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Influence of Electric Field Non-uniformity on Discharge Characteristics in SF_6/N_2 Gas Mixtures Under Power Frequency Voltage

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***Abstract*—In recent years, SF_6/N_2 gas mixtures with low SF_6 mixing ratio was getting used as insulating medium in gas-insulated metal-enclosed transmission line in order to replace pure SF_6. For the application of SF_6/N_2 gas mixtures in power equipment, this paper studied on the breakdown characteristics of SF_6/N_2 gas mixtures with low SF_6 mixing ratio in different electric field non-uniformity under power frequency voltage, and the characteristic of partial discharge initial voltage was studied in non-uniform electric field. In order to study the breakdown characteristic of SF_6/N_2 gas mixtures under high voltage grade, a fully enclosed power frequency voltage test device was set up. The sphere-plane and rod-plane electrodes were used to simulate the slightly non-uniform field and local-field enhancement in GIS or GIL. The research indicates that the breakdown voltage of SF_6/N_2 gas mixtures increases linearly with increase of gas pressure in slightly non-uniform electric field. With the increase of the electric field non-uniformity, the linearity of breakdown voltage weakens and the stable corona discharge appears. Because of the space charge effect, the N-curve characteristic of breakdown voltage appears in SF_6 and its mixtures. When electric field non-uniformity exceeds a certain value, the stable corona discharge appears before the electric breakdown of electrodes gap. But the breakdown occurs immediately with the appearance of corona when the gas pressure exceeds a certain value. Meanwhile, the synergistic effect was strengthened and then weakened. And the amplitude and range of N-curve extend when electric field non-uniformity increased.**

Keywords*—power frequency voltage; electric field non-uniformity; SF_6/N_2; gas mixtures; synergistic effect; partial discharge inception voltage; N-curve characteristic

I. INTRODUCTION

Due to the excellent electric insulation strength and great chemical stability, SF_6 gas has been widely used in electric power system. Nonetheless, as potent greenhouse gas, SF_6 has caused serious environmental problem with the rapid increase of its amount. In 1997, SF_6 has already been listed as one of gases which need to be limited in the Kyoto Protocol [1]. In addition, SF_6 has high sensitivity to the electric field non-uniformity, i.e., with the increase of electric field non-uniformity, the insulation strength of SF_6 drops rapidly. Moreover, if SF_6 gas was used in gas insulated metal-enclosed transmission lines (GIL) as insulating medium, its economy effectiveness will be discounted because of its high price.

At present, the single alternative gas to SF_6 gas is still not found[2]. So SF_6 gas mixture has become a good solution to instead of SF_6 gas [2]. The critical breakdown electrical field strength of binary gas mixtures is different from that of the single gas, and it can be divided into four types, respectively is: linear relationship, synergistic effect, positive synergistic effect and negative synergistic effect [3]. Because that N_2 has the great chemical stability and is easy to be prepared as the main components in the atmosphere, SF_6/N_2 gas mixture has the best application prospect, meanwhile it has synergistic effect.

The researches of SF_6 gas mixtures have been started since 1970s, and most of them focused on the breakdown characteristic with low voltage grade under steady state voltage [4-5]. But most of the researchers studied with one electrode structure which represents slightly non-uniform or strongly non-uniform field[6]. In another word, the study about the influence of electric field non-uniformity on breakdown characteristic of SF_6/N_2 gas mixtures is still rare. The more important is that SF_6/N_2 gas mixtures as synergistic effect gas mixtures, the researches on its synergistic effect influenced by the electric field non-uniformity, gas pressure and other factors have no definite results.

This paper studied on the discharge characteristics of SF_6/N_2 gas mixtures with different electrode structures. And the U-shape characteristic of breakdown voltage was analyzed. It is effective for guiding the application of SF_6/N_2 gas mixtures as insulation medium in the electric power equipment such as GIL, and it is also valuable for clarifying the gas discharge mechanism of SF_6/N_2 gas mixtures.

