Abstract—Along with the increasing level of distribution network intelligence and the network complexity, the automatic fault location technology for distribution network is particularly important. But the traditional fault location methods based on one information source is impossible to locate the faults accurately because of there are losses or faults in the information from the distribution. So, the information fusion based fault location method for distribution network is proposed. When a fault occurs, one information matrix is created based on the action of all the protective relays, and the other information matrix is created based on the wave data of the current which is recorded at the foot node. The above information matrices are combined using D-S evidence theory and the fault location is realized. The simulation results show that the fault location method for distribution network not only realizes accurate fault location, but also possesses stronger robustness.

Index Terms—distributed network, fault location, information fusion, D-S evidence theory

I. INTRODUCTION

With the increasing complexity of the distribution network, feeder automation has a rapid development. Feeder automation provides strong support for fault location in distribution network. At the same time, it also provides strong support for improving the quality and reliability of power supply [1-3]. The traditional fault location methods based on coordination between recloser and sectionalizer exist many shortcomings, such as, reclosing to fault point again, slow response rate and expanding fault regions easily. So the fault section location based on information of protection units and feeder terminal units (FTUs) are becoming research hotspots. Where the matrix algorithm [1, 2] and the over heated arcs searching algorithm [4, 5] have the simple principle and well definition. But these methods are based on complete and accurate information uploaded by FTUs. The intelligent fault location algorithm can realize fault section location at the case of exiting uncertain information, such as, genetic algorithm based fault location [6], rough set theory based fault location [7-8], multi-agent based fault location [9], Bayes probability based fault location [10] and Petri-Nets based fault location [11]. But these methods can only provide a certain diagnosis result and the diagnosis result have the following disadvantages:

• It cannot reflect the fitness of the method. When the quality of communication is good, the information based on SCADA is reliable. But when the communication channel is disturbed, the information isn’t reliable and the diagnosis result may be wrong. The difference cannot be reflected.

• It cannot provide the failure indication information.

• It makes against combination of different fault section location methods.

In one word, there are two problems for the control center to resolve the fault location with the information uploaded by the feeder automation system:

• For the vast amount and redundancy of the information, it is hard to process the data manually for the operators.

• Under the influence of the work environment of the equipment and the communication system, there are always some losses or faults in the information from the distribution network.

As a result, it is very important to syncretize the information from different information resources and find a new fault location method to locate the fault accurately even there are losses or faults in the information from the distribution.

Dempster-Shafer (D-S) evidence theory is one of the mathematical tools developed in the 70s. D-S evidence theory can robustly deal with incomplete data. The D-S evidence theory can be a tool for system modeling and information fusion. In fault diagnosis, because different evidences make different contributions to different faults, evidence importance should be considered for specific fault diagnosis through multi-resource information fusion [12, 13].

In this paper, in order to improve the fault location accuracy and robustness, through constructing the information matrices based on the action of all protective relays switch and the wave data of the current respectively, the fault information are combined using the D-S evidence theory.
A. Principle of Fault Location Based on Reclosers and Sectionalizers

Now, there are three methods to implement the feeder automation, that is, mutual coordination of recloser with voltage-time type of sectionalizer, recloser with recloser and recloser with over-current pulse count type sectionalizer. Among them, the mutual coordination of recloser with voltage-time type of sectionalizer is the most popular one [14].

The Figure 1 shows the schematic diagram of fault isolation based on mutual coordination of recloser with voltage-time type of sectionalizer for typical radial distribution networks, where A is a recloser and B, C, D are sectionalizers. The first reclosing time of the recloser is 15s and the second reclosing time is 5s. The X-time limits of the sectionalizers B and D are 7s and the Y-time limits are 5s. The X-time limits of the sectionalizers C and E are 14s and the Y-time limits are 5s. The operation logics of the recloser and sectionalizers are showed as Figure 2.

