Study on Surface Flashover Characteristics in SF$_6$/CF$_4$ Mixture

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Abstract. Surface flashover characteristic of epoxy resin composite material in SF$_6$/CF$_4$ mix gas were studied through experimental method, and the influence of several key parameters were analyzed, such as gas pressure, SF$_6$ mix ratio and voltage polarity. It is shown that, when the mix ratio of SF$_6$ in the mixed gas is 40%, the flashover voltage of epoxy resin insulator can reach over 60% of the flashover voltage in SF$_6$ with the same pressure. The synergistic effects in the needle-plate electrodes system have significant difference between positive and negative polarity. The synergistic effect for negative polarity is weaker than that in negative polarity. Comprehensive environmental requirements and surface flashover characteristics, the results provide a potential SF$_6$ alternative for GIS equipment.

1. Introduction

With the expansion of the power grid, the consumption of SF$_6$ gas increases year by year. However, due to the high liquefaction temperature of SF$_6$, its decomposition have strong greenhouse effect, so it is urgent to find the corresponding replacement gas. As a potential alternative gas to SF$_6$, CF$_4$ is a colorless, odorless and non-flammable compressible gas with high volatility and stable chemical properties at room temperature. The global warming coefficient is 1/3 of SF$_6$, the liquefaction temperature is -184°C, but the insulation capacity is weaker than SF$_6$ gas [1].

The non-uniformity of electric field and gas environment are two important factors affecting the flashover. Literature [2] studied the flashover characteristics of SF$_6$/CF$_4$ mixed gas in 25.8kv GIS insulator and the feasibility of mixed gas in actual operation. Literature [3] has studied the surface flashover characteristics of the post insulator in SF$_6$/CO$_2$ and SF$_6$/N$_2$ mixture at low pressure. In this paper, the needle - plate electrode structure is used to simulate the non-uniform electric field through experimental research. The variation of flashover voltage with gas pressure, SF$_6$ mixture ratio and voltage polarity was analyzed.
2. Experimental Equipment and Methods

2.1. Electrode Structure Design

In this paper, the needle-plate electrode structure was used to simulate the non-uniform electric field. The electrode structure was shown in figure 1. The needle electrode’s radius of curvature is 0.8mm, with the sample at an angle of 45°. The material is tungsten steel. The plate electrode material is brass, the top is chamfered to prevent point effect. The electrode gap is 5mm. The electric field unevenness of the needle-plate electrode is calculated according to the following formula:

\[ f = \frac{E_{\text{max}}}{E_{\text{avg}}} \]  

\( f \) is the electric field non-uniformity coefficient, \( E_{\text{max}} \) is the maximum value of the field intensity, \( E_{\text{avg}} \) and is the average value of the field intensity. \( f = 5.16 \) under the needle-plate electrode was obtained by finite element calculation, was extremely uneven electric field.

![Figure 1. Structure of needle-plate electrodes](image)

The surface flashover test circuit is composed of high-voltage DC generator, protective resistance, resistance-capacitance divider, high-voltage digital meter and sealed gas chamber. Non-inductive resistance is used for current limiting protection.

3. Experimental Results and Analysis

3.1. Influence of Mixture Ratio on Flashover Voltage

During the experiment, the mixture ratio of SF₆ in the mixed gas was 100%, 80%, 60%, 40%, 20% and 0, the experimental pressure was 0.1MPa-0.4MPa. FIG. 2 shows the change curve of flashover voltage along the surface of the insulator under the needle-plate electrode in SF₆ mixing ratio when DC voltage of positive and negative polarity is applied. In order to facilitate the comparison between positive and negative polarity flashover voltage values were expressed by absolute values.
Taking the flashover voltage of the insulators in SF\textsubscript{6} as a reference, this paper analyses the substitution effect of mixed gas on SF\textsubscript{6} when the volume fraction of SF\textsubscript{6} changes, and defines the flashover voltage ratio as:

\[
K = \frac{U_M}{U_S} \times 100\%
\]  \hspace{1cm} (2)

