

Article

Fault Handling and Localization Strategy Based on Waveform Characteristics Recognition with Coordination of Peterson Coil and Resistance Grounding Method

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Abstract: To address challenges in locating high-impedance grounding faults (HIGFs) and isolating fault areas in resonant grounding systems, this paper proposes a novel fault identification method based on coordinating a Peterson coil and a resistance grounding system. This method ensures power supply reliability by extinguishing the fault arc during transient faults with the Peterson coil. When a fault is determined to be permanent, the neutral point switches to a resistance grounding mode, ensuring regular distribution of zero-sequence currents in the network, thereby addressing the challenges of HIGF localization and fault area isolation. Fault calibration and nature determination rely on recognizing neutral point displacement voltage waveforms and dynamic characteristics, eliminating interference from asymmetric phase voltage variations. Fault area identification involves assessing the polarity of zero-sequence current waveforms attenuation during grounding mode switching, preventing misjudgments in grounding protection due to random initial fault angles and Peterson coil compensation states. Field experiments validate the feasibility of this fault location method and its control strategy.

Keywords: high-impedance grounding fault; fault area isolation; waveform characteristics; polarity difference



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1. Introduction

With the advancement of digital distribution systems, economically efficient and self-healing distribution networks are widely recognized as primary development goals for power systems. [1] Accurately detecting and isolating single-line-to-ground (SLG) represents a critical research challenge that needs to be addressed in self-healing distribution systems [2–4].

Traditional fault handling strategies often struggle to achieve fault isolation in resonant grounded systems. Automatic Peterson coils, equipped with series-connected damping resistors, can operate in various compensation states, including over-compensation, under-compensation, or full compensation. Moreover, the tuning of automatic Peterson coils is random, leading to unpredictable levels of output compensation current. These factors result in the zero-sequence current distribution in the network becoming irregular under fault conditions. Consequently, this irregularity complicates fault line selection and fault area location [5]. Furthermore, due to the complex operating conditions of distribution networks, traditional methods often employ broader fault detection thresholds to ensure selectivity, leading to potential misidentification of HIGFs [6].

In small-resistance grounded systems, identifying HIGFs poses a critical challenge in fault zone identification. During HIGF events, significant fault transition resistances are connected in series within the fault zero-sequence circuit. This results in minimal changes in zero-sequence current amplitude, which may not be sufficient to activate zero-sequence

current protection. Even when fault handling procedures are initiated, these subtle variations in zero-sequence current amplitude typically do not offer adequate support for precise fault zone identification. Moreover, in cases involving small-resistance or metallic grounding faults, ground protection devices often lack the capability to determine if fault point insulation can self-recover, thereby significantly affecting power supply continuity [7]. In summary, small-resistance grounded systems face challenges in meeting the power supply reliability and fault identification accuracy requirements of distribution networks.

Although the single neutral point grounding method has unique advantages, it cannot meet the multidimensional requirements related to the safety and reliability of distribution networks. Both academia and industry are investigating fault handling approaches that integrate various neutral point grounding methods, including ‘multi-mode grounding’ and ‘flexible grounding’, with the aim of addressing safety and reliability concerns within power distribution systems [8,9].

Wan et al. proposed a fault line identification method for flexible grounding systems where Peterson coils are connected in parallel with small-resistance grounding. This method aims to mitigate the chaotic disturbances caused by the randomness of Peterson coil compensation states by analyzing the trajectory of changes in the zero-sequence currents of feeders and zero-sequence voltages of buses after the parallel resistors are engaged [10,11]. Zeng proposed a delay switching strategy utilizing Peterson coils and resistor grounding to amplify fault electrical quantities for the identification of faulted feeders. The objective was to ensure power supply reliability while simultaneously considering grid safety [12]. Wang proposed an identification method for single-phase grounding faults using Neutral Point-to-Ground Complex Impedance (EHPC) adaptive control based on Peterson coils. This method ensures the amplification of zero-sequence parameters while preventing ground arc reignition, thus achieving fault point identification [13,14]. However, due to changes in the operation mode of distribution networks or the influence of unstable grounding factors (such as tree obstructions and flashovers), previous methods generally lack the capability to accurately identify grounding faults. This results in insufficient criteria for determining whether the insulation at the grounding fault point can correctly recover and for accurately identifying the faulted feeder.

Voltage and current waveform characteristics contain a wealth of fault information, making the application of waveform features in fault identification and localization both practical and feasible. Y. Xue et al. developed several methods, including the transient zero-sequence current projection coefficient method, the transient energy method, and the wavelet coefficient energy analysis method, to identify single-phase grounding faults under complex conditions based on the resonance frequency proportion coefficient during the fault process [15–18]. B. Wang et al. applied the dynamic trajectory of the volt-ampere characteristics of zero-mode voltage and current to the identification of HIGFs [19,20]. M.A. Barik et al. utilized the polarity characteristics of transient electrical quantities during ground faults to quantitatively or qualitatively calculate fault location information [21–26].

While the above-mentioned methods have demonstrated the capability to identify faulted feeders or fault regions and have shown satisfactory performance in handling HIGFs under ideal conditions, complex factors including special fault phase angles and the randomness of Peterson coil compensation states may lead to waveform characteristic disturbances. Particularly under conditions of HIGFs, threshold-based methods relying on waveform characteristics exhibit significant deficiencies due to the difficulty in capturing characteristic quantities.

This paper proposes a collaborative control method involving Peterson coils and resistor grounding to identify single-phase grounding fault regions. By establishing zero-sequence circuit models for various grounding modes, the evolving mechanisms of fault features during fault perception and segment identification with the concurrent application of different grounding methods are revealed. The waveform characteristics of neutral point displacement voltage during fault inception and zero-sequence current at node switching when grounding methods change are extracted using empirical wavelet transform (EWT).

The DC attenuation component in voltage waveform characteristics is utilized to detect fault occurrence and eliminate interference from asymmetrical phase voltage changes, while the current waveform characteristics are used to derive attenuation coefficients and identify fault regions based on their polarity differences. The proposed method combines waveform and frequency domain features for fault identification, enabling the identification of HIGFs under any fault initial phase angle. Moreover, the method utilizes the polarity changes in zero-sequence current attenuation at the fault node when a Peterson coil is disconnected, thereby indicating the fault region independently of the Peterson coil compensation state.

2. Analysis of Challenges in Ground Fault Identification under Complex Operating Conditions

There are difficulties in identifying SLGs in Peterson coil grounded systems, and issues with unreliable power supply and HIGF identification in small-resistance grounded systems. Although the combined application of both can leverage strengths and mitigate weaknesses to some extent, the asymmetric voltage changes in the grid environment and the complex operating conditions at fault points constrain their seamless integration. Consequently, this paper establishes a fault zero-sequence circuit model to elucidate the evolving mechanism of fault characteristic quantities during the collaborative processing of single-phase ground faults. Figure 1 illustrates the equivalent model of the fault zero-sequence circuit during the transition of neutral point grounding methods.

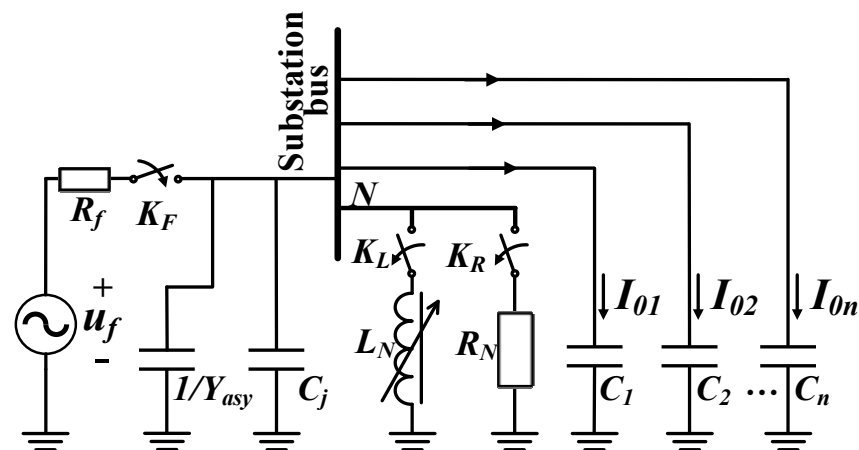


Figure 1. Fault Zero-Sequence Circuit during Cooperative Control of Neutral Point Grounding Methods.

Due to the relatively small unit inductance and resistance of distribution lines, the primary component of impedance in the zero-sequence circuit is the distributed capacitance to ground of the lines. To analyze the zero-sequence fault characteristics of SLG, we have neglected the line's inductance and resistance values, focusing solely on the effect of the distributed capacitance to ground of the lines. In Figure 1, u_f represents the virtual power source at the fault point; switches K_L and K_R are, respectively, used to connect/disconnect the Peterson coil L_N and grounding resistor R_N at the neutral point N ; $C_1, C_2, \dots, C_j, \dots, C_n$ represent the ground capacitance of each feeder line. The closure of switch K_F indicates the occurrence of a ground fault; Y_{asy} denotes the virtual asymmetrical admittance.

The mathematical expression for the virtual asymmetrical admittance Y_{asy} is given by Equation (1) [27],

$$Y_{asy} = G_A + j\omega C_A + a^2(G_B + j\omega C_B) + a(G_C + j\omega C_C) \quad (1)$$

where $a = e^{j120}$ is the rotation factor; G_A, G_B, G_C represent the leakage conductance to ground of the three phases; and C_A, C_B, C_C denote the capacitance to ground of the three phases.

By using Equation (1), the asymmetrical voltages in the system can be expressed as Equation (2),

$$\dot{U}_{NN'} = -U_{ph} \frac{Y_{asy}}{G_{\Sigma} + j\omega C_{\Sigma}} \quad (2)$$

where $\dot{U}_{NN'}$ represents the virtual asymmetric voltage of the distribution system; $G_{\Sigma} = G_A + G_B + G_C$ represents the total system ground leakage conductance; $C_{\Sigma} = C_A + C_B + C_C$ denotes the total system ground capacitance; U_{ph} stands for the amplitude of phase source voltage. The detailed derivation of Equation (2) can be found in Appendix A, Equations (A1) and (A2).

