Single-Phase Grounding Fault Identification Based on Transition Conductance Tracking Method

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The instability of single-phase grounding faults makes it difficult to track the fault development process accurately. In this paper, a transition conductance tracking method for single-phase grounding fault identification is established to perceive the health state of the distribution network. To solve the situation that the insulation parameters of the neutral ungrounded system are difficult to obtain, a phase-shift method is proposed to measure the insulation parameters accurately. Based on the measurement results of insulation parameters, a transition conductance tracking model is constructed to monitor the changes of transition conductance in real time. Since the transition conductance varies steadily, it can be used as an important parameter to evaluate the development of a single-phase grounding fault. The innovative tracking method is verified by the simulation model, and the error analysis shows that the tracking error of transition conductance is less than 9%. The simulation results demonstrate that the proposed method can track the development of grounding faults effectively and give a quick warning to the operator. The fault identification theory adopted in this paper is not limited by the neutral grounding mode and especially can be applied to situations where the neutral point parameters are not adjusted.

1. Introduction

The single-phase grounding faults (SPGFs) in the medium voltage distribution network account for more than 75% of the total faults. In addition, all other faults are mostly developed from single-phase grounding faults [1, 2]. More seriously, with the increasing proportion of renewable energy access, SPGFs must be removed quickly and accurately to prevent large-scale off-grid of renewable energy units [3, 4]. As the most typical fault category in a power system, SPGFs are generally accompanied by fault resistance at the fault grounding point. Among these, the fault characteristics of SPGFs through a low transition conductance in the distribution network are not obvious [5–7]. In addition, these faults become more difficult to identify due to the asymmetric parameters of the distribution network [8].

Accurate measurement of the insulation parameters of the static distribution network is a prerequisite for sensing the health state of the power network [9, 10]. The measurement of insulation parameters in the power grid can be divided into different categories according to different neutral grounding modes [11, 12]. The state equation of insulation parameters can be established by adjusting the value of inductance for the system whose neutral point is grounded via the arc suppression coil [13]. To better suppress the capacitive current in the system, a grounding method of arc suppression coil in parallel with a reactor was adopted [14]. In this case, the authors in [15] measured the voltage displacement of the neutral point by changing the value of additional inductance and resistance. The distributed capacitance of the system was calculated according to the measured voltage displacement. The application of the methods above was based on the premise that the parameters of the neutral point can be adjusted. Therefore, these methods can no longer be applied to neutral ungrounded systems.

A few improvements were proposed according to the deficiency of the injection current method. Reference [16] proposed a method that injected current signals into the
secondary side of the reactor. By collecting the returned voltage signal, the insulation parameters could be obtained easily. A single frequency measurement method was proposed in [17], but the neglect of excitation impedance would lead to the deviation of the calculation results. In reference [18], the insulation parameters were measured by the relationship between the injection current and the return voltage between the two voltage transformers. In reference [19], the injection method was improved to reduce the influence of leakage impedance of voltage transformers. The main advantage of the injection current method is that it avoids direct contact with the primary side and improves safety. However, the measurement accuracy of the injection current method is mainly affected by the frequency of the injection signal. Meanwhile, the transformer parameters need to be collected in the application of the injection current method. Therefore, the measurement accuracy of transformer parameters will ultimately affect the measurement accuracy of insulation parameters.

Furthermore, in the existing research on insulation parameter measurement of distribution networks, most scholars default the line parameters as symmetric [20–22]. Research on fault detection requires a rigorous and meticulous approach. Ignoring asymmetric parameters will inevitably interfere with fault identification. Therefore, it is urgent to develop an advanced measurement method of insulation parameters that can meet the operation requirements of the distribution network.

When a permanent SPGF occurs, the system can remain in operation for one to two hours according to the rules. Power electronic devices in renewable energy systems have a weak ability to withstand short-circuit currents. Thus, the grounding resistances and the grounding currents of the SPGFs would be changed greatly [23, 24]. In this way, to avoid the further development of the accident into a multiphase short circuit and expand the scope of the accident, it is of great significance to track the dynamic development of the distribution network grounding fault [25, 26]. Most SPGFs in medium voltage distribution networks are non-metallic, which are usually accompanied by transition resistance (conductance) [27]. Authors in [28, 29] assumed that the transition resistance remained unchanged in the process of fault development and analyzed the interference of transition resistance on fault line selection qualitatively. A method of calculating the transition resistance by measuring the phase voltage and phase current changes before and after the fault was proposed in [25]. However, this method needs to detect the fault phase and fault line in advance and is greatly affected by system asymmetry. At present, zero-sequence voltage and zero-sequence current are the most widely used characteristics to determine whether an SPGF occurs [30]. Therefore, the transition resistance parameters can be obtained indirectly by measuring the zero-sequence parameters. Based on the measured zero-sequence parameters and fault phase voltage, the calculation method of transition resistance was deduced in [31]. Reference [32] accurately calculated the transition resistance based on the network damping rate and network insulation parameters measured before and after the fault. The existing researches focus mainly on the calculation method of transition resistance and fault determination, and there are few in-depth studies on the development tracking and identification technology of SPGFs.

SPGFs account for more than 75% of all power system faults, and most other types of faults are also developed from SPGFs. In this paper, we focus on the development tracking technology of SPGFs in the medium-voltage distribution network, and the main contribution of this paper lies in the following three aspects:

(i) A phase-shift method is constructed to measure the insulation parameters of the system during normal operation
(ii) An analytical model of transition conductance is established based on the measurement results of insulation parameters in the distribution network
(iii) By tracking the change of transition conductance in real-time, the development of grounding fault is evaluated indirectly, which provides a basis for grounding fault protection and disposal

The rest of this paper is organized as follows: Section 2 introduces the measurement method of line insulation parameters based on the phase-shift method when the system operates normally. Section 3 derives the calculation theory of transition conductance at length. Section 4 verifies the transition conductance tracking method and identifies the development of SPGFs effectively. Section 5 presents the result analysis. Finally, Section 6 concludes the whole paper.

