Analysis of the Causes of Gas Leakage of a 500kV SF$_6$ Circuit Breaker

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Abstract: The SF$_6$ gas in the 500kV circuit breaker leaks to atmospheric pressure in about 10 minutes, and there is no leakage sign before the air leakage, resulting in unplanned outage of the equipment. This situation is rare in the power industry, and the article disintegrates from the equipment. The full analysis and force simulation of the air-side opposite porcelain sleeves analyzed the air leakage events of the circuit breaker and proposed effective control measures.

1. Introduction

Due to the excellent insulation and arc-extinguishing properties of SF$_6$ gas, in recent years, high-voltage electrical equipment using SF$_6$ gas as an insulating medium has achieved remarkable development, accompanied by an increase in SF$_6$ gas insulation accidents, and leakage of SF$_6$ gas as a running process. One of the common defects will not only greatly reduce the arc-extinguishing performance of the equipment, but also cause unplanned power outages. It will also increase the humidity of the SF$_6$ gas in the equipment, and the internal insulation will be broken down, resulting in an accident and will result in greenhouse effect. The large greenhouse effect is 20,000 times that of CO$_2$ [1]. Therefore, the SF$_6$ gas leak detection work is very important.

At 14:54:34 on May 20, 2018, the 500kV XX substation reported 5033B phase circuit breaker SF$_6$ low air pressure alarm. After 25 seconds, it reported SF$_6$ air pressure lock; into the on-site inspection, about 10 minutes, the SF$_6$ pressure was reduced from the blocking value to 0.0MPa; after ten minutes, the dispatcher ordered the 5033 circuit breaker to be isolated, and the 17:52, 5033 circuit breaker was turned into an overhaul state. This air leakage event caused the 5033 and 5023 circuit breakers to be unplanned for 14 days, 500kV Ganlei II returned line and 500kV II mother turned hot standby, and resumed power transmission after 2 hours.

The fault circuit breaker was put into operation in January 2012 and has been in operation for 6 years. The last inspection date was May 2015.

The most recent pressure patrol record was May 14 (a sudden leak on May 20), and the pressure recorded on the patrol record was 0.83 MPa (rated at 0.80 MPa), which was normal. The gas pressure patrol cycle of 500kV equipment is once a week, and the patrol data before May 14th is 0.83MPa, showing no signs of air leakage.

2. Leakage circuit breaker air leakage rate calculation and air leakage point positioning method

2.1. Calculation of SF6 air leakage rate
The pressure of the fault circuit breaker is reduced from an alarm value of 0.72 MPa to the blocking value of 0.70 MPa in 25 seconds, and the air leakage rate can be calculated according to the pressure drop method formula.

The pressure drop method is suitable for measuring the air leakage rate when the equipment/compartment air leakage is large or during operation [2]. Through the pressure drop, the air leak rate (%/year) and the air supply interval (year) can be calculated. The formula (1) is as follows:

\[ F_y = \frac{12 \Delta p}{P_1 + 0.1} \times 100 \]

In the formula (1): \( \Delta p = p_1 - p \)

\( P_1 \): Pressure before pressure drop (converted to standard atmospheric conditions), MPa;

\( P \): Pressure after pressure drop (converted to standard atmospheric conditions), MPa;

\( \Delta t \): The time of pressure drop, month.

25 seconds is approximately equal to 9.65 × 10^{-6} months. The formula can be used to calculate the air leakage rate of 3,454,200%/year. That is, if the defect is not processed, the daily filling gas (from 0.0 MPa to the rated value) is about 95 times, the filling gas is about 4 times per hour, which is a critical defect.

The common air leakage of SF₆ equipment is the aging of the sealing ring, the uneven tightening torque of the joint bolt, the blisters, etc. [3], and all of them are slow leaks. The air leakage speed is fast, and the test and material analysis are required to be disassembled.

2.2. Positioning the leak point using an infrared imaging leak detection system

The infrared imaging leak detector can detect the leakage gas absorbed by the infrared light in the infrared region. When the infrared light radiated by the object passes through the SF₆ gas, the video image in the region will produce a contrast image different from the air, thereby generating a mist Shadow [1]. Therefore, the sample concentration can be determined by measuring the infrared spectrum of gas molecules [4].

The maintenance personnel perform air supply after the fault circuit breaker is turned into maintenance, and at the same time perform infrared imaging leak detection, and find that there are two leak points: one is the pouring part of the porcelain sleeve on the side of the double-break chamber and the T-chamber. (on the top); the other is the flange leak detection hole (three holes) connected to the porcelain sleeve, and the air leakage is very large, as shown in Figure 1.

