Simulation and analysis of single-phase grounding fault in small current grounding system

Jinwei Fu¹, Changkai Shi, Wenbo Fan and Shilei Guan
China Electric Power Research Institute, Haidian District, Beijing 100192, China
¹E-mail: fujinwei@epri.sgcc.com.cn

Abstract. The characteristics and distribution of single-phase grounding faults in small current grounding system are not easy to capture, and it is not easy to collect and cover all possible situations in operation site. This paper builds a fault simulation model of distribution network based on PSCAD. By changing the fault location, line type, transition resistance, fault time and other factors, and combining with the analysis of fault mechanism, the factors affecting single-phase grounding faults are obtained. The impacts of fault feature distribution provide theoretical guidance for fault identification equipment function detection and so on.

1. Introduction

Single-phase grounding fault is one of the most common types of faults in distribution network in China. The steady-state and transient characteristics of different types of faults in different grounding modes are different, and are affected by many factors, such as fault time and fault location. Especially for single-phase grounding fault in low current grounding system, the fault characteristics and its distribution rules are not easy to capture. It is of great significance for the accurate identification and treatment of distribution network faults and the detection of functional performance completeness of fault identification equipment to master the characteristics and distribution rules of single-phase grounding faults in distribution network.

Due to the fact that the faults occurring on the operation field are individual, random and inexhaustible, it is not easy to collect and cover all possible cases, and there is much interference information in the operation field data, so it is difficult to analyze the fault characteristics and distribution rules directly using the operation field data. At present, the analysis of distribution network faults focuses more on the theoretical study of fault characteristics [1-13], and the simulation using simulation tools (such as PSCAD) is also mainly used to verify the accuracy of fault line selection and fault location. The direct analysis of the influence of different factors on fault characteristics is still insufficient. For example, in Reference [1], empirical mode decomposition (EMD) method is used to analyze the characteristic frequency band component of zero sequence current; in Reference [3], the distribution of electrical quantity at the outlet of both ends of loop with the change of fault location and line parameters is analyzed when the loop is grounded; Reference [4] uses wavelet transform to analyze zero-sequence voltage low-frequency signal of single-phase grounding fault. References [14, 15] validate the adaptability of the proposed fault type identification method through PSCAD simulation. Literatures [16, 17] validate the feasibility of the proposed fault location method in different fault scenarios through MATLAB simulation.

Therefore, this paper uses simulation modeling to reproduce the scene of operation field. By changing the parameter settings of relevant factors such as fault location, line type, transition...
resistance and fault time, the influence of different factors on the distribution of fault characteristics is analyzed. To grasp the influence of different factors on fault characteristics provides a basis for selecting typical fault feature waveforms and optimizing fault waveform database.

2. Distribution network fault simulation model

In this paper, PSCAD is used to simulate distribution network and output waveforms. The transformer in the simulation system is an ideal component, that is to say, the impedance of the transformer is approximately zero. However, the simulation analysis shows that the impedance of the transformer has a certain influence on the simulation of single-phase grounding fault [18]. Therefore, it is necessary to study the influence of the impedance of the transformer, and analyze the influence of the impedance of the transformer and the problems it brings.

Assuming that the simulation system has \( n \) regular lines and one fault line, the parallel connection of all sound lines is equivalent to line 1, and the fault line is line 2, as shown in Figure 1.

![Figure 1. Schematic diagram of transformer impedance effect analysis.](image)

In Figure 1, when the switch \( K \) is closed, the voltage of A-phase bus (\( \alpha \)) is \( U_{\alpha} \), the voltage of B-phase and C-phase parallel equivalent bus (\( \beta \)) is \( U_{\beta} \), and the voltage of neutral point (\( \gamma \)) is \( U_{\gamma} \), the nodal voltage equations can be listed and written as follows:

\[
\begin{align*}
\left( \frac{2}{Z_T} + \frac{1}{Z_{T_{11}}} + \frac{2}{Z_{C_1}} + \frac{2}{3Z_{L_{11}}} + \frac{2}{3Z_{L_{21}}} \right) \hat{U}_{\beta} &= \frac{1}{2} \Delta I_{\beta} \\
\left( \frac{2}{3Z_{L_{11}}} + \frac{2}{3Z_{L_{21}}} \right) \hat{U}_{\alpha} &= \frac{1}{2} \Delta I_{\gamma} - \frac{2}{Z_T} \hat{U}_{\gamma} = 0 \\
\hat{U}_{\alpha} &= \hat{U}_{f} \\
\left( \frac{3}{Z_T} + \frac{1}{Z_X} \right) \hat{U}_{\gamma} - \frac{1}{Z_T} \hat{U}_{\alpha} - \frac{2}{Z_T} \hat{U}_{\beta} &= 0
\end{align*}
\]

