A New Phase Selection Method for Single-Phase Grounding Faults in Distribution Networks with Full Compensation Arc Suppression Technology

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Abstract—**Faulty phase selection is one of the core technologies of full compensation arc suppression system for single-phase grounding faults in distribution networks. At present, faulty phase selection is mainly used for single-phase automatic reclosing and distance protection algorithms in direct-earthing systems. These methods have applicability problems in single-phase-to earth faults in non-effectively grounded distribution networks because of different neutral voltage. when the theoretical current is injected, whose value is determined by the full compensation arc supperssion method, voltage of the healthy phase, which is the miss-selected phase, will approach to a non-zero certain value as transition resistance increases; if the phase is selected correctly, when the corresponding current is injected, the selected phase voltage will be close to 0. This feature is used to distinguish the faulty phase, and thus promoting the full compensation arc suppression technology used in distribution networks.**

Index Terms—**Keywords: Distribution network; faulty phase selection; injection current; full compensation arc suppression;**

I. INTRODUCTION

According to the 13th Five-Year Plan for Chinese distribution networks, large-scale construction would be carried out. And one of the main missions is to replace the overhead line to power cable [1]. And then the single-phase grounding fault would hardly self-extinguish because of the large capacitive single-phase-to-ground fault current [2].

The full compensation arc suppression technology in distribution networks could be divided into current arc-extinguishing methods and voltage arc-extinguishing methods. The current arc-extinguishing methods use the neutral point grounding reactance to compensate the ground fault residual current. In recent years, a series of arc suppression technologies with continuous controllable impedance grounding equipment have appeared[3,4]. And new arc suppression coil based on single-phase active filtering technology has been proposed and analyzed in some papers [5-9]. But the capacity of the neutral point ground compensation device based on the current arc suppression methods increases, and the equipment cost would become too high. The essence of the voltage arc-extinguishing in the distribution networks is to adjust the voltage of the faulty phase[10-11]. The arc-suppression equipment is designed to guarantee the faulty phase voltage equals zero by injecting one proper current through the neutral point.

In the full compensation arc suppression technology based on voltage control methods by injecting one proper current, the effectiveness of the arc suppression depends on the injecting current, which is calculated by the selected faulty phase. At present, faulty phase selection methods in distribution networks can be divided into transient signal-based methods [12] and steady-state signal-based methods [13-14]. Because the zero-sequence loop in non-effectively grounding system is different from that in the direct-grounding system, so these methods cannot be directly used in distribution networks with full compensation arc suppression technology.

Firstly, the characteristics of the three-phase voltage after the single-phase grounding fault occurs in the distribution network with arc-suppression coil grounding mode. And then the characteristics of the three-phase voltages are analyzed under correct and false faulty phase selection scenario with full compensation arc suppression technology. Finally, the voltage characteristics are used to realize the fault phase selection method. Its effectiveness has been proved by PSCAD simulation.

II. BASIC PRINCIPLE OF FULL COMPENSATION ARC SUPPRESSION TECHNOLOGY IN DISTRIBUTION NETWORKS

A resonant grounded distribution network with full compensation arc suppression technology is shown in Figure 1. $\dot{E}_A$, $\dot{E}_B$, $\dot{E}_C$ are respectively the three-phase power supply voltage in the distribution network, separately. $\dot{U}_0$

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represents the neutral point displacement voltage, which equals the zero-sequence voltage after the ground fault occurs. And L is the inductance of the arc-suppression coil.

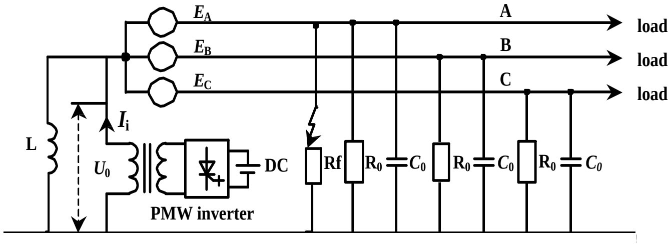

Figure 1. Resonant grounded distribution network with full compensation arc suppression technology

Compensated current can be injected by the PWM active inverter, which equals $\dot{I}_i$. By setting a reasonable value, let $\dot{U}_0 = -\dot{E}_A$, and thus the fault phase voltage $\dot{U}_A = \dot{E}_A + \dot{U}_0 = 0$, that is, the fault phase recovery voltage is always 0. And then the arc can be suppressed effectively.

