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Mechanism Analysis of Particle-Triggered Flashover in Different Gas Dielectrics Under DC Superposition Lightning Impulse Voltage

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ABSTRACT When DC GIL in operation endures the lightning impulse voltage, the charge accumulation at the gas-solid interface area will seriously affect the insulation performance of the spacer. Considering that gas side conduction is one of the important factors affecting charge accumulation, for the purpose of clarifying of the insulation characteristics of gaseous medium in the flashover process of gas-solid interface, an experimental platform for simulating the working conditions of the spacer is built. The spacer flashover tests were carried out with and without aluminum particle in SF_6, 4% C_3F_7CN /96% CO_2 and 20% SF_6/80% N_2 gas mixture. The measurement and analysis of surface potential distribution behavior of the spacer was conducted. The experiment results show that the gas dielectric is not the factor which dominate the potential distribution process without aluminum particle, and there is little difference in potential distribution with various gaseous conditions. When the linear aluminum particle appears on the surface of the insulator, it will cause severe electric potential distortion and these potential distorted areas are located around the end of the metal particle near the central conductor, and along with flashover pathway. It has also demonstrated that the gaseous dielectric has influence on the surface charge accumulation behavior especially with metallic particle adhere to spacer surface. Under the C_3F_7CN/CO_2 gas mixture, the surface flashover voltage decrease percentage is about 16.82% and may be lower. Besides, the insulation strength of the gaseous dielectric itself is also a key factor affecting flashover.

INDEX TERMS DC GIL, superimposed voltage, metal particle, C_3F_7CN/CO_2, surface charge.

I. INTRODUCTION

Due to the development of electrical power system, there is an increasing demand for high-voltage direct current (HVDC) systems. The DC gas-insulated transmission line (DC GIL) shows great potential to be applied in actual engineering due to its outcomes of large transmission capacity, high voltage level, and excellent operational reliability [1]. An important characteristic of DC GIL is that it needs to withstand DC voltage during operation. In practical applications, DC GIL inevitably faces two major problems, one is the problem of surface charge accumulation [2], [3], and the other is the problem of metal particles [4]. In particular, when these two defects exist at the same time, the insulation strength of the interface of the gas-solid insulation material will be notably decreased, and the surface flashover phenomenon of the insulator may be induced [5]. In addition, unfortunately, the main insulating gas currently used by GIL is SF_6, a greenhouse gas, which is widely criticized for environmental considerations. Driven by the contradiction between ensuring the rapid development of the electrical power industry and the requirements of environmental protection, scientists are working hard to find a more environmentally friendly SF_6 alternative gas. The SF_6 alternative gas represented by the SF_6/N_2 mixture and the

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C_3F_7CN/CO_2 mixture is distinguished from many potential alternative gases due to its better balance between insulation and environmental protection requirements [6]. Under this background, studying the influence of new gaseous dielectric on the flashover characteristics of insulators has important reference value for the design and manufacture of GIL insulation equipment.

The flashover characteristics of insulators are largely related to the potential distribution on the spacer surface or the degree of charge accumulation behavior. This conclusion has been recognized by scholars. Some scholars pointed out that there are three main sources of charge accumulated on spacer surface: the charge conducted through the gas side, the charge conducted through the solid bulk and the charge conducted through the solid surface [7]–[9]. L. Zhang, *et al.* reviewed the research status of surface charge measurement and characterization technology [10]. Some researchers have studied the effect of applied voltage polarity and operating ambient temperature on the degree of charge accumulation on the insulator surface [11], [12]. These research results have laid a solid foundation for subsequent exploration. Since the flashover characteristic of insulators is an important aspect of insulator insulation performance, many researchers have conducted flashovers under the DC voltage, pulse voltage, and DC superimposed pulse composite voltage, that is, the dangerous conditions faced by electrical equipment in operation [13], [14]. Hasegawa *et al.* [13] studied the effect of DC superimposed impulse voltage on the flashover characteristics of insulators. The results show that the polarization effect caused by DC voltage cannot be ignored in GIS applications. However, this study was conducted in a simulated cavity. The experimental conditions are different from the actual operating conditions of the GIL chamber. In addition, the insulating gas used in the experiment is pure SF_6. The Al_2O_3 filled epoxy resin insulator model was used by Ma *et al.* [15], to study the effect of DC voltage pressurization time, metal particles on the surface and the polarity of the composite voltage on the insulation performance of the spacer under the effect of DC superimposed impulse voltage. It is reported that with the increase of voltage applied time, the flashover voltage of the insulator decreases significantly under the effect of composite voltage; when there are metal particles on the surface of the insulator, the flashover voltage along the surface of the insulator is obviously reduced compared to the case where the surface of the insulator is clean and free of particles; When the polarity of the pre-applied DC voltage and the lightning impulse voltage are opposite, the insulation performance of the insulator decreases most. However, This research is conducted in an SF_6 gas environment.