2. Line Insulation Parameter Tracking and Measurement

Insulation parameters of the medium voltage distribution network include capacitance and conductance to the ground. When the system is running normally, the insulation parameters are updated dynamically at a certain period. Most 6–10 kV and some 35 kV medium voltage power grids adopted neutral point ungrounded operation mode.

The distribution network is usually radiant. As shown in Figure 1, the 10 kV bus is led from the upper high voltage power supply through the transformer. Several medium voltage distribution lines are led out from the public bus and
then step down to 400 V by the transformers. The research of this paper covers the line between two sets of transformers since zero-sequence parameters cannot span the transformers. Insulation parameters are inherent characteristics of the transmission lines. In this way, distribution lines can be equivalent to a model consisting of a power source and transmission line.

2.1. Partially Installing Capacitance Method. Since the neutral parameters of the ungrounded system are unadjustable, the conventional methods cannot be applied in this case. Therefore, a partially installing capacitance method can be adopted, which is mainly suitable for the low asymmetric ungrounded system. The disturbance state of the system is measured by cutting on and off the external capacitor in phase A, and the insulation parameters can be obtained by solving the state equation.

As shown in Figure 2, the equivalent circuit diagram for the normal operation of an ungrounded neutral system is established. \(C_A\), \(C_B\) and \(C_C\) are the distributed phases-to-ground capacitance; \(G_A\), \(G_B\) and \(G_C\) are the distributed phase-to-ground conductance. \(E_A\), \(E_B\) and \(E_C\) are three-phase power supply voltages; Switch \(K\) controls the switching of the external capacitor \(C_{ad}\). When the switch \(K\) is closed and the external capacitor is connected to the system, the KCL equation is formulated supposing phase A as the reference phase, and the neutral voltage \(U_0\) is described as follows:

\[
    U_0 = \frac{-E_A k_U - E_A j\omega C_{ad}}{j\omega (C_A + C_{ad}) + G_C} \tag{1}
\]

\[
    k_U = (j\omega C_A + G_A) + \alpha^2 (j\omega C_B + G_B) + \alpha (j\omega C_C + G_C) \tag{2}
\]

All formula descriptions in this paper take phase A as the reference phase, and all symbols are unified in the whole paper. In the expressions above, \(E_A\) is the electromotive force of the phase A power supply. \(E_A\) is the phase voltage of the power supply to which the external element is connected. \(k_U\) is the vector sum of the grid asymmetric parameters and \(\alpha = e^{120^\circ}\). \(C_x = C_A + C_B + C_C\) is the distributed capacitance of the system, and \(G_x = G_A + G_B + G_C\) is the distributed conductance of the system. \(j\) is the imaginary unit.

The partially installing capacitance method is generally used in neutral ungrounded systems. The measurement process assumes the strict symmetry of the line parameters and neglects the line-to-ground conductance, that is, \(C_A = C_B = C_C\). \(E_A = E_B = E_C = 0\) in (1). In this case, the neutral voltage after the external capacitor \(C_{ad}\) is connected to phase A is

\[
    U_0 = \frac{E_A C_{ad}}{C_x + C_{ad}} \tag{3}
\]

\[
    U_0 = U_A - E_A \tag{4}
\]

where \(U_A\) is the A-phase voltage after installing an external capacitor \(C_{ad}\). Substitute expression (4) into equation (3), and the calculation of total grid capacitance is as follows:

\[
    C_x = \frac{U_A C_{ad}}{E_A - U_A} \tag{5}
\]

According to expression (5), the capacitance of the line to earth can be obtained indirectly by tracking the A-phase voltage in real time.

2.2. Shortcomings of Partially Installing Capacitance Method. In practical engineering applications, the asymmetry of the overhead line is usually between 0.5% and 2.5%, while the asymmetry of the cable is much smaller than that of the overhead line, and the theoretical limit of power grid asymmetry is 3.5%. When considering the asymmetry of grid line parameters and the insulation conductance, that is, \(C_A\), \(C_B\) and \(C_C\) are not all equal and \(G_A\), \(G_B\) and \(G_C\) are not all equal to zero in (2), then the voltage at the neutral point after installing the external capacitor \(C_{ad}\) is

\[
    U_0 = \frac{-E_A k_U - E_A j\omega C_{ad}}{j\omega (C_x + C_{ad}) + G_C} \tag{6}
\]

After arranging the formula above, the expression of the total capacitance of the grid line to the ground can be written as follows:

\[
    C_x = \frac{U_A C_{ad}}{E_A - U_A} + j \left( G_C \frac{E_A k_U}{\omega} - \frac{E_A k_U}{\omega (E_A - U_A)} \right) \tag{7}
\]

When the asymmetry and insulation conductance of the line are ignored, \(G_C = 0\) and \(k_U = 0\), then (7) is same as (5). According to (7), it can be known that the measurement accuracy of the partially installing capacitance method is affected by the insulation conductance \(G_C\) and the vector sum of the grid asymmetric parameters \(k_U\). The theoretical error of the partially installing capacitance method will increase with the increase of power network asymmetry or damping rate.

In addition, the external capacitor used in the partially installing capacitance method has a large impact at the moment of grounding, and the energy release of the capacitor is sluggish after the measurement. Meanwhile, the capacitance reactance in high harmonic is very small, and the harmonic leakage current is large, which affects the measurement accuracy and operation safety.
In this way, it is necessary to develop a capacitance measurement method that can eliminate the influence of line insulation resistance, network asymmetry, and an improved method for the selection of external elements.

