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Analysis and Simulation on Intermittent Arc Grounding Overvoltage for Neutral Grounding via Arc-suppression Coil with Shunt Resistance in 35 kV Urban Distribution System

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Abstract

Due to the significant increase of line-to-ground capacitive current, for urban distribution networks mixed by overhead lines and a larger number of cables, the higher electromagnetic transient overvoltage presents not only always on fault phase and neutral point, but also on non-fault phases when some intermittent arc grounding faults occur. Some arc-suppression coil which has a relatively smaller overcompensation tuning-off degree is mainly used to compensate the line-to-ground capacitive current, reduce the arc residual current and reignition times, and then increase the self-restoration probability after a single phase intermittent arc grounding fault occurs. At the same time, according to the characteristics and performance requirements of distribution systems, a relatively smaller shunt resistance is mainly used to quickly release the charge of line-to-ground capacitance, improve the decay rate of overvoltage of fault phase, non-fault phases and neutral point respectively, reduce the rising speed of neutral point recovery voltage and its amplitude after the intermittent arc dies out, so that the transient overvoltage can be restrained effectively. Results of transient numerical analysis and ATP simulation have demonstrated the mode of neutral grounding via arc-suppression coil with shunt resistance is an optimum choice which is applicable to 35 kV urban distribution networks mixed by overhead lines and cables.

Keywords: *distribution system, neutral grounding, arc-suppression coil, shunt resistance, overvoltage, ATP simulation*

1. Introduction

In recent years, with the constant urbanization and the upgrading of urban distribution systems, more and more 35 kV urban distribution networks are used, and the urban network structures mixed by overhead lines and a large number of cables are formed gradually [1, 2]. Due to the increase of the quantity of distribution cables, when some intermittent arc grounding fault occurs, the power system line-to-ground capacitive current has significantly increased and the arc is difficult to extinguish, so the higher arc grounding overvoltage or resonance overvoltage presents not only on fault phase and neutral point, but also on non-fault phases [3, 4].

The mode of neutral grounding via arc-suppression coil with shunt resistance is more applied in the study of fault line selection, but with regard to restraining arc grounding overvoltage, the in-depth researches are still insufficient [5, 6]. In this neutral grounding mode, inductive current of arc-suppression coil compensates the capacitive current and then reduces the flow of arc grounding fault residual current, so as to reduce the reignition times

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and increase the self-restoration probability after single phase intermittent arc grounding fault occurs[7, 8]. At the same time, the shunt resistance on both sides of the arc-suppression coil can increase the damping ratio of power system and improve the decay rate of overvoltage of fault phase, non-fault phases and neutral point respectively in the first few cycles of single-phase arc grounding fault. It can also prolong the recovery voltage rise time so as to reduce the rising speed of neutral point recovery voltage and its amplitude after the intermittent arc grounding fault is also reduced, thereby the transient overvoltage can be restrained effectively[9].

The paper presents the mode of neutral grounding via arc-suppression coil with shunt resistance for 35 kV urban distribution systems, provides the transient numerical analysis of the generating mechanism of intermittent arc grounding overvoltage, simulates the overvoltage of six cases of neutral grounding for one 35 kV urban distribution system by using ATP(Alternative Transient Program) software, and also confirms the value of overcompensation tuning-off degree and the value of shunt resistance in the case of neutral grounding via arc-suppression coil with shunt resistance by comparison. Results of transient numerical analysis and ATP simulation have demonstrated the mode of neutral grounding via arc-suppression coil with shunt resistance, which has a relatively smaller overcompensation tuning-off degree and a relatively smaller shunt resistance, is an optimum choice, which is applicable to 35 kV urban distribution systems.

2. Transient Numerical Analysis

Figure 1 shows an urban distribution system of neutral grounding via arc-suppression coil with shunt resistance. In Figure 1, X_L represents then arc-suppression coil used for capacitiv e current compensation; R_0 represents the shunt resistance used for earth fault line selection and overvoltage suppression, etc; and R_d represents the equivalent resistance which includes arc grounding transition resistance and zero sequence resistance of lines. Among them, the a rc grounding fault occurs at point ‘K’ on phase C of LINE. l.

