Influence of polarity and pressure on the SF$_6$ decomposition characteristics under DC voltage

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Abstract. A comparative study of the decomposition characteristic of SF$_6$ under direct voltage with different polarities and pressure was conducted in this paper. The changes of discharge capacity, discharge energy and decomposition product concentrations were observed and analyzed in detail. The results indicate that SF$_6$ decomposition characteristics are closely related to polarity and pressure. Discharge energy and concentrations of decomposition products under positive polarity are obviously higher than those under negative polarity, which can be explained by different discharge energy and distribution characteristic of space charges. Concentrations of typical products including SOF$_2$, SO$_2$F$_2$, and SO$_2$ decrease with the increasing pressure according to the decreasing effective dissociation volume.

1. Introduction
HVDC transmission has become an important component of long-distance cross-regional power transmission due to its advantages of low line loss, low line cost, high system stability and reliable operation[1,2]. DC gas-insulated equipment (such as gas-insulated transmission lines GIL, through-wall bushings, valve-side bushings of converter transformers) plays an important role in DC power transmission[3,4]. There will inevitably be some insulation defects in these equipment, which might lead to failure eventually. For example, a 500 kV SF$_6$ gas-insulated busbar in a converter station was subjected to excessive mechanical external forces during the transportation or installation, resulting in cracks inside the insulator and eventually leading to the blowing up of the supporting insulator. Therefore, the detection of operating conditions, timely detection of defects and faults in the equipment, to ensure the normal operation of the power system is of great importance[5,6].

Studies have shown that SF$_6$ decomposes under discharge may produce a variety of decomposition products such as SOF$_2$, SO$_2$F$_2$, and SO$_2$. Analysis of decomposition products enables the diagnosis of the insulation status of SF$_6$ insulated equipment. Hence, conducting research on the decomposition characteristics of SF$_6$ under DC voltage provides theoretical support for the detection of discharge...
inside DC high-voltage gas-insulated equipment and the diagnosis of insulation fault types, which is of great significance to ensure the normal operation of DC high-voltage gas-insulated equipment[7-9].

The decomposition characteristics of SF₆ and its application have been vastly investigated. Tang et al have studied decomposition characteristics of SF₆ under four typical insulation defects and proposed a three-ratio method[10]. Zhong et al have investigated the decomposition characteristics of SF₆ under three typical defects including metal protrusion defect, floating potential defect and insulator defect and proposed a triangle method utilizing composition of by-products[11]. However, the mechanism and process of discharge decomposition under DC voltage is not fully understood, and the mechanism of influence on voltage polarity, air pressure and other factors also remains to be studied.

The presented paper investigated the decomposition characteristics of SF₆ under DC voltage. The influence of voltage polarity and pressure was analyzed in detail.

2. Experimental platform

The schematic diagram of experimental setup is shown in Fig. 1. It mainly includes three parts: DC voltage source, discharge chamber and analysis system. The voltage regulator (T1: 0-380V) and transformer (T2: 50kVA/100kV) are used together to generate high AC voltage. A bridge rectifier circuit composed by four high voltage silicon reactor and a filter capacitor is then applied to converts AC voltage into DC voltage. R1 (20kΩ) is a protection resistor used for limiting transient current due to discharge. A resistance voltage divider composed by Rh and R1 is set for measuring the DC voltage.

![Figure 1. Schematic diagram of the experimental setup.](image)

The defect model is set in a gas chamber with volume of 60L. Metal protrusion defects, the most typical one, is chosen in this paper and simulated by a needle-plate electrode. Partial discharge is monitored by DDX9121b partial discharge detector based on pulse current method. The point electrode with a curvature radius of about 100 μm is connected to the high voltage. In addition, two electrodes are separated by 5mm. The gas decomposition products are detected by a gas chromatograph (GC).

3. Experimental platform

3.1. The influence of voltage polarity

In this paper, the effect of voltage polarity on the discharge and decomposition characteristics of SF₆ under DC voltage is firstly studied, with the moisture content at 400±10μL/L, the pressure at 0.35MPa, and the needle-to-plate gap at 5mm.

