Research on DC grounding finder to effectively prevent microcomputer protection malfunction caused by one-point grounding of secondary circuit

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Abstract. The problem of protection malfunction caused by one-point grounding of the secondary circuit has received extensive attention, which have been updated in several domestic industrial standards, but the problem of microcomputer protection malfunction due to one-point grounding of the secondary circuit still occurs frequently during operation. According to the analysis, with the comprehensive promotion of microcomputer protection, low-power operating element have been used on a large scale, which makes the grounding resistance of the DC system larger. The relevant parameter setting, principle design and specification requirements of the original DC grounding finder have not been taken into account, which leads to frequent occurrences of secondary equipment malfunction in the DC grounding search process. In-depth analysis of the typical grounding situation showed that the detection resistance value of the existing DC grounding finder is too small, and when both positive and negative electrodes are grounded with high resistance, protection malfunction caused by DC grounding finder may occur. According to the asymmetric characteristics of existing secondary circuits, an asymmetric DC grounding finder was designed, with a strong anti-protection malfunction ability, it was verified by actual measurement that the detection sensitivity of the instrument on ground resistance was improved by more than 50%.

1. Introduction
Abnormal grounding of DC system is unavoidable, so in order to prevent the failure of loop power supply resulted from grounding and protection malfunction, high-resistance grounding is generally adopted in the current DC system, and the positive and negative resistances are the same, that is, the grounding is undergone high-resistance balanced resistance. Grounding that occurs in DC system is classified as a major defect and needs to be processed in time limit to find out the fault point.

In order to prevent protection malfunction caused by one-point grounding of secondary circuit, the protection circuit from malfunction due to one-point grounding of the secondary circuit, the industrial standard "DLT 1392-2014 Technical specification of insulation monitoring devices for DC power system" and "DLT 1397.6-2014 General specification for DC power system test equipment of electric power system Part 6: Portable grounding detection apparatus" first proposed the concept of "risk factor of protection malfunction" when they were revised in 2014, and used large text and requirements to prevent the occurrence of such incidents. However, in the using process, it was found that these measures cannot completely avoid the secondary equipment malfunction.
2. Typical case analysis
In 2015, GXC-64 2M communication interface device of the 500kV line of a 500kV substation frequently alarmed. The inspection found that when the incoming cable for alarm signal of the "GXC-64 2M communication interface device" for the measurement and control equipment at this interval was directly grounded, and a portable DC grounding finder was being used to find the fault, the alarm was restored once the output of the DC grounding finder was turned off.

In order to verify the relationship between the portable DC grounding finder and the microcomputer protection malfunction, two typical instruments before and after the implementation of the latest standard commonly used on the market are used to simulate the metal grounding of the external circuit of different microcomputer protection devices. The actions of the protection device and the portable DC grounding finder are shown in Table 1.

Table 1. Portable DC Grounding Finder and Computer Protection Coordination Test

| Instruments     | NARI Protection | Beijing Sifang Protection |
|-----------------|-----------------|---------------------------|
|                 | Whether the failure point can be found | Protection action | Whether the failure point can be found | Protection action |
| Instruments1    | NO              | Maloperation repeatedly   | NO              | Running light off |
| Instruments2    | YES             | misoperation              | YES             | misoperation     |

![Fig1. Common ground fault models](image)

![Fig 2. Output of portable DC grounding finder](image)

![Fig 3. Internal structure diagram of optocoupler](image)

The model is shown in Fig. 1. In order to check the cause of the fault, the voltage of the DC system bus to ground was measured, and the DC bus voltage was found to have a large fluctuation, with an amplitude between 20V and 96V. As shown in Fig. 1 (the magnification of the test pen was 10 times). To further analyze the output of the portable DC grounding finder, the fault recorder was used to check the output of the portable DC grounding finder, and it was found that the output, shown in Fig. 2, contained a square wave with an amplitude from 35V to 38V and a frequency of 2Hz; The output of the negative pole was 3V greater than that of the positive; It also contained a certain amount of AC harmonics.
The internal component of the false alarm signal is an optocoupler, and its internal structure is shown in Figure 3. Among them $R_2 + R_3 = 100\Omega$. Its operating voltage is 55% -70% UE.

