Performance test of small-current grounding line selection device based on the real-time digital simulation system

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Abstract. Single phase grounding fault is the most common fault type in small-current grounding distribution network, but the small-current grounding line selection device put into operation on site is often difficult to meet the application requirements, affecting the rapid and accurate treatment of grounding fault. Considering that there are many small-current grounding line selection manufacturers and various device forms, it is difficult to intuitively evaluate the line selection performance of different devices and make horizontal comparison, and there is no supporting basis for the selection and application of on-site line selection devices. Therefore, based on the real-time digital simulation system (RTDS), this paper establishes a test platform for small-current grounding line selection device. Based on the constructed test platform, four line selection devices form different manufacturers are tested in parallel, the performance of the devices is compared, and the influencing factors affecting the accuracy of line selection results are analyzed. The conclusions of this paper can provide strong support for the pilot application of small-current line selection devices.

1. Introduction
Small-current grounding is widely used in the distribution network of power grid, which means the neutral point of the system is not grounded, or is grounded through arc suppression coil (ASC) or high resistance [1, 2]. When a grounding fault occurs, the fault current can be very small since the impedance between the circuit and the ground is very large. Therefore, it can operate for a period of time after fault. However, with the increasingly demanding on power supply, small-current grounding also brings some problems. On the one hand, the non-fault phase voltage and intermittent arc grounding overvoltage will threaten the insulation, and the long-term existence of grounding arc can ignite the line and result in line-to-line fault [3]. On the other hand, the weak characteristics of grounding fault can threaten the accuracy of fault handling [4] . Therefore, the earth fault selection device is delivered to quickly determine the fault line after grounding fault and help the operators to quickly troubleshoot the fault line.

At present, the line selection functions are based on different types of methods such as the steady-state principle, the transient principle and the injecting principle [5-7]. Typical methods include the zero sequence amplitude comparison, the harmonic amplitude comparison, the active component judgement, the first half-wave judgement, the wavelet analysis, and the external signal injection [8-10]. However, the application of these small-current grounding line selection devices in the field is not well
due to the low accuracy, and therefore provide no key auxiliary role for the field operation personnel [11, 12].

In addition, since there are many manufacturers of small-current line selection devices, and the performance of these products is quite different, it is difficult to horizontally compare the advantages and disadvantages [13]. In particular, as for the specific line selection device, the actual fault scene encountered in the field is very few and actually difficult to reproduce, so there is no way to evaluate the performance of line selection device using the field data.

Therefore, based on RTDS real-time digital simulation system, this paper builds a performance test platform for grounding line selection device using in distribution network, which can simulate various operation and fault scenarios, and test the performance of grounding line selection devices from different manufacturers. Through the same competition under all-round fault scenarios, the performance of different devices is evaluated, and strong support for the selection of line selection devices in the field can be provided.

2. Test Platform of Grounding Line Selection Device Based on RTDS

RTDS is the abbreviation of Real Time Digital Simulation system. It is a parallel computer system that can carry out power system transient simulation in real time. It has the advantages of real-time, closed-loop and continuous digital simulation. In addition, RTDS can form a closed-loop system with various protection and automation devices through IO boards and power amplifier, which can record the action of devices and complete the functional performance test. The performance test platform of grounding line selection based on RTDS system is mainly composed of the RSCAD workstation, central RACK, IO card, power amplifier and small-current grounding line selection device. The RSCAD is the user interface of the real-time simulation system, which is responsible for the graphical modeling of the primary system. The central RACK implements the real-time simulation calculation of the primary system. The calculated electrical quantities are interconnected with the external device through the IO boards. The schematic diagram of the overall RTDS-based line selection device test platform is shown in Fig. 1.

![Fig. 1 Schematic diagram of test platform for line selection device based on RTDS](image)

When the grounding fault is simulated in the RSCAD workstation, the central RACK can calculate the fault electrical quantity in real time and multi-channel signals such as the bus voltage, the zero sequence voltage and current of each line can be sent to the power amplifier. The scaling ratio of the power amplifier is set according to the actual transformer ratio, so as to ensure that the output of the power amplifier is in the same degree with the actual secondary value. The output signal of the power amplifier is connected to the grounding line selection device through hard wiring, so that the hardware-in-the-loop test of the line selection device can be realized.
Four different manufacturers of line selection devices are selected for parallel testing in this paper, which are referred to as device 1, device 2, device 3 and device 4 respectively. The electrical quantities needed to be introduced to each line selection device are the bus voltage, the zero sequence voltage and current information of each feeder. Therefore, each test device, the voltage quantity is connected in parallel and the current quantity is connected in series so as to ensure that the line selection scenarios and electrical quantities of all devices are completely the same, and all devices are tested in parallel under the same fault scenario. The actual wiring diagram of the small-current grounding line selection device is shown in Fig. 2.