Using Equation (2), the expression for the neutral point displacement voltage $\dot{U}_{N0}$ can be derived as shown in Equation (3),

$$\dot{U}_{N0} = \frac{Y_C}{Y_C + Y_N} \dot{U}_{NN'} \quad (3)$$

where Y_C represents the system's ground capacitance admittance; $Y_N = 1/j\omega L_N$ for resonant grounded systems; $Y_N = 1/R_N$ for resistance grounded systems. The detailed derivation of Equation (3) can be found in Appendix A, Equation (A3).

2.1. Voltage Asymmetry Leading to Misidentification of SLGs

When the neutral point is initially grounded through Peterson coils, the neutral point displacement voltage $\dot{U}_{N0}$ of the unbalanced power grid can be represented by Equation (4),

$$\dot{U}_{N0} = -\frac{Y_C j\omega L}{Y_C j\omega L + 1} U_{ph} \sum_1^n \frac{Y_{asy}}{G_{\Sigma} + j\omega C_{\Sigma}} \quad (4)$$

where U_{ph} represents the system phase voltage.

Analysis of Equation (4) reveals that the inductive current provided by Peterson coils differs in direction from the current vector provided by the virtual asymmetrical admittance in the unbalanced power grid. This leads to variations in the trend of $\dot{U}_{N0}$. Considering the ground resistance R_S and the damping resistance R_Z of the Peterson coil, the zero-sequence circuit of the asymmetrical network and the voltage-current phasor diagram can be depicted based on Equation (4), as illustrated in Figure 2.

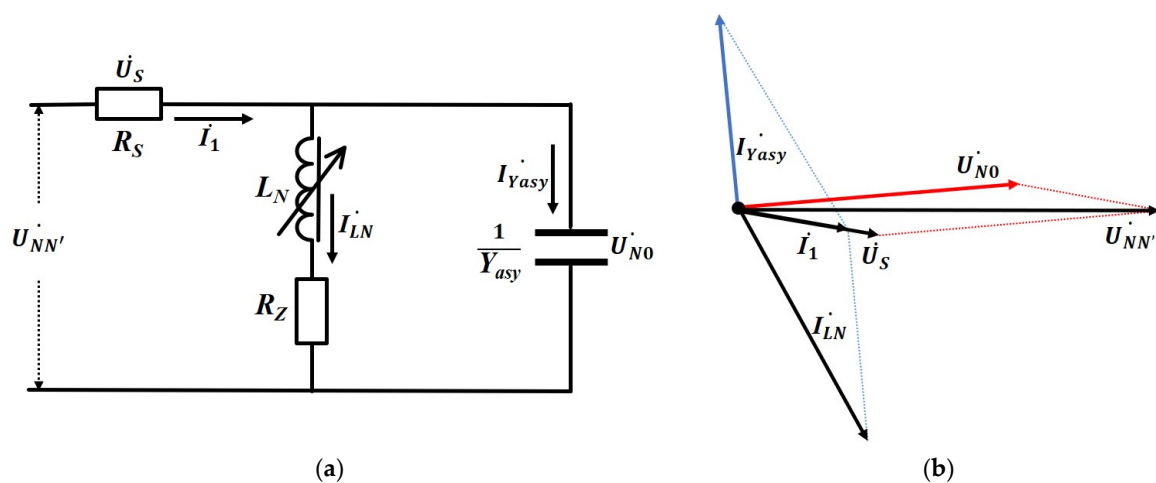


Figure 2. (a) Zero-sequence circuit of the asymmetrical network with Peterson coil grounding system; (b) Voltage-current vector model.

From the vector diagram, it is evident that the inductance and damping resistance of the Peterson coil branch jointly cause the branch current to lag behind $\dot{U}_{N0}$ and deviate. By synthesizing the current in the Peterson coil branch with the current in the virtual admittance branch, the current in the loss resistance branch can be derived to determine the voltage direction. Subsequently, the vector model of the asymmetrical voltage $\dot{U}_{NN'}$ is synthesized.

Combining the above characteristics leads to the conclusion that the direction and magnitude of $\dot{U}_{N0}$ vary under the influence of the Peterson coil branch and the virtual asymmetrical admittance. However, during HIGFs, the only observed change is in the capacitive current leading $\dot{U}_{N0}$, which overlaps with the range of $\dot{U}_{N0}$ variation during non-fault periods. The dispersion in the tuning range of the Peterson coil and the magnitude of the asymmetrical admittance leads to irregularities in the deviation direction of the asymmetrical voltage. Consequently, it is not possible to utilize effective waveform characteristic changes of $\dot{U}_{N0}$ to judge the occurrence of faults.

2.2. Special Fault Initial Phase Causes Disappearance of Fault Characteristics

When a ground fault occurs, the waveform of $\dot{U}_{N0}$ in the resistor grounding system exhibits a significant DC attenuation component. Utilizing this waveform characteristic can partly address the issue of asymmetric interference. However, the randomness of the fault initial phase angle may lead to the disappearance of the voltage waveform attenuation feature. In this paper, we establish differential Equation (5) at the moment of a single-phase ground fault occurrence in the resistor grounding system to analyze this problem,

$$u_f = u_{N0} + R_f(C_\Sigma \frac{du_{N0}}{dt} + \frac{u_{N0}}{R_N}) \quad (5)$$

where R_N represents the neutral point grounding resistance; R_f denotes the fault point transition resistance; u_f represents the fault virtual voltage source $u_f = U_{ph}\cos(\omega t + \varphi)$; and u_{N0} represents the transient neutral point displacement voltage.

Solving the first-order differential Equation (5) yields Equation (6).

$$u_{N0}(t) = \frac{U_{ph}}{\sqrt{R_f^2 C_\Sigma^2 \omega^2 + (R_f + R_N)/R_N}} \cos(\omega t + \varphi - \tan^{-1} R_f C_\Sigma \omega) + K e^{-(R_f/R_N + R_f C_\Sigma \omega)t} \quad (6)$$

Under the assumption of ideal conditions with three-phase symmetry, the overall response equation of the circuit can be derived as Equation (7).

$$\begin{cases} u_{N0}(t) = (U_{N0ph} \cos \theta_1 - \frac{U_{ph} \cos(\varphi - \tan^{-1} R_f C_\Sigma \omega)}{\sqrt{R_f^2 C_\Sigma^2 \omega^2 + (R_f + R_N)/R_N}})k \\ \quad + \frac{U_{ph} \cos(\omega t + \varphi - \tan^{-1} R_f C_\Sigma \omega)}{\sqrt{R_f^2 C_\Sigma^2 \omega^2 + (R_f + R_N)/R_N}} \\ k = e^{-(\frac{R_f}{R_N} + R_f C_\Sigma \omega)t} \end{cases} \quad (7)$$

From Equation (7), it is evident that during a ground fault, the alternating component of the $\dot{U}_{N0}$ increases, while a decaying direct current component also emerges. As the transition resistance increases, the peak value of the DC offset decreases, and the decay time increases, as illustrated in Figure 3a. Figure 3 shows the neutral point displacement voltage waveforms under balanced phase voltage conditions for different transition resistances and different initial fault angles.

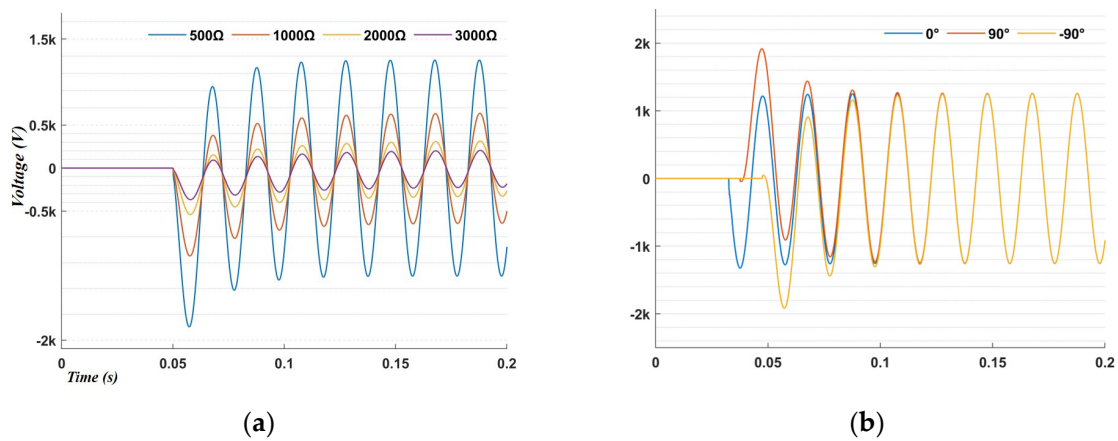


Figure 3. (a) U_{N0} under Different Transition Resistances; (b) U_{N0} under Different Initial Fault Angles.

Assuming the equilibrium value of the initial fault angle is θ_2 , the expression for θ_2 can be derived from Equation (7) as shown in Equation (8).

$$\theta_2 = \cos^{-1}(U_{ph}^{-1}(U_{N0ph} \cos \theta_1 \sqrt{R_f^2 C_\Sigma^2 \omega^2 + (R_f + R_N)/R_N} - \tan^{-1} R_f C_\Sigma \omega)) \quad (8)$$

Considering the influence of the fault initial phase angle φ , the DC offset component decay process indicates the following trends: when $\varphi = \theta_2$, the DC decay vanishes. As φ moves away from θ_2 , the peaks of the DC decay rise, reaching their maximum at $\varphi = \theta_2 + \pi/2$, as depicted in Figure 3b.

In summary, the random distribution characteristics of the initial fault angle can result in the disappearance of the attenuation features in the neutral point displacement voltage waveform. Therefore, when using waveform characteristics for fault identification, it is not sufficient to rely solely on the attenuation component as an indicator of fault occurrence.

3. Coordinated Fault Identification Strategy Using Peterson Coil and Resistor

3.1. Structure and Principles of the Proposed Fault Identification Method

The structure of the Peterson coil-resistor collaborative fault handling device is shown in Figure 4.

