Extremely low frequency-based faulty line selection of low-resistance grounding system

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Abstract
The single-phase-to-ground faulty line selection methods based on the signals of the frequency above 10 Hz has a low discrimination of fault characteristic signal and characteristic signal may be covered by noise in cases of high-resistance fault. To solve the problem, a line selection method based on system's own extremely low frequency signal (SOELFS) is proposed. Due to the obvious attenuation characteristic of extremely low frequency signals in healthy lines, the extremely low frequency signal has a larger discrimination and hardly affected by imbalanced current noise. Moreover, as the amplitude of the SOELFS is affected by the initial phase angle of the fault, an additional line selection method based on artificially injected extremely low frequency signal is proposed. Cooperating with the specially designed and implemented measuring device, simulations and experimental verification are carried out. The results show that the discrimination of characteristic signal increases from 31 obtained by power frequency to more than 500, the high-resistance fault protection ability increases from 2 to 10 kΩ.

1 INTRODUCTION

In 6–35 kV distribution networks, the grounding methods mainly include isolated grounding, resonant grounding and low-resistance grounding [1, 2]. Isolated grounding and resonant grounding are called the non-effectively neutral grounding method. When a single-phase-to-ground (SPG) fault occurs, the amplitude of the fault current is small and the line voltage of the system is still symmetrical in the non-effectively neutral grounding system. Thus, it can continue to operate for 1–2 h after the fault occurs, which makes it widely used in distribution system [3]. However, it is difficult to identify the SPG faults in non-effectively neutral grounding system due to the current through the faulty line is not too much larger than the healthy lines [3, 4]. In addition, with the development of urban infrastructure, the distribution network has gradually evolved from mainly overhead lines to cable lines [5]. The increasing usage of cables in the distribution network makes the capacitive current increase when an SPG fault happens and makes it easy to evolve into an interphase short-circuit fault, which needs to be cut as soon as possible to prevent the accident from expanding, and the advantage of continued operation of the non-effectively neutral grounding system no longer exists [6]. Low-resistance grounding system can effectively limit overvoltage and eliminate resonant overvoltage, and SPG faults with low resistance will be quickly removed by zero-sequence current protection [7], more in line with the trend of urban power grids. When an SPG fault occurs, the large short-circuit current in the low-resistance grounding system facilitates zero-sequence current protection to remove grounding fault rapidly.

However, in case of high-resistance fault, the zero-sequence current is significantly reduced, and the threshold of zero-sequence protection may not be reached, resulting in a protection dead zone. Failure to remove faults timely can lead to...
serious accidents such as fires, equipment damage and injuries. However, if the threshold is lowered to meet the need of high-resistance fault protection, the number of misbehaviour of the protection will increase significantly [8]. The two goals of improving protection ability and improving protection stability are mutually constrained and the development and application of low-resistance grounding are limited. Therefore, it is necessary to optimize the zero-sequence protection of low-resistance grounding systems and improve the ability of high-resistance grounding fault protection.

In recent years, various methods have been proposed for the protection of high-resistance grounding faults in distribution networks. The first category of those methods is based on the improvement of the classical protections. The grounding fault protection based on zero-sequence voltage ratio restraint produces proportional current restraint signals according to the size of the zero-sequence voltage, adaptively adjusting the zero-sequence overcurrent protection value [9]. This method can deal with high-resistance grounding fault with resistance up to 1 kΩ, but requires additional acquisition of zero-sequence voltage signals, which brings engineering difficulty. Zero-sequence inverse-time overcurrent protection method uses the difference of the size of the fault current between faulty line and healthy lines to cause the difference in protection speed, making the protection device in the faulty line to act faster than healthy lines’ devices, so as to selectively cut the fault [10]. This method can deal with high-resistance grounding fault with resistance up to 1.5 kΩ, but there are disadvantages of complex tunings and adaptations when the method is used in different systems. High-resistance fault identification method based on composite power can increase the protection fault resistance to 2 kΩ without checking the transformer polarity. But it is susceptible to measurement errors, calculation errors and noise interference [11].

The second category of protections are algorithms focusing on analysing the characteristics of the fault waveform. Harmonic-based fault identification methods are highly sensitive, but have requirements for signal quality and are susceptible to other factors [12–15]. Wavelet transform is widely used to extract the characteristics of SPG faults, but it is easy to misjudge when the signal has interference, and the algorithm need large amount of calculation, which make wavelet transform methods difficult to apply in practice [16, 17]. Besides, the energy of sequence component [18], neural networks [19], hierarchical clustering [20–22] have been developed for detecting SLG faults. However, fault waveforms have small amplitude under high-resistance grounding fault condition, which brings great difficulties to the identification of fault characteristics, therefore they are not applicable to high-resistance grounding fault.

All of aforementioned methods use the signals with the frequency above 10 Hz as the characteristic signals of the line selection and identify the faulty line through the amplitude difference of the characteristic signals between the faulty line and the healthy lines. Those methods can be called conventional frequency methods. In the occurrence of high-resistance grounding fault, the amplitude of the characteristic signals in the faulty line and the healthy lines are significantly reduced. The conventional frequency methods and conventional current transformer cannot measure the characteristic signals and handle the faint differences among the outgoing lines [23], so the conventional frequency method is difficult to identify high-resistance grounding faults. In the existing literature, the conventional frequency methods can only protect the fault with a rather small resistance, such as fault resistance up to 2 kΩ [11].

