Research Article

Realization of Single-Phase Grounding Fault Location and Recovery Technology in Distribution Network

Di Zhang, Haiguo Tang, Jiran Zhu, Hengyi Zhou, Zhidan Zhang, and Xingrong Song

State Grid Hunan Electric Power Company Limited Research Institute, Changsha 410007, Hunan, China

Correspondence should be addressed to Haiguo Tang; 20152600036@m.scnu.edu.cn

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In order to locate the single-phase-to-ground fault in distribution network, a research method of single-phase-to-ground fault location and recovery technology in distribution network is proposed. According to the characteristics of single-phase-to-ground fault in distribution network, the fault characteristics of zero-sequence current and three-phase current transient records are extracted by generalized S transform of correlation coefficient, and multi-source redundant information is formed. Fuzzy C-means clustering analysis method is used to fuse multiple fault features online location strategy. The simulation results show that the fuzzy clustering based on FCM changes continuously with the accumulation of samples, and the sample center changes with the enrichment of the samples. When the arc suppression coil is grounded with different initial phase angle transition resistance and intermittent fault, the state of each measuring point can be correctly identified, and the accurate energization rate is 97%. The test results show that the system can achieve accurate positioning for all sections.

1. Introduction

For many years, single-phase grounding fault line selection of small current grounding system has been a research topic at home and abroad, such as zero-sequence power method, zero-sequence electricity current active component method, harmonic component method, first half wave method, negative sequence current component method, transient component method, zero-sequence admittance method, wavelet analysis method, residual current increment method, and so on. However, in practice, the line selection effect of these protection methods is not ideal. In view of the fact that there is no certain characteristic quantity that is sensitive to all kinds of small current ground faults, before the breakthrough in the research of fault feature information detection and extraction, how to break through the limitation of fault detection only at the front end of the line is the key to solve the problem.

China’s medium voltage power distribution network is mainly neutral point without direct grounding. The fault of distribution network line is mainly divided into phase short circuit fault and single-phase grounding fault. If single-phase grounding fault occurs in distribution line, it can be allowed to supply power to load for 1–2 h with fault according to regulations to improve the reliability of power supply. However, it causes the non-fault phase voltage to rise to line voltage, which can be extended to phase short circuit for long time operation with fault, which affects the safety of the power system. Therefore, the study of single-phase grounding fault section location technology has become one of the hot spots to improve the power supply reliability of distribution network [1]. With the practical application of power distribution automation main station, distribution terminals and fault indicators of various types of different manufacturers are connected to the power distribution automation main station. When single-phase grounding fault occurs, the overhead transient recording electricity fault indicator sends fault recording. Other fault indicators or power distribution terminals send fault information. Therefore, the following two problems need to be solved in locating single-phase grounding faults based on the main station of power distribution automation: (1) the fault feature extraction based on fault recording, the fault
processing strategy integrating fault feature and fault event information, and the unified fault processing in the scenario that the single-phase grounding fault turns into short circuit fault in the field equipment mixed installation; (2) Figure 1 shows how to solve the failure of locating faults caused by the loss of device installation diversity information and startup criteria in engineering applications.

2. Literature Review

Mendes et al. proposed a DC open circuit and AC tracing fault location method suitable for single-phase grounding fault of distribution network. Based on the principle of injection method, the fault point is maintained in breakdown state by applying high voltage under power failure state, and the injection signal is traced to determine the fault area or location. The S signal injection method to avoid the small current grounding system gets the influence of the coil, applicable to install two-phase current transformer power network overhead line, but the method needs to use signal injection equipment, and signal strength is restricted and the injected signal may affect the power quality, in addition to the high resistance grounding fault and intermittent fault special fault condition, such as this. The fault location effect of the method is not ideal [2]. Neiva et al. proposed a fault segment location method based on xOR operation of matrix, which multiplied the network description matrix and fault information matrix to obtain the fault discrimination matrix; then, xOR operation was performed on the elements of the fault discrimination matrix and the corresponding criteria were used to obtain the fault segment. However, this method requires matrix mathematical operation, which takes a long time when the distribution network is large in scale [3]. Almeida and Muniz improved the zero-sequence power method and used the zero-sequence active power component to determine the fault segment, which was suitable for the arc suppression coil grounding system. However, the method was interfered by the unbalanced current of the current transformer, resulting in low reliability of fault location [4]. The transient zero-mode power direction method proposed by Bhatia is used to calculate the transient zero-mode voltage and current to determine the fault direction and then the field terminal measuring equipment is used to determine the fault section. This method makes use of the characteristics of large transient signal and overcomes the influence of arc suppression coil to a certain extent [5]. Kazhekin used the expert system to establish the expert system database of the segmented switch and protection device of the circuit breaker. When the fault information occurs, the fault information set can be deduced. Finally, the fault section can be determined through the analysis of the credibility [6]. Xu and Hu applied neural network to the expert system, which made the traditional expert system have self-adaptive ability and effectively improved the accuracy of fault location [7]. Through the distribution network to establish a suitable equivalent model, Zhao et al. used ant colony algorithm to realize fault location, and fault location problem can be converted to optimization algorithm of global optimization problems. However, it is difficult to overcome the problem of local optimal solution, which leads to the appearance of false fault segments. Depending on its own advantages, intelligent algorithm has become a hot spot in current research [8].