Although the predecessors' researches have been comprehensive, most of these existing studies are carried out on the model, and the charge accumulation before and after the composite voltage is not measured. It is difficult to directly show the effect of the DC superimposed impulse voltage on the interface charge and insulation performance of the insulator. With the promotion of environmentally-friendly insulating gases, the insulation of the interface between the alternative gas and spacer under DC superimposed impulse voltage is also worthy of attention. In order to support the reliable application of alternative gases in engineering, it is necessary to conduct a more in-depth study on the insulation performance of solid insulating interface in new gas insulating media. Among which, the flashover characteristics and laws of the insulator in the C_3F_7CN gas environment, in the presence of metal particles, are still unclear. Thus, this paper establishes an experimental platform for comparing the effects of metal particles in the three insulating gases on the insulation performance of the insulator. Studies on the charge behavior and flashover characteristics of the insulator surface under different harsh conditions with different gas mixtures is carried out to lay the foundation for the optimal design of the environmentally friendly gas DC GIL.

II. EXPERIMENT SETUP

A. EXPERIMENTAL PLATFORM

As shown in Figure 1, the experimental platform used to study the flashover behavior of insulator under DC superimposed pulse voltage is mainly composed of superimposed voltage power supply and coaxial cylindrical test model.

The spacer surface potential measurement system is the most important part of the experiment. The measurement system consists of an electrometer (TREK 347), a capacitance probe, an amplifier, an oscilloscope, and a computer connected to it. During the experiment, the surface electric potential of the insulator is applied to represent the charge accumulation characteristics. Some have pointed out that such simplification is reasonable and acceptable [2], [11]. Combine the AC/DC voltage power supply and pulse voltage generator according to the connection shown in the figure to form a composite voltage power supply. According to literature [15] and the actual situation of this experimental system, the parameters of this composite voltage supply system were determined. As is shown in the schematic diagram, the DC voltage transmit through a protective resistor with the resistance of 10 MΩ, and the impulse voltage pass through the capacitor with the capacitance of 10nF. Through such a design, the safe operation of the DC voltage source and the negative pulse voltage generator can be ensured, and the mutual influence between the two power sources is avoided. By placing the coaxial cylindrical electrode in a closed chamber with a relatively large size, it was ensured that the electric field environment of the spacer in the experiment was basically consistent with the real internal condition of 126kV GIL. In the experiment, Al_2O_3 epoxy resin insulator with an outer diameter of 260 mm provided by Shandong Taikai High Voltage Switch Co., Ltd. was used. Because under normal operating conditions, the central conductor temperature can reach 70 °, and its shell temperature slightly higher than the room temperature, which makes the GIL will form a temperature gradient in the pipeline. Limited by experimental conditions, it is difficult to simulate the working current-carrying

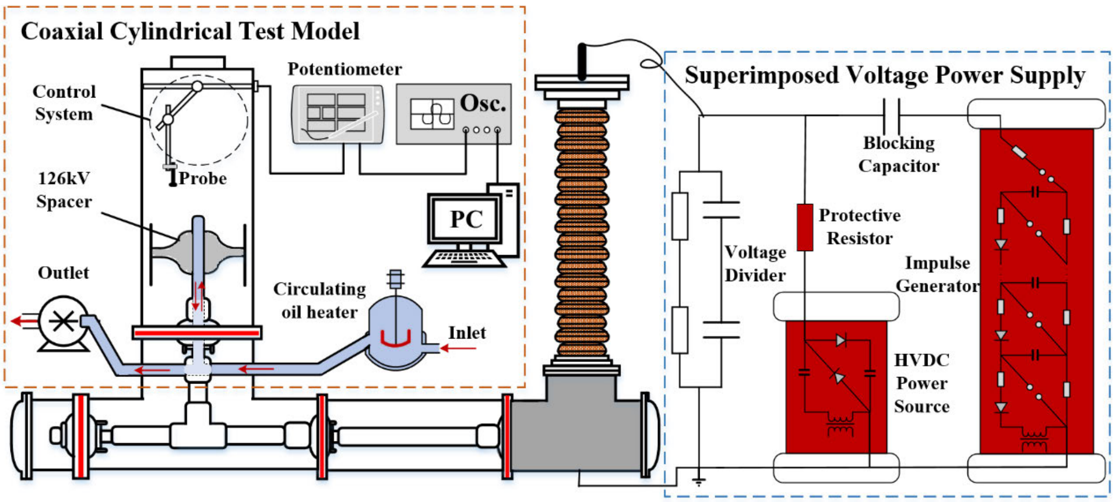


FIGURE 1. The diagram of the experiment platform.

situation of GIL – simultaneously applying high voltage and large current. In order to simulate the actual working conditions, the circulating oil heating device was used to heat central conductor in the experiment to realize the control of the temperature gradient field.

B. TEST METHOD

For the purpose of eliminating the influence of the residual charge on the applied material on the initial discharge voltage and discharge characteristics, it is necessary to wipe the various materials used in the experiment, including insulator surface, center conductor surface, aluminum linear particles (with the diameter of 0.25 mm and length of 20 mm) and metal shield, with anhydrous ethanol-soaked silk before conducting the experiment. Wait for the ethanol to completely evaporate and then select the location on the insulator surface on which the electric field lines are the densest and the field deformation is the largest, and use conductive silver glue to fix the metal particles onto the location.

