Effect of Particles on Discharge Characteristics of SF6/N2 Mixed Gas under Power Frequency Voltage

Xianhai Pang1, Xiao Wang2, Songsong Qiao3, Houfa Liu3, Yuyou Long2 and Shixin Xiu2,*

1State Grid Hebei Electric Power Research Institute, Shijiazhuang, China;
2College of Electrical Engineering, Xi’an Jiao tong University, Xi’an, China;
3Shandong Taikai High Voltage Switchgear Co Ltd, Taian, China

*Corresponding author e-mail: 1262699135@qq.com

Abstract. Residual metal particles appear in gas-insulated equipment, which may affect the insulation properties of electrical equipment. In this paper, a specific experimental device is designed to study the discharge characteristics of SF6/N2 mixed gas at different pressures and different mixing ratios under power frequency voltage, and the effect of particle shape, particle material type and gas pressure on the discharge characteristics of SF6/N2 mixed gas. The distortion effect of the shape of the particles and the type of the particulate material on the electric field between the electrodes was simulated. It is found that the breakdown voltage of SF6/N2 mixed gas increases with the increase of gas pressure and SF6 concentration. When the particles are present, the nonlinear effect of metal particles on the breakdown characteristics of SF6/N2 mixed gas in-creases with the increase of gas pressure. Obviously; the more irregular the shape of the particles, the greater the uneven-ness of the corresponding electric field, the greater the breakdown voltage of the SF6/N2 mixed gas; the particulate materi-al also affects the breakdown voltage of the SF6/N2 mixed gas, copper particles and The breakdown voltage of aluminum particles is approximately the same at the same gas pressure, and the influence of iron particles on the breakdown voltage is smaller than that of copper particles and aluminum particles. The research results of the paper have reference value for the study of SF6/N2 mixed gas characteristics and its application in electrical equipment such as GIS.

1 Introduction

SF6 gas is a gas with very good insulation properties. The electrical strength of SF6 is about 2.5 times that of air, and its arc extinguishing capacity is more than 100 times that of air. However, SF6 will cause great damage to the environment, and it is necessary to limit it[1]. Therefore, finding an alternative gas has become an urgent issue. Some scholars have proposed to use pure N2 as a substitute gas for SF6, because N2 is an environmentally friendly gas without causing the greenhouse effect, and the production cost is lower than that of SF6 gas, but the electrical strength of N2 is much smaller than SF6 gas. It is also necessary to take corresponding measures to strengthen the electrical strength of N2, which will increase the manufacturing cost. Therefore, the most widely adopted measure at this stage is to use SF6 / N2 mixed gas instead of pure SF6 gas[2].

In the actual operation of electrical equipment, there may be residual particles inside, these particles
will greatly affect the normal operation of electrical equipment[3]. This paper studies the relationship
between the discharge characteristics of SF$_6$/N$_2$ mixed gas with different mixing ratios, particle shape,
gas pressure, and particle materials at power frequency voltage. The particles are analyzed based on
the band theory. The change law of the influence of materials on breakdown voltage, which has a
certain reference effect on the application of SF$_6$/N$_2$ mixed gas in power equipment such as GIS.

2 Experimental equipment and methods

2.1 Experimental cavity

The equipment includes a high-pressure bushing, two independent sealed air cavity, a high-voltage
bus, an adjustment mechanism, and a barometer. The lower air cavity is the deflation cavity of the
experimental electrode plate of the experiment, and the upper air cavity is to be isolated from the
high-pressure bushing and save the amount of experimental gas.

The plate and plate electrodes used in the experiment are placed at the flat contacts in the figure.
The pull rod can be adjusted by the moving mechanism outside the air cavity to adjust the Clearance
distance. The role of the basin insulator is to effectively isolate the upper and lower air cavity. At the
same time, in order to better observe the process of the gap discharge between the plates, two
observation windows are set in the air chamber. The electric spark when the gas in the plate gap is
broken down can more accurately determine whether the gas is broken down.

