Analysis of Suspended Potential Discharge Defects by SF6 Decomposition Products

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Abstract. The type and content of SF6 decomposition products are directly related to the type, location and degree of fault. Based on the analysis of the abnormal SF6 gas decomposition product content and discharge type of 126kV Porcelain Column type circuit breaker, the potential fault of the circuit breaker is judged to be suspension potential discharge fault. After disassembling the circuit breaker, it is found that the abnormal phase of the insulation rod is deformed, the pin become thin, and there are solid decomposition products, the sulfides and fluoride, which are mainly composed of iron, aluminum, chromium and manganese, further confirm that the potential fault of the circuit breaker is suspension potential discharge fault. The forming process and reaction mechanism of the suspended potential discharge fault are analyzed. Once the fault occurs, its function will promote the development of the fault. The influence of the suspension potential discharge fault on the performance of the circuit breaker is also analyzed. When the suspension potential discharge fault exists, it will cause the abnormality and even affect the normal operation of the circuit breaker.

Keywords: SF6 decomposition products; Circuit breaker; Suspended potential; Discharge defects.

1. Introduction

Under the action of electric arc, partial discharge or other abnormal working conditions, SF6 gas will generate decomposition products such as SO2 and H2S. Through the detection of SF6 gas decomposition products, the running state of the equipment can be judged. Under normal operation, SF6 gas will not decompose and will not react with other materials. But under the action of electric discharge or high temperature, SF6 gas will decompose and react with water, oxygen, metal vapor and other impurities to form many kinds of sulfur-containing and fluorine-containing compounds. A small amount of the gas is also released when the organic insulating material in the equipment is cracked. The type and content of decomposition products are directly related to the type, location and degree of fault. When there is internal fault in SF6 electric equipment, the SF6 gas and solid insulation material in the fault area will be cracked under the action of heat and electricity to produce the characteristic components such as SO2, SOF2, SO2F2, H2S, CO, CO2, HF and CF4, C3F8. Therefore, the internal fault of the equipment can be diagnosed by detecting the content of these characteristic components[1]. SF6 gas decomposition products detection is a commonly used live detection technology, which has been widely used in production practice[2]. Compared with the means of electricity and acoustics, its remarkable advantage is that it is free from the interference of external environment such as electromagnetism and noise[3-4]. The analysis of SF6 decomposition products can be used to judge the type, degree and trend of breakdown according to the volume fraction and gas production rate of each gas component, which is the hot spot of live detection and diagnosis of SF6 gas insulation.
At present, the most commonly used detection methods in production sites are the electrochemical sensor method, the detection tube method and the gas chromatography method. In this paper, the gas decomposition products of abnormality circuit breaker are measured by these three methods, and the defect types are preliminarily judged, and the latent defect types are further determined by disassembly inspection, and the defect producing process and principle are analyzed, to avoid the occurrence of power accidents, to ensure the safe, stable and reliable operation of power equipment.

2. Detection of SF₆ Gas Decomposition Products
During the general test of SF₆ electric equipment, the Power Grid Company found that the content of gas decomposition products of a 126 kV Porcelain column type SF₆ circuit breaker was abnormal. The decomposition products of SF₆ gas of the circuit breaker were detected by electrochemical sensor method, detection tube method and Gas chromatography method respectively (Note: The three methods are conventional methods and the instruments and equipment used are commonly used instruments.), and the results are shown in Table 1.

| Detection method          | SO₂  | H₂S  | CO   | HF   |
|--------------------------|------|------|------|------|
| Electrochemical sensor method | >100 | 56.3 | 13.2 | 7.4  |
| Detection tube method     | —    | 0    | —    | 10   |
| Gas Chromatography        | 440.9| 0    | 14.6 | —    |

Note: ‘—’ means unmeasured.