Figure 1. Schematic diagram of typical radial distribution networks

Figure 2. Scheme of operation logic of all switches

The figure 1 (a)-(g) show the process of the fault section location. The figure 1 (a) is the normal operation state for the radial distribution networks. The figure 1 (b) shows that when a permanent fault happens in the c section, the recloser A trips off, and it leads to losing voltage of the line and the sectionalizers B, C, D and E tripping. The figure 1 (c) shows the recloser A performs the first reclosing operation after 15s of the fault tripping. The figure 1 (d) shows that after 7s time limits, the sectionalizer B recloses automatically and the power supply arrives at the b section. The figure 1 (e) shows that after another 7s time limits, the sectionalizer D recloses automatically and the power supply arrives at the d section. The figure 1 (f) shows that after 14s time limits
after the sectionalizer B reclosing, the sectionalizer C recloses automatically. Because the fault of C section is the permanent fault, the recloser A trips off again and leads to the line losing voltage and the sectionalizer B, C, D and E tripping again. Because the sectionalizer C loses voltage before its Y-time limit (5s), the sectionalizer is locked. The figure 1 (g) shows that after 5s time limits after the recloser B trips off again, the recloser A recloses secondly and the sectionalizer B, D and E recloses automatically. Because the sectionalizer C is locked in the switching-off state, the fault section is isolation and the power supply of the non-fault area is restored.

B. Problem of Fault Location Based on Reclosers and Sectionalizers

After fault isolation, the operation logics of switches are sent to the control center through the intelligent distributed terminal, the control center determines the fault location to remove the fault source. But the information received by the control center may be wrong because of existing strong electromagnetic interference in the communications network of the distribution network. The control center will make the wrong decision.

III. FAULT LOCATION METHOD BASED ON INFORMATION FUSION

A. Fault Location Method Based on D-S Evidence Theory

Let $\Theta$ be the frame of discernment i.e. the finite set of $N$ mutually exclusive and exhaustive hypotheses. $2^\Theta$ is the power set of $\Theta$, such that if $\Theta=\{1, 2, \ldots, N\}$, then $2^\Theta=\{\emptyset, \{1\}, \{2\}, \ldots, \{N\}, \{1,2\}, \{1,3\}, \ldots, \{N-1, N\}, \{1,2,3\}, \Theta\}$, where $\emptyset$ denotes the empty set.

**Definition 1** A basic probability assignment is a function $m: 2^\Theta \rightarrow [0, 1]$, which satisfies the following conditions:

$$\sum_{A \in \Theta} m(A) = 1$$

$$m(\emptyset) = 0$$

$m(A)$ is called basic probability number. It represents the proportion of all relevant and available evidence that supports the claim that a particular element of $\Theta$ belongs to the set $A$ but to no particular subset of $A$.

**Definition 2** The plausibility function is defined as:

$$Pl : 2^\emptyset \rightarrow [0, 1] \quad \text{and} \quad Pl(A) = \sum_{B: A \subseteq B} m(B)$$

The belief function $Bel(A)$ measures the total amount of probability that must be distributed among the elements of $A$. It reflects inevitability and signifies the total degree of belief of $A$ and constitutes a lower limit function on the probability of $A$. On the other hand, the plausibility function $Pl(A)$ measures the maximal amount in $A$. It describes the total belief degree related to $A$ and constitutes an upper limit function on the probability of $A$.

Suppose $m_1$ and $m_2$ are two basic probability assignment functions formed based on information obtained from two different information sources in the same frame of discernment $\Theta$. According to Dempster’s orthogonal rule of evidence combination, the combination of $m_1$ and $m_2$ is as follows:

$$m_1 \oplus m_2(C) = \frac{\sum_{A \in K} m_1(A)m_2(B)}{1 - \sum_{A \in \Theta} \sum_{B \in \Theta, A \neq B} m_1(A)m_2(B)}$$

The belief values of the action information of reclosers and sectionalizers and the current wave information at root node is regarded as $m_1$ and $m_2$ respectively. Then the $m_1$ and $m_2$ are combined according to equation (3) and the belief value of every protection zone is obtained. According to the belief value $m$, the fault location can be determined. The scheme of fault location method based on D-S evidence theory is showed as Figure 3.