2.3. Measurement of Insulation Parameters Based on Phase-Shift Method. The asymmetric three-phase parameter is a common state in the distribution network. For some lines with high asymmetry, the calculation accuracy of insulation parameters will be greatly reduced if the influence of asymmetry is ignored directly. A phase-shift method is proposed to measure the insulation parameters accurately by improving the partially installing capacitance method. The asymmetric can be dealt with theoretically by switching the external element between two different phases. Figure 3 is an equivalent circuit diagram of the phase-shift method.

Switch \( K_1 \) and switch \( K_2 \) control the connection of external elements, which can be resistance-inductance or resistance-capacitance elements. The equivalent admittance of the external element is set to be \( G_M + jB_M \). The closed switch \( K_0 \) represents the neutral point grounded through a conductance \( G_0 \); the disconnection of switch \( K_0 \) represents the neutral point is ungrounded.

The key point of the phase-shift method measuring insulation parameters is to cut on/off the same external element on any two phases of the power line. In this paper, phase A and phase B are taken as examples to derive the formula. Taking phase A as the reference phase, the method is introduced by first connecting the external element to phase A and then connecting it to phase B. The recovery time of the circuit breaker is usually 10 cycles (0.2 s). With a certain margin, the switching interval of the two offset elements is set to 15 cycles (0.3 s).

As shown in Figure 3, when the switch \( K_1 \) is closed, the external element \( G_M + jB_M \) is connected to the phase and the neutral voltage can be expressed according to the KCL equation as follows:

\[
\dot{U}_{0A} = \frac{-\dot{E}_A k_U - \dot{E}_A (G_M + jB_M)}{j(\omega C_2 + B_M) + G_2 + G_M + G_0} \tag{8}
\]

The physical meaning of each symbol in the above formula is the same as that in \( (6) \).

Similarly, when switch \( K_2 \) is closed, the external element \( G_M + jB_M \) is connected to phase B and the neutral voltage is

\[
\dot{U}_{0B} = \frac{-\dot{E}_A k_U - \dot{E}_B (G_M + jB_M)}{j(\omega C_2 + B_M) + G_2 + G_M + G_0} \tag{9}
\]

Subtracting \( (7) \) from \( (6) \) helps eliminate the vector sum of the asymmetric grid parameters, that is, eliminating the influence of the system’s natural asymmetry on the measurement result.

\[
\dot{U}_{0A} - \dot{U}_{0B} = \frac{-\dot{E}_{AB} (G_M + jB_M)}{j(\omega C_2 + B_M) + G_2 + G_M + G_0} \tag{10}
\]

It is not hard to go from equation \( (10) \) to equation \( (11) \) by a parameter transformation.

\[
j(\omega C_2 + B_M) + G_2 + G_M + G_0 = \frac{\dot{E}_{AB} (G_M + jB_M)}{U_{0A} - U_{0B}} \tag{11}
\]

Separating the real part from the imaginary part on both sides of the \( (9) \), the total capacitance and total conductance to the ground are expressed as follows:

\[
C_\Sigma = \frac{1}{\omega} \Im \left( \frac{\dot{E}_{AB} (G_M + jB_M)}{U_{0A} - U_{0B}} \right) - \frac{B_M}{\omega} \tag{12}
\]

\[
G_\Sigma = \Re \left( \frac{\dot{E}_{AB} (G_M + jB_M)}{U_{0A} - U_{0B}} \right) - (G_M + G_0) \tag{13}
\]

To obtain the exact calculated value of the vector sum of the grid asymmetric parameters, divide \( (6) \) with \( (7) \) as follows:

\[
\frac{\dot{U}_{0A}}{\dot{U}_{0B}} = \frac{-\dot{E}_A k_U - \dot{E}_A (G_M + jB_M)}{-\dot{E}_A k_U - \dot{E}_B (G_M + jB_M)} \tag{14}
\]

The expression of the vector sum of the grid asymmetric parameters can be obtained by separating the variables as follows:

\[
\dot{k}_U = \frac{\dot{E}_A U_{0B} - \dot{E}_B U_{0A} (G_M + jB_M)}{\dot{E}_A (U_{0A} - U_{0B})} \tag{15}
\]

The phase-shift method can be used in a neutral ungrounded or resistive grounding system, which is not affected by the neutral grounding mode. Meanwhile, the input of external elements can be in or out of the substation, increasing the flexibility of the phase-shift method. Compared with the partially installing capacitance method, the phase-shift method makes significant improvements in two aspects:

(i) The phase-shift method eliminates the measurement error of insulation parameters caused by the asymmetry of the three-phase circuit by connecting external elements with two different phases.

(ii) Existing research on insulation parameter measurement is mainly focused on the capacitance of the grid line to the ground. The line-to-ground conductance parameters and asymmetric parameter \( k_U \) can both be measured by adopting the phase-shift method.
2.4. Selection of External Elements. Since only one single capacitor is used as an external element in the partially installing capacitance method, full discharge is required for an actual measurement while the external elements used in the phase-shift method will not be restricted. The selection of the external element should meet the following constraints: (a) the neutral point displacement voltage caused by external elements switching between the two phases should be large enough to ensure the measurement accuracy and (b) the neutral point displacement cannot lead to excessive voltage damage to weaken the insulation equipment.