Pure SF_6 gas, SF_6/N_2 mixture and C_3F_7CN/CO_2 mixture were selected for comparison test in order to analyze the flashover characteristics of the gas-solid interface in different insulating gases. Among the three gases involved in the experiment, the 20% SF_6/80% N_2 gas mixture has been used in the actual engineering of GIL equipment [16]. In addition, many studies have pointed out that the insulation performance of 4% C_3F_7CN/96%CO_2 gas mixture is very good, so it has huge application potential [17]. During the experiment, SF_6 (or C_3F_7CN) was first filled, and then N2 (or CO_2) was filled, until the pressure of pure gas or mixed gas reached 0.1MPa. After the aeration, the gases were left to mix evenly for more than 24 hours. In addition, in order to set the temperature of the insulator close to the actual conditions, it is necessary to continuously heat for more than 7 hours using the circulating oil bath heating device. Some studies have shown that surface charge accumulation can be accelerated at high temperatures [2].

At the beginning, a +100kV DC voltage was applied to the insulator by a uniform boosting method and held for 2 hours. Maintain the 100 kV DC voltage output, turn on the pulse voltage generator, and use the step normal method to superimpose a standard negative lightning pulse voltage (1.2/50 μs) of a certain amplitude on the basin-type insulator, and record the flashover voltage using an oscilloscope. Then the surface charge of the insulator after flashover is obtained. Ensure that each set of experiments under the same conditions is repeated 3 times.

III. EXPERIMENTAL RESULTS

A. SURFACE POTENTIAL MEASUREMENT WITHOUT LINEAR PARTICLE

After applying 100 kV DC positive voltage for 2 hours, the potential distribution before and after flashover on the surface of the insulator without particles (filled with pure SF_6, SF_6/N_2 mixture and C_3F_7CN/CO_2 mixture) are given in Figure 2. Table 1 shows the average, maximum and minimum value of potential before flashover.

In the case of before flashover, we can see that the charge distribution pattern is substantially centrally symmetric and the overall potential is basically positive and decreases along the radial gradient by comparing the potential distribution of the insulator surface in these three kinds of insulating gas mixture. Meanwhile, some randomly distributed positive and negative potential distortion regions appear on the surface of the insulator, and the potential at the edge of the insulator or at the junction of the insulator and the flange tends to reach a negative polarity.

From the comparison of these two groups, it seems that the charge distribution patterns show a significant change after the flashover caused by the negative lightning impulse voltage. A potential distortion channel connecting the center conductor and the grounding flange appears on the surface of the insulator, and coincides with the flashover path. The

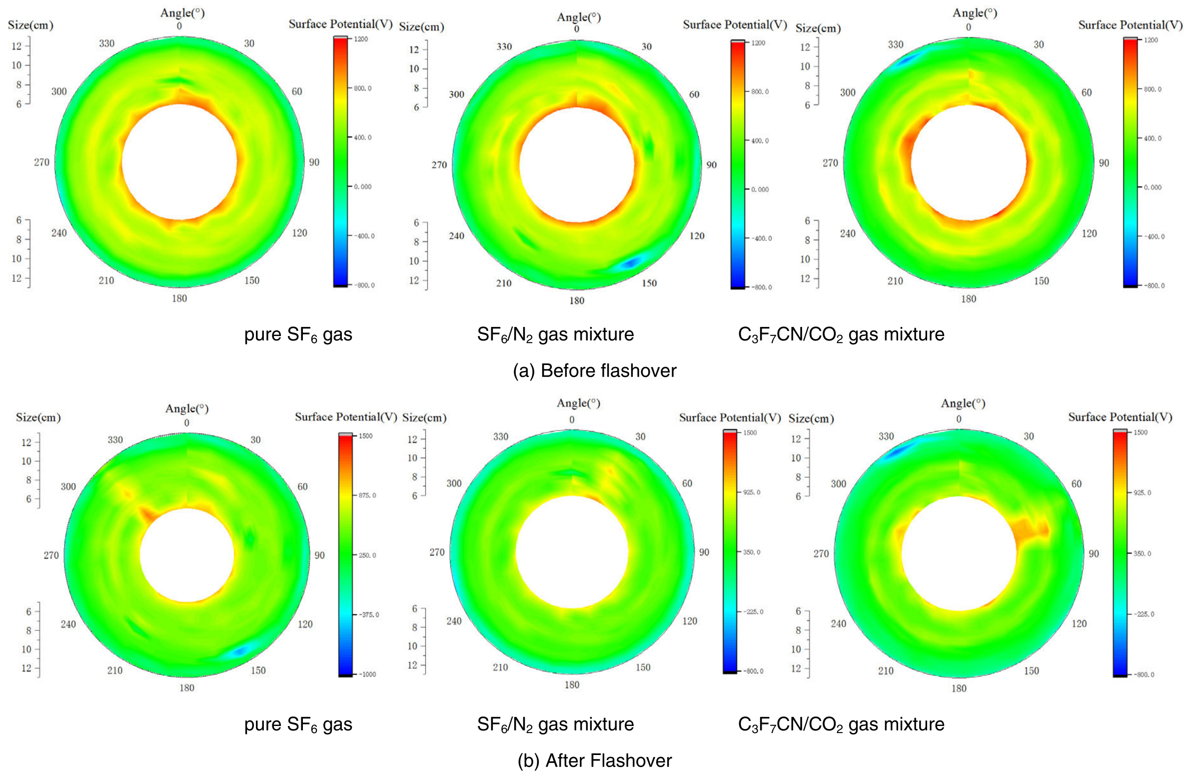


FIGURE 2. Surface potential distribution behavior of the spacer without aluminum particle.