This paper proposes grounding faulty line selection methods based on the system’s own extremely low frequency signal (SOELFS) and the artificially injected extremely low frequency signal (AIELFS). AIELFS is additionally proposed due to the uncertainty in the amplitude of the SOELFS. Extremely low frequency signals have larger discrimination than conventional frequency characteristic signals due to the difference of capacitance between faulty line and healthy lines. Moreover, extremely low frequency signal is less affected by noise than power frequency signal. By using extremely low frequency signal as faulty line characteristic signal, the range of high-resistance grounding fault protection is significantly improved; the contradiction between rejection and misbehaviour in SPG fault protection of low-resistance grounding systems is eased. The proposed method is independent of line length or network topology and is resistant to noise interference. Moreover, a specialized measuring device is designed and implemented to measure the extremely low frequency signal. The validity and reliability of the proposed method are proved through the simulations and tests with realistic experimental system.

The rest of the paper is organized as follows. In Section 2, the characteristics of low-resistance grounding system after an SPG fault is analysed. The faulty line identification methods are proposed and simulated in Section 3. Section 4 presents the experimental tests with realistic experimental system. Finally, Section 5 draws the conclusions.

2 | CHARACTERISTICS OF SPG FAULT

In this section, the mathematical models for the low-resistance grounding system are derived. The analysis is carried out from the situation of steady state and transient state. Theoretical proof is given to demonstrate the conventional methods have a rather low discrimination and have difficulty to implement identification of high-resistance fault.

2.1 | Steady-state characteristics of SPG fault

The SPG fault characteristics are analysed in a typical low-resistance grounding system of 10 kV. The model of 10 kV distribution network with SPG fault is shown in Figure 1. In Figure 1, \( E_A, E_B, E_C \) represent the three-phase voltage of the network; \( C_1, C_2, ..., C_n \) represent the capacitances to ground corresponding to lines \( L_1, L_2, ..., L_n \); \( R_N \) represents the neutral grounding resistance. Suppose there is a phase A-to-ground fault in \( L_m \) and the fault resistance is \( R_f \).

When considering a zero-sequence network, Figure 1 can be simplified to Figure 2, which shows the zero-sequence...
FIGURE 1 The model of 10 kV distribution network with an SPG fault

FIGURE 2 The zero-sequence equivalent circuit of low-resistance system with SPG fault

The zero-sequence currents through the healthy lines $i_{01}$, $i_{02}$, ..., $i_{0n}$ equals to zero-sequence currents through capacitances to ground:

$$i_{0} = j\omega C_{0} \dot{u}_{0} = -j\omega C_{0} \dot{u}_{A} Z_{0} + 3R_{f}$$  \hspace{1cm} (4)

The zero-sequence current through faulty line $i_{0n}$ is the vector sum of all zero-sequence currents through healthy lines and the zero-sequence current through neutral line:

$$i_{0n} = i_{0}(j\omega C_{0} + \frac{1}{3R_{N}}) = -i_{0} \frac{Z_{0}(3j\omega R_{N} C_{01} + 1)}{3R_{N}(Z_{0} + 3R_{f})}$$  \hspace{1cm} (5)

where $C_{01}$ represents the sum of the capacitances of healthy lines.

It can be seen from formulas (2)–(5) that with the increase of the fault resistance, the zero-sequence bus voltage, the zero-sequence current through the fault point, the zero-sequence current through the faulty line and the healthy lines will decrease. According to formula (5), the zero-sequence current through faulty line changes with the fault resistance as shown in Figure 3. As can be seen from the diagram, the amplitude ratio of the zero-sequence currents can reach hundreds of times under different fault resistances. The single threshold protection cannot meet the needs of SPG fault protection under different fault resistances.

2.2 Transient characteristics of SPG fault

The transient process of an SPG fault can be regarded as a zero-state response under the excitation of the virtual source at the fault point, so the virtual source at the fault point can be
expressed as a function related to time, that is,

\[ u_f = U_m \sin(\omega t + \varphi), \]  

where \( U_m \) represents the amplitude of the fault phase voltage and \( \varphi \) represents the initial phase angle of the fault. According to Figure 2, the following relationship exists in the zero-sequence circuit of the low-resistance grounding system when an SPG fault occurs:

\[ u_f = u_0 + 3i_f R_f = u_0 + 3(\xi_n + iC_\Sigma)R_f \]

\[ = u_0 + 3\left( \frac{u_0}{3R_N} + C_\Sigma \frac{dn_0}{dt} \right) R_f, \]  

(Collating formula (7) yields the following first-order differential equation:

\[ u_f = \left( \frac{R_f}{R_N} + 1 \right) u_0 + R_f C_\Sigma \frac{dn_0}{dt}. \]  