The cause analysis of false alarm: It can be seen from Fig. 1 that when the other end of the optocoupler is directly grounded, the voltage at both ends of the optocoupler is the voltage of the negative bus of the DC system to the ground. When the signal of the DC system was injected into the portable DC grounding finder caused the voltage of the negative bus to the ground of the DC system to exceed the action voltage of the optocoupler, with 55% of the rated voltage, then the optocoupler malfunctioned.

In order to prevent such incidents from happening again, the existing industrial standards propose the following requirements:
1) The DC-to-earth voltage fluctuation caused during the grounding detection shall not exceed 10% Un.
2) The peak value of the sinusoidal AC low-frequency excitation signal shall not be greater than 10V, and the frequency shall not be greater than 5HZ.

Indeed, by decreasing the amplitude of the excitation signal of the instrument, the risk of protection malfunction could be reduced, but at the same time the problems brought about are more prominent, and the detection sensitivity of the instrument decreased linearly. In the meantime, it could not completely avoid the voltage at both ends of the input element below the allowable value of 55%Un, so it could not completely avoid protection malfunction, especially in the process of searching for switching resistance and DC grounding, which were discussed in depth as follow.

3.Introduction of the status quo

3.1 DC system model
The secondary circuit of the secondary system of the DC system mainly includes a switch quantity circuit, a power circuit, and an output control circuit, among which, the switch quantity circuit occupies the vast majority. Basically, the switch quantity circuit of all secondary devices such as protection, measurement and control, and fault recording devices uses the positive electrode as the common terminal, and the negative electrode is connected to the end of the opening component. The common grounding model is shown in Fig.1. Thereinto, the red part is the cable of input element, and the cyan part is the cable of the common port. Grounding faults generally occur in outdoor cables, that is, the red and cyan parts of the cable grounding occupy the majority, while the red part can account for more than 80%. In this type of model, because of the introduction of input elements, the grounding detection is more difficult, with greater risks. Therefore, in the design of DC grounding finder, the effects of this type of grounding fault should be carefully considered.

3.2 Changes of input elements
In the era of relay, the input elements were mainly relay, with relatively small internal resistance. For example, the most sensitive relay coil resistance of 220V DC system was 20k ohms.

In the initial stage of microcomputer protection, such as RCS series protection of NARI-Relays, photoelectric isolation components were used (most of the optocouplers were integrated inside the opening board, and a small part adopted independent optocoupler components), and their internal resistance could reach 20kΩ. The relationship between the internal resistance and the voltage at both ends of the input element is shown in Fig. 4.

The existing microcomputer protection equipment basically has a large internal resistance in order to reduce power and heat generation. For example, the internal resistance of the PCS protection input elements of NARI is 100KΩ, as shown in Fig.5. Beijing Sifang's CSC series protection has a maximum opening resistance of 166kΩ. The measurement and control device of NARI Technology is infinity when it is lower than 55V. The input elements of Changyuan Shenrui and Nanjing Automation Protection are similar to those of NARI Technology. When the voltage at both ends decreases, the internal resistance is infinite.
Therefore, the existing specification "DLT 1397.6-2014 General specification for DC power system test equipment of electric power system Part 6: Portable grounding detection apparatus"
requires the detection range of grounding resistance to be \(0 \sim 100\, \text{k}\Omega\), which cannot meet the existing requirements of microcomputer protection. At the same time, the input elements of the existing microcomputer protection shutdown when the voltage at both ends of the input element is relatively low, which also makes this type of defect undetectable and has a large hidden danger. Protection manufacturers should take measures to avoid this type of phenomenon.

4. Switching detection resistance causes protection malfunction.

4.1 Cause analysis of malfunction

The existing DC grounding finder includes two parts: a host and a handheld finder. The function of the host is to calculate the output of the excitation power supply and the bus resistance. The function of the handheld finder is to measure the leakage current of the branch and calculate the ratio of the leakage current of the branch to the output current of the host, so as to calculate the grounding resistance of the branch.