TABLE 1. Basic informations of surface potential without particle.

Item		Pure SF_6	SF_6/N_2	C_3F_7CN/CO_2
Surface potential (V)	Average value	388.46	399.55	411.43
	Maximum value	1168.06	1305.61	1289.31
	Minimum value	-586.86	-656.74	-509.62

TABLE 2. Basic informations of surface potential with particle.

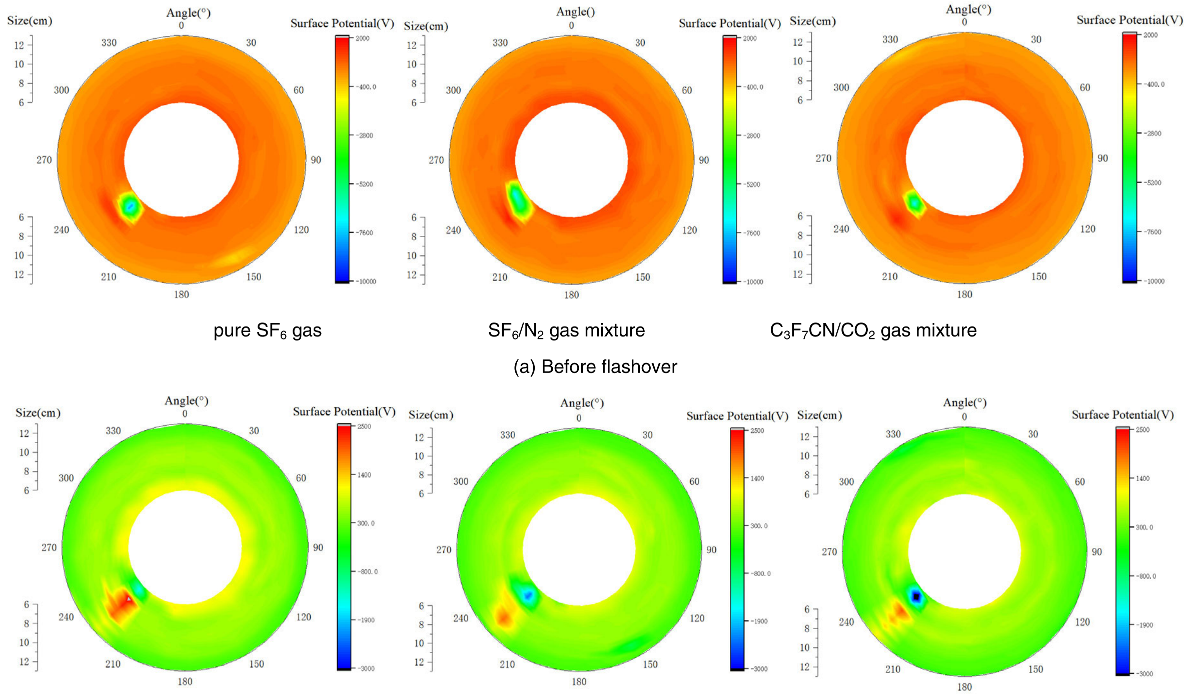
Item		Pure SF_6	SF_6/N_2	C_3F_7CN/CO_2
Surface potential (V)	Average value	419.93	306.81	328.17
	Maximum value	1658.86	1614.52	1546.33
	Minimum	-11895.65	-10458.63	-9954.86
Item		Pure SF_6	SF_6/N_2	C_3F_7CN/CO_2
	value			

potential of this region is positive and significantly higher than other parts.

B. SURFACE POTENTIAL MEASUREMENT WITH LINEAR PARTICLE

Figure 3 shows the potential distribution with aluminum particle are placed on the spacer surface. Table 2 shows the average, maximum and minimum value of potential before flashover when metal particles are present.