![Figure 3. Scheme of fault location method based on D-S evidence theory](image)

B. Model of Distribution Network

The simulation model is a 17-node 24.9kV distribution network with feeder automation, which is built in PSCAD/EMTDC, showed as Figure 4. R1-R4 indicate the reclosers and D1-D9 indicate the sectionalizers[16].

![Figure 4. Simulation model of distribution network](image)

C. Belief Assignment of FTU Information

According to the actions of reclosers and sectionalizers, the information matrix of the reclosers and sectionalizers is defined as $R$ and $D_u(k=1, 2, \ldots, u)$:

$$R = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} \\ r_{21} & r_{22} & r_{23} & r_{24} & r_{25} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ r_{u1} & r_{u2} & r_{u3} & r_{u4} & r_{u5} \end{bmatrix}$$

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where \( u \) is the number of the reclosers in the distributed network, \( v \) is the number of the sectionalizers in the corresponding recloser protection zone. In the information matrix, the first column indicates the first opening action, the second column indicates the first closing action, the third column indicates the second opening action, the forth column indicates the second closing action and the fifth column indicates the third opening action. Each row of the information matrix \( R \) corresponds to a recloser. The first row of the information matrix \( D_k \) indicates the switch actions of the corresponding recloser and the rows from 2 to \( n \) indicate the switch actions of the sectionalizers in corresponding recloser protection zone. \( r_{ij}=1 \) or \( d_{ij}=1 \) indicates that the corresponding action happens and \( r_{ij}=0 \) or \( d_{ij}=0 \) indicates that the corresponding action doesn’t happen.

Suppose the actual information matrix of reclosers received by the control center from the distributed network is \( RA \), the actual information matrix of sectionalizers in different protection zone received by the control center from the distributed network is \( DA_k \) respectively. The matrix \( RA \) is compared with an \( m \times 5 \) matrix which elements are all 1, and a statistics matrix \( RAS \) is obtained by counting the number of same elements in every row between the two matrices. After the matrix \( RAS \) is normalized, the action probability matrix of reclosers \( PR \) is obtained. Similarly, the matrix \( DA_k \) is compared with every ideal information matrix when faults occur in corresponding sectionalizer protection zone, and a statistics matrix \( DAS_k \) is obtained by counting the number of same elements between the two matrices. The first row of \( DAS_k \) is set to 0. After the matrix \( DAS_k \) is normalized, the action probability matrix of sectionalizers \( PD_k \) is obtained.

Suppose the permanent fault occurs in the node 856. The reclosers \( R_1, R_2, R_4 \) and the sectionalizers of their protection zone don’t act. Only \( R_3, D_4, D_5, D_6 \) and \( D_7 \) perform automatic switch-off and switch-on action. After several automatic switch-off and switch-on actions, the fault section is isolated and the power supply of the sound area is restored. The action time sequence diagram is showed as Figure 5.