The calculation principle of bus resistance is shown in Fig. 8, where \(R_1\) is the balance resistance of the bus. \(R_2\) is the detected resistance of the DC grounding finder, and \(K_1\) and \(K_2\) are the switches.

![Fig 8: Principle of calculating bus resistance](image)

\[
\frac{U_{+1}}{U_{-1}} = \frac{R_+ + R_2}{R_- + R_2} \tag{1}
\]

\[
\frac{U_{+2}}{U_{-2}} = \frac{R_+}{R_- + R_2} \tag{2}
\]

Since \(R_2, U_{+1}, U_{-1}, U_{+2}\) and \(U_{-2}\) were all known, the grounding resistance \(R^+\) and \(R^-\) of the positive and negative poles could be calculated from equation 1 and 2.

The resistance of the balancing resistor has different values at different stages. In the early insulation monitoring device, a DC relay was used, with resistance of \(30\, \text{k}\Omega\). The microcomputer-based insulation monitoring device with fault branch finders, which emerged in the 1990s, has a large balancing resistance ranging from \(100\, \text{k}\Omega\) to \(200\, \text{k}\Omega\). In 2013, the enterprise standards of State Grid and South Grid limited the resistance to \((15 \pm 2.5)\, \text{k}\Omega\) (the system of \(110\, \text{V}\)) and \((30 \pm 5)\, \text{k}\Omega\) (the system of \(220\, \text{V}\)), while "DL/T 1392-2014 Technical specification of insulation monitoring devices for DC power system" cancelled this requirement again. Meanwhile, "DLT 1397.6-2014 General specification for DC power system test equipment of electric power system Part 6: Portable grounding detection apparatus" requires that the detection resistance of the product switching should meet the following requirements:
A) The detection resistance value of the nominal voltage of 220V is not less than 50kΩ;
B) The detection resistance value of the nominal voltage of 110V is not less than 30kΩ;

As shown in Fig. 9, before the DC grounding finder starts to detect the voltage, assuming that the DC system is in an equalized charging state, the positive and negative poles are well insulated, and its bus voltage is 120V. The voltage calculation at both ends of the input element is shown in equation 3, and the calculated results are shown in Table 1:

![Fig 9. Common types of ground fault](image)

It can be seen from Table 2 that no matter what kind of input element, its voltage is lower than the operation voltage, the input element will not malfunction at this time.

After the DC grounding finder starts to detect the voltage, when K1 is closed, the voltage at both ends of the opening component is calculated based on equation 4, and the calculation results are shown in Table 3:

\[ U1 = \frac{R1+R}{R1+R2+R} \times 120V \]  

| Resistance of Optocoupler balance resistance | 15  | 30  | 100 | 200 |
|---------------------------------------------|--|-----|-----|-----|
| 125                                         | 56.6 | 53.6 | 42.9 | 33.3 |
| 100                                         | 55.8 | 52.2 | 40.0 | 30.0 |
| 50                                          | 52.2 | 46.2 | 30.0 | 20.0 |
| 30                                          | 48.0 | 40.0 | 22.5 | 13.9 |
| 3                                           | 17.1 | 10.0 | 3.4  | 1.75 |

As can be seen from Table 3, when the resistance of the opening component is greater than 50kΩ and the DC grounding finder switches to detect the resistance, the voltage at both ends of the input element will be greater than the operation voltage, resulting in the malfunction of input element.

### 4.2 Analysis of anti-malfunction measures

It can be seen from the above analysis, in the measurement of busbar resistance, when the resistance of the positive electrode is detected, the voltage of the negative electrode will be raised, this moment the secondary input element may malfunction. In order to prevent the occurrence of such events, the wiring mode of the detection resistance was changed to the mode shown in the figure below. At this
time, when measuring the bus resistance, the voltage of the DC bus negative pole will only decrease, not increase, so it can effectively avoid protection malfunction.