Most parts of the surface keep a uniform potential distribution and mainly accumulates a positive charge, which maintain the basic principle of decreasing the gradient. However, at the region near the tip of metal particle proximal to high-voltage electrode, severe negative charge accumulation appears and spreads to the central conductor, and positive charge accumulation region is born at another tip, which form a heteropolar charge pair. After the flashover occurs, based on no significant change in the potential of other regions, the area of high-potential positive-polarization near the tip of the metal particle remote to high voltage electrode expands and spreads to the ground flange. In addition, the potential of positive charge accumulation part drops significantly. It is a common under three kinds of insulating gases that the phenomenon of opposite polarity potential distortion zones occurs on one side or both sides of the metal particle in the radial direction after flashover with the influence of metal particle. As shown in the statistics in Table 2, the minimum surface potential value is -11895.65 V in pure SF_6, and the minimum value in C_3F_7CN/CO_2 gas mixture is −9954.86 V, which is 16.32% lower than the former. The lowest surface potential in SF_6/N_2 mixture is -10458.63 V. The value in C_3F_7CN/CO_2 gas mixture is 4.82% lower than that in SF_6/N_2



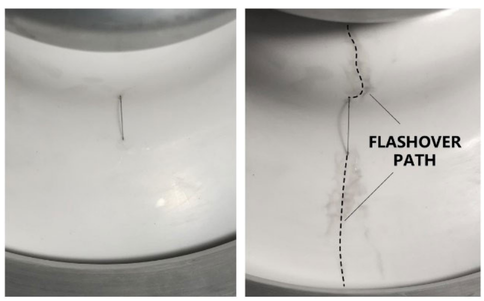
pure SF_6 gas SF$_6$/N$_2$ gas mixture C_3F_7CN/CO_2 gas mixture

(a) Before flashover

pure SF_6 gas SF_6/N_2 gas mixture C_3F_7CN/CO_2 gas mixture

(b) After Flashover

FIGURE 3. Surface potential distribution behavior of the spacer with aluminum particle attached.



(a) (b)

FIGURE 4. Arrangement of metal particle on spacer surface and condition of spacer surface, (a) before and (b) after flashover.

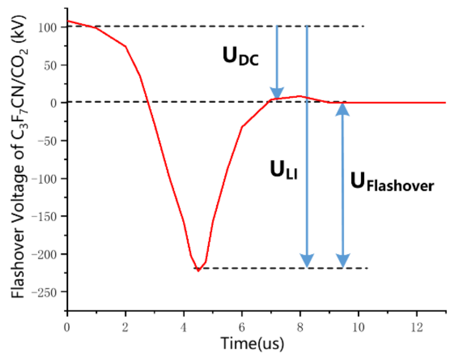


FIGURE 5. The superimposed voltage of DC and negative pulse voltage curve triggered flashover in C_3F_7CN/CO_2 mixture.

and the value in SF_6/N_2 gas mixture is also 12% lower than that in the pure gas.

C. FLASHOVER UNDER SUPERIMPOSED VOLTAGE

Figure 4(a) shows the layout of the metal particle in the initial state, and the flashover path triggered by metal particle under the C_3F_7CN/CO_2 gas mixture is given in Figure 4(b). In each experiment, the particle is arranged at the same position on the surface. By comparing the charge distribution behavior shown in Figure 3 with the flashover path shown in Figure 4, it can be known that when the surface flashover induced by metal particle occurs, the particle arranged along the axial direction just become part of the flashover path.

The composite voltage curve that causes surface flashover under C_3F_7CN/CO_2 mixture is shown in Figure 5. Thus, the flashover voltage under the superimposed voltage of DC and negative pulse voltage can be defined as:

$$U_{\mathrm{Flashover}} = U_{\mathrm{LI}} - U_{\mathrm{DC}} \tag{1}$$

And the parameters U_{DC} and U_{LI} have been shown in Figure 5.

Figure 6 shows the flashover voltages with and without metal particle, and each is the average value of these 3 times experiments. It can be clarified that in pure SF_6, the surface flashover voltage keeps the highest, and the flashover voltage values are very close in both the SF_6/N_2 gas mixture and

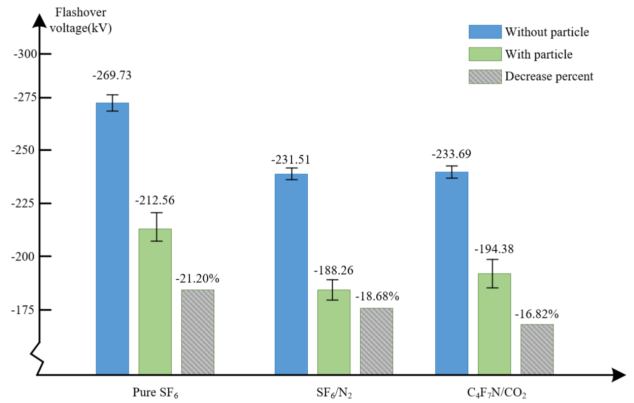


FIGURE 6. Flashover voltage and its decrease percent.

C_3F_7CN/CO_2 mixture, which shows that C_3F_7CN/CO_2 gas mixture has excellent potential to replace SF_6 or SF_6/N_2 gas mixture. It is worth noting that when the linear metal particle appears on the spacer surface, the decrease percentages of both SF_6/N_2 mixture and C_3F_7CN/CO_2 mixture are lower than that of pure SF_6. The decrease percentage of pure SF_6 is 21.20%, of SF_6/N_2 is 18.68% and of C_3F_7CN/CO_2 is 16.82%, which shows that C_3F_7CN/CO_2 mixture has better insulation performance. Under pure SF_6, the surface flashover voltage is highest, and other two gas mixtures are relatively low, which also shows that the flashover voltage value of gas-solid interface is closely related to the dielectric strength of the gas medium. For gaseous dielectric with high insulation strength, the flashover voltage might be higher.