2.2 Power frequency withstand voltage experiment platform

The power frequency voltage insulation experiment uses 750 kV non-partial discharge power
frequency experimental equipment, which is suitable for power frequency withstand voltage, partial
discharge experiments and other research experiments of 330 kV and below tap changers and their
insulation products. It is mainly composed of cascade-free experimental transformer, capacitor voltage
divider, column voltage regulator, low-voltage switchgear, console and other parts, which can meet the
requirements of the experiment. The power frequency voltage used in the experiment is applied to the
experimental cavity through an insulating sleeve. On the ground, the shell of the GIS forms a loop.

2.3 Experimental plates and metal particles

In order to minimize the uneven distribution of the electric field at the edge of the plate electrode,
the experimental plate electrodes used in this paper have been edge treated; and in order to reduce the
effect of the surface roughness of the plate on the surface electric field, The experimental plate was
polished; the above measures were taken to ensure that the electric field between the experimental
electrode gap and the surface was sufficiently uniform, so that the uniform electric field in the actual
GIS equipment could be accurately simulated.

According to many actual accident data and operating experience, it can be shown that the particles
often appear in the actual GIS operation are chromium, copper, iron, aluminum, silver and other metal
particles[4]. Therefore, the experimental metal particle materials used in this experiment are iron,
copper and aluminum, and the particle shape selected is flake, linear and irregular spherical particles.

Before putting the metal particles, wipe the experimental cavity and the experimental electrode
plate clean with a cleaning paper dipped in alcohol, and then use a vacuum pump to vacuum the
experimental cavity. After stabilization, fill the cavity with SF$_6$/N$_2$ mixed gas. SF$_6$ and N$_2$ mixed gas
can be regarded as ideal gas in practical use, so it meets Dalton's partial pressure law, as shown in
Equation 1:

\[
\frac{n_A}{n_B} = \frac{P_A}{P_B}
\]

(1)

When filling a mixed gas, in order to improve the accuracy of the mixing ratio, a small amount of
SF$_6$ gas is filled first, and then N$_2$ is filled. In order to ensure that the SF$_6$/N$_2$ mixed gas is fully mixed
in the experimental chamber, it should be left for one day when filling the gas to meet the
requirements of the accuracy of the experimental results[5].
3 Experimental results and analysis

3.1 Influence of air pressure on breakdown characteristics of SF\textsubscript{6} / N\textsubscript{2} mixed gas

Under the same conditions, the pressure of the SF\textsubscript{6}/N\textsubscript{2} mixed gas is changed to explore the effect of different SF\textsubscript{6}/N\textsubscript{2} mixed ratios on the discharge characteristics of the SF\textsubscript{6}/N\textsubscript{2} mixed gas. The relationship is shown in Figure 1 below. It can be seen from the figure that when the pressure increases, the breakdown voltage of the SF\textsubscript{6}/N\textsubscript{2} mixed gas ratio increases; at the same pressure, the higher the proportion of SF\textsubscript{6} gas, the breakdown voltage of the SF\textsubscript{6}/N\textsubscript{2} mixed gas. The larger, but the breakdown voltage of SF\textsubscript{6}/N\textsubscript{2} mixed gas does not increase linearly with the proportion of SF\textsubscript{6} gas increasing, but the increasing degree is smaller and smaller. When a small amount of SF\textsubscript{6} is added to N\textsubscript{2}, its breakdown voltage can be significantly increased, and when the mixing ratio exceeds 30%, the increase rate of the breakdown voltage of the mixed gas is slowed down with the increase of the mixing ratio. Taking the results at 0.5 MPa as an example, the breakdown voltage of a 15% mixing ratio of SF\textsubscript{6}/N\textsubscript{2} mixed gas is equivalent to 62% of the breakdown voltage of pure SF\textsubscript{6} gas, and the breakdown voltage of 30% mixing ratio of SF\textsubscript{6}/N\textsubscript{2} mixed gas is equivalent. At 82.6% of the breakdown voltage of pure SF\textsubscript{6} gas and 94.2% of the breakdown voltage of SF\textsubscript{6}/N\textsubscript{2} gas mixture with a mixture ratio of 50%, it can be seen that when the mixture ratio exceeds 30%.

