Influence of Trace SF_6 on Discharge Characteristics of SF_6/N_2 Gas Mixture under Lightning Impulse

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***Abstract-* As one kind of synergistic effect gas, the discharge characteristics of SF_6/N_2 gas mixtures would be influenced significantly by trace amounts of SF_6. That is, the discharge characteristics of pure N_2 is quite different from that of SF_6/N_2 gas mixtures with relatively low content of SF_6. For the application of SF_6/N_2 gas mixtures in power system equipment, this paper studied on the discharge characteristics of SF_6/N_2 gas mixtures with low SF_6 mixing ratio in extremely non-uniform electric field under positive and negative lightning impulse. Meanwhile, the characteristic of SF_6/N_2 gas mixtures were compared with that of pure N_2 and SF_6. The experimental results indicate that the 50% breakdown voltage increases linearly with the rise of gas pressure under negative lightning impulse, and the rising rate of breakdown voltage with pure N_2 is greater than SF_6/N_2 gas mixtures even greater than pure SF_6 gas. At high gas pressure, the 50% breakdown voltage of pure N_2 is higher than that of SF_6/N_2 gas mixtures, that is to say, the negative synergistic effect appeared. Under positive lightning impulse, the influence of gas pressure on 50% breakdown voltage is weaker, but the N-curve characteristic appeared because of the effect space charge. Meanwhile, the negative synergistic effect also appeared under positive lightning impulse at high gas pressure. The experimental results indicate that the breakdown time delay of pure N_2 is much longer than that of SF_6/N_2 gas mixtures with 1% SF_6 mixing ratio because of the obvious difference between the formative time delay of N_2 and SF_6/N_2 gas mixtures. The phenomenon of breakdown time delay demonstrates that the discharge form of N_2 is different from that of SF_6/N_2 gas mixtures, that is to say, the streamer propagation changes to streamer-leader propagation.**

I. INTRODUCTION

Because of the excellent insulation characteristic and significant arc extinction property, SF_6 has become one of the most widely used insulation medium. Due to the extensive use of SF_6 gas in power system as insulation medium, its negative impact on the environment is increasingly serious because of its greenhouse effect. So there is no doubt that the consumption of SF_6 gas should be restricted [1]. Another disadvantage of SF_6 is the weakening of insulation property with the increase of electric field non-uniformity, which increases the difficulty of power equipment manufacture. In addition, there is a great demand for SF_6 gas as insulation medium in gas insulated metal-enclosed transmission lines (GIL), which would raise the cost considerably.

Considering the difficulty of searching single pure gas as replacement of SF_6, SF_6/N_2 gas mixtures which have been applied in power system equipment such as GIL has become a proper choice as alternating gas [2]. SF_6/N_2 gas mixtures as insulation medium are the symbol of the second generation GIL. The synergistic effect is one of the most remarkable characteristics of SF_6/N_2 gas mixtures, that means the insulation strength of SF_6/N_2 gas mixtures with relatively low mixing ratio is considerable [3].

The researches of discharge characteristics with SF_6/N_2 gas mixtures were started since 1970s. In uniform electric field, the breakdown characteristics with steady state voltage were studied systematically, and the synergistic effect is significant [4,5]. On the other hand, fewer researches about discharge characteristics with SF_6/N_2 gas mixtures under lightning impulse were put forward [6,7]. And the difference of discharge characteristics between positive and negative polarities of lightning impulse is rarely mentioned. In addition, the discharge characteristics were more complicated in non-uniform electric field, and the synergistic effect of SF_6/N_2 gas mixtures in non-uniform electric field was not investigated intensively.

This paper studied on the discharge characteristics of SF_6/N_2 gas mixtures with low SF_6 mixing ratio in extremely non-uniform electric field under positive and negative lightning impulse. The phenomenon of negative synergistic effect appeared with the experimental results. In order to investigate the discharge mechanism of negative synergistic effect, the characteristics of breakdown time delay were studied with pure N_2 and 1% SF_6/N_2 gas mixtures. The research result could guide the application of SF_6/N_2 in power system equipment like GIL, and is conducive to understanding the synergistic effect mechanism of SF_6/N_2 gas mixtures.

II. EXPERIMENTAL SETUP

A. Experiment System

In order to study the discharge characteristics of SF_6/N_2 gas mixtures under lightning impulse via electric parameter and optical parameter, an optical-electric combination experiment device was set up in the laboratory. The optical-electric combination experiment device is consist of five parts, respectively is: Marx generator, test chamber, electric measurement system, optical measurement system and gas circuit system. The integral structure of optical-electric combination experiment device is shown in Fig.1.