Solving the differential equation yields the zero-sequence voltage of the bus:

\[ u_0 = \frac{-U_m}{3R_f C_\Sigma \sqrt{\delta^2 + \omega^2}} \sin (\varphi - \theta)e^{-\delta t} + \]

\[ \frac{U_m}{3R_f C_\Sigma \sqrt{\delta^2 + \omega^2}} \sin (\omega t + \varphi - \theta), \]

where \( \theta = \arctan \frac{3R_f R_N C_\Sigma \omega}{R_f + R_N} \) and \( \delta = \frac{R_f + R_N}{3R_f R_N C_\Sigma}. \)

The zero-sequence current through the faulty line is

\[ i_{0n} = i_f - i_{CN} = iC_\Sigma + \xi_n - i_{CT} \]

\[ = (C_\Sigma \frac{dn_0}{dt} + \frac{u_0}{3R_N}) - C_{0n} \frac{dn_0}{dt} \]

\[ = \frac{U_m}{9R_f R_N C_\Sigma \sqrt{\delta^2 + \omega^2}} \sin (\varphi - \theta)e^{-\delta t} \]

\[ + \frac{U_m \sqrt{1 + 9\omega^2 R_f^2 (C_\Sigma - C_n)^2}}{9R_f R_N C_\Sigma \sqrt{\delta^2 + \omega^2}} \sin(\omega t + \varphi - \theta + \lambda), \]

where \( \lambda = \arctan[3R_N \omega (C_\Sigma - C_n)]. \)

The zero-sequence currents through the healthy lines are:

\[ i_{0k} = C_{0k} \frac{dn_0}{dt} \]

\[ = \frac{U_m \delta C_{0k}}{3R_f C_\Sigma \sqrt{\delta^2 + \omega^2}} \sin (\varphi - \theta)e^{-\delta t} \]

\[ + \frac{U_m \omega C_{0k}}{3R_f C_\Sigma \sqrt{\delta^2 + \omega^2}} \cos(\omega t + \varphi - \theta). \]

And as the fault resistance increases, the steady-state component and the amplitude of the transient voltage and current will decrease.

The ratio of the characteristic signal amplitude of the faulty line to the maximum of the characteristic signal amplitudes of the healthy lines is defined as the discrimination \( D \) of the characteristic signal.

Since the value of the grounding resistance of the system is much smaller than the normal line capacitive reactance, the zero-sequence current through the faulty line is approximated to the zero-sequence current through the neutral line. So the discrimination of the power frequency zero-sequence current can be calculated as follows:

\[ D = \left| \frac{i_{0n}}{i_{00}} \right| \approx \left| \frac{i_{0n}}{i_{00}} \right| = \frac{1}{3 \omega R_N C_{00}}. \]  

Substituting line parameters, a result for reference is \( D \approx 31.2 \).

By analysing the steady-state and transient characteristics of SPG faults, it can be found that as the fault resistance increases, the amplitude of zero-sequence current, zero-sequence voltage and other common characteristic signals for line selection will be greatly reduced. Due to the low discrimination of the conventional frequency methods, it is difficult to distinguish the difference between the characteristic signals of faulty and healthy lines when the amplitudes of the values in both faulty and healthy lines are substantially reduced. In addition, conventional transformers cannot accurately measure the characteristic signals of faulty lines at milliampere or even microampere levels [23]. Therefore, as the fault resistance increases, the conventional frequency method gradually fails to identify the high-resistance faults.

3 | PRINCIPLE AND SIMULATION OF LINE SELECTION METHOD BASED ON EXTREMELY LOW FREQUENCY SIGNAL

In order to further improve the protection ability of high-resistance grounding faults, it is necessary to solve the problem of insufficient discrimination between the characteristic signals in the faulty line and the healthy lines in the case of high-resistance fault by proposing a more distinguishing characteristic signal that only exists in the faulty line. The extremely low frequency signal has such characteristic, so a novel SPG faulty line selection method can be proposed based on the extremely low frequency signal to solve the problem of difficulty in identifying high-resistance grounding faults.

3.1 | Line selection based on the SOELFS

3.1.1 | Principle of line selection based on the SOELFS

The zero-sequence current flowing through the faulty line can be expressed as the zero-sequence current itself multiplied by a
Simulation of line selection based on step function, namely:

\[
I_{0n}(t) = \frac{U_m}{9R_f R_n C_0 \sqrt{\delta^2 + \omega_0^2}} \left[ 3R_n \delta (C_0 - C_n) - 1 \right] \sin(\varphi - \theta) e^{-\delta t} n(t) + \frac{U_m}{9R_f R_n C_0 \sqrt{\delta^2 + \omega_0^2}} \sqrt{1 + 9\omega_0^2 R_n^2 (C_0 - C_n)^2} \right] \times \sin(\omega_0 t + \varphi - \theta + \lambda) n(t)
\]

\[= A_n e^{-\delta t} n(t) + B_n \sin(\omega_0 t + \varphi - \theta + \lambda) n(t),\]

where \(\omega_0\) represents the angular frequency of the fault phase voltage. For the convenience of analysis, the coefficients of the transient part and the steady-state part of the zero-sequence current function are recorded as \(A_n\) and \(B_n\), respectively. Record \(f_1(t) = e^{-\delta t} n(t)\) and \(f_2(t) = \sin(\omega_0 t + \varphi - \theta + \lambda) n(t)\).

