

Research on Fault Location and Isolation Method of Power Distribution System Based on Intelligent Sensing

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Abstract: Fault location and isolation in the power distribution system are the core links to ensure the reliability of power supply, and the traditional methods have problems such as insufficient positioning accuracy and slow isolation response in complex power grid structures. The introduction of intelligent sensing technology provides a new path for distribution network fault handling, and with the help of multi-source sensor data collection and deep integration of machine learning algorithms, the goal of accurate capture and rapid research and judgment of fault signals can be achieved. At the fault location level, a technical system including signal feature extraction, type recognition, multi-terminal fusion and single-phase grounding high-sensitivity positioning is constructed, and at the isolation level, adaptive criterion and distributed collaborative isolation scheme are proposed, which combines network reconstruction and multi-level protection coordination to improve power supply reliability. The simulation results show that the proposed method has better positioning accuracy and isolation speed, and has strong practical value in engineering applications.

Keywords: Intelligent perception; Fault location; Fault isolation; Feeder automation; Power distribution system

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1. Introduction

The distribution network is directly oriented to the end user, and its operational reliability will have a significant impact on industrial production and residential electricity consumption. With the large-scale access of distributed power sources and the increasingly complex topology of the power grid, the fault patterns begin to show diversified characteristics, and the traditional localization methods have obvious limitations in adaptability and real-time. Intelligent sensors, the Internet of Things and artificial intelligence technologies are accelerating their penetration into the power system, which brings new technical support for distribution network fault handling. The accurate location of faults is the premise of achieving accurate isolation, and the isolation efficiency directly determines the speed of power supply recovery in non-fault areas.

2. Fault location method of power distribution system based on intelligent perception

2.1. Fault sensing signal acquisition and feature extraction

After the failure of the distribution system, the line voltage and current signals will produce significant transient disturbances, and high-quality collection of the disturbance signals is the basis for accurate fault location. The intelligent sensing terminal synchronously collects the three-phase current and zero-sequence voltage signals of each monitoring node according to the high sampling rate, and combines the time synchronization protocol to ensure the temporal consistency of multi-point data, uses wavelet transform to carry out multi-scale decomposition of the original signal, extracts characteristic parameters such as energy entropy, waveform mutation variable and frequency domain amplitude, and forms a high-dimensional eigenvector input subsequent recognition model after normalization (Figure 1). The quality of feature extraction directly determines the upper limit of subsequent recognition and localization links, and plays a leading role in the overall method system^[1].

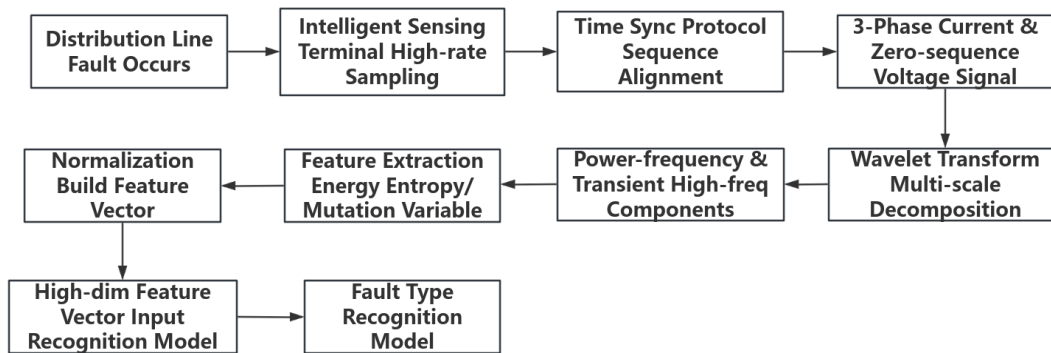


Figure 1. Fault sensing signal acquisition and feature extraction process.

2.2. Machine learning-based fault type identification model

On the basis of obtaining standardized eigenvectors, a fault type recognition model with random forest as the core is constructed to automatically classify typical faults such as single-phase grounding, two-phase short circuit, three-phase short circuit, and disconnection^[2]. Random forest outputs discriminant categories by integrating the voting results of multiple decision trees, which has the advantages of strong anti-noise interference ability and high robustness to sample imbalance. Compared with support vector machines and backpropagation neural networks, random forests show comprehensive advantages in recognition accuracy and computational efficiency (Table 1), and the fault type labels output by the model are directly transmitted to the segment localization algorithm, forming a key intermediate link in the localization process.