![Figure 1. Discharge characteristics of SF\textsubscript{6}/N\textsubscript{2} mixed gas with different mixing ratios](image1)

Subsequently, when the gap between the plates is 5 mm, the discharge characteristic curve of pure SF\textsubscript{6} and SF\textsubscript{6}/N\textsubscript{2} mixed gas with a mixing ratio of 3: 7 is obtained, as shown in Figure 2. As can be seen from the figure, the breakdown voltage of pure SF\textsubscript{6} gas at 0.4 MPa is 69.1 kV, and the breakdown voltage of SF\textsubscript{6}/N\textsubscript{2} gas mixture with a mixing ratio of 0.52 MPa of 3: 7 is 71.1 kV. The values of are approximately equal, that is, when the pressure of the SF\textsubscript{6}/N\textsubscript{2} mixed gas mixture with a 3: 7 mixing ratio is increased by about 1.3 times, the power frequency breakdown of the SF\textsubscript{6}/N\textsubscript{2} mixed gas mixture with a 3: 7 mixing ratio and the pure SF\textsubscript{6} before the pressure is increased The voltages are approximately the same.

![Figure 2. Discharge characteristics of pure SF\textsubscript{6} and 30% mixed ratio SF\textsubscript{6}/N\textsubscript{2} mixed gas](image2)

The experimental results of Figure 4 are explained from the discharge mechanism\textsuperscript{[9-11]}. Gas effective ionization coefficient $\alpha_{SF\textsubscript{6}}$ and $\alpha_{N\textsubscript{2}}$ are:

$$\alpha_{SF\textsubscript{6}} = K_{S} \left[ E - \left( \frac{E}{p} \right) \cdot p \right]$$  \hspace{1cm} (2)

$$\alpha_{N\textsubscript{2}} = A \cdot e^{-\frac{B(p)}{E}} \cdot p$$  \hspace{1cm} (3)
While $K_s$，$A$，$B$ are discharge constant，$p$ is air pressure。

The effective ionization coefficient of the SF$_6$/N$_2$ mixed gas with a mixing ratio of 3: 7 is expressed by the sum of the effective ionization coefficients of each gas component, as shown in formula (4).

$$\alpha = x_{SF_6} \cdot \alpha_{SF_6} + (1 - x_{SF_6}) \cdot \alpha_{N_2}$$  \hspace{1cm} (4)

$x_{SF_6}$ is SF$_6$ gas volume fraction.

This article adopts the discharge column theory as the flow column discharge theory, because the flow column theory can take into account the distortion of the space charge to the plate gap electric field to make the calculation result more accurate, that is, after the local self-sustained discharge occurs, the flow column will cause the space discharge and self-sustained discharge. The conditions are as follows:

$$K = x_{SF_6} \cdot K_{SF_6} + (1 - x_{SF_6}) \cdot K_{N_2}$$  \hspace{1cm} (5)

$K_{SF_6}$=10.5；$K_{N_2}$=5.

Equations (2)-(5) are simultaneous，and the breakdown strength of SF$_6$/N$_2$ mixed gas with different SF$_6$ volume fractions can be obtained. When the pressure of SF$_6$ is 0.5 MPa，the breakdown voltage calculated by the above formula is 74.8 kV The breakdown voltage of pure SF$_6$ with an air pressure of 0.35 MPa is 73.9 kV. This calculation result is almost consistent with the experimental result.

3.2 Effect of particle shape on discharge characteristics of SF$_6$/N$_2$ mixed gas

According to the simulation results，the experiment uses metallic copper particles as the experimental particles，which are flaky，linear and spherical. The above three kinds of particles are used on the grounded electrode，and then the power frequency withstand voltage test is performed on the presence of different particles. The obtained results are compared with the SF$_6$/N$_2$ mixed gas with a mixing ratio of 3: 7 when no particles are added. The breakdown voltage is compared. As shown in Figure 3.