Figure 2 shows the variation law of the discharge with time for positive and negative polarity voltage respectively (the voltage amplitude is 40kV). It can be clearly seen that the discharge under positive polarity voltage is stronger than that under negative polarity. The discharge under positive polarity is concentrated in 60-120pC, while that under negative polarity is concentrated in 30-100pC.
Figure 2. discharge capacity under positive and negative polarities.

The trend of discharge energy with time at different voltages is shown in Figure 3. It can be seen that the cumulative discharge energy shows a linear trend with the pressurization time. Under the same voltage level, the total discharge energy under positive polarity is always higher than that under negative polarity.

Figure 3. The trend of discharge energy with time at different voltages and polarities.

The variation of decomposition product content with time for the same value and different polarity is shown in Figure 4. Main decomposition products include SO$_2$F$_2$, SOF$_2$, and SO$_2$. It can also be seen from figure 4 that the product concentrations at positive polarity are higher than those at negative polarity. This is due to the fact that the positive ions have an enhancing effect on the field strength in the discharge channel when the needle is positive, while the ions have a weakening effect on the field strength in the discharge channel when the needle is negative. The discharge capacity and discharge energy under positive polarity is higher than that under negative polarity. As a result, SF$_6$ is more
likely to dissociate by electron collision to generate low fluorine sulfide, and eventually more stable decomposition products can be generated.

![Figure 4. Concentration of decomposition products under different discharge patterns](image)

3.2. The influence of pressure

The effect of pressure (from 0.25MPa to 0.40MPa at intervals of 0.05MPa) on the discharge and decomposition characteristics of SF$_6$ under DC voltage is studied with the voltage amplitude at 40kV, the needle-to-plate gap at 5mm and the moisture content at 400±10μL/L. The average discharge and the repetition rate of discharge at different pressures for positive and negative polarity are shown in Figure 5 and Figure 6. The capacity and repetition rate of discharge under positive polarity gradually become larger with the increase of air pressure. On contrary, the change trends under negative polarity are converse with those under positive polarity. The discharge repetition rate is related to the migration rate of charge in the discharge channel. Since the migration rate of positive and negative ions is much smaller than that of electrons, this paper mainly considers the effect of electrons. As the air pressure increases, the space charge enhances the field strength in front of the positive polarity and weakens the field strength in front of the negative polarity. Since the change of field strength is greater than the change of air pressure, the repetition rate of discharge under positive polarity becomes larger with increasing air pressure while it becomes smaller with increasing air pressure under negative polarity.

![Figure 5. Average discharge capacity and repetition rate under positive polarity](image)
The effect of gas pressure on the decomposition characteristics of SF\textsubscript{6} under DC voltage is shown in Figure 7 and figure 8. The concentrations of SOF\textsubscript{2}+SO\textsubscript{2} and SO\textsubscript{2}F\textsubscript{2} under positive and negative polarities both show a nearly linear increase with time. Besides, the concentration of the products at both polarities decreases significantly with the increasing air pressure. This can be explained by the decomposition model.

According to the decomposition model, the decomposition process can be divided into two stages. The first stage is the dissociation process of SF\textsubscript{6} according to electron collision, which generates a series of low-fluorine sulfide. Subsequently, further reactions of low-fluorine sulfide in the second stage form stable decomposition products. With the increase of pressure, the molecular density N becomes larger, and the value of field strength in the discharge channel is almost constant. As a result, the E value determined by the critical field strength, (E/N)\textsubscript{c}=375Td, becomes larger. So the lower boundary of the dissociation region moves in the direction of the needle electrode, and the volume of the dissociation region of SF\textsubscript{6} gas discharge becomes smaller. Hence, the concentration of SF\textsubscript{6} dissociation to generate low-fluorine sulfide is reduced and the concentration of decomposition products decreases.
Figure 8. Change trend of decomposition products with pressure under negative polarity.

4. Conclusion

(1) Typical decomposition products include SOF₂, SO₂F₂, and SO₂. Product concentrations at positive polarity are higher than those at negative polarity owing to the influence of space charge distribution and discharge energy.

(2) As the air pressure increases, the average discharge capacity, repetition rate and the cumulative discharge energy under positive polarity increase, while the above mentioned parameters decrease under negative polarity. Besides, concentrations of SOF₂, SO₂F₂, and SO₂ decrease with the increasing pressure according to the decreasing effective dissociation volume.

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