Grounding Fault Analysis and Protection Measures Study of Composite Grounding Arc-suppression Modes

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Abstract. Centering on analysis of single-phase ground fault, and based on a wide-range survey of typical structure and accessing equipment of 10kV distribution network, accurate simulation model reflecting engineering practice is established according to the existing power design standards. For composite grounding arc-suppression modes, this paper describes both the principle and fault treatment process of grounding fault transfer mode and intelligent multimode grounding mode. According to the fault treatment process, a line selection method based on the first transient half wave of fault grounding and operation grounding of the own line is put forward for grounding fault transfer mode, and the effect of transition resistance on zero-sequence current protection for intelligent multimode grounding mode is analyzed. All of this is verified by our simulation model in PSCAD. This research lays a solid theoretical foundation for the engineering application of composite grounding arc-suppression mode.

1. Introduction

Widely distributed distribution network always operates in complex environment. Power outages caused by frequent random failures have resulted in significant economic losses. Building a strong and safe distribution network is an important part of the national development strategy named “developing smart grid and distributed energy” [1]. Neutral grounding mode of distribution network which is closely related to its safe and reliable operation. System with different grounding modes has different fault characteristics under single phase grounding fault [2]. The grounding mode relates to ground fault current, the insulation level of equipment, communication interference, dynamic stability, the reliability of relay protection and power supply, safety and so on[3], which has attracted much attention in the network construction of city and rural. The increasingly complex network structure, the gradually increasing cable proportion, the rising automation degree of system and the increment of new energy permeability [4]-[5] contributed to the complicated situation that a variety of grounding modes coexist and safety control strategies diversify.

The typical neutral grounding mode including unground, resonant ground and low resistance ground. With the reconstruction of city network, the capacitive current is more and more big. There is insufficient capacity for arc suppression coil to compensate power component and harmonic components. And the low resistance ground mode trips frequently. Therefore, relevant experts and scholars began to get involved in the research for composite grounding arc-suppression modes, such as grounding fault transfer mode [6], intelligent multimode grounding mode [7] and flexible grounding mode [8]. For neutral non-grounded mode, literature [6] elaborated a grounding fault transfer mode that makes the bus phase with fault grounding. This mode switches arc grounding fault of lines to

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metallic grounding fault on bus. For resonant grounding mode, in addition to the way cooperating with grounding fault transfer mode in [9], intelligent multimode grounding mode that consists of arc suppression coil and parallel resistance was put forward by [7], which not only can eliminate transient grounding fault automatically, but also can isolate permanent grounding fault quickly. In the background of rapid development of power electronics technology, the authors of [8] proposed flexible grounding arc suppression method. This method can realize the total compensation of fundamental reactive component, fundamental active component and harmonic components by using the active inverter to inject current. At present, there is few literature on the action mechanism and protection countermeasures of composite grounding arc-suppression modes.

All things considered, the wiring form of typical neutral grounding modes and composite grounding arc-suppression modes are introduced. The system simulation model reflecting the actual distribution network is established for the analysis of single-phase grounding fault. Based on this, grounding fault analysis and fault protection measures study for grounding fault transfer mode and intelligent multimode grounding mode are respectively well done.

2. Grounding mode and simulation modeling for distribution network

As shown in figure 1, the wiring form of unground, resonant ground and low resistance ground, grounding fault transfer and intelligent multimode grounding are depicted. When the switch K is switched off, the neutral point are not grounding. When K is closed to L_C, it is resonant ground mode. When K is closed to R_d, the neutral point grounds through low resistance. QK is fault phase grounding switch used to transfer the earthing fault quickly. When K is closed to L_C and K1 is closed, it is intelligent multimode grounding mode. K1 is high voltage vacuum contactor.

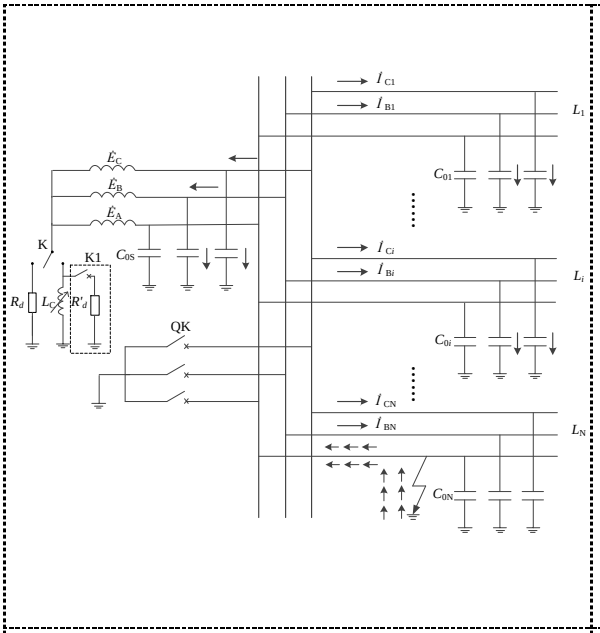


Figure 1. Schematic diagram of different neutral grounding modes.