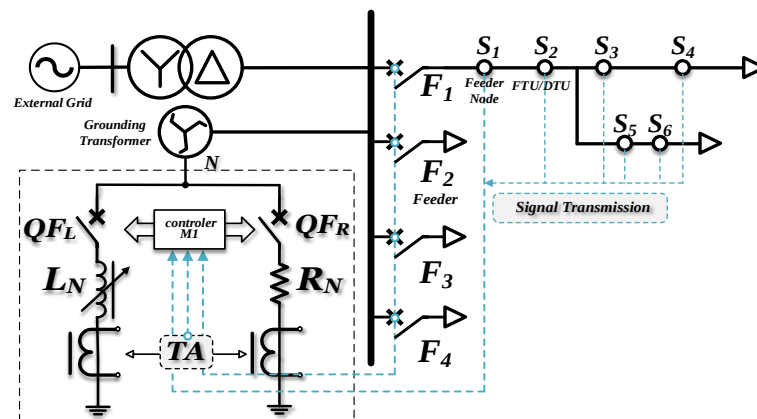


Figure 4. Structure of the Peterson Coil-Resistor Collaborative Fault Handling Device.

In the figure, L_N represents the inductance of the Peterson coil, and R_N represents the neutral point grounding resistor. To distinguish from the theoretical analysis in Figure 1, Q_{FL} is used here to represent the switch of the Peterson coil branch of the device and Q_{FR} represents the switch of the resistance branch.

In normal operation, the distribution network utilizes resistance grounding at the neutral point. The criterion for detecting single-phase ground faults is based on the voltage variation characteristics of the neutral point displacement. Peterson coil branches are activated upon detection of a single-phase ground fault to suppress capacitive fault currents.

After a specific delay ΔT_X (the delay time corresponds to the duration for the fault arc to extinguish, as detailed in reference [28]), the Peterson coil is deactivated. Then, the resistance branch is reconnected. Since the time allocated for the fault arc to extinguish is generally 2–3 s, the response speed of the switches can be neglected. Subsequently, the nature of the faults is determined based on changes in U_{N0} and zero-sequence current amplitude. If, upon switching back to the resistance grounding branch, differences in characteristic quantities persist compared to the normal state, the faults are classified as permanent. The fault line and section can then be determined through the zero-sequence current fault characteristics when the Peterson coil branch switch is engaged.

Manual switching of the Peterson coil grounding mode is necessary to ensure the reliability of the Peterson coil operation when there is a change in the operating mode of the grid. After completing measurements of grid capacitance currents and performing automatic tuning, the Peterson coil switches back to the resistance grounding mode to dampen overvoltage in the grid.

3.2. Application of Electrical Quantity Waveform Feature Recognition in Coordinated Fault Handling

In the fault identification strategy proposed in this paper, waveform feature extraction and attenuation component processing techniques are utilized to identify the occurrence of ground faults and the fault regions. To address the challenge of difficult fault perception caused by high-resistance grounding faults in asymmetric power systems, this paper introduces a method for identifying the attenuation characteristics of neutral point displacement voltage waveforms. By combining this approach with mode frequency differences, the proposed method achieves accurate detection of grounding faults. Furthermore, to enhance precise fault area identification, the paper extracts attenuation coefficients from zero-sequence current waveforms and utilizes polarity differences in these coefficients to identify fault regions.

3.2.1. Analysis of Fault Attenuation Process in Neutral Point Displacement Voltage

The transient process of grounding faults occurring in resistance-grounded systems has been analyzed through the zero-sequence circuitry in the preceding sections. Due to the sinusoidal trajectory of U_{N0} during normal operation, θ_2 varies with factors such as the faulted phase and fault inception angle, leading to ineffective detection of DC attenuation components.

However, higher transition resistances exert a more pronounced damping effect on the oscillation process during fault occurrences, presenting a significant contrast to the voltage asymmetry changes during normal grid operation.

This paper utilizes the Variational Mode Decomposition (VMD) method to decompose the neutral point displacement waveforms under typical special fault phase angles during HIGF and voltage asymmetry conditions. The VMD method was proposed by Dragomiretskiy et al. This method assumes that any signal is composed of a series of sub-signals with specific center frequencies and finite bandwidths. By constructing and solving a variational problem, it determines the center frequencies and bandwidth constraints and identifies effective components corresponding to each center frequency in the frequency domain. The decomposition steps of the VMD method are referenced from [29].

Figures 5 and 6 depict the decomposed modes for two different scenarios. By analyzing the frequency characteristics of these decomposition modes using Fast Fourier Transform (FFT), the resonant frequency bands of the original waveforms can be identified.

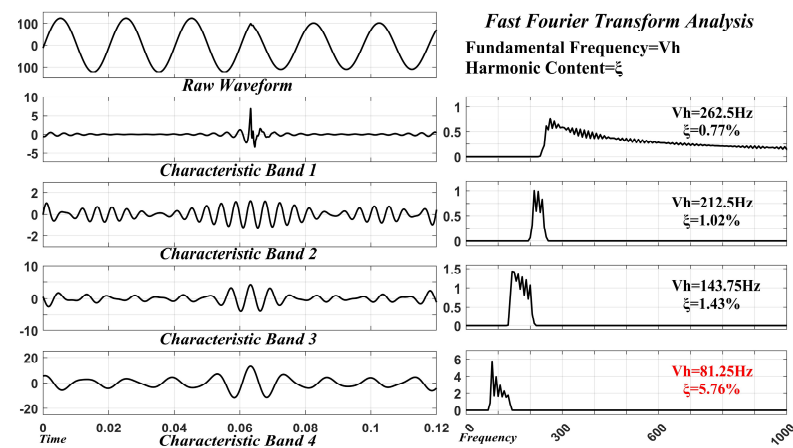


Figure 5. Decomposition and FFT Analysis of Voltage Waveform under High-Resistance Grounding Fault.

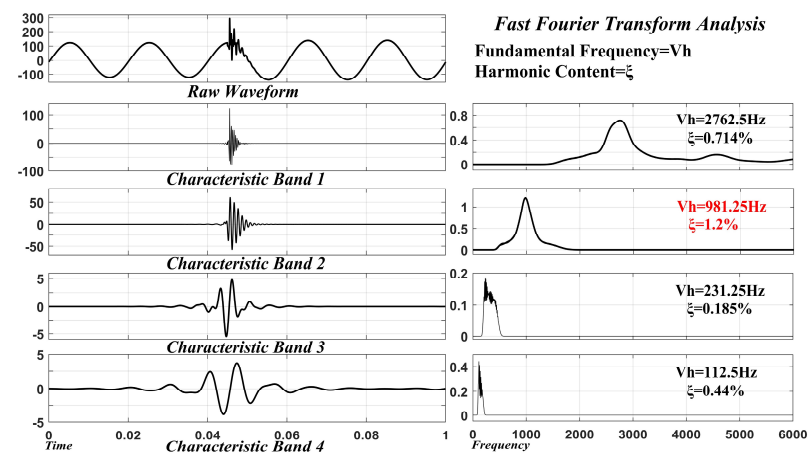


Figure 6. Decomposition and FFT Analysis of Voltage Waveform with Phase Voltage Asymmetric Variations.

In the above figure, V_h represents the modal center frequency, and ξ denotes the proportion of the center frequency within the fundamental wave.

A comparison between Figures 5 and 6 allows us to draw the following conclusion: due to the damping effect of the transition resistance, the harmonic frequencies during high-resistance grounding faults are concentrated near the fundamental frequency, with minimal high-frequency harmonic content. In contrast, during dynamic changes in phase voltage asymmetry, there is a distribution of both low-frequency and high-frequency harmonics. The harmonic content during asymmetric voltage changes is related to the closing angle. When the closing angle is 0° , the harmonic frequency content is minimal, reaching its peak at 90° , as shown in Tables 1 and 2.

Table 1. The frequency band of the U_{N0} in HIGF.

HIGF C Phase $\varphi = \theta_2$	1 k Ω	2 k Ω	3 k Ω	4 k Ω	5 k Ω
V_h :	125 Hz	112 Hz	87.5 Hz	83.8 Hz	65 Hz
ξ :	5.66%	4.67%	4.02%	3.58%	1.99%

Table 2. The frequency band of the U_{N0} in asymmetric voltage variation.

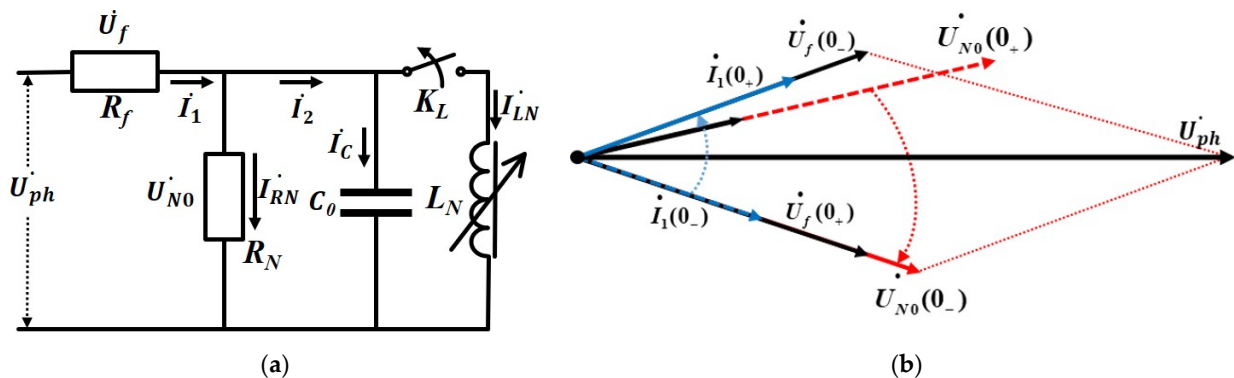
U_{N0}		Change Value				
Initial Value: 86.6 V		80.83 V	75.06 V	69.28 V	63.51 V	57.74 V
0°	V_h :	2805 Hz	2743 Hz	2657 Hz	2682 Hz	2732 Hz
	ξ :	0.11%	0.12%	0.11%	0.10%	0.11%
90°	V_h :	996 Hz	1001 Hz	1042 Hz	1050 Hz	987 Hz
	ξ :	0.55%	0.45%	0.36%	0.44%	0.42%

A comparison between Tables 1 and 2 leads to the conclusion that when there is an asymmetric variation, the resonant frequency of U_{N0} is higher, typically distributed within the high-order modal frequency band. However, during high-resistance grounding faults, the resonant frequency of U_{N0} is lower, situated within the lowest frequency band mode of the decomposed modal frequencies.