The frequency domain function after Fourier transform is

\[I_{0n}(\omega) = A_n f_1(\omega) + B_n f_2(\omega)\]

\[= \frac{A_n}{\delta + j\omega} + B_n \left[ -\frac{e^{j(\varphi - \theta + \lambda)}}{2(\omega - \omega_0)} + \frac{\pi e^{j(\varphi - \theta + \lambda)} \delta(\omega - \omega_0)}{2j} \right] \]

\[+ \frac{e^{-j(\varphi - \theta + \lambda)}}{2(\omega + \omega_0)} - \frac{\pi e^{-j(\varphi - \theta + \lambda)} \delta(\omega + \omega_0)}{2j}.\]

In the extremely low frequency band, there is \(\omega \ll \omega_0\), thus the amplitude of the impulse function in the formula is approximately zero. The formula (14) can be simplified to formula (15):

\[I_{0n}(\omega) = \frac{A_n}{\delta + j\omega} + B_n \left[ -\frac{e^{j(\varphi - \theta + \lambda)}}{2(\omega - \omega_0)} + \frac{\pi e^{j(\varphi - \theta + \lambda)} \delta(\omega - \omega_0)}{2j} \right] \]

\[+ \frac{e^{-j(\varphi - \theta + \lambda)}}{2(\omega + \omega_0)} - \frac{\pi e^{-j(\varphi - \theta + \lambda)} \delta(\omega + \omega_0)}{2j} \]

\[= \frac{A_n}{\delta + j\omega} - B_n \frac{j\omega \sin(\varphi - \theta + \lambda) + \omega_0 \cos(\varphi - \theta + \lambda)}{\omega^2 - \omega_0^2}.\]

Taking \(\omega_0 = 100\pi\) and \(\omega = 2\pi\). Based on MATLAB, a diagram of the amplitude of the zero-sequence current extremely low frequency signal \(I_{0n}(\omega)\) change with the initial phase angle \(\varphi\) is shown in Figure 4. It can be seen from Figure 4 that when \(\varphi = 0^\circ\) or \(\varphi = 180^\circ\), the amplitude of extremely low frequency signal takes the maximum value. When \(\varphi = 90^\circ\), the amplitude of the extremely low frequency signal takes the minimum value, and the minimum value is not zero. That is, the zero-sequence current extremely low frequency signal exists in the faulty line at any initial phase angle. Similarly, it can also be proved that extremely low frequency signals exist in healthy lines at any initial phase angle.

According to the analysis, after the grounding fault occurs, both the faulty line and the healthy lines have the SOELFS to pass through. The capacitance to ground has an extremely strong attenuation effect on extremely low frequency signal. The extremely low frequency signal can circulate from the capacitance to ground in the faulty line, and also from the grounding point, but can only flow through the capacitance to ground in the healthy lines. Therefore, the zero-sequence current extremely low frequency signal almost only exists in the faulty line; the amplitude of the extremely low frequency signal is much larger than that of the healthy lines. In addition, as long as there is no grounding path other than the grounding capacitance in the healthy line, no matter the line length or the network topology change, it will not affect the line selection through SOELFS. So the SOELFS can be used as the basis for identifying the faulty line.

3.1.2 Simulation of line selection based on the SOELFS

A typical low-resistance grounding system simulation model is built in PSCAD as shown in Figure 5. The zero-sequence and positive-sequence distributed parameters of the cable lines were given as \(R_L = 0.06 \Omega/km\), \(L_{L1} = 0.05 \Omega/km\),
The extremely low frequency zero-sequence current waveforms of each line

\[ X_{C1} = 6740 \, \text{M\Omega/km}, \quad R_0 = 2.7 \, \Omega/km, \quad X_L = 0.32 \, \Omega/km, \quad X_{C0} = 6740 \, \Omega/km \text{ and } R_N = 6 \, \Omega. \]

An SPG fault with a fault resistance of 10 k\( \Omega \) is set at the end of line 4, and the initial phase angle of the fault is set to 0\(^\circ\). The PSCAD simulation data is subjected to extremely low frequency filter processing through MATLAB, and the extremely low frequency zero-sequence current waveforms of each line are obtained as shown in Figure 6. An SPG fault occurred at 1 s after the simulation running, and the transient process of the zero-sequence current of each line lasted about 0.3 s, and there were obvious transient extremely low frequency components. The amplitude of the extremely low frequency component in the faulty line 4 is significantly higher than that of the other three healthy lines, and the discrimination of the extremely low frequency component is \( D_{LF} = 854.9 \), where the discrimination of the power frequency zero-sequence current is \( D_{PF} = 31.1 \) under the same condition.

The peak values of the zero-sequence current transient extremely low frequency zero-sequence currents of each line are expressed as \( \lambda_1, \lambda_2, \lambda_3, \lambda_4 \). Simulations are operated at different fault locations, initial phase angles and fault resistance values and the characteristic values of each line under different fault conditions are shown in Table 1.

