Power Frequency Breakdown Characteristics of SF$_6$/CO$_2$/N$_2$ and CF$_3$/NO$_2$/N$_2$ at Different Mixing Ratios

Xiao-ning YE* and Xue-jiao LEI

Dept. of New Energy and Statistics State Grid Energy Research Institute Company LTD.
Beijing, China

*Corresponding author

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Abstract. Although SF$_6$ gas has good insulation performance, due to its intense greenhouse effect, the search for alternative gases of SF$_6$ has become a research hotspot of scholars at home and abroad in recent years. In this paper, the discharge parameters of SF$_6$/CO$_2$/N$_2$ and CF$_3$/CO$_2$/N$_2$ gas mixtures with different ratios are calculated by Boltzmann equation analysis method. Preliminary prediction of insulation strength of mixed gases at different mixing ratios is carried out so as to select the mixed gases with better insulation performance and larger substitutability for in-depth research.

Introduction

Because of its good insulation and arc extinguishing performance, electronegative SF6 gas insulating medium has been widely used in power equipment, and its usage has increased year by year [1-3]. However, the potential global warming potential (GWP) of SF$_6$ is 23,900 times that of CO$_2$, and the lifetime of SF6 in the atmosphere is 3,200 years [4-7], which has a cumulative effect on global warming [8]. Therefore, the 1997 Kyoto Protocol designated SF$_6$ as a restricted high temperature room effect gas. By 2020, the use of SF$_6$ needs to be gradually reduced. In view of the increasingly more severe global warming, it is urgent to find new gases with insulation performance equal to or better than SF$_6$ and lower greenhouse effect index to replace SF$_6$.

CF$_3$I and its mixtures are widely concerned in the field of electrical equipment as a potential substitute for SF$_6$ due to their high insulation performance and small GWP[10]. With the purpose to facilitate the optimal design of mixed gases, it is a hotspot to calculate the insulation performance of SF$_6$ at various mixing ratios by theoretical analysis before an experiment.

At present, the research object of SF$_6$ substitute gas at home and abroad mainly concentrates on binary mixture gas, and there is little research on the insulation performance of ternary mixed gas by experiment and simulation. Therefore, the critical breakdown field strength of SF$_6$/CO$_2$/N$_2$ and CF$_3$/CO$_2$/N$_2$ ternary mixtures with different ratios is simulated by Boltzmann equation analysis method. The influential laws of CO$_2$/N$_2$ mixing ratio (20%-80%) on the power frequency breakdown characteristics of CF$_3$I and SF$_6$ mixtures under uniform electric field and 0.1 MPa pressure is researched. The results of this paper can provide a reference for the research of SF$_6$ alternative gases.

Calculation Method of Critical Breakdown Field Intensity

In this paper, Boltzmann equation analysis method is used to calculate the critical breakdown field intensity of mixed gases. The calculation principle of this method is as follows:

\[
\frac{\partial f}{\partial t} + v \cdot \nabla f - \frac{e}{m} \cdot E \cdot \nabla_v f = C[f]
\]  

(1)

Where, $v$ is the electron velocity, $e$ is the electron charge, $m$ is the electron mass, $E$ is the electric field intensity, $\nabla_v$ is the operator of the velocity gradient, and $C$ is the change rate caused
by collision. The binomial approximation method is used to simplify the equation. The distribution function \( f \) in spherical coordinate system is expanded as

\[
f(v, \cos \theta, z, t) = f_0(v, z, t) + f_1(v, z, t) \cos \theta
\]

(2)

Where, \( f_0 \) is the isotropic part of \( f \), \( f_1 \) is the anisotropic perturbation part, and \( \theta \) is the angle between electric field and electron velocity direction. Then \( f \) is standardized as.

\[
\int \int \int f d^3 v = 4 \pi \int_0^\infty f_0 v^2 dv = n
\]

(3)

Where, \( n \) is the electron density.

Equation (2) is substituted to Equation (1), both are multiplied by Legendre polynomials and \( \cos \theta \) is integrated, obtaining:

\[
\frac{\partial f_0}{\partial t} + \frac{\gamma}{3} E^2 \frac{\partial f_0}{\partial z} - \frac{\gamma}{2} \frac{\partial}{\partial z} (E f_1) = C_0
\]

(4)

\[
\frac{\partial f_1}{\partial t} + \frac{\gamma}{3} E^2 \frac{\partial f_0}{\partial z} - E \gamma \frac{1}{2} \frac{\partial f_0}{\partial z} = -N \sigma_m \varepsilon^2 f_i
\]

(5)

In the equation, \( C_0 \) represents the change of \( f_0 \) caused by collision, and \( \sigma_m \) is the total momentum conversion cross section containing all collision forms.