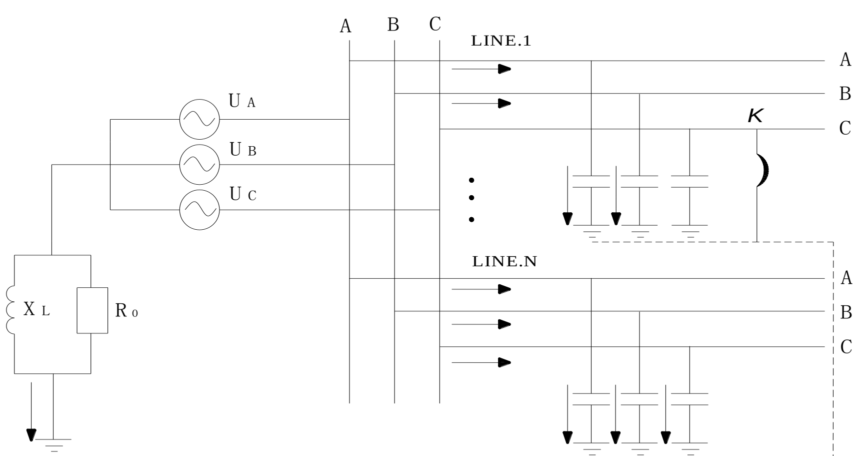


Figure 1. Diagram of Distribution System of Neutral Grounding via Arc-suppression Coil with Shunt Resistance

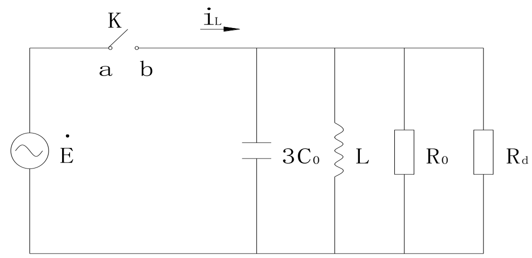


Figure 2. Equivalent Circuit of Distribution System of Neutral Grounding via Arc-suppression Coil with Shunt Resistance

Figure 2 shows the equivalent circuit of the above-mentioned distribution system which neglects the loss of arc-suppression coil and the admittance against the ground. In Figure 2, the gap between points 'a' and 'b' indicates the arc clearance; 'K' represents then arc state switch, when 'K' disconnect it means arc extinguishes and when 'K' closes it means arc is burning, and the current flowing through 'K' is the grounding residual current; the potential of point 'b', which is denoted with $u_0(t)$, is the zero sequence voltage of neutral point of this compensation distribution system.

Then, suppose the arc grounding fault occurs, that is, the arc state switch 'K' closes, the zero sequence current of arc-suppression coil is i_L. Taking $u_0(t)$ as the research variable, from equivalent circuit the following state equation is written:

$$\begin{cases} L\dfrac{di_L}{dt} = u_0 \\ 3C_0\dfrac{du_0}{dt} = -i_L - \dfrac{1}{R_d}u_0 - \dfrac{1}{R_0}u_0 - \dfrac{1}{R_d}u_p(t) \end{cases} \tag{1}$$

Solving state equation (1), zero sequence voltage of neutral point of the distribution system can be obtained as follows:

$$\begin{aligned} u_0(t) = {} & \frac{R_0}{R_d + R_0}U_m \cdot e^{-\delta t}[(\frac{\omega_0^2}{\omega'\omega}\cos\varphi - \frac{\delta}{\omega'}\sin\varphi)\sin\omega't + \sin\varphi\cos\omega't] \\ & + [-U_m\frac{\omega_0}{\omega'} \cdot e^{-\delta t}\sin(\omega't+\varphi) + U_m\sin(\omega't+\varphi)] \end{aligned} \tag{2}$$

where i_L is the zero sequence current of arc-suppression coil; u_0 is the zero sequence voltage of distribution system; $3C_0$ is the zero sequence equivalent capacitance of line-to-ground state; U_m is the amplitude of phase voltage; $\omega_0 = \sqrt{\frac{1}{L \cdot 3C_0}}$ is the resonant frequency of equivalent circuit; φ is the initial phase-angle of fault phase voltage determined by R_0 at the moment of arc extinction; $d = \frac{1}{\omega R' \cdot 3C_0}$ is the damping ratio of power system with $R' = \frac{R_0 R_d}{R_0 + R_d}$; $\delta = \frac{1}{2R_0' \cdot 3C_0}$ is the attenuation coefficient and there is $\delta = \frac{\omega d}{2}$; $\omega' = \sqrt{\omega_0^2 - \delta^2}$ is the free oscillation frequency of equivalent circuit.