3. Modelling and Fault Test Scenario Setting of Distribution Network

According to the standard DL/T872-2016 《Technical conditions of single phase grounding fault line selection device in grounding system》, the grounding line selection device should be able to accurately select the line and display the number of the grounding line and bus when a grounding fault occurs in the system. It also points out that before the line selection device put into operation, grounding faults tests are required both in the neutral point ungrounded system and the ASC grounding system, and the grounding faults must be including permanent grounding and intermittent arc grounding.

Fig. 2 The wiring of line selection devices from four different manufacturers

Fig. 3 Simulation of a typical 10kV distribution network
Therefore, based on the full investigation of 110/10kV substation, a typical 10kV distribution network simulation model is built in the RSCAD workstation, the parameters of the system are determined according to the design specifications, and the system diagram is shown in Fig. 3. The primary system includes a 110/10kV transformer and a Zigzag grounding transformer. In the 10kV side there are five lines, including two overhead lines, two cable lines, and a cable-overhead hybrid line. It should be noted that the simulation system can be adjusted according to the topology of the substation in simulating the actual distribution network if necessary.

3.1. Parameter Setting of the Line
For the overhead line and cable model in the system, the relevant parameters setting originally need to be adjusted according to the specific line type and layout in the simulation process of practical problems. However, in order to quantitative design the ASC parameters in this paper, the Bergeron model is used for all overhead lines and cable models, and the parameters are set according to the typical parameters used in the existing literature, as shown in Tab. 1.

| Parameters                        | Line type  | Overhead line | Cable  |
|-----------------------------------|------------|---------------|--------|
| Positive sequence resistance (Ω/km) |            | 0.27          | 0.175  |
| Positive sequence reactance (Ω/km) |            | 0.08          | 0.38   |
| Positive sequence capacitance (μF/km) |            | 0.00939       | 0.3832 |
| zero-sequence resistance (Ω/km)   |            | 2.7           | 0.23   |
| zero-sequence reactance (Ω/km)    |            | 0.32          | 1.72   |
| zero-sequence capacitance (μF/km) |            | 0.011374      | 0.398  |

3.2. Fault Location Setting
In order to consider the influence of fault location on line selection, the faults on the overhead lines, cables, cable-overhead hybrid lines and bus are considered in the test. For cables and overhead lines, the fault locations are the begin of the line, one-third of the line, two-thirds of the line and the end of the line. Therefore, for an overhead line with 8km length, the fault location settings are 0km, 2.67km, 5.33km and 8km. For a cable with 2km length, the fault location is set to 0km, 0.67km, 1.33km and 2km. For the hybrid line, the fault location is considered as the cable head, the cable midpoint, the cable connection point, the overhead line midpoint and the overhead line end. For the hybrid line composed of 2km cable and 8km overhead line, the fault location is set to 0km, 1km, 2km, 6km, and 10km.

3.3. Grounding Fault Module Setting
Considering that the high resistance grounding fault has a great influence on the accuracy of line selection, the setting interval of the resistance in the high resistance area is finer in the test, and the setting of the resistance is mainly considered as 3000Ω, 2800Ω, 2600Ω, 2400Ω, 2200Ω, 2000Ω, 1000Ω, 500Ω and 0.1Ω.

In addition, the closing angles are set as 0°, 30°, 60° and 90° to reflect the influence of fault closing angle on line selection. As the frequency of the system voltage is 50 Hz, and each cycle wave corresponds to 20 ms, so the fault is controlled by accurately detecting the zero-crossing point of the voltage in the RSCAD, and based on which a fixed time delay is performed to trigger the fault after the zero-crossing point, so as to simulate the fault angle accurately. For example, if the fault angle is 90°, the fault can be triggered by a delay of 5 ms after the zero-crossing point.
3.4. Arc Fault Module

According to the test requirements, the model should be set to permanent fault or arc grounding fault. However, the typical Cassie and Mayr models in the RSCAD system are difficult to simulate the arc characteristics of arc grounding in the distribution network. Therefore, a control theory based arc model referred to [14] is established using the controlled resistance elements in this paper. The mathematical expression of the nonlinear controllable model of arc conductance is as below:

\[
\frac{dg}{dt} = \frac{1}{\tau_b}(G_s - g)
\]

\[
\tau_b = \beta \times \frac{I_{i4}}{l}
\]

\[
G_s = \frac{V_{i0} \times I_{i4} \times l}{k_s}
\]

