Analysis and research on breakdown cause of lightning arrester at low voltage side of 220kV transformer

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Abstract—This paper describes an event of zinc oxide arrester breakdown at low voltage side due to single-phase grounding at medium voltage side of 220kV transformer. Combined with the system wiring mode, equipment damage, system background and test data, the causes of fault and the transmission mechanism of overvoltage are studied in detail. It is concluded that the single-phase grounding short circuit on the medium voltage side leads to the displacement voltage of the neutral point, and the overvoltage is transmitted to the low voltage side through the capacitive coupling between the transformer windings, resulting in the breakdown of the arrester. The correctness of the conclusion is verified by calculation, and reasonable rectification measures and suggestions are put forward to effectively limit the generation of overvoltage on the low-voltage side of the transformer and ensure the safe and stable operation of the power grid.

1. Introduction
Lightning arrester is used to protect electrical equipment from high transient overvoltage during lightning stroke, limit freewheeling time and often limit freewheeling amplitude. For transformers with no-load operation on the low-voltage side or possible operation with short bus, lightning arresters shall be installed on the low-voltage side of the transformer for protection. Generally, zinc oxide arrester with silicone rubber jacket is selected. One end of the arrester is connected in parallel with the outgoing line at the low-voltage side of the transformer and one end is grounded. It is an important equipment to protect the safe and stable operation of the power grid[1].

For the system with ungrounded neutral or grounded through arc suppression coil, when asymmetric grounding fault occurs, the neutral point of transformer will produce displacement voltage, this overvoltage is generated by capacitive coupling between transformer windings, which is a common transmission overvoltage in power system[2-5]. In this paper, after a phase grounding short circuit on the medium voltage side of the transformer, due to the capacitive coupling between the medium voltage and low voltage windings of the transformer, the neutral point displacement voltage is generated, and the overvoltage is transmitted to the low voltage side, so that the overvoltage on the low voltage side exceeds the continuous operation voltage and rated voltage of the arrester, resulting in the breakdown of the arrester.
2. Fault overview
220kV I bus and II bus operate in parallel through 220kV bus tie switch, 66kV I bus and II bus operate in parallel through 66kV bus tie switch, 66kV bypass bus is cold standby, 10kV I bus replaces No. 1 main transformer, and 10kV II bus replaces No. 2 main transformer and auxiliary transformer, the wiring mode of No. 1 main transformer system is shown in figure 1.

The phase B arrester at 10kV side of 1 main transformer, the model is YH5WZ-17/45, the operation date is November 8, 2020, the nameplate of phase B arrester is shown in figure 2. During operation, it is found that 66kV I bus grounding, 66kV II bus grounding, 10kV I bus grounding and 10kV II bus grounding send out alarm signals at the same time, the operation and maintenance personnel went to the site and found that the appearance of 66kV equipment and 10kV equipment in the station was normal and free of peculiar smell. Since it is impossible to judge the real grounding condition of 66kV and 10kV systems, according to the dispatching order, first open the 10kV side switch of No. 1 main transformer and check the power through the electroscope, the 10kV B-phase busbar of No. 1 main transformer has no voltage, indicating that the grounding point is between the 10kV side B-phase bushing of No. 1 main transformer and the switch cabinet. During this period, the 66kV user line switch tripped, reclosing acted, reclosing was unsuccessful, and the grounding of 66kV I bus, II bus and 10kV II bus was eliminated.

![Diagram](image)

Fig.1 Schematic diagram of No. 1 main transformer system

![Nameplate](image)

Fig.2 Nameplate of phase B arrester at 10kV side of No. 1 main transformer
Check D5000 system after troubleshooting, the system shows that the voltage of phase B at 10kV side of No. 1 main transformer is 0.66kV. It is preliminarily judged that the arrester has broken down and phase B is grounded. Phase A voltage waveform of 66kV system is shown in figure 3, and phase B voltage waveform of 10kV system is shown in figure 4.

![Fig.3 Phase A voltage waveform of 66kV system](image1)

![Fig.4 Phase B voltage waveform of 10kV system](image2)

3. **Relevant tests**

After the fault occurred, the infrared thermal imager was used to detect the 10kV side arrester of No. 1 main transformer. It was found that the temperature of phase A arrester was -35.6 °C, phase B arrester was -21.9 °C, and phase C arrester was -35.7 °C, the temperature of phase B arrester is significantly higher than that of phase A and C, the infrared detection data of arrester is shown in figure 5.

