

Article

Location Method for Asymmetrical Latent Cable Faults in Low-Resistance Systems Based on Multidimensional Information

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Abstract

The incipient cable fault in active low-resistance-grounded distribution networks is a typical asymmetrical fault and is difficult to locate because the fault current is weak, short-lasting, and easily affected by distributed generation (DG). To address this typical asymmetrical problem, this paper proposes a fault section location method based on multidimensional information correlation analysis. First, an equivalent incipient fault model is established by combining the Kizilcay arc model with an insulation-defect resistance, so that the intermittent arc behavior and the conductive path of degraded insulation can be represented simultaneously. Then, the generalized S-transform is used to extract three features from the transient zero-sequence current, namely the transient current energy index, group phase-angle polarity, and waveform similarity. On this basis, a multidimensional feature vector and a comprehensive similarity coefficient are constructed to identify the fault section, and an auxiliary downstream energy comparison rule is introduced to distinguish the actual fault section from DG-connected pseudo-fault sections. The method is verified in MATLAB/Simulink R2025a under different fault locations, DG access conditions, penetration levels, noise levels, and key parameter variations. The simulation results under the tested conditions indicate that the proposed method can effectively identify asymmetrical incipient cable fault sections in active low-resistance-grounded distribution networks.

Keywords: distribution network; low-resistance grounding; fault; latent; cable



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1. Introduction

As urban power grids develop toward higher reliability and safety [1–3], underground power cables have been widely applied in medium-voltage (MV) distribution networks, gradually replacing traditional overhead lines due to their advantages of a small footprint, strong resilience against environmental interference, and high operational safety [4–6]. However, the rapid increase in the cabling rate [7–9] leads to a significant rise in the total system capacitive current to ground. This makes it difficult for traditional small-current grounding systems (such as ungrounded systems or systems grounded via arc-suppression coils) to guarantee detection sensitivity during single-phase-to-ground faults [10,11]. In contrast, the low-resistance grounding method [12] can provide sufficient zero-sequence

current to facilitate detection during single-phase grounding faults [13] while simultaneously limiting fault overvoltage levels. Consequently, it has become the mainstream choice for urban cable-dominated MV distribution networks.

However, in cable-dominated low-resistance grounding systems, the issue of incipient faults has become increasingly prominent [14–16]. Such faults typically manifest as short-duration, self-clearing intermittent arc discharges. Their underlying causes primarily stem from the degradation of cable insulation during long-term operation due to factors such as electrical stress, thermal aging, moisture ingress, and mechanical damage [17], which lead to the formation of defects including partial discharges, water trees, and electrical trees [18,19]. Incipient faults are characterized by short durations, low current amplitudes, and small transient energy, thus often failing to trigger conventional protection devices. If not detected and addressed promptly, these faults will recur and progressively deteriorate, ultimately evolving into permanent breakdowns and causing large-scale power outages. Particularly in low-resistance grounding systems, the fault current contains a significant zero-sequence component flowing through the grounding resistor, which exacerbates the threat of incipient faults to the safe operation of the system.

For the detection and location of incipient faults, existing research is primarily based on transient feature extraction and signal similarity analysis [20–23]. For instance, Wang et al. [20] utilized the S-transform to extract transient energy distribution features for faulty section identification. Pang et al. [21] integrated multi-feature information fusion to improve fault identification accuracy. Zhang et al. [22] obtained the faulty section through clustering analysis by utilizing the difference in center-of-gravity frequencies of zero-sequence currents on both sides of the fault point. Addressing the difficulty in selecting the center-of-gravity frequency downstream of the fault, Xu et al. [23] proposed a processing method based on kurtosis analysis. These methods perform well in traditional radial distribution networks, but their theoretical foundations are mostly based on the assumption of a single power source and a unique small-current flow path. When distributed generation (DG) is integrated into the system [24], this assumption no longer holds. The connection of DG alters the distribution paths of zero-sequence currents, which may cause “pseudo-fault” features to appear in healthy sections [25]. Furthermore, the fast control loops of inverter-based DGs [26–28] change the timescale of the transient response, leading to distortions in transient energy distribution and phase angle characteristics, thereby rendering traditional locating methods based on single-dimensional features ineffective. Recent studies on renewable-energy utilization and flexible energy systems also indicate that modern distribution-side energy systems are becoming increasingly coupled and operationally complex [29,30]. In addition, intelligent diagnostic methods have also been increasingly applied in power-system monitoring and security assessment. For example, Wang et al. [31] proposed a particle swarm optimization–attention temporal graph convolutional network model for detecting dummy data injection attacks in power systems.

Existing research on incipient fault detection with the integration of DG still presents the following limitations: (1) Most studies focus on a single feature of the fault transient signal (such as energy or phase angle difference), failing to comprehensively characterize the differences between the upstream and downstream sides of the fault point from a multi-dimensional feature perspective; (2) Traditional criteria mostly rely on fault current amplitudes or transient energy ratios. When the DG injection path and the neutral point of the main grid form a parallel channel, these criteria are prone to failure due to the power shunting effect; (3) Existing models primarily use ideal arcs or fixed equivalent impedances as approximations, ignoring the dynamic conductive characteristics of the insulation defect channels in cables, which makes it difficult to accurately reflect the underlying mechanisms of incipient faults.

Therefore, there is an urgent need for an incipient fault location method that remains robust and discriminative under the integration of DG, so as to enhance the self-healing capability and operational reliability of low-resistance grounding systems.

To address these issues, targeting the challenges of small current and short duration of cable incipient faults, as well as the failure of traditional locating methods caused by DG integration in active low-resistance grounding systems, this paper proposes a faulty section location method based on multi-dimensional information correlation analysis. By establishing an equivalent model of incipient faults that considers arc characteristics and the impedance of insulation defect channels, the formation mechanism of the fault transient is represented. The Generalized S-transform (GST) is utilized to extract three types of features from the zero-sequence current: transient current energy index, phase angle polarity, and waveform similarity. Subsequently, a comprehensive similarity criterion is constructed to achieve faulty section identification. Simulations are conducted to verify the effectiveness of the proposed method under representative fault locations, DG integration locations, penetration levels, and disturbance conditions. The main contributions of this paper are summarized as follows:

- (1) An equivalent incipient cable fault model is established by combining the Kizilcay arc model with the insulation-defect resistance, which reflects both intermittent arc behavior and the conductive path caused by insulation degradation.
- (2) A multidimensional feature vector is constructed using the GST-based transient current energy index, group phase-angle polarity, and waveform similarity, so that the fault section can be identified from amplitude, directional, and waveform perspectives.
- (3) A comprehensive similarity coefficient and an auxiliary downstream energy comparison rule are proposed to distinguish the actual fault section from DG-connected pseudo-fault sections under active distribution network conditions.

