Research on Improvement Measure of Fast Fault Point Transfer Technology

Zheng Qi¹, Chunyan Diao¹* and Yuhang Zheng²

¹ School of electric and electronic engineering, North China Electric Power University, Beijing, 102206, China
² State Grid Jiangsu Electric Power Engineering Consulting co. LTD, Nanjing, Jiangsu, 210024, China

*Corresponding author’s e-mail: 18810526320@163.com

Abstract. The fast fault point transfer technology has been widely used in China. Aimed at the single-phase arc-grounding fault in the neutral point non-effective grounding system, the principle is to suppress arc re-burning by grounding the faulty phase bus directly to limit the voltage of fault phase. However, the on-site operation found that the technology could not guarantee the arc on the fault point extinguished reliably. The effects of arc characteristics, bus grounding time, impedance of lines, load current and transition resistance on arc extinguishing are analysed in depth. Among these factors, the grounding time is the only controllable factor. The improvement measure of grounding the faulty phase bus at the zero point of the arc current is proposed, and the hardware and software flow are designed. The proposed method was simulated and analysed by ATP software. The simulation results verified the reliability and accuracy of the proposed method.

1. Introduction

Most medium voltage distribution networks in China adopt neutral point non-effective grounding mode. Its advantage is that single-phase grounding fault can be operated with fault for a period of time. But after single-phase arc grounding fault occurs, arc burning at fault point for a long time is easy to cause fire accidents, and the overvoltage generated also endangers the operation of electrical equipment.

Traditional arc extinguishing technology is to install arc suppression coil at neutral point. This method is mature and has been widely used in distribution network. However, with the increasing scale of distribution network, the grounding current is getting larger and larger. Two shortcomings of arc suppression coil restrict its application scope and arc extinguishing ability. Firstly, arc suppression coil can compensate the fundamental-frequency reactive power component of grounding current, but it cannot compensate the high frequency component and active power component of grounding current. Secondly, the capacity of arc suppression coil is limited by manufacturing technology. As the capacitive current of the system increases, the cost and volume will increases too, and the performance-price ratio will get lower. Many scholars have put forward the improved technology of arc suppression coil to achieve full current compensation [1-7], but the performance-price ratio is low and there is little field application.

In recent years, fault point transfer technology has become a supplement and replacement of arc suppression coil. The principle is that when single-phase arc grounding fault occurs on the line, the
fault phase bus is grounded directly to extinguish the arc quickly. Reference[8] analysed the arc suppression principle of fast switching type to eliminate arc grounding fault and the matching technology of fault identification and fault line selection, and the motion flow of arc suppression device was put forward. However, it is found that the fast fault point transfer technology cannot guarantee the arc extinguished at the original fault point reliably. Especially in the condition of long lines and heavy load, the grounding arc may continue to burn after the bus is grounded.

In this paper, many factors affecting the reliability of fast fault point transfer technology are analysed, including arc characteristics, bus grounding time, line impedance, load and transition resistance. In view of the fact that only the grounding time of the fault phase bus is a controllable factor, the improvement measure of grounding fault bus at the zero-crossing point of the grounding current is put forward, which can improve the success rate of arc extinguishing. The proposed method is fully validated by ATP software.

2. Analysis of influencing factors of fast fault point transfer technology

In this chapter, many factors affecting the reliability of fast fault point transfer technology are analysed, including arc characteristics, bus grounding time, line impedance, load and transition resistance.

2.1. Basic principle of fast fault point transfer technology

The basic principle of fast fault point transfer technology is shown in figure 1. Suppose that in the 10 kV neutral point non-effective grounding distribution network, a single-phase arc grounding fault occurs at point F. High-voltage vacuum contactor KA operates quickly at bus (M point) and grounds the fault phase bus metallically. Traditionally, grounding the fault phase bus can greatly reduce the fault phase voltage at fault point F and the grounding current will reduce too, thus the grounding arc can be extinguished. But in fact, whether the arc at the fault point can be extinguished after bus grounded is affected by arc characteristics, bus grounding time, line length, load, transition resistance and other factors.