During HIGF, the accurate detection of ground faults can be achieved utilizing the aforementioned characteristics. When $\varphi \neq \theta_2$, HIGF can be identified using the direct current offset component. When $\varphi = \theta_2$, differentiation between HIGF and dynamic changes in phase voltage asymmetry can be made based on the difference in high-frequency harmonic content.

3.2.2. Analysis of Zero-Sequence Current Attenuation Process during Grounding Method Switching

When the fault is permanent, switch Q_{FL} is opened at time T_1 , and the Peterson coil circuit exits operation. At this moment, the ground capacitance loses the compensating effect of inductive current, regardless of whether the Peterson coil was in an under-compensation or over-compensation state. This process can be equivalent to the closure of capacitor C in an RC series-parallel circuit at time T_1 , as shown in Figure 7.

**Figure 7.** (a) Zero-Sequence Equivalent Circuit During Fault Coordination Process; (b) Voltage-Current Vector Model.

Before the switching operation, $U_{N0}(0_-) = R_N I_{RN}$; $u_C(0_-) = U_{N0}(0_-)$. According to the switching rule, after the switching operation, we obtain $u_C(0_-) = u_C(0_+)$. According to the KVL and KCL, the relationship between the voltages and currents of each component after the switch is closed, as illustrated in Equation (9).

$$\begin{cases} \dot{U}_{ph} = R_f \left(C \frac{d\dot{u}_C}{dt} + \frac{\dot{u}_C}{R_N} \right) + \dot{u}_C \\ \dot{I}_C = \frac{\dot{U}_{ph} - \dot{u}_C}{R_f} - \frac{\dot{u}_C}{R_N} \end{cases} \quad (9)$$

Assuming the time constant of the capacitor circuit is τ , $\tau = R_N C_0$. The voltage total response equation of the capacitor circuit during this stage can be represented by Equation (10).

$$u_c = \frac{R_N U_{ph}}{R_N + R_f} + (R_N I_{RN} - \frac{R_N U_{ph}}{R_N + R_f}) e^{-\frac{t}{\tau}} \quad (10)$$

In Equation (10), the first half on the right-hand side represents the steady-state component, while the second half represents the decaying free component. The decay component is directly related to the transition resistance at the fault point and the neutral point resistance. As the transition resistance increases, the peak value of the offset component decreases, and the decay time increases. The decay process of the zero-sequence current after capacitor closure is given by Equation (11).

$$\dot{I}_C = C_0 \frac{du_c}{dt} = (-I_{RN} + \frac{U_{ph}}{R_N + R_f}) e^{-\frac{t}{\tau}} \quad (11)$$

In a resistance-grounded system, significant differences exist in the amplitude and direction of zero-sequence currents between the upstream node (near the substation) and the downstream node (far from the substation) at the fault point. Due to the shunting effect of line-to-ground capacitance, the zero-sequence current gradually increases from the substation feeder to the fault point, reaching its maximum value at the node just before the fault point. Subsequently, the zero-sequence current gradually decreases at nodes downstream of the fault point, as illustrated in Figure 8.

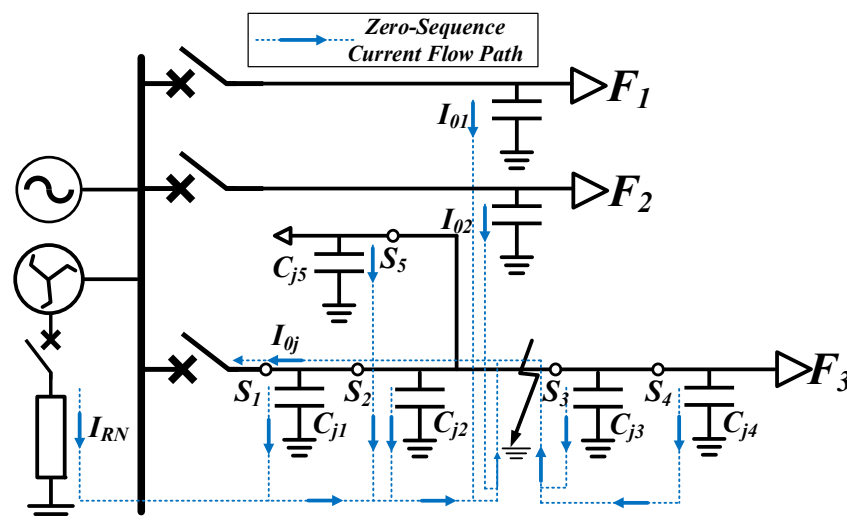


Figure 8. Zero-Sequence Current Network Distribution Structure.

Let $C_{j1}, C_{j2}, \dots, C_{jn}$ denote the line-to-ground capacitances of the fault feeder sections, and $G_{j1}, G_{j2}, \dots, G_{jn}$ denote the line-to-ground conductance of the fault feeder sections. The fault occurs at node i . Based on Kirchhoff's Current Law (KCL), the relationship for zero-sequence currents upstream and downstream of the fault point can be derived as Equation (12),

$$\left\{ \begin{array}{l} I_o^{\bullet Power} = U_{N0} j\omega (C_\Sigma - \sum_{i=1}^k C_{ji}) - \frac{\dot{U}_f}{R_f + \sum_{i=1}^k G_{ji}} + \frac{\dot{U}_{N0}}{R_N} \\ I_o^{\bullet Load} = \frac{\dot{U}_f}{R_f + G_{in}} - U_{N0} j\omega C_{jn} \end{array} \right. \quad (12)$$

where I_0^{power} represents the zero-sequence current at the upstream node of the fault point, while I_0^{Load} represents the zero-sequence current at the downstream node of the fault point.

The analysis above indicates that accurate localization of small-resistance grounding faults can be achieved through the magnitude of zero-sequence currents at nodes. However, due to the current-limiting effect of high-resistance grounding resistors, differentiating the fault characteristics of zero-sequence currents at various nodes becomes challenging, making it difficult to precisely locate HIGF areas using traditional methods. The zero-sequence currents in the resistance-grounding system exhibit directional distribution within the network. After the Peterson coil is removed from operation, the attenuation components of zero-sequence currents at upstream and downstream nodes exhibit different attenuation directions. Therefore, this paper proposes utilizing the disparity in the attenuation directions of zero-sequence currents as a supplementary method for detecting HIGFs. Figure 9 depicts the waveform differences between the upstream and downstream nodes upon the removal of the Peterson coil.

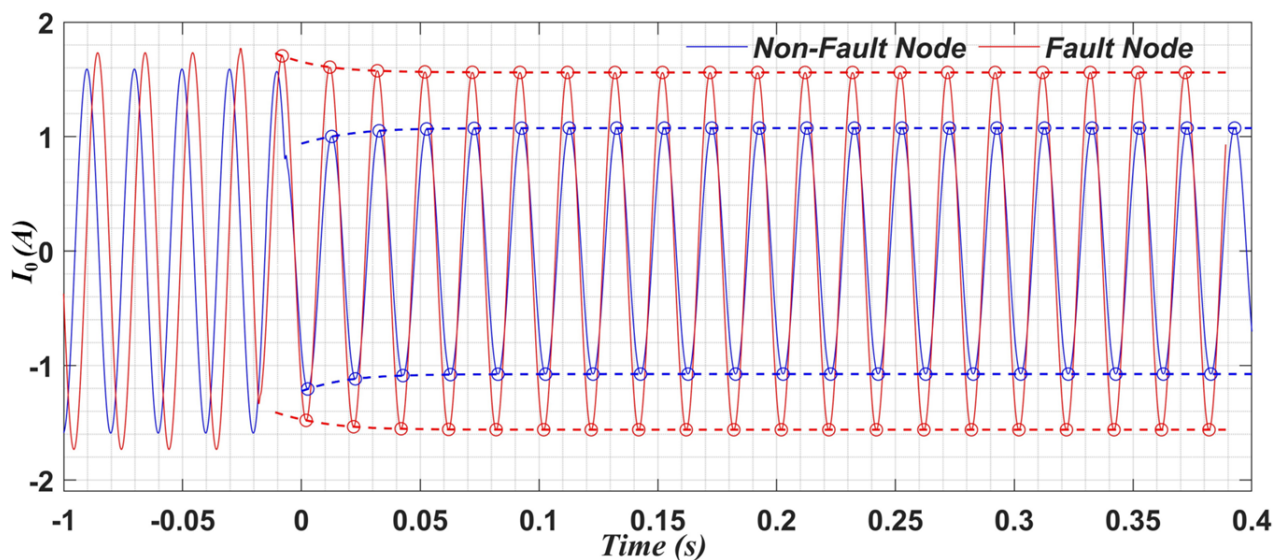


Figure 9. Differences in Zero-Sequence Current Waveforms between Upstream and Downstream Nodes during Faults.

3.3. Extracting and Analyzing Waveform Characteristics

Given the time-frequency characteristics of neutral point displacement voltage and zero-sequence current in fault coordination processes, this paper employs EWT [30] to decompose the feature quantities and construct modal components for each frequency band. The EWT combines the adaptive capability of Empirical Mode Decomposition (EMD) with the orthogonality of wavelet methods. It provides better physical interpretability while avoiding the issues of mode mixing and over-decomposition [31]. The modal signals obtained from this method exhibit good stability and robustness. The decomposition process is described in detail in the literature [32].

3.3.1. Fault Detection Based on Voltage Attenuation Components and Modal Frequencies

We can detect ground faults based on the direct current modal component in the modal components obtained through EWT decomposition of neutral point displacement voltage. Figure 10 illustrates the modal components obtained through the EWT method when a permanent HIGF occurs.