2. Modeling and Feature Analysis of Cable Incipient Faults

2.1. Characteristics of Incipient Faults

Incipient faults in distribution cables refer to intermittent arcing phenomena caused by insulation defects, environmental influences, or external damage. They typically occur repeatedly at the same location and are characterized by their self-recovering nature and short duration. The fault current generally extinguishes at the zero-crossing point of the power frequency and reignites at the voltage peak, conforming to the power-frequency arc extinction theory. This results in a “zero-pausing” phenomenon in the current and “saddle-shaped” fluctuations in the voltage [32,33]. In this study, the zero-crossing point of the power frequency refers to the instant at which the fundamental-frequency fault current crosses zero. The power-frequency arc extinction theory indicates that an intermittent arc tends to extinguish near the current zero crossing and may reignite when the recovery voltage across the defect channel exceeds the reignition condition.

2.2. Kizilcay Arc Model

Cable incipient faults are essentially intermittent arcing processes, and their dynamic characteristics can be described by the Kizilcay arc model [32]:

$$\frac{dg(t)}{dt} = \frac{1}{\tau}(G(i_f, u_{st}(t)) - g(t)) \quad (1)$$

where τ is the arc time constant determined by the thermal inertia of the arc; $g(t)$ denotes the instantaneous electrical conductance; G is the static equivalent conductance of the

arc, which is a function of the instantaneous arc current i_f and the static arc voltage. The relationship between the arc voltage and current is expressed as:

$$\begin{cases} i_f(t) = G(t)u_{st}(t) \\ R_{arc}(t) = \frac{1}{g(t)} \end{cases} \quad (2)$$

where $R_{arc}(t)$ denotes the time-varying arc resistance calculated from the Kizilcay arc conductance model, reflecting the dynamic characteristics of the intermittent fault arc.

The static arc voltage can be expressed as:

$$u_{st}(t) = u_0 + r_0|i_f(t)| \quad (3)$$

where u_0 is the characteristic arc voltage, and r_0 is the characteristic arc resistance.

2.3. Equivalent Model Extension

Relying solely on the arc model is insufficient to fully characterize the features of incipient faults. The un-discharged regions within defect channels, such as water trees, electrical trees, and moisture-induced conductive paths, may still retain weak conductivity before complete breakdown. Therefore, they can be represented by an equivalent insulation-defect resistance R_0 . R_0 is not a fixed physical constant, but an equivalent parameter related to the aging degree, moisture condition, and defect morphology of the cable. By connecting R_0 in series with the time-varying arc resistance $R_{arc}(t)$, an equivalent model for cable incipient faults is constructed, as shown in Figure 1, which can be described by the following equation:

$$u_f(t) = i_f(t)(R_0 + R_{arc}(t)) \quad (4)$$

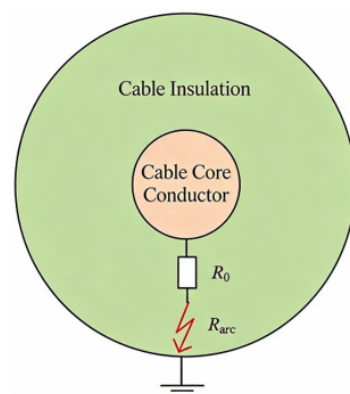


Figure 1. Equivalent model of latent cable fault. The red arrow indicates the intermittent arc discharge path through the insulation-defect channel.

This model can not only reproduce the “zero-pausing” and “saddle-shaped” characteristics of the arc, but also reflect the influence of insulation defects on the fault evolution process.

The model in (4) is intended to describe the physical coupling between intermittent arc conduction and the weak conductive channel of degraded insulation. In this equivalent model, $R_{arc}(t)$ mainly determines the rapid arc extinction and reignition behavior, whereas R_0 represents the residual conductive path before complete breakdown. Therefore, the parameters in this section are introduced from the viewpoint of physical modeling rather than as fixed simulation constants. The specific simulation settings and the influence of R_0 are described in the simulation section.

Based on the single-phase-to-ground equivalent circuit and the line-to-ground capacitive current relationship, the current at the fault point can be approximately expressed as:

$$i_f(t) = \frac{U_{ph} \cdot g(t) \sin(\omega t + \varphi)}{1 + g(t)X_C} \quad (5)$$

where U_{ph} is the root-mean-square value of the phase voltage, X_C is the line-to-ground capacitive reactance, ω is the power-frequency angular frequency. The corresponding arc voltage obtained from the simulated arc process is shown in Figure 2.

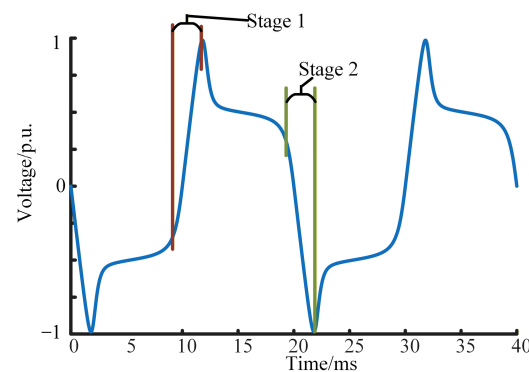


Figure 2. Voltage variation process at the fault point. The blue curve represents the per-unit voltage at the fault point.

As can be seen from Figure 2, the arc at the fault point extinguishes and reignites during Stage 1 and Stage 2 of each cycle. Although this transition time is very short, it alters the impedance profile of the power grid, causing the fault transient process to recur. The fault occurrence process in any given stage can be represented by the following equivalent circuit, shown in Figure 3:

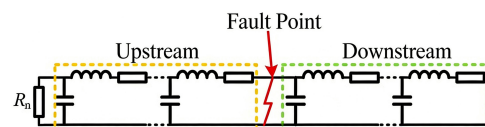


Figure 3. Equivalent circuit during the transient stage.

Based on transmission line theory, the line can be regarded as consisting of an infinite number of resistors, inductors, and capacitors, which makes direct analysis difficult. Generally, it can be approximated by the equivalent capacitance and inductance of the line. During the short transient interval, the equivalent resistance mainly affects the attenuation rate of the oscillatory component. Under a weakly damped approximation, the main resonant frequency can be expressed by the following equation:

$$f_{res} \approx \frac{1}{2\pi\sqrt{L_{eq}C_{tot}}} \quad (6)$$

where L_{eq} is the equivalent inductance of this line section, and C_{tot} is the total equivalent capacitance of this line section and the lines behind it.

