Single-phase-to-ground fault model analysis of arc suppression coil grounding system in distribution network

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Abstract. Start your abstract here…The short-circuit fault type of China's medium-voltage distribution network is 80% single-phase ground fault. Since the non-effective grounding system can continue to operate for 1~2 hours after single-phase-to-ground fault, the analysis of the single-phase-to-ground fault model is very necessary for the arc-suppression coil grounding mode in distribution network. In this paper, by establishing a single-phase ground fault model of the distribution network with arc-suppression coil grounding method, it is theoretically analysed that is the different transition resistances in metallic grounding, high-resistance grounding and intermediate state, and use ATP/EMTP simulation to analyse the fault occurrence, the change and difference of the current waveform on the fault line and the normal line as well as the arc suppression coil. It is concluded that when the single-phase ground fault occurs in the distribution network under the grounding mode of the arc suppression coil, no matter how the transition resistance changes, the current direction of the fault line and the normal line (when the predetermined reference direction is the bus flowing to lines) is reversed, but the difference between the fault current and the normal current is weakened with the change of the transition resistance, so different faults models should be used for different grounding resistances to analyse the transient currents of normal and fault lines on the zero sequence circuit model.

1. Introduction

Most power distribution networks in China adopt the operation mode of neutral ungrounded or grounded through arc suppression coil (i.e., grounded with small current) [1]. When single-phase grounding fault occurs in this system, it is very difficult to detect the fault because of the small current amplitude at the fault point. It is of great significance to identify the fault line in time and accurately for the safe and stable operation of the distribution system.

At present, there is no accurate theoretical analysis for the single-phase grounding fault model of distribution network under the grounding through arc suppression coil in China [2-8]. All the
conclusions came out from discussing based on that the fault grounding resistance is metallic and the corresponding small line parameters are ignored under the high resistance state. In the analysis model proposed in Reference [9], during the initial transient process of single phase grounding fault, the inductance value of arc suppression coil connected to the neutral point of distribution network is obviously larger than the equivalent inductance of power network, and the influence of equivalent resistance value and inductance value of arc suppression coil can be ignored. The transient capacitance current is obtained by a series second-order loop composed, in the transient equivalent circuit, of zero-sequence equivalent parameters of the network, L0 and R0, and three-phase equivalent capacitance to ground, C. In Reference [10], the equivalent line model of single-phase grounding fault is analyzed respectively when the system was grounded through the arc suppression coil and when it is ungrounded. The grounding mode through the arc suppression coil can be divided into two cases: when the grounding resistance is small (metallic grounding) and when the grounding resistance is large (high resistance grounding). The inductance and resistance parameters of the arc suppression coil and the line itself are ignored respectively, and the second-order differential equation was obtained to solve the capacitance current.

From the above description, it can be seen that there is no accurate analysis of single-phase grounding fault model under the grounding mode of arc suppression coil. Therefore, this paper establishes a simulation model to analyze the single-phase grounding fault model of small current grounding system in detail in terms of theory and simulation, including the following situations: (1) When the fault grounding resistance is small, the influence of arc suppression coil inductance is ignored; (2) When the fault grounding resistance is large, the inductance parameters of the line are ignored; (3) When the fault grounding resistance is in the intermediate state of the conditions (1) and (2), neither the arc suppression coil nor the line inductance is ignored.

2. Diagram of Arc Suppression Coil Grounding Model in distribution network

Figure 1 is the diagram of Arc Suppression Coil Grounding Model in distribution network. Where, L is equivalent inductance of arc suppression coil, G and Cg are equivalent three-phase inductance and capacitance of transformer and generator. C1, C2 and C3 are equivalent capacitances of Line 1, 2 and 3 respectively. The fault condition shown in Figure 1 is a single-phase ground fault in phase A of line 3.

![Figure 1. Schematic diagram of 10kV arc suppression coil grounding system](image)

The resistance and inductance parameters of the line are not marked in the figure 1, and the fault point position of the line 3 will change with different situations in the subsequent simulation process.
3. Theoretical analysis

Figure 2 is the zero-sequence equivalent circuit diagram of 10kV system when single-phase grounding fault occurs under the grounding mode of arc suppression coil. As shown in the figure 2, we divide the diagram into four parts, I is the non-fault line part, II is the arc suppression coil, III is the upstream of the fault line, and IV is the downstream of the fault line. According to the overall study of the model in figure 2, the differential equation established in the transient process is 7th order. I, II and IV contain capacitance and inductance respectively, and II is an inductance. It is very difficult to solve the 7th-order differential equation. Besides, when there are many bus outgoing lines, the non-fault lines are connected in parallel, so the equivalent inductance value of I of the non-fault lines becomes smaller and smaller, and then the inductance value of normal lines can be ignored. In the theoretical analysis model of this paper, it is assumed that the fault occurs in a short line and is grounded, and that the fault line itself has no parameters L and C, so the equivalent inductance of the normal lines cannot be ignored in this situation. From the above, we can get a simplified model which is more in line with reality and simplifies the equation solving.