II. EXPERIMENT DETAILS

A. Experiment System

To investigate the breakdown characteristic of SF_6/N_2 gas mixtures under power frequency voltage, a fully enclosed inflatable test device was set up in the laboratory; its structure is shown in Fig. 1. The test device is composed of four parts:

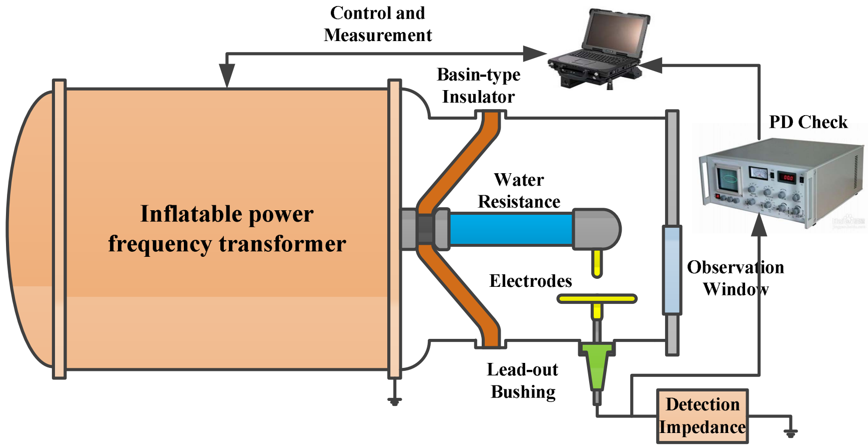


Fig. 1. Structure of power frequency voltage test device.

inflatable power frequency transformer, test chamber, partial discharge measurement system, control and measurement system. SF_6 is the insulation medium in the inflatable power frequency transformer, and the bus leads to the test chamber through the basin insulator. The water resistance in series with the bus limits the breakdown current, and the terminal of it is a shielding sphere which reserved a thread hole for installing electrodes. The plane electrode was grounded via the lead-out bushing, which makes the plane electrode insulated from the test chamber. So the partial discharge inception voltage can be measured through this single grounding terminal. The voltage can be measured by the embedded measurement winding in power frequency transformer through the control and measurement system.

The sphere-plane electrodes were used to simulate the slightly non-uniform electric field in GIS or GIL, and rod-plane electrodes represented the condition which electric field is more non-uniform. The specific arrangement of electrodes is shown in Fig. 2. The material of electrodes is stainless steel because of the good ablation resistance. The radius curvatures of sphere and rod electrodes are 40mm and 15mm to 1mm separately, and the plane electrode is Rogowski electrode with diameter of 300 mm, in addition the distance of gap is 33 mm. The electric field non-uniform coefficient *f* simulated by Ansoft software is shown in Table 1.

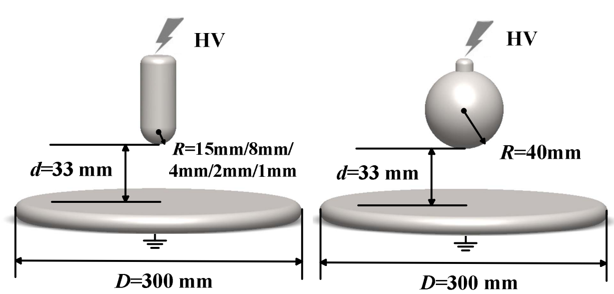


Fig. 2. Arrangement of electrodes used for test.

B. Experimental Method

In this paper, Dalton's law of partial pressures is used to prepare gas mixtures for the tests and then stew them for 24 hours to make them mixed uniformly. For enhancing the accuracy of mixing ratio, the test chamber should be inflated with SF_6 gas which has low content first, then inflated with N_2 gas.

The valid test number of each data group is more than 10 times. The time interval between adjacent two tests is 10 min for the recovery of dielectric strength of gas.