With the popularization and application of distribution automation, the fault indicator and distribution terminal are connected to the main distribution station, which creates conditions for the online location of the single-phase grounding fault section of the main distribution station. In view of the complexity of fault processing caused by the access of distribution terminal in engineering application of various fault indicators, this paper proposes to extract the characteristic values of the fault recording of overhead transient fault indicator (hereinafter referred to as the fault recording type) by using a variety of algorithms and fuzzy C. The mean clustering analysis method integrates all characteristic parameters to improve the strategy of single-phase grounding fault location and optimizes the fault processing process to meet the needs of engineering applications.

3. Research Method

3.1. Overall Solution for Online Single-Phase Grounding of the Main Power Distribution Station. When single-phase grounding occurs, the power distribution monitoring equipment installed on site (power distribution terminal fault indicator, etc.) collects distribution network operation information such as current, voltage, and electric field and performs single-phase grounding fault recording detection or judgment processing according to the set value and judgment conditions. Through wireless optical fiber and other communication channels, the IEC 60870-5-101/104 power communication protocol is used to communicate with the distribution master station. The master station analyzes and locates faults based on the received information (see Figure 2).

The overall structure of single-phase grounding positioning based on distribution master station is divided into distribution master station layer, communication network layer, and equipment layer.

3.1.1. Main Station Layer. Analyze the fault information and fault recording files collected by various fault indicators and distribution terminals, extract the fault characteristic quantity, and collect the real-time fault information of the topological distribution network of the main distribution station for single-phase grounding fault location and treatment.

3.1.2. Communication Layer. Through the communication channel of optical fiber wireless network, IEC 60870-5-101/104 communication protocol is used to realize the data communication between distribution monitoring equipment and distribution master station.

3.2. Single-Phase Grounding Fault Processing and Feature Extraction. When single-phase grounding occurs in distribution network, according to the selection of the State
Grid Distribution Line Fault Indicator Technical Principle (Trial) and Distribution Automation Terminal Technical Specification (Trial) Distribution, terminals or non-overhead transient wave recording fault indicators are required to have single-phase grounding indication and send single-phase grounding fault signs. The main power distribution station can directly locate faults online according to the fault signs sent; however, the fault recording type fault indicator sends the fault recording to the distribution master station, which depends on the distribution master station to parse the fault recording and extract the fault characteristic quantity and locate the fault according to the diagram mode and topology of distribution automation [9]. As shown in Figure 3, in order to adapt to the needs of various complex application scenarios, the power distribution master station automatically detects the type of fault information when receiving it and starts different fault processes.

In engineering application, only current transformer is installed for data collection of fault indicator of wave recording type. When single-phase fault occurs, the fault phase current zero-sequence current transient wave recording file is sent to the main distribution station [10].

3.2.1. Similarity Feature Extraction of Zero-Sequence Current Waveform. When single-phase grounding fault occurs in the low-current grounding system, a virtual voltage source is added to the fault point accessory of the original system after the fault, and the characteristics of single-phase grounding zero-sequence current of the low-current grounding system are analyzed [11]. In digital signal processing, the correlation coefficient reflects the similarity of waveforms, that is, the larger the correlation coefficient is, the more similar the waveforms are, and the smaller the correlation coefficient is,
the more different the waveforms are. Therefore, fault line selection and fault location can be realized by analyzing the relation number of transient zero-sequence current recording waveforms [12]. The number of phase relation of transient zero-sequence current recording wave is calculated as follows:

\[ \rho_{mn} = \frac{\sum_{i=1}^{N} X_i \cdot X_{i-m}}{\sqrt{\sum_{i=1}^{N} X_i^2 \cdot \sum_{i=1}^{N} X_{i-m}^2}} \] (1)

(2) Based on the correlation coefficient matrix \( \rho \), the comprehensive correlation coefficient \( E\rho_i \) of each measurement point \( i \) can be calculated, as shown in the following formula:

\[ E\rho_i = \frac{1}{L-1} \left( \sum_j \rho_{ij} - \rho_{i0} \right), \quad j = 1, \ldots, L \] (2)

In equations (1) and (2), \( N \) is the number of samples collected and \( L \) is the number of measurement points.