It can be seen that: (1) As C_{tot} increases (the line is longer, there are more parallel branches, or the zero-mode capacitance per unit length is larger), f_{res} decreases; (2) As L_{eq} increases (the fault point is closer to the middle, the upstream/downstream length is greater, the line-mode inductance per unit length is larger, or the equivalent inductance increases after taking transformer leakage reactance into account), f_{res} also decreases. Therefore, if the rapid variation process at the fault point introduces a transient process to the system,

the generated transient characteristics will differ upstream and downstream of the fault point due to the different composition scales of inductive and capacitive reactances in those regions.

2.4. Impact of DG Integration

In a low-resistance grounded system, the main components of a single-phase-to-ground fault current are the zero-sequence current flowing through the grounding resistor and the line-to-ground capacitive current. After the integration of DG, the current provided by the DG and the introduction of new neutral points cause significant changes in the distribution and amplitude of the fault current.

On the one hand, regarding power-frequency components: When a DG is connected to the faulted section, its output current is injected directly into the fault point, resulting in a significant increase in the power-frequency zero-sequence current within the faulted section. When a DG is connected upstream of the fault point, the fault current is split between the main grid and the DG, causing a significant increase in the upstream zero-sequence current. When a DG is connected to a downstream section, the DG output current forms a zero-sequence component through the grounding resistor, causing a zero-sequence current of a certain amplitude to appear in the downstream line. When a DG is connected to a healthy line far from the fault point, since the zero-sequence current can spread rapidly in a low-resistance grounded system, the DG current may cause a weak zero-sequence current component to appear at the detection point of that healthy line, thereby interfering with fault identification.

On the other hand, regarding non-power-frequency components: The introduction of a new neutral point provides a new path for the flow of transient fault currents, making it difficult to distinguish between the non-power-frequency components flowing to the system's neutral point and those flowing to the distributed generator's neutral point.

Therefore, in small-resistance grounding systems, to improve the identification capability of incipient fault sections, it is necessary to establish comprehensive criteria based on multi-dimensional features such as energy amplitude, phase angle polarity, and waveform similarity, thereby enhancing the robustness and adaptability of the method under multi-source coupling conditions.

3. Multi-Dimensional Feature Extraction

3.1. Feature Selection

Based on the modeling of incipient faults and the analysis of DG integration, the fault point can be equivalent to an intermittent excitation source, which causes significant differences in the zero-sequence current characteristics between the upstream and downstream lines. This is primarily manifested in the following three aspects:

(1) Difference in Transient Energy Amplitude

The upstream line contains the busbar and more healthy lines, exhibiting a stronger response to the fault excitation. Its transient energy is usually several times that of the downstream line, and the exact magnitude depends on their respective equivalent capacitances and equivalent inductances. Therefore, the transient energy amplitude can serve as an amplitude criterion. Furthermore, based on the maximum energy principle, the frequency corresponding to the maximum transient energy of the system can be defined as the fault characteristic frequency.

(2) Differences in phase angle polarity

Fault currents of any frequency split upstream and downstream at the fault point. The upstream current flows toward the busbar, while the downstream current flows toward

the load, resulting in a 180° phase difference between the two at characteristic frequencies. In contrast, the current directions at both ends of a healthy section are consistent, and their phases are basically identical. Therefore, phase angle polarity can serve as a directional criterion.

(3) Differences in waveform similarity

The zero-sequence current in a healthy section is primarily determined by the line-to-ground capacitive current, and the waveforms at both ends are highly consistent (with a correlation coefficient close to 1). In the faulted section, however, the similarity drops sharply due to the sudden change in current direction. Therefore, waveform similarity can effectively distinguish between faulted and healthy sections.

3.2. Principle of Generalized S-Transform

GST is an improved time-frequency analysis method [19]. By using an adjustment factor g to optimize the time-frequency resolution, GST can better balance time and frequency resolutions compared to the traditional S-transform. In this study, the value and influence of g are further discussed in the sensitivity analysis. Its discrete form is as follows:

$$GST(k, n) = \sum_{m=0}^{N-1} h(m) \exp\left(-\frac{(n-m)^2}{2(gk)^2}\right) e^{-j2\pi km/N} \quad (7)$$

where $h(m)$ denotes the sampled transient zero-sequence current at the i -th detection point, N is the number of sampling points in one power frequency cycle, k is the frequency index, and n is the time index. By taking the modulus and the phase angle, the amplitude matrix $S(k, n)$ and the phase angle matrix $\varphi(k, n)$ can be obtained, thereby simultaneously acquiring both time-domain and frequency-domain features.

3.3. Transient Current Energy Index

After the GST is applied to the sampled transient zero-sequence current, the amplitude matrix reflects the distribution of transient current components in both the time and frequency domains. Since an incipient fault behaves as an intermittent excitation source, the transient current response is usually concentrated around several dominant frequency components. Therefore, the frequency corresponding to the maximum GST amplitude-energy response is selected as the characteristic frequency for feature extraction. The transient current energy index at this characteristic frequency is then used to describe the amplitude difference between adjacent detection points.

At the characteristic frequency, the transient current energy index of the i -th detection point can be defined as:

$$W_i(a) = \sum_{b=n}^{n+N/4} S_i(a, b)^2 \quad (8)$$

where a is the frequency index, and b is the time index, S is amplitude matrix.

Energy ratio of adjacent detection points:

$$p_{(i,i+1)} = \frac{W_i}{W_{i+1}} \quad (9)$$

Normalized to obtain the amplitude feature:

$$Q_{(i,i+1)} = \frac{p(i, i+1) - p_{\min}}{p_{\max} - p_{\min}} \quad (10)$$

where the index defined above is not the total electromagnetic energy of the circuit, but an amplitude-related indicator used to quantify the transient zero-sequence current intensity at the characteristic frequency. When the normalized amplitude feature approaches 1, it indicates a faulted section, and when it approaches 0, it indicates a healthy section.

3.4. Group Phase Angle Polarity

At the characteristic frequency, the transient zero-sequence currents on the two sides of a healthy section generally flow in the same direction, and their phase angles are close to each other. In contrast, for a faulted section, the fault point acts as a transient injection point, and the currents at the two ends of the section may flow in opposite directions. This leads to an evident phase-angle polarity difference. Therefore, the phase-angle polarity is introduced as a directional feature to distinguish the faulted section from healthy sections.