The experimental electrodes in this paper are needle-plane electrodes, which represent the strongly non-uniform electric field, as shown in Fig. 2. The radius curvature of needle electrodes shown in Fig. 2 is 0.5mm, and the gap between needle electrode and Rogowski plane electrode is 20mm. The

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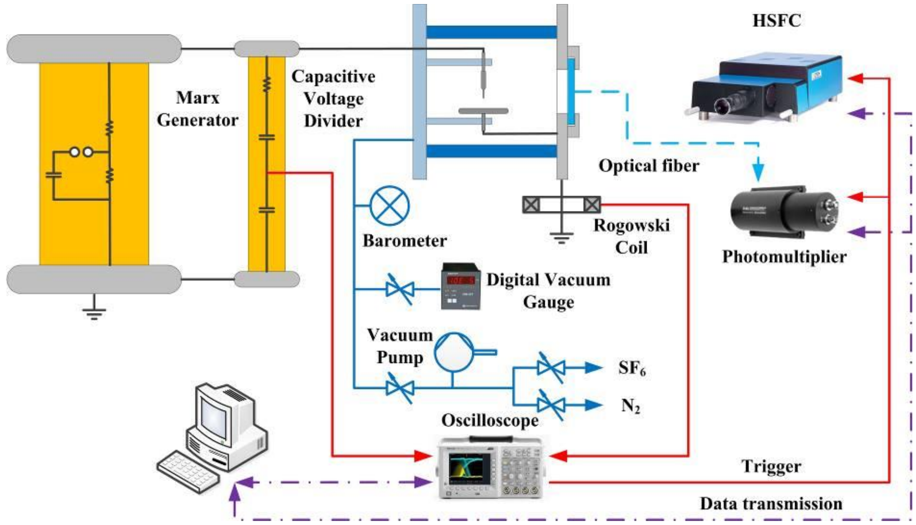


Fig. 1. Optical-electric combination experiment device

material of electrodes is stainless steel because of its great ablation resistance. The electric field non-uniform coefficient *f* was calculated as 26.9 through the simulation result with Ansoft. It represents the typical strongly non-uniform electric field which simulates the local electric field enhancement in GIS or GIL.

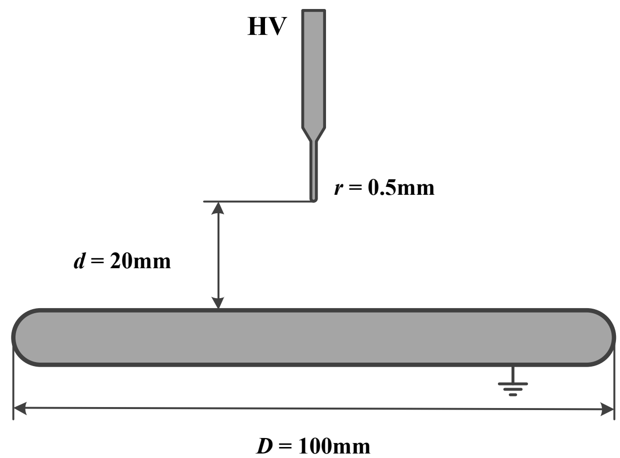


Fig. 2. Experimental electrodes.

B. Experimental Method

The experimental gas is prepared according to Dalton's law of partial pressures. The standing time of experimental gas mixtures before experiment is 24 hours, which would make the experimental gas mixtures mixed completely. The content of SF_6 gas is fewer than N_2 gas in the experiment. For improving the accuracy of mixing ratio, SF_6 would be inflated into test chamber first.

The 50% breakdown voltage was obtained by more than 30 times valid tests with Up and down method. Considering the recovery of dielectric strength, the time interval between adjacent tests is no less than 10min. The digital oscilloscope (Tektronix DPO4104) was applied to record the experimental results.

III. Experimental Results

A. Negative Synergistic Effect of SF_6/N_2 Gas Mixtures in Non-uniform Electric Field

Fig. 3 shows the relationship between 50% breakdown voltage and gas pressure with different mixing ratio under lightning impulse. It can be seen that the N-curve characteristic appeared with SF_6/N_2 gas mixtures under positive lightning impulse, especially with 1% mixing ratio. The breakdown voltage of pure N_2 increases slightly with the rise of gas pressure under positive lightning impulse. The results are quite different from the breakdown characteristics in slightly non-uniform electric field. It demonstrates that the influence of gas pressure on breakdown voltage weakened with increase of electric non-uniformity to some extent. Under negative lightning impulse, the breakdown voltage of three kinds of gas increases obviously with the rise of gas pressure, and N-curve characteristics would not appear. The reason for that phenomenon is the time for migration and diffusion of space charge is short because of the short breakdown time delay under lightning impulse, which makes the N-curve characteristic weaker than that under steady state voltage. Meanwhile the N-curve characteristic would appear at lower gas pressure. Under negative lightning impulse, the radius of streamer corona is larger than that under positive lightning impulse, which is similar to the increase of radius of electrode curvature. That means the N-curve characteristic would appear earlier under positive lightning impulse with the increase of gas pressure. And the breakdown voltage would increase significantly in a wide range of gas pressure because of space charge under negative lightning impulse.