**Figure 3.** Mixed gas breakdown voltage diagram under different particle shapes

It can be seen from the figure that after adding the particles，the breakdown voltage of the SF$_6$/N$_2$ mixed gas at the same mixing ratio and air pressure significantly decreases. The non-uniformity coefficient of the electric field gradually increases，and the experimental results also show that the impact of the three different shapes of particles on the breakdown voltage is about the same as the result of the simulation，that is the flake copper particles that cause the smallest change in the non-uniformity of the electric field. The breakdown voltage value is the highest，the breakdown voltage is the lowest after the spherical copper particles are added，and the mixed gas breakdown voltage value is between the two kinds of particle values after the linear copper particles are added.

When flake copper particles are placed on the electrode plate，the electric field non-uniformity calculated by simulation is $f$=1.775，the power frequency breakdown voltage of SF$_6$/N$_2$ mixed gas at different pressures and pure SF$_6$ changes basically in the same trend，in the range of 0.3~ 0.6 MPa，the power frequency breakdown voltage increases with the increase of air pressure. The breakdown voltage of SF$_6$/N$_2$ mixed gas and pure SF6 shows a linear growth trend，and the linearity is good. When the copper particles are shaped，the electric field non-uniformity is calculated by simulation as $f$ = 2.43. As the pressure increases，the voltage rise rate of SF6 is lower than the voltage rise rate of the
SF$_6$/N$_2$ mixed gas at each pressure, that is, the gap between the breakdown voltage of SF$_6$/N$_2$ mixed gas and SF$_6$ is narrowing at higher pressure [12]. When the particles placed on the plate are spherical particles, the non-uniformity of the electric field calculated by the previous simulation is $f = 2.79$, and the degree of non-uniformity is larger than that of flake and linear particles. It can be seen that the breakdown voltage in the presence of spherical particles does not increase with the increase of air pressure, but an insignificant "hump" phenomenon appears[13].

3.3 Effect of particulate materials on discharge characteristics of SF$_6$/N$_2$ mixed gas

In this paper, flake-shaped aluminum, iron, and copper particles are used to ensure that their sizes are the same as much as possible, and then a power frequency withstand voltage test is performed on them. It can be seen from Figure 4 that the breakdown voltage of copper particles and aluminum particles is about the same under the same pressure, and the influence of iron on the breakdown voltage is the smallest. According to the band theory, the electronic arrangement of copper, aluminum, and iron is analyzed. The outermost electrons of copper and aluminum are 1, which means that it is very easy to lose the outermost electrons. The macro performance is lively metallic. And the outermost layer of iron has two electrons. Compared with copper and aluminum, iron is less likely to lose electrons, so the iron metal is less[14].

![Figure 4. Mixed gas breakdown voltage diagram under different particulate materials](image)

Therefore, when the same voltage is applied, the amount of induced charge generated by the iron particles is smaller than that of the copper and aluminum particles, so the degree of distortion of the electric field around the iron particles is smaller than that of the other two particles, and the electric field around the copper and aluminum is smaller. A greater degree of distortion occurs, and the insulation level of the air gap decreases more significantly than that of iron, so the breakdown voltage is higher than the breakdown voltage of the other two particles.

4 Conclusion

In this paper, by studying the power frequency breakdown characteristics of SF$_6$/N$_2$ mixed gas and the corresponding simulation results in the presence of different particles, the following conclusions are obtained:

1) When no particles are present, and the experimental electrodes filled with SF$_6$/N$_2$ mixed gas between the plates are subjected to the power frequency breakdown test. The breakdown voltage of the SF$_6$/N$_2$ mixed gas increases with the increase in gas pressure; at the same pressure, the breakdown voltage of the SF$_6$/N$_2$ mixed gas increases with the increase of the SF$_6$ gas concentration, but the rate of increase of the breakdown voltage getting smaller and smaller.