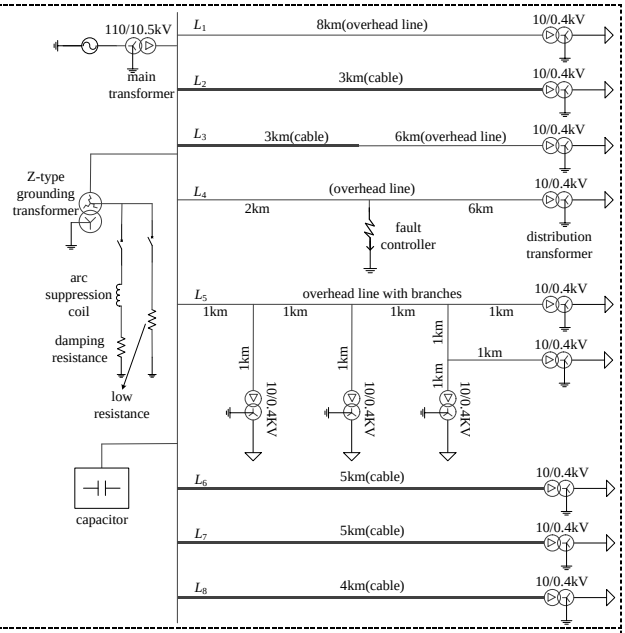


Figure 2. Schematic diagram of PSCAD simulation model for 10kV distribution network.

For accurate fault analysis of composite grounding arc-suppression modes, great efforts are taken to establish a system simulation model for 10kV distribution network. We make a full investigation of the structure, feeder, distribution transformer and load configuration of 110kV substation. Besides, a large amount of design manuals and standard specifications related to the substation and distribution network are consulted. On the premise of a given load, equipment selection and parameter calculation is carried out according to the design standard and specification. Finally, we realize simulation modeling on the platform of PSCAD (Power Systems Computer Aided Design) as shown in figure 2. The simulation system includes main transformer, Z-type grounding transformer, neutral-point

grounding device, parallel compensation capacitor group and eight feeders. Distribution transformers are arranged on every feeder. The specific electrical parameters are as follows.

2.1. Transformer

The main transformer: the rated capacity is 20MVA, the change ratio is 110/10.5, the connection group is YNd11, the short-circuit loss is 88.4kW, and the no-load loss is 17.6kW. The distribution transformer: the rated capacity is 2MVA, the change ratio is 10/0.4, the connection group is Dyn11, the short-circuit loss is 13.1kW, and the no-load loss is 2.58kW. Z-type grounding transformer: the rated capacity is 250kVA, the connection group is ZNyn11, the short-circuit loss is 540W, the no-load loss is 580W, and zero sequence impedance is 22.8Ω.

2.2. Feeder

L_1 and L_4 are overhead line. L_2, L_6, L_7 and L_8 are cable line. L_3 is hybrid overhead cable line. L_5 is overhead line with branches. L_1 is 8km long. L_2 is 3km long. L_3 is the combination of 3km cable and 6km overhead line. L_4 is 6km long. The parameters of feeders refer to [10].

2.3. Neutral-point grounding device

The inductance of the arc suppression coil is 0.596H, and the series damping resistance is 18.7Ω. In order to make the over voltage less than twice the peak of the maximal phase voltage, the grounding resistance is set as 15Ω.

2.4. Parallel compensation capacitor group

The capacity of the parallel compensation capacitor is 30% that of the main transformer. So its rated capacity is 6Mvar and the capacitance of each phase is 173uF.

In reality, the majority of grounding fault is arc grounding [11]. In order to simulate real grounding arc, the two classical arc models of Mayr and Cassie are combined to construct our arc model. Inputting arc voltage and arc current into the model so as to output arc resistance, which regulates voltage and current in turn. The process is controlled in closed-loop. What's more, temporal logic is designed for intermittent arc.

3. Grounding fault transfer mode

3.1. Fault analysis

As for grounding fault transfer mode, fast switches used for grounding are arranged on three phases of bus. The switches are opening during normal running. When single-phase arc grounding fault happens to line, Whether single-phase ground fault happens and the grounding phase are judged according to the change of the angle between zero sequence voltage and line voltage. Then fault phase fast switch closes instantly. The unstable fault grounding point is turned into stable metallic grounding point. The voltage of fault point is close to 0 so that the grounding arc can't reignite. The overvoltage of non-fault-phase can be stabilized around 1.732 times phase voltage, which makes devices run safely. For fault through resistance or fault with arc extinguishing, the grounding current is the capacitive current to the ground. For metallic grounding fault, the fault point will have shunting current.