In equation (2), the first item is the transient zero sequence voltage generated by the oscillation process of power system, the second one is the zero sequence voltage of neutral point generated by the power source of distribution system. The basic prerequisite for oscillation process is $R' > \frac{1}{2}\sqrt{\frac{L}{3C_0}}$. In addition, i_L and u_0 present periodically attenuation in the process of oscillation. At this point, the value of $\delta = \frac{1}{2R' \cdot 3C_0}$ is small and it can be considered $\omega' \approx \omega_0$. Meanwhile, the value of $\nu = 1 - \frac{1}{\omega^2 L \cdot 3C_0}$ is very small, so equation (2) can be simplified as:

$$u_0(t) = -\frac{R_0}{R_d + R_0} U_m \cdot e^{-\delta t} \sin(\omega' t + \varphi) - \frac{R_0}{R_d + R_0} U_m \sin(\omega t + \varphi) \quad (3)$$

If 'K' is switched off, which means the arc is extinguished, the voltage of point 'a' can be written as:

$$u_a(t) = U_m e^{j(\omega t + \varphi)}$$

However, the variation of the voltage of point 'b' is an oscillating attenuation process, and it can be written as:

$$u_b(t) = -U_m e^{-\delta t} \cdot e^{j(\omega_0 t + \varphi)}$$

Then, the recovery voltage of fault phase (phase C), the voltage between the points 'a' and 'b', can be obtained as:

$$u_h(t) = U_m [e^{j(\omega t + \varphi)} - e^{-\delta t} \cdot e^{j(\omega_0 t + \varphi)}]$$

After simplification, the recovery voltage can be expressed as:

$$u_h(t) = U_m \cos(\omega t + \varphi) - U_m e^{-\delta t} \cos(\omega_0 t + \varphi) \quad (4)$$

In addition, the overcompensation tuning-off degree of arc-suppression coil is $\nu = 1 - \frac{1}{\omega^2 L \cdot 3C_0}$, so there is $\omega_0 = \omega\sqrt{1 - \nu}$. Generally, ν is smaller, then there is:

$$\omega_0 = \omega\sqrt{1 - \nu_0} = \omega\left(1 - \frac{1}{2}\nu + \frac{1}{2 \times 4}\nu^2 - \frac{1 \times 3}{2 \times 4 \times 6}\nu^3 + \cdots\right) \approx \omega\left(1 - \frac{1}{2}\nu\right)$$

Hence, equation (4) can be written as:

$$u_h(t) = U_m [\cos(\omega t + \varphi) - e^{-d\delta t/2} \cos(\omega_0 t - \frac{1}{2}\nu\omega t + \varphi)] \quad (5)$$

When the distribution system is running in undercompensation state (That is $\nu > 0$) or in overcompensation state(That is $\nu < 0$), due to the different frequency between ω and ω_0 in equation (4), the recovery voltage presents clap-frequency properties inevitably and its angular frequency is $\omega - \omega_0$. Maybe oscillation overvoltage presents in the fault phase if tuning-off degree is relatively larger, while a relatively smaller tuning-off degree is helpful in reducing the rising speed of fault phase overvoltage, and the resonance phenomenon rarely occurs. Therefore, the overcompensation tuning-off degree of neutral grounding distribution system via arc-suppression coil with shunt resistance should be kept in the range of 10% [10-11].

With regard to the distribution system of neutral grounding via arc-suppression coil with shunt resistance, due to the energy loss on shunt resistance, the damping ratio of power system is increased, the decay speed of neutral point potential accelerated, the recovery voltage rise time prolonged, the amplitude of recovery voltage also reduced, and the intermittent arc quenched easily. In addition, when the tuning-off degree is fixed, if the shunt resistance is too large, the damping ratio will diminish, which easily leads to the production of large overvoltage in the latter stage of voltage recovery; on the contrary, if the shunt resistance is too small, the damping ratio will become larger, which easily leads to the production of large grounding residual current, and the arc cannot be quenched easily. In general, the value of shunt resistance should be selected according to the characteristics and performance requirements of distribution system.