IV. DISCUSSION

A. GAS-DOMINANT CHARGE DISTRIBUTION

The charge accumulated behavior on the spacer surface is transferred from the source that generates the charged ions by bulk conduction in solid spacer, surface conduction or gas conduction. The mechanism of the three modes on the formation of accumulation on surface can be expressed as [18]:

$$\frac{\partial \rho_S}{\partial t} = \mathbf{n} \cdot \mathbf{J}_B - \mathbf{n} \cdot \mathbf{J}_G - \mathbf{J}_S \tag{2}$$

The current in bulk can be calculated by:

$$\mathbf{J}_B = \kappa_B \cdot \mathbf{E}_d \tag{3}$$

And the current on surface can be described as [19]:

$$\mathbf{J}_S = \kappa_S \cdot \mathbf{E}_\tau \tag{4}$$

where $\partial\rho_s/\partial t$ is the transient change of surface charge; n is the direction of the unit normal vector defined from bulk to gas; $\mathbf{J}_B$, $\mathbf{J}_G$ and $\mathbf{J}_S$ are current flow from bulk, from gas and along the surface respectively; κ_B and κ_S are the volume conductivity and surface electric conductivity of the spacer material; $\mathbf{E}_d$ and $\mathbf{E}_\tau$ is the tangential component of the electric field in the bulk and on the gas-solid interface separately.

It is easy to clarified that from above expressions of $\mathbf{J}_B$ and $\mathbf{J}_S$ that currents conducted through the bulk and the surface are both closely related to the electric field environment and body material of spacer.

The source of charge accumulation from the gas side would be more complex, involving ion generation, recombination, migration and diffusion of space ions in the microscopic scale. In the electric field environment, the motion of the gas side carriers depends on the Coulomb force of the particles, and the diffusion of carriers is determined by the uniformity of their concentration. The dynamic change of positive carrier concentration can be expressed by the generation, recombination and migration of positive and negative ions. Then, the small current flow through the gas side can be determined by the drift of ions due to the applied electric field and diffusion due to local gradient of ion concentration [20]. In the approximate calculation, it can also be considered as:

$$\mathbf{J}_S = \kappa_G \cdot \mathbf{E} \tag{5}$$

where κ_G is the volumetric conductivity of the gas side.

Since the surface leakage of the spacer is relatively small, it is considered to be negligible in many classical models. Actually, the current of the clean insulator is negligible in this experimental environment, and it can be seen from equations (2)-(5) that the accumulation of surface charge is related to the difference in current between the two sides of the solid-gas interface. It is assumed that the direction of the electric field line at the solid-gas interface is consistent with the direction of n. When the solid-side current is dominant, the surface area is positively charged; when the gas-side current is dominant, the surface area is negatively charged. The measured volume conductivity of the insulator is in the order of 10^{-18} S/m at room temperature. The volume conductivity of most electronegative insulating gases is on the order of 10^{-22}~10^{-20} S/m [21]. Since the experimentally observed charge distribution behavior is the same as the applied voltage polarity, it can be judged that the distribution pattern of the overall charge with the same charge is due to the dominant side of the solid side current. Thus, it could be explained that the charge accumulation behavior on the surface of the spacer is similar in the three kinds of gas dielectrics used in this experiment.

B. EFFECT OF METAL PARTICLE

It is not uncommon to see faults caused by metal particles in the GIL. When metallic particles adsorbed on the insulator surface appears, the surface charge accumulation behaviors of the insulator will show some unique conditions. Taking the case of the experimental setup in this paper as an example, as described in section III B, under a long period of applied voltage, an opposite polarity charge pair appears on both sides of the metal particles. This may be closely related to the surge in electric field strength caused by the tip of the metal particles. Under the action of a strong field, corona discharge occurs in the electric field distortion region of the tip of the metal particle, and the gas molecules in the region are ionized

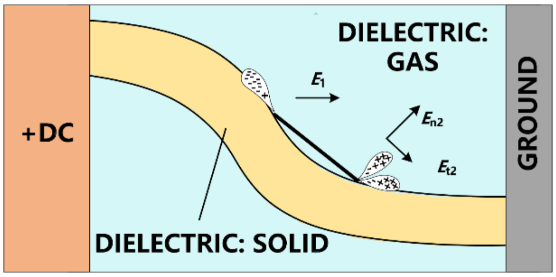


FIGURE 7. Schematic diagram of charge accumulation mechanism under the influence of particles.

as shown in Figure 7. Since the voltage applied by the conductor of the experimental center is positive, under the action of the normal component of the electric field, the positive ions generated by the discharge of the tip of the particle migrate into the gas along the electric field line under the action of the electric field, and the negative ions are injected into the surface of the insulator. The potential increases and the area gradually expands with time increasing; under the action of the tangential component of the electric field, the positive and negative ions migrate in the opposite direction along the surface of the insulator. Thereby, under the action of the positive polarity voltage, a large amount of negative charges is accumulated at one end of the center conductor of the metal fine particles, and a positive charge is accumulated at one end of the far center conductor.