III. SINGLE-PHASE GROUNDING FAULTY PHASE SELECTION

A. Voltage characteristics of each phase when a single-phase grounding fault occurs

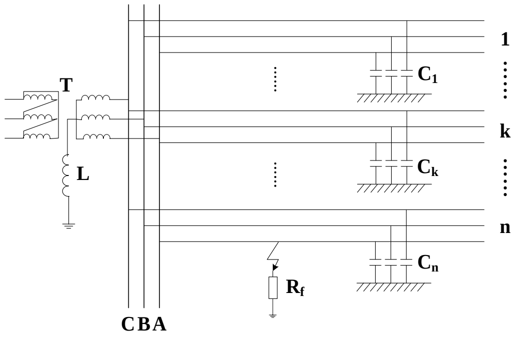

Figure 2. A-phase grounding fault with grounded distribution system through arc suppression coil

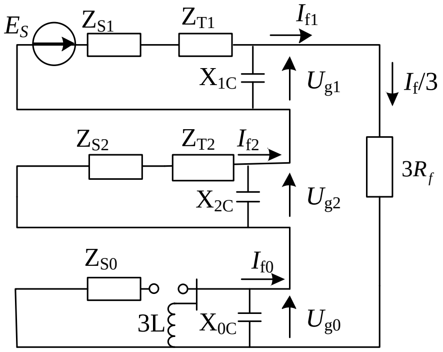

Figure 3. A-phase grounding fault in the feeder of the resonant ground distribution system

As shown in Figure 1, a single-phase (A-phase) ground fault occurs in a resonant grounded power distribution system. The corresponding sequence network diagram is formed based on the symmetrical component method, as shown in Figure 2.

X_{0C}、X_{1C}、X_{2C} respectively are the ground-to-ground capacitance of the zero-sequence, positive-sequence, and negative-sequence of the distribution line, E_S is the equivalent potential of the system-side generator (only the positive sequence component), and L is the inductance value of the arc-suppression coil, R_f is the fault point of grounding transition resistance, $\dot{U}_{g0}$, $\dot{U}_{g1}$, and $\dot{U}_{g2}$ respectively are fault-point zero-sequence, positive-sequence, and negative-sequence voltage sources. $\dot{I}_{f0}$, $\dot{I}_{f1}$, and $\dot{I}_{f2}$ respectively are the corresponding zero-sequence, positive-negative, and negative-sequence currents. Ignoring the impedance of the distribution line itself, the zero sequence impedance of the network shown in Figure 2 is given as follows:

$$Z_0 = X_{0C} // j3\omega L = \frac{j3\omega L}{1-3\omega^2 LC} \tag{1}$$

The zero sequence voltage of the network shown in Figure 2 is given as follows:

$$\dot{U}_g = -\dot{I}_{f0} Z_0 = -\frac{\dot{E}_A}{1+jR_f(3\omega C-1/\omega L)} \tag{2}$$

$$\dot{U}_A = \dot{E}_A - \frac{\dot{E}_A}{1+jR_f(3\omega C-1/\omega L)} \tag{3}$$

$$\dot{U}_B = \dot{E}_B - \frac{\dot{E}A}{1+jR_f(3\omega C-1/\omega L)} \tag{4}$$

$$\dot{U}_C = \dot{E}_C - \frac{\dot{E}A}{1+jR_f(3\omega C-1/\omega L)} \tag{5}$$

Using phase A as the reference vector, a grounding fault occurs when the phase is zero. Using MATLAB, the voltages of the three phases A, B, and C under the A phase ground fault are shown in Figure 4.

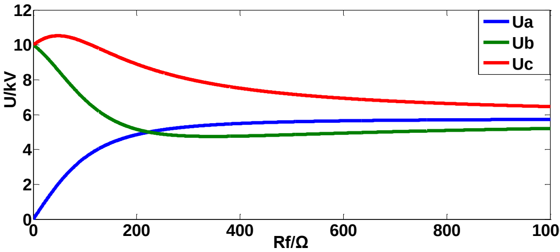

Figure 4. Change in voltage of three phases A, B, C with resistance

It can be seen from Fig. 4 that a ground fault occurs when the phase of phase A is zero, before the intersection of $\dot{U}_A$ and $\dot{U}_B$, the faulty phase can be selected by comparing the magnitudes of the two remaining phase voltages, but after the junction, the voltage comparison will not be applicable to fault phase selection. Injecting current, as a new method proposed in this paper, can avoid the influence of the transition resistance so that the fault phase can be accurately selected.

