Research on the synergy of SF$_6$/N$_2$ mixture gas in low temperature environment

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Abstract. For high latitudes, due to the deficiencies of liquefaction of SF$_6$ and extreme greenhouse effect, gas-insulated metal-enclosed switchgear (GIS), gas-insulated metal-enclosed transmission lines (GIL) and other electrical equipment have begun to use mixed gas of SF$_6$ and N$_2$ as the insulation medium. For this purpose, slightly non-uniform electric field distribution is generated using hemisphere-plane electrodes. Under the excitation of a negative DC high voltage, the breakdown voltage of the SF$_6$/N$_2$ mixture gas is measured at a temperature of 0 to -15$^\circ$C and a gas pressure of 15 to 60 kPa. The voltage is used to calculate the synergistic coefficient of the mixed gas, and the effect of the temperature and pressure on the synergy of the mixed gas is analyzed. The results show that under slightly non-uniform electric field conditions, the synergy of the mixed gas decreases with decreasing temperature, and increases with increasing gas pressure. It follows that good insulating property of SF$_6$/N$_2$ gas mixture used in a low temperature environment can be achieved by selecting a reasonable temperature and gas pressure.

1. Introduction

SF$_6$ is a colorless, odorless, non-toxic, incombustible, non-flammable and electronegative gas with high insulation capacity. Gas-insulated metal-enclosed switchgear (GIS) and gas-insulated metal-enclosed transmission lines (GIL) in transmission lines all use SF$_6$ as insulating medium. However, SF$_6$ has a high molecular weight, and it tends to liquefy under high pressure and low temperature environments, such as 1.28Mpa while 0$^\circ$C and 0.84Mpa at -15$^\circ$C, which degrades the insulation performance. Therefore, it is not suitable to use in high-cold areas. Moreover, the greenhouse effect produced by SF$_6$ molecules is more than 20,000 times that of CO$_2$ molecules. It is listed as one of the six types of restricted gases in the “Kyoto Protocol” issued in 1997. Thus, it is of high theoretical and practical value to find a SF$_6$ alternative gas that can perform stably under low temperature conditions.

In the existing research of SF$_6$/N$_2$ insulation performance, Boltzmann equation calculations [1], experiments and simulations [2] are used to analyze the discharge parameters, breakdown characteristics, and discharge decomposition products of the mixed gas, to study the insulation performance at various discharge conditions with different gas pressures, mixed gas ratio and power supply excitation types [3-5]. However, the study of its insulation properties is mostly at room temperature, and the performance of the mixed gas under low temperature conditions is less studied [6]. And SF$_6$/N$_2$, as a kind of mixed gas with synergy, the research on how the discharge conditions affect its synergy at low temperatures should be improved.
In this paper, under the excitation of negative DC high voltage in slightly non-uniform electric field, the synergy coefficient of the mixed gas is calculated by measuring the breakdown voltage of the SF$_6$/N$_2$ mixture gas at the low temperature, and the synergy change with the temperature and pressure is analyzed.

2. The analysis method of Synergy

After the two gases are mixed, due to the interaction between the gas particles, the breakdown field strength of the mixed gas is not equal to the weighted breakdown field strength, and this effect between the particles is called synergy. The existence of synergy makes the insulation properties of gases mixed diverse. According to the relationship between the breakdown field strength and the weighted breakdown field strength after the two gases are mixed, the interaction of the insulating properties of the two gases can be divided into linear relationships, conventional synergies, positive synergies, and negative synergies [7]. The synergy of SF$_6$/N$_2$ mixture is conventional that the breakdown field of the mixed gas is stronger than that of each component, but no matter what the mix gas ratio is, the breakdown voltage is less than that of pure SF$_6$ under the corresponding conditions.

In order to quantify the strength of the synergy and compare the strengths of the synergies better, synergistic coefficient is introduced, which satisfies Formula (1) [8].

$$U_b = U_{N_2} + \frac{\varphi_{SF_6} \cdot (U_{SF_6} - U_{N_2})}{\varphi_{SF_6} + (1 - \varphi_{SF_6}) \cdot C}$$  \hspace{1cm} (1)

In the formula, $U_b$ is the breakdown field strength of the mixed gas, $U_{N_2}$ is the breakdown field strength of N$_2$, $U_{SF_6}$ is the breakdown field strength of SF$_6$, $\varphi_{SF_6}$ is the content of SF$_6$ in the mixed gas.

Therefore, the calculation method of synergistic coefficient of mixed gas can be obtained according to Formula (1), as shown in Formula (2).

$$C = \frac{\varphi_{SF_6} \cdot (U_{SF_6} - U_{N_2})}{U_b - U_{N_2} - \varphi_{SF_6}}$$ \hspace{1cm} (2)

According to Formula (1) and Formula (2), the breakdown voltage corresponding to different synergistic coefficients can be plotted as the variation curve of the percentage content of SF$_6$ in the mixed gas. As can be seen from Figure 1, when $C = 0$, the breakdown voltage of the mixed gas is equal to the breakdown voltage of pure SF$_6$; when $C = 1$, the breakdown voltage of the mixed gas is equal to weighted breakdown voltage obtained by the partial pressure of SF$_6$ and N$_2$. When $0 < C < 1$, the smaller the value of $C$, the stronger the synergy is.