![Figure 2. Zero-sequence equivalent circuit diagram](image)

3.1. The situation ignoring the inductance parameters of arc suppression coil

When the fault grounding resistance is small, the charging speed of the zero-mode capacitor is relatively fast, and the free oscillation frequency of the capacitor current is relatively high. When calculating the zero-mode current $i_f$ in the transient process, the influence of the inductance of the arc suppression coil can be ignored. Assuming that the fault occurs when the voltage peaks and
\( u_f(t) = U_m \cos(\omega t) \), the transient zero-sequence current flowing through the grounding point can be obtained as follows:

\[
i_f(t) = U_m \omega C I \left( \frac{\omega_0}{\omega} e^{-\delta t} \sin \left( \sqrt{\omega_0^2 - \delta^2} t \right) - \sin(\omega t) \right)
\]  \( (1) \)

Where, \( \delta = \frac{R_f}{2L} \) is the attenuation coefficient of free component; \( \omega_0 = \sqrt{\frac{1}{L C}} \) is the resonant angular frequency of the loop.

It can be seen from figure 3 that the current direction of fault lines are the same as the current direction of the normal lines under the reference direction of figure 3, that is, under the current reference mode in figure 1, the zero sequence current direction of fault lines are opposite to that of normal lines.

3.2. The situation ignoring the line inductance parameters

![Figure 4. Zero-sequence equivalent circuit diagram when grounding with high resistance](image)

When the fault occurs and the grounding resistance is large, the influence of line series inductance can be ignored. Due to the slow charging speed of zero-mode capacitor, the transient process lasts for a long time after single-phase grounding fault occurs in distribution network. Therefore, for distribution network system grounded by arc suppression coil, the influence of inductance parameters of arc suppression coil must be considered.

According to the basic theory of nonlinear circuit, the differential equation for solving zero sequence current can be established:

\[
u_f(t) = R_f C I \frac{d^2 i_f(t)}{dt^2} + L_c \frac{di_f(t)}{dt} + R_f i_l(t) \quad (2)
\]

According to the characteristic root of Formula (2), it can be concluded that the angular frequency of the zero-sequence current flowing through the grounding point is:

\[\omega_0 = \frac{1}{\sqrt{C_l L_c}}\]

Attenuation coefficient of grounding fault current is:

\[\delta = \frac{1}{2R_f C_l}\]
3.3. The situation not ignoring arc suppression coil and line inductance

![Figure 5. Zero-sequence equivalent circuit diagram keeping arc suppression coil and line inductance](image)

In figure 5, $R_f$ is grounding resistance, $L_c$ is equivalent inductance of arc suppression coil and $L_I$ and $C_I$ are equivalent inductance and capacitance of normal line respectively. In figure 5, transformer inductance is neglected and transformer capacitance is equivalent to $C_I$, $u_f$ is zero sequence voltage of grounding point. $i_I$ is the sum of currents in normal lines whose reference direction in figure 3 is the same as that of the system schematic diagram. $i_f$ is current in fault lines whose reference direction in figure 2 is opposite to that specified in the system. $i_c$ is the current flowing through the arc suppression coil.

According to Kirchhoff's law and Ohm's law, the following equations can be established:

$$
\begin{align*}
    u_f(t) &= R_f i_f + L_c \frac{di_c(t)}{dt} \\
    L_c \frac{di_c(t)}{dt} &= L_I \frac{di_I(t)}{dt} + u_c(t) \\
    C_I \frac{du_c(t)}{dt} &= i_c 
\end{align*}
$$

(3)

The image functions of current $i_I$ and current $i_f$ obtained through Laplace transform are:

$$
\begin{align*}
    I_c(s) &= \frac{C_1 L_c s^2}{R + L_c s + C_1 R (L_c + L_I) s^2 + C_1 L_c L_I s^3} U_f(s) \\
    I_f(s) &= \frac{1 + C (L_c + L_I) s^2}{R + L_c s + C R (L_c + L_I) s^2 + C L_c L_I s^3} U_f(s)
\end{align*}
$$

(4)