The figure 3 shows the schematic diagram of grounding fault transfer mode which has two arc-suppression schemes. Scheme one only installs fault phase fast grounding device. Fault phase fast switch closes for 14 to 20ms after single-phase grounding fault. Scheme two combines arc suppression coil with fault phase fast grounding device. When metallic grounding fault or fault through resistance happens, fault phase fast switch doesn't operate and arc suppression coil is switched on for following capacitive current compensation. When single-phase arc grounding fault happens, fault phase fast switch closes rapidly and arc is extinguished. After about 6ms, arc suppression coil is switched on to reduce the grounding current of fast switch of fault phase.

The above two arc-suppression schemes are simulated in a situation where stable arc grounding fault happens to C phase. When the voltage of C phase peak, the fault locates at L_2 the distance of 1.8km from bus. For scheme one, single-phase arc grounding fault occurs to C phase at 0.12s. Fast grounding switch of C phase is switched on at 0.135s. On one hand, the current of fault point changes to 0. On

the other hand, the voltage of non-fault phase reaches line voltage and the voltage of neutral point reaches phase voltage. Assuming that arc fault extinguishes, fast switch turns off at 0.195s. On the same time, the overvoltage of non-fault phase will rise in some degree. The voltage of fault phase recover from 0.2s at low speed due to the voltage of neutral point can't reduce to 0 instantly. The process is shown in figure 4.

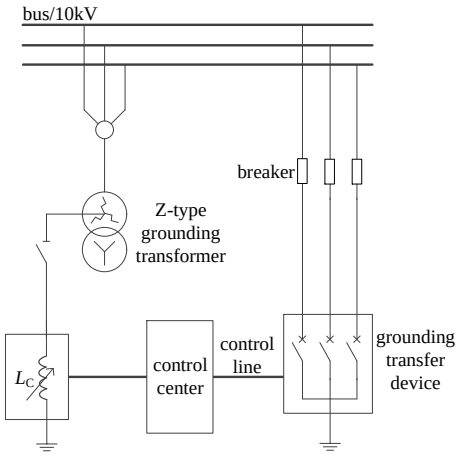
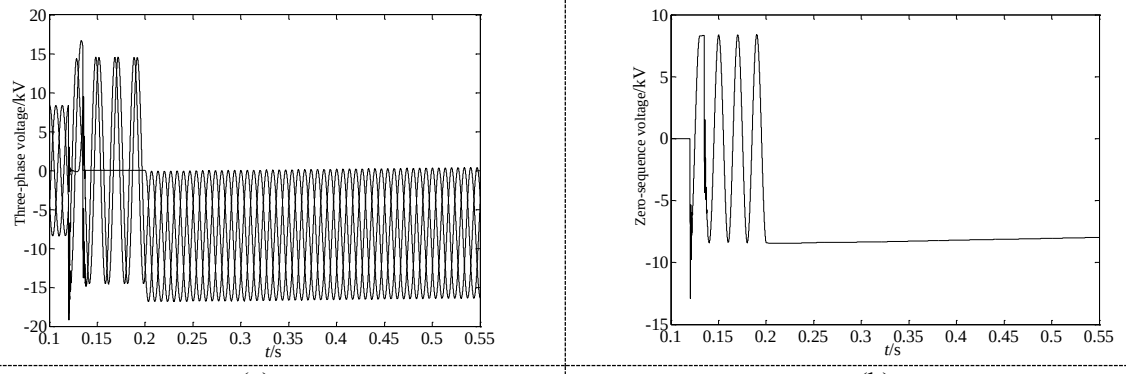


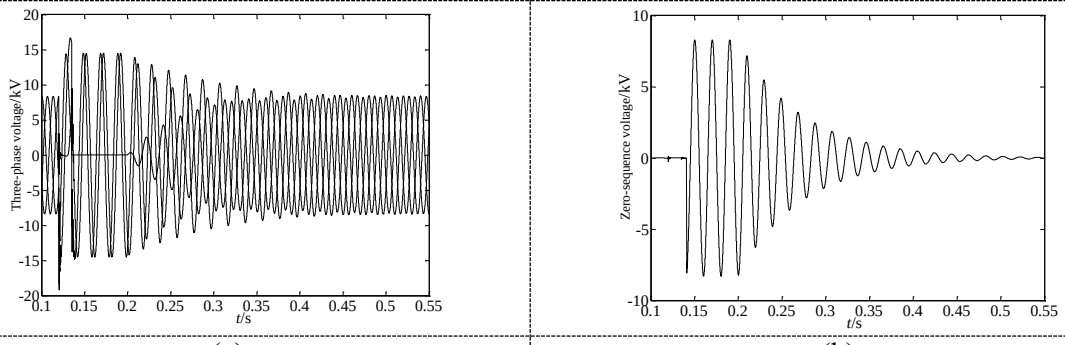
Figure 3. Wiring diagram of grounding fault transfer mode.



(a) (b)

Figure 4. Three-phase voltage and zero-sequence voltage of scheme one.