![Figure 1](image_url)  \hspace{1cm} Figure 1. The variation of breakdown voltage with the percentage of SF$_6$ under different synergy coefficients.
In Figure 1, each curve changes with the percentage of SF₆ content from 0 to 100%. The synergy coefficient of the entire curve is same [9], and the intensity of synergy under different discharge conditions (temperature, gas pressure) is characterized. Therefore, the average synergy coefficient \( \bar{C} \) is introduced to average the synergy of the mixture ratios under specific discharge conditions, which is:

\[
\bar{C} = \frac{\sum_{n(SF_6)} \left[ \varphi_{n(SF_6)} \cdot (U_{SF_6} - U_{N_2}) - \varphi_{n(SF_6)} \right]}{N \cdot \left(1 - \varphi_{n(SF_6)}\right)}
\]

By calculating the average synergy coefficient in each discharge condition, the relationship between the synergy of mixture gas with temperature and pressure can be obtained.

3. Experimental design and methods

To analyze the strength of the synergy, the breakdown voltage of the mixed gas must first be calculated to calculate the synergy coefficient. The circuit schematic used in the breakdown test is shown in Figure 2.

![Figure 2. The circuit principle.](image)

According to the circuit principle in the figure above, the schematic diagram of the breakdown experimental platform device is shown in Figure 3. The experimental platform mainly includes the gas distribution system, ionization chamber, and low temperature generation and measurement system. In the experiment, the discharge chamber was cooled by using low-temperature nitrogen gas that was released from liquid nitrogen. After testing, the low temperature range could be reduced to 0~15°C.

![Figure 3. Configuration of breakdown voltage test device.](image)

The non-uniformity of the electric field generated by the hemisphere-plane electrode is measured by the coefficient of non-uniformity of the electric field. According to the definition, for the non-
uniformity coefficient of the electric field between the discharge electrodes, the size is the ratio of the maximum electric field strength to the average electric field strength, that is:

\[ f = \frac{E_{\text{max}}}{E_{av}} \]  \hspace{1cm} (4)

In the formula, \( E_{\text{max}} \) is the maximum electric field strength, \( E_{av} \) is the average electric field strength.

According to the definition, the electric field with a non-uniform coefficient of 1-4 is generally defined as a slightly non-uniform electric field, and the electric field with a non-uniform coefficient greater than 4 is defined as severely non-uniform electric field. In order to obtain the electric field non-uniformity accurately, the empirical formula [10] of the electric field non-uniform coefficient between rod-plate electrode structures is shown in Formula (5).

\[
f = \begin{cases} 
0.85 \cdot (1 + \frac{d}{r}), & d / r \leq 3 \\
0.45 \cdot (\frac{d}{r}) \cdot \ln\left(\frac{6d}{r}\right), & d / r \geq 3 
\end{cases}
\]  \hspace{1cm} (5)

In the formula, \( d \) is the electrode spacing, \( r \) is the electrode tip radius.

The hemisphere-plane electrode is used to construct slightly non-uniform electric field in the breakdown experiment, and its design is shown in Figure 4. From the formula above, the non-uniformity coefficient of the electric field is 1.105 when the hemisphere-plane electrode is at a distance of 6mm. It is slightly non-uniform electric field. Therefore, the breakdown experiment was carried out at a distance of 6mm.

![Figure 4. Arrangement of electrodes used for test.](image)

In the experiment, the gas mixture is first filled into the experimental chamber to 0.1 Mpa (an atmospheric pressure), and then the experimental chamber is cooled by the low temperature nitrogen volatilized from the liquid nitrogen. The gas in the cavity is pumped out to the experimental pressure after the temperature reaches the test temperature. The breakdown experiment is carried out to measure the breakdown voltage under the corresponding experimental condition.

4. Experimental results and analysis

The breakdown voltage of each mixed gas at low temperature was measured through experiments, and the synergy coefficients under corresponding discharge conditions were calculated to analyze the relationship between the synergy with temperature and pressure.

4.1. Breakdown characteristics

Under a slightly non-uniform electric field, the breakdown voltage of pure N\(_2\) under 15kPa, 30kPa, 45kPa, and 60kPa changes with temperature is shown in Figure 5. As can be seen from the figure, the breakdown voltage of N\(_2\) does not change significantly with temperature under each atmospheric pressure, indicating that the insulation performance of N\(_2\) is less sensitive to temperature, and is almost unaffected by temperature in the range of 0~15°C. As can be seen from the longitudinal observation curve, the pressure has a uniform effect on the breakdown voltages of N\(_2\) at each temperature, and the breakdown voltages increase by about 2.5kV for every 15kPa increase in pressure.
Under slightly non-uniform electric field, the breakdown voltages of SF$_6$/N$_2$ mixed gas of 25/75, 50/50, 75/25, 100/0 ratio under 15kPa, 30kPa, 45kPa and 60kPa pressure change with temperature, such as Figure 6 shows. As can be seen from the curve, under each gas pressure, the breakdown voltages of the mixed gas increase slightly with decreasing temperature. Looking at the curves of four breakdown voltages as a function of temperature, it can be seen that the breakdown voltages increase with increasing gas pressure, and the effect is more balanced.