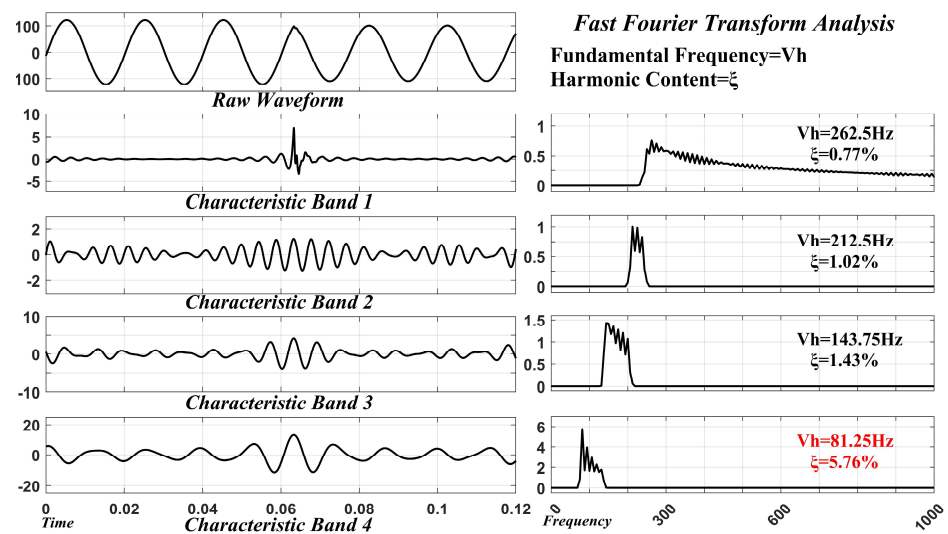


Figure 10. Decomposition of Neutral Point Displacement Voltage Waveform in HIGF.

When a specific fault phase angle causes the disappearance of the DC component, the resonance band distribution characteristics obtained from the previous analysis can distinguish between HIGF and voltage asymmetry changes. The variance contribution ratio can intuitively reflect the energy provided by the decomposition modes to the signal fluctuation in the original waveform. The process of calculating the mode variance contribution rate is as follows: after calculating the variance for each mode, the proportion in the original signal variance is computed, as shown in Equation (13).

$$PCR = \frac{s_i^2}{\sigma_o^2} = \frac{\int [e_i^2(t) - \bar{e}_i]^2 dt}{\int [Y^2(t) - \bar{y}]^2 dt} \quad (13)$$

The harmonic main frequencies V_X of each mode are obtained through FFT. Weighted averaging of the harmonic main frequencies is performed using PCR as the weighting factor to calculate the maximum frequency value V_g in the energy spectrum, as shown in Equation (14). The value V_g describes the harmonic frequency in the decomposition mode that has the greatest impact on signal fluctuations.

$$V_g = \frac{\sum_{i=1}^N V_X^i PCR_i}{\sum_{i=1}^N PCR_i} \quad (14)$$

The directional nature of V_g in the decomposition mode frequency bands can distinguish between HIGF and voltage asymmetry changes. If V_g points to the high-frequency modal component, it is judged that a voltage asymmetry change has occurred; if V_g points to the low-frequency modal component, it is considered that an HIGF has occurred. Figure 11 visually illustrates the frequency characteristics of the neutral point displacement voltage under different conditions.

As shown in Figure 11, under the condition of a specific initial fault angle, V_g successfully indicated the frequency band characteristics in both HIGF and voltage asymmetry changes. During high-resistance grounding faults, V_g pointed to the low-frequency modal component, while in voltage asymmetry changes, V_g pointed to the high-frequency modal component.

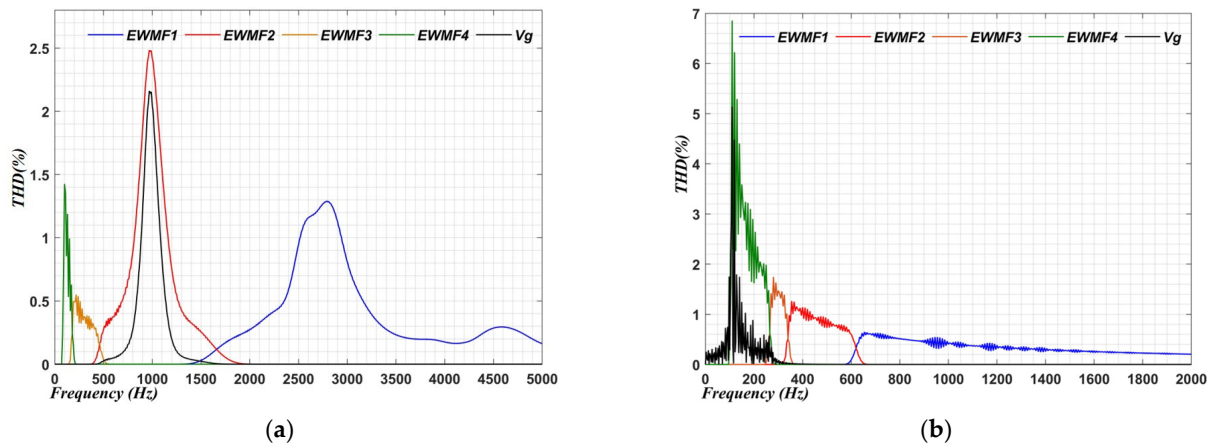


Figure 11. (a) Modal Frequency Band Distribution During Voltage Asymmetry Changes; (b) Modal Frequency Band Distribution During HIGF.

3.3.2. Fault Zone Localization Based on Zero-Sequence Current Attenuation Coefficient

Based on the analysis above, the fault zone can be determined using the attenuation polarity of the zero-sequence current at feeder nodes when the Peterson coil is removed. Firstly, EWT is applied to decompose the zero-sequence current waveforms at the beginning of each feeder. The decomposed DC attenuation component characterizes the direction of zero-sequence current attenuation. Then, the fault zone is identified based on the polarity characteristics of zero-sequence current attenuation at the nodes of the faulted feeder.

The method for extracting the polarity characteristics of zero-sequence current attenuation is as follows. First, the EWT is used to decompose the zero-sequence current at each feeder and node, resulting in the nonlinear attenuation mode $E_{res}(t)$. Then, the Nonlinear Least Squares (NLS) method is applied to fit the attenuation term and obtain a nonlinear attenuation model. The objective function is shown in Equation (15).

$$E(t) = \delta_f e^{-\lambda_f t} + \alpha \quad (15)$$

The fitting process includes minimizing the sum of squared residuals (Equation (16)) and iteratively solving for the optimal parameters using the Levenberg–Marquardt method.

$$S(\theta) = \sum_{i=1}^n [e_{res} - (\delta_f e^{-\lambda_f t} + \alpha)]^2 \quad (16)$$

The above process yields two variables: the attenuation coefficient λ_f and the attenuation zero-point δ_f . The sign of the attenuation coefficient indicates the direction of zero-sequence current attenuation, while the attenuation zero point represents the time when attenuation terminates.

The identification of fault sections can be achieved by leveraging the opposite polarity of the attenuation coefficients of zero-sequence currents at upstream and downstream fault nodes. Specifically, the fault area can be located by examining the sign of the zero-sequence current attenuation coefficient λ_f at each node before the attenuation zero-point δ_f .

3.4. Process Flow of Neutral Point Coordination Control Method for SLG

The fault characteristic identification stage of the neutral point grounding SLG coordination control method consists of five time sequences (T_0 – T_4), as shown in Figure 12.

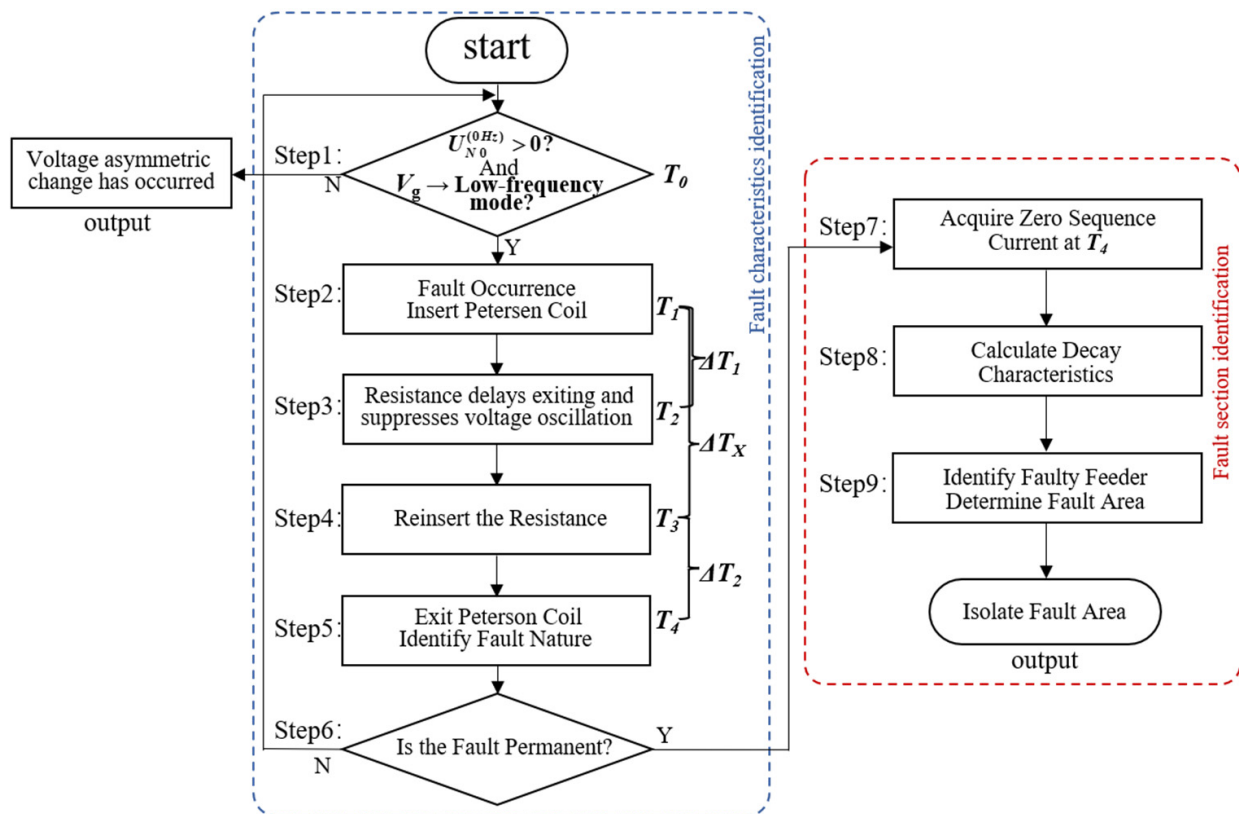


Figure 12. Flowchart of Neutral Point Coordinated Fault Handling Strategy.