For scheme two, the condition different from scheme one is that arc suppression coil will be put into at 0.141s. As shown in figure 5 and figure 6, the current of grounding point on bus is compensated. The voltage of neutral point is close to 0 after continuing damped oscillation. The voltage of fault phase rise to normal phase voltage. The voltage of non-fault phase decay to normal phase voltage. Therefore, scheme two has advantages of grounding current compensation and quick voltage recovery.



(a) (b)

Figure 5. Three-phase voltage and zero-sequence voltage of scheme two.

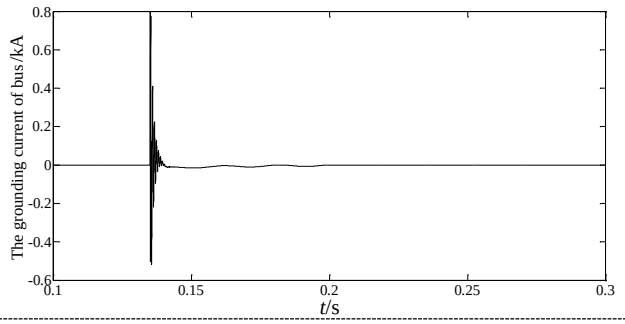


Figure 6. The grounding current of bus of scheme two.

3.2. Protection measures

Although grounding fault transfer mode extinguishes arc effectively, fault may happen again for the damaging insulation of fault line. Fault line need to be found quickly. Because fast switch will finish closing within one period after fault, transient process may be not over. It would be unreliable to use line selection method based on steady character of zero-sequence current.

Taking zero-sequence voltage as a reference, traditional line selection based on the first transient half wave judges fault line by comparing the polarity of the first transient half wave of zero-sequence current of all lines. It is a kind of group phase comparison method about transient zero-sequence current. It can be seen that there is few method using the characters of the development process of fault to select the fault line. Since there are two process of fault grounding and operation grounding, we can study fault line selection method by combining with the transient character of the two process.

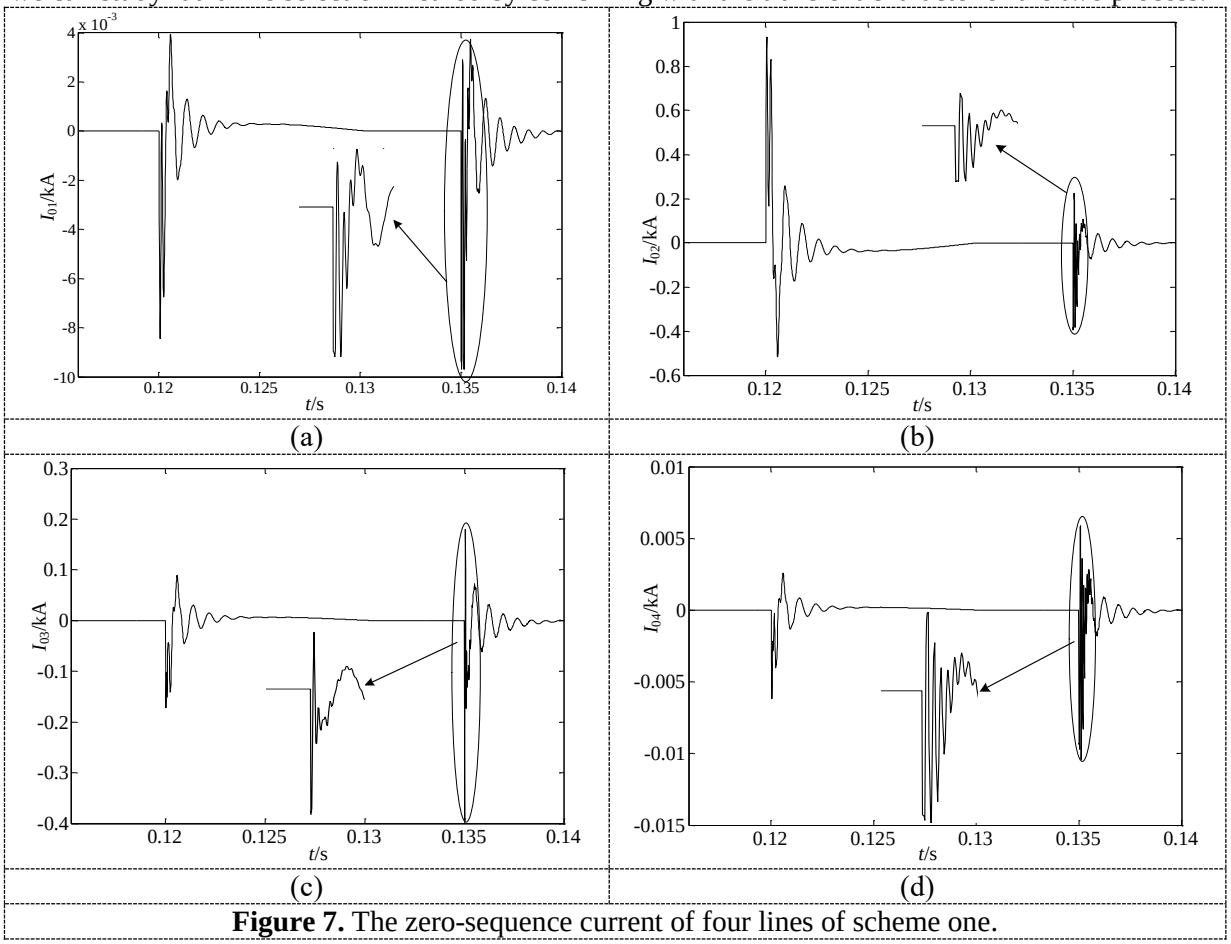


Figure 7. The zero-sequence current of four lines of scheme one.