B. New method for fault phase selection based on neutral point injection current

The true situation is when A phase has grounded fault, firstly measure the phase voltages of the three phases A, B and C. Assuming that the minimum amplitude phase is the fault phase, according to the literature[4], if the minimum amplitude phase is exactly phase A, then when the neutral point is injected with the compensation current $\dot{I}_1 = -\dot{E}_A(3/R_0 + 1/\mathrm{j}\omega L + \mathrm{j}3\omega C_0)$, $\dot{U}_{A1}=0$, $\dot{U}_{B1}=\dot{E}_B - \dot{E}_A$. The A-phase voltage equals zero after the injection current. Thereby the arc would be suppressed.

If the minimum amplitude is not the A phase, it may be the B phase or the C phase. When the B phase is wrongly selected, the compensation current is injected to $\dot{I}_2 = -\dot{E}_B(3/R_0 + 1/\mathrm{j}\omega L + \mathrm{j}3\omega C_0)$.

The true relationship between the actual phase voltages of A, B, and C and the injected current is as follows:

$$\dot{I} = (\dot{U}_0 + \dot{E}_A)(\mathrm{j}\omega C_0 + \frac{1}{R_0} + \frac{1}{R_f}) + (\dot{U}_0 + \dot{E}_B)(\mathrm{j}\omega C_0 + \frac{1}{R_0}) + (\dot{U}_0 + \dot{E}_C)(\mathrm{j}\omega C_0 + \frac{1}{R_0}) + \frac{\dot{U}_0}{\mathrm{j}\omega L} \tag{6}$$

$\dot{U}_0$ is the neutral point displacement voltage, and the power supply is balanced in three phases.

$$\dot{E}_A + \dot{E}_B + \dot{E}_C = 0 \tag{7}$$

Since the A, B, and C phase voltages have the following relationship:

$$\dot{U}_A = \dot{E}_A + \dot{U}_0 \tag{8}$$

$$\dot{U}_B = \dot{E}_B + \dot{U}_0 \tag{9}$$

$$\dot{U}_C = \dot{E}_C + \dot{U}_0 \tag*{(9)}$$

Then there are:

$$\dot{U}_A = \frac{\dot{I} + \dot{E}_A(\frac{3}{R_0} + \frac{1}{\mathrm{j}\omega L} + j3\omega C_0)}{\frac{3}{R_0} + \frac{1}{j\omega L} + j3\omega C_0 + \frac{1}{R_f}} \tag{11}$$

$$\dot{U}_B = \dot{E}_B + \frac{\dot{I}R_f - \dot{E}_A}{R_f(\frac{1}{R_f} + \frac{1}{j\omega L} + j3\omega C_0 + \frac{3}{R_0})} \tag{12}$$

$$\dot{U}_C = \dot{E}_C + \frac{\dot{I}R_f - \dot{E}_A}{R_f(\frac{1}{R_f} + \frac{1}{j\omega L} + j3\omega C_0 + \frac{3}{R_0})} \tag{13}$$

The $\dot{U}_A$ and $\dot{U}_{\mathrm{B}}$ obtained above are the true values of the A-phase grounding fault. When $\dot{I}_2$ is injected, there are:

$$\dot{U}_{A2} = \frac{(\dot{E}_A - \dot{E}_B)(\frac{3}{R_0} + \frac{1}{\mathrm{j}\omega L} + j3\omega C_0)}{\frac{3}{R_0} + \frac{1}{j\omega L} + j3\omega C_0 + \frac{1}{R_f}} \tag{14}$$

$$\dot{U}_{B2} = \dot{E}_B - \frac{\dot{E}_B(\frac{3}{R_0} + \frac{1}{\mathrm{j}\omega L} + \mathrm{j}3\omega C_0)R_f + \dot{E}_A}{R_f(\frac{1}{R_f} + \frac{1}{Z_0} + j3\omega C_0 + \frac{3}{R_0})} \tag{15}$$

$$\dot{U}_{C2} = \dot{E}_C - \frac{\dot{E}_B(\frac{3}{R_0} + \frac{1}{\mathrm{j}\omega L} + \mathrm{j}3\omega C_0)R_f + \dot{E}_A}{R_f(\frac{1}{R_f} + \frac{1}{Z_0} + j3\omega C_0 + \frac{3}{R_0})} \tag{16}$$

The phase A is used as the reference vector, and the ground fault occurs when the phase is zero. When the B phase is wrongly selected, the relationship between the voltage amplitudes of the A, B, and C phases and the transition resistance of the injection compensation current $\dot{I}_2$ is obtained by MATLAB simulation. is shown in Fig 5.