3. Simulation of Arc Grounding for 35 kV Urban Distribution System

Intermittent arc grounding overvoltage can be explained by arc extinction theory of high frequency or that of power frequency[12-13]. However, the value of overvoltage analyzed by power frequency arc extinction theory is closer to the engineering practice. Therefore, by combining with a 110/35 kV urban distribution system of Langfang(Hebei Province of China) and using power frequency arc extinction theory and ATP software, the paper sets up a simulation model and presents some comparative analysis of intermittent arc grounding overvoltage.

3.1. Model and Simulation for One 35 kV Urban Distribution System

Figure 3 shows a 110/35 kV urban distribution system of Langfang. On the bus side of the system, there are five overhead lines, and the length of each line is listed as follows: L_1=18 km, L_2=21 km, L_3=25 km, L_4=23 km, L_5=26 km. Z-T model is used for overhead line simulation, and its positive sequence resistance is 0.17 Ω/km; its positive sequence impedance is 1.21 mH/km; its positive sequence capacitive reactance is 0.00969 μF/km; its zero sequence resistance is 0.23 Ω/km; its zero sequence impedance is 5.478 mH/km; and its zero sequence capacitive reactance is 0.00689 μF/km. The type of main transformer (T_1) is SFPSZ9-240000/110, and its connection mode is Y_0/Δ_0. After calculation, the maximum capacitance current of the distribution system is set as 14.08 A. Considering the problems like system expansion, overcompensation is set and arc-suppression coil with shunt resistance is connected with distribution system through grounding transformer (T_2). The impact of distribution system load on zero sequence circuit of single-phase earth fault is smaller, therefore the load impedance of each output line for simulation model is set as Z=(400+j20) Ω.

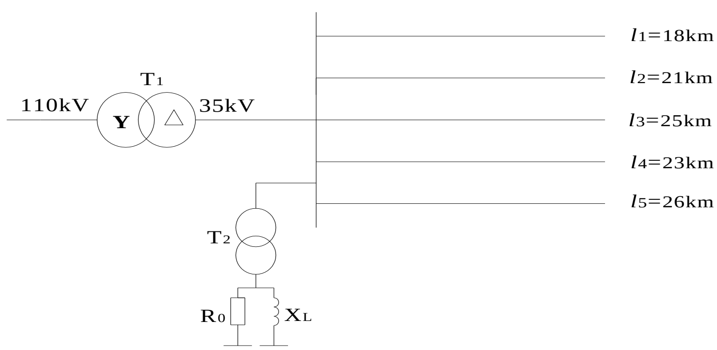


Figure 3. Diagram of 110/35 kV Urban Distribution System

Using ATP software, the above-mentioned model is simulated. During the simulation, the time control switch ‘K’ is used to simulate the burning and extinguishing of the intermittent arc. In the simulation, given the most serious overvoltage occurrence mechanism, earth fault occurs at the peak time of voltage of phase C, and each time interval of arc is about half of the power frequency cycle(10 ms). The control sequence of switch ‘K’ presents as follows:

The first arc ‘burning—quenching’: ‘K’ closes at 0.02215s, then switches off at 0.03215s;

The second arc ‘burning—quenching’: ‘K’ closes at 0.04215s, then switches off at 0.0521 5s; The third arc ‘burning—quenching’: ‘K’ closes at 0.06215s, then switches off at 0.0721 5s, and then earth fault disappears.

3.2. Selection of Neutral Grounding Mode

According to the characteristics and performance requirements of this 35 kV urban distribution system, six neutral grounding cases used for comparative analysis are as follows:

Case 1: isolated neutral system.

Case 2: neutral grounding via small resistance.

Case 3: neutral grounding via medium resistance.

Case 4: neutral grounding via arc-suppression coil.

Case 5: neutral grounding via arc-suppression coil with series resistance.

Case 6: neutral grounding via arc-suppression coil with shunt resistance.

Assume that intermittent arc grounding fault occurs at the point of phase C of L_5, which is 12 km away from the transformer. In the simulation, the value of arc channel resistance is taken as 4 Ω according to the ideal condition; the value of small resistance is taken as 5 Ω; the value of medium resistance is taken as 50 Ω; the value of series resistance is taken as 5 Ω; the value of shunt resistance is taken as 5 Ω; the value of overcompensation tuning-off degree is taken as 0.06; the value of arc-suppression coil inductance is taken as 4.767 H; the values of other parameters are constant.