Figure 7 shows the zero-sequence current of L_1, L_2, L_3, L_4 in scheme one. It can be seen that the amplitude and phase of zero-sequence current for L_2 change obviously after grounding fault and the closure of fast switch, and that of normal lines change little. As for the fault line, the polarity of the first transient half wave of zero-sequence current after grounding fault is the opposite of that of zero-sequence current after the closure of fast switch. Besides the impact value of the former is bigger than that of the latter. But the case of normal lines is the exact opposite. In view of the above-mentioned facts, we construct the line selection criterion below.

$$\begin{cases} |If_i| > |It_i| \\ \mathrm{sgn}(If_i) \neq \mathrm{sgn}(It_i) \end{cases} \quad i \in [1,\ \mathrm{N}] \tag{1}$$

Where If_i is the amplitude of the transient current travelling wave of the ith line after grounding fault; It_i is the amplitude of the transient current travelling wave of the ith line after grounding transfer. The method has the advantage that line selection only needs the character of the first transient half wave of fault grounding and operation grounding of this line.

4. Intelligent multimode grounding mode

4.1. Fault analysis

Intelligent multimode grounding mode develops on the base of resonant grounding mode and low resistance grounding mode. On one hand, it keeps the advantage of handling the transient fault quickly of resonant grounding mode. On the other hand, it inherits the merits of isolating grounding fault quickly and accurately from low resistance grounding mode.

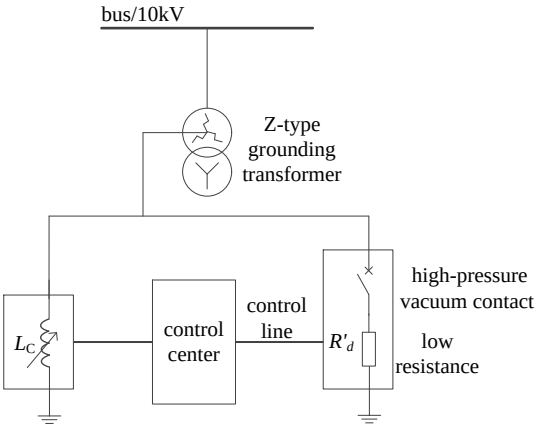


Figure 8. Wiring diagram of intelligent multimode grounding mode.

As shown in figure 8, intelligent multimode grounding mode can realize the integrated control of grounding fault of feeders. Different responding scheme will be adopted for different fault. The principle of intelligent multimode grounding mode can be described as: when grounding fault happens, short-time controllable reactor which has the advantages of quick compensation and continuing stepless regulation will compensate capacitive current accurately within around 5ms, then grounding arc can be extinguished. The transient single-phase grounding fault can be removed and related fault information will be recorded automatically. As for permanent single-phase grounding fault, if the time of grounding exceeds the set value (10s), low resistance will be put into system by high-pressure vacuum contact. Then line protection device makes the grounding line trip.

Simulating the above two situations in the simulation system. The function of short-time controllable reactor is simplified as that of arc suppression coil. Other simulation conditions are the same as the previous section.

Transient grounding fault is removed after compensating current is output by arc suppression coil. Residual current of grounding point, arc suppression coil compensation current, three-phase voltage and zero-sequence voltage for transient grounding fault are shown in figure 9 and figure10.