Generally, the capacitive current of each line is much smaller than the load current. According to the 10 km overhead line, the capacitive current is about 1A, and the over-compensation is usually 5%. By solving the above equation, the relationship between the current through the transformer and capacitive current can be obtained as follows:
\[
\left\{ \begin{array}{l}
\Delta I_{1AL} \approx \frac{2}{11} \Delta I_{1AC} \\
\Delta I_{1BL} \approx \frac{1}{11} \Delta I_{1BC} \\
\Delta I_{1CL} \approx \frac{1}{11} \Delta I_{1CC}
\end{array} \right. 
\] (2)

It can be seen that the grounding current passing through the main transformer at the side of 10kV distribution network is very small, and the smaller crossing current has little effect on the non-fault line. Therefore, according to the parameters of distribution network, a real case system can be built based on PSCAD to analyze the transient characteristics of single-phase grounding fault in distribution network with neutral ungrounded and arc suppression coil grounded. Modeling and Simulation of four lines, configuration as shown in Figure 2.

The information of electrical parameters is as follows:

- **Main transformer:** \( S_N = 40 \text{MVA} \), \( P_0 = 2.88 \text{kW} \), Y/Y or Y/D wiring.
- **Cable lines:** \( r_1 = 0.157 \Omega/\text{km} \), \( x_1 = 0.076 \Omega/\text{km} \), \( b_1 = 132 \times 10^{-6} \text{S/km} \); \( r_0 = 0.307 \Omega/\text{km} \), \( x_0 = 0.304 \Omega/\text{km} \), \( b_0 = 110 \times 10^{-6} \text{S/km} \).
- **Overhead lines:** \( r_1 = 0.27 \Omega/\text{km} \), \( x_1 = 0.352 \Omega/\text{km} \), \( b_1 = 3.178 \times 10^{-6} \text{S/km} \); \( r_0 = 0.42 \Omega/\text{km} \), \( x_0 = 3.618 \Omega/\text{km} \), \( b_0 = 0.676 \times 10^{-6} \text{S/km} \).

**Figure 2.** Simulating modeling diagram of single-phase grounding fault in small current grounding system based on PSCAD.

The model can intuitively reflect the operation condition and operation process of the switches in the network. Considering the influence of phase voltage angle on single-phase grounding fault, it is necessary to detect phase voltage angle of the line in the fault control logic circuit.

The simulation results show that there is no obvious change of phase current before and after the fault point, only a little burr in the waveform, while the transient characteristics of zero-sequence current of the regular line and the fault line change more obviously [19]. Therefore, we mainly carry out analysis based on zero-sequence current.
3. Grounding fault analysis
Based on the above analysis, aiming at the factors affecting the characteristics of single-phase grounding fault in distribution network, including line type, fault location and grounding resistance, we study the change of fault characteristics before and after single-phase grounding fault occurs when neutral point is not grounded and neutral point is grounded by arc suppression coil.

3.1. Change the fault location
The fault line is #4, and the grounding point is gold attribute grounding. The fault locations are the first end of the line (10% of the line length is from the bus), the middle (50% of the line length is from the bus) and the end (90% of the line length is from the bus). The transient characteristics of zero sequence current are shown in Figure 3.

![Figure 3](image)

It can be seen from the above figure that the waveform of zero-sequence current of fault line does not change much when the fault location is different, but it will affect the oscillation frequency of high-frequency component of zero-sequence current. The oscillation frequency of zero-sequence current is relatively high when the fault location is at the beginning of the line.

3.2. Change the fault line type
The fault point is in the middle of the line, and the grounding point is gold attribute grounding. The fault lines are #1 line (overhead line), #2 line (cable line) and #4 line (overhead line and cable line hybrid line), respectively. The transient characteristics of zero sequence current are shown in Figure 4.

![Figure 4](image)

As can be seen from the figure above, the transient component of zero sequence current of pure cable lines is larger than that of pure overhead lines, and the transient current attenuation process is shorter.

3.3. Change the transition resistance of grounding point
The fault line is #4 and the fault point is at the beginning of the line. The grounding modes are metal grounding, transition resistance (10 Ω, 100 Ω, 200 Ω, 300 Ω, 1000 Ω) grounding. The transient characteristics of zero sequence current are shown in Figure 5.

![Figure 5](image)
Figure 5. Zero sequence current simulation waveform of different transition resistance at grounding points.

As can be seen from the figure above, when the transition resistance is small, the transient process of fault line and non-fault line is obvious, and large transient zero-sequence current is generated. With the increase of transition resistance, the attenuation speed of transient current is accelerated. When the transition impedance is large, the transient process of zero-sequence current in fault line and non-fault line is not obvious, and the amplitude of zero-sequence current in fault line and non-fault line decreases obviously, and it quickly transits to steady state.

3.4. Change the fault time

The equivalent circuit of the fault circuit when the fault occurs is shown in Figure 6.