Where \( g \) presents the instantaneous arc conductance, \( G_s \) presents the steady-state arc conductance, \( \tau_b \) presents the arc time constant, and \( V_{i0} \) presents the pressure drop per unit arc length, which is generally 75 V/cm, \( I_{i4} \) is the instantaneous arc current, and \( l \) is the gap length of the arc. \( \beta \) is a constant coefficient, generally 7.5e-6, \( I_s \) presents the arc current amplitude, approximately equal to the steady-state current amplitude of metal grounding fault. Since the simulation test shows that the arc conductance and arc current are mainly affected by the arc length, the sets of the arc length are 30 cm, 75 cm and 120 cm for simulation in this paper.

3.5. ASC Settings

In the neutral grounding system with ASC, the ASC is generally selected as over compensation so as to compensate the capacitance current. The compensation degree is generally about 10%, that is to say the fault current after compensation is about 10% of the fault current before compensation, and the fault current after compensation is inductive. In this paper, the over compensation degree of ASC is selected as +5% and +10%.

When the ASC current fully compensates the capacitance current, the fault current at the grounding point is approximately 0 in theory, under which condition the inductance should satisfy the following function:

\[
\omega L = 1/(3\omega C_x)
\]

Where \( L \) is the ASC inductance, \( C_x \) represents the three relative capacitances for the system. According to the parameters of the system cable and overhead line listed in Tab. 1, it can be obtained that when \( L \) equals to 1.27H the current of the capacitances can be fully compensated. Therefore, when the overcompensation degree is 5%, the value of \( L \) is calculated as 1.2095H, and when the degree is 10%, the value of \( L \) is calculated as 1.1545H.

4. Test Results and Analysis of Four Devices

Based on the above RTDS grounding platform, the performance tests of the grounding line selection devices from four different manufacturers are carried out. According to the test fault scenarios, they can be divided into four categories, which are permanent fault of ungrounded system, permanent fault of system with ASC, arc grounding fault of the ungrounded system and arc grounding fault of system with ASC (referred as Type 1, Type 2, Type 3 and Type 4 respectively). In the above four kinds of fault scenarios, the “Control variable method” is used to conduct multi-scenario parallel simulation test for the following five factors: fault location, fault closing angle, transition resistance, compensation degree and arc length. The results are as follows.

4.1. Permanent Fault of Ungrounded System

The total number of test scenarios in Type 1 is 378. In the test the device 1 fails to select the fault line 32 times, which are all high transition resistance occasions. The device 2 fails to select the fault line
once when the first line fails at the end, the closing angle is 0°, and the transition resistance is 3000Ω. Besides, there are 257 times of fault phase selection and most of them occurs in the scenarios with transition resistance more than 1000Ω. The device 3 selects the fault line correctly in all scenarios, and there are six times the fault phase is not correct under the hybrid line failure with a transition resistance of 1000Ω. The device 4 fails to select the fault line for three times and fails to select the fault phase for 33 times. The line selection errors occur in bus faults, and the occurrence of phase selection errors is relatively scattered.

4.2. Permanent Fault of System with ASC
The total number of test scenarios in Type 2 is 672. In the test the device 1 fails to select the fault line two times, which are all resistance with 3000Ω. The device 2 fails to select the fault line for 10 times under the hybrid line failure. Besides, there are 225 times of fault phase selection and most of them occurs in the scenarios with transition resistance more than 1000Ω. The device 3 fails to select the fault line 18 times with fault on the bus, and there are 38 times the fault phase is not correct under the high resistance condition. The device 4 fails to select the fault line for 67 times and fails to select the fault phase for 395 times. The line selection is completely correct when the fault occurs in the overhead line, and the occurrence of phase selection errors is relatively scattered.

4.3. Arc Grounding Fault of Ungrounded System
The total number of test scenarios in Type 3 is 126, and all of the four devices can select the right fault line. The difference lines in that the times of error phase selection for the four devices are 27, 30, 29, and 24, and the phase selection is wrong under the condition of gap length with 120 cm.