Assuming $u_f(t) = U_w \sin(\omega t)$ ( $\omega$ is the angular frequency of the fundamental frequency), then $U_f(s) = U_w \omega \left(s^2 + \omega^2\right)^{-1}$. The following can be obtained through Laplace transform:
Among them:
- #1 an expression composed of five quantities \(C_t\), \(L_t\), \(L_c\), \(R_f\) and \(\omega\) through addition, subtraction, multiplication and multiplication. When their values are definite values, the value of #1 is a constant;
- #2\(=\sum_{n=0}^{\infty} \frac{e^{\omega t}}{n!}\);
- #3\(=\sum_{n=0}^{\infty} \frac{\omega^2 e^{\omega t}}{n!}\);
- #4=\text{rootof}\(\{R + L_c s_3 + C_l R(L_c + L_1) s_3^2 + C_l L_c L_1 s_3, s_1\}\);
- #5=\text{rootof}\(\{L_c + 3C_l L_c L_1 r_3^2 + 2C_l L_c R r_3 + 2C_l L_1 R r_3\}\);
- #6 an expression composed of five quantities \(C_t\), \(L_t\), \(L_c\), \(R_f\) and \(\omega\) through addition, subtraction, multiplication and multiplication. When their values are definite values, the value of #6 is a constant;
- #7=\text{rootof}\(\{R + L_c s_3 + C_l R(L_c + L_1) s_3^2 + C_l L_c L_1 s_3, s_1\}\);
- #8=\text{rootof}\(\{R + L_c s_3 + C_l R(L_c + L_1) s_3^2 + C_l L_c L_1 s_3, s_1\}\);
- #9=\text{rootof}\(\{R + L_c s_3 + C_l R(L_c + L_1) s_3^2 + C_l L_c L_1 s_3, s_1\}\);
- #10=\text{rootof}\(\{R + L_c s_3 + C_l R(L_c + L_1) s_3^2 + C_l L_c L_1 s_3, s_1\}\);

Conclusion: After a fault occurs, the current values of both fault lines and non-fault lines contain fundamental frequency components, and the final current values are related to the roots of the equation \(23333(\#10) = 0\). If the roots are both real numbers, there are direct current components; if the roots are complex numbers, there are high frequency components. According to the parameters of the equation, the roots of the equation are related to the related parameters of the lines. The solution of the root of one-variable cubic equation can be given by Shengjin Formula [11].
Through the analysis of the above situations, it can be concluded that the characteristics of the transient process of the single-phase grounding fault in the neutral point grounding system via the arc suppression coil are related to the grounding resistance of the fault point, the resistance, capacitance and inductance parameters of the line and the compensation of the arc suppression coil.

4. Simulation modelling
The simulation model is built by software ATP/EMTP, and the model is shown in figure 6. The power station system has an incoming line for returned current, and three low-voltage outgoing single buses come out through a main transformer connected by star angle. The lines include: Line 1 - pure overhead line, Line 2 - pure cable line and Line 3 - mixed line. The arc suppression coil is grounded through the neutral point of Z-transformer, and the overcompensation is 10%. The simulation sampling rate of the simulation system is 1MHz, the fault occurrence time is 0.0883s, and the operation time of the simulation system is 0.5s.

Main electrical simulation parameters are as follows:
- Main transformer: $S_N = 2$ MVA, $P_k = 20.586$ kW, $U_k\% = 6.37\%$, $P_0 = 2.88$ kW, $I_0\% = 0.61\%$, Y/Δ connection.
- Cable route: $r_1 = 0.123\Omega/km$, $x_1 = 0.072\Omega/km$, $b_1 = 132 \times 10^{-4} S/km$; $r_0 = 1.23\Omega/km$, $x_0 = 0.288\Omega/km$, $b_0 = 110 \times 10^{-6} S/km$.
- Overhead lines: $r_1 = 0.21\Omega/km$, $x_1 = 0.4\Omega/km$, $b_1 = 3.178 \times 10^{-4} S/km$; $r_0 = 0.21\Omega/km$, $x_0 = 2.2\Omega/km$, $b_0 = 0.676 \times 10^{-6} S/km$.
- Distribution transformer: $S_N = 0.5$ MVA, Δ/Yn connection.
- Load: The load capacity accounts for 80% of the distribution transformer capacity, and the power factor is 0.85.

![Simulation model](image)

5. Simulation analysis

5.1. Different simulation scenarios
In this section, types of factors affecting fault line selection of single-phase grounding in resonant grounding system will be analysed first. In the case of different line types, fault locations and transition resistance, the single-phase ground fault may occur in the simulated neutral point grounding system through arc suppression coil, then the change rule of line fault current characteristics before and after the fault occurs will be analysed.
5.1.1. Fault location.
According to 2.2 of the theoretical analysis in the second section, the fault points can be divided into the head end of the line (the distance between the fault point and the bus is 10% of the length of the line), the middle (50%) and the end (10%), and the fault phase is Phase A.

5.1.2. Type of fault line.
Simulation is carried out, assuming that faults occur on three types of Line 1, 2 and 3, in which Line 1 is a pure overhead line, Line 2 is a pure cable line and Line 3 is a mixed line.