TABLE I. THE ELECTRIC FIELD NON-UNIFORM COEFFICIENT *f* OF ELECTRODES

Electrode type	Rod-Plane Electrodes					Sphere-Plane Electrodes
Radius/mm	1	2	4	8	15	40
f	24.3	14.0	7.39	4.29	2.77	1.58

III. RESULTS AND DISCUSSION

A. Breakdown characteristics of SF_6/N_2 gas mixtures in slightly non-uniform electric field

Fig. 3 shows the breakdown voltage of SF_6/N_2 gas mixture as a function of gas pressure under power frequency voltage with R=40 mm sphere-plane electrodes which represent the typical slightly non-uniform electric field. It can be seen that breakdown voltage of SF_6/N_2 gas mixtures in different mixing ratio increases with gas pressure linearly under power frequency voltage. With the increase of mixing ratio k, the rise rate of breakdown voltage with the increase of gas pressure speeds up, and this is because $(E/P)_0$ (express E_{cr} in terms of the pressure-independent property)increases with the increase of the content of SF_6. The result under power frequency voltage is same with the result under lightning impulse.

In addition, the breakdown voltage of SF_6/N_2 gas mixtures with low SF_6 content is obviously higher than that of pure N_2 gas. With the increase of mixing ratio, saturated trend of breakdown voltage appears, and it becomes obvious when SF_6 content exceeds 30%. That is to say, the relationship between breakdown voltage and mixing ratio deviates from the linear relationship significantly, that is to say, synergistic effect appears in SF_6/N_2 gas mixtures significantly.

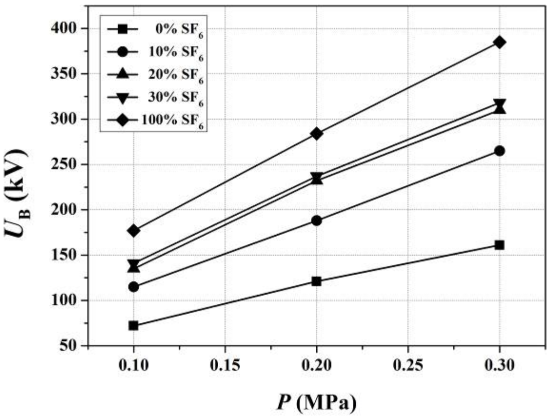


Fig. 3. Breakdown voltage as a function of gas pressure under power frequency voltage with R=40 mm sphere-plane electrodes.

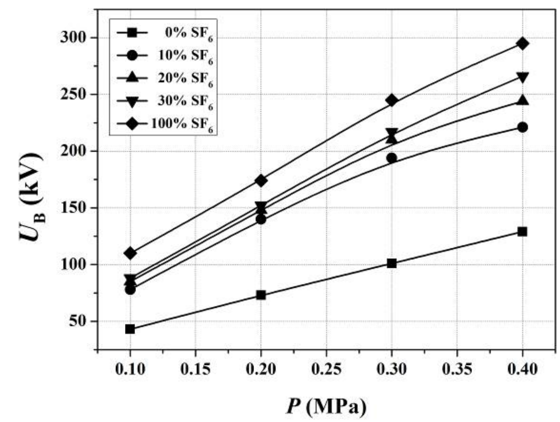
B. Breakdown characteristics of SF_6/N_2 gas mixtures with R=15 mm and R=8 mm rod-plane electrodes

Fig. 4 illustrates the relationship between breakdown voltage of SF_6/N_2 gas mixtures and gas pressure under power frequency voltage with R=15 mm and R=8 mm rod-plane electrodes, and the electric field was transformed from slightly uniform to non-uniform. It can be seen that breakdown voltage of SF_6/N_2 gas mixtures in different mixing ratio still increases with gas pressure linearly under power frequency voltage. But the saturated trend of breakdown voltage with the increase of gas pressure appears at high gas pressure. With the increase of mixing ratio k, the rise rate of breakdown voltage with the increase of gas pressure still speeds up, but the rise rate decreases with the electric non-uniformity enhanced. That is to say, the influence of gas pressure on breakdown voltage weakens with increase of electric non-uniformity.