![Infrared picture](a) Infrared picture ![Visible light picture](b) Visible light picture

Figure 1. Picture of 5033B phase circuit breaker porcelain cover leak

3. Gas leakage circuit breaker disintegration and porcelain casing return test

3.1. Replacement and disassembly of fault circuit breaker

On May 30, the replacement of the fault circuit breaker was completed, and it was returned to the factory the next day. On June 8, the dismantling analysis was carried out at the XXX factory in Beijing.

After disintegration, there was no abnormality in the sealing surface of the air chamber of the
circuit breaker and the sealing surface of the flange; the sealing ring was in good condition and no foreign matter was observed. The dimensions of the porcelain sleeve sealing surface and the T gas chamber sealing surface of the arc extinguishing chamber are measured in accordance with the drawings.

A crack with an arc length of about 98 mm was found inside the top porcelain sleeve of the glue injection part, and the porcelain sleeve was directly cracked, and the outer crack arc length was about 240 mm, as shown in Figure 2. The reason for the leak is that there is a penetrating crack in the porcelain sleeve.

![Internal and external crack pictures](image)

**Figure 2. Picture of 5033B phase circuit breaker’s porcelain crack**

3.2. Test of returning porcelain sleeves

Carry out a full analysis of 7 test items on both sides of the returned porcelain sleeve (leakage, no air leakage), the specific items are shown in Table 1.

| Serial number | Serial number of porcelain sleeve | Inspection and analysis |
|---------------|-----------------------------------|-------------------------|
| 1             |                                   | Visual inspection       |
| 2             |                                   | Dyeing penetration test  |
| 3             | The air leakage side is #01, and the other side is #02 (no air leakage) | Ultrasonic flaw detection |
| 4             |                                   | Bending damage test     |
| 5             |                                   | Size and material analysis of flange |
| 6             |                                   | Chemical composition analysis of porcelain |

3.2.1. Visual inspection, ultrasonic testing

There is a peeling phenomenon on the surface of the cement surface of the porcelain jacket at the air leakage (the top is opened when the air leaks), and the rest have no cracking or peeling. The crack was detected by ultrasonic flaw detection, and showed a crack defect waveform (crack on the end surface) as shown in Figure 3. All the other porcelain end faces were tested for ultrasonic flaw detection.

![Ultrasonic flaw detection](image)

**Figure 3. Ultrasonic flaw detection**
3.2.2. Dyeing penetration test
After dyeing and penetrating inspection, it can be seen that the length of the porcelain end face of the gas leakage side #01 is nearly 1/4 of the circumference (about 240 mm), and there is an obvious crack in the circumferential direction of the "crescent" cloth on both sides of the porcelain end, the middle part of which penetrates into the inside of the main body of the porcelain bottle, and the lowest point of the crack is 21 mm from the lower end of the porcelain, as shown in Figure 4.

![Figure 4. Dyeing penetration test](image)

3.2.3. Visual inspection, stain penetration test and ultrasonic test results
After the test, obvious crack waves can be seen in the cracked part of the lower end surface of the gas leakage side, and there is visible cracking. The specific test results are shown in Table 2.

| Detection position                  | Ultrasonic flaw detection                      | Dyeing penetration test | Visual inspection |
|------------------------------------|------------------------------------------------|------------------------|-------------------|
| #01 upper end face (leakage side)  | Normal waveform                                | Normal qualified       |                   |
| #01 under end face (leakage side)  | Defect waves are visible in the cracked part   | Visible cracking       | Visible cracking  |
|                                    | of the porcelain body.                         |                        |                   |
| #02 upper end face (gas leakage    | Normal waveform                                | Normal qualified       |                   |
| opposite side)                     |                                                |                        |                   |
| #02 under end face (gas leakage    | Normal waveform                                | Normal qualified       |                   |
| opposite side)                     |                                                |                        |                   |

3.2.4. Formal bending test on the gas leakage side #01 porcelain sleeve
According to the technical documentation, the rated bending failure test load of the porcelain sleeve is 19.53 kN, and the routine bending test value is 70% of the damage rating, that is, not less than 13.67 kN. After the application of 13.67 kN for 10 seconds, after rising to 26.083 kN, the root of the lower flange of the porcelain sleeve broke and the test was terminated, as shown in Fig. 5. After disintegration inspection, no foreign matter was found in the cement block and the asphalt buffer layer.

![Figure 5. Picture of bending damage test](image)
3.2.5. Internal water pressure type test of gas leakage opposite side #02 porcelain sleeve

According to the requirements of the technical documents, an internal hydraulic pressure test of 3.5 MPa was applied to the side of the #02 porcelain sleeve, and the pressure was maintained for 5 minutes. The test passed, and the porcelain sleeve was intact, no damage, no pressure relief.