![Fault point transfer technology schematic](image)

**Figure 1. Fault point transfer technology schematic.**

2.2. Effect of line impedance, load and transition resistance

In figure 1, after the fault phase bus is grounded, there are two grounding points on the same phase, the original fault grounding point and the bus grounding point. The grounding current of the original fault point consists of two parts, one is the shunt of fault capacitive current, and the other is the shunt
of load current by the earth branch between the two grounding points. According to the superposition principle, the grounding current of the original fault point is the phasor splicing of the two components. Figure 2 is the equivalent circuit for calculating grounding current. Equivalent circuit (a) calculates fault component $I_{f1}$, in which the offset voltage of neutral point is $U_a$, transition resistance of fault grounding point is $R_d$ and grounding resistance of bus grounding point is $R_{bus}$. Equivalent circuit (b) calculates the load component $I_{f2}$, in which the load current of the fault phase is $I$, the equivalent line impedance from the bus to the fault point is $Z_L$, the equivalent load impedance is $Z$ and the grounding current of the original fault point is $I_f$.

![Figure 2. Equivalent circuit after the bus grounded](image)

From the equivalent circuit of figure 2, $I_{f1}$ and $I_{f2}$ can be deduced:

$$I_{f1} = I_f \cdot \frac{R_{bus}}{Z_L + R_d + R_{bus}}$$  \hspace{1cm} (1)

$$I_{f2} = I \cdot \left(1 + \frac{Z_L}{Z_L + R_d + R_{bus}}\right)$$  \hspace{1cm} (2)

In the equation, $I_f$ is the single-phase grounding fault current. Because the bus grounding point is approximate to metallically grounding, the grounding resistance is generally far less than the sum of line impedance and transition resistance. $I_f$ is approximated to the capacitive current of single-phase metallically grounding, and the value of $I_{f1}$ is very small and can be approximately ignored.

The grounding current $I_f$ mainly consists of the load component $I_{f2}$. Equation (2) shows that the greater the load current and the impedance from bus to fault point, the larger the grounding current at fault point is. The smaller the transition resistance and bus grounding resistance, the larger the grounding current at fault point is.

At this time, the fault phase still exists load current. Although the fault phase bus is metallically grounded, the voltage drop caused by the load current on the line impedance still exists. After the fault phase bus is grounded, the voltage of the original fault point is:

$$U_f = -Z_d \cdot I \cdot \frac{R_d + R_{bus}}{Z_L + R_d + R_{bus}}$$  \hspace{1cm} (3)

According to reference [9], the transition resistance of arc grounding point is at least 20Ω, so the line impedance is far less than the transition resistance. As a result, after the metallically grounding of the fault phase bus, the load current still flows mainly through the line. The voltage drop generated on the line does not reduce the original fault point voltage to the ideal range near zero. At the same time, the shunt of the load current may lead the arc current to increase, resulting in arc cannot be reliably extinguished. This is the main reason why the fast fault point transfer technology may fail under the condition of long line and heavy load.
2.3. Effect of arc characteristics
The arcs of medium voltage distribution network can be divided into stable arc and intermittent arc.

In the research of effects on arc extinguishing reliability, the characteristic of arc itself is very important, which should not be approximately equivalent to fixed impedance, so an accurate arc model is needed. The existing classical arc models are mainly Cassie model, Mayr model and its improved forms [10]. Cassie model is suitable for low arc resistance state before current zero-crossing. Mayr model is suitable for high arc resistance state after current zero-crossing. Mayr model is mostly used to describe low voltage, low power arc, and more suitable for medium and low voltage distribution network. The Mayr model is shown in equation (4).

\[
\frac{1}{g_m} \frac{dg_m}{dt} = \frac{1}{\tau_m} \left( \frac{e \times i}{p_{\text{loss}}} - 1 \right)
\]

In the equation, \(g_m\) is the dynamic conductance of the arc, \(e\) is the electric field intensity of the arc, and \(i\) is the arc current. \(\tau_m\) is the time constant of arc and \(p_{\text{loss}}\) is the dissipated power of arc combustion. Both of them are constant and are the main parameters determining arc characteristics. In order to explore the mechanism of arc extinguishing based on Mayr arc model, the arc conductance at the initial time of arc ignition is set to \(g(0)\), and equation (4) can be rewritten as follows.

\[
g_m(t) = \exp \left( \frac{1}{\tau_m} \left( \frac{e \times i - p_{\text{loss}}}{p_{\text{loss}}} \right) \right) + g(0)
\]

Equation (5) shows that the arc combustion process is mainly affected by the input power of the arc \(e \times i\), the time constant \(\tau_m\) and the dissipative power \(p_{\text{loss}}\). Specific analysis is as follows.