Table 1. Maximum Values of Phases and Neutral Point in Six Neutral Grounding Modes

Cases	Neutral point (kV)	Non-fault phase A (kV)	Non-fault phase B (kV)	Fault phase C (kV)
1		-55.2	-56.7	-55.1
2	6.99	41.5	44.0	-29.1
3	21.1	41.8	48.3	35.3
4	3.79	44.5	44.0	34.4
5	7.50	42.8	44.8	28.8
6	3.09	43.4	43.7	32.7

After ATP simulation for six different neutral grounding cases, higher overvoltage can be shown on the voltage curves of fault phase, non-fault phases and that of the neutral point recovery voltage. Moreover, longer time and more serious voltage deviation can be presented on the phase A, B and C for the isolated neutral system after the arc grounding fault, which would seriously affects the insulation of electrical equipment. Then comparing the voltages of fault phase, non-fault phases and the neutral point recovery voltage of other cases of neutral grounding modes, which are shown in Table 1, it can be seen that the overvoltage differences of fault phase C and non-fault phase A and B are unconspicuous. But the values of recovery voltage of neutral grounding modes, which consist of neutral grounding via arc-suppression coil and neutral grounding via arc-suppression coil with shunt resistance, are minimal. Therefore, after a comprehensive comparison, it can be considered that neutral grounding via arc-suppression coil and neutral grounding via arc-suppression coil with shunt resistance are relatively optimal ways.

Then, the comparison of neutral point recovery voltage and its attenuation process between case 4 and case 6 are shown as Figure 4. Figure 4 shows the recovery voltage attenuation of case 6, a neutral grounding via arc-suppression coil with shunt resistance, is more rapid than c ase 4, a neutral grounding via arc-suppression coil, and at the sixth cycle after the third arc bu rning the recovery voltage of neutral grounding via arc-suppression coil with shunt resistance has decayed to less than 10%, which is mainly due to the fact that the shunt resistor rapidly re leases the charge of line-to-ground capacitance. At this point, it can be identified primarily th at neutral grounding via arc-suppression coil with shunt resistance is the ideal way for this 35 kV urban distribution system. In the event of three intermittent arc grounding faults of case 6, the voltage curves of fault phase C, non-fault phase A and B, and the neutral point recovery voltage curve are shown as Figure 5.

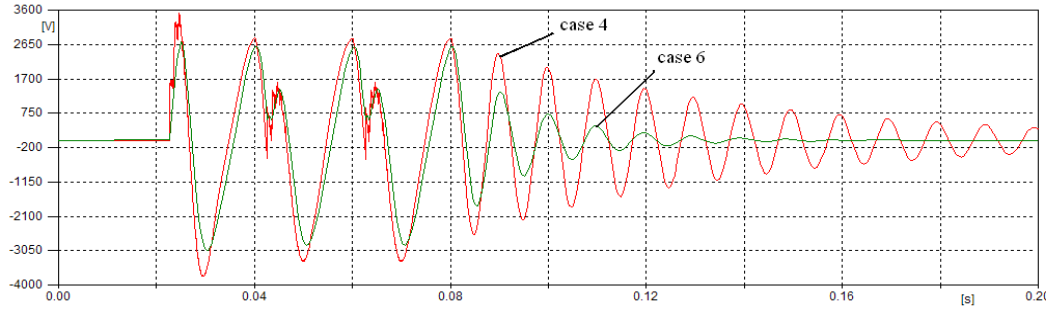


Figure 4. Neutral Point Recovery Voltage Curves of Case 4 and Case 6 for 35 kV Urban Distribution System