Given the short measurement time of the phase-shift method, the neutral point voltage will only increase to 10%–15% of the phase voltage:

\[ 10\% \times E_A \leq U_0 \leq 15\% \times E_A, \]  

where the expression of \( U_0 \) is shown in expression (8). For a neutral ungrounded system, \( G_0 \) is equal to zero. Meanwhile, \( k_U \) can also be omitted in the simplified calculation. Then, the following simplified expression can be obtained.

\[ U_0 = \frac{E_A (G_M + jB_M)}{(G_Z + j\omega C_Z) + (G_M + jB_M)} \]  

Substitute expression (17) into expression (16) to obtain the selection conditions of external elements.

\[ 11.1\% |G_Z + j\omega C_Z| \leq |G_M + jB_M| \leq 17.7\% |G_Z + j\omega C_Z|. \]  

The upper limit of the inequality is taken if the external element is a resistance-capacitance element, and the lower limit is taken if the external element is a resistance-inductance element.

(1) If the external element is a resistor, there will be no energy release problem since the resistor is not an energy storage element. Moreover, it is less affected by harmonics.

(2) If the external element is an inductance element that has good impact resistance, the residual energy of the inductance needs to be released after the measurement. Thus, a reactor paralleling with a damping resistance is an appropriate choice. However, the reactor satisfying (18) works in the state of under-compensating. In this case, if one line is cut off during the measurement, it will cause a large resonant overvoltage, which is not conducive to the safety of measurement.

(3) If the external element is capacitive, the capacitor series resistance can reduce the charging effect of the capacitor at the moment of grounding. After the measurement, the capacitor energy storage shall be released by constructing a series circuit between the resistor and the capacitor. If one of the lines is cut off during the measurement of the resistive and capacitive external element, the neutral voltage will increase. However, the displacement degree of the zero-sequence voltage is smaller than that of the resistive external element, which guarantees the security of measurement.

The characteristics of the various external elements are analyzed based on the safety of the actual measurement operation above. In practice, there are a large number of capacitors used for reactive power in the actual distribution line. The reactive power compensation capacitor equipped in the system can be directly used as the external element, which creates favorable conditions for the application of the phase-shift method. Therefore, a capacitance is the best selection for the external element.

3. Transition Conductance Tracking Method in Case of Single-Phase Grounding Fault

Existing researches focus on fault identification criteria, and few scholars have carried out research to track the fault development process. However, the power electronics of renewable energy units make SPGFs detection more complicated. The transition conductance varies steadily and can be used as an important parameter to evaluate the development of a single-phase grounding fault. In this section, the tracking method of transition conductance is, respectively, discussed in the case of neutral point ungrounded and grounded via an arc suppression coil when an SPGF occurs. The accurate identification of SPGFs can be realized indirectly by tracking the transition conductance.

3.1. Neutral Ungrounded Power System. The line voltage remains unchanged when an SPGF occurs in the case that the neutral point is ungrounded. The three-phase balance of the power system will not be damaged as well. Therefore, the power system can be allowed to continue operating within two hours. However, to avoid further deterioration of the accident, it is necessary to eliminate the fault in time.

3.1.1. Ignoring the Asymmetrical Factors of Power Grid Parameters. The schematic diagram of a simplified circuit is shown in Figure 4.

In this case, if an SPGF occurs in phase A through the transition conductance \( G_F \) (Taking phase A as an example, the formulas for the other two phases can be derived in the same way). Then, the grid neutral voltage can be expressed as in the following equations:

\[ \bar{U}_{GF} = \frac{-E_A}{j\omega C_Z + G_F}, \]  

\[ G_F = \lambda\omega C_Z, \]

where \( E_A \) is the electromotive force of the phase A power supply. \( C_Z = C_A + C_B + C_C \) is the distributed capacitance of the system, and \( G_Z = G_A + G_B + G_C \) is the distributed conductance of the system. \( \lambda \) is a proportionality factor to establish the relationship between insulation parameters and transition conductance. According to expression (19), the displacement degree of the neutral point voltage \( \rho_F \) can be written as

\[ \rho_F = \lambda\omega C_Z. \]
Since the asymmetry of the line is simplified, the transition advance by the measuring method for insulation parameters.

The equation above establishes the relationship between \( \rho_F \) and \( \lambda \). Based on expression (21), it can be found that \( G_F = 0 \) and \( \lambda = 0 \) when the transition resistance is infinite. Thus, the displacement degree of the voltage at the neutral point \( \rho_F = 0 \) as well. By contrast, \( G_F \) goes to infinity when a single-phase direct grounding fault occurs. Therefore, the displacement degree of the voltage at the neutral point \( \rho_F = 1 \).


damping rate of the power grid is usually far less than 1, so \( k_U \) can also be approximated as \( \rho_0 j \omega C_x \) in some cases. The parameters above describing the degree of power grid asymmetry are measured during the normal operation of the system.

Taking the influence of the power grid asymmetry into account, if an SPGF through a transition conductance occurs in phase A of the power grid, the voltage at the neutral point of the power grid will be changed as

\[
U_{\text{uf}} = -\frac{\dot{E}_A}{G + j \omega C_x + G_{\Sigma}}.
\]

Furthermore, the voltage displacement of the neutral point can be expressed as

\[
\dot{U}_{\text{UV}} = -\frac{\dot{E}_A}{j \omega C_x + G_{\Sigma}}. \tag{23}
\]

where \( I_G \) is the sum of the current flowing through the distributed conductance and \( I_C \) is the sum of the current flowing through the distributed capacitance. It can be obtained from the equation above that \( G_{\Sigma} = \omega C_{\Sigma} \), and then, the vector sum of the grid asymmetric parameters can be expressed as

\[
\dot{k}_U = \rho_0 (j \omega C_x + G_{\Sigma}) = \rho_0 \omega C_x (j 1 + d). \tag{26}
\]

With practical engineering experience, the damping rate of the power grid is usually far less than 1, so \( k_U \) can be approximated as \( \rho_0 j \omega C_x \) in some cases. The parameters above describing the degree of power grid asymmetry are measured during the normal operation of the system.