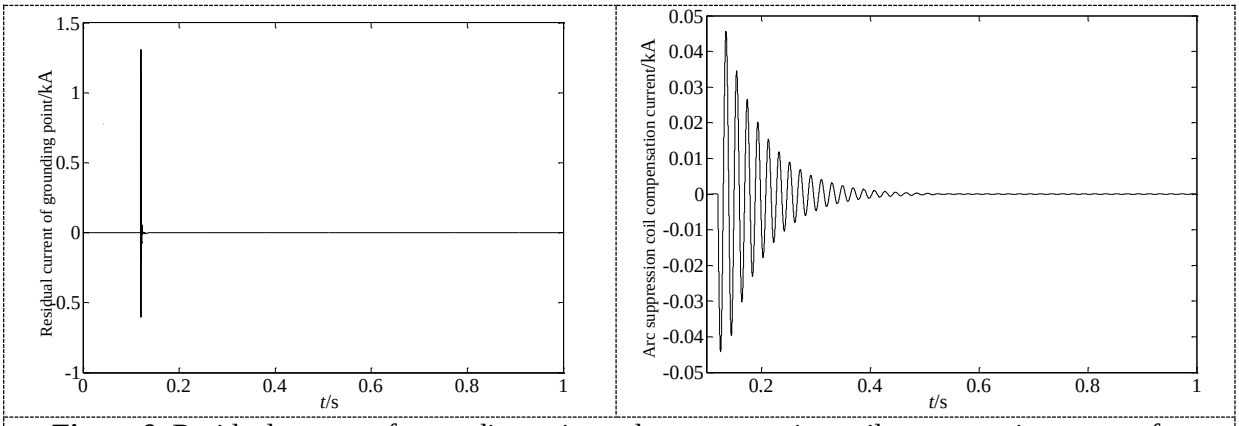


Figure 9. Residual current of grounding point and arc suppression coil compensation current for transient grounding fault.

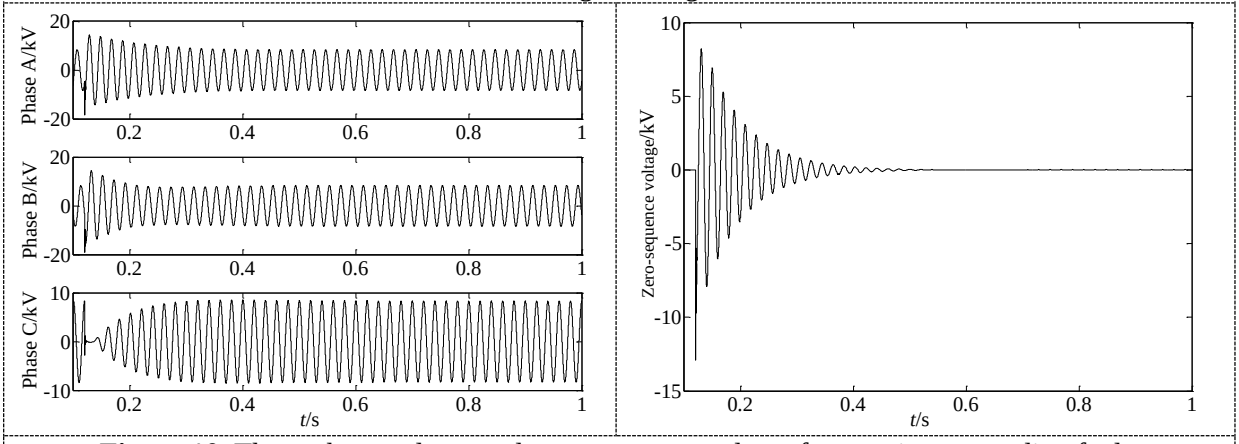


Figure 10. Three-phase voltage and zero-sequence voltage for transient grounding fault.

For permanent grounding fault, we set the same fault condition except the fault is metallic grounding fault. Arc suppression coil compensates the fault current of grounding point after fault. For the convenience of simulation, low resistance device will be put into after 3.12s, and arc suppression coil will drop out at the same time. Assuming that line protection device operating tripping at 3.32s, the system will go back to normal running. The waveform of electrical parameters in this process are shown in figure 11 and figure 12.

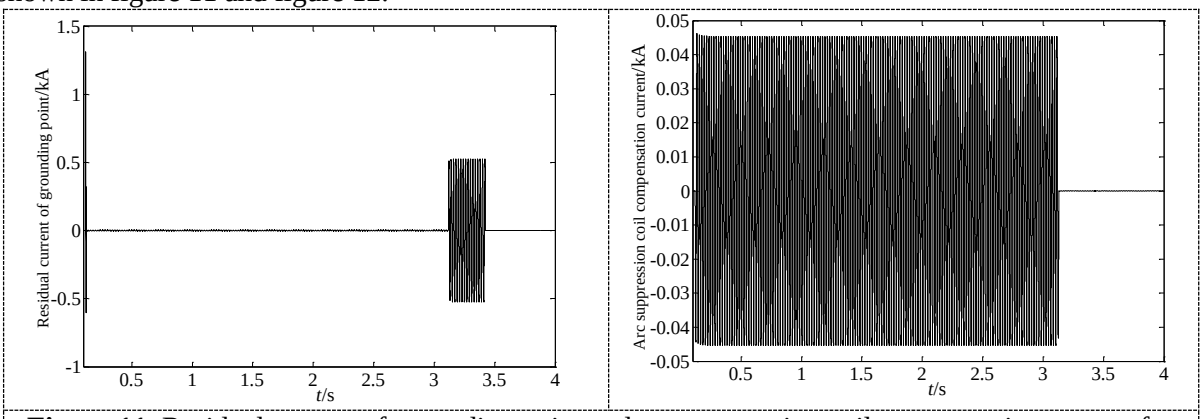


Figure 11. Residual current of grounding point and arc suppression coil compensation current for transient grounding fault.