It can be seen that the characteristic values of the faulty line are significantly larger than the healthy line in all cases, and have a high discrimination. The extremely low frequency signal method can correctly identify the faulty line under the cases of different fault locations, different initial phase angles and different fault resistances. However, the amplitude of the characteristic signal is related to the initial phase angle, and the transient process often does not last long. The peak duration of the transient extremely low frequency signal is even shorter, which has higher requirements for the sampling rate of the measurement device. In extreme cases, there is possibility that the extremely low frequency signal cannot be monitored.

3.2 Line selection based on the AIELFS

The SOELFS has the advantages of reaching peak quickly and large amplitude, and the simulation results verify the effectiveness of using it as an SPG fault characteristic signal. However, the amplitude of the SOELFS is greatly affected by the initial phase of the fault. For example, the two sets of data of line 3 in Table 1, the amplitudes at different phase angles are 1.103 and 16.003 mA. This will cause the SOELFS’ amplitude to be very low in extreme cases, making the line selection method based on SOELFS not totally stable. Besides, the transient process often does not last long, and the duration near the peak of the transient extremely low frequency signal is shorter, which has a high requirement for sampling rate of the measuring device. In order to make up for the above disadvantages of the SOELFS, the injection source can artificially inject continuous and stable extremely low frequency components into the system, and use it as a supplementary basis for identifying the faulty line.

3.2.1 Principle of line selection based on the AIELFS

The principle of passive injection device is shown in Figure 7. In the figure, \( r \) represents the internal resistance of the device, and D1–D6 are diodes.

When in use, connect the passive injection device to the neutral line of the system and connect it in series with the

![Figure 6: The extremely low frequency zero-sequence current waveforms of each line.](image)

### TABLE 1 Simulation result of line selection based on SOELFS

| Faulty line | Fault location (km) | Initial phase angle (°) | Fault resistance (Ω) | Characteristic value \( \lambda_1, \lambda_2, \lambda_3, \lambda_4 \) (mA) | Discrimination \( D \) |
|-------------|---------------------|-------------------------|----------------------|------------------------------------------|---------------------|
| Line1       | 2                   | 90                      | 1K                   | \( \{10.635, 0.010, 0.018, 0.015\} \)   | 591.1               |
|             |                     |                         | 4K                   | \( \{40.198, 0.027, 0.047, 0.039\} \)  | 853.3               |
| Line2       | 3                   | 45                      | 2K                   | \( \{0.025, 54.182, 0.096, 0.079\} \)  | 562.0               |
|             | 7                   | 0                       | 10K                  | \( \{0.006, 16.005, 0.019, 0.015\} \)  | 855.2               |
| Line3       | 12                  | 90                      | 10K                  | \( \{0.001, 0.0013, 1.103, 0.002\} \) | 620.3               |
|             | 12                  | 0                       | 10K                  | \( \{0.006, 0.011, 16.003, 0.015\} \) | 1025.8              |
| Line4       | 6                   | 45                      | 4K                   | \( \{0.010, 0.019, 0.034, 27.121\} \) | 789.8               |
|             | 10                  | 0                       | 10K                  | \( \{0.006, 0.011, 0.019, 16.004\} \) | 854.9               |

The bold values refer to the maximum value in the same set of data, that is, the lines corresponding to the bold value is the faulty lines.
grounding resistance of the system. When the system is operating normally, the three-phase system is balanced, and the current flowing through the neutral line is basically zero. The diodes of the passive injection device are not conductive because the voltage across them is lower than the threshold voltage, so the system is still running in the low-resistance grounding method. When an SPG fault occurs, due to a large fault current flowing through the neutral line, the parallel opposite diodes are turned on in the positive half cycles and the negative half cycles, respectively. Because the number of forward and reverse diodes is inconsistent, the larger the number of diodes is, the higher the threshold voltage is required. After the diode is turned on, the voltages across the passive injection device in the positive and negative half cycles are inconsistent, so that the positive and negative half-cycle amplitudes of the zero-sequence current in the system are different, and an equivalent steady-state component whose frequency is close to 0 Hz is generated, thereby achieving extremely low frequency line selection.

It is easy to know from formula (12) that the discrimination of zero-sequence current increases with decreasing frequency. Considering the influence of the injection device on the amplitude of the extremely low frequency signal of the faulty line, the discrimination of the extremely low frequency signal will be higher than the power frequency zero-sequence current. Because the AIELFS has stable amplitude during the period of an SPG fault and the extremely low frequency signal has a long duration, it is easier to be monitored.

3.2.2 Simulation of line selection based on the AIELFS

Based on the simulation model shown in Figure 5, a passive injection device is connected in series in the neutral line, as shown in Figure 8. The internal resistance of the passive injection device is set to 6 Ω, the single diode threshold voltage is 0.75 V and the other parameters remain unchanged.