4.4. Arc Grounding Fault of System with ASC
The total number of test scenarios in type 4 is 216. The device 1 has two line-selection errors and 12 phase-selection errors, and the gap length is 120cm when phase selection is wrong. The device 2 has two line-selection and 16 phase-selection errors. The device 3 has 96 line-selection errors without error phase selection, the error behaves in that the device can display instability when the gap length is 75 cm or 120 cm. The device 4 has 4 line-selection errors and 37 phase-selection errors, most of which are in the case of gap length of 120 cm.

4.5. Analysis of Grounding Line Selection Device
The 1392 times parallel test results of the four devices are comprehensively compared and the results are shown in Tab. 2. In the table, the LSR and PSR are used to represent the line selection rate and phase selection rate of each device.

| Devices | Type 1/% | Type 2/% | Type 3/% | Type 4/% | Total/% |
|---------|----------|----------|----------|----------|---------|
| Device 1 | LSR 91.53 | 99.70 | 100.00 | 99.07 | 97.41 |
|          | PSR 100 | 100 | 78.57 | 94.44 | 97.20 |
| Device 2 | LSR 99.74 | 98.51 | 100.00 | 99.07 | 99.07 |
|          | PSR 32.01 | 66.52 | 76.19 | 92.59 | 62.07 |
| Device 3 | LSR 100 | 97.17 | 100.00 | 55.56 | 91.81 |
|          | PSR 98.41 | 94.35 | 76.98 | 100 | 94.76 |
| Device 4 | LSR 99.21 | 90.03 | 100.00 | 98.15 | 94.68 |
|          | PSR 91.27 | 41.22 | 80.95 | 82.87 | 64.87 |
Through the comparison of the test results of the above 1392 fault scenarios, it can be obtained that the performance of the device 1 is relatively stable as a whole, and the correct rate of line selection is relatively high and the fault phase can be selected if the fault line is carried out. Therefore, the device 1 has no obvious short board. The overall line selection accuracy of device 2 is the highest, but the accuracy of phase selection is poor. Only when the resistance is less than 1000Ω, the fault phase can be selected. The line selection accuracy of the device 3 is the lowest, but the line selection accuracy is higher for ungrounded system. The line selection ability for the system with ASC is relatively general, and the arc fault phase selection accuracy of the ASC grounding system is low. As for the device 4, the line selection accuracy of the neutral point ungrounded system is high, but the accuracy is relatively low under the ASC grounding mode, especially for the arc fault.

4.6. Influence of Different Factors on Action of Line Selection Device

1) Fault location: in this paper, the influence of fault location on the line selection accuracy of line selection device is not obvious. Theoretically, the farther the fault point is from the start end of the line, the greater the voltage drop on the fault line, and the less obvious the fault characteristics are. However, in this test, due to the loss on the line is relatively small relative to the system voltage, the fault location does not significantly affect the line selection device.

2) Fault closing angle: the simulation test also shows that the higher the closing angle is, the higher the accuracy of the line selection device is. This is because the closer the fault closing angle is to 90°, the more obvious the characteristic quantity generated by the fault is, which has a positive effect on the improvement of the line selection accuracy of the line selection device.

3) Transition resistance: as for the permanent fault, the transition resistance has the greatest influence on the accuracy of device line selection. In the case of large transition resistance, the accuracy of line selection of four devices will be reduced to varying degrees, and the accuracy of line selection of device 1 is the largest. In the case of high transition resistance, the device 1 will be unable to select the line.

4) Compensation degree of ASC: in the ASC grounding system, the difference in compensation degree affects the magnitude of steady-state fault current, and therefore has little effect on the transient line selection method. Therefore, in the simulation test, the change of ASC compensation degree has different influence on the four devices. When the degree is large, the phase selection accuracy of device 2 is low. For the other three devices, the influence of the compensation degree on the line selection and phase selection accuracy is not obvious.

5) Arc length: for arc fault, the longer the arc length is, the greater the arc resistance value is, and the more unstable the arc fault characteristics are. Therefore, it is more difficult to achieve accurate line selection for the line device when the arc length is long. In the test in this paper, the line selection accuracy of the four devices will decrease in different degrees when the arc length is long.

5. Conclusion

In this paper, the grounding model and the test platform of distribution network are built based on RTDS system. For the neutral point ungrounded and ASC grounding system, the influence of fault location, fault closing angle, fault type, transition resistance and compensation degree on the line selection device is simulated and the characteristics and performance evaluation results of the four devices are obtained, which provides an important reference for the selection of grounding line selection equipment in the actual field.

The next research focus is to collect the actual fault recording data on the site, and test the devices based on the recording playback function of RTDS platform, and in this way the grounding line selection test system can be improved by combining digital simulation and recording.

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