Under the condition that the frequency index k takes the characteristic frequency, setting the phase angle threshold $\theta_{\text{set}} = 90^\circ$, the polarity is defined as:

$$\theta(k, n) = \text{sign}(|\varphi(k, n) - \theta_{\text{set}}|) \quad (11)$$

The polarity feature of adjacent detection points is:

$$\text{pol}_{(i,i+1)} = \frac{\sum_{n=1}^{N/4} \text{sign}(\theta^i(k, n) \cdot \theta^{i+1}(k, n))}{\left| \sum_{n=1}^{N/4} \text{sign}(\theta^i(k, n) \cdot \theta^{i+1}(k, n)) \right|} \quad (12)$$

If $\text{pol}_{(i,i+1)} = -1$, it is determined as a faulted section; if $\text{pol}_{(i,i+1)} = 1$, it is determined as a healthy section.

3.5. Waveform Similarity

The waveform similarity feature is introduced to describe the consistency of transient zero-sequence current waveforms at the two ends of a section. For a healthy section, the transient zero-sequence currents at two adjacent detection points are mainly determined by the same current path, so their waveforms are highly similar and their initial polarities are usually consistent. For a faulted section, the fault point changes the current path and current direction, resulting in a significant waveform difference between the two ends of the section. Therefore, the correlation coefficient of the transient current waveforms can be used as a shape-related feature for section identification.

Within a $1/4$ cycle, the waveform similarity between detection points i and $i + 1$ is defined as:

$$D_{(i,i+1)} = \sum_a \sum_b (S_i(a, b) - S_{i+1}(a, b))^2 \quad (13)$$

After normalization, the correlation coefficient is obtained as:

$$\rho_{(i,i+1)} = \frac{\sum_a \sum_b S_i(a, b) S_{i+1}(a, b)}{\sqrt{\sum_a \sum_b S_i(a, b)^2} \cdot \sqrt{\sum_a \sum_b S_{i+1}(a, b)^2}} \quad (14)$$

For a healthy section, $\rho_{(i,i+1)} \approx 1$, and for a faulted section, $\rho_{(i,i+1)} \approx 0$.

3.6. Multi-Dimensional Feature Vector

The multi-dimensional feature vector for section $(i, i + 1)$ is:

$$\mathbf{A}_{(i,i+1)} = [Q_{(i,i+1)}, pol_{(i,i+1)}, \rho_{(i,i+1)}] \quad (15)$$

This vector comprehensively reflects the energy difference, phase angle polarity, and waveform similarity, providing input for the subsequent construction of the comprehensive similarity criterion.

4. Fault Detection and Location Method

4.1. Section Distance Metric

After the three feature components are normalized, each section can be regarded as a point in a three-dimensional feature space. The coordinates of this point represent the amplitude, directional, and waveform-shape characteristics of the corresponding section. For healthy sections, these feature points are usually close to each other because their transient current paths and waveform characteristics are similar. For the faulted section, the feature point deviates from those of the healthy sections because the fault point changes the amplitude distribution, current direction, and waveform similarity at the two ends of the section. Therefore, the Euclidean distance between two section feature vectors can be used to quantify their feature difference.

After obtaining the three-dimensional feature vector for each section $(i, i + 1)$, the Euclidean distance between section $A_{(i,i+1)}$ and section $A_{(j,j+1)}$ can be defined as:

$$\begin{aligned} D(A_{(i,i+1)}, A_{(j,j+1)}) \\ = \sqrt{(Q_i - Q_j)^2 + (pol_i - pol_j)^2 + (\rho_i - \rho_j)^2} \end{aligned} \quad (16)$$

If the distribution network has l sections, an $l \times l$ section Euclidean distance matrix can be constructed:

$$\mathbf{D} = \begin{bmatrix} 0 & D(A_{(1,2)}, A_{(2,3)}) & \dots & D(A_{(1,2)}, A_{(l,l+1)}) \\ D(A_{(2,3)}, A_{(1,2)}) & 0 & \dots & D(A_{(2,3)}, A_{(l,l+1)}) \\ \dots & \dots & \dots & \dots \\ D(A_{(l,l+1)}, A_{(1,2)}) & D(A_{(l,l+1)}, A_{(2,3)}) & \dots & 0 \end{bmatrix} \quad (17)$$

This matrix reflects the degree of feature difference among the sections. To simplify section determination, utilizing the Euclidean distance matrix between sections, the comprehensive similarity coefficient between section $(i, i + 1)$ and other sections is defined as:

$$D_{(i,i+1)} = \frac{1}{l-1} (\sum_{j=1}^l D(A_{(i,i+1)}, A_{(j,j+1)})) \quad (18)$$

The comprehensive similarity coefficient $D_{(i,i+1)}$ represents the average distance between section $(i, i + 1)$ and all the other sections. A larger value of $D_{(i,i+1)}$ indicates that the corresponding section is more different from the remaining sections in the normalized multidimensional feature space. Therefore, the faulted section is expected to have a larger comprehensive similarity coefficient than healthy sections.

For a faulted section, its feature vector differs significantly from those of other sections, resulting in low similarity, therefore $D_{(i,i+1)} < 1$; for a healthy section, apart from a large difference with the faulted section, its feature vector has high similarity with other healthy sections, therefore $D_{(i,i+1)} < 1$.

Therefore, in the normalized feature space it is adopted as an empirical criterion for identifying the faulted section under the tested system. The applicability of this empirical criterion is further examined through the sensitivity analyses in Section 5.5.

4.2. Handling of Special Cases Under DG Integration

When DG integration causes more than one suspected section, the additional suspected section is usually related to the DG-connected section. For the DG-connected section downstream of the fault point, the upstream detection point may be affected by the fault current path, whereas the downstream detection point mainly carries a relatively small capacitive current. In contrast, for the actual faulted section, the detection points adjacent to the fault current path present stronger transient current energy. Therefore, the downstream transient current energy of the suspected sections can be compared to distinguish the actual faulted section from the DG-connected pseudo-fault section.

When a DG is connected downstream of the fault point, the comprehensive similarity coefficient of the DG section may also be greater than 1, leading to the appearance of multiple suspected fault sections. For this reason, this paper introduces a downstream transient energy amplitude comparison method to distinguish them:

For suspected sections $(i_1, i_1 + 1)$ and $(i_2, i_2 + 1)$, if the energy at the downstream detection point satisfies:

$$W_{i_1+1} > W_{i_2+1} \quad (19)$$

Then $(i_1, i_1 + 1)$ is determined to be the actual faulted section; otherwise, it is $(i_2, i_2 + 1)$.