If the metal particles present on the spacer surface can be regarded as an additional ion source, the more easily ionized gas components at the same voltage will form more charged ions, and the overall surface electric potential of the insulator will be lower. The trend we get in this experiment is also in line with conclusion of [22].

There are some differences in surface charge accumulation with the influence of metallic particle in the 3 kinds of different mixtures. Figure 3(a) has shown that the charge distribution behavior is similar in 20% SF_6/80% N_2 and in 4% C_3F_7CN/ 96% CO_2, in which the insulator surface potential is lower than in pure SF_6. In addition, the negative potential concentration region in C_3F_7CN/CO_2 and SF_6/N_2 is slightly smaller than that in pure SF_6, and the maximum value of the negative potential is also lower.

It is well known that in extremely uneven fields, some properties of pure SF_6 are very poor. In this case, the SF_6 molecule is highly susceptible to ionization to produce charged ions. In these two kinds gas mixture, the SF_6 and C_3F_7CN molecules greatly reduce the possibility of ionization respectively under the action of buffer gas. Thus, more negative and positive ions are generated in pure SF_6 with the influence of metal particle, and they are driven by the electric field inside the cavity and form a more serious charge accumulation behavior on surface. This also verifies the conclusion acquired in literature [23], which indicates that the discharge sensitivity by particle (DSP) of C_3F_7CN/CO_2 and SF_6/N_2 gas mixtures is less than that of pure SF_6.

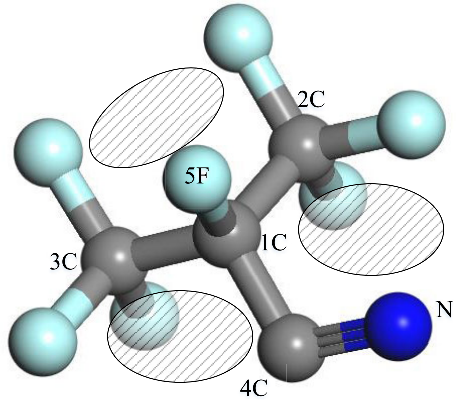


FIGURE 8. C_3F_7CN gas molecular structure.

The insulation performance of C3F7CN/CO2 gas mixture is more prominent, which may be due to the following reasons:

1) In terms of relative molecular weight, C_3F_7CN (195) is larger than SF_6 (146), so the mobility of negative ions of C_3F_7CN molecules in the electric field is smaller. In addition, because the C_3F_7CN molecule has a larger collision cross section, the C_3F_7CN/CO_2 mixed gas can effectively capture the electrons and ions generated after collision [24], thereby reducing the number of effective collision ionization and electron avalanches caused by electrons;

2) The structure of C_3F_7CN molecule is more complex than SF6, as shown in Figure 8. When CO_2 molecules are embedded in the gaps of C_3F_7CN molecular skeletons (the spatial regions shown by the shadow in Figure 8), a relatively large molecular aggregation area may be formed. At this time, although electrons are more likely to collide, effective collision ionization is less likely to occur;'

3) The bond energy of each bond in the C_3F_7CN molecule is shown in Table 3. The atomic numbers in the table correspond to the atomic numbers in Figure 8. It can be seen from Table 3 that the covalent bond between the central C atom and the C atom in the -CF_3 group has the lowest energy and is easier to break, while the carbon-nitrogen covalent triple bond has higher stability. Therefore, C_3F_7CN will crack to produce CF_3, C_3F_4N and CFCN molecules under the influence of electricity, heat and other factors. The above-mentioned molecules have strong electronegativity and can cooperate with CO_2, so they still show excellent electrical resistance. strength;

4) H. E. Nechmi, *et al.* measured and calculated the ionization coefficient α and adsorption coefficient η of C_3F_7CN molecule based on the SST method [25]. The study found that the (α-η)/N value (density normalized effective ionization coefficient) of C_3F_7CN molecule was much lower than that of SF_6 molecule. For the 4% C_3F_7CN/CO_2 mixed gas used in this article, its effective ionization coefficient is lower than that of the SF_6 mixed gas under certain conditions.

TABLE 3. Some bond energies of C_3F_7CN.

Bond	Bond Energy（kJ/mol）
1C-5F	438.8
1C-2/3C	367.2
2/3C-F	512.0
1C-4C	485.1
4C-N	893.2

C. SURFACE CHARGE ACCUMULATION BEHAVIOR

As is shown in Figure 2 (b), a large amount of positive charge will accumulate on the flashover path without particle. When applied voltage reaches the flashover voltage, the positive charge accumulation region will first ionize due to the severe electric field distortion. The electrons generated by ionization will move toward the positive charge accumulation region and concentrate with the positive charge to form a high conductivity channel under the influence of negative impulse voltage. The field strength between the head of the channel and the shell increase to form an electron collapse. The electron collapse will develop from the shell to the central electrode, eventually forming a flashover channel. For the circumstance with particle, the positive part of bipolar charge will extend along the ground electrode, which is in line with the previous analysis. As analyzed in section III B, SF_6 is more susceptible to ionization under strong distorted electric fields, and ionization is also more intense. Therefore, the positive potential region left on the surface of the insulator in SF_6 is also larger and higher. In addition, the potential value of the negative part is significantly lower, which may be due to the rapid dissipation of negative charges.