The main reason for the effect of temperature on the breakdown voltage is that the decrease in temperature makes the thermal motion of the gas particles slow, and the energy loss during the collision increases. The above two points make the gas particles unable to obtain a greater speed, and thus it is more difficult for impact ionization to generate new carriers. Even low-speed electrons are more likely to be adsorbed by SF$_6$ molecules, hindering the development of discharge, increasing the breakdown voltage, and improving the insulation performance. Under this experimental condition, the ionization of the mixed gas with the same gas pressure corresponding to each temperature has a 5.7%
increase in the number of molecules per unit volume at -15°C relative to 0°C. The more molecules per unit volume, the shorter the free path of free electrons is. The smaller the speed increase in the free path, the impaired ionization process is also weakened, the adsorption process is enhanced, the discharge development is slowed, and the breakdown voltage is increased.

4.2. Synergy Analysis
SF₆ as a strong electronegative gas, the molecule itself can absorb free electrons to form negative ions. The mass of negative ions is large, plays a negative role in the development of the discharge process, thereby reducing the carrier concentration, hindering the development of discharge process, so it has a high voltage tolerance limit. However, the occurrence of this process is probabilistic. The attach cross section indicates the probability of occurrence of this process. The size of the attach cross section depends in part on the energy of the free electrons themselves. The greater the kinetic energy of electrons, the faster the velocity of the electrons, the smaller the probability of adsorption, and the smaller the attach cross section. The other part depends on the electron's movement time around the electronegative gas molecules. The longer the time, the easier it is to absorb and the larger the attach cross section. N₂ is not an electronegative gas, and its collision cross section is relatively large and it is easy to collide with surrounding electrons. When SF₆ is mixed with N₂, N₂ gas molecules inelastically collide with free electrons. A part of the free electrons' kinetic energy is converted into the internal energy of the gas molecules, causing N₂ molecules to be excited into excited states. The free electrons' kinetic energy is reduced, it is more easily to be adsorbed by electronegative SF₆ gas molecules. This process leads to a synergy of N₂ and SF₆ gas mixtures. The synergy makes the insulating properties of the SF₆/N₂ mixed gas containing micro SF₆ significantly better than pure N₂.

From the calculation method of the average synergy coefficient in Formula (3), the average synergy coefficient of the mixed gas under different discharge conditions is calculated by using the data obtained from the breakdown experiments of the mixed gas under slightly non-uniform electric field, as shown in Table 1.

| T/°C | Average synergy coefficients |
|------|-------------------------------|
|      | 15kPa | 30kPa | 45kPa | 60kPa |
| 0    | 0.2738 | 0.2489 | 0.2101 | 0.1153 |
| -5   | 0.3206 | 0.2423 | 0.2276 | 0.1617 |
| -10  | 0.3439 | 0.2627 | 0.2460 | 0.2167 |
| -15  | 0.5152 | 0.3298 | 0.2926 | 0.2278 |

From Table 1, it can be seen that the average synergy coefficient has a certain degree of regularity with temperature and pressure. Under four kinds of gas pressure conditions, the average synergy coefficients increase with the decrease of temperature, which means that the decrease of temperature plays a negative role in the synergy of SF₆/N₂ mixture gas. The lower the temperature, the synergy of the mixture gas correspondingly is weakened. The reason is that the lower temperature generally reduces the energy of particles in the gas, and the number of electrons that reduce its energy due to collision with N₂ is smaller than the amount of electrons that SF₆ itself adsorbs, and accordingly the synergy is weakened.

In the temperature range of 0°C to -15°C, the average synergy of the mixed gas decreases with increasing gas pressure, indicating that the increase in gas pressure also has a positive effect on the synergy of the gas mixture. The higher the gas pressure, the stronger the synergy of the gas mixture is. The reason is that the higher the gas pressure is, the smaller the spacing between the particles is, and it is easier for N₂ to collide, and it is difficult for the particles to obtain sufficient acceleration within an
effective free path. Therefore, the free electrons in the gas generally have less energy and are easier to be adsorbed by SF$_6$, which leads to a stronger synergy.

5. Conclusions
In this paper, the synergy coefficient of SF$_6$/N$_2$ mixed gas at 0~15°C, 15kPa~60kPa under slightly non-uniform electric field is calculated from breakdown voltages obtained by breakdown experiments, and the synergy of mixed gas decreases with temperature decreases, and increases as the pressure increases. According to analysis, the effect of temperature and gas pressure on the synergy is mainly achieved by influencing the micro motion process of gas particles. Among them, the temperature mainly enhances the adsorption by affecting the energy loss during the movement and collision, and the pressure increases the adsorption by affecting the particle spacing and reducing the kinetic energy of the particles. This shows that for the SF$_6$/N$_2$ mixed gas used under low temperature conditions, its synergy can be enhanced by increasing the gas pressure of the mixed gas, thereby improving its insulation performance.

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