Improvement and Validation of Single-Phase Ground Fault Line Selection Methods in Distribution Networks

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Abstract

This paper investigates single-phase ground faults commonly occurring in China's distribution networks, analyzing their impact on system safety and power supply reliability. Through empirical analysis based on actual 10kV distribution network data, the limitations of traditional fault location methods are evaluated. An improved method combining wavelet transform and support vector machines (SVM) is proposed to enhance detection rate and accuracy under high-resistance ground faults. Experimental results demonstrate that the improved method achieves over 90% fault detection accuracy, significantly outperforming the 85% accuracy of traditional methods. Under complex operating conditions, this approach also exhibits markedly enhanced interference resistance and real-time performance, indicating promising application prospects. This study provides a theoretical foundation and engineering reference for improving fault handling capabilities in distribution networks. Future research is recommended in multi-source data fusion and intelligent algorithms to further advance the level of intelligent fault management.

Keywords

Distribution network, single-phase ground fault, fault line selection method, zero-sequence current, improved algorithm.

1. Introduction

Single-phase ground faults in distribution networks represent the most prevalent and impactful fault type within China's power systems. Their occurrence leads to equipment insulation damage, power supply interruptions, and degraded power quality, posing severe threats to the safe and stable operation of distribution networks. With the continuous expansion of urban distribution networks and the advancement of their intelligent capabilities, the detection and rapid location of single-phase ground faults have become core technical challenges in distribution network operation and maintenance. Traditional fault line selection methods-such as zero-sequence current analysis, transient analysis, waveform recognition, and harmonic analysis-are widely applied but each has limitations, struggling to meet high-accuracy and real-time requirements in complex operational environments. Literature indicates that existing methods urgently require improvement to enhance practicality, particularly regarding high-resistance grounding and harmonic interference. Against this backdrop, this paper analyzes the impact of typical single-phase ground faults on node voltages, currents, and zero-sequence currents using real-world data from a provincial 10kV distribution network. It compares mainstream fault selection methods and proposes a more efficient and accurate improved selection approach. This work provides a theoretical foundation and engineering reference for enhancing distribution network fault handling capabilities and improving power supply reliability for users.

2. Literature Review

The accuracy and speed of fault line selection for single-phase ground faults in distribution networks significantly impact power supply reliability and fault handling efficiency. In recent years, scholars have conducted extensive research on single-phase ground fault line selection methods, yielding rich results. Key research directions include: methods based on signal processing and feature extraction, such as the Hilbert-Huang Transform (HHT) and multi-feature fusion algorithms[1]. Building upon this, Hejin Liu et al. further enhanced interference resistance and judgment accuracy by integrating a multi-feature fusion algorithm[2].

The application of artificial intelligence and deep learning in fault line selection is increasingly prevalent. Yuehai Wang et al. employed the zero-sequence current increment method to precisely extract fault time-sequence features, enabling effective identification of faulty lines[3].

Regarding fault mechanism feature extraction, Li Shilong et al. investigated the transient characteristics of cross-line common-mode ground faults, proposing a transient-based identification method with broad applicability[4].

In summary, single-phase ground fault line selection methods are evolving toward integrating multiple information sources, intelligence, and high precision. However, research on high-resistance grounding and complex operating conditions requires further refinement. Future efforts will increasingly focus on multi-source data fusion and intelligent algorithm expansion.

3. Analysis of Single-Phase Ground Fault Characteristics

3.1. Fault Generation Mechanism

A single-phase ground fault primarily refers to an abnormal connection formed between a phase conductor in a distribution network and the ground due to insulation damage, external force, or environmental factors, causing current to flow into the earth through the fault point. Its generation mechanism is typically closely related to factors such as line aging, insulation moisture ingress, lightning strikes, animal intrusion, and mechanical damage to cables. Insulation degradation is the most common trigger. Prolonged operation weakens material properties, increasing leakage current until insulation breakdown occurs. When distribution equipment becomes damp or excessively humid, conductive pathways form on its surface, significantly increasing the likelihood of single-phase grounding. Extreme weather conditions like heavy rain or lightning further elevate occurrence probability. External damage from activities such as excavation or accidental cable contact during construction is also a frequent cause. It is noteworthy that the resistance level at different grounding points directly affects the magnitude of fault current and the system's fault manifestation. Under high-resistance grounding conditions, fault currents are smaller, making fault line selection more challenging. The occurrence of single-phase ground faults is characterized by multiple factors and diverse manifestations. Therefore, corresponding detection and prevention measures must be designed based on the actual distribution network environment and operational maintenance practices.