5.1.3. Earthing resistance. The simulation is carried out for metallic grounding, 10 Ω, 100 Ω, 200 Ω, 500 Ω, 1 000 Ω, 2 000 Ω, 5 000 Ω, etc.

5.2 Simulation of Different Fault Locations
Suppose that a grounding fault occurs on line 1, and the grounding resistance is 10 Ω, carry out the analysis of characteristics of transient zero sequence current of fault line and non-fault line by changing different fault points.

From the current waveform group diagram shown in figure 7, it can be seen that although the waveform change of the zero-sequence current changes little with different fault points, the oscillation frequency of high-frequency component of zero-sequence signal is affected accordingly. The transient zero-sequence oscillation frequency at the head end of the line is relatively high. And the farther the fault distance is, the longer the attenuation time is.

![Figure 7. Simulation current waveform diagram of different fault locations](image-url)
5.3. Simulation of Different Line Types

Suppose that Phase A grounding fault occurs on Lines 1, 2 and 3, respectively, with the grounding resistance of 10Ω, analyze and the fault point is in the middle of the line. Then the characteristics of transient zero sequence current of fault lines and non-fault lines can be analysed.

From the current waveform group diagram in figure 8, it can be seen that attenuation process of the zero-sequence current transient component on pure cable lines is shorter than that on pure overhead lines, and the oscillation frequency is higher.

![Figure 8. Simulation current waveform diagram of different types of lines](image)

(a) Overhead lines

(b) Cables

(c) Mixed lines

5.4. Simulation of Different Grounding Resistance

Suppose that Phase A grounding fault occurs on Line 1, and the fault point is in the middle of the line. Then the characteristics of transient zero sequence currents of fault lines and non-fault lines can be analysed by changing different grounding resistances.

From the current waveform group diagram in figure 9, it can be seen that the transient process of the zero sequence current of the fault line and the normal line is not obvious when the transition impedance is large, and the amplitude is small, and it quickly transits to the steady state, which is consistent with the actual situation of the project. When the transition impedance is small, that is, when grounded with metal, the transient process of fault line and normal line is obvious, and the amplitude of transient zero sequence current is obviously larger than that when grounded with high resistance, so the attenuation speed of transient current will accelerate with the increase of transition resistance.

Therefore, when the transition resistance is small, the charging speed of zero-mode capacitor is faster, the free oscillation frequency of capacitor current is higher, and the attenuation time of free
component is longer. We can use the model shown in figure 3. When the transition resistance is too large, the attenuation speed of transient current is accelerated, the transient process is not obvious, and the amplitude is obviously reduced, so the model shown in figure 4 can be used for analysis. When the transition resistance is in the intermediate state of the above two cases, neither the influence of the arc suppression coil nor the influence of the resistance and inductance of the line can be ignored. Because the oscillation and attenuation of the free component are related to several parameters as described in 2.3, ignoring any one of them will affect the accuracy of fault line selection.

(a) Metallic grounding

(b) 10 Ω grounding resistance

(c) 100Ω grounding resistance

(d) 200Ω grounding resistance

(e) 500Ω grounding resistance

(f) 1000Ω grounding resistance
6. Conclusion
In this paper, the single-phase grounding fault model of distribution network system with neutral point grounded by arc suppression coil has been analysed. The equivalent zero-sequence model diagram has been drawn for short fault line to analyse it theoretically. The third-order differential equation has been established and the current expressions on fault line and non-fault line have been solved. According to different line conditions, fault locations, grounding resistances and other conditions, the following conclusions are drawn:

When single-phase grounding fault occurs in distribution network grounded by arc suppression coil, the current direction of fault line is always opposite to that of normal line no matter how the transition resistance changes. The factors affecting the characteristics of single-phase grounding fault in distribution network with neutral point grounded by arc suppression coil include grounding type, line type, fault location, transition resistance and so on. The fault characteristics of cable lines with the same length as overhead lines are more obvious; from the simulation situation, the influence of fault location is relatively weak; the fault characteristic becomes less obvious with the increase of grounding resistance at fault points, which makes fault identification and fault line selection more difficult.

When the fault grounding resistance reaches hundreds of ohms or more, oscillation and attenuation phenomenon will appear in the free component in transient zero-sequence current. If the transition resistance reaches a certain extreme condition, the oscillation period will approach the power frequency value, and the attenuation time constant of the free component can reach tens of milliseconds.

Under different fault grounding resistances, the characteristics of fault line current and normal line current given by the zero-sequence equivalent model are consistent with the simulation results. Therefore, under different transition resistances, the zero-sequence equivalent model matching with its characteristics should be selected for transient current analysis, otherwise, the accuracy of line selection method will be affected to a certain extent.

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