An SPG fault with a fault resistance of 10 kΩ is set at the end of line 4, and the initial phase angle of the fault is set to 0°. The DC values of zero-sequence currents of each line are observed as characteristic signal. The amplitude of the steady-state extremely low frequency component in faulty line 4 is significantly higher than that of the other three healthy lines. Stable data in the 8–9 s after the fault is taken to calculate the discrimination, and the result is \( D_{LF} = 637.7 \), where the discrimination of the power frequency zero-sequence current is \( D_{PF} = 31.1 \) under the same condition.

The PSCAD simulation data is processed by MATLAB for extremely low frequency filtering to verify that the passive injection device does not affect the line selection of the SOELFS method, and the values of zero-sequence current steady-state extremely low frequency signal of each line under different conditions are shown in Table 2.

It can be seen that the characteristic values of the faulty line are significantly larger than the healthy line in all cases, and have a high discrimination. The extremely low frequency signal method can correctly identify the faulty line under the cases of different fault locations, different initial phase angles and different fault resistances.

In order to test the impact of changing the network topology on the proposed method, an SPG fault in new network topology is simulated. The simulation model of new topology is shown in Figure 9. An SPG fault with a fault resistance of 10 kΩ is set at the end of line 4 branch 1, and the initial phase angle of the fault is set to 0°. The characteristic values of each line are \( 3.460 \times 10^{-5}, 7.449 \times 10^{-5}, 9.942 \times 10^{-5}, 0.028 \text{ mA} \). The amplitude of characteristic signal in faulty line is significantly greater than those in healthy lines, which proves that the proposed method is not affected by network topology changes.

3.3 The influence of noise interference

Noise interference mainly has two aspects: the noise in the system and the noise introduced by the measuring device.

Part of the noise in the system comes from the unstable current through the lines. It may include components of various frequencies, but it will hardly affect the measurement of zero-sequence current. For example, suppose there is a DC current in
### TABLE 2
Simulation result of line selection based on AIELFS

| Faulty line | Fault location (km) | Initial phase angle (°) | Fault resistance (Ω) | Characteristic value $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ (mA) | Discrimination $D$ |
|-------------|---------------------|-------------------------|----------------------|-------------------------------------------------|------------------|
| Line1       | 2                   | 90                      | 1K                   | (0.494, 2.370 × 10^{-4}, 3.905 × 10^{-4}, 3.369 × 10^{-5}) | 1264.1           |
|             | 4                   | 0                       | 4K                   | (0.034, 3.248 × 10^{-3}, 5.627 × 10^{-3}, 4.655 × 10^{-6}) | 610.1            |
| Line2       | 3                   | 45                      | 2K                   | (2.051 × 10^{-3}, 0.236, 7.445 × 10^{-3}, 6.017 × 10^{-5}) | 3173.1           |
|             | 7                   | 0                       | 10K                  | (1.838 × 10^{-3}, 0.034, 5.626 × 10^{-3}, 4.655 × 10^{-5}) | 610.6            |
| Line4       | 6                   | 45                      | 4K                   | (7.572 × 10^{-5}, 1.180 × 10^{-5}, 1.893 × 10^{-5}, 0.110) | 582.3            |
|             | 10                  | 0                       | 10K                  | (1.753 × 10^{-5}, 3.115 × 10^{-5}, 5.390 × 10^{-5}, 0.034) | 637.7            |

The bold values refer to the maximum value in the same set of data, that is, the lines corresponding to the bold value is the faulty line.

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**FIGURE 9** The simulation model of new network topology

Phase A. When the system is running normally, the DC current will flow through the measurement point in the opposite direction in phase B and C, so it does not affect the zero-sequence current measurement.

Another part of the noise in the system comes from fluctuation of zero-sequence voltage. Low-frequency components may be generated when the zero-sequence voltage suddenly changes. But in the measured frequency band below 0.1 Hz, the capacitive reactance of the cable line can reach more than 842 kΩ. Therefore, the amplitude of the leakage zero-sequence current generated by fluctuation of the zero-sequence voltage is extremely low, which has little effect on the proposed method. A zero-sequence voltage fluctuation of 2 kV in the healthy network is simulated, and it is obvious that the assumed zero-sequence voltage fluctuation is greater than the actual situation. And the topology of the network is same as Figure 8. The simulation result is shown in Figure 10.

It can be seen that the noise amplitude is less than 3.4 μA, which is smaller than the characteristic value of the faulty line when an SPG fault occurs. Compared with the characteristic value of the faulty line when a 10-kΩ SPG fault occurs, the noise is about 1/10 of the characteristic value, so it does not affect the proposed method. In the same situation, Figure 11 shows that the power frequency noise amplitude reaches 5 A, which has even exceeded the power frequency zero-sequence current...
of the faulty line shown in Figure 13. Thus, the extremely low frequency method is more resistant to the interference of unbalanced voltage. In summary, the noise in the system will not cause the proposed method to fail in line selection.

As for the noise introduced by the measuring device, a particular magnetic modulator is used, which specifically measures signals below 0.1 Hz. The magnetic modulator uses an external annular shielding layer to greatly weaken the interference of stray magnetic fields and uses an internal differential structure to increase measurement sensitivity. Besides, a digital vector demodulation algorithm is adopted to weaken zero drift, excitation source fluctuation and interference introduced by spatial noise. Therefore, the magnetic modulator has good anti-noise performance and high measurement accuracy, greatly reduce the noise introduced by the measuring device.