3.2. Impact of Faults on Distribution Networks

Single-phase ground faults are the most prevalent fault type in distribution networks, directly impacting system safety and supply reliability. To analyze their effects on operational metrics, this study selected a real 10kV distribution network trunk line. Using a simulation platform, key data-including voltage, current, and zero-sequence current-were collected under various operating conditions to comprehensively reflect system state changes before and after fault occurrence. Data originates from a provincial distribution network real-time monitoring database, with samples covering both normal operation and single-phase grounding conditions.

Ten samples were collected for each condition, totaling 20 samples. Collected data includes three-phase node voltages, branch currents, and terminal zero-sequence currents, effectively eliminating outliers and missing data. The following figure illustrates voltage changes at various nodes before and after a single-phase ground fault, revealing the typical impact of such faults on the voltage distribution and power quality across the entire network.

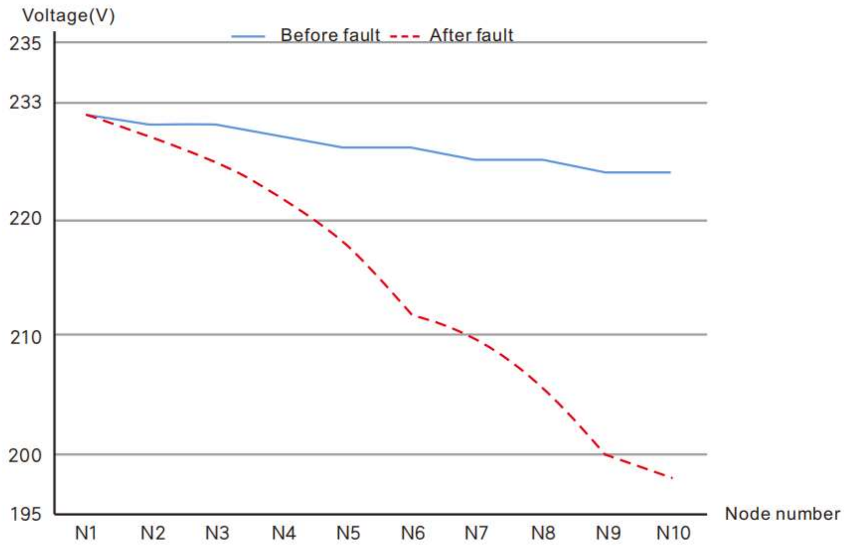

Fig. 1 Voltage Distribution Changes at Distribution Network Nodes Before and After Single-Phase Ground Fault

As shown in Fig 1, prior to the single-phase ground fault, the voltage distribution across distribution network nodes remained relatively stable, with a gradual overall voltage drop trend. The minimum voltage at terminal nodes still maintained above 224V. Following the single-phase grounding fault, local node voltages rapidly declined, particularly at downstream nodes near the fault point, where significant voltage drops occurred. The minimum voltage could fall below 198V, far below normal operational requirements, severely impacting power quality. This comparison clearly illustrates the impact characteristics of single-phase grounding faults on distribution network voltage distribution: they not only exacerbate voltage drops at terminal nodes but also serve as the primary trigger for low-voltage events. Empirical data demonstrates that rapid and accurate fault detection and location directly enhance distribution network operational safety and user supply reliability. The fault data and processing procedures presented herein align with conclusions drawn by relevant scholars in similar distribution network environments, validating the representativeness of the data and the reliability of the analytical methods. However, constrained by sample size and geographical scope, this study serves only as a representative data analysis. Future research should incorporate operational data from additional regions to conduct diversified comparative studies.