3.2.2. Feature Extraction Based on Generalized S Transform

(1) Generalized S Transform Obtains Time-Frequency Matrix of Measuring Point. The generalized S-transform combines the advantages of short-time Fourier transform and wavelet transform, and has good time-frequency local variation characteristics. It can effectively reflect the characteristics of the signal at each frequency and fully show the details of the fault characteristics of the signal to be analyzed. It can improve the accuracy and reliability of fault detection and has been preliminarily applied in single-phase ground fault determination [13]. The generalized S-transform discrete formula is as follows:

\[ S(m,n) = \sum_{k=0}^{N-1} X(n+k)e^{2\pi jk^2/n^2}e^{j2\pi mk/N} \] (3)

\[ = A(m,n)e^{j\theta_i}, \quad n \neq 0, \] (3a)

\[ S(m,n) = \frac{1}{N} \sum_{k=0}^{N-1} x(k), \quad n = 0, \] (4)

\[ X(n) = \frac{1}{N} \sum_{k=0}^{N-1} x(k)e^{-j(2\pi nk/N)}, \] (5)

**Figure 3: Process for troubleshooting single-phase grounding faults of the main power distribution station.**
where \( N \) is the sampling number, \( A(m, n) \) is the amplitude \( S(m, n) \), and \( \theta_{\text{mn}} \) is the phase angle of \( S(m, n) \). For the collected \( N \) discrete signal points \( x(k) \), \( S \) transformation is carried out by using equations (3)–(5), and the complex time-frequency matrix can be obtained, where row corresponds to frequency and column corresponds to sampling time point.

### 3.2.3. Zero-Mode Energy Function and Eigenvalue Extraction

The zero-mode energy function of each measuring point is the product and integral of zero-mode voltage and current within a certain time. Considering unified use of bus zero-sequence voltage, after applying \( S \) transformation, its energy function can be equivalent to: the amplitude square of zero-sequence voltage, after applying \( S \) transformation, its current within a certain time. Considering unified use of bus zero-sequence voltage and zero-mode energy function of each measuring point is the product and integral of zero-mode voltage and zero-mode energy function of each measuring point is extracted as the characteristic frequency corresponding to the maximum secondary energy of a measuring point \( I \) at the corresponding frequency \( f_n \) is shown in the following equation:

\[
W_{i-n} = \sum_{m} [A(m, n)]^2, \quad i = 1, \ldots, L. \tag{6}
\]

Only the energy function time-frequency matrix is obtained through \( S \) change transformation for signal analysis, and further extraction of its characteristic quantity is needed to directly reflect the fault characteristics.

### 3.2.4. Extraction of Energy Moment Characteristic Quantity in Characteristic Frequency Band

After \( S \) transformation, the energy moment analysis of its characteristic frequency band shows that the corresponding energy difference between measuring points on both sides of the fault section in the characteristic frequency band is large, and the difference between measuring points on the front and back end of the fault point and on the sound line is small [14]. The extraction process of characteristic frequency energy moment is as follows. According to formula (6), the transient energy of a measurement point \( f_n \) is obtained, and the frequency corresponding to the maximum secondary energy of a measurement point is extracted as the characteristic frequency band. The average value of the corresponding energy moment in the characteristic frequency band is taken as the energy characteristic quantity, and the energy characteristic quantity \( E_i \) of the measuring point \( i \) is shown in the following formula:

\[
E_i = \frac{(W_{i-f_1} + W_{i-f_2})}{2}. \tag{7}
\]