### 3.4 The influence of distributed generation (DG) sources

In recent years, it has become a common phenomenon for DG sources to be connected to the distribution network. However, the connection of DG sources has brought huge challenges to the protection of distribution networks [24]. The DG sources can be divided into two types: inverter-based type and rotary type.

For inverter-based DGs, they will not introduce new zero-sequence grounding point, so they will not affect the proposed method. For rotary DGs, whether there is a new grounding point depends on the grounding type of the grid-connected transformer. In practice, transformers are generally not grounding when DGs are connected to the network. This is because the non-grounding of the grid-connected transformers does not affect the low-resistance grounding system to quickly remove the SPG fault, and it can also prevent the system from multipoint grounding to produce harmonic circulation or unbalanced current circulation [25, 26]. Therefore, in most cases, DGs do not affect the proposed method. The influence of DG sources connected by non-grounded transformer is simulated. The simulation model of network connected with a DG source is shown in Figure 12. SPG fault with a fault resistance of 10 kΩ is set at the end of line 3, and the initial phase angle of the fault is set to 0°. A DG is connected to the distribution network through an Y0/Δ transformer. The characteristic values of each line are 7.900 \( \times 10^{-6} \), 1.365 \( \times 10^{-5} \), 0.020, 1.936 \( \times 10^{-5} \) mA. The result shows that if grid-connected transformer is non-grounded, the DG connected to the network does not affect the proposed method.

In addition, there are indeed a few grid-connected transformers grounded in order to provide a reliable grounding point for the DG during island operation. Most unplanned island operations need to be prevented by removing DGs through anti-island protection. For those rare planned island operation cases, the proposed method will fail to select the faulty line when the healthy lines are connected with DGs. Thus, a special criterion can be designed to determine whether a DG is connected to the outline of substation. This is also one of our possible future research directions.

### 3.5 Comparison with existing methods

In the low-resistance grounding system, the line selection methods can be divided into mainly two types: the amplitude methods represented by overcurrent protection and the phase methods represented by power protection.

For overcurrent protection, the threshold value of conventional overcurrent protection is generally set to 50–60 A [11]. In case of 10 kΩ fault resistance, the zero-sequence current in simulation is shown in Figure 13. Obviously, the peak values of zero-sequence current of each line are much lower than the threshold value of overcurrent protection. Therefore, the traditional overcurrent protection will fail to select the faulty line. Similarly, the adaptive overcurrent protection proposed in reference [10] also cannot achieve 10 kΩ high-resistance grounding.
fault protection because the minimum of the threshold value is 3 A.

For power protection, since it uses the zero-sequence current phase of each line for line selection, its threshold can be set to be slightly higher than the normal imbalanced current. However, the polarity of the transformers will directly affect the line selection result, and the judgement of the polarity of the transformers is a troublesome task. Besides, in case of 10 kΩ high-resistance grounding fault, the standard IEC60044-8 shows that the error of transformer will increase significantly due to the low amplitude of the current. The phase error may cause the power vector to fall into the protection dead zone, resulting in failure of line selection.

Compared with existing methods, the proposed method has the following advantages.

When an SPG fault with 10 kΩ fault resistance occurs, the discrimination of AIELFS is \(D_{f,i} = 637.7\), which is shown in Table 2. Compared to the discrimination of the power frequency zero-sequence current \(D_{pf} = 31.1\), the discrimination of AIELFS is significantly higher. This means that the difference between the faulty line and the healthy lines is more obvious in the extremely low frequency perspective than in the power frequency perspective.

From the comparison between Table 2 and Figure 10, it can be seen that the extremely low frequency noise is about 1/10 of the characteristic value in case of 10 kΩ fault resistance. But in the same situation, the power frequency noise reaches 5 A in Figure 11, which exceeds the power frequency zero-sequence fault current in Figure 13. This shows that in case of high-resistance grounding faults, the power frequency noise may be of the same magnitude as the power frequency zero-sequence fault current, or even higher than it. And this is why the method proposed in [10] has to set a threshold value of 3 A to avoid normal imbalanced current. In conclusion, the AIELFS has a higher signal-noise ratio than the power frequency signal. Thus the method based on AIELFS can break through the limit of the power frequency imbalanced current, thereby identifying high-resistance grounding faults that cannot be protected by the conventional frequency methods due to noise interference.