Step 1: Upon detection of a fluctuation in U_{N0} , grounding faults are diagnosed by analyzing the decay of the direct current component of the neutral point displacement voltage to identify HIGF while excluding asymmetrical disturbances in grid operation. The calculation method is shown in Equations (13) and (14). Mark the occurrence of the fault as T_0 .

Step 2: At time T_1 , the Peterson coil is activated to suppress fault currents. During the delay ΔT_1 , both the Peterson coil branch and the resistance branch operate simultaneously in the grounding circuit, with the resistance branch rapidly suppressing the attenuation component in the Peterson coil.

Step 3: At time T_2 , the resistance grounding branch is deactivated, allowing the Peterson coil to extinguish the fault arc within the delay ΔT_X .

Step 4: At time T_3 , the resistance branch is reactivated to suppress the electrical quantity free oscillation process caused by disconnecting the Peterson coil.

Step 5: After a delay of ΔT_2 , the Peterson coil is disconnected. The fault nature is determined by assessing whether the U_{N0} and zero-sequence current amplitudes of each feeder have returned to normal.

Step 6: If all characteristics return to normal, the fault is classified as transient, and the resistance branch continues to operate. If the fault characteristics do not return to normal, the fault is deemed permanent.

Step 7: At time T_4 , the fault feeder is determined by analyzing the attenuation of the zero-sequence current free component of each feeder, thereby completing the identification of the fault region.

Step 8: At time T_4 , the calculation of the zero-sequence current attenuation coefficients at the starting end of the faulted line and at the line node is implemented using Equations (15) and (16).

Step 9: By comparing the polarity of the zero-sequence current attenuation coefficients between upstream and downstream nodes at the fault point, the identification of the fault region is achieved.

4. Experimental Analysis

4.1. Detection Experiment of HIGF and Voltage Asymmetry

To validate the accuracy of the proposed method for fault detection, we constructed a typical 10 kV distribution system in the PSCAD 5.0 simulation environment, as illustrated in Figure 13.

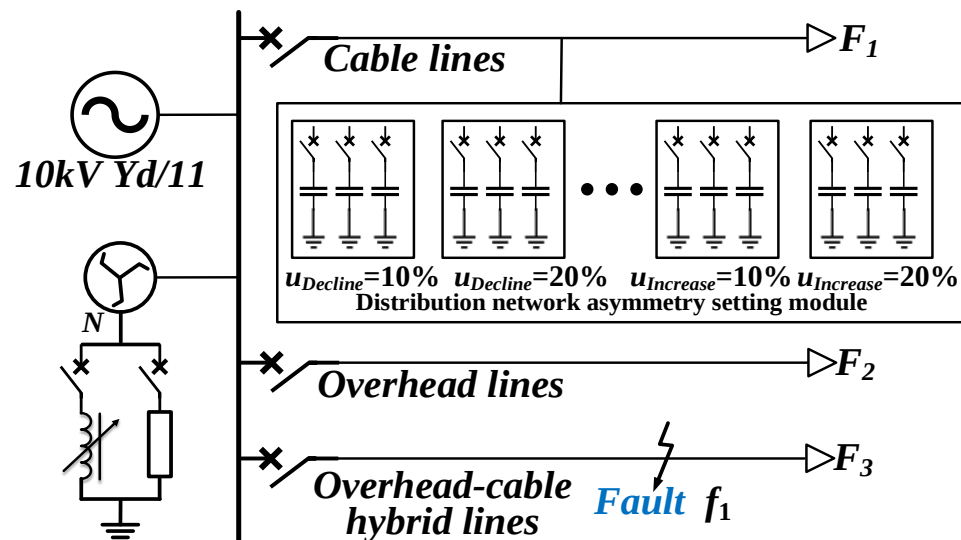


Figure 13. Simulation Experiment Distribution Network Structure.

Three lines ($F_1 \sim F_3$) in the distribution network are set up using lumped parameter line models. Specifically, F_1 represents a cable line, F_2 represents an overhead line, and F_3 represents a hybrid overhead-cable line. Line F_1 is equipped with a three-phase voltage asymmetry offset testing module, which operates by adjusting the asymmetrical state of the three-phase voltages through varying the capacitance to ground of each phase, and the degree of asymmetry is defined by the displacement of the neutral point voltage $u_{00}(\%)$. The parameters of the cable and overhead lines are listed in Table 3. Line F_3 is equipped with a single-phase ground fault module, simulating a high-resistance ground fault by varying the fault resistance value and the fault occurrence time.

Table 3. Cable and overhead line simulation parameters.

Line Impedance (Ω/km)	Positive Sequence Parameter			Zero Sequence Parameters		
	$R^{(1)}$	$X_L^{(1)}$	$X_C^{(1)}$	$R^{(0)}$	$X_L^{(0)}$	$X_C^{(0)}$
Cable line	0.27	0.08	8469.9	2.7	0.3488	11,538.8
Overhead line	0.17	0.38	318,471.3	0.25	1.72	398,289.2

During normal operation, the effective value of U_{N0} is 86.6 V, with phase A having the highest voltage and phase C having the lowest voltage. In line F_1 , the capacitance parameters to ground of the three phases are adjusted to induce variations in U_{N0} within the range of 1.0% to 2.0%. The value Δu represents the difference in these variations, simulating changes in the asymmetry of the three-phase voltages in the distribution network. Under the influence of the three-phase asymmetry, the behavior of the neutral point displacement voltage during ground faults and normal operation is illustrated in Figure 14.

From Figure 14, it can be observed that when the HIGF occurs precisely at a specific initial phase angle of the fault, the decay component of the U_{N0} disappears. Moreover, the variation in the magnitude of U_{N0} is similar to that observed when voltage asymmetry occurs. The results of applying the method proposed in this paper and the traditional steady-state magnitude judgment method are shown in Tables 4 and 5, respectively.

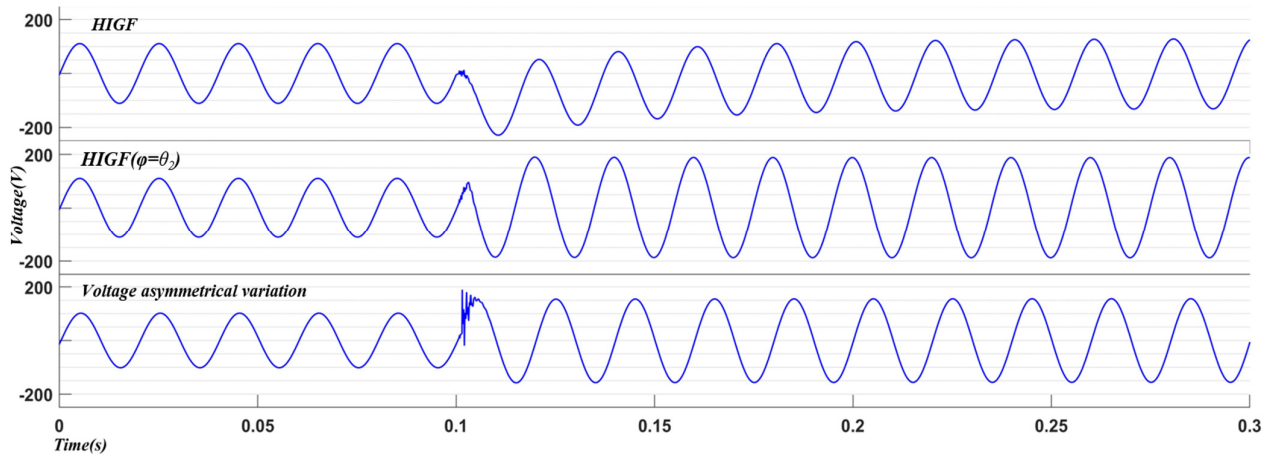


Figure 14. Variations in Neutral Point Displacement Voltage Waveform.

Table 4. U_{N0} on HIGF ($\varphi = \theta_2$).

R_f (Ω)	Modal Frequency Band (Hz)	V_g (Hz)	Method in This Paper	Steady-State Method
1 k Ω	[2250~15,587, 1293~2662, 781~1637, 181~568]	226	Fault	Fault
2 k Ω	[2200~13,712, 1293~2100, 781~1637, 103~577]	171	Fault	/
3 k Ω	[1656~8675, 1056~1618, 856~1000, 91~603]	138	Fault	/
4 k Ω	[1068~5925, 1006~1093, 968~1018, 88~581]	116	Fault	/
5 k Ω	[756~5300, 581~748, 443~593, 68~426]	97	Fault	/

Table 5. U_{N0} on voltage asymmetrical variations.

Δu (V)	Modal Frequency Band (Hz)	V_g (Hz)	Method in This Paper	Steady-State Method
−28.87	[3456~12,150, 1512~4031, 556~1818, 118~793]	1975	Non-fault	/
−23.096	[3568~10,381, 1537~4068, 493~1818, 106~693]	2238	Non-fault	/
−17.322	[4893~12,268, 3556~5675, 1656~3593, 218~1731]	2713	Non-fault	/
−11.548	[3668~10,193, 1631~4081, 493~1806, 106~681]	3077	Non-fault	/
−5.774	[3637~11,831, 1937~4062, 493~1756, 106~668]	4166	Non-fault	/
5.774	[4131~16,156, 3306~4600, 1675~3225, 231~1700]	3972	Non-fault	/
11.548	[4075~16,068, 3187~4506, 1700~3306, 231~1675]	3656	Non-fault	/
17.322	[4931~15,993, 2931~5418, 1768~3368, 218~1633]	2713	Non-fault	/
23.096	[4843~15,400, 2912~5431, 1743~3381, 234~1455]	2659	Non-fault	/
28.87	[4781~14,518, 2918~5437, 1756~3393, 248~1662]	2021	Non-fault	Fault

Analyzing the data from the charts, we can conclude that the average frequency based on the energy spectrum shows excellent directionality across different modal frequency bands, allowing for clear differentiation between faults and voltage asymmetry changes even when the DC decay component disappears. Compared to other methods, the approach presented in this paper accurately identifies ground faults for transition resistances below 5 k Ω and does not produce false positives during voltage asymmetry changes.

4.2. Fault Zone Localization Experiment

We used centralized capacitors to simulate the line-to-ground capacitance. The distribution test network was constructed using transformers, circuit breakers, primary and secondary integrated intelligent circuit breakers, and oscillographs. To validate the observability of the attenuation component by the zero-sequence current transformer, we utilized primary and secondary integrated intelligent switches as nodes to measure the zero-sequence current variations according to the proposed method. Figure 15 shows the

architecture of the experimental network. The fault point is simulated using several groups of heat-dissipating resistors and a fast switch. The simulation method for the fault point and the line is shown in Figure 16.