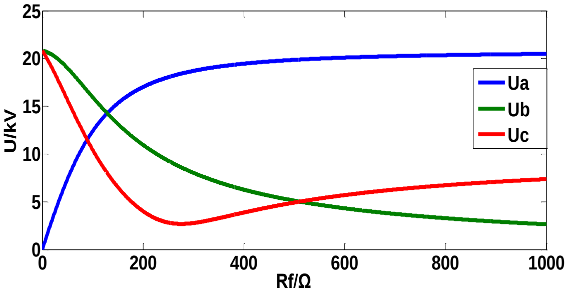

Figure 5. Change in voltage of three phases A, B, C with resistance

When the C phase is wrongly selected, $\dot{I}_3 = -\dot{E}_C(3/R_0 + 1/\mathrm{j}\omega L + \mathrm{j}3\omega C_0)$. And the relationship between the voltage amplitudes of transition resistance, A, B, and C, which are injected with the compensation current $\dot{I}_3$, is shown in Fig. 6 by MATLAB simulation.

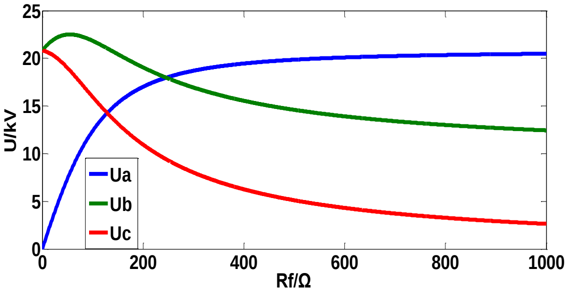

Figure 6. Change in voltage of three phases A, B, C with resistance

It can be seen from Fig 5 and Fig.6 that if the phase selection error is made, when the theoretical current value determined by the zero residual flow arc suppression is injected the non-fault phase voltage of the miss elected phase will approach to a non-zero certain value as R_f increases; if the phase is selected correctly, when the current value is injected, the selected phase voltage will be close to 0.According to this, it can be judged whether the phase selection result is correct by observing the magnitude of the voltage value of the phase selected after the injection current .Based on the above principle, a new method for fault phase selection of distribution network based on the characteristics of selected phase voltage after injection current is constructed. The specific process is shown in Figure 7.

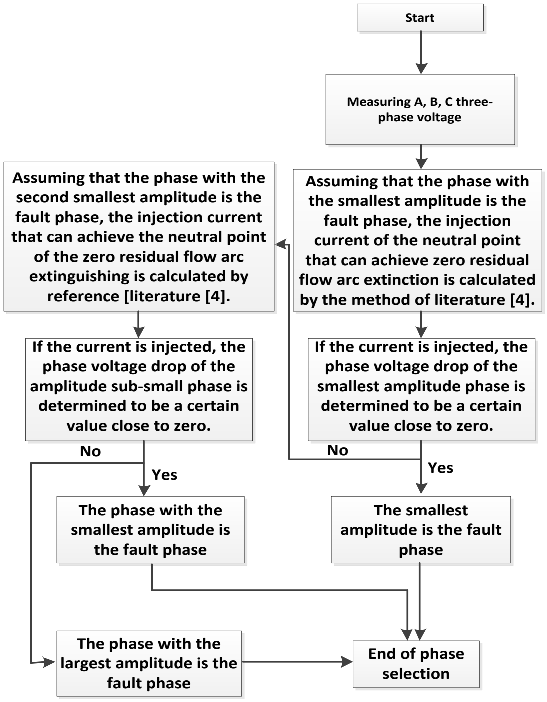

Figure 7. Flowchart of implementing the fault phase selection method in a resonant grounded distribution system

IV. SIMULATION ANALYSIS

In this paper, the electromagnetic transient simulation software PSCAD is used to establish a 10kV asymmetric neutral point arc suppression coil grounding system single-phase ground fault distribution network feeder model, which is a Π equivalent distribution network model, A, B, C three-phase power supply voltage is 110kV. When the 110 kV high voltages with a rated capacity of 50 MVA is transformed from 110kV to 10.5kV the distribution line parameters is set as listed in literature [15].

The feeder line is composed of overhead lines and cables. There are 6 outlet lines, of which lines 1, 2, 3 and 4 are separately made up cables of 30km, 3km, 10km and 30km; lines 5 and 6 are overhead lines. The neutral point of the transformer is grounded through the arc suppression coil, as shown in Figure 8.

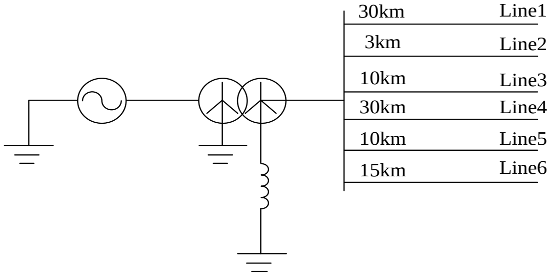

Figure 8. The simulation model of resonant grounding system

The simulation model is operated in overcompensation mode. When the overcompensation degree is 10%, the arc suppression coil inductance value is 0.13552H, When the whole simulation process is set to 0.5s, the ground fault (A phase) occurs at 0.15 seconds, at this time the fault phase is 205 °. A lot of simulations have been carried out but only three representative cases are described in this paper.