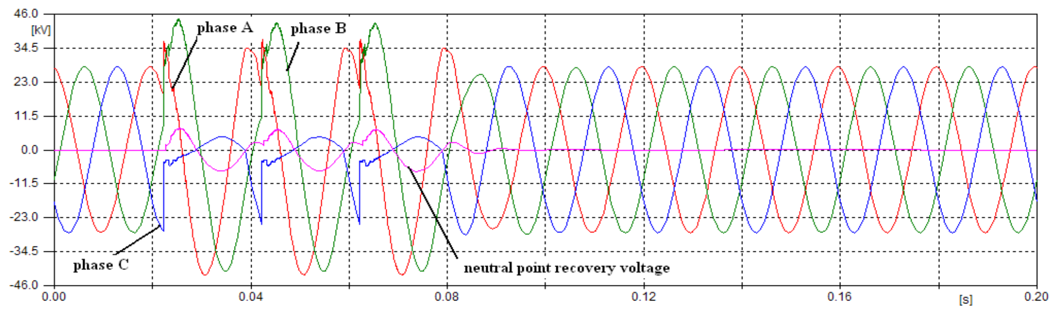


Figure 5. Intermittent Arc Grounding Overvoltage Curves of Case 6 for 35 kV Urban Distribution System

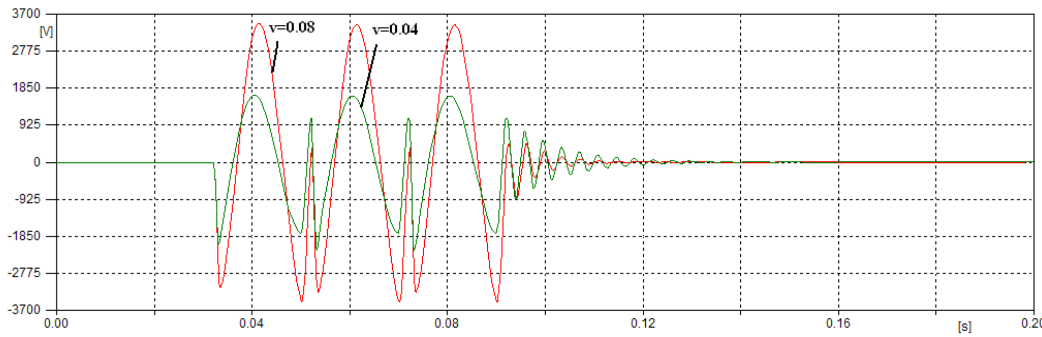
3.3. Selection of Overcompensation Tuning-off Degree

After taking the value of shunt resistance as 5 Ω and 50 Ω, and the value of overcompensation tuning-off degree as 0.04 and 0.08 respectively, ATP simulation of intermittent arc grounding fault has been taken corresponding to the following four cases of neutral grounding via arc-suppression coil with shunt resistance for the 35 kV urban distribution system, and the simulation results are shown in Table 2 which contain the maximum overvoltages of fault phase C, non-fault phase A and B, and recovery voltage of neutral point.

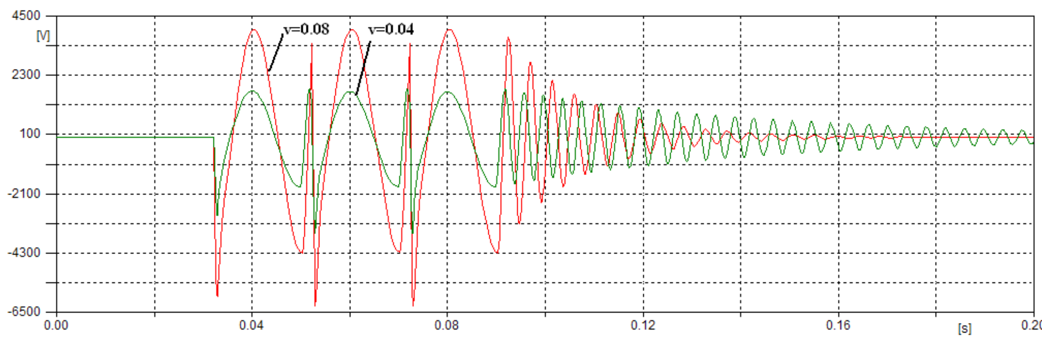
Table 2. Maximum Values of Phase and Neutral Point Voltage under 4 kinds of Different Parameters

Resistance, Inductance	Neutral point (kV)	Phase A (kV)	Phase B (kV)	Fault phase C (kV)
5 Ω，8.06 H	3.51	25.94	28.74	20.71
5 Ω，3.02 H	2.21	25.34	29.62	23.62
50 Ω，8.06 H	6.36	26.50	28.71	25.76
50 Ω，3.02 H	3.61	25.52	30.86	25.26