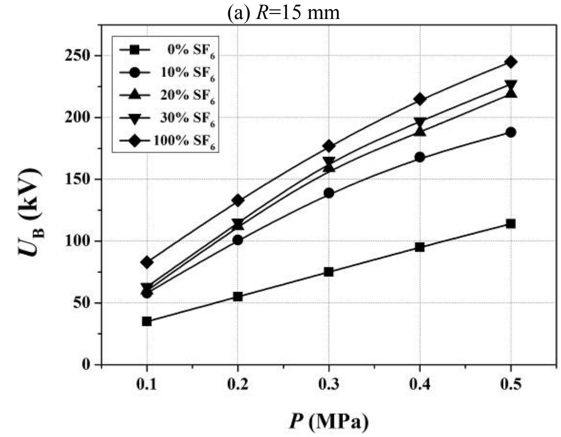
C. Discharge characteristics of SF_6/N_2 gas mixtures in non-uniform electric field

Fig. 5 illuminates breakdown voltage and partial discharge inception voltage of SF_6/N_2 gas mixtures as a function of mixing ratio under power frequency voltage with R=4 mm, R=2 mm and R=1 mm rod-plane electrodes. It can be illustrated that the obvious and stable partial discharge occurs before gas breakdown and the partial discharge inception voltage of SF_6/N_2 gas mixtures increases with gas pressure linearly regardless of electric non-uniformity. With the increase of mixing ratio k, the rise rate of partial discharge inception voltage raises slightly. The reason is same with that of breakdown voltage, that is, $(E/P)_0$ increases with the increase of the content of SF_6. But the rise rate of partial discharge inception voltage drops obviously with the increase of electric non-uniformity. In another words, the influence of gas pressure on partial discharge inception voltage weakens with increase of electric non-uniformity.

The relationship between breakdown voltage and gas pressure is no longer linearity but obvious N-curve characteristic. That is, the breakdown voltage deviates from the partial discharge inception voltage obviously at low gas pressure, and rises to the maximum value V_{Bm} with gas pressure increases to P_m. Then the breakdown voltage decreases with the increase of gas pressure until a certain pressure P_c. The partial discharge inception voltage is close to the breakdown voltage even non-detectable when gas pressure exceeds P_c, and the breakdown voltage increases slowly with gas pressure rising.



(a) R=15 mm

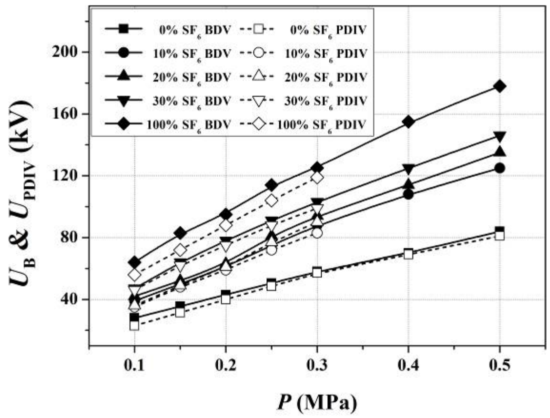


(b) R=8 mm

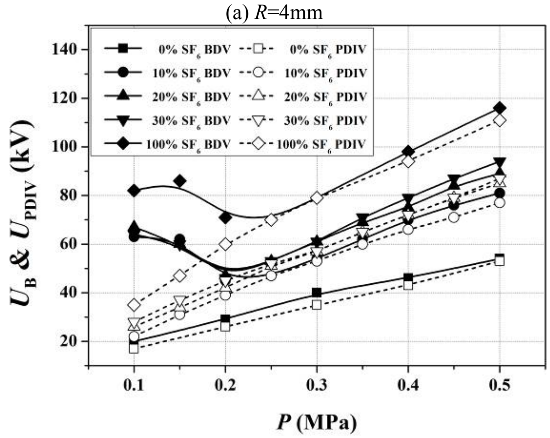
Fig. 4. Breakdown voltage as a function of gas pressure under power frequency voltage with R=15 mm and R=8 mm rod-plane electrodes.

As can be seen, P_m is less than 0.15 MPa and P_c is around 0.2 MPa-0.25 MPa with R=2 mm rod-plane electrodes. V_{Bm} of SF_6 and gas mixtures are around 85kV and 60-70 kV respectively. As for R=1 mm rod-plane electrodes, P_m is approximately 0.15MPa-0.2MPa and P_c is around 0.3 MPa-0.35 MPa. V_{Bm} of SF_6 and gas mixtures are around 100 kV and 70-80 kV respectively. The result proves that the range and amplitude of N-curve enlarge with increase of electric non-uniformity. That is, the improvement effect of space charge on local electric enhancement is more apparent, which is same with pure SF_6.