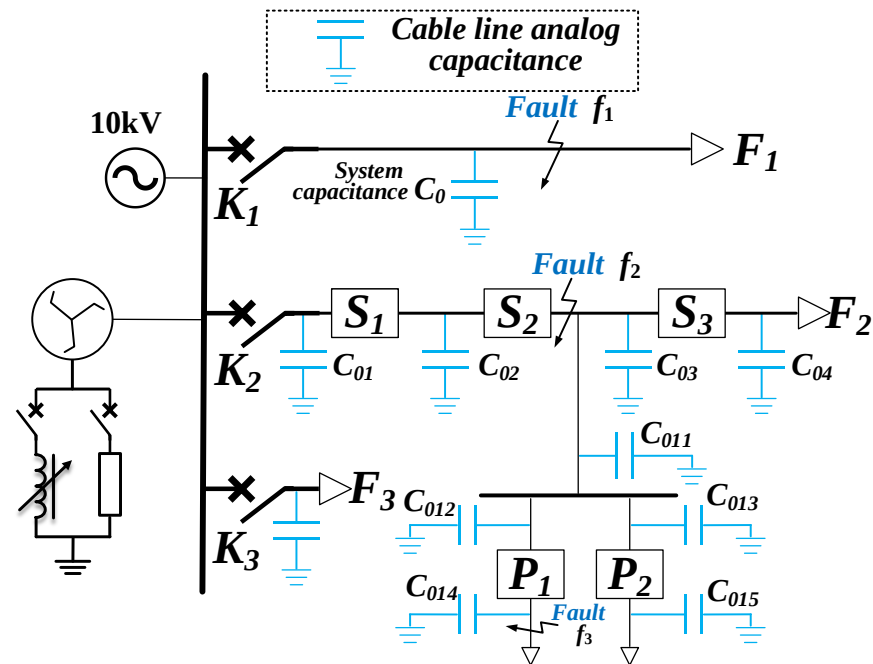


Figure 15. Architecture of the Distribution Experimental Network.

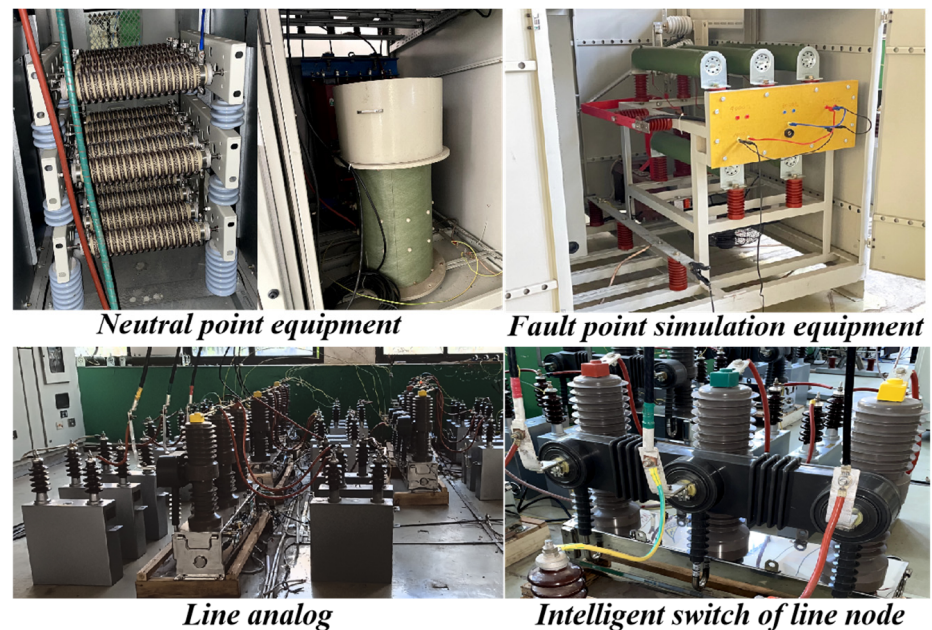


Figure 16. Layout of the Distribution Experimental Network.

The identification of fault areas was validated through comparative experiments by setting fault points f_2 and f_3 . Figure 17 shows the recorded zero-sequence currents at nodes S_2 and S_3 when a $3000\ \Omega$ transition resistance ground fault occurs at fault point f_2 .

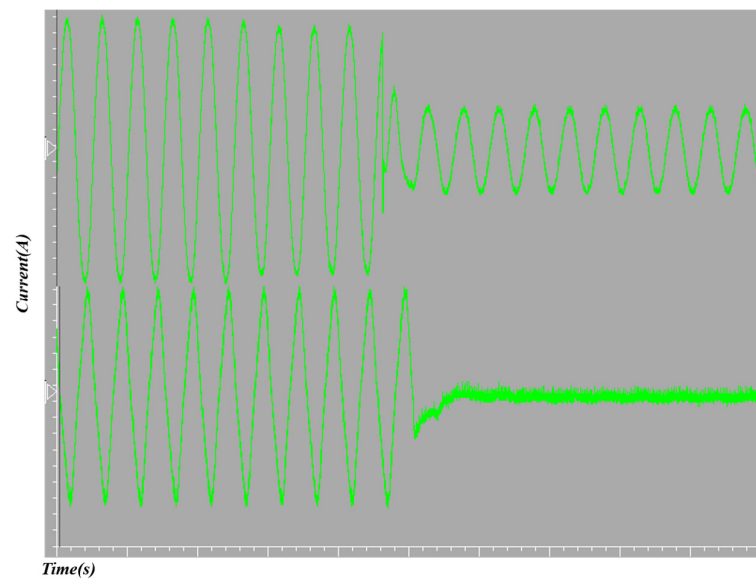


Figure 17. Experimental Network Waveform Data.

After extracting the recorded data, filtering was performed using a FIR filter. It was observed that during the process of Peterson coil disconnection, each node correctly observed the direction of zero-sequence current attenuation and the variation in its magnitude. Figure 18 illustrates the variation of zero-sequence currents at nodes in the distribution experimental network for fault points f_2 and f_3 . Dashed lines in the figure indicate the trend of waveform changes.

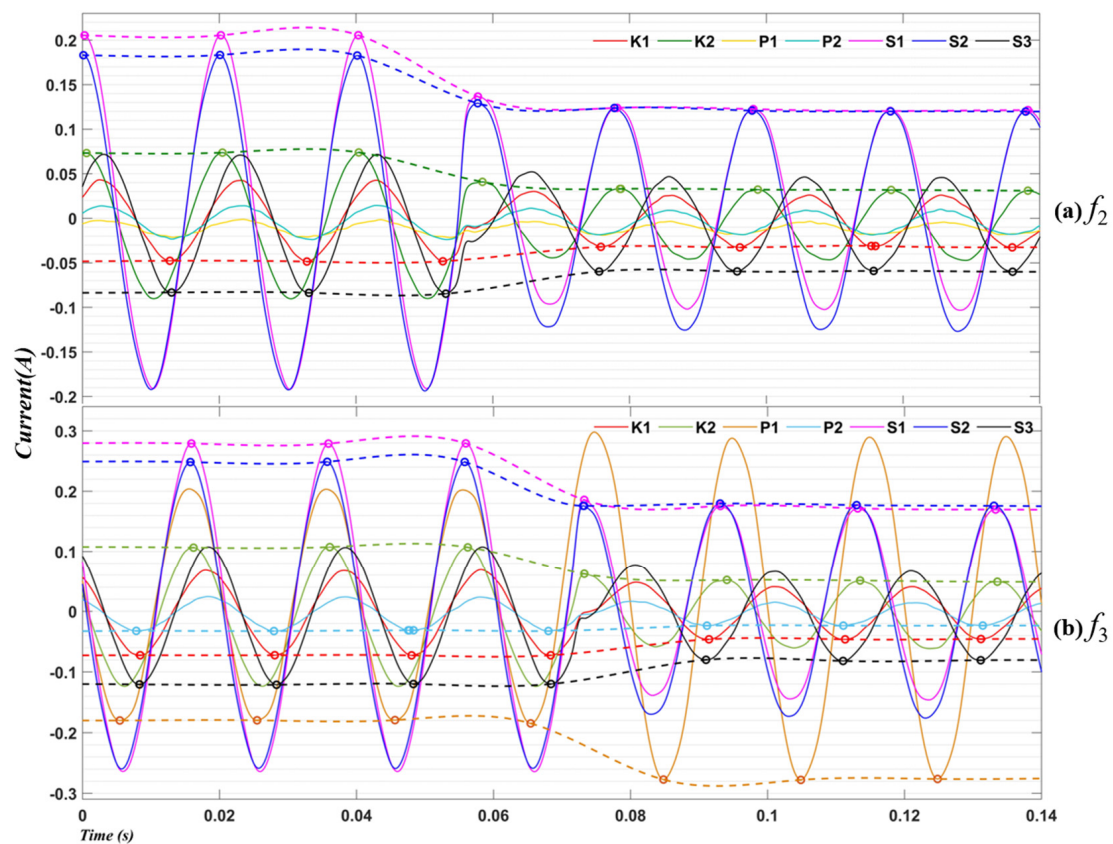


Figure 18. Zero-Sequence Current Waveform Analysis Chart.

Comparing Figure 18a,b, it is evident that the nodes exhibit opposite directions of zero-sequence current attenuation before and after the fault. Moreover, when branch line node P_1 is included as the upstream node of the fault, its zero-sequence current magnitude notably increases, indicating the same waveform attenuation direction as the upstream fault node.

After validating the observability of the zero-sequence current attenuation process, we proceeded with ground fault experiments at fault points with transition resistances ranging from 1 k Ω to 5 k Ω . The attenuation coefficients λ_f obtained from some experiments are illustrated in Figure 19. Table 6 compares the judgment accuracy between our proposed method and the transient fault current polarity comparison method [19].