The Figure 5 shows the operation logic of the recloser and sectionalizers in \( R_1 \) protection zone. Suppose the fault happens at 0.3s, the recloser \( R_1 \) acts firstly, the four sectionalizers switch off because of losing voltage. After 1.5s, the recloser recloses automatically. Then, the sectionalizers \( D_4, D_5, D_6 \) and \( D_7 \) reclose automatically in turn after itself 0.7s time limits, where the sectionalizers \( D_4, D_5 \) and \( D_6 \) reclose successfully. When the sectionalizer \( D_7 \) recloses, the fault is connected to the system again because the fault section is located in \( D_7 \) section, the recloser \( R_3 \) switches off again and all the sectionalizers switches off because of losing voltage. Because the time interval between the two switching-on time of \( D_7 \) is less than the setting time limit 0.5s, the sectionalizer is locked. After 0.5s, the recloser recloses automatically, and the sectionalizers \( D_4, D_5 \) and \( D_6 \) recloses automatically in turn after itself 0.7s time limits, where the sectionalizers \( D_4, D_5 \) and \( D_6 \) recloses successfully. The locked sectionalizer \( D_7 \) don’t reclose, the fault section is isolated and the power supply of the sound zone is restored.
According to these wrong information matrixes, the first belief value $m_1$ can be calculated as following. Comparing $Ra$ with a $4 \times 5$ matrix which elements are all 1, a statistics matrix $RAS$ is obtained by counting the number of same elements in every row between the two matrices. After the matrix $RAS$ is normalized, the action probability matrix of reclosers $P_R$ is obtained as following:

$$RWS = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Every element in $P_R$ from top to down is the probability value of the recloser $R_1$, $R_2$, $R_3$ and $R_4$ respectively.

Similarly, the matrix $DA_1$, $DA_2$, $DA_3$ and $DA_4$ is compared with the corresponding ideal information matrix when the fault occurs in corresponding sectionalizer protection zone respectively, and the statistics matrix $DAS_1$, $DAS_2$, $DAS_3$ and $DAS_4$ is obtained respectively by counting the number of same elements between the two matrices. The first row of $DAS_i$ is set to 0. After the matrix $DAS_i$ is normalized, the action probability matrix of sectionalizers $PD_k$ is obtained. These matrixes are as followed as:

$$m_1 = PD_1 = \begin{bmatrix} 0 \\ 0.4348 \\ 0.3043 \\ 0.2609 \end{bmatrix}, \quad m_2 = PD_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix},$$

$$m_3 = PD_3 = \begin{bmatrix} 0 \\ 0.1935 \\ 0.2419 \\ 0.2581 \\ 0.3056 \end{bmatrix}, \quad m_4 = PD_4 = \begin{bmatrix} 0 \\ 0.6667 \\ 0.3333 \end{bmatrix}$$

So, the probability that the fault locates in recloser $R_1$, $R_2$, $R_3$ and $R_4$ is 0, 0, 1 and 0 respectively. If the fault locates in the recloser $R_1$ protection zone, the locked probability of the recloser $R_4$, the sectionalizer $D_k$ and $D_j$ is 0, 0.6667 and 0.3333 respectively.

### D. Belief Assignment of Fault Recorder Information

When a permanent fault occurs and the corresponding protection acts, the actions of the reclosers will result in appearing a current pulse at the root node. So, two section fault current corresponding to two protection action at the root node can be detected. The diagram comparing operation logic of the recloser $R_1$ with the current waveform is showed as Figure 6. The diagram shows that the time interval between two current pulses is corresponds with the time interval between two reclosing, and the time interval between two reclosing corresponds with the locked sectionalizer. So, through calculating the time interval between the two current pulses at the root node, the control center can determine the locked sectionalizer, and the fault zone can be located.

![Diagram comparing operation logic with the current waveform](image-url)

(a) Node 856 permanent fault

![Diagram comparing operation logic with the current waveform](image-url)

(b) Node 830 permanent fault

Figure 6. Diagram comparing operation logic with the current waveform

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The time interval $T$ has relationship with the location of the locked sectionalizer. It shows as Figure 7.

\[ T = t_{d1} + t_x \times d \]  \hspace{1cm} (6)

where $T$ is the setting time interval between two tripping actions, $t_{d1}$ is the setting time of the first reclosing and $t_{d1}=1.5s$, $t_x$ is the X-time limit of sectionalizer and $t_x$ =0.7s, $d$ indicates the position of the locked fault zone, for example, when the fault located at node 856, $d$ is set at 4; when the fault located at node 830, $d$ is set at 2.