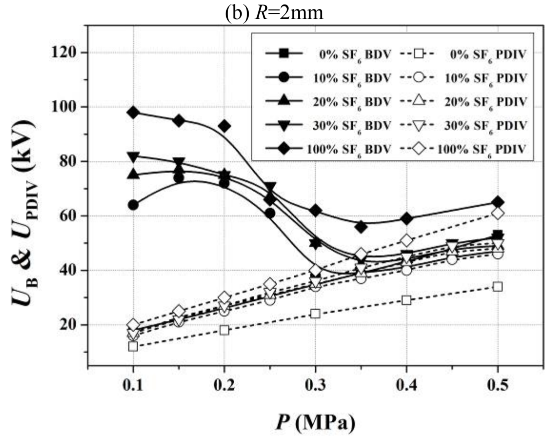
When the gas pressure is relatively low, partial discharge inception voltage raises with increase of gas pressure. And the stabilization effect of space charge leads the deviation of breakdown voltage from partial discharge inception voltage. When gas pressure exceeds a certain value, the diffusion of space charge is restrained and the volume of corona is significantly compressed, so the stabilization of space charge effect is reduced. This leads the rise rate of breakdown voltage decrease, even the breakdown voltage would decrease with the rise of gas pressure. In another words, the maximum of breakdown voltage V_{Bm} appears. When gas pressure exceeds



(a) R=4mm



(b) R=2mm



(c) R=1mm

Fig. 5. Breakdown voltage and discharge inception voltage as a function of gas pressure under power frequency voltage with R=4mm, R=2mm and R=1mm rod-plane electrodes.

the critical value, the partial discharge could hardly occur before breakdown. Due to the invalidation of space charge effect, the corona leads to breakdown immediately. So the characteristic of breakdown voltage is same with that of partial discharge inception voltage. If the electric non-uniformity enhanced, the inception voltage of corona is lower and the diffusion of space charge is more significant. So the more uniform distribution of space charge could improve the electric field significantly, and the stabilization effect of space charge would be enhanced. That is why the amplitude of N-curve

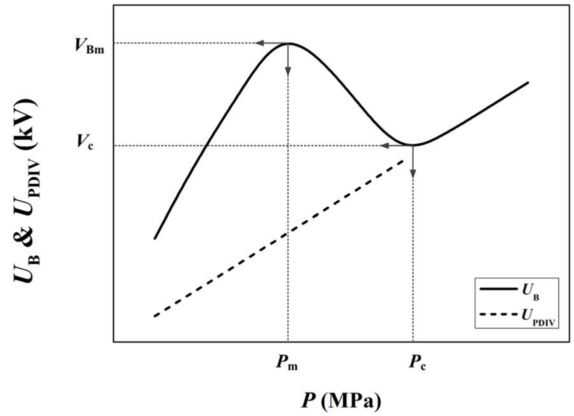


Fig. 6. The definition of N-shape characteristic.

increases, and the space charge could be restrained at higher gas pressure which makes the range of N-curve expanded.

IV. Conclusion

The breakdown and partial discharge inception voltage characteristics of SF_6/N_2 gas mixtures in different electric field non-uniformity under power frequency voltage were studied in this paper. The results indicate that the breakdown voltage of SF_6/N_2 gas mixtures increases linearly with increase of gas pressure in slightly non-uniform electric field. With increase of the electric field non-uniformity, the saturated trend of breakdown voltage of SF_6/N_2 gas mixtures appears. When electric field non-uniformity exceeds a certain value, the stable corona discharge appears before the electric breakdown of electrodes gap. Because of the space charge effect, the N-curve characteristic of breakdown voltage appears in SF_6 and SF_6 mixtures. And the amplitude and range of N-curve extend when electric field non-uniformity increased.

Acknowledgment

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