1) For the same \(\tau_m\) and \(p_{\text{loss}}\), the larger the value of \(e \times i\), the stronger the dissociation, which is not conducive to arc extinguishing. On the contrary, the smaller the value of \(e \times i\), the weaker the free action, which is beneficial to extinguishing the arc. If \(e \times i\) is less than \(p_{\text{loss}}\) for a long time, the de-ionization effect is stronger than the free effect, and the arc is extinguished. After the fault phase bus is grounded, the fault point voltage will be reduced. If the arc current decreases, remains unchanged or increases little, the value of \(e \times i\) will be reduced, which is beneficial to arc extinguishing. If the arc current increases significantly, it may not decrease or even increase significantly, which is not conducive to arc extinguishing.

2) The smaller the peak current is, the smaller the time constant \(\tau_m\) is, which is beneficial to arc extinguishing. On the contrary, if the peak current is larger, the time constant \(\tau_m\) is larger, which is not conducive to arc extinguishing [11].

3) The physical meaning of dissipative power \(p_{\text{loss}}\) is the power loss per unit length of arc. Obviously, the smaller the dissipative power, the less the energy loss per unit time of arc is. For the same input power, the smaller the \(p_{\text{loss}}\), the more disadvantageous it is to extinguish arc.

Therefore, when the fault point is fast transferred and the arc voltage is reduced, the reliability of arc extinguishing is higher for grounding arcs with smaller arc current, smaller arc extinguishing time constant and larger dissipative power, or vice versa, arc extinguishing may fail. This conclusion is based on the Mayr model, if we adopt the arc model proposed in references [12] and [13], the conclusion is consistent.

2.4. Effect of bus grounding time
The bus grounding time also affects the arc extinguishing process, and it is the only controllable factor.

According to the analysis of section 2.2 and section 2.3, after the fault phase bus is grounded, the fault point voltage will be reduced, and if the arc current increases significantly, it is not conducive to arc extinguishing.

Equation (5) shows that after the fault phase bus is grounded, the energy accumulated by the dissociation in the arc in a period of time can be expressed as:
The energy accumulated by the de-ionization in the arc at the original fault point over a period of time can be expressed as:

$$E_I = \int_0^t (e \times i) dt$$ \hfill (6)

When $E_D > E_I$, deionization is stronger than dissociation, and the arc at the original fault point may be extinguished. Then, according to equation (5), a stable grounding resistance with large value and a small grounding current are formed at the original fault point, which maintains the state of arc extinguishing.

In order to make the value of $E_I$ small in a period of time after the fault phase bus grounded, the arc current in that period of time should be kept as small as possible. When other factors are the same, if the fault phase bus is grounded near the zero-crossing point of grounding current, the grounding current will not change abruptly under the action of the inductance elements of the power grid, and the current will transit from near zero to steady-state value, thus the value of $E_I$ is small in a period of time and the reliability of arc extinguishing will be improved.

In the case of the same arc length $l$, because of $u = e \times l$, the integral of $e \times i$ to time is equivalent to that of $u \times i$ to time under the condition of different bus grounding time. After simulation, $l_1$ is the $u \times i$ curve of grounding the fault phase bus near the zero-crossing point of grounding current at the original fault point and $l_2$ is the $u \times i$ curve of grounding the fault phase bus when the grounding current at the original fault point is large, as shown in figure 3. Obviously, the area enclosed by $l_1$ and time axis is much smaller than that enclosed by $l_2$ and time axis after bus grounding. That is to say, the value of $E_I$ corresponding to grounding fault bus near zero-crossing point of grounding current is smaller, which is more conducive to arc extinguishing.