Supposed the correlation between \( f_0 \) & \( f_1 \) and energy is not related to time and space, the Equation (4) and Equation (5) are further simplified. The distribution function can be expressed as follows:

\[
f_{0,1}(\varepsilon, z, t) = \frac{1}{2 \pi \varepsilon} F_{0,1}(\varepsilon) n(z, t)
\]

(6)

Testing Apparatus and Experiment Method

Testing Apparatus

Testing apparatus mainly consists of discharge experimental cavity, power frequency voltage source and discharge electrode. The experimental cavity is a cylindrical organic cavity with inner diameter of 200mm, height of 300m and designed tolerance pressure of 0.3MPa. The voltage regulating range of induction regulator of power frequency voltage source is 0-380V. The rated capacity of testing transformer is 60kVA, rated current 1.0A/150A, rated transformation ratio of high and low voltage winding 60kV/400V. And the Qmax of transformer is less than 5pC.

The experiment electrode is made in board - board construction brass. Either electrode thickness of upper and lower boards is 10mm, diameter 100mm. To avoid distortion happens in the marginal field strength, profile bevel is conducted to the electrode. The radius of profile bevel is 5mm, the gap distance between upper and lower electrodes is fixed at 5mm.

Experiment Method

The experiment is usually carried out under the room temperature. Before the experiment, the first is to wipe the electrode surface with ethyl alcohol to make sure the surface is clean. The second is to seal the cavity and vacuumize it. When the vacuum is 10^{-2}kPa, the cavity can be filled with air. The purity of CO\(_2\) and N\(_2\) adopted in the experiment is 99.999%, SF\(_6\) 99.99%, CF\(_3\)I 99.9%. In the course of air filling, low content gas is filled before high content gas. The content of SF\(_6\) or CF\(_3\)I remains 20%. The gas is considered fully mixed when the mixed gas is stand for more than 24h after filling; and the testing pressure is 0.1MPa.
Before the breakdown experiment, 2-3 “sophistication” experiment are conducted to the electrode, to eliminate the impact from particles and little spines on the electrode surface. 75% voltage boosting method is adopted in the experiment with the voltage boosting rate of 1kV/s. Each group of experiment is conducted at least 10 times, the average value of 10 groups of valid data is taken as the breakdown voltage. And the maximum deviation between the 10 groups of valid data and average value is not greater than 3%.

Calculation and Test Result

Equivalent Critical Breakdown Field Strength of SF₆/CO₂/N₂ and CF₃I/CO₂/N₂ Mixed Gas

The relation curves between α/N, η/N, (α-η)/N and E/N in SF₆/CO₂/N₂ mixed gas with different ratio are shown as Fig. 1 – Fig. 3. The SF₆ gas content in the mixed gas remains at 20%. K in the figure refers to CO₂ gas content in the mixed gas. It can be seen from the figure that, in the range of 150 Td<E/N<300 Td, with the increase of E/N, the α/N, η/N and (α-η)/N in the SF₆/CO₂/N₂ mixed gas with different ratio present nonlinear upward or downward trend. In the other hand, under the same E/N value, α/N increases with the increase of CO₂ gas content in the mixed gas, and the increase rate is faster and faster; η/N is the opposite, under the same E/N value, η/N decreases with the increase of CO₂ gas content in the mixed gas, and the decrease rate is slower and slower; Similar to α/N, under the same E/N value, (α-η)/N increases with the increase of CO₂ gas content in the mixed gas, the upward trend of mixed gas (α-η)/N with different ratio with increasing is basically identical.

![Figure 1. Relation Curve between α/N and E/N in SF₆/CO₂/N₂ Mixed Gas.](image)

![Figure 2. Relation Curve between η/N and E/N in SF₆/CO₂/N₂ Mixed Gas.](image)
Figure 3. Relation Curve between \((\alpha-\eta)/N\) and \(E/N\) in \(SF_6/CO_2/N_2\) Mixed Gas.

The equivalent critical breakdown field strength of the gas is the corresponding \(E/N\) value when \((\alpha-\eta)/N=0\). Fig. 4 is the relation curve between equivalent critical breakdown field strength \((E/N)_{lim}\) and \(CO_2\) gas content in \(SF_6/CO_2/N_2\) mixed gas with different ratio, which shows that equivalent critical breakdown field strength \((E/N)_{lim}\) in \(SF_6/CO_2/N_2\) mixed gas decreases with the increase of \(CO_2\) content.

Figure 4. Relation Curve between \((E/N)_{lim}\) and \(CO_2\) in \(SF_6/CO_2/N_2\) Mixed Gas Electric Strength with Different Ratio.

**Power Frequency Breakdown Characteristics of \(SF_6/CO_2/N_2\) and \(CF_3I/CO_2/N_2\) Gas Mixtures**

The power frequency breakdown characteristics of \(SF_6/CO_2/N_2\) and \(CF_3I/CO_2/N_2\) gas mixtures in different ratio under the condition of 0.1MPa and a uniform electric field are shown in Fig. 5.

Figure 5. Power Frequency Breakdown Characteristics of \(SF_6/CO_2/N_2\) and \(CF_3I/CO_2/N_2\) Gas Mixtures under 0.1MPa and Uniform Electric Field.