This method utilizes the difference in current distribution after DG integration: only a small capacitive current flows downstream of the DG-connected section, whereas a significant fault current flows downstream of the faulted section. Therefore, the energy comparison is highly discriminative.

4.3. Fault Location Process

Combining the above steps, the flowchart of the fault location method based on the comprehensive similarity criterion proposed in this paper is shown in Figure 4. The process is as follows:

- (1) The system detects an incipient fault;
- (2) The distribution terminals collect the zero-sequence current for 1/4 cycle after the fault at each detection point and perform the generalized S-transform;
- (3) Extract three types of features to construct the vector $A_{(i,i+1)}$;
- (4) Calculate the Euclidean distance matrix D to obtain the comprehensive similarity coefficient $D_{(i,i+1)}$;
- (5) Determine the section with $D_{(i,i+1)} > 1$ as the faulted section;
- (6) If multiple candidate sections appear, further compare the downstream energy W_{i_1+1} to make the final determination.

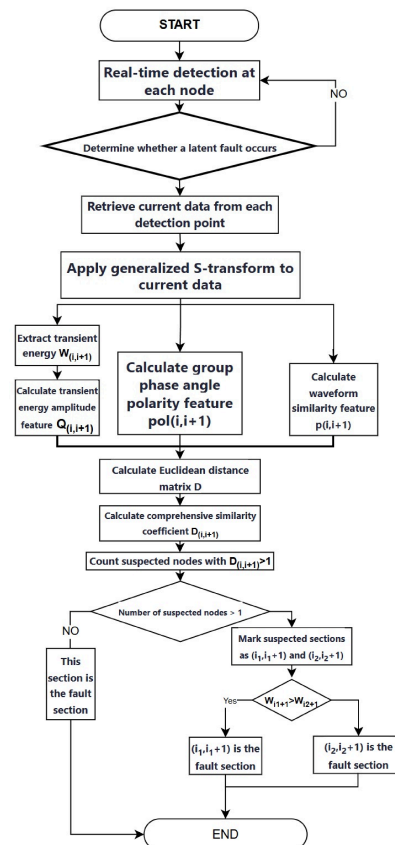


Figure 4. Flowchart of the fault location method.

5. Simulation Verification and Result Analysis

A 10 kV medium-voltage low-resistance grounding system model is established in the MATLAB/Simulink R2025a (The MathWorks, Inc., Natick, MA, USA) environment, as shown in Figure 5. The system parameters are as follows:

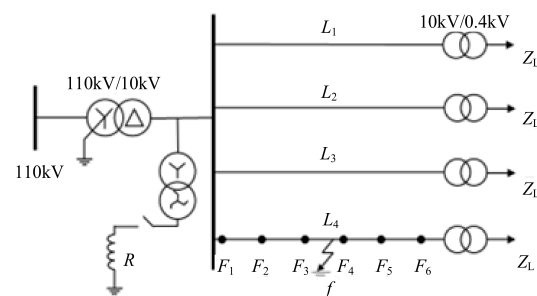


Figure 5. Schematic diagram of a medium-voltage low-resistance-grounded distribution system.

Line parameters: positive-sequence impedance $Z_1 = 0.2649 + j0.2895 \, \Omega/\text{km}$, positive-sequence admittance to ground $b_1 = j3.584 \, \text{mS}/\text{km}$; zero-sequence impedance $Z_0 = 0.5271 + j1.8067 \, \Omega/\text{km}$, zero-sequence admittance to ground $b_0 = j1.3673 \, \text{mS}/\text{km}$.

Main transformer: transformation ratio 110/10 kV, capacity 80 MVA.

Load: equivalent load impedance at the end of each feeder $Z_L = 400 + j20 \, \Omega/\text{km}$.

Feeder configuration: The lengths of the four feeders are $L_1 = 22 \, \text{km}$, $L_2 = 20 \, \text{km}$, $L_3 = 20 \, \text{km}$ and $L_4 = 25 \, \text{km}$, respectively.

Grounding parameters: The system grounding resistance is $R = 10 \, \Omega$.

To achieve sectional detection, feeder terminal units (FTUs) are installed at points F_1 – F_6 on feeder L_4 , forming 5 sections. An incipient cable fault is applied in section

(3,4) of feeder L_4 , and the DG capacity is set to 8 MVA. The sampling frequency is set to 10 kHz, corresponding to a sampling interval of 0.1 ms. The transient zero-sequence currents at each detection point of L_4 are collected within a 1/4-cycle window after the fault. This window is selected as a compromise between transient-feature completeness and rapid response.

In the incipient fault simulation, the parameters of the Kizilcay arc model, including the arc time constant, characteristic arc voltage, and characteristic arc resistance, are selected according to the typical arc-model settings in [32,33] and adjusted to reproduce the intermittent arc extinction and reignition process. The insulation-defect resistance R_0 is used to represent the equivalent conductive path of the degraded insulation channel. Since R_0 may vary with the cable aging condition and environmental factors, its influence is further examined in the sensitivity analysis in Section 5.5.

It should be noted that the DG is represented by an equivalent source model in the present simulation. The main focus is placed on the influence of DG access location and penetration level on the zero-sequence transient features. Detailed control characteristics of different DG technologies, such as inverter-based photovoltaic units, synchronous DGs, and wind converters, are not distinguished in this model and are discussed as future work.

5.1. Simulation Analysis of High-Frequency Features

The recorded transient zero-sequence current data at each detection point are processed using the GST to obtain the amplitude time-frequency matrix S and the phase time-frequency matrix P . According to the definition of the generalized S-transform, the rows in matrices S and P correspond to frequencies. Given that the number of sampling points within a $T/4$ cycle time window is $N = 50$ and the maximum frequency is 5 kHz, the frequency interval for each row is 50 Hz. The transient energy distributions at each detection point, corresponding to F_1 – F_6 , are denoted as W_1 – W_6 , as shown in Figure 6.