![Equivalent circuit diagram of single phase grounding fault circuit.](image)

Assuming that the fault time is \( T \), when the switch \( K_1 \) is closed, the current of the fault circuit is:

\[
I_f = \frac{U \omega C_1 \sin(\omega t)}{(\omega^2 L_1 (C_1 + C) + \omega R (C_1 + C) + 1)}
\]  \( (3) \)

In general, \( C >> C_1 \), the above formula can be simplified as follows:
From the above formula, it can be seen that the current amplitude of the fault line is related to the time of fault occurrence, while the frequency and attenuation rate of the whole waveform are related to the line parameters of fault occurrence and independent of the time of fault (voltage phase angle). To illustrate this situation, the transient current waveforms at the time of fault occurrence are shown in Figure 7 when $t = 0, 1, 3, 5$ ms, respectively.

$$If = \frac{U \omega C \sin(\omega t)}{\left(\omega^2 L_C + \omega RC + 1\right)} = \frac{\omega C}{\omega^2 L_C + \omega RC + 1} \times U \sin(\omega t) \quad (4)$$

Figure 7. Transient current simulation waveform at different fault time.

As can be seen from the above figure, the frequency components of transient signals are basically the same at different fault occurrence times, only the amplitude changes significantly.

4. Fault mechanism analysis

According to the different characteristics of fault points, single-phase grounding faults of small current grounding can be generally divided into stable grounding (including gold attribute grounding (low resistance grounding), high resistance grounding), intermittent grounding and arc grounding.

4.1. Stable grounding

Stability grounding is usually the conductor directly laid on the grounding metal body. In the process of the conductor laying on the grounding metal body, the conductor moves to the grounding metal body at a certain speed. With the approaching of the two, the distance between them is less than that between insulating breakdown voltage (generally when the ground voltage is higher, such as near the
peak value), or when the lightning arrester breaks down due to insufficient insulation strength, the fault occurs. The charge on the distributed capacitor of the line discharges to the ground, forming a discharge current pulse, and the amplitude of the voltage to the ground drops suddenly. The discharge pulse has the following characteristics: (1) At the moment of grounding fault, a transient current with high frequency and large amplitude appears at the grounding point. The amplitude of the transient current component is several to tens times larger than the steady-state value of the capacitive current flowing through the same point. (2) At the instant of grounding, the fault phase capacitance charge discharges to the fault point through the fault phase line, and the distributed capacitance, inductance and resistance of the fault line attenuate the high frequency transient component.

4.2. Intermittent grounding
When grounding point insulation can be restored in a short time, intermittent grounding faults will generally occur, such as grounding faults caused by wet insulators. When grounding current dries wet grounding passages, insulation will be restored, but soon due to rain or wet is broken down again, so repeated. Another example is that damp branches are regularly laid and detached from the conductor due to the wind. The fault usually occurs at the time when the voltage between the conductor and the ground is high. Each grounding will produce a transient current and voltage signal. The signal characteristics are similar to the transient signal generated when the conductor is grounded stably.

4.3. Arc grounding
Arc grounding is caused by air breakdown between two conductors when they are close to each other but not in contact, and air is ionized to form an arc channel, which results in grounding fault and instantaneous transient current and voltage signals [20]. The conductive channel formed by arc channel is unstable due to the external air flow, which causes a large number of harmonics in the grounding current. Such faults are easy to occur when conductors are laid on the ground and insulators are broken down.

Intermittent grounding and arc grounding belong to unstable grounding. They sometimes transform each other. For example, arc light will be extinguished in strong wind (ionized air will be blown away, arc resistance will increase or even insulation will be restored), and extinguished arc light will break down and reburn at high voltage, which will produce similar characteristics of intermittent discharge. The conductor with intermittent grounding will also produce arc grounding during its movement, and so on.

Considering that the main faults in actual operation are mostly insulation breakdown, usually near the peak point of ground voltage, so the faults are usually set when the voltage is high. Without losing its generality, the voltage phase angle of fault also considers other angles such as 0°, 30°, 60°, 90°, 120°, 150°.

5. Conclusions
Based on PSCAD, a simulation model of distribution network for single-phase-to-ground fault simulation and analysis of small current grounding system is built. By changing the fault location, fault line type, transition resistance of grounding point, fault time, and combining with the mechanism of fault occurrence, the influence of various factors on the distribution of fault characteristics is analyzed and acquired, which solves the problem that it is impossible to systematically analyze and summarize the distribution of fault characteristics in the absence of real field data covering various possibilities. It can be seen that the fault location, line type, transition resistance and fault time all affect the distribution network single-phase grounding fault characteristic distribution; the influence of fault location is relatively weak; the fault characteristic of cable line is more obvious under the same length; the larger the transition resistance, the less obvious the fault characteristic; and the fault time more affects the fault waveform amplitude.

From the point of view of detection, combined with the actual situation of field operation, it is more realistic to select the overhead-cable hybrid line for simulation. The overhead proportion is
larger, the requirements for equipment detection are more stringent, and the test results are more practical. The fault time can be selected according to a certain time series interval (for example, $30^\circ$) to meet the detection requirements.

Acknowledgement
This paper is funded by the State Grid Corporation of China Science and Technology Project: Research on Test and Inspection Technology of Distribution Automation Terminal Equipment (PD71-16-012).

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