Taking the influence of the power grid asymmetry into account, if an SPGF through a transition conductance occurs in phase A of the power grid, the voltage at the neutral point of the power grid will be changed as

\[
U_{\text{uf}} = -\frac{\dot{E}_A G_F + \dot{k}_U}{G_F + j \omega C_x + G_{\Sigma}}. \tag{27}
\]
\[ \dot{\rho}_F = \frac{U_{\text{of}}}{E_A} \frac{G_F + j\omega C_F + G_C}{G_F + j\omega C_F + G_C} = \frac{\lambda + \dot{\rho}_b (j1 + d)}{\lambda + (j1 + d)} \]  

(28)

Separating variables of \( \lambda \) in expression (29), the expression of \( \lambda \) can be obtained as shown in the following equation:

\[ \lambda = \frac{(\dot{\rho}_F - \dot{\rho}_b) (j1 + d)}{1 - \dot{\rho}_F} \]  

(29)

In this case, the transition conductance can be calculated by the following equation:

\[ G_F = \lambda \omega C_F = \frac{(\dot{\rho}_F - \dot{\rho}_b) (j1 + d)}{1 - \dot{\rho}_F} \omega C_F. \]  

(30)

In practice, the value of natural asymmetry and voltage displacement of the neutral point after SPGFs can be calculated directly according to the voltage measuring device in the substation.

\[ G_F = \lambda \omega C_F = \frac{-U_{\text{of}}/E_A + U_{\text{uv}}/E_A}{1 + U_{\text{of}}/E_A} \omega C_F \]  

(31)

According to the expression of transition conductance above, for transmission networks with the same insulation parameters, the capacitance parameters and natural damping rate \( d \) of the network are consistent. As a result, if the single-phase grounding fault occurs, the real-time tracking method of transition conductance can be obtained according to the value of \( G_F \) in the case that the neutral point is ungrounded.

3.2. Arc Suppression Coil Grounding System. The neutral point grounded via the arc suppression coil is also a common grounding method in the medium voltage distribution network. By installing an arc suppression coil at the neutral point, the capacitive current in the network can be compensated, and the arc overvoltage can be suppressed effectively.

3.2.1. Ignoring the Asymmetrical Factors of Power Grid Parameters. In most applications, the arc suppression coil generally runs in the state of overcompensation to suppress the displacement degree of the voltage at the neutral point within a reasonable range.

The detuning degree of the arc suppression coil can be denoted as \( \nu \), and its expression is as follows:

\[ \nu = \frac{I_C - I_L}{I_C} = \frac{\omega C_F - 1/(\omega L_c)}{\omega C_F} \]  

(32)

where \( I_C \) is the sum of the current flowing through the distributed capacitance, \( I_L \) is the current flowing through the arc suppression coil, and \( L_c \) is the equivalent inductance of the arc suppression coil. After rearranging the equation, it is easy to find that \( \omega C_F - 1/(\omega L_c) = \nu \omega C_F \).

As shown in Figure 6, a simplified equivalent circuit of neutral point grounding via an arc suppression coil is established. Ignoring the influence of ground conductance parameters and three-phase asymmetry on the distribution network, an SPGF occurs in phase A through a transition conductance \( G_F \), and the voltage at the neutral point of the grid is denoted as follows:

\[ U_{\text{of}} = -E_A/\left(\omega C_F - 1/(\omega L_c) + G_F\right) \]  

(33)

where \( G_F = \lambda \omega C_F \), then the displacement degree of the voltage at the neutral point can be written as

\[ \dot{\rho}_F = \left| \frac{U_{\text{of}}}{E_A} \right| = \left| \frac{G_F}{\omega C_F - 1/(\omega L_c) + G_F} \right| = \frac{\lambda}{\sqrt{\nu^2 + \lambda^2}} \]  

(34)

The expression of \( \lambda \) can be obtained in this case by separating variables of \( \lambda \) in expression (34).

\[ \lambda = \frac{\nu \cdot \dot{\rho}_F}{\sqrt{1 - \dot{\rho}_F^2}} \]  

(35)

Substituting the expression for \( \lambda \) into formula (17), the transition conductance \( G_F \) can be obtained as follows:
\[ G_F = \lambda \omega C_\Sigma = \frac{|v \cdot \rho F| \omega C_\Sigma}{\sqrt{1 - \rho_F^2}}. \quad (36) \]

3.2.2. Considering the Asymmetrical Factors of Grid Parameters. To improve the measurement accuracy of transition conductance further, it is necessary to consider the asymmetrical parameters of the power grid in an SPGF. Figure 7 shows the accurate equivalent circuit with consideration of the conductance parameter of the transmission line.

Thus, the neutral point voltage in normal operation can be expressed as

\[ U_{UV} = -E_A \left[ \omega C_\Sigma - 1/(\omega L_c) \right] + G_\Sigma. \quad (37) \]

The displacement degree of the neutral point voltage can be further deduced when the power grid system grounded via the arc suppression coil is in normal operation.

\[ \hat{\rho}_0 = \frac{U_{UV}}{E_A} = \frac{\hat{k}_U}{\omega C_\Sigma - 1/(\omega L_c)} + G_\Sigma. \quad (38) \]

According to the natural damping rate of the power grid mentioned above, it can be known that \( G_\Sigma = d\omega C_\Sigma \). Therefore, the vector sum of asymmetric grid parameters can be expressed as

\[ \hat{k}_U = \rho_0 [ j \omega C_\Sigma - 1/(\omega L_c) ] + G_\Sigma = \rho_0 \omega C_\Sigma (jv + d). \quad (39) \]

In the actual power system operation, the neutral voltage of the resonant grounding system should be less than 15% of the phase voltage (\( \rho_0 < 0.15 \)), and the natural damping rate of the power grid \( d \) generally does not exceed 3%. Therefore, the vector sum of the grid asymmetric parameters can also be approximately expressed as \( k_U = \rho_0 \omega C_\Sigma << \omega C_\Sigma \). Similarly, the parameters above describing the degree of power grid asymmetry are measured during the normal operation of the system.