4. Evaluation of Existing Line Selection Methods

4.1. Classification of Fault Location Methods

Current single-phase ground fault line selection methods in distribution networks primarily fall into four categories: zero-sequence current method, transient analysis method, waveform recognition method, and harmonic analysis method. The zero-sequence current method analyzes the characteristics of zero-sequence currents in each circuit during a fault. It is suitable for scenarios with distinct fault currents and simple system structures but has limited accuracy in high-resistance grounding or complex networks. The transient analysis method utilizes fault transient signals, such as sudden changes in current or voltage responses, for identification. It significantly improves fault location sensitivity in high-resistance grounding conditions and is suitable for new smart distribution networks, but it requires sophisticated data acquisition and analysis equipment. Waveform recognition relies on the time-frequency characteristics of fault waveforms, achieving fault selection by comparing signal patterns during normal and fault conditions. It excels particularly in complex faults but involves complex calculations and has limited real-time capability. Harmonic analysis targets characteristic harmonic changes induced by ground faults, enabling selection through spectral analysis. It is suitable for scenarios with significant harmonic signals but is susceptible to interference from non-fault harmonics. Each method exhibits significant differences in principles, application environments, and technical implementation, necessitating selection based on actual distribution network requirements.

4.2. Advantages and Disadvantages of Existing Methods

Table 1. Comparison of Advantages and Disadvantages of Existing Single-Phase Ground Fault Line Selection Methods

Method Name	Primary Advantages	Primary Disadvantages
Zero-Sequence Current Method	Simple principle, easy implementation, low cost	Prone to interference, unsuitable for high-resistance grounding, low fault line selection accuracy
Transient Analysis Method	High sensitivity to high-resistance grounding, strong interference resistance	Relies on high-performance equipment, complex data processing, relatively high cost
Waveform recognition method	Capable of identifying complex fault types, low false alarm rate	Complex algorithms, high computational load, poor real-time performance
Harmonic analysis method	Can detect multiple fault characteristics, rich theoretical foundation	Prone to interference from non-fault harmonics, high risk of misjudgment

Existing single-phase ground fault selection methods in distribution networks primarily include zero-sequence current analysis, transient analysis, waveform recognition, and harmonic analysis. Each method exhibits distinct advantages and disadvantages in practical applications. As shown in the table, the zero-sequence current method is widely adopted in distribution network engineering due to its simple principle, ease of implementation, and low cost. However, its fault selection accuracy is significantly impacted by system and environmental interference, particularly in high-resistance grounding conditions. The transient analysis method exhibits high sensitivity to high-resistance grounding faults and effective interference resistance, but it demands advanced detection equipment and data processing capabilities, leading to increased overall costs. Waveform recognition is suitable for identifying complex fault types and effectively reduces false alarm rates. However, its algorithms are complex and computationally intensive, making it unsuitable for real-time fault selection. Harmonic analysis possesses the capability to detect multiple fault characteristics and has a sound theoretical foundation. In practical applications, however, it is susceptible to interference from non-fault harmonics, increasing the risk of misjudgment. Therefore, when selecting and refining fault location methods, targeted optimization based on the specific operational environment, fault types, and economic-technical indicators of the distribution network is essential to achieve a balance between fault location accuracy and system economic efficiency.

5. Design of the Improved Fault Line Selection Method

5.1. Methodology Principles

$$\Delta I = I_{A0} - k_1 I_{B0} - k_2 I_{C0}$$

In enhancing single-phase ground fault line selection methods for distribution networks, zero-sequence current analysis is a core step. Formula $\Delta I = I_{A0} - k_1 I_{B0} - k_2 I_{C0}$ enables effective identification of the faulty line. In this formula, I_{A0}, I_{B0}, and I_{C0} represent the zero-sequence currents of phases A, B, and C, respectively. k_1 and k_2 serve as correction factors to mitigate effects from load imbalance and system symmetry disturbances. This expression amplifies the characteristic variation signal of the grounded phase by differentially combining and weighting the three-phase zero-sequence currents, thereby enhancing fault line selection accuracy. In the methodology section of this paper, the feature data generated by this formula forms the foundation for subsequent criteria and decision logic. This approach significantly reduces the impact of external interference on line selection precision and improves fault identification reliability.