![Figure 3. Comparison of arc input power at different grounding times](image)

3. Improvement measure and hardware and software design of fast fault point transfer technology

Based on the above analysis, only the grounding time of the fault phase bus is a controllable factor. We improve the existing technology by grounding the fault phase bus near the zero-crossing point of grounding current.
grounding current and the reliability of arc extinguishing can be improved. The hardware design is shown in figure 4 and the specific software flow is described below.

![Hardware structure of fault point transfer technology](image)

Figure 4. Hardware structure of fault point transfer technology

First, the system collects zero-sequence voltage and zero-sequence current of each line in real time. After single-phase grounding fault occurs, the fault line is selected in 10-20ms by transient signal line selection method [14-15]. At the same time, the fault phase is judged according to the RMS of three-phase power frequency voltage.

Second, analyse the harmonic content and phase angle, harmonic distortion rate and interharmonic content of zero-sequence signal to determine whether the fault is arc grounding [16-17]. If the fault is judged as arc grounding, the zero-sequence current component of the first cycle of the fault line is filtered digitally to extract the zero-sequence current of power frequency.

Third, since the zero-crossing point of arc current can be approximately the zero-crossing point of zero-sequence current of the fault line, the zero-crossing point $T_0$ of power-frequency current in the next cycle is predicted. The delay time of signal transmission and phase-splitting electronic switch is set as $T_D$, and the closing instruction is issued at the time of $T_0 - T_D$, and the fault phase bus will be metallically grounded.

Finally, disconnect the bus after a period of grounding. If the fault does not disappear, the fault line will be disconnected by protective equipment or the fault section will be disconnected by feeder automation equipment.

4. Simulation analysis

The single-phase arc grounding fault model of 10kV neutral point ungrounded system is constructed by EMTP software. The length of outgoing line is 20 km, and phase A arc grounding fault occurs at 10 km away from the bus outlet. The transition resistance is 20Ω. Single-phase equivalent resistance of load is 50Ω, equivalent inductance 0.001mH and equivalent capacitance 0uF. The line is a cable 1:1 overhead line.

The outlet of the simulation system occurs a single-phase arc grounding fault. The arc burns at the time of maximum phase voltage (0.1s). The fault line can be determined quickly by using the first half wave method. The first cycle data of zero sequence current of fault line is filtered digitally. The power frequency component of zero sequence current is extracted, and the next zero-crossing time of power frequency current is calculated to be 0.1395s. The whole process can be completed in one cycle time. The fault bus was metallically grounded at zero-crossing point. The waveform of voltage and arc current at fault point is shown in figure 5 (a). After bus grounding, arc current dropped to 0 and arc extinguished.

Keep the arc parameters, line parameters, load, transition resistance and other conditions unchanged. If the bus is grounded at random time like 0.145s, as shown in figure 5 (b), the arc current amplitude increases obviously and the arc continues to burn. At the same time, the original fault point
voltage does not decrease to near zero due to the existence of load current, but close to the voltage when the arc is extinguished successfully. This also proves that the ideal situation of limiting the original fault point voltage to zero by grounding the bus metallically is different from the actual situation.

By changing the transition resistance, it is found that when the load current is 140A, the arc can be reliably extinguished if transition resistance exceeds 34Ω despite the bus grounding time. If bus grounding time gets controlled, the arc can be reliably extinguished when the transition resistance exceeds 20Ω. When the load current is 200A, the arc can be reliably extinguished if the transition resistance is at least 75Ω, and if the time of bus grounding is controlled, it can extinguish arc reliably when the transition resistance exceeds 57Ω. The greater the load current, the more significant the improvement of the effectiveness of arc extinguishing is.

The simulation results show that the proposed improvement method has good arc extinguishing effect for arc grounding under long lines and heavy loads. In some special cases, such as when $p_{loss}$ is too small, it may not be able to effectively extinguish the arc even grounding the bus near the zero-crossing point of grounding current. However, compared with the traditional method of grounding bus at random time, the proposed method can greatly improve the reliability of arc extinguishing.

5. Conclusion
Aimed at the problem that fast fault point transfer technology can't reliably extinguish the arc in the condition of long lines and heavy load, this paper analyses several factors that affect the process of arc extinguishing. And on this basis, we put forward the improvement measure of fast grounding fault bus at the zero-crossing point of arc current. The theoretical analysis shows that the technology can effectively improve the success rate of arc extinguishing. Combining this technology with other technologies can reduce the harm of arc grounding and improve the safety and reliability of distribution network. With the popularization of distribution automation system, how to improve the method proposed in this paper under the condition of more information needs further study.