In this case, after the SPGF via a transition conductance occurs in phase A of the power grid, the voltage at the neutral point of the power grid is expressed as follows:

\[ U_{0F} = -E_A G_F + \hat{k}_U \left[ \omega C_\Sigma - 1/(\omega L_c) \right] + G_\Sigma. \quad (40) \]

where the meanings of the parameters in (37) are consistent with those above.

The voltage displacement degree of the neutral point can be expressed as

\[ \hat{\rho}_F = \frac{U_{0F}}{E_A} = \frac{G_F + \hat{k}_U}{G_F + j [\omega C_\Sigma - 1/(\omega L_c)] + G_\Sigma} = \frac{\lambda + \rho_0 (jv + d)}{\lambda + (jv + d)}. \quad (41) \]

Similarly, the following formula can be obtained by separating variables \( \lambda \) in the above formula.

\[ \lambda = \frac{(\hat{\rho}_F - \hat{\rho}_0) (jv + d)}{1 - \hat{\rho}_F}. \quad (42) \]

Therefore, for the system whose neutral point is grounded by an arc suppression coil, the transition conductance of SPGF can be calculated by the following formula:

\[ G_F = \lambda \omega C_\Sigma = \frac{(\hat{\rho}_F - \hat{\rho}_0) (jv + d)}{1 - \hat{\rho}_F} \omega C_\Sigma. \quad (43) \]

Similarly, the calculation of voltage displacement of the neutral point also depends on the voltage measurement results in the case of the neutral point being grounded by an arc suppression coil, and the transition conductance can be tracked as

\[ G_F = \frac{(U_{UV} - U_{0F}) (jv + d)}{E_A + U_{0F}} \omega C_\Sigma. \quad (44) \]

If the insulation parameters, single-phase grounding fault type, and compensation degree of arc suppression coil of the two power grids are the same, it can be derived that the detuning degree, natural damping rate, and transition conductance parameters of the two power grids are the same as well. Thus, the real-time tracking method of transition conductance is obtained in the case that the neutral point is grounded by an arc suppression coil.

3.3. Identification Method of Single-Phase Grounding Fault. The distribution system with renewable energy access has higher requirements on the security of power supply. The method proposed in this paper meets these requirements. According to the analysis above, the insulation parameters of the line should be measured when the system runs normally according to the method proposed in Section 2. The transition conductance can be tracked accurately by the three-phase unbalance parameters of the line. The three-phase unbalance parameters are linearly dependent on the voltage of the neutral point. In this way, the transition conductance of the system can be tracked indirectly through the real-time measurement of the voltage of the neutral point.

The specific detection process of SPGFs based on the transition conductance tracking method is shown in Figure 8 explicitly.

As shown in Figure 8, the phase-shift method is adopted to measure the insulation parameters \( G_\Sigma/G_\Sigma \) and asymmetric parameter \( k_U \) of the distribution network. Generally, the insulation parameters and asymmetric parameters need to be measured again only when the network structure changes. Meanwhile, it is necessary to collect the neutral unbalanced voltage \( U_{UV} \) and calculate the natural asymmetry \( \rho_0 \) when the system is running normally. According to the transition conductance tracking method, the transition conductance
GF can be tracked in real time by repeatedly refreshing the value of the neutral voltage $U_{0F}$.

Depending on the calculation theory in Section 3, the value of transition conductance equals zero if no SPGF occurs in the network. In other words, if the calculated value of transition conductance is greater than zero, a single-phase grounding fault occurs.

In practice, the line parameters are considered symmetrical if the line asymmetry is less than 0.5%. At the same time, most of the voltage transformers used in the system are more accurate than level 1.0. In this way, the measurement deviation of the voltage mutual inductor is lower than ±1.0%. Considering the above, set the detection threshold $\varepsilon$ to 1.5% $G_N$. Once the calculated transition conductance exceeds the threshold, the system is thought to encounter an SPGF. Thus, the SPGF criterion based on transition conductance is formed.

The transition conductance tracking method constructed in this paper is based on the measurement results of insulation parameters. For the arc suppression coil grounding system, the phase-shift method or injection current method can both be used to measure the insulation parameters. Based on the obtained insulation parameters, the SPGF can be identified according to the transition conductance tracking method. Meanwhile, the proposed phase-shift method innovatively solves the problem of measuring the insulation parameters of neutral ungrounded systems. Therefore, in the following part, we focus on the phase-shift method to obtain the insulation parameters of the neutral ungrounded system and detect the SPGFs based

**Figure 8: Technical process of single-phase grounding fault identification based on transition conductance tracking method.**
on the transition conductance tracking method. Therefore, the subsequent case analysis will mainly deal with the SPGF detection of the neutral ungrounded system.

4. Case Study

4.1. Simulation Model and Parameters Setting. To verify the effectiveness of the proposed method, a three-phase asymmetric distribution network is simulated on the Simulink platform. As shown in Figure 9, the system is set up on a 10 kV distribution network. By comparing the partially installing capacitance method with the phase-shift method, the feasibility and accuracy of the phase-shift method in measuring the insulated parameters are verified. Then, the SPGF is simulated on the transmission line to demonstrate the validity of the fault detection based on the transition conductance tracking method.