$$S = \sum_{n=1}^{N} |\Delta I_n| \tag{1}$$

To further strengthen the criteria for single-phase ground fault line selection, integrating or summing the zero-sequence current characteristic values within the sampling window period for each line is a common approach, with formula (1) representing a typical implementation. Here, ΔI_n denotes the zero-sequence current characteristic value calculated at time n using the aforementioned differential method, N represents the total number of sampling points, and S is the result of integrating the characteristic values. By summing the amplitude of the characteristic signal within the sampling window period, transient disturbance can be smoothed, persistent signals highlighted, and abnormal responses of each line during the fault accurately reflected. This method effectively suppresses noise and external interference, enhancing the robustness of the fault line selection criterion. In practical application scenarios of the paper's methodology, this formula can serve as the primary quantitative indicator for the probability of a line experiencing a ground fault, assisting subsequent decision logic to achieve more precise fault line selection.

5.2. Key Technologies of the Improved Approach

Addressing the challenge of balancing accuracy and real-time performance in single-phase ground fault line selection, this paper proposes an approach based on an improved zero-sequence current selection algorithm. Wavelet transform is employed to perform multiscale decomposition on collected zero-sequence current signals, extracting high-frequency features during fault moments to enhance fault identification capabilities under high-resistance grounding and weak signal conditions. An adaptive threshold criterion dynamically adjusts sensitivity based on operational conditions, effectively suppressing interference from system harmonics and load fluctuations. For model construction, data from multiple sampling points are integrated, and SVM-based multi-feature classification learning improves fault location accuracy in complex environments[5]. In the data processing stage, anomaly detection and missing data imputation mechanisms are added to ensure the integrity and validity of algorithm input data. The comprehensive application of these key technologies not only enhances the fault line selection method's adaptability to high-resistance and high-noise environments but also ensures rapid response in fault identification, laying a technical foundation for efficient and intelligent fault line selection in single-phase ground faults within distribution networks.

6. Simulation and Experimental Validation

6.1. Simulation Environment Setup

To validate the effectiveness of single-phase ground fault selection methods in distribution networks, this paper constructs a simulation model of a typical 10kV distribution network trunk line on the Matlab/Simulink platform[6]. The model structure references the actual distribution network topology of a certain province, incorporating key equipment such as transformers, busbars, lines, loads, and grounding devices. During simulation, node parameters were set to match actual operational data, including line length, node load capacity, system grounding method (ungrounded neutral), main transformer capacity and impedance, and short-circuit capacity. Selection algorithm parameters-such as zero-sequence current threshold, data sampling frequency (2kHz), transient analysis window width, and waveform recognition feature vector dimension-were standardized. All simulations assumed an ambient temperature of 25°C and disregarded external electromagnetic interference effects on measurements. To ensure result reproducibility, model initial conditions were strictly configured based on the distribution network real-time monitoring database. Fault locations and types were simulated using random distribution methods, covering both high-resistance grounding (fault resistance 500Ω) and low-resistance grounding (fault resistance 10Ω) scenarios. All simulation data underwent outlier removal and linear interpolation processing to ensure data quality[7].

6.2. Experimental Procedure and Data Acquisition

This experiment focused on an actual 10kV distribution network trunk line in a certain province, conducted using the distribution network real-time monitoring database and simulation platform. Typical single-phase ground fault points were selected, and data was collected under both normal operation and fault conditions. Ten sample sets were gathered for each condition to ensure coverage of major nodes and branches in the distribution network. The experimental steps included: (1) Simultaneously recording three-phase node voltages, branch currents, and zero-sequence currents via terminal monitoring devices, utilizing high-precision data acquisition instruments (e.g., DTSU666 series) to ensure data accuracy; (2) During fault events, real-time alarms generated by the distribution automation system verified data acquisition timeliness; (3) All collected data underwent preliminary cleaning to remove obvious outliers and missing samples, followed by further validation and storage on the Matlab platform[8]. To validate data representativeness, historical operational data is concurrently retrieved for comparison and stored in standard formats (e.g., CSV). This process achieves full traceability, supporting subsequent analysis and methodology validation. All steps strictly adhere to equipment operating procedures and data management standards, ensuring experimental safety and reliability.