The situation of A-phase fault when R_f=0.1Ω,if the correct phase selection, obtain three-phase voltages of A, B, and C injected current, the waveform is shown in Figure 9,10.

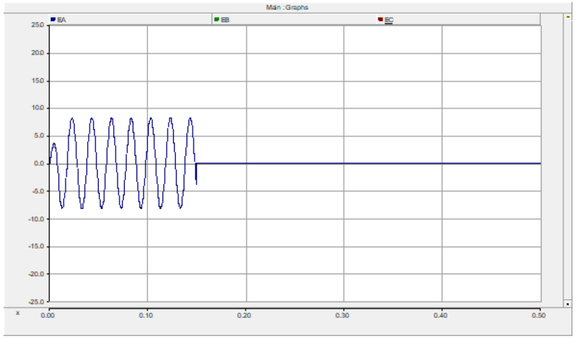

Figure 9. Phase voltage waveform of Phase A after $\dot{I}_1$ is injected when the transition resistance is 0.1Ω.

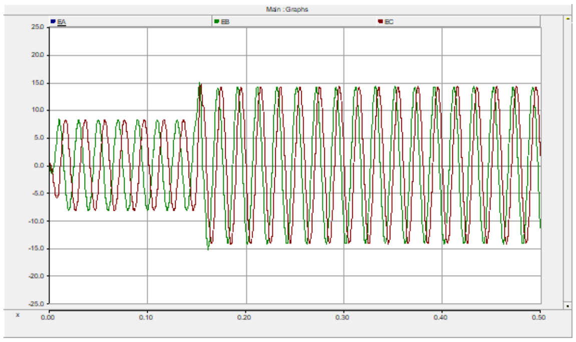

Figure 10. Phase voltage waveforms of phase B and phase C after $\dot{I}_1$ is injected when the transition resistance is 0.1Ω.

When the selected phase is wrongly chosen as phase B, obtain three-phase voltages of A, B, and C injected current, the waveforms are respectively shown in Figure 11 and 12:

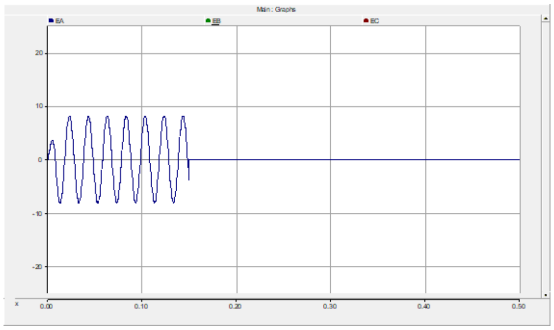

Figure 11. Phase voltage waveforms of Phase A after injection of $\dot{I}_2$ is injected when the transition resistance is 0.1Ω

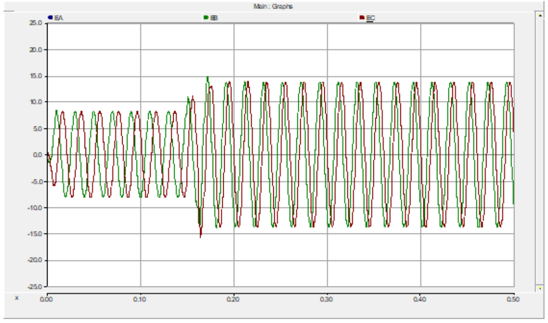

Figure 12. Phase voltage waveforms of phase B and phase C after $\dot{I}_2$ is injected when the transition resistance is 0.1Ω.

When the selected phase is chosen as the C phase, obtain three-phase voltages of A, B, and C injected current, the waveforms are respectively shown in Figs 13 and 14.