The simulation system is a 10 kV distribution network with a frequency of 50 Hz, where the damping rate is set as 3.379%. Based on that, the three-phase insulation parameters of the simulation system are $C_A = 12.850 \mu F$, $R_A = 7.281 \text{k}\Omega$, $C_B = 11.530 \mu F$, $R_B = 8.080 \text{k}\Omega$, $C_C = 12.660 \mu F$, and $R_C = 7.572 \text{k}\Omega$ respectively. The total distributed capacitance of power grid lines is $C_\Sigma = 37.040 \mu F$, and the total conductance of power grid lines is $G_\Sigma = 3.932 \times 10^{-4} \text{S}$.

4.2. Measurement of Insulation Parameters Based on Phase-Shift Method. The phase-shift method mainly solves the dilemma of accurately measuring the insulation parameters of the neutral ungrounded system. Therefore, a medium-voltage neutral ungrounded distribution network is simulated. Subsequently, according to the selection of an external element in Section 2, a single-capacitor element is finally adopted in the case study model. The external element is a capacitance of $5.556 \times 10^{-6} \text{F}$, and it is adopted both in the two measurement methods. In this way, the insulation parameters measured by the phase-shift method can be compared with those measured by the partially installing capacitance method as well.

The instantaneous value of neutral voltage during phase-shift operation is shown in Figure 10. The external element is put into phase A at 1.0 sec and withdrawn from phase A at 1.2 sec. Then, the external element is put into phase B after an interval period of 0.3 sec. The measurement process based on the phase-shift method is less than 1.0 sec. Since the external element is only cut on and off once, the process of partially installing the capacitance method can be treated as the first half part of the phase-shift method. The comparison and error analysis of line parameter measurements are listed in Table 1 according to the simulation results.
The simulation results are compared in Table 1. According to the theoretical derivation, the partially installing capacitance method ignores the asymmetric effect of circuit parameters, so it has some fundamental defects. Compared with the partially installing capacitance method, the theoretical derivation of the phase-shift method constructed in this paper is more perfect, and there is no systematic error in the measurement process. The results of error analysis show that the measurement accuracy of insulation parameters based on the phase-shift method is less than 0.5%, which is much lower than the partially installing capacitance method.

According to the analysis in Section 3, the measurement of line insulation parameters is a necessary basis for the tracking of transition conductance. Therefore, the measurement accuracy of line insulation parameters directly affects the tracking accuracy of transition conductance and then affects the discrimination of single-phase grounding faults.

4.3. Transition Conductance Tracking. Based on the measurement results of insulation parameters in the normal operation of the system, the model simulation of single-
phase grounding fault through different transition conductances is carried out. In the case of a neutral ungrounded system, the simulation results of simulated faults are shown below successively.

For the neutral ungrounded system, single-phase grounding faults grounded by transition resistances of 500 ohms, 2000 ohms, and 4000 ohms are, respectively, simulated in the model. The occurrence time of grounding fault is set at 1.0 sec, and the simulation time is set for 2.0 sec. The instantaneous changes of the three-phase voltage in three different cases are shown in Figure 11. Meanwhile, the voltage amplitude and phase angle fluctuation at the system neutral point are shown in Figure 12.

Figure 11 shows the fluctuation of three-phase instantaneous voltage in the distribution network after an SPGF occurs via different transition conductance. It can be found that as the transition conductance decreases (the transition resistance increases), the three-phase instantaneous voltage fluctuation becomes weaker after the fault occurs. Therefore, in the protection process of the distribution network, it is difficult to identify the SPGF directly with the decrease in transition conductance.

According to the voltage and phase angle changes of the neutral point in Figure 12, the voltage of the neutral point tends to be stable again 0.3 sec after the occurrence of the single-phase grounding fault. Therefore, for the neutral ungrounded system, the detection time interval of the neutral point voltage vector can be set to 0.3 sec in the actual power system fault warning process. Meanwhile, the amplitude and phase change of neutral voltage after single-phase grounding faults with different transition conductance are compared. As shown in Figure 12(a), the amplitude of the neutral voltage increases by 10 times after the occurrence of SPGF. With such fault characteristics, the occurrence of faults can be quickly identified by conventional fault identification methods. In contrast, the fluctuation of voltage amplitude at the neutral point shown in Figures 12(b) and 12(c) is much weaker after the SPGF occurs. In this paper, the transition conductance is selected as the fault characteristic in constructing the transition conductance tracking method, forming a more powerful criterion.

Based on the measurement results of neutral point voltage after SPGF, the tracking and identification of transition conductance can be realized. The fluctuations of
transition conductance after SPGF are shown in Figure 13, and the specific calculation results of three different cases are shown in Table 2.

As shown in Figure 13, SPGF development in the system can be observed directly by tracking the fluctuations of transition conductance. Meanwhile, the transition conductances are stabilized within 0.3 sec in the cases above, and the transition conductance obtained by the tracking method during the fault is much higher than the fault identification threshold. In this way, the SPGF identification based on the transition conductance tracking method constructed in this paper is more robust. Moreover, it can be seen from the calculation results in Table 2 that the measurement errors of transition conductance are less than 9% for three different cases. According to the transition conductance tracking method, the criterion for the occurrence of SPGF is 1.5% \( G_{\xi} \). After calculation, the threshold value \( \epsilon \) is \( 5.9266 \times 10^{-6} \)S which is far less than the measured value of transition conductance. In this way, it can indirectly reflect the occurrence of SPGF according to the accurate detection result of transition conductance.