In order to further detect SF₆ gas decomposition products of abnormal circuit breaker, three detection methods were used to measure SF₆ gas decomposition products at intervals of 8 hours and 12 hours respectively. The results are shown in Table 2.

| Detection time | Detection method          | SO₂  | H₂S  | CO   | HF   |
|---------------|--------------------------|------|------|------|------|
| 8-hour intervals | Electrochemical sensor method | >100 | 60.4 | 12.8 | 7.3  |
|                | Detection tube method     | —    | 0    | —    | 9    |
|                | Gas Chromatography        | 435.3| 0    | 14.4 | —    |
| 12-hour intervals | Electrochemical sensor method | >100 | 57.5 | 13.4 | 8.0  |
|                | Detection tube method     | —    | 0    | —    | 11   |
|                | Gas Chromatography        | 448.6| 0    | 13.8 | —    |

Note: ‘—’ means unmeasured.

As shown in Table 1, the content of H₂S measured by the electrochemical sensor method is higher than that measured by the other two methods, and the content of H₂S measured by the other two methods is 0. This is because when the electrochemical sensor method is used, the SO₂ content exceeds the measuring range, and the instrument algorithm is invalid, and so the H₂S content indication is abnormal. The products of gas decomposition measured by the three methods all contain a large amount of SO₂ gas, and a certain amount of HF and CO. It can be seen from tables 1 and 2, the contents of SO₂ detected at different detection times have little change, while the contents of CO and HF gases are essentially unchanged.

The experiment and operation experience show that under the normal arc breaking condition, the decomposition product of SF₆ gas can produce SO₂ gas, but the SO₂ content will decrease to 0 at a certain time after disconnection, in addition, the circuit breaker is in the state of closing for 6 months during the testing period, and there is no break and no arcing. The circuit breaker in normal operation
contains only trace or even no SO₂ gas. Therefore, it can be concluded that the circuit breaker had latent defects.

3. Determine the Type of Fault

3.1. Analysis of the Internal Discharge Type of Incircuit Breaker

Generally speaking, the internal faults of circuit breakers can be divided into two categories: discharge and overheat. The overheat faults and partial discharge faults all involve solid insulation materials, and some H₂S and CO gases are generated in the decomposition products. From the results of tables 1 and 2, it can be seen that the decomposition products contain a small amount of CO but no H₂S gas. The analysis shows that CO may be an impurity gas in SF₆ fresh gas. Therefore, the potential defects in the circuit breaker may be discharge-type faults that do not involve solid insulating materials.

In the circuit breaker, the discharge faults which do not involve the solid insulating materials include the suspended potential discharge and the discharge of some high potential conductors to the ground potential body. The suspended potential discharge is mainly manifested in the following aspects, the suspension potential discharge caused by the bad contact between the moving contact and the pulling rod, the suspension potential discharge caused by the bad contact between the conducting rod and the electric connecting part of the conducting rod, the suspension potential discharge caused by the loosening of the fixing screw of the shield cover and the discharge of the electric potential body to the ground caused by the conductive particles in the gas, etc. The intensity and the voltage grade of suspended potential discharge is related to the equivalent capacitance of suspended potential, and the larger the equivalent capacitance is, the stronger the discharge is. A large amount of decomposition products, mainly SO₂ gas, can be produced by the continuous suspended potential discharge. Ground discharge of high potential conductor mainly includes geopotential body discharge due to insulation defects, this discharge involves solid insulation. The discharge fault of high potential conductor to ground usually has high energy, so a large amount of SO₂ gas is produced.

From the above analysis, it can be concluded that the potential defects in the circuit breaker may be suspended potential discharge.

3.2. Circuit Breaker Break Check

In order to accurately judge the type of partial discharge in circuit breaker, the physical examination of circuit breaker was carried out, and the following phenomena were found in the circuit breaker.

1) As shown in Fig. 1, the mechanical tie rod connection with a pin that appears normal but is actually abnormal. The arrow refers to a pin connecting an insulating tie rod to a tie rod of a movable contact in an arc extinguishing chamber.