Table 1. Comparison of fault type recognition performance of different machine learning algorithms

Algorithm	Single-phase ground recognition rate (%)	Two-phase short circuit recognition rate (%)	Three-phase short circuit recognition rate (%)	Broken wire recognition rate (%)	Average accuracy (%)	Training time(s)
Random forest	98.6	99.1	99.4	97.8	98.7	12.4
Support vector machines	94.2	96.3	97.1	91.5	94.8	28.7
Backpropagation neural networks	92.7	95.4	96.2	89.3	93.4	35.2

2.3. Fault section location algorithm for multi-terminal information fusion

The data of a single measurement point cannot accurately describe the fault location, so a multi-terminal information fusion strategy is introduced to improve the positioning accuracy, and each terminal uploads the fault current amplitude, phase, and traveling wave arrival time to the master station, establishes a segment fault probability evaluation model according to the network topology, and completes the segment judgment through the weighted fusion algorithm^[3]. The fault localization error evaluation is calculated using the following formula:

$$e = \frac{|d_m - d_t|}{L} \times 100\% \quad (1)$$

Where: represents the relative error of fault location (%); d_m denotes the fault ranging result output by the algorithm (km); d_t is the actual distance from the fault point to the reference terminal (km); L stands for the total length of the tested line (km).

In the process of fusion, the confidence weight mechanism is introduced to automatically downgrade the abnormal measurement data, which effectively suppresses its interference with the positioning results.

2.4. High-sensitivity localization strategy for single-phase ground faults

The frequency of single-phase ground fault is the highest and it is extremely difficult to detect, and the amplitude of the fault current is often much lower than the load current value, which is difficult to achieve effective response treatment with traditional overcurrent protection. To solve this problem, the zero-sequence current direction comparison method combined with the transient energy feature extraction composite strategy is used to improve the perceived sensitivity of high-resistance ground faults. Each monitoring node will calculate the direction characteristics of the zero-sequence current in real time, judge the attribution of the fault interval by comparing the consistency of the direction of adjacent nodes, and use the section where the transient energy extreme point of the zero-sequence loop is located as the auxiliary positioning basis, so as to make up for the risk of misjudgment of the direction criterion under special transition impedance conditions. The logical fusion of the two criteria can lay the foundation for the precise execution of subsequent isolation control^[4].

3. Fault isolation control strategy based on intelligent perception

3.1. Adaptive fault isolation criterion and action logic

After the fault section is confirmed, the isolation control system will formulate the switching action instructions according to the real-time electrical quantity to avoid unnecessary power outage losses caused by the large isolation range, and the adaptive isolation criterion takes the current sudden variable at both ends of the fault section and the voltage drop depth as the core inputs, and dynamically adjusts the isolation action threshold to adapt to the changes of different working conditions^[5]. The calculation model for isolation action time is as follows:

$$T = T_0 + k \cdot \frac{\Delta I}{I_n} \quad (2)$$

Where T : Delay Time for Isolation Action (ms); T_0 is the reference action time (ms); k is the adaptive adjustment coefficient (dimensionless), The tuning parameters reflecting the sensitivity of the system to current sudden variables; ΔI is the fault current mutation variable (A); I Rated current for the line (A).

When the mutation is large, the delay is shortened to speed up the response, and the delay near the setting boundary is appropriately extended to improve reliability, and the action logic is executed according to the timing

sequence of first disconnecting the fault side switch and then closing the contact switch.

3.2. Distributed feeder automation collaborative isolation scheme

Distributed feeder automation is based on the peer-to-peer communication of each intelligent terminal, abandoning the traditional centralized master station single-point decision-making mode, so that each switch terminal has the ability to make independent judgment and collaborative action. Adjacent terminals exchange local power information with the help of high-speed communication networks, independently complete fault section voting confirmation according to preset cooperative logic, and start the isolation process without waiting for the master station instructions. The cooperative logic has a built-in anti-malfunction mechanism, which requires at least two adjacent terminals to confirm the fault signal at the same time before triggering the action, eliminating the risk of false isolation caused by single-point measurement errors, and the redundant communication link design ensures that the collaborative function is not affected when some links are interrupted.