In the process of SPGF development, the stable value of transition conductance is far higher than the threshold. After the SPGF is removed, the stable value of transition conductance will return below the threshold. Taking \( R_F \) equal to 2000 ohms as an example, the whole-process fluctuation of transition conductance is shown in Figure 14 when the fault is removed after 1.5 sec.

Due to space limitations, this paper only presents the case analysis of SPGF occurring in phase A. According to the rotation of the distribution network, a similar transition conductance tracking method can also be obtained when SPGF occurs in phase B or phase C. In this way, by tracking the transition conductance of three phases simultaneously, the development of SPGF in the fault phase can be observed.

The transition conductance tracking method based on the phase-shift method constructed in this paper does not make any approximation in the theoretical derivation. Therefore, the main source of calculation error lies in the measurement error and error transmission and amplification of insulation parameters in the first stage. Nevertheless, the power supply radius of the 10kV distribution network generally does not exceed 15 km. Take the capacitance current of 1.3A per kilometer as an example, and the capacitance current of 15km is 19.5A. Meanwhile, the capacity of the distributed capacitance is about 0.003377S, and the transition resistance of 1.5% zero-sequence resistance is 19737 \( \Omega \). In other words, the maximum detected transition resistance is 19.7k \( \Omega \), which can completely meet the protection requirements of the distribution network.

### 5. Results

In this paper, the identification of single-phase grounding fault based on the transition conductance tracking method in a medium voltage distribution network is studied. The transition conductance tracking process is mainly divided into two stages.

In the first stage, a phase-shift method is constructed to measure the insulation parameters of the system during normal operation. The phase-shift method eliminates the calculation error of asymmetric parameters by connecting the external components with different phases twice. Compared with the partially installing capacitance method which ignores the asymmetric parameters directly, the...
phase-shift method improves the measurement accuracy of insulation parameters from the fundamental principle. In addition, the currently popular methods can only obtain the distributed capacitance parameters of the distribution network. By contrast, the phase-shift method can also obtain the distributed conductance and asymmetric parameters of the network. Simulation results show that the measurement error of insulation parameters by the phase-shift method is less than 0.5%.

In the second stage, a transition conductance tracking method based on the measurement of insulation parameters is deduced in this paper when an SPGF occurs and is discussed in the case of a neutral point ungrounded or grounded via an arc suppression coil. The theoretical calculation result of transition conductance is equal to zero in the normal operation of the system. Considering a certain tolerance range, the margin of fault identification is set as 1.5% insulation parameter. When the calculated result of transition conductance exceeds the threshold, the single-phase grounding fault is considered to have occurred. Simulation results show that the calculation error of transition conductance is less than 9% based on the transition conductance tracking method. Compared with the traditional fault identification method, the transition conductance is selected as the criterion of whether a fault occurs. For single-phase grounding faults with transition conductance, the fault characteristics are amplified and the safety of distribution network protection is improved. By tracking the transition conductance in three phases simultaneously, the development of SPGF in the fault phase can be observed.

6. Conclusion

A novel single-phase grounding fault identification based on the transition conductance tracking method is proposed in this paper to evaluate the development of fault degree. The phase-shift method in the proposed scheme is introduced to realize the fast and economical detection of insulation parameters. Accurate tracking of the transition conductance can be achieved based on the measurement results of line insulation parameters. According to the tracking process of transition conductance, the occurrence of single-phase grounding faults can be identified indirectly. In the following research, the transient information of single-phase grounding faults can be further mined to further shorten the time of fault identification.

Nomenclature

\[ \begin{align*}
C_A, C_B, C_C & : \text{Distributed phases-to-ground capacitance (} \mu \text{F)} \\
G_A, G_B, G_C & : \text{Distributed phase-to-ground conductance (} \Omega \text{)} \\
L_A, L_B, L_C & : \text{Distributed phase-to-ground inductance (} \mu \text{H)} \\
R_A, R_B, R_C & : \text{Distributed phase-to-ground resistance (k} \Omega \text{)} \\
E_A, E_B, E_C & : \text{Electromotive force (} \text{V)} \\
C_{af} & : \text{External capacitor (} \mu \text{F)} \\
U_0 & : \text{Neutral voltage in partially installing capacitance method (} \text{V)} \\
U_{0A}, U_{0B} & : \text{Neutral voltage in phase-shift method (} \text{V)} \\
k_U & : \text{Vector sum of grid asymmetric parameters} \\
U_A, U_B, U_C & : \text{Phase voltage (} \text{V)} \\
G_M + jB_M & : \text{Equivalent admittance of external element} \\
G_0 & : \text{Neutral ground conductance (} \text{S)} \\
U_{0G} & : \text{Neutral voltage after SPGF occurs (} \text{V)} \\
G_T & : \text{Transition conductance (} \text{S)} \\
\lambda & : \text{Proportionality factor} \\
\rho_u & : \text{Displacement degree of neutral point voltage} \\
U_{UV} & : \text{Unbalanced voltage during normal operation (} \text{V)} \\
\rho_f & : \text{Natural asymmetry of neutral ungrounded system} \\
d & : \text{Natural damping rate} \\
I_G & : \text{Current flowing through distributed conductance (} \text{A)} \\
I_C & : \text{Current flowing through distributed capacitance (} \text{A)} \\
I_L & : \text{Current flowing through arc suppression coil (} \text{A)} \\
v & : \text{Detuning degree of arc suppression coil} \\
L & : \text{Equivalent inductance of arc suppression coil (} \text{H)} \\
\epsilon & : \text{Identification threshold of SPGFs (} \text{S)}.
\end{align*} \]

Data Availability

All the experimental data needed are included in our manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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