### 3.2.5. Relative Information Entropy Feature Extraction

Relative information entropy reflects the degree of information ordering. The more orderly information is, the lower the relative information entropy will be, and the higher it will be otherwise. According to the fault characteristic analysis, the difference of zero-sequence current waveform on both sides of the fault point is large, and the relative information entropy is large. The front and back end of the fault point is similar to the zero-sequence current waveform of the non-fault line, and its relative entropy is small, so the relative entropy can be used as a characteristic quantity to locate the fault segment [15]. The extraction process of the feature quantity of relative information entropy based on \( S \) transformation is as follows. After the energy function is transformed by generalized \( S \), the weight coefficients \( q_{i-n} \) of each measurement point can be calculated according to the transient energy \( f_n \) at frequency, as shown in the following formula:

\[
q_{i-n} = \frac{W_{i-n}}{\sum_{n=1}^{K} W_{i-n}}, \tag{8}
\]

where \( \sum_{n=1}^{K} W_{i-n} \) is the total sum of all the measurements under frequency \( f_n \); according to the relative entropy theory, the relative information entropy \( m_{ij} \) between the measurement points \( i \) and \( j \) can be calculated, and the information entropy matrix \( M \) can be obtained. According to the information entropy matrix \( M \), the comprehensive energy entropy of the measurement points \( i \) can be calculated as follows:

\[
m_{ij} = \sum_{n=1}^{K} q_{i-n} \ln \frac{q_{i-n}}{q_{j-n}}, \tag{9}
\]

\[
M_i = \frac{1}{L-1} \left( \sum_{j} (M_{ij} - M_{ij}) \right), \quad j = 1, \ldots, L. \tag{10}
\]

\( n \) in equations (9) to (10) is the corresponding frequency band; \( l \) is the total number of measurement points.

### 3.2.6. Correlation Analysis and Calculation of Phase Current Mutation

When a fault occurs in the small current grounding system, the system line voltage remains symmetric after the fault. It can be known from the analysis of the change of the sound phase fault current mutation before and after the fault point of the sound line and each fault line: sound line three-phase current mutation amplitude is equal, phase is the same, and waveform is the same [16]. By analyzing the correlation characteristics of phase current mutation between two phases, the correlation characteristics of phase mutation between two phases can be extracted as follows for fault interval location.

The phase current mutation is calculated in the following formula:

\[
\Delta I(k) = I(k) - I(k - N), \tag{11}
\]

where \( N \) represents the sampling points of power frequency cycle.

Calculate the correlation coefficient \( \rho_{AB}, \rho_{BC}, \rho_{CA} \) between two phases of phase current mutation based on formula (1). Take the average of the correlation coefficient between two phases of three-phase current mutation as the comprehensive correlation coefficient of the measurement point, and the comprehensive correlation coefficient \( I\rho_i \) of the measurement point \( i \) is shown in the following formula:

\[
I\rho_i = \frac{\rho_{AB} + \rho_{BC} + \rho_{CA}}{3}. \tag{12}
\]

### 3.3. Multi-Criteria Integrated Fault Location Based on Fuzzy C-Means Clustering

#### 3.3.1. Fault Determination Process

Due to external interference of line parameters in neutral ground mode, each characteristic quantity does not necessarily have a clear
boundary, and there may be misjudgment in fault location by using a single characteristic quantity. In order to overcome the deficiency of single location method, information fusion methods such as fuzzy theory of extreme learning machine, D-S evidence theory, fuzzy neural network clustering analysis, and other information fusion methods are used to fuse the fault characteristics to improve the correctness of single-phase grounding fault. Among them, fuzzy C-means clustering algorithm (FCM) algorithm is a data clustering method based on the optimization of the objective function. It has the characteristics of unsupervised and does not need human intervention and is the most extensive and successful in information fusion [17]. Figure 4 shows the troubleshooting process of single-phase grounding fusion based on fuzzy C-means clustering analysis.

Specific steps are as follows:

(1) Load the fault recording file and extract its characteristic quantity according to formulas (2), (7), (10), and (13).

(2) Considering the complex structure of distribution network, the characteristic quantity of energy moment information entropy amplitude varies greatly between different faults, so the normalized data preprocessing is carried out for the same fault data. Keep them at the same level of quantity and reduce their influence on the conclusion. The sample set $X$ generated by normalization is shown in the following formula:

$$X_i = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}}. \quad (13)$$

(3) Parameter setting and initialization. Set the classification number $c$, weighting index $q$, iteration number $N$, and convergence condition. Random numbers are generated in the interval $[0,1]$ to form the initial membership matrix $U$, and the initial clustering center matrix $V$ is calculated.

(4) The objective function of fuzzy clustering is calculated according to equation (14), and the membership matrix and clustering center matrix are updated according to equations (15) and (16).
\begin{equation}
I_q(U, V) = \sum_{k=1}^{N} \sum_{i=1}^{c} (u_{ik})^q (d_{ik})^2,
\end{equation}
\begin{equation}
d_{ik} = \left( \sum_{j=1}^{m} (x_{kj} - v_{ij})^2 \right)^{\frac{1}{2}},
\end{equation}
\begin{equation}
v_{ij} = \frac{\sum_{k=1}^{N} (u_{ik})^q x_{ij}}{\sum_{k=1}^{N} (u_{ik})^q}, \quad 1 \leq i \leq c,
\end{equation}

where \( d_{ik} \) is the distance between sample \( x_i \) and the \( k \)th clustering center [18, 19].