### 3.6 Chapter summary

Through principle analysis and simulation verification, the line selection methods based on SOELFS and AIELFS can identify the faulty line under the cases of different fault locations, different initial phase angles and different fault resistances. In conventional frequency methods, both the faulty line and the healthy line contain anomalous components, and the differences in component amplitudes are used for line selection. In the extremely low frequency case, the extremely low frequency signal hardly exists in the healthy line, and only passes through the faulty line. Therefore, the extremely low frequency signal has larger discrimination, so the maximum protection ability of the fault resistance is much higher than other methods, and it can reach 10 kΩ in simulation verification. Of the two proposed line selection methods based on extremely low frequency signals, the method based on SOELFS uses transient characteristic for line selection, which has a higher amplitude and faster selecting speed, but there are also problems of momentary transient process and uncontrollable amplitude affected by initial phase angle; the method based on AIELFS injects a stable extremely low frequency component into the system, and uses the steady-state characteristic of SPG fault to select the faulty line, which has lower amplitude than transient signal but has advantage of stability. According to the process of extremely low frequency signal, at the transient process of the SPG fault, the line selection based on SOELFS operates first. If the SPG fault cannot be identified, when the transient process ends and turns to the steady-state process, identify the faulty line through the method based on AIELFS. The proposed methods give full play to their respective advantages and make up for the disadvantages, have both sensitivity, reliability and rapidity, and finally achieve fast and reliable line selection.

### 4 EXPERIMENTAL TESTS

In order to further verify the feasibility of the extremely low frequency line selection methods, the experimental verification was carried out on the basis of the realistic experimental system of the low and medium voltage distribution network. The system uses real 10 kV distribution switchgear, equipped with Peterson coils and low-resistance grounding devices. The system can simulate various SPG faults, interphase short-circuit faults and wire break faults. The diagram of the experimental model connection is shown in Figure 14. The measuring coil is installed at the beginning of the line, connected to the signal acquisition box through cables, and then connected to the analysis and processing terminal, and the measured data and waveforms are displayed through the software.

The measuring device used in the tests is a fully digitized magnetic modulator, which is characterized in that it does not
measure the power frequency signal, only the extremely low frequency signal below 0.1 Hz. The magnetic modulator converts the analogue signals of voltage at the excitation port and the output port into digital signals and performs Fourier analysis to obtain the initial phase and amplitude, and then the second harmonic voltage is zero by vector method and proportional coefficient calibrated to obtain extremely low frequency value in real time. In the measurement process, according to the fluctuation of the excitation source frequency and amplitude, the proportional coefficient is corrected in real time to eliminate the influence of the power supply fluctuation. The measurement range of the magnetic modulator is 5–1000 μA; the precision can reach 0.5%; the linear error is better than $2 \times 10^{-4}$ [27]. It can effectively suppress the measurement error caused by the change of the excitation source frequency and amplitude or other factors, and can accurately and stably measure microampere level extremely low frequency current.

### 4.1 Tests of line selection based on the SOELFS

In order to eliminate randomness, faults with different parameters were set and 20 tests were conducted. The specific parameters are shown in Table 3.

According to the measured data, the faulty line can be clearly distinguished from the healthy lines. Taking the data with number 3 as an example, the characteristic signal of the healthy lines is almost 0, and the faulty line 4 has an extremely low frequency signal with a peak value of 16.036 mA, which is significantly higher than other lines. The characteristic values of each line of all the tests are shown in Table 4. By comparing the characteristic values, it is inferred that the line with the largest characteristic value is the faulty line. Obviously, the identification of the 17 faulty lines is correct.

### 4.2 Tests of line selection based on the AIELFS

The specific parameters of tests of line selection based on the AIELFS are shown in Table 5.

The DC value of the characteristic signal when it reached the steady state is selected as the characteristic value. For the above six cases, the measured characteristic values are shown in Table 6.
TABLE 6 Results of tests of line selection based on AIELFS

| No. | Characteristic value of | Identification result |
|-----|------------------------|-----------------------|
|     | Line4 (mA)  | Line3 (mA)  | Line2 (mA)  |                     |
| 1   | 1426.487     | 0.020        | 0           | Line4, Correct      |
| 2   | 3.963        | 0            | 0           | Line4, Correct      |
| 3   | 1.505        | 0            | 0           | Line4, Correct      |
| 4   | 0.720        | 0            | 0           | Line4, Correct      |
| 5   | 0.333        | 0            | 0           | Line4, Correct      |
| 6   | 0.104        | 0            | 0           | Line4, Correct      |

The results of experimental tests show that the line selection method based on extremely low frequency signal proposed in this paper can correctly identify the faulty line under different fault locations, different fault angles and different fault resistances. The accuracy rate of the methods is 100%, and the methods can protect high-resistance grounding fault of 10 kΩ fault resistance, with good selectivity and reliability.

5 | CONCLUSION

This paper proposes the line selection method based on the SOELFS to improve the protection ability in case of high-resistance fault. And the line selection method based on the AIELFS is additionally proposed to deal with the uncertainty in the amplitude of SOELFS. Compared with other fault characteristic signals, extremely low frequency signal has larger discrimination between the faulty line and healthy lines and has a stronger ability to resist imbalanced current noise. Cooperating with the extremely low frequency measurement equipment, the method proposed solves the high-resistance fault identification problem and is not affected by line length, network topology and noise interference. According to the process of extremely low frequency signal, the proposed method achieves sensitive and reliable SPG fault line selection, leading to significant improvement in protection ability of high-resistance faults. Through simulations and tests, both extremely low frequency line selection methods can achieve SPG fault protection in case of 10 kΩ fault resistance, which proves the effectiveness of the methods which have great practical application potential. However, in terms of practical application, the method may require further research, such as the impact of distributed generators’ connection to the distribution network.

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