Fig 10. Improve principle structure for calculating bus resistance

5. Protection malfunctions caused by grounding detection

After the existing DC grounding finder calculates the grounding resistance in switching the detection resistance, it disconnects the switch of the detection resistance, outputs the characteristics signal, and then finds the leakage current of each branch by the handheld finder. In this process, when the output of the instrument is too large, it may cause protection malfunction, so the existing specifications require the peak value of the excitation signal not greater than 10V. However, according to analysis, this requirement cannot fully meet the requirements of the input elements of the existing microcomputer protection.

5.1 Analysis of cause of protection malfunction caused by too-large output characteristic signal

As shown in Fig. 9, assuming that the resistance of the positive and negative poles are the balanced resistance of the insulation monitoring device or the grounding finder, the internal resistance of the input element is $R_{input}$, the operating voltage is just 55% * $U_E$ = 60.5V, and the grounding resistance of the positive electrode is $R$, while the average charging voltage of the 110V system is 120V, so

$$R_\pm = \frac{R_{input} R_{op}}{R_{input} + R_{op}}$$  \hspace{1cm} (5)

$$R_+ = R_1$$  \hspace{1cm} (6)

$$U_- = \frac{R_-}{R_- + R_+} \times 120V$$  \hspace{1cm} (7)

The results are shown in Table 4. It can be seen that when the balancing resistance is set to 15kΩ or 30kΩ, and if the internal resistance of the input element is relatively large, the voltage amplitude at both ends of the input element may exceed 55% of the rated voltage (60.5V), resulting in the malfunction of the input element.

| Resistance of Optocoupler balance resistance | 15  | 30  | 100 | 200 |
|---------------------------------------------|-----|-----|-----|-----|
| 20  | 43.6 | 52.1 | 17.1 | 10  |
|     | $(\pm 10)$ | $(\pm 10)$ | $(\pm 10)$ | $(\pm 10)$ |
| 100 | 55.8 | 52.2 | 40.0 | 30.0 |
|     | $(\pm 10)$ | $(\pm 10)$ | $(\pm 10)$ | $(\pm 10)$ |
| 150 | 57.1 | 54.5 | 45  | 43.6 |
|     | $(\pm 10)$ | $(\pm 10)$ | $(\pm 10)$ | $(\pm 10)$ |

5.2 The negative electrode is grounded through the input element and the positive electrode is grounded through high resistance.

When the negative electrode is grounded through the input element and the positive electrode is grounded by the metal again, the input element directly malfunctions. However, when the positive
 electrode is grounded through high resistance, the input element may not malfunction, but at this time, if the excitation power of the DC grounding finder is connected, then the malfunction may occur, as shown in Fig. 11.

![Fig 11. Two point grounding causes protection malfunction](image)

The bus voltage changes of the original ground finder during the grounding search in different balance resistances and positive grounding resistances were separately calculated, as shown in Table 5. Thereinto, the initial values of the data in red are all less than 60.5V, but in the DC grounding finding, the AC excitation voltage output of the host (no more than 10V) will make the maximum DC bus voltage to earth greater than 60.5V, this moment the secondary input element will malfunction due to DC grounding finding. The initial value of the data in yellow is greater than 60.5V, this moment the secondary input element may have acted. Therefore, it is necessary to conduct a general detection on the input element of the secondary equipment before the DC grounding search, to check whether the input element is malfunctioned. Otherwise, the malfunction of input element will change 1 to 0 in the DC grounding search.

| balance resistance | Positive ground resistance | Infinity | 200 | 100 | 80.0 | 50.0 | 30.0 |
|--------------------|---------------------------|----------|-----|-----|-----|-----|-----|
| 15.0               |                           | 55.8     | 58.0| 60.0| 61.0| 63.7| 67.9|
| 30.0               |                           | 52.2     | 56.3| 60.0| 61.7| 66.2| 72.7|
| 100.0              |                           | 40.0     | 51.4| 60.0| 63.5| 72.0| 82.1|
| 200.0              |                           | 30.0     | 48.0| 60.0| 64.6| 75.0| 86.3|

5.3 Analysis of anti-malfunction measures

From the above analysis, it can be seen that in the DC grounding detection process, the maximum voltage of the bus negative pole to the ground exceeds the operating voltage of the input element, resulting in protection malfunction. Therefore, in order to prevent the occurrence of such events, the maximum voltage of the DC bus to earth must be reduced. In order to achieve this purpose, the existing industrial standards limit the output amplitude of the DC grounding finder, and the maximum value must not exceed 10V. Although this can effectively reduce the fluctuation of the DC bus voltage, it cannot effectively prevent protection malfunction.