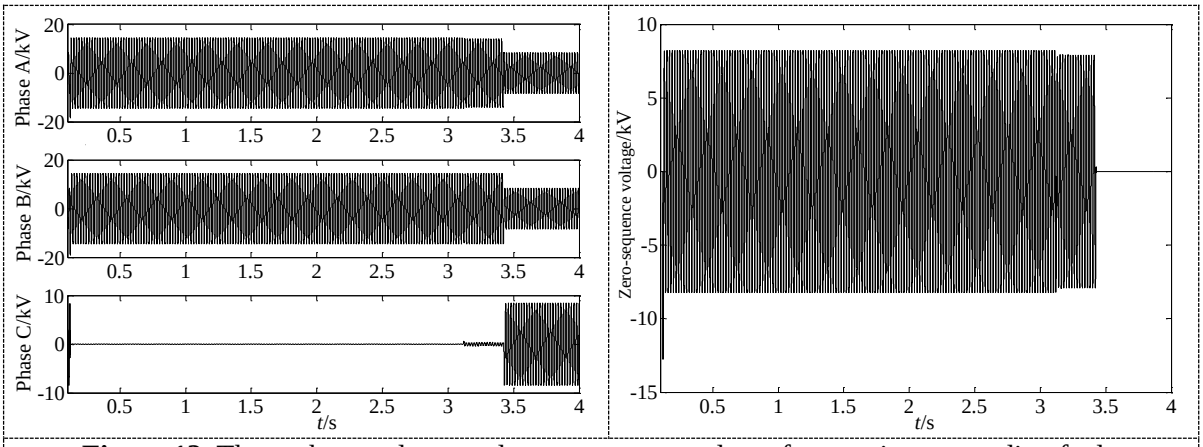


Figure 12. Three-phase voltage and zero-sequence voltage for transient grounding fault.

4.2. Protection measures

Intelligent multimode grounding mode can remove the transient grounding fault by quick and accurate compensation. For the permanent grounding fault, the fault line is removed by zero-sequence current protection after low resistance's join. The single-phase grounding fault of feeders often grounds with transition resistance [12]. The resistance will reduce the fault current. And a high-resistance will cause reject-action of protection. This section will analyze the process that zero-sequence current protection removes the permanent grounding fault after adding low resistance and define the influence of transition resistance to the sensitivity of zero-sequence current protection.

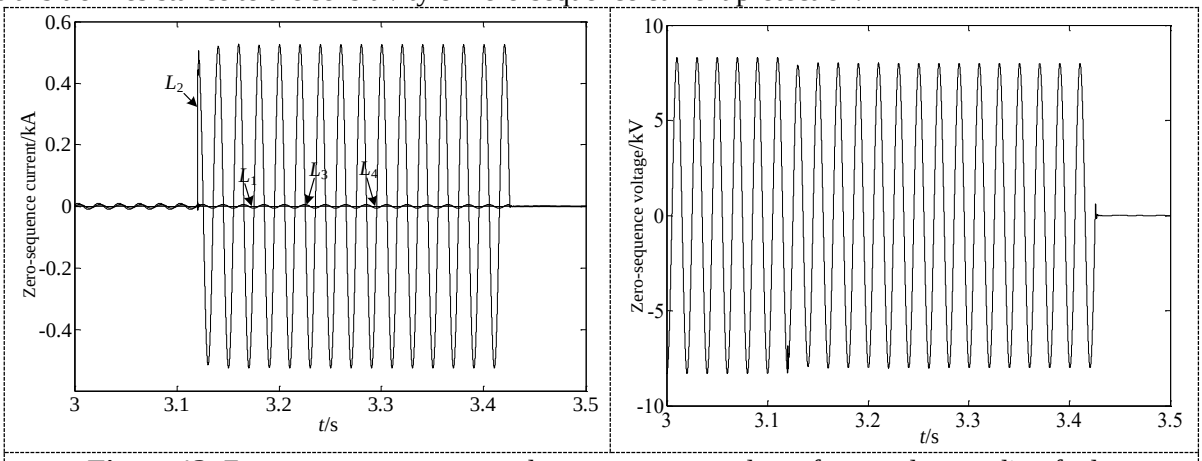


Figure 13. Zero-sequence current and zero-sequence voltage for metal grounding fault.