3.3. Network reconstruction and load transfer optimization after fault isolation

After the fault section is isolated, the power supply recovery in the power loss area relies on the rapid reconstruction of the distribution network, which minimizes the power outage load and optimizes the network loss as the dual goals, and transfers the lost load to the adjacent sound feeder by adjusting the contact switch state. The reconstruction algorithm adopts the improved particle swarm optimization method, takes the thermal stability limit of each feeder and the voltage qualification rate as the constraints to search for the optimal switching operation sequence, introduces an importance classification mechanism in the load transfer process to give priority to the recovery of primary loads such as medical and communication, and implements orderly cutting operations for low-priority loads when the capacity is limited. After the reconstruction is completed, the system automatically reports the new operating topology and the load factor of each feeder, forming a complete closed-loop control process of isolation and recovery.

3.4. Reliability analysis of multi-level protection coordination and isolation

The protection system of the distribution system includes substation outlet protection, feeder section protection and user-side protection to form a multi-level cooperation relationship, and the protection value setting and action timing of each level should be strictly coordinated to ensure that the isolation selectivity and rapidity meet the requirements at the same time. The principle of time limit and level difference cooperation stipulates that the delay of the upper level protection action must always be greater than that of the lower level protection to avoid leapfrog tripping and expanding the scope of power outage. Under the condition of intelligent perception, terminals at all levels can obtain the action status of the upper and lower levels in real time, and then realize adaptive fixed value switching, and when the protection of the lower level fails, the upper level will automatically shorten the delay as a backup, and the isolation reliability analysis uses Monte Carlo simulation to statistically model the communication delay, sensor error and switch rejection and other factors, and quantitatively evaluate the success probability of isolation.

4. Simulation experiments and method performance verification

4.1. Simulation platform construction and experimental scene design

The simulation and verification platform is built based on PSCAD software, and a 10 kV system model with 10

feeders is built with reference to the typical urban distribution network architecture, with a total length of about 85 km, and is connected to distributed photovoltaic power generation to simulate the new energy penetration scenario. The intelligent sensing terminal is embedded in the form of a software module to simulate the sampling rate and communication delay characteristics of the actual device, and the experimental scenario covers three types of faults: single-phase grounding, two-phase short circuit and three-phase short circuit, and sets the combination of different fault positions, transition resistances and load levels, and generates a total of 1200 sets of simulation samples. Among them, 800 sets of samples are used for model training, and 400 sets of samples are used as independent test sets, and there is no sample crossover between the training set and the test set, so as to ensure the objectivity of the evaluation results.

4.2. Comparative analysis of fault location accuracy

Based on the multi-terminal information fusion localization algorithm, all fault scenarios of the test sample set are positioned and calculated, and compared horizontally with the impedance method and the single-ended traveling wave method. The comparison dimension includes three core indicators: average positioning error, maximum positioning error and positioning success rate, and the evaluation results are presented in quantitative form (Table 2), and the average positioning error of the fusion algorithm is reduced by about 62% compared with the impedance method and about 38% lower than that of the single-ended traveling wave method. The samples with large errors are concentrated in the extreme working conditions with a transition resistance of more than 200 Ω , because the amplitude of the zero-sequence signal is extremely weak, which is the direction that needs to be focused on in subsequent research.

Table 2. Comparison of fault location performance of different positioning methods

Method	Average positioning error (%)	Maximum positioning error (%)	Success rate of single-phase grounding positioning (%)	Success rate of two-phase short-circuit positioning (%)	Three-phase short-circuit positioning success rate (%)
Multi-terminal information fusion algorithm	1.83	4.21	96.5	98.7	99.2
Single-ended traveling wave method	2.96	7.84	87.3	94.1	96.8
Impedance method	4.82	12.37	71.6	88.4	92.3