3.2.6. The formal wear bending failure test of gas leakage opposite side #02 porcelain sleeve

According to the requirements of the technical documents, a routine bending test of 13.67 kN for 10 seconds was applied to the #02 porcelain sleeve on the opposite side of the leaking gas, and the porcelain sleeve passed the test. Then, when it rises to 40.325 kN, the root of the lower flange of the porcelain sleeve breaks and the test is terminated.

3.2.7. Chemical composition analysis of the size of the lower flange and the porcelain of the lower end of the two porcelain parts

The straight mouth dimensions of the lower flange are in accordance with the 300+0.5 (mm) requirements specified in the flange pattern, indicating that the lower flange is not deformed. The chemical composition analysis of the porcelain samples on the lower end of the two porcelain parts is as follows. The analysis results are in accordance with the requirements of the chemical composition of porcelain in the documents of XX Electric Porcelain Company. See Table 3 for details.

| Sample category | SiO₂ (%) | Al₂O₃ (%) | Fe₂O₃ (%) | TiO₂ (%) | K₂O+Na₂O (%) |
|-----------------|----------|-----------|-----------|----------|---------------|
| Specified value of TJ-5 file | 39-44 | 50-57 | <1.8 | <2.5 | 2.7-3.2 |
| #01 Porcelain sleeve (leakage side) | 42.81 | 50.09 | 1.75 | 1.75 | 2.73 |
| #02 Porcelain sleeve (gas leakage opposite side) | 50.72 | 1.63 | 1.68 | 2.84 |

4. Force simulation analysis of gas leakage circuit breaker

Under the action of the gravity moment of the porcelain sleeve itself, the end of the porcelain sleeve cast with the T-shaped aluminum casting is subjected to an upward force, and the end of the porcelain sleeve is fastened to the pillar by the flange, so that it is subjected to the flange downward. The interaction force, if the squeezing force is greater than the force that can be withstood by the end of the ruptured porcelain sleeve, may result in damage to the end of the porcelain sleeve, as shown in Figure 6(a).

Due to the limitations of the simulation software and equipment structure, only the stress of each part of the equipment was qualitatively simulated. It can be seen from Fig. 6(b) and (c) that the stress at the top of the porcelain sleeve at the joint with the casting is larger than that in other regions, and the porcelain sleeve is damaged. As a result of the cumulative effect of the force, cracking and gas leakage eventually occur.

Figure 6. Stress analysis and simulation diagram
5. Summary of the cause of leakage

(1) From the production of porcelain sleeves to the whole process of on-site installation analysis, the possible links affected by local external forces are: porcelain sleeve handling and installation process. In the process of moving, hoisting and other moving porcelain sleeves, since the porcelain sleeve is a brittle material, improper protection will cause external forces to act on the porcelain parts, causing damage. In particular, there are abnormal vibrations, bumps, etc. during transportation, which may cause damage to the porcelain parts in this part [5].

(2) The top of the porcelain sleeve at the joint with the T-shaped casting has a large stress. As the operating environment changes (thermal expansion and contraction) and the number of operations increases, the damage will gradually expand, eventually leading to cracks running through the porcelain sleeve and rapid leakage.

6. Conclusion

(1) The porcelain factory must strictly carry out the factory test, focusing on ultrasonic flaw detection and eliminating defective products.

(2) It is recommended that the circuit breaker should be installed with an impact recorder during transportation. The impact acceleration should not exceed the requirements of the product technical documents. The impact record should be filed with the installation technical documents. The casing should be placed horizontally, using a steel belt to secure the upper sleeper and the bottom of the box.

(3) On-line monitoring of the pressure of SF₆ equipment can be carried out to prevent accidents from expanding, and it is beneficial to analyzing the cause of the accident. The current monitoring methods cannot obtain the air leakage during the period from normal operation to alarm.

References

[1] Peng Jiang, Cheng Xu, Liu Ming, Jiao Fei. Power grid equipment charging detection technology [M]. China Electric Power Press, Beijing, 2014.12, 235-240.

[2] Xu Zhigang, Wu Jiang. Infrared Detection and Prevention Measures of Air Leakage Fault of 500 kV SF₆ Circuit Breaker[J]. Modern Industrial Economics and Informatization, 2015, 107(23): 60-61.

[3] Zhang Tao, Li Yining, Shen Hongzhi. Training material for sulfur hexafluoride gas recovery and treatment technology [M]. China Electric Power Press, Beijing, 2012.4, 230-233.

[4] Gu Lingxia. Development of a full temperature range calibration device for SF₆ gas density relay[J]. High Voltage Apparatus, 2015, 51(1): 127-132.

[5] Zhu Anming, Song Zhaohui, Fang Yong et al. Analysis of Air Leakage of 800kV Tank Circuit Breaker[J]. Power System and Clean Energy, 2010, 26(6): 55-56,61.