2) The pin of the abnormal phase tie rod has obvious electric erosion mark caused by partial discharge, and the pin has been seriously deformed, the middle part is obviously thinner, and the pin will form suspended potential between the pin and the connecting rod during operation, as shown in Fig. 2.

![Figure 1. The mechanical tie rod connection with a pin that appears normal but is actually abnormal](image1)

![Figure 2. Tie Rod Pin with abnormal phase](image2)
3) There is obvious gap between the tie pin and the tie hole of the abnormal phase insulated tie rod, and there is obvious bump damage on the outer edge of the tie hole, as shown in Fig. 3.
4) There are a lot of solid decomposition products in the gas chamber of abnormal phase arc extinguishing chamber, as shown in Fig. 4. The composition of SF$_6$ solid state product in the porcelain bottle was analyzed by x-ray powder diffraction (XRD) and scanning electron microscopy (SEM). It was found that the SF$_6$ solid state product was mainly composed of iron, aluminum, chromium and manganese sulfides and fluoride. The SEM and energy diagram of the sample are shown in Fig. 5.

![Figure 3. Aluminum connecting Rod at upper end of abnormal phase insulated tie rod](image)

![Figure 4. Gray solid powder on the inner wall of the tube in the ARC quenching chamber](image)

(a) Scanning electron micrograph of sample  
(b) Sample energy diagram

![Figure 5. Scanning electron microscope and energy diagram of sample](image)

Therefore, from the above phenomena, it can be concluded that the potential fault of the circuit breaker is suspended potential discharge fault.

4. Study on Theoretical Modeling

4.1. Formative Process

1) Through the disassembly inspection, it is found that The hidden trouble may be due to the abnormal fit between the breaker B phase tie rod connection and the pin during the assembly process. During the operation of the circuit breaker, the metal parts vibrated under the action of mechanical and Electric Forces, resulting in the suspended potential and the continuous energy release.
2) In the presence of suspended potential, the pin will be corroded by electric erosion and chemical erosion of SF$_6$ gas decomposition products, which causes the pin to be corroded and consumed, deform over time, and wear and tear due to the large impact force of the initial process, the middle part of the pin becomes thinner and there is a gap between the pin and the connecting rod, which promotes the generation of suspended potential.
3) Under the condition of suspended potential discharge, the decomposition products of SF₆ gas react with the metal to form metal sulfides and fluoride, which form gray solid powder attached to the inner wall of the tube.

4.2. Mechanism Analysis
When the suspension potential discharge occurs in the circuit breaker, the pin and the tie rod will be deformed by the electric erosion and the chemical reaction, and the corrosion will cause the middle of the pin to become thinner and the gap between the pin and the pull hole to increase, this phenomenon promotes the discharge of suspended potential, increases the discharge amount, accelerates the electrical erosion of the pin and promotes the decomposition of SF₆ gas. Therefore, once the floating potential fault occurs, it will promote the development of the fault due to its own role. The main reaction mechanisms are as follows:
The SF₆ gas is decomposed to low-fluorine sulfide and F atom or ion under the condition of suspended electric potential discharge. When impurities (mainly H₂O and O₂) are present in the gas, the decomposition products will continue to react with the impurities to form HF, SO₂F₂, SOF₂ and SOF₄. SOF₄ reacts with water to form a certain amount of SOF₂, and SOF₂ reacts with water to form SO₂ and HF.

The main reaction equations are as follows:

\[ 2\text{SOF}_4 + \text{H}_2\text{O} \rightarrow \text{SOF}_2 + 2\text{HF} \]  
\[ \text{SOF}_2 + \text{H}_2\text{O} \rightarrow \text{SO}_2 + \text{HF} \]

The main components of the moving contact and the tie rod are iron and aluminum (represented by M). Partial discharge may occur between any two parts of the contact, the metal tie rod, the metal terminal of the insulating tie rod and the connecting piece. Under the action of the discharge arc, the metal parts, the sulfur hexafluoride gas and the impurities in the gas take part in the chemical reaction. As shown in equations (3) and (4), the metal parts react with small amounts of O₂ and H₂O in the gas at high temperatures, metal oxides and metal bases are formed; F atoms or ions from the decomposition of SF₆ gas react with metal vapors to form metal fluoride, as shown in formula (5); and once HF in the decomposition product is formed, it is immediately adsorbed on the surface of the metal and reacts with it to form metal fluoride salts, as shown in formulas (6) and (7); SO₂F₂, SOF₂ and SOF₄ in the decomposition products of SF₆ react with metals to form metal fluoride, metal sulfide and metal oxide, as shown in formula (8).