In this paper, by increasing the detection resistance at the negative bus of the DC system, and maintaining the access state during the DC grounding search process, the bus voltage of the DC system was kept below 55% Ue-10V, so that the maximum bus voltage of the DC system would not exceed 55% Ue caused by the DC grounding finder, so as to effectively avoid protection malfunction. The detailed schematic diagram is shown in Fig. 12. When the balancing resistance was greater than or equal to 100KΩ, the detection resistance was set as 100kΩ; when the balancing resistance of the DC system was greater than 15kΩ and less than 100kΩ, the detection resistance was set as 50kΩ. Closed K1 first to detect whether the bus voltage of the DC system is greater than 45%*Ue. If yes, continued to close K2; otherwise, no action.
The newly improved instrument repeated the above calculation, and the results are shown in Table 6. It can be seen from Table 6 that the original data in red of the Table 5 had been greatly reduced. Even if the excitation voltage (peak value not greater than 10V) output by the host was added, the maximum voltage at both ends of the input element did not exceed 60.5V (55% * Ue). Therefore, the newly developed DC grounding finder could effectively prevent this type of protection malfunction.

Table 6. Average voltage of input element

| balance resistance | Positive ground resistance | 15.0 | 30.0 | 100.0 | 200.0 |
|--------------------|---------------------------|------|------|-------|-------|
|                    | Infinity                  | 49.0 | 41.4 | 40.0  | 30.0  |
|                    | 100                         | 47.6 | 41.1 | 48.0  | 45.0  |
|                    | 80.0                        | 48.5 | 42.6 | 43.2  | 40.0  |
|                    | 50.0                        | 51.4 | 46.8 | 51.4  | 50.0  |
|                    | 30.0                        | 55.4 | 53.3 | 62.4  | 62.7  |

6. Testing of the new type of DC grounding finder

In order to improve the detection ability on high resistance, high-precision AC sampling CT was adopted, and the signal source was changed to sinusoidal signal. In the design of anti-interference capacitor, the angle of the sinusoidal signal could be used to filter the influence of the interference capacitor, thereby improving the detection accuracy. To check the detection ability and anti-interference ability of the instrument, the detection accuracy of each grounding resistance was measured without system capacitance and with a system capacitance of 40μF, respectively.

Fig 12. Schematic diagram of anti-protection maloperation

Fig 13. Resistance testing precision (No system capacitor)
The newly improved instrument was compared with the instruments 1 and 2, and the test results are shown in table 7.

| Instruments          | NARI Protection | Beijing Sifang Protection |
|----------------------|-----------------|---------------------------|
|                      | Whether the failure point can be found | Protection action | Whether the failure point can be found | Protection action |
| Instruments1         | NO              | Maloperation repeatedly   | NO              | Running light off |
| Instruments2         | YES             | misoperation              | YES             | misoperation     |
| Improved instrument  | YES             | Protection without exception | YES             | Protection without exception |

As can be seen from the table above, the improved instrument can greatly improve the detection capability for high-impedance and effectively prevent protection malfunction.

7. Conclusions
Because the internal resistance of the optocoupler used in the existing microcomputer protection is much larger than that of the conventional relay, protection malfunction is caused in various kinds of DC grounding search. In this paper, the analysis showed that the existing secondary circuit was asymmetrical, and the asymmetric DC grounding finder was designed, which had strong abilities of anti-protection and anti-malfunction and had been verified by actual measurement.

The existing standards have lower requirements for search capabilities on high-impedance grounding, and there may be protection malfunction in the common high-impedance grounding search. In this paper, through the development of a new type of DC grounding finder, the related defects in the existing regulations could effectively be avoided, greatly improving the safety of products.
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