\(U_M\) is the flashover voltage value in a certain proportion of mixed gas; \(U_S\) is the flashover voltage in SF\textsubscript{6} under the same pressure; \(K\) is the flashover voltage ratio under the same pressure. Corresponding to flashover voltage value in figure 2, take the mixture gas with SF\textsubscript{6} mixing ratio of 40\% as an example, calculate the \(K\) value of the insulator under the needle-plate electrode under positive and negative DC voltage. The results were shown in table 1. It can be seen from the table that the flashover voltage of the insulator under the needle-plate electrode can reach above 63\% under the action of different polar voltages, so the insulation performance was relatively reliable when SF\textsubscript{6} gas mixture was relatively low. When SF\textsubscript{6} mixing ratio increased from 40\% to 80\%, the negative flashover voltage increased by about 25\%, while the positive flashover voltage increased by only about 10\%. This shows that blindly increasing the content of SF\textsubscript{6} in the mixture gas cannot achieve the optimal insulation effect.

![Figure 2. Variation of Flashover Voltage with Mixture Ratio of SF\textsubscript{6} in Needle-plate Electrodes](image)

Table 1 Relationship between \(K\) and pressure (%)

| Intensity of pressure/MPa | Needle-plate electrode(+) | Needle-plate electrode(-) |
|--------------------------|----------------------------|--------------------------|
| 0.1                      | 80.0                       | 63.3                     |
| 0.2                      | 90.8                       | 69.3                     |
| 0.3                      | 86.5                       | 72.4                     |
| 0.4                      | 75.8                       | 73.3                     |

3.2. Synergistic Effect of Flashover Voltage in Mixed Gas

According to the synergistic effect analysis method in clearance breakdown of mixed gas, the synergistic coefficient of flashover voltage in mixed gas was defined as:

\[
U_M = U_{CF_4} + \frac{\rho_{SF_6}(U_{SF_6} - U_{CF_4})}{\rho_{SF_6} + (1 - \rho_{SF_6})c}
\]  \hspace{1cm} (3)
$U_{SF_6}$ and $U_{CF_4}$ were flashover voltages of insulator samples when SF$_6$ and CF$_4$ gases act alone; $U_M$ was the flashover voltage of the insulator sample at the current mixing ratio; $P_{SF_6}$ and $P_{CF_4}$ was the partial pressure ratio of SF$_6$ and CF$_4$ gas; C was the coefficient of synergistic effect. Taking SF$_6$ mixed gas with a mixture ratio of 40% as an example, the relationship between the synergy coefficient and gas pressure under different polarities was analysed, the result was shown in figure 3.

![Figure 3. Synergy coefficient changes with pressure (SF6 mixing ratio is 40%)](image)

It can be seen from figure 3 that CF$_4$ and SF$_6$ gas show a relatively good synergistic effect in the surface flashover process when the positive polarity voltage was applied under the needle-plate electrode. Under the negative voltage there is a certain synergistic effect under high pressure, but there is a negative synergistic effect at 0.1MPa. In this paper, in the presence of an insulator, the cooperative coefficient of the mixture gas under the needle-plate electrode presents a nonlinear change law that first decreases with the increase of air pressure. One possible explanation is, when the pressure is low, with the increase of the pressure, the average free travel of the free electrons becomes shorter and easier to be captured by SF$_6$ molecules, and so the synergy coefficient decreases. Therefore, when the air pressure rises from 0.1MPa to 0.3MPa, the synergy coefficient increases. The reasons were: The surface charge accumulation of insulator will weaken the synergistic effect of mixed gas to some extent. In this experiment, under the needle-plate electrode, the local field intensity around the tip is high, and the corona layer at the tip will lead to serious charge accumulation on the surface of the insulator sample, these large accumulations of electric charges weaken the synergistic effect of the gas mixture.