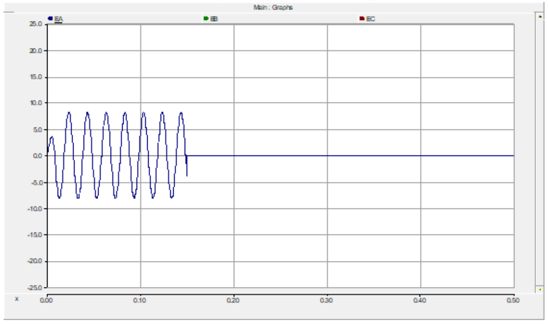

Figure 13. Phase voltage waveform of phase A after $\dot{I}_3$ is injected When the transition resistance is 0.1Ω

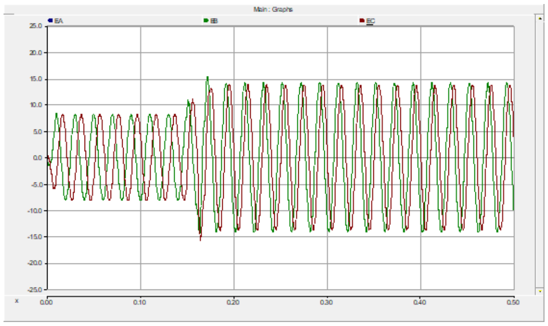

Figure 14. Phase voltage waveforms of Phase B and Phase C after $\dot{I}_3$ is injected when the transition resistance is 0.1Ω

In the case of A-phase fault, when R_f=100Ω, if the phase is selected correctly, obtain three-phase voltages of A, B, and C injected current, the waveforms are respectively shown in Figs 15 and 16.

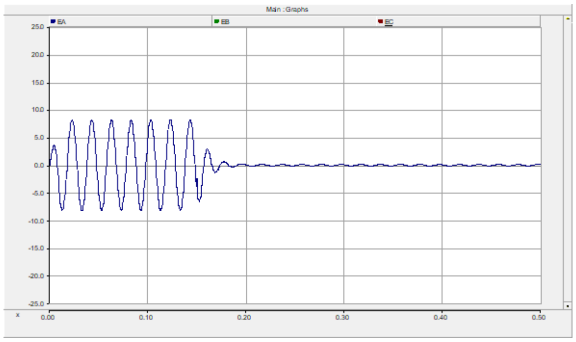

Figure 15. Phase voltage waveform of phase A after $\dot{I}_1$ is injected when the transition resistance is 100Ω

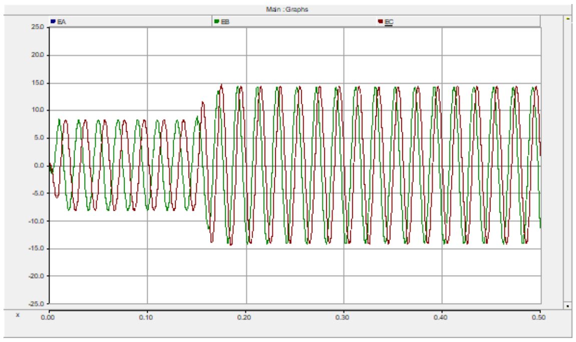

Figure 16. Phase voltage waveforms of Phase B and Phase C after $\dot{I}_1$ is injected with a transition resistance of 100Ω

When the selected phase is wrongly chosen as phase B, obtain three-phase voltages of A, B, and C injected current, the waveforms are respectively shown in Figure 17 and 18.

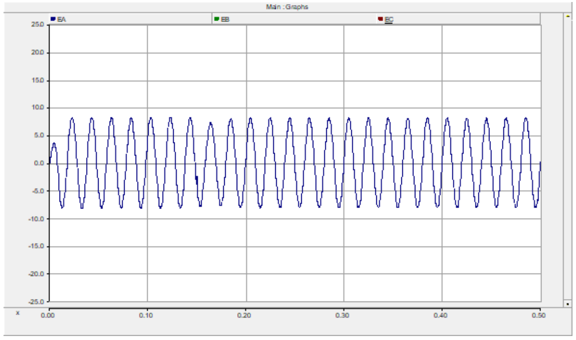

Figure 17. Phase voltage waveform of phase A after $\dot{I}_2$ is injected when the transition resistance is 100Ω

When the selected phase is chosen as the C phase, obtain three-phase voltages of A, B, and C injected current, the waveforms are respectively shown in Figs 19 and 20.

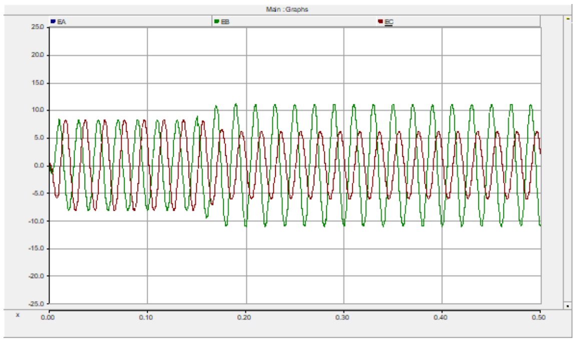

Figure 18. Phase voltage waveforms of Phase B and Phase C after $\dot{I}_2$ is injected when the transition resistance is 100Ω