It can be seen from the figure above that the power frequency breakdown voltage of \(SF_6\) and \(CF_3I\) gas mixtures decreases with the increase of \(CO_2\) content in the gas mixture, and \(SF_6\) gas mixture curve decreases more significantly than \(CF_3I\) gas mixture. The decline slope of \(SF_6\) gas mixture curve is 0.047, and that of \(CF_3I\) gas mixture curve is 0.015. On the other hand, under the same mixing ratio, the power frequency breakdown voltage of \(SF_6\) gas mixture is always higher than that of \(CF_3I\) gas mixture, but the gap between them decreases with the increase of \(CO_2\) content in the gas mixture, that is, the power frequency breakdown characteristics of the gas mixtures of \(SF_6\) with \(N_2\)
and CF₃I with N₂ under a uniform electric field are better than those of SF₆ with CO₂ and CF₃I with CO₂ respectively.

**Discussions**

Under a uniform electric field, the breakdown voltage of gas can be expressed as the equation

\[ U_b = (E_b / N)_{\text{lim}} \cdot N \cdot d \]

where d denotes the gas gap distance and N denotes the number of gas molecules per unit volume. Fig. 6 shows a comparison between the reduced critical breakdown field strength \((E_b/N)_{\text{lim}}\) calculated by the power frequency breakdown voltage of SF₆/CO₂/N₂ and CF₃I/CO₂/N₂ gas mixtures in different mixing ratios and the critical breakdown field strength \((E_c/N)_{\text{lim}}\) calculated by Boltzmann equation analysis method.

![Figure 6. Comparison Between \((E_b/N)_{\text{lim}}\) and \((E_c/N)_{\text{lim}}\) of SF₆/CO₂/N₂ and CF₃I/CO₂/N₂ Gas Mixtures at Different Mixing Ratios.](image)

As can be seen from the figure above, the four curves all nearly decrease linearly with the increase of CO₂ content in the gas mixture. The decline slopes of the four curves are 0.108, 0.416, 0.394 and 0.955 respectively from bottom to top. Regardless of \((E_b/N)_{\text{lim}}\) or \((E_c/N)_{\text{lim}}\), SF₆ gas mixture curve decreases more significantly. Therefore, the reduced critical breakdown field strength obtained by Boltzmann equation analysis method is different from that obtained by the power frequency breakdown voltage. Although the values of the two methods are inconsistent, it also can be seen from the figure that the trend of two reduced critical breakdown field strengths calculated by the above two methods changing with the CO₂ content in the gas mixture are approximately the same. Gas breakdown voltage is often used to characterize gas insulation in practical applications. However, for mixed gases, it will take a lot of time and manpower to perform lots of experiments to obtain the breakdown voltage of different gas mixtures at different mixing ratios and different atmospheric pressures. Therefore, on the basis of known gas collision cross section, the reduced critical breakdown field strength \((E/N)_{\text{lim}}\) of gas mixture can be obtained by means of calculation, and the insulation strength of gas mixture in different ratios can be preliminarily predicted, and eventually the gases with better insulation and greater alternative possibility can be selected for further study.

**Conclusions**

Boltzmann equation analysis method is used to calculate the reduced critical breakdown field strength of SF₆/CO₂/N₂ and CF₃I/CO₂/N gas mixtures in different ratios in the paper. The conclusions are as followings:

1. Within the range of 150 Td\(<E/N<300\ Td\), \(\alpha/N\) of SF₆/CO₂/N₂ and CF₃I/CO₂/N gas mixtures increases with the increase of CO₂ content in the gas mixture, and it’s going up faster and faster; \(\eta/N\) decreases with the increase of CO₂ content in the gas mixture, and it’s going down slower and slower; \((\alpha-\eta)/N\) increases with the increase of CO₂ content in the gas mixtures, and the upward trend of \((\alpha-\eta)/N\) of the gas mixtures in different ratios with the increase of CO₂ content is basically the same; The reduced critical breakdown field strength \((E/N)_{\text{lim}}\) of the gas mixture decreases with the increase of CO₂ content.
The power frequency breakdown voltage of SF$_6$/CO$_2$/N$_2$ and CF$_3$I/CO$_2$/N$_2$ gas mixtures decreases with the increase of CO$_2$ content in the gas mixture, and SF$_6$ gas mixture curve decreases more significantly than CF$_3$I gas mixture; Under the same mixing ratios, the power frequency breakdown voltage of SF$_6$ gas mixture is always higher than that of CF$_3$I gas mixture, but the gap between them gradually decreases with the increase of CO$_2$ content in the gas mixture.

The reduced critical breakdown field strength (E/N)$_{lim}$ of gas mixture can be obtained by means of calculation, and the insulation strength of gas mixture in different ratios can be preliminarily predicted, and eventually the gases with better insulation and greater alternative possibility can be selected for further study.

References