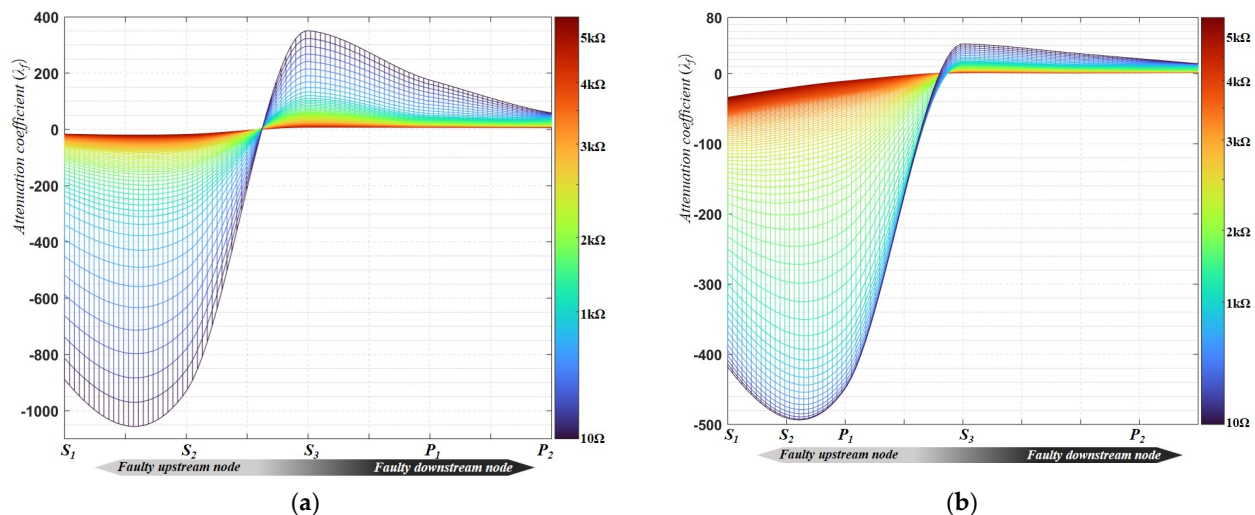


Figure 19. (a) Fault Point f_2 ; (b) Fault Point f_3 .

Table 6. Comparison of Fault Zone Criteria and Methods.

R_f (Ω)	Fault Point	Attenuation Coefficient (λ_f)					Method in This Paper	Comparison Method
		S_1	S_2	S_3	P_1	P_2		
1 k	f_2	−308.23	−297.18	64.03	10.58	18.22	$S_2 \sim S_3$	$S_2 \sim S_3$
	f_3	−311.05	−303.24	65.23	−323.30	12.24	$P_1 \sim$	$S_2 \sim S_3$
3 k	f_2	−56.40	−49.29	12.11	4.22	6.02	$S_2 \sim S_3$	$S_2 \sim S_3$
	f_3	−56.40	−49.29	10.33	−52.50	5.29	$P_1 \sim$	/
5 k	f_2	−30.23	−26.58	5.14	2.12	1.88	$S_2 \sim S_3$	/
	f_3	−28.39	−23.10	3.32	−30.21	1.21	$P_1 \sim$	/

The analysis of experimental results reveals the following: in the experiments conducted at fault point f_2 , the attenuation coefficients of nodes S_1 and S_2 upstream of the fault are negative, while those of nodes S_3 , P_1 , and P_2 downstream of the fault are positive. Consequently, the fault area is determined to be between nodes S_2 and S_3 . Similarly, in the experiments at fault point f_3 , the attenuation coefficients of nodes S_1 , S_2 , and P_1 upstream of the fault on the feeder are negative, whereas those of nodes P_2 and S_3 downstream of the fault are positive, indicating that the fault area is at branch line P_1 .

In Table 6, the node criteria intuitively display the polarity differences of the attenuation coefficients at fault nodes. The comparative method, influenced by the fault initial phase angle and resonant compensation angle, resulted in misjudgments of the fault area for high-resistance ground faults. The method proposed in this paper determines the fault area based on the characteristic of the attenuation direction of the zero-sequence current at each node when disconnecting the Peterson coil. It is not affected by the fault initial phase angle or resonant compensation angle. In 10 fault area determination experiments,

the accuracy rate of the comparative method was 30%, while the method proposed in this paper achieved 100% accurate fault determination.

4.3. Engineering Application Validation

The methodology proposed in this paper has been applied in several distribution networks in central China, yielding favorable outcomes in fault handling. Field experiments were conducted on a distribution feeder located in Hubei Province, China, to assess fault handling and fault area determination. Figure 20 illustrates the topological structure of the feeder line. Under normal conditions, the grid is powered by transformer T_1 with switch B506 in the open position. When a fault is detected, switches on both sides of the fault location (such as switches B309 and B022 on either side of fault location f_2) can be opened, and switch B506 can be closed to restore power to the affected area via transformer T_2 .

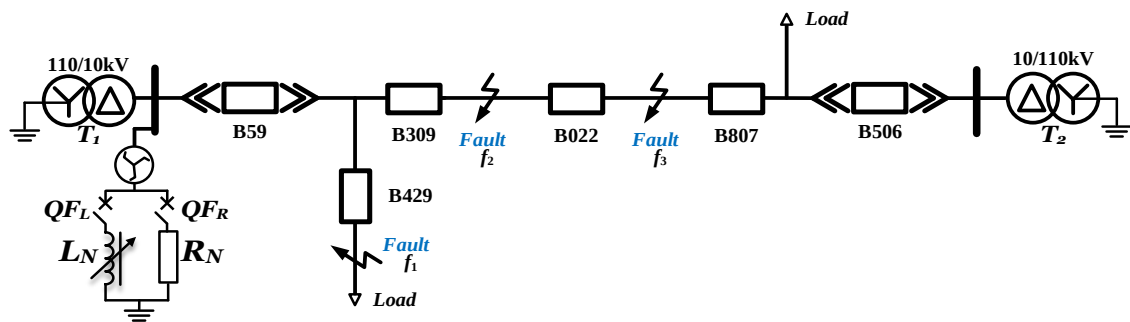


Figure 20. Experimental Feeder Line Topological Structure.

The experiments were conducted at fault points f_1 , f_2 , and f_3 with increasing fault resistance. The experimental data are shown in Table 7.

Table 7. Comparison of Fault Zone Criteria and Methods.

Point of Failure	Fault Point Resistance (Ω)	Fault Area Judgment Result
fault point 1	0	After B429 switch
	1000	After B429 switch
	4000	After B429 switch
fault point 2	0	B309–B022
	1000	B309–B022
	4000	B309–B022
fault point 3	0	B022–B807
	1000	B022–B807
	4000	B022–B807

The data indicate that in testing environments with fault transition resistances below 4 k Ω , the proposed method accurately identifies the fault region and demonstrates good engineering practicality.

5. Conclusions

This paper proposes a novel fault identification method based on coordinated control of a Peterson coil and resistance grounding, aimed at enhancing the safety of distribution systems while ensuring power supply reliability. Furthermore, fault perception and fault region identification methods based on waveform characteristics are introduced, effectively improving the accuracy and sensitivity of identifying ground faults. The following conclusions can be drawn:

- (1) The approach proposed in this paper utilizes the Peterson coil to eliminate transient faults and switches to resistance grounding during permanent faults. This method alters the distribution pattern of zero-sequence currents between faulty and non-faulty

feeders, addressing challenges in ground selection and fault region identification associated with Peterson coil grounding. Moreover, it resolves issues concerning the lack of power supply reliability associated with small-resistance grounding.

- (2) Time-frequency variations in neutral displacement voltage waveforms accurately detect ground faults. The temporal decay components of the voltage waveform can discern HIGFs, while differences in harmonic frequency bands in the frequency domain can precisely differentiate voltage asymmetry changes from HIGFs. This paper combines the time-frequency characteristics of voltage waveforms to achieve accurate fault detection while eliminating interference from voltage asymmetry changes and specific fault initial phase angles.
- (3) Waveform characteristics of zero-sequence currents during the transition of neutral grounding modes can identify fault regions. When disconnecting the Peterson coil, the zero-sequence current waveforms exhibit opposite attenuation directions at the upstream and downstream regions of the fault feeder, as well as at the head ends of the fault feeder and the healthy feeder. The polarity difference in the attenuation coefficients of zero-sequence currents can be utilized to identify the fault area, unaffected by the compensation status of the Peterson coil. Compared to quantitative methods based on threshold judgment, the qualitative analysis approach proposed in this paper enhances the accuracy of identifying high-resistance ground faults.

Experimental data demonstrate that our proposed method can accurately identify the fault area under a fault transition resistance of 5 kΩ. In practical engineering validation, the method accurately identifies the fault area under conditions where the fault transition resistance (R_f) is less than or equal to 4 kΩ.

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Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

In ungrounded systems, the three-phase voltages satisfy Kirchhoff's law. Therefore, Equation (A1) can be derived,

$$\dot{U}_A Y_A + \dot{U}_B Y_B + \dot{U}_C Y_C = 0 \quad (\text{A1})$$

where Y_A , Y_B , and Y_C represent the admittances of the three phases of the power grid to ground.

Due to inevitable operational differences among the three phases, these differences are reflected in the virtual asymmetric admittance and ultimately manifest in the degree of offset in the three-phase voltages. The voltage offset among the three phases adheres to the principles of trigonometry. Thus, Equation (A2) can be derived.

$$\dot{U}_{NN'} = - \frac{\dot{U}_A (G_A + j\omega C_A) + \dot{U}_B (G_B + j\omega C_B) + \dot{U}_C (G_C + j\omega C_C)}{G_A + G_B + G_C + j\omega C_A + j\omega C_B + j\omega C_C} \quad (\text{A2})$$

Combining Equation (1) enables the rewriting of the asymmetric voltage $\dot{U}_{NN'}$ as expressed by Equation (2) in the paper.

Using the equivalent zero-sequence circuit shown in Figure 1, the relationship between the neutral point displacement voltage $\dot{U}_{N0}$ under non-fault conditions and the asymmetric voltage $\dot{U}_{NN'}$ can be expressed as Equation (A3),

$$\dot{U}_{N0} = -\frac{j\omega(C_A + a^2C_B + aC_C)}{j\omega C_\Sigma + Y_N + 1/R_S} U_{ph} \quad (A3)$$

where R_S represents the resistive losses, which must be accounted for when the neutral point is grounded through the Peterson coil.

Equation (3) in the paper can be derived from Equation (A3).

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