2) When particles are present, the effect of air pressure on the breakdown voltage of SF$_6$/N$_2$ mixed gas with or without particles is different. The larger the pressure, the smaller the effect of metal particles on the breakdown voltage of SF$_6$/N$_2$ mixed gas; the experimental results prove that the breakdown voltage of the SF$_6}$/N$_2$ mixed gas is the lowest when the regular spherical particles are present, and the breakdown voltage of the SF$_6$/N$_2$ mixed gas is the highest when the flake particles are present. This phenomenon is the same as the simulation result, which indicates that different shapes of metal particles cause different The non-uniformity of the electric field makes the breakdown voltages different.
Acknowledgments

This work was financially supported by Science and Technology Projects of State Grid Corporation of China (kj2018-080).

References

[1] ZHAO zhida. High voltage technology [M]. 3rd ed. Beijing, China: China Electric Power Press, 2013.
[2] DENG Yunkun, XIAO Dengming, CHEN Jiong. Insulation Performance Analysis of CF3I-N2 Mixed Gas as SF6 Alternative Gas for GIS/C-GIS [J]. High voltage technology, 2013, 39(9): 2288-2293.
[3] REN Xiaolong. Study on the Correlation between Discharge Quantity and SF6 Decomposition Component under Different Insulation Defects [D]. Chongqing: Chongqing University, 2012.
[4] Caliap L, Lesaint O, Denat A, et al. Influence of a metallic particle at a metal/insulator/gas triple junction in air and SF6[C]. Conference on Electrical Insulation and Dielectric Phenomena, 2009.
[5] DAI Qiwei. Effect of Free Metal Particles on Power Frequency Breakdown Characteristics of SF6 and SF6/CO2. Chongqing University Master thesis.
[6] Wu Chao. Research on gas gap and insulator insulation characteristics in DC GIL [D]. Chengdu: Southwest Jiaotong University, 2009.
[7] Lee B, Huh C, Chang Y. AC breakdown voltage characteristics simulation of SF6/N2 in non-uniform field and extra high voltage[C]// 4th International Power Engineering and Optimization Conference, Shah Alam, Selangor, Malaysia: IEEE, 2010, 210-214.
[8] NIU Wenjun, WEI Junmei, ZHANG Duo et al. Study on Insulation Performance of 550 kV SF6 / N2 Inflatable Bus Bar [J]. High voltage electrical appliance, 2014, 1: 50-1.
[9] Lee B, Huh C, Chang Y. AC breakdown voltage characteristic simulation of sf6/n2 in non-uniform field and extra high voltage[C]// 4th International Power Engineering and Optimization Conference, Shah Alam, Selangor, Malaysia: IEEE, 2010, 210-214.
[10] Ward S A. Optimum SF6-N2, SF6-Air, SF6-CO2 mixtures based on particle contamination[C]. International Symposium on Electrical Insulation, Anaheim, CA USA, 2000.
[11] Cressault Y, Connord V, Hingana H, et al. Transport properties of CF3I thermal plasmas mixed with CO2, air or N2 as an alternative to SF6 plasmas in high-voltage circuit breakers[J]. Journal of Physics D: Applied Physics, 2011, 44(49): 495202.
[12] Kieffel Y, Biquez F, Ponchon P, Irwin T. SF6 alternative development for high voltage Switchgears[C]// IEEE Power & Energy Society General Meeting. Denver, USA: IEEE, 2015: 26–30.
[13] Kieffel Y, Biquez F, Ponchon P. Alternative gas to SF6 for use in high voltage switchgear: g3[C]// In Proceedings of the 23rd International Conference on Electricity Distribution. Lyon, France: [s.n.], 2015:15-18.
[14] Owens J. Greenhouse gas emission reductions through use of a sustainable alternative to SF6[C]// IEEE Electrical Insulation. Conference. [Sl.]: IEEE, 2016: 535-538.