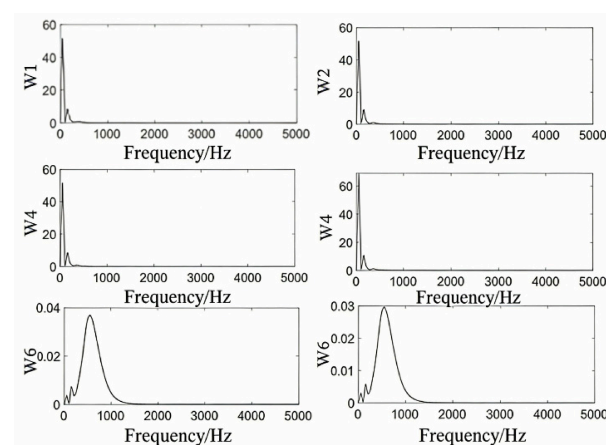


Figure 6. Transient current energy distribution at detection points along L_4 .

As can be seen from Figure 6, the characteristic frequencies of F_1 , F_2 , F_3 , and F_4 are at and around 150 Hz, whereas the characteristic frequencies of detection points 5 and 6 are at and around 600 Hz. Furthermore, there is a significant difference in the transient amplitudes upstream and downstream of the fault point. Consequently, this ultimately leads to the formation of distinct fault characteristics in different sections.

5.2. Simulation Analysis Under Different Fault Sections

To demonstrate the impact of DG on the fault location criterion, a DG (capacity of 8 MVA) is fixedly connected to section (4,5) to analyze whether the DG integration interferes

with the discrimination performance of the comprehensive similarity coefficient under different fault sections.

In the constructed 10 kV medium-voltage low-resistance grounded system, with the DG connection point fixed at section (4,5), incipient cable faults are applied respectively in sections (1,2), (2,3), (3,4), (4,5), and (5,6). The feature vectors and comprehensive similarity coefficients for each section are calculated, and the results are shown in Tables 1–5.

Table 1. Fault occurring between sections (1,2).

Detection Section	Feature Vector	$D_{(i,i+1)}$
(1,2)	$[0, -1, 0.991]$	2.074
(2,3)	$[8.68 \times 10^{-4}, 1, 0.994]$	0.609
(3,4)	$[8.47 \times 10^{-4}, 1, 0.994]$	0.607
(4,5)	$[1, 1, 0.745]$	1.312
(5,6)	$[2.17 \times 10^{-3}, 1, 0.995]$	0.739

Table 2. Fault occurring between sections (2,3).

Detection Section	Feature Vector	$D_{(i,i+1)}$
(1,2)	$[8.48 \times 10^{-4}, 1, 0.994]$	0.683
(2,3)	$[0, -1, 0.991]$	2.384
(3,4)	$[8.82 \times 10^{-4}, 1, 0.989]$	0.647
(4,5)	$[1, 1, 0.712]$	1.373
(5,6)	$[1.53 \times 10^{-3}, 1, 0.998]$	0.699

Table 3. Fault occurring between sections (3,4).

Detection Section	Feature Vector	$D_{(i,i+1)}$
(1,2)	$[7.78 \times 10^{-4}, 1, 0.984]$	0.613
(2,3)	$[7.57 \times 10^{-4}, 1, 0.999]$	0.629
(3,4)	$[0, -1, 0.992]$	2.093
(4,5)	$[1, 1, 0.737]$	1.422
(5,6)	$[1.17 \times 10^{-3}, 1, 0.995]$	0.658

Table 4. Fault occurring between sections (4,5).

Detection Section	Feature Vector	$D_{(i,i+1)}$
(1,2)	$[7.18 \times 10^{-4}, 1, 0.999]$	0.639
(2,3)	$[7.74 \times 10^{-4}, 1, 0.993]$	0.643
(3,4)	$[7.79 \times 10^{-4}, 1, 0.983]$	0.663
(4,5)	$[0, -1, 0.998]$	2.314
(5,6)	$[2.11 \times 10^{-3}, 1, 0.995]$	0.739

Table 5. Fault occurring between sections (5,6).

Detection Section	Feature Vector	$D_{(i,i+1)}$
(1,2)	$[6.31 \times 10^{-3}, 1, 0.995]$	0.647
(2,3)	$[6.68 \times 10^{-3}, 1, 0.994]$	0.699
(3,4)	$[6.47 \times 10^{-3}, 1, 0.984]$	0.697
(4,5)	$[0, 1, 0.999]$	0.712
(5,6)	$[1, -1, 0.625]$	2.657

As shown in Table 1, when the fault is located in section (1,2), the comprehensive similarity coefficients of section (1,2) and section (4,5) are significantly greater than 1; however, by comparing the energy W , the correct fault section can be determined to be (1,2).

As shown in Table 2, similarly, when the fault is located in section (2,3), the fault location can be correctly determined as section (2,3) in this case.

As shown in Table 3, the criterion value for fault section (3,4) is significantly higher than those of the other sections, demonstrating the good adaptability of the “multi-dimensional feature correlation” method to middle fault locations.

As shown in Tables 4 and 5, when a fault occurs in the terminal section (4,5) or (5,6), the D value of the corresponding section remains significantly greater than 1, verifying the effectiveness of the method under terminal fault conditions.

Overall, regardless of whether the fault occurs in the middle or at the end of the feeder, the criterion values of each section can significantly distinguish the faulty section from the healthy sections. Meanwhile, DG integration does not compromise the effectiveness of the location criterion, proving the accuracy and robustness of the proposed method in the environment of an active low-resistance grounded distribution network.

5.3. Simulation Analysis Under Different DG Connection Locations

With the fault location fixed at section (3,4), DG units, each with a capacity of 8 MVA, are connected to different sections of the feeder: (2,3), (3,4), (4,5), and (5,6), respectively. Under each operating condition, the feature vectors and comprehensive similarity coefficients of each detection section are calculated.

As shown in Tables 6–9, the change in the DG connection location only slightly affects the fault criterion, but it does not affect the location result. Therefore, the method can still accurately locate the faulty section, demonstrating strong adaptability.

Table 6. DG connected section (1,2).

Detection Section	Feature Vector	$D_{(i,i+1)}$	Location Results
(1,2)	$[5.93 \times 10^{-3}, 1, 0.996]$	0.654	F_3-F_4
(2,3)	$[3.17 \times 10^{-3}, 1, 0.984]$	0.647	
(3,4)	$[0, -1, 0.994]$	2.443	
(4,5)	$[2.13 \times 10^{-2}, 1, 0.987]$	0.712	
(5,6)	$[2.73 \times 10^{-2}, 1, 0.995]$	0.739	

Table 7. DG connected section (2,3).