(5) Determine whether the objective function calculated by formula (15) is greater than the set threshold \( \varepsilon \) and the number of iterations \( N \). If the number of iterations \( N \) has not reached the maximum and is greater than the threshold, return (4); otherwise, turn to (6);

(6) Output partition matrix and cluster center matrix.

(7) The distance \( d_{ik}, d_{2k} \) between the sample data \( x_i \) to be tested and the fault clustering center and the non-fault clustering center is calculated one by one. The sum of the distance between all the feature values of the sample and the fault clustering center is \( d_1 \), and the sum of the distance between the non-fault clustering center is \( d_2 \). If \( d_1 > d_2 \), the sample is judged to belong to the non-fault category; otherwise, it is judged to be the fault category.

(8) After the fault is determined, the sample set to be tested is stored in the database [20]. After correctly identifying the fault or non-fault state of the test
points, the samples to be tested will be classified into the corresponding categories as historical data according to the identification results to enrich the sample database. Meanwhile, the samples will be returned to (4) and the clustering centers of various types will be re-evaluated to prepare for the next fault determination.

After FCM fuzzy clustering analysis of the fault recording files of each measuring point, it can be determined whether each measuring point belongs to the fault class or non-fault class. The output of the fault class is defined as 1, and the output of the non-fault class is defined as 0.

4. Interpretation of Result

4.1. Simulation and Verification. In order to verify the effectiveness of the algorithm, Matlab simulation software is used to build the distribution network wiring diagram model and its simulation and calculation.

The distribution network wiring diagram in Figure 5 shows a typical 110 kV/10 kV distribution network wiring. The main transformer is triangle or star wiring, and the neutral point on the low-voltage side is controlled by a switch to determine whether it is grounded by arc suppression coil.

The simulation of distribution network without direct grounding is carried out, the grounding of distribution network through arc suppression coil is simulated, different initial phase angle, transition resistance or intermittent single-phase grounding of distribution network are also simulated (see Figure 6 for the specific simulation results).

The simulation results show that the fuzzy clustering based on FCM has the ability to learn with the accumulation of samples, and the sample center changes with the enrichment of samples. When the arc suppression coil is grounded with different initial phase angle transition resistance and intermittent fault, the state of each measuring point can be correctly identified, and the accuracy rate is 97%.

4.2. Online Positioning Software for Single-Phase Grounding Based on Distribution Automation. Based on the analysis of single-phase earthing locating technology, the online
locating software of single-phase earthing is designed [21], as shown in Figure 7.

(1) Data Layer. It mainly includes event information about distribution network faults, topology information about the power distribution network, real-time operating status data of distribution network, distribution network attributes, fault records, and their analytical results.

(2) Application Service Layer [22, 23]. It provides basic services, including recording data reading, fault feature extraction, event collection, data collection, and fault location. New services include fault recording, fault feature extraction, event collection, adjustment and optimization of fault location data collection, and fault processing.

(3) Presentation Layer. The real-time status and fault of distribution network are displayed by graphical GIS and other visualization techniques [24, 25].

5. Conclusion

(1) The fault characteristic quantity of transient zero-sequence current three-phase current fault recording file is extracted by digital processing method when single-phase grounding is performed. The fuzzy C-means clustering analysis method was used to fuse the feature information from multiple dimensions, effectively utilizing the complementary information between feature quantities, avoiding the inherent defects of single algorithm, and improving the adaptability of fault location accuracy.

(2) With the field operation, a large number of single-phase grounding fault recording data are obtained. The fuzzy C-means clustering analysis method automatically updates the fault or non-fault clustering center, applies its self-adaptive and self-learning ability to reflect the single-phase grounding fault characteristics more truly, and further improves the accuracy of fault location.

(3) With the operation of the field, the single-phase grounding fault recording data in the whole province and the national network are accessed, and the fault recording data can be automatically clustered by the fuzzy C-means clustering analysis method. Divide the types of single-phase faults such as grounding impedance and grounding fault types. The next step is to explore the application of big data technology theory fuzzy C-means clustering analysis to extract the threshold value of fault characteristic quantity for the massive recording data of single-phase grounding fault, so as to improve the accuracy of single-phase grounding fault research.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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