When spacer is contaminated by metal particle, unlike the non-contaminated, the pair of bipolar charge appear on the surface, which is shown in Figure 3. Typical flashover trace induced by metal particle are recorded in Figure 9. Because the composite lightning impulse voltage is negative polarity and a large number of homocharges accumulate at the tip near the central conductor, where the local electric field is weakened, discharge will bypass the area. Thus, the discharge channel would curve. In contrast, at the tip near the shell surface heterocharges would increase electric field distortion and facilitate the development of creepage, so this part of trace keeps straight. These conclusions are also consistent with the characteristics pointed out by Ma *et al.* [26] and Okubo *et al.* [27].

The charge accumulation on the surface of the insulator causes the electric field distortion due to the discharge of the tip of the metal particles, and the charged ions generated by the corona discharge migrate into the gas, which accelerates the development of the electron collapse. It is worth noting that the carbonization flashover path of the insulator surface directly connects the central conductor and the ground electrode through the metal particles, and the particle probably lift the arc from spacer surface, so the presence of the metal particles is equivalent to shortening the length of the flashover arc developed at the gas-solid interface. Therefore, the surface flashover voltage of the particle-contaminated insulator will drop significantly.

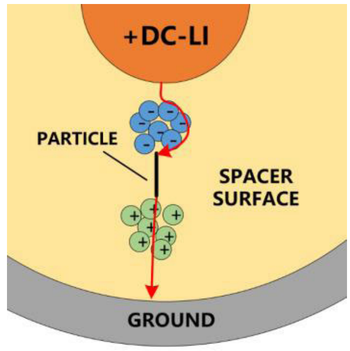


FIGURE 9. Schematic diagram of the effect of charge accumulation caused by particles on the flashover path.

It cannot be ignored that the flashover voltage of the insulator under pure SF_6 is still the highest. Even though the metal particles act as a suspended conductive channel equivalent to reducing the creeping distance, the spacer creepage distance is still very long.

Under the circumstance, flashover voltage may closely relate to the insulation strength of the gas. From [6] and [28], it can be found that under the same function of E/N C_3F_7CN/CO_2 mixture is very close to electron drift velocity and electron diffusion coefficient of SF_6/N_2 mixture, and the values of pure SF_6 is much lower than them in the same situation. After comparison, we found that the characteristic of normalized effective ionization coefficient ($(\alpha\text{-}\eta)$/N) of three kinds of dielectric gases reported in literature [28], [29] maintains the same trend. In addition, the macroscopic property, breakdown field strength, of C_3F_7CN/CO_2 and SF_6/N_2 are similar [30]. Unfortunately, it is not yet clear what role gas plays in the flashover process.

V. CONCLUSION

In this paper, a full-size 126kV spacer surface potential measurement and flashover voltage test platform is designed, and a DC Voltage Superimposed Impulse Voltage test circuit is built. The insulation performance of the spacer with and without linear metal particle in pure SF_6, 20% SF_6/80% N_2 and 4% C_3F_7CN/96% CO_2 gas mixtures is tested. Following conclusions can be summarized from the experiment results:

The basic mode of charge accumulation on the spacer surface does not change significantly in different gas insulating medium. Not considering the influence of the surface current, the charge transferred by gas side is much lower than the charge conducted through the bulk, which is the reason that the surface charge of the insulator is consistent with the polarity of the center conductor voltage.

There is a distinct feature of surface charge accumulation under the influence of the metal particles. An opposite polarity charge pair appears at the tips of the metal particle. the charge accumulation in pure SF_6 is more serious than the other two gas mixtures. This is closely related to the characteristics of the insulating gas itself.

When flashover occurs on the clear surface spacer, the flashover path appears randomly on the surface of the insulator and positive charge accumulates along the path. When flashover occurs on the spacer surface adhered metal particle, the negative charge on the tip of negative polarity rapidly dissipates, and the charge further accumulates on the positive side. This may be related to the migration and motion characteristics of positive and negative charges.

Under the influence of metal particle, the flashover voltage decreased by 21.2% in pure SF_6, 18.68% in 20% SF_6/80% N_2, and 16.82% in 4% C_3F_7CN/96% CO_2. Although the surface charge accumulation in SF_6 gas is more serious under various conditions, the flashover voltage is still the highest. This shows that the flashover of the insulator is closely related to the gas characteristics, but there is no theory to explain its mechanism clearly.

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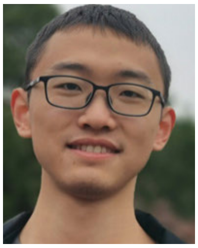

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