So, the second belief assignment $m_2$ can be obtained through detecting the time interval between two section fault current at the root node, the process is followed as:

- Firstly, the time interval between two fault current pulses, showed as Figure 8.

Secondly, a $1 \times u$ probability matrix $PC_k$ of the locked recloser or sectionalizer corresponding to the protection zone $k$ is initialized to 0, where $u$ is the maximal number of sectionalizers in the recloser protection zones. The locked probability of each recloser or sectionalizer is calculated according to the time interval $T$. The probability distributions are showed as Figure 9.

Finally, suppose $u=5$, according to $T$, the locked probability of recloser and sectionalizer is as follows.

If $T<0.8s$, the element of the first row of $PC_k$ is set to 1. The elements of other rows of $PC_k$ are determined as follows:

\[ (T - 0.8) \times 0.7 = d \cdots \cdots \cdot \]  \hspace{1cm} (7)

\[ 0 \hspace{1cm} \text{if } y \leq 0.05 \]  \hspace{1cm} (8)

\[ \frac{y - 0.05}{0.6} \hspace{1cm} \text{if } 0.05 < y < 0.65 \]  \hspace{1cm} (8)

\[ 1 \hspace{1cm} \text{if } y \geq 0.65 \]  \hspace{1cm} (8)

The element of $d+1(d>0)$ row of $PC_k$ is set to $p$ and the element of the $d$ row of $PC_k$ is set to $1-p$. The probability matrixes of other protection zone are composed of before $m$ row of the $PC_k$, where $m$ is the number of sectionalizers of corresponding to protection zone.

For example, the detected time interval between two fault current pulses is 4.2926s, the belief distribution matrix is followed as:
The belief matrix shows that the locked probability of the fourth sectionalizer is 1, and the locked probabilities of the other sectionalizers are 0.

E. Fault Location Method Based on D-S Evidence Theory

The probability matrix $PD_k$ and $PC_k$ is regarded as $m_{1k}$ and $m_{2k}$ respectively. Then the $m_{1k}$ and $m_{2k}$ are combined according to equation (3) and the probability assignment $P_k$ of every protection zone is obtained. Then the element $pr_i$ of the matrix $PR$ multiplies the matrix $P_k$ respectively and the final probability assignment matrix $P$ is obtained. According to the matrix $P$, the fault location can be determined.

IV. SIMULATION ANALYSE

In the simulation model showed as Figure 4, suppose the permanent fault occurs in the $D_3$ protection zone. The information matrixes received by the control center receive from the distribution network are as follows:

$$RA = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad DA = \begin{bmatrix} 1 & 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 \end{bmatrix}$$

$$DA_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 \end{bmatrix}, \quad DA_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

According to above principle, the action probability matrixes are as follows:

$$PR = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \quad m_{11} = PD_{1} = \begin{bmatrix} 0 \\ 0.2667 \\ 0.3333 \end{bmatrix}, \quad m_{12} = PD_{2} = \begin{bmatrix} 0 \\ 0.3409 \\ 0.2727 \end{bmatrix}$$

$$m_{11} = PC_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \quad m_{22} = PC_2 = \begin{bmatrix} 0 \\ 0.9977 \\ 0 \end{bmatrix}$$

According to formula (3), the action probability matrix $m = m_1 \oplus m_2$ is combined. The element $pr_1 \cdot pr_4$ of the matrix $PR$ multiplies the matrix $m_1 \cdot m_4$ respectively and the final probability assignment matrix $P$ is obtained.

$$P = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

So, the fault position locates the sectionalizer $D_3$ of the recloser $R_1$ protection zone. The result of fault location is true.

V. CONCLUSION

The fault location method based on the information of reclosers and sectionalizers will be wrong when the electromagnetic interference exits in the communication system. Using D-S evidence theory, the information of reclosers and sectionalizers and the information of current wave at root node can be combined. The combined information can locate the fault position accurately.

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