Detection Section	Feature Vector	$D_{(i,i+1)}$	Location Results
(1,2)	$[5.32 \times 10^{-3}, 1, 0.983]$	0.657	F_3-F_4
(2,3)	$[5.11 \times 10^{-3}, 1, 0.989]$	0.649	
(3,4)	$[0, -1, 0.998]$	2.443	
(4,5)	$[2.57 \times 10^{-2}, 1, 0.994]$	0.728	
(5,6)	$[2.79 \times 10^{-2}, 1, 0.996]$	0.734	

Table 8. DG connected section (3,4).

Detection Section	Feature Vector	$D_{(i,i+1)}$	Location Results
(1,2)	$[7.49 \times 10^{-4}, 1, 0.991]$	0.618	F_3-F_4
(2,3)	$[7.18 \times 10^{-4}, 1, 0.987]$	0.604	
(3,4)	$[0, -1, 0.998]$	2.304	
(4,5)	$[2.83 \times 10^{-3}, 1, 0.987]$	0.718	
(5,6)	$[2.93 \times 10^{-3}, 1, 0.998]$	0.739	

Table 9. DG connected sections (4,5) and (5,6).

Detection Section	Feature Vector	$D_{(i,i+1)}$	Location Results
(1,2)	$[7.49 \times 10^{-4}, 1, 0.991]$	0.618	F_3-F_4
(2,3)	$[7.18 \times 10^{-4}, 1, 0.987]$	0.604	
(3,4)	$[0, -1, 0.998]$	2.304	
(4,5)	$[2.83 \times 10^{-3}, 1, 0.987]$	0.718	
(5,6)	$[2.93 \times 10^{-3}, 1, 0.998]$	0.739	

5.4. Simulation Analysis Under Different DG Penetration Levels

In practical medium-voltage distribution networks, the connected capacity of DGs varies across different systems, and the level of their penetration will also affect the accuracy of fault location. Therefore, with the fault location fixed at section (3,4), the impacts of different DG penetration levels and multi-DG integration on the proposed method are investigated. The DG penetration levels are set to 20%, 30%, and 40%, respectively, and simulation analyses are conducted accordingly. The results are shown in Tables 10–12. The asterisk “*” indicates that the section is a DG connection section.

As shown in Tables 10–12, when the DG penetration levels vary and multiple DGs are connected, the proposed method can accurately locate the faulty section in all cases, indicating that its applicability is not affected.

Table 10. DG penetration level of 20%. The asterisk “*” indicates that the section is a DG connection section.

Detection Section	Feature Vector	$D_{(i,i+1)}$	Location Results
(1,2)	$[7.78 \times 10^{-4}, 1, 0.984]$	0.613	F_3-F_4
(2,3)	$[7.57 \times 10^{-4}, 1, 0.999]$	0.629	
(3,4)	$[0, -1, 0.992]$	2.093	
(4,5) *	$[1, 1, 0.737]$	1.422	
(5,6) *	$[1.17 \times 10^{-3}, 1, 0.995]$	0.658	

Table 11. DG penetration level of 30%. The asterisk “*” indicates that the section is a DG connection section.

Detection Section	Feature Vector	$D_{(i,i+1)}$	Location Results
(1,2)	$[5.48 \times 10^{-3}, 1, 0.994]$	0.683	F_3-F_4
(2,3) *	$[4.38 \times 10^{-3}, 1, 0.984]$	0.698	
(3,4)	$[0, -1, 0.989]$	2.647	
(4,5) *	$[1, 1, 0.783]$	1.337	
(5,6) *	$[1.63 \times 10^{-2}, 1, 0.998]$	0.759	

Table 12. DG penetration level of 40%. The asterisk “*” indicates that the section is a DG connection section.

Detection Section	Feature Vector	$D_{(i,i+1)}$	Location Results
(1,2) *	$[3.78 \times 10^{-3}, 1, 0.989]$	0.613	F_3-F_4
(2,3) *	$[3.37 \times 10^{-4}, 1, 0.998]$	0.629	
(3,4)	$[0, -1, 0.991]$	2.427	
(4,5) *	$[1, 1, 0.707]$	1.937	
(5,6) *	$[2.49 \times 10^{-3}, 1, 0.999]$	0.632	

5.5. Sensitivity Analysis of Key Parameters and Practical Disturbances

To further evaluate the robustness of the proposed method and respond to the influence of key parameter settings and practical measurement disturbances, additional sensitivity analyses are considered. The fault section is fixed at section (3,4), and the DG is connected to section (4,5), which represents a typical case where the DG-connected section may produce pseudo-fault transient features. The GST adjustment factor g , the insulation-defect resistance R_0 , the signal-to-noise ratio (SNR), and the time-alignment error caused by synchronization error or communication-delay-induced window deviation are varied, respectively.

As shown in Table 13, although the comprehensive similarity coefficients of all sections fluctuate slightly with g , the coefficient of the actual fault section (3,4) remains significantly larger than those of the healthy sections. The DG-connected section (4,5) may also present a relatively large coefficient because of the pseudo-fault transient feature introduced by DG integration, but it is still distinguishable from the actual fault section by the downstream energy comparison rule. Therefore, the proposed criterion is not highly sensitive to the selection of g within the tested range.

Table 13. Sensitivity analysis of the GST adjustment factor g .

g	$D_{(1,2)}$	$D_{(2,3)}$	$D_{(3,4)}$	$D_{(4,5)}$	$D_{(5,6)}$	Location Result
0.5	0.642	0.655	2.218	1.361	0.681	F_3-F_4
1.0	0.613	0.629	2.093	1.422	0.658	F_3-F_4
1.5	0.628	0.641	2.176	1.397	0.674	F_3-F_4
2.0	0.667	0.683	2.041	1.336	0.702	F_3-F_4
2.5	0.694	0.711	1.936	1.284	0.735	F_3-F_4

As shown in Table 14, the insulation-defect resistance R_0 represents the equivalent conductive path formed by water trees, electrical trees, moisture ingress, or other insulation degradation mechanisms before complete breakdown. As R_0 increases, the comprehensive similarity coefficient of the fault section (3,4) decreases slightly because a larger defect resistance weakens the transient zero-sequence current. Nevertheless, $D_{(3,4)}$ remains larger than 1 and is still significantly higher than those of the healthy sections. The location results are unchanged under the tested R_0 values, indicating that the proposed method has a certain tolerance to variations in the insulation-defect resistance.

Table 14. Sensitivity analysis of insulation-defect resistance R_0 .