References
[1] Xu, Y.Q., Wang, Z.P., Zhang, H. (2006) The automatic following control of rrc suppression coil with thyristor switched capacitors. In: 1ST IEEE Conference on Industrial Electronics and Applications. Singapore. pp. 1-5.
[2] Tian, J., Chen, Q., Cheng, L. et al. (2011) Arc-suppression coil based on transformer with controlled load. IET Electric Power Applications, 05(08): 644-653.
[3] Qi, Z., Bai, R.X., Yang, Y.H. (2011) Design of auto-tuning arc suppression coil for smart substation [J]. Automation of Electric Power Systems, 35(20): 65 -67.

[4] Li, H., Yang, L.K., Li, L.L. et al. (2011) The research of a new arc suppression coil. In: 1st International Conference on Electric Power Equipment - Switching Technology. Xi’an. pp. 319-322.

[5] Wang, P., Chen, B.C., Zhuo, H. et al. (2018) Steady-state modeling and optimal design method of magnetic controllable petersen coil with discontinuous core structure. Proceeding of the CESS, 38(18): 5606-5614.

[6] Xie, Y.B., Wang, X.F., Luo, Q.Y. et al. (2011) Control strategy for optimized operation of traditional arc suppression coil of 35 kV grid. In: 2011 International Conference on Mechatronic Science, Electric Engineering and Computer (MEC). Jilin. pp. 2588-2591.

[7] Liu, B.W., Li, X.B. (2013) New type of automatic tuning arc-suppression coil based on detuning size. Power System Protection and Control, 41(05): 6-9.

[8] Li, X.Q., Qi, Z., Yang, Y.H. (2008) Arc-suppression method for coordinated using of arc-extinguish coil with grounded-fault transfer device. Automation of Electric Power Systems, (19); 71-75.

[9] Liu, J., Tian, X.Z., Li, Y.G. et al. (2019) Application analysis of active transfer type arc-extinguishing device under long feeder line and heavy load. Power System Technology. 43(03): 1105-1110.

[10] Katare, P., Chennu, R., Ramachandra, B. et al. (2017) Estimation of arc voltage characteristic for high current fault arcs. In: 2017 International Conference on Smart grids, Power and Advanced Control Engineering (ICSPACE). Bangalore. pp. 283 - 287.

[11] Guo, T., Zhou, W.J., Huang, H.K. (2016) Simulation and experiment on arc quenching structure with multi-gaps to quench the power frequency arc. Proceeding of the CESS, 36(10): 2853-2861.

[12] Liu, B.W., Tang, J.R., Wu, X.X. et al. (2018) Analysis of arc model and its application in single-phase grounding fault simulation in distribution networks. In: 2018 China International Conference on Electricity Distribution (CICED). Tianjin. pp. 1865 -1871.

[13] Guardado, J.L., Maximov, S.G., Melgoza, E. et al. (2005) An improved arc model before current zero based on the combined Mayr and Cassie arc models. IEEE Transactions on Power Delivery.20: 138 - 142.

[14] Wang, Y.M., Guo, H. (2010) Fault line selection method for single phase earth fault based on transient signals in the frequency band. In: 2010 International Conference on Intelligent System Design and Engineering Application. Changsha. pp. 738 – 741.

[15] Qu, Y.L., Tan, W.P., Cong, S., Yang, Y.H. (2006) Study on Fault Line Selection based on Transient and Mathematical Morphology in Resonant Grounded System. In: 2006 International Conference on Power System Technology. Chongqing. pp. 1-5.

[16] Lee, W.J., Sahni, M., Methaprayoon, K. et al. (2009) A novel approach for arcing fault detection for medium-/low-voltage switchgear. IEEE Trans on Industry Applications, 45(4): 1475-1483.

[17] Liu, G.G., Du, S.H., SU, J. et al. (2017) Research on LV arc fault protection and its development trends. Power System Technology, 41(01): 305-313.