As can be seen from Table 2, in the cases of the same shunt resistance value with different overcompensation tuning-off degree, although the difference of maximum voltage values of fault phase C and non-fault phase A and B are unconspicuous, the variation of the recovery voltage value of neutral point is obvious. Also in the case of overcompensation tuning-off degree whose value is 0.04, at the first few cycles of single-phase arc grounding fault, the recovery voltage rise time is prolonged so as to reduce the rising speed of neutral point recovery voltage and its amplitude is relatively low, which can also be seen in Figure 6. Therefore, in the cases of neutral grounding via arc-suppression coil with shunt resistance, a relatively smaller overcompensation tuning-off degree is an optimal choice, and the distribution system rarely has any resonance phenomenon.



(a) $R_0 = 5\Omega$, $v = 0.04$; and $R_0 = 5\Omega$, $v = 0.08$

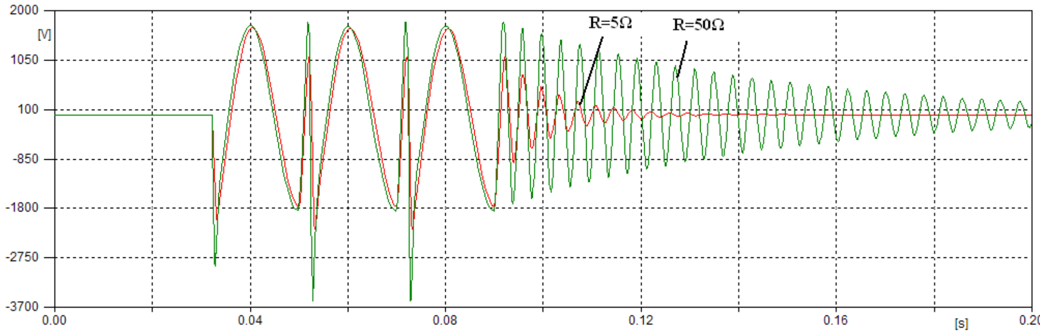


(b) $R_0 = 50\ \Omega$, $v = 0.04$; and $R_0 = 50\ \Omega$, $v = 0.08$

Figure 6. Neutral Point Recovery Voltage Curves of Case 6 for 35 kV Urban Distribution System

3.4. Selection of Shunt Resistance Value

Given that a smaller overcompensation tuning-off degree is selected, for the 35 kV urban distribution system whose neutral point is grounded via arc-suppression coil with shunt resistance, although the difference of maximum voltage values of fault phase C and non-fault phase A and B are unconspicuous, the variation of recovery voltage of neutral point is more obvious. This is mainly embodied in higher amplitude and its relatively slower attenuation for neutral point recovery voltage after three times of arc grounding faults occur, where a larger resistance is paralleled with the arc-suppression coil, and it is shown in Figure 7. By comparison, in the same overcompensation tuning-off degree, a relatively lower resistance of shunt resistor, whose value is 5 Ω, is the optimum choice.



$v = 0.04$, $R_0 = 5\Omega$; and $v = 0.04$ $R_0 = 50\ \Omega$

Figure 7. Neutral Point Recovery Voltage Curves in 35 kV Urban Overcompensation Distribution System

Therefore, according to the characteristics and performance requirements of 35 kV urban distribution system, the mode of neutral grounding via arc-suppression coil with shunt resistance, which has a relatively smaller overcompensation tuning-off degree and a relatively smaller shunt resistance, is the optimum choice.

4. Conclusion

Results of transient numerical analysis and ATP simulation have demonstrated the mode of neutral grounding via arc-suppression coil with shunt resistance is the optimum choice, which is applicable to 35 kV urban distribution system mixed by overhead lines and cables. In this grounding mode, some arc-suppression coil which has a relatively smaller overcompensation tuning-off degree should be selected and mainly used to compensate the capacitive current, reduce the arc residual current and reignition times, and then increase the self-restoration probability after a single phase intermittent arc grounding fault occurs. At the same time, according to the characteristics and performance requirements of distribution system, a relatively smaller shunt resistance should be selected and mainly used to quickly release the charge of line-to-ground capacitance, improve the decay rate of overvoltage of the fault and non-fault phases and neutral point, reduce the rising speed of neutral point recovery voltage and its amplitude after the intermittent arc puts out, so that the transient overvoltage can be restrained effectively.

Acknowledgments

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