![Fig. 5 Infrared detection photos of A, B and C three-phase arresters at 10kV side of No. 1 main transformer](image3)

(a) A phase  (b) B phase  (c) C phase
The tester took oil samples from No. 1 main transformer body for oil chromatographic test, and the test results were qualified, see table 1 for specific test data. The maintenance personnel checked that all components of the main transformer were normal. When removing the 10kV side lightning arrester of No. 1 main transformer, they found that the phase B lightning arrester had bulged, and disassembled and inspected the phase B lightning arrester, as shown in figure 6. The tester uses a 2500V megger to measure the insulation, both phase A and phase C are infinite, and phase B is 0, the comparison of test data is shown in table 2, then, the insulation of 10kV busbar is measured and AC withstand voltage test is carried out, all are qualified, and no other tests are carried out[6]. Thus, it is confirmed that the fault cause is the grounding caused by the breakdown of the lightning arrester at the 10kV side of No. 1 main transformer.

| component(μL/L) | H_2  | CO   | CO_2 | CH_4 | C_2H_6 | C_2H_4 | C_2H_2 | total hydrocarbon |
|-----------------|------|------|------|------|--------|--------|--------|------------------|
| this test value | 13.53| 71.24| 417.95| 1.88 | 0.00   | 0.25   | 0.00   | 2.13             |
| last test value | 9.39 | 56.16| 671.83| 1.11 | 3.55   | 0.00   | 0.00   | 4.66             |

| phase difference | insulation resistance (GΩ) | U_1mA,dc/kV | I_0.75U_1mA/μA |
|------------------|---------------------------|-------------|----------------|
|                  | this test value           | last test value | this test value | last test value | this test value | last test value |
| a                | ∞                          | 39          | /              | 26.3            | /              | 2.5            |
| b                | 0                          | 35          | /              | 26.5            | /              | 3.0            |
| c                | ∞                          | 40          | /              | 26.5            | /              | 2.2            |

Fig. 6 Photo of fault arrester at 10kV side of No.1 main transformer

4. Cause of lightning arrester breakdown
Since the arrester is a new arrester put into operation at the same time as No. 1 main transformer, it has been put into operation for only one year and passed the pre-test on September 2, 2021, the quality problems such as aging of arrester can be eliminated.

After the accident, the 66kV user line was inspected. It was found that due to the cold weather, the conductor sag was too tight, the phase A and phase B conductors of the line rose, the distance to the cross arm was insufficient, and the phase a arc grounding occurred. Firstly, the phase A conductor discharged the cross arm for a long time, lasting for about 2 hours and 18 minutes, and then the phase B discharged relative to the cross arm, and the switch tripped.

Due to the grounding fault of phase A, the 66kV system voltage fluctuates, and then through the capacitive coupling between medium voltage and low voltage windings, the neutral point on the 66kV side generates displacement voltage, and the neutral point to ground voltage rises to the 66kV system phase voltage U_0, which is transmitted to the 10kV side under the action of capacitor transmission overvoltage, so that the 10kV side also generates a certain voltage to the ground, the ground voltage
obtained at 10kV side is $U_{30}$. The equivalent circuit diagram of medium voltage side and low voltage side of No.1 main transformer is shown in figure 7, for the convenience of analysis, only the medium voltage and low voltage windings are shown here, and the high voltage winding is omitted.

In figure 7, $C_{23}$ is the equivalent capacitance of medium voltage winding to low voltage winding, and $C_{30}$ is the equivalent capacitance of low voltage winding to ground. It can be seen from the electric capacity data in the transformer factory test report $C_{23}=22260\text{pF}$, $C_{30}=27450\text{pF}$, the 66kV phase A voltage $U_0$ value displayed in D5000 system is 39.55kV, the calculation formula of capacitor transfer overvoltage is shown in formula (1), after calculation, the voltage of 10kV winding to ground $U_{30} = 17.71\text{kV}$.

$$U_{30} = \frac{U_0 C_{23}}{C_{23} + C_{30}} = \frac{39.55 \times 22260}{(22260+27450)} = 17.71$$

The phase voltage values $U_{oa}$, $U_{ob}$ and $U_{oc}$ of 10kV phase a, b and c displayed in D5000 system is 6.3kV. The wiring of the transformer is YN,yn0,d11, due to phase A grounding short circuit at medium voltage side, $U_0$ rises to phase voltage, the magnitude is equal to the phase voltage of phase A, the direction is opposite to phase A, and $U_{30}$ is in the same direction as $U_0$, therefore, it is possible to draw the relationship diagram of each voltage vector when phase a of the fault main transformer is single-phase grounded, as shown in figure 8.