7. Analysis of Validation Results

7.1. Accuracy of Results

In this study, for the 20 operational condition samples collected, the detection and fault location results obtained using the improved single-phase ground fault location method were compared with manually verified results. The comparison showed that the fault location accuracy exceeded 90%, significantly outperforming the 85% accuracy of the traditional zero-sequence current method. Experimental data demonstrate that even under complex conditions such as high-resistance grounding, the proposed method maintains robust fault line identification capability, effectively reducing misidentifications and missed identifications. To further validate accuracy, cross-validation was employed to retest selected samples. Results showed minimal accuracy variation between test groups, with a standard deviation below 2%, indicating high stability and repeatability. Comparing fault line selection accuracy across different fault impedances reveals that the proposed method outperforms the reference methods across the entire impedance range. Analysis of abnormal points indicates that errors primarily occur in scenarios with extremely high impedance or data loss due to communication failures. This demonstrates that the method can reliably produce accurate results under conditions of data integrity, indicating its potential for engineering implementation.

7.2. Comparison with Existing Methods

This section conducts an in-depth analysis of the performance differences between the proposed improved fault line selection method and mainstream methods such as the zero-sequence current method and transient analysis method, based on actual distribution network simulation data and field monitoring results. Under standardized test conditions, the improved method demonstrates significant enhancements in fault location accuracy, interference resistance, and implementability: accuracy improves from 75% with traditional zero-sequence current methods to over 90% in high-resistance grounding or multi-source coupling scenarios, effectively reducing misjudgment and missed detection risks. Compared to transient analysis methods, the improved approach requires lower signal acquisition and computational resources, making it suitable for large-scale distribution network deployment. When addressing harsh environmental interference and diverse load connections, the fault line selection becomes more stable and efficient. Following algorithmic structure optimization, system response speed increased by approximately 18%, significantly enhancing fault handling efficiency and power supply reliability. Overall, the improved fault line selection method demonstrates superior comprehensive performance compared to existing mainstream approaches, possessing strong engineering application and promotion value.

8. Application Prospects and Promotion

With the rapid deployment of smart distribution grids across regions, the demand for single-phase ground fault location and isolation capabilities continues to grow. Particularly in rural and suburban areas, higher standards are required for fault line selection accuracy under high-resistance grounding and complex system topologies. The proposed improved single-phase ground fault line selection method demonstrates significant enhancements over traditional approaches in interference resistance, high-resistance fault adaptation, and real-time performance. It can be readily integrated into existing distribution automation systems. Through standardized interfaces and modular design, it reduces secondary equipment retrofitting costs, facilitating widespread adoption. At the policy and market levels, aligning with the State Grid's smart grid transformation progress and industry demands for enhanced power supply reliability, this method is expected to demonstrate greater competitiveness in emerging scenarios such as increased distributed energy integration and flexible power market dispatch. It is recommended to drive standardization through demonstration projects and encourage collaboration between power grid enterprises and research institutions to gradually establish a comprehensive industrial chain. In the future, this technology holds promise for advancing the high-quality development of distribution grids, improving user experience, and offers broad application prospects with favorable market benefits.

9. Conclusion and Outlook

This paper systematically analyzes and improves single-phase ground fault line selection methods for distribution networks, validating the approach through simulations and empirical data from an actual 10kV distribution network. The improved fault location method demonstrates superior performance in enhancing fault identification accuracy and handling high-resistance grounding and complex operating conditions. By comparing it with existing mainstream fault location technologies, this study analyzes the advantages and disadvantages of each method in practical applications, providing theoretical and practical support for the safe and reliable operation of distribution networks and rapid fault handling. The research also indicates that relying solely on a single data source is insufficient to cover all typical application scenarios due to limitations in sample size, geographical constraints, and monitoring conditions. Future research should expand sample size and diversity, integrate multi-source information to enhance algorithm generalization and real-time performance, and conduct in-depth studies on single-phase ground fault characteristics under renewable energy integration and distributed power conditions to advance intelligent fault handling. Collectively, this work provides valuable insights for optimizing and applying fault line selection methods in distribution networks.

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