R_0	$D_{(1,2)}$	$D_{(2,3)}$	$D_{(3,4)}$	$D_{(4,5)}$	$D_{(5,6)}$	Location Result
100 Ω	0.621	0.638	2.286	1.451	0.672	F_3-F_4
300 Ω	0.613	0.629	2.093	1.422	0.658	F_3-F_4
500 Ω	0.635	0.646	1.978	1.376	0.684	F_3-F_4
800 Ω	0.681	0.702	1.846	1.318	0.723	F_3-F_4
1000 Ω	0.716	0.735	1.762	1.271	0.756	F_3-F_4

As shown in Table 15, with the decrease in SNR, the comprehensive similarity coefficients of the healthy sections increase slightly, while the coefficient of the fault section decreases. This indicates that noise weakens the distinction among section features to some extent. However, when the SNR is no lower than 10 dB, the coefficient of the actual fault section is still the largest and remains greater than 1. Therefore, the proposed method can maintain correct location results under the tested noise conditions. It should be noted that only additive Gaussian white noise is considered in this paper, and more complex field disturbances such as current transformer (CT) saturation require further investigation.

Table 15. Influence of different SNR levels.

SNR	$D_{(1,2)}$	$D_{(2,3)}$	$D_{(3,4)}$	$D_{(4,5)}$	$D_{(5,6)}$	Location Result
10 dB	0.781	0.806	1.514	1.176	0.842	F_3-F_4
20 dB	0.692	0.711	1.823	1.298	0.736	F_3-F_4
30 dB	0.641	0.658	1.976	1.367	0.689	F_3-F_4
40 dB	0.612	0.626	2.085	1.435	0.661	F_3-F_4
No noise	0.613	0.629	2.093	1.422	0.658	F_3-F_4

In practical distribution automation systems, the signals collected by different FTUs may not be perfectly aligned due to clock synchronization errors or communication-delay-induced window deviation. A fixed communication delay mainly affects the arrival time of uploaded data and does not change the sampled waveform if accurate time stamps are available. Therefore, the unfavorable case of data-window misalignment is simulated by shifting the sampled zero-sequence current signals at different detection points. As shown in Table 16, $D_{(3,4)}$ decreases gradually as the time-alignment error increases, while those of the healthy sections increase slightly. This is mainly because the waveform similarity feature is more sensitive to time deviation. However, within the tested range, $D_{(3,4)}$ remains the largest among all sections, and the fault section can still be correctly identified. Therefore, the proposed method shows a certain tolerance to millisecond-level time-alignment errors.

Table 16. Influence of time-alignment error caused by synchronization error or communication delay.

Maximum Time-Alignment Error	$D_{(1,2)}$	$D_{(2,3)}$	$D_{(3,4)}$	$D_{(4,5)}$	$D_{(5,6)}$	Location Result
0 ms	0.613	0.629	2.093	1.422	0.658	F_3-F_4
0.1 ms	0.628	0.641	2.071	1.405	0.672	F_3-F_4
0.5 ms	0.692	0.718	1.953	1.331	0.743	F_3-F_4
1.0 ms	0.748	0.783	1.824	1.276	0.801	F_3-F_4
2.0 ms	0.836	0.867	1.591	1.184	0.891	F_3-F_4
3.0 ms	0.902	0.931	1.417	1.097	0.956	F_3-F_4

5.6. Comparative Analysis with Other Methods

To verify the effectiveness of the proposed section location method, it is compared with existing location methods. Zhang et al. [22] proposed a fault section location method that utilizes the line transient centroid frequency for clustering analysis. Xu et al. [23], addressing the difficulty in selecting the transient centroid frequency, proposed a method using kurtosis analysis on the zero-sequence current component at fault monitoring points. Both methods exhibit excellent performance in grounding faults of traditional distribution networks. The method proposed in this paper is compared with these two methods, with the fault location set at section (3,4) and the DG connection location set at section (4,5). The location results are shown in Table 17.

Table 17. Comparison with other fault section location methods.

Method	Faulty Section	DG Connection Section	Location Results
Reference [22]	(3,4)	(4,5)	F_4-F_5
Reference [23]	(3,4)	(4,5)	F_3-F_4, F_4-F_5
Proposed method	(3,4)	(4,5)	F_3-F_4

Based on the analysis of Table 17, under the typical operating condition of incipient cable faults with DG integration, the methods proposed by Zhang et al. [22] and Xu et al. [23] may not distinguish the faulty section from the DG-connected pseudo-fault section, resulting in deviations in the location results. In contrast, the proposed method can distinguish the actual fault section from the DG-connected section under this tested condition. Therefore, the comparison verifies the effectiveness of the proposed multidimensional criterion in the studied system.

5.7. Computational Burden and Implementation Feasibility

For a feeder with M sections, the construction of the section distance matrix requires approximately $O(M^2)$ operations after feature extraction. Since each section is represented by only a three-dimensional feature vector, the calculation of the comprehensive similarity coefficient is simple. The main computational burden is associated with the GST processing of the short data window. Therefore, the proposed criterion has potential for online implementation in feeder protection and distribution automation systems, although embedded processor-level validation is still required in future engineering applications.

6. Conclusions

To address the issues of small current and short duration of latent cable faults in active low-resistance distribution networks, as well as the failure of traditional methods caused by the integration of DG, this paper proposes a fault section location method based on multi-dimensional information correlation analysis. The main conclusions are as follows:

Based on the mechanisms of cable insulation aging and arc characteristics, an equivalent latent fault model consisting of a Kizilcay arc and a defect resistance in series is constructed to represent typical fault characteristics such as the zero-pause and saddle-shaped waveform. By applying the generalized S-transform to extract three types of features, namely the transient current energy index, phase angle polarity, and waveform similarity, a three-dimensional feature vector is constructed, and a comprehensive similarity coefficient criterion is established to identify the fault section. Simulation verification results under the tested conditions show that faults in different sections can be identified; when DG integration causes pseudo-fault features, the auxiliary downstream energy comparison rule helps distinguish the actual fault section from the DG-connected section.

In summary, the proposed method can locate latent cable faults in the simulated active low-resistance-grounded distribution network and provides a reference for improving fault detection and self-healing control. It should be noted that the present study is mainly based on MATLAB/Simulink R2025a simulations. Although the proposed method has been verified under different fault sections, DG access locations, DG penetration levels, noise levels, key parameter variations, and time-alignment errors, field data and hardware-in-the-loop tests are not included at this stage. In addition, the detailed transient characteristics of different DG technologies, complex measurement-chain disturbances such as CT saturation, and more complex network topologies such as ring networks and DG-energy storage hybrid systems require further investigation. These issues will be addressed in future work.

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