1) Reactions of metal compounds in solid state with small amounts of O₂ and H₂O in SF₆ gas at high temperatures:

\[ \text{M} + \text{O}_2 \rightarrow \text{M}_x\text{O}_y \]  
\[ \text{M} + \text{H}_2\text{O} \rightarrow \text{M(OH)}_x \]

2) Reaction of metal with decomposition products:

\[ \text{M} + x\text{F} \rightarrow \text{MF}_x \]  
\[ \text{M}_x\text{O}_y + \text{HF} \rightarrow \text{MF}_x \]  
\[ \text{M(OH)}_x + \text{HF} \rightarrow \text{MF}_x \]  
\[ \text{M} + \text{SO}_m\text{F}_n \rightarrow \text{MF}_x + \text{M}_x\text{S}_y + \text{M}_x\text{O}_y \]

The suspended potential discharge is a continuous process, and the decomposition products of SF₆ gas are also a continuous accumulation process. The decomposition of SF₆ was caused by the continuous suspended potential discharge, which led to the increase of the decomposition product content in the equipment, so as to reach a higher content. Because HF reacts with metal and is consumed, SO₃, gray solid powder and a small amount of HF gas can be found in the decomposition products of SF₆ gas under the condition of suspended electric potential discharge. No insulation material is involved, no H₂S occurs.
(Note: The chemical equations in this paper only represent the principal reactants and principal products of a chemical reaction. It's just a reaction, not all reactants and products, so the equation can not be balanced by all the elements.)

5. Impact on Circuit Breaker Performance
When the suspension potential discharge fault exists, it will cause the abnormality in the operation of the circuit breaker and even affect the normal operation of the circuit breaker. The main performance is as follows:

1) When the suspension potential discharge fault occurs in the circuit breaker, the decomposition product of SF₆ gas will contain SO₂ gas, and the SF₆ solid powder will be formed inside the circuit breaker and adhere to the inside of the porcelain sleeve of the arc-extinguishing chamber of the circuit breaker, which will affect the insulation performance of the sleeve and cause the breaking failure when the high current is cut off.

2) Under the action of levitation potential discharge, the gap between pin and hole is further enlarged because of the influence of electric erosion and chemical erosion, there will be a big impact force between the pin and the hole, which will break the pin and cause the circuit breaker to refuse to move.

6. Conclusion
(1) When the suspended potential discharge occurs in the circuit breaker, the decomposition product of SF₆ gas will contain SO₂ gas, and a large number of gray powder will be produced, the main components of which are iron, aluminum, chromium and manganese sulfide and fluoride.

(2) When suspended potential discharge occurs in circuit breaker, because of the effect of electric erosion and chemical erosion of SF₆ gas decomposition products, the connecting pin will be corroded and deformed, and the middle of the pin will become thinner, which will lead to the increase of the gap between the pin and the hole and the energy of suspended potential discharge. When the switch is opened or closed, there will be a large impact force between the pin and the hole, which will break the pin and cause the circuit breaker to refuse to move.

(3) When the suspension potential discharge fault occurs in the circuit breaker, the decomposition product of SF₆ gas will contain SO₂ gas, and the SF₆ solid powder will be formed inside the circuit breaker and adhere to the inside of the porcelain sleeve of the arc extinguishing chamber of the circuit breaker, which will affect the insulation performance of the sleeve and cause the breaking failure when the high current is cut off.

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