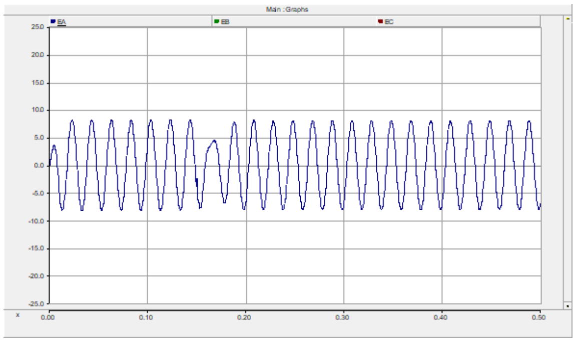

Figure 19. Phase voltage waveform of phase A after $\dot{I}_3$ is injected when the transition resistance is 100Ω

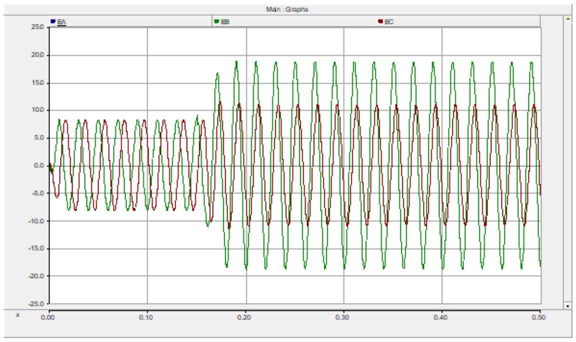

Figure 20. Phase voltage waveforms of Phase B and Phase C after injection $\dot{I}_3$ when the transition resistance is 100Ω

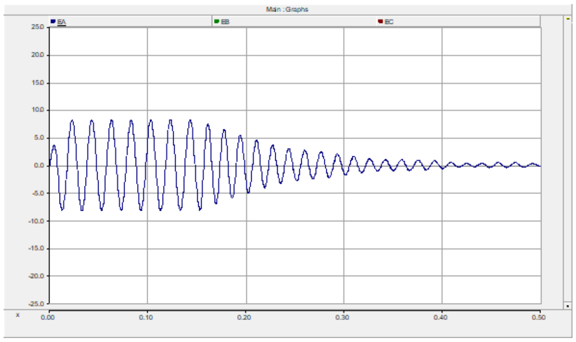

Figure 21. Phase voltage waveform of phase A after injection of $\dot{I}_1$ when the transition resistance is 1000Ω

In the case of A phase fault, when R_{f}=1000Ω, if the phase is selected correctly, obtain three-phase voltages of A, B, and C injected current, the waveforms are respectively shown in Figs 21 and 22.

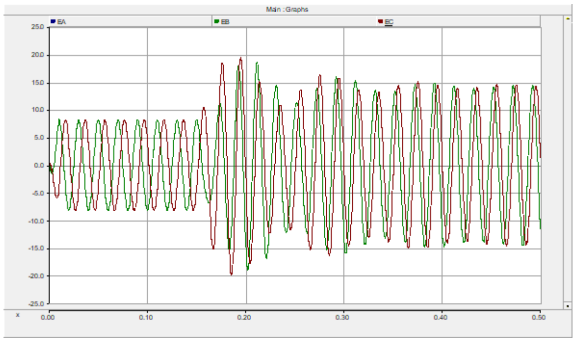

Figure 22. Phase voltage waveforms of Phase B and Phase C after injection of $\dot{I}_1$ when the transition resistance is 1000Ω

When the selected phase is chosen as the B phase, obtain three-phase voltages of A, B, and C injected current, the waveforms are respectively shown in Figs 23 and 24.

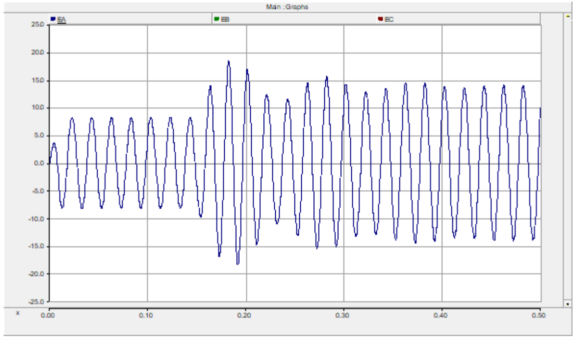

Figure 23. Phase voltage waveform of phase A after $\dot{I}_2$ is injected when the transition resistance is 1000Ω