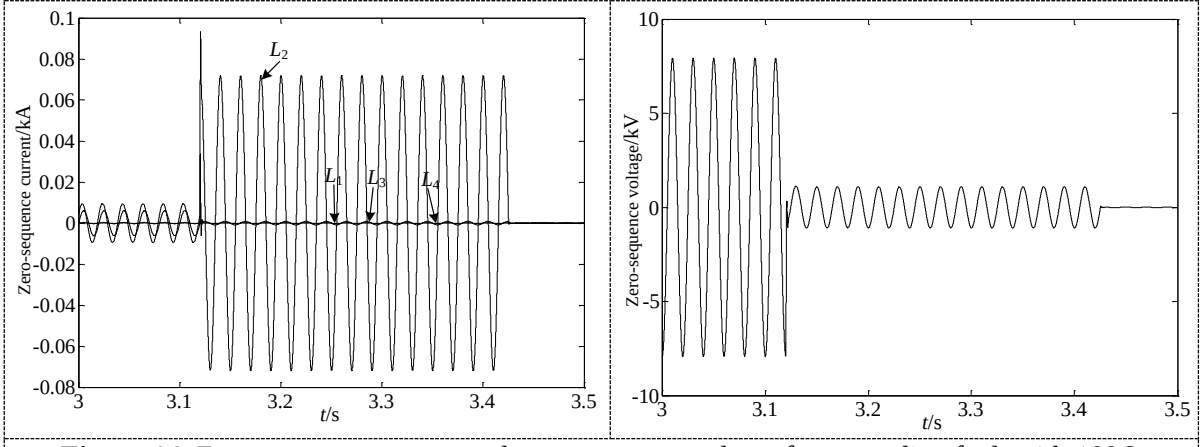


Figure 14. Zero-sequence current and zero-sequence voltage for grounding fault with 100Ω transition resistance.

Figure 13 and figure 14 shows the zero-sequence current of L_1~L_4 and system zero-sequence voltage in the case of metallic ground and ground with transition resistance after adding low resistance. As we can see from figure13, under metallic short-circuit fault, there is a short-time transient process after adding low resistance. The zero-sequence current peak of the fault line is about 526.5A, which is small for the impedance Z-type transformer and lines. But it's amplitude is greater than that of non-fault lines. In figure15, the zero-sequence current amplitude of L_2 is close to that of L_3 before adding low resistance, which may cause wrong line selection result. The enlargement of transition resistance will greatly reduce the amplitude of zero-sequence current and zero-sequence voltage of the fault line, which may cause reject-action of protection. So we should study the influence of transition resistance to zero-sequence current of feeders. According to the stipulations of DL/T 584-2007, the relay setting of the first section of zero-sequence current protection refers to the minimal single-phase grounding fault current.

$$I_{0\mathrm{I}}^{(line)} = \frac{I_{D\min}^{(1)}}{k_{LM}} \tag{2}$$

Where $I_{D\min}^{(1)}$ is the minimal single-phase grounding fault current, k_{LM} is the sensitive coefficient which is equal or greater than 2. The relay setting of the second section of zero-sequence current protection should be bigger than capacitive current of lines and unbalanced current of phase-to-phase fault.

$$I_{0\mathrm{II}}^{(line)} = K_K^{'} I_C \tag{3}$$

Where I_C is the capacitive current of this line, $K_K^{'}$ is the reliable coefficient which is set as 1.5. The relay setting of the second section will increase with the length of cables increasing. Then the ability of zero-sequence current protection to reverse transition resistance will decline sharply.

The relay setting of the first section of zero-sequence current protection is set as 186A and that of the second section is set as 9A. The simulation results of different transition resistance are shown in figure 16. With the increase of transition resistance, zero-sequence current of the fault line will decrease. When transition resistance is low, zero-sequence current decrease rapidly with the increase of transition resistance. When transition resistance is bigger than 16Ω, zero-sequence current is smaller than 186A so that the first section can't trip and the second section trip with long time. When transition resistance is bigger than 640Ω, zero-sequence can't operate reliably.

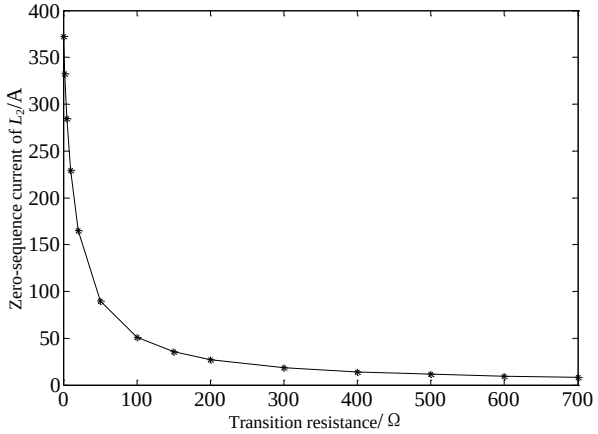


Figure 15. The effect of transition resistance on zero-sequence current.

5. Conclusion

With the large scale of construction and renewal of distribution network, the enlargement of cables leads to more complex grounding modes. This paper makes fault analysis and fault protection measures study for grounding fault transfer mode and intelligent multimode grounding mode based on the accurate simulation model. Research results help to enhance our recognition for the change of

electric parameters in composite grounding arc-suppression modes. It also lays the theoretical foundation for applying to practice and has important implications for improving reliability and security of distribution network.

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Acknowledgments

This research is supported by the Science and Technology Project of State Grid Hunan Electric Power Company Limited (Grant No. 5216A516002Y). B Yu wishing to thank the research supervisor for the helpful guidance. I will remember you forever. Thanks for the meet with T Wang. You are always in my heart.