. Iss. 1. P. 179–186. https://doi.org/10.1109/TIA.2020.3029760.
5. Xu Biao, Yin Xianggen, Zhang Zhe, Pang Shuai, Li Xusheng. Fault location for distribution network based on matrix algorithm and optimization algorithm // Automation of Electric Power System. 2019. Vol. 43. Iss. 5. P. 152–158. https://doi.org/10.7500/AEPS20180115002.
6. Sun Kongming, Chen Qing, Gao Zhanjun. An automatic faulted line section location method for electric power distribution systems based on multisource information // IEEE Transactions on Power Delivery. 2016. Vol. 31. Iss. 4. P. 1542–1551. https://doi.org/10.1109/TPWRD. 2015.2473681.
7. Kong Pei, Liu Jianfeng, Zhou Jian, Zhou Yongliang, Song Ziheng. Fault-tolerant algorithm for fault location in distribution network based on integer linear programming // Power System Protection and Control. 2020. Vol. 48. Iss. 24. P. 27–35.
https://doi.org/10.19783/j.cnki.pspc.200073.
8. Zheng Tao, Ma Wenlong, li Wenbo. Fault section location of active distribution network based on feeder terminal unit information distortion correction // Power System. 2021. Vol. 45. Iss. 10. P. 3926–3935. https://doi.org/10.13335/j.1000-3673.pst.2020.1991.
9. Li Wenbo, Su Jianjun, Wang Xin, Li Jiamei, Ai Qian. Fault location of distribution networks based on multi-source information // Global Energy Interconnection. 2020. Vol. 3. Iss. 1. P. 77–85. https://doi.org/10.14171/j.2096-5117.gei.2020.01.009.
10. Sun Kongming, Chen Qing, Zhao Pu. Automatic faulted feeder section location and isolation method for power distribution systems considering the change of topology // Energies. 2017. Vol. 10. Iss. 8. P. 1081. https://doi.org/10.3390/en10081081.
11. Zheng Tao, Ma Long, Zhang Bo. Fault tolerant fast fault section location method for active distribution network // Journal of North China Electric Power University. 2022. Vol. 49. Iss. 1. P. 12–21.
12. Ding Yi, Zhang Xin, Wang Xudong. A New Method for Fault Section Location of Feeder Based on Peak-Combination // Proceedings of the CSU-EPSA. 2021. Vol. 33. Iss. 9. P. 26–31. https://doi.org/10.19635/j.cnki.csu-epsa.000789.
13. Jiang Yazhou. Toward detection of distribution system faulted line sections in real time: a mixed integer linear programming approach // IEEE Transactions on Power Delivery. 2019. Vol. 34. Iss. 3. P. 1039–1048. https://doi.org/10.1109/TPWRD.2019.2893315.
14. Ji Xingquan, Zhang Shuo, Zhang Yumin, Han Xueshan, Xiao Yundong, Zeng Ruomei. Fault section location for distribution network based on improved electromagnetism-like mechanism algorithm // Automation of Electric Power Systems. 2021. Vol. 45. Iss. 22. P. 157–166. https://doi.org/10.7500/AEPS20210121007.
15. Guo Z., Xu Q., Hong J. – просьба прописать полностью или заменить источник Integer linear programming based fault section diagnosis method with high fault-tolerance and fast performance for distribution network // Proceedings of the CSEE. 2017. Vol. 37. Iss. 3. P. 786–794. https://doi.org/10.13334/j.0258-8013.pcsee.152361.
16. Gong Xuan, Ren Xinxu, Wang Qiujie, Chen Ting, Wang Ling. A section location method with high fault tolerance stability for distribution network with distributed generation // High Voltage Engineering. 2021. Vol. 47. Iss. 11. P. 3992–4006.
https://doi.org/10.13336/j.1003-6520.hve.20201665.
17. Liu Pengcheng, Li Xinli. Fault-section location of distribution network containing distributed generation based on the multiple-population genetic algorithm // Power System Protection and Control. 2016. Vol. 44. Iss. 2. P. 36–41.
18. Džafić R. A. Jabr S. Henselmeyer, Đonlagić. T. Fault location in distribution networks through graph marking // IEEE Transactions on Smart Grid. 2018. Vol. 9. Iss. 2. P. 1345–1353. https://doi.org/10.1109/TSG.2016.2587583.
19. Guo Mou-Fa, Gao Jian-Hong, Shao Xiang, Chen Duan-Yu. Location of single-line-to-ground fault using 1-d convolutional neural network and waveform concatenation in resonant grounding distribution systems // IEEE Transactions on Instrumentation and Measurement. 2021. Vol. 70. https://doi.org/10.1109/TIM.2020.3014006.
20. Kiaei I., Lotfifard S. Fault section identification in smart distribution systems using multi-source data based on fuzzy Petri nets // IEEE Transactions on Smart Grid. 2020. Vol. 11. Iss. 1. P. 74–83. https://doi.org/10.1109/TSG.2019.2917506.
21. Zhang Guangxiao, Tong Xiaoyang, Hong Qiteng, Lu Xuemin, Booth C. D. A novel fault isolation scheme in power system with dynamic topology using wide-area information // IEEE Transactions on Industrial Informatics. 2022. Vol. 18. Iss. 4. P. 2399–2410. https://doi.org/10.1109/TII.2021.3095254.

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