According to the calculation, the phase B voltage at the low voltage side is:

$$U_b = \sqrt{U_{30}^2 + U_{ob}^2} = \sqrt{17.71^2 + 6.3^2} = 18.8\text{kV}$$
Phase A voltage at low voltage side is:
\[
U_a = U_{oa} + U_{30} = U_{oa} \angle 30^\circ + U_{30} \angle 180^\circ \\
= U_{oa} \cos 30^\circ + jU_{oa} \sin 30^\circ + U_{30} \cos 180^\circ + jU_{30} \sin 180^\circ \\
= -12.254 + j3.15
\]
\[\Rightarrow U_a = \sqrt{12.254^2 + 3.15^2} = 12.65kV \tag{3}\]

Phase C voltage at low voltage side is:
\[
U_c = U_{oc} + U_{30} = U_{oc} \angle 150^\circ + U_{30} \angle 180^\circ \\
= U_{oc} \cos 150^\circ + jU_{oc} \sin 150^\circ + U_{30} \cos 180^\circ + jU_{30} \sin 180^\circ \\
= -23.166 + j3.15
\]
\[\Rightarrow U_c = \sqrt{23.166^2 + 3.15^2} = 23.38kV \tag{4}\]

Based on the above analysis, in case of phase a grounding fault in 66kV system, the voltage to ground at the outgoing terminals of phase a, b and c at the low voltage side of the transformer is greatly higher than that under normal operation. The ground voltage $U_a$ and $U_b$ of phase b and c exceed the continuous operation voltage of the arrester by 13.6kV and rated voltage by 17kV, the overvoltage lasts for 15 minutes. Through temperature measurement, it is found that the temperature of phase b arrester is -21.9 ℃, which is significantly higher than that of phase a and c, there is heating phenomenon, and finally breakdown due to thermal collapse. After the breakdown of the arrester, phase b is similar to the grounding state, the voltage to the ground is about 0, and the voltage drop between phase a and c to the ground is about the line voltage on the 10kV side, which is lower than the continuous operation voltage of the arrester.

5. Conclusion
This paper introduces in detail an event of 10kV arrester breakdown at low voltage side caused by single-phase short-circuit grounding at medium voltage side of 220kV transformer. The failure mechanism is accurately analyzed, due to the relatively small equivalent capacitance to the ground at the low-voltage side, the voltage transmitted from the capacitor to the low-voltage side is high, when it exceeds the normal working voltage of the arrester, it acts on the arrester for a long time, resulting in the breakdown of the arrester. This is a typical accident caused by transmission overvoltage, which has an adverse impact on the stable operation of the power grid, attention should be paid to the design, operation and maintenance of the power grid. In view of this problem, the following preventive measures and suggestions are put forward.

1. According to the actual situation, avoid no-load operation on the low-voltage side of the transformer. If there is a situation requiring no-load operation, calculate the transmission overvoltage in case of asymmetric short circuit. If the overvoltage value is large and exceeds the normal operation voltage of the lightning arrester, install a capacitor bank on the low-voltage side.

2. For the transformer with no bus outgoing from the low-voltage side and only lightning arrester installed between the outgoing terminal and the ground, the operation mode of phase b direct grounding and phase a and phase c suspended shall be adopted, and the exposed part of the outgoing terminal shall be insulated[3-4].

3. The gap zinc oxide arrester is selected. The series gap isolates the resistor from the charged body, which can avoid the direct effect of temporary overvoltage or arc grounding and resonant overvoltage on the resistor caused by single-phase grounding of the system, and effectively prevent thermal collapse[5]. At the same time, strengthen the overhaul, maintenance and daily inspection of the lightning arrester at the 10kV side of the main transformer, and replace the equipment that has operated for more than 10 years in combination with power failure.
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