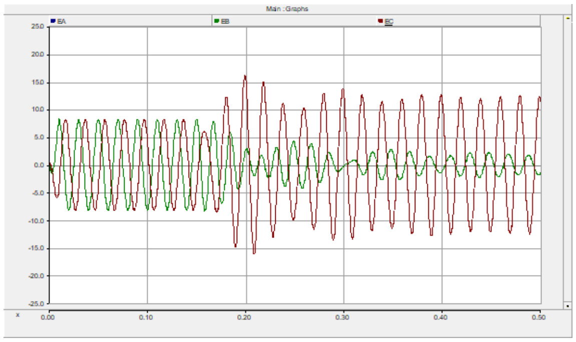

Figure 24. Phase-voltage waveforms of Phase B and Phase C after $\dot{I}_2$ is injected with a transition resistance of 1000Ω

When the selected phase is chosen as the C phase, obtain three-phase voltages of A, B, and C injected current, the waveforms are respectively shown in Figs 25 and 26.

Table 1. Voltages of each phase when phase selection result is correct or not

Fault phase	Transition resistance /Ω	Three phase	Phase A is selected /kV	Phase B is selected /kV	Phase A IS selected /KV
Grounding fault in phase B	0.1	A	13.721	14.127	13.755
		B	0.0100	0.0002	0.0103
		C	14.135	14.128	13.773
	100	A	10.999	14.057	6.095
		B	8.196	0.060	8.084
		C	18.844	14.093	10.991
	1000	A	*1.820*	14.130	12.281
		B	*14.242*	0.128	13.927
		C	*15.743*	14.081	1.768
Grounding fault in phase C	0.1	A	*13.757*	14.142	14.121
		B	*13.737*	13.755	13.625
		C	*0.011*	0.0108	0.0002
	100	A	*10.907*	18.691	14.093
		B	*5.988*	10.918	14.047
		C	*8.226*	8.071	0.061
	1000	A	*2.261*	15.608	14.261
		B	*12.649*	1.802	14.118
		C	*14.008*	14.071	0.122

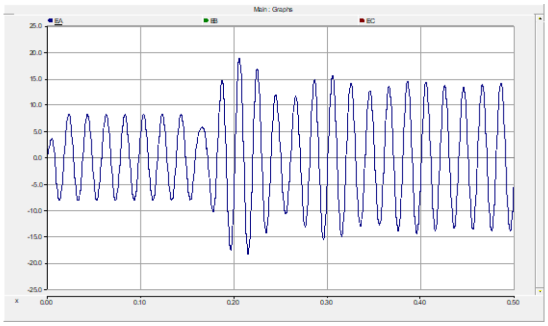

Figure 25. Phase voltage waveform of phase A after $\dot{I}_3$ is injected when the transition resistance is 1000Ω

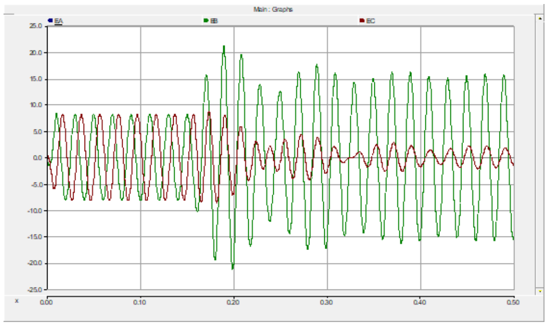

Figure 26. Phase voltage waveforms of Phase B and Phase C after $\dot{I}_3$ is injected with a transition resistance of 1000Ω

The PSCAD simulation results are shown in Table 1 when the phase B and phase C are wrong.

The above PSCAD simulation is in the order of phase A, phase B, and phase C grounding fault. (fault phase is 205°).With three case of representative grounding resistances, it can be concluded from the waveform diagrams that: if the phase selection is correct, the selected phase voltage will be close to 0 when the theoretical current value determined by the zero residual current arc suppression is injected; if the phase selection is wrong, the wrongly selected non-fault phase will approach to a non-zero certain value with the increase of grounding resistance when the current is injected.

By observing the magnitude of voltage value of the phase selected after the injection current can judge whether the phase selection result is correct. If the error occurs, the phase selection is continued. This method can determine the fault phase by performing phase selection at most two times that offers several advantages, such as the high efficiency, accuracy, and simple process.

V. CONCLUSION

A new faulty phase selection method for single-phase grounding faults in distribution networks with full compensation arc suppression technology is proposed and analyzed. Using the PWM-active-inverter-based arc extinguishing device, when the theoretical current obtained by the full compensation algorithm is injected, the phase-selected voltage characteristics are used to determine the correctness of the faulty phase selection result. The simulation analysis shows that the proposed method can correctly perform faulty phase selection which can be used to improve the full compensation arc suppression methods in distribution networks.

VI. REFERENCES

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