4.3. Isolation and recovery response performance evaluation

The isolation performance evaluation records the response time of the entire process from the occurrence of the fault to the completion of the isolation action in each fault scenario, and compares it with the traditional recloser timing scheme. The average response time of the distributed collaborative isolation scheme is 187 ms, which is about 54% shorter than the traditional scheme, and the speed advantage is more prominent in the feeder terminal fault scenario (Figure 2), the network reconstruction algorithm can complete the solution and execution of the optimal switching operation sequence within 3 seconds in all test scenarios, the recovery rate of the primary load power supply reaches 98.6%, and the multi-level protection coordination mechanism reduces the isolation malfunction rate to less than 0.8%, which is significantly better than that of the control group. The above data show that the proposed method achieves the expected goals in terms of response speed, isolation accuracy and power supply recovery ability, and has the technical conditions to be popularized and applied to the actual distribution network.

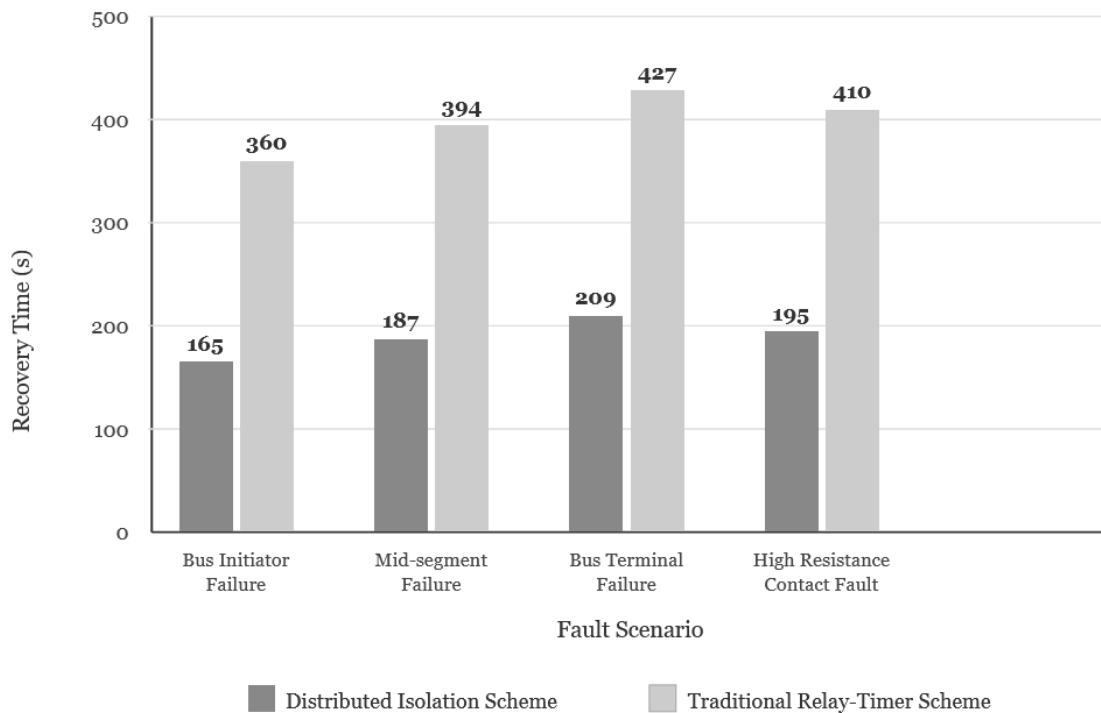


Figure 2. Comparison of response time of different isolation schemes.

5. Conclusion

Aiming at the actual problems of insufficient fault location accuracy and lag in isolation response in the power distribution system, a complete technical scheme for fault location and isolation based on intelligent perception is proposed. In terms of fault localization, the collaborative application of multi-terminal information fusion and machine learning models significantly improves the positioning accuracy under complex working conditions, and the high-sensitivity strategy of single-phase grounding fault effectively makes up for the blind spot of traditional methods. In terms of fault isolation, the combination of adaptive criterion and distributed collaboration mechanism shortens the time required for isolation action, and network reconstruction and multi-level protection coordination further ensure the reliability of the isolation process. The simulation results support the effectiveness of the above methods, and the follow-up research can carry out field tests in the direction of real distribution networks, and explore the adaptive optimization and popularization of the proposed method in the scenario of high proportion of new energy access.

Disclosure statement

The authors declare no conflict of interest.

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