3.3. Polarity Effect of Flashover Voltage in Mixed Gas

FIG. 4 had showed the relationship between flashover voltage and air pressure under the action of DC voltage of different polarity in the needle-plate electrode structure. It can be seen from the figure that the mixed gas under the needle-plate electrode has obvious polarity effect under positive and negative polarity. As pure SF$_6$ gas, the pressure is lower than the critical pressure, the difference between positive and negative flashover voltage is small; the pressure is higher than the critical pressure, the negative flashover voltage is significantly higher than the positive flashover voltage. For pure CF$_4$ gas, the difference between positive and negative flashover voltage is small within the measured pressure range, and there is no obvious polarity effect. When SF$_6$ gas mixed with CF$_4$, flashover voltage in different mixing ratios shows obvious polarity inversion, that is, when the pressure is lower than the critical pressure value, flashover voltage of positive polarity is higher than negative polarity. When the pressure is higher than the critical value, the flashover voltage of negative polarity is higher than that of positive polarity.
This phenomenon can be explained from the perspective of space charge. The electrons and positive ions produced during flashover cause the distortion of the electric field. SF₆ gas and CF₄ gas are both electronegative gases, both gases have the ability to adsorb electrons. Compared with electrons, the volume and mass of the negative ions formed by the adsorption of electrons by gas molecules and the positive ions generated in the process of electron collapse were larger and the solid movement was slower.

Under the needle-plate electrode, when the needle electrode was positive polarity: when the pressure was lower than the critical pressure value, the electrons in the electron collapse move rapidly to the needle electrode extreme, and the movement of positive ions is relatively slow, but temporarily stay near the needle electrode. The positive ions near the needle electrode weaken the field strength near the needle electrode and strengthen the field strength at the far end. But the pressure is low, the influence on the electric field strength is weak, so the flashover voltage is high. When the air pressure is higher than the critical value, the number of positive ions increases and the free travel decreases, thus forming tight ion clusters. In this case, the strengthening effect on the distal electric field is strong conducive to the development of the flow to the plate electrode, and the solid flashover voltage is low, when the needle current is extremely negative: When the air pressure is lower than the critical value, the electrons quickly move to the plate electrode, while the relatively slow positive ions temporarily stay near the needle electrode, strengthening the electric field near the needle electrode and weakening the strength of the electric field at the far end. However, the flashover voltage is lower because of the lower air pressure, which has a weak influence on the field strength at the far end. When the air pressure is higher than the critical value, the influence on the distal field intensity is enhanced, so the flashover voltage is higher.

4. Conclusion
In this paper, the DC flashover characteristics of epoxy resin samples in SF₆/CF₄ mixed gas under the needle-plate electrode structure were experimentally studied, and the effects of gas pressure, SF₆ mixture ratio and voltage polarity on flashover characteristics were analyzed. The following conclusions could be drawn from the paper:

1) In SF₆/CF₄ mixed gas with the same mixing ratio at the needling-plate electrode, the flashover voltage of both positive and negative polarity increases with the increase of pressure, and when the pressure is negative, the flashover voltage tends to saturate with the increase of pressure.

2) In 40% SF₆/60% CF₄, the flashover voltage of positive and negative polarity in the mixed gas at the needle plate electrode 0.4 MPa can reach more than 73.3% of the surface flashover voltage of pure SF₆ gas, while the consumption of SF₆ can be reduced by 60%.

3) Under the needling-plate electrode, in SF₆/CF₄ mixed gas with the same mixing ratio, the
synergy coefficient decreases first and then increases with the increase of pressure when the polarity is positive and negative.

(4) With the increase of gas pressure, the polarity of positive and negative flashover voltage is reversed. The positive flashover voltage was higher than the negative flashover voltage when it was lower than the critical air pressure, and the negative flashover voltage was higher than the positive flashover voltage when it was higher than the critical air pressure.

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