The electric field non-uniformity plays a vital role in impacting the 50% breakdown voltage. The initial electron occurs quite easily in strong non-uniform electric field, and streamer is easy to transform to leader propagation, which

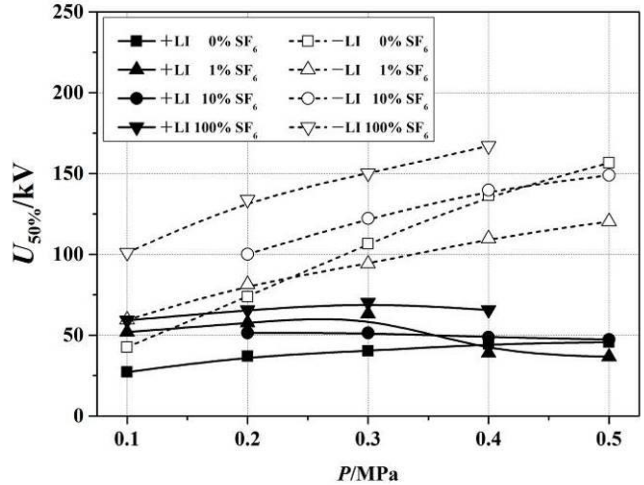


Fig. 3. The relationship between 50% breakdown voltage and gas pressure under lightning impulse

leads to lower breakdown voltage of gas. The mean free path decreases with the rise of gas pressure, so the improvement influence on breakdown voltage would weaken remarkably. Considering the smaller radius of streamer corona under positive lightning impulse, the charge density is more concentrated in the streamer channel, which leads to the easier appearance of leader from streamer. So the breakdown voltage under positive lightning impulse would hardly be affected by gas pressure. The analysis is in accordance with the result which the rise rate dU/dP under negative lightning impulse is higher than that under positive polarity shown in Fig. 3. It can be seen that the breakdown voltage of SF_6/N_2 gas mixtures is lower than that of pure N_2 at high gas pressure. That is, the negative synergistic effect appears. Add trace of SF_6 into N_2, the breakdown voltage would decrease obviously at 0.5MPa, which is different from that in slightly non-uniform.

B. Discharge Time Delay of SF_6/N_2 gas mixtures in Non-uniform Electric Field

Fig. 3 illustrates that the negative synergistic effect appeared, that is, the influence of trace SF_6 on discharge characteristics of SF_6/N_2 gas mixtures is significant. In order to investigate the mechanism of negative synergistic effect, the discharge time delay of SF_6/N_2 gas mixtures and pure N_2 as an important parameter of gas discharge under lightning impulse voltage was studied and compared with that of pure N_2 in this paper.

Discharge time delay t_d is consist of voltage rise time delay t_0, statistical time delay t_s and formative time delay t_f. The probability of discharge occurrence with interval [0,t] is shown as [8]:

$$P(0,t)=\frac{1}{\bar{t}_s}\int_0^t e^{-\frac{t_s}{\bar{t}_s}}\left\{\frac{1}{\sigma\sqrt{2\pi}}\cdot\int_{t_s}^t e^{-(t-t_s-\bar{t}_f)^2/2\sigma^2}\mathrm{d}t\right\}\mathrm{d}t_s \qquad (1)$$

Where, $\bar{t}_s$ represents the average statistical time delay; $\bar{t}_f$ and σ^2 represent the average and variance of formative time delay.

Though the cumulative probability of discharge $P(t,\infty)$ in (1) with logarithmic coordinates is different from that when the formative time delay is constant, the average statistical time delay and the average formative time delay could be obtained by the relationship between $P(t,\infty)$ and t. When the average statistical time delay is greater than average formative time delay, the distribution of cumulative probability tends to exponential distribution. When the average statistics time delay is much less than average discharge form delay, the distribution of cumulative probability tends to normal distribution.

If the statistical time delay accounts for the main body of the breakdown time delay, the breakdown time delay would follow the exponential distribution roughly. Thus the statistics time delay and formative time delay could be obtained via Laue plot. According to the experimental results, the discharge time delay of SF_6/N_2 gas mixtures is relatively short, so the statistical time delay is comparable. That is, the Laue plot is appropriate for analyzing the discharge time delay of SF_6/N_2 gas mixtures. As for pure N_2, the discharge time delay is much longer than the statistical time delay. So the statistics time delay and formative time delay could not be obtained through Laue plot. In this paper, the phenomenon of the first streamer corona burst can be observed near the tip of needle electrode through photomultiplier tube (PMT), and the corresponding time delay is longer than statistical time delay. Considering the time delay of the first streamer corona burst is short enough, and streamer corona would burst would follow the appearance of initial electron immediately, the time delay of the first streamer corona burst was treated as the statistical time delay. Fig. 4 shows the typical figure of first streamer corona via PMT. Based on the assumption that the statistical time delay is constant which equals the time delay of first streamer corona burst, the discharge time delay would follow the normal distribution. The average is the sum of the statistical time delay and formative time delay (ignoring the voltage rise time delay).

The discharge time delay characteristics of 1% SF_6/N_2 gas mixtures and N_2 under positive and negative lightning impulse were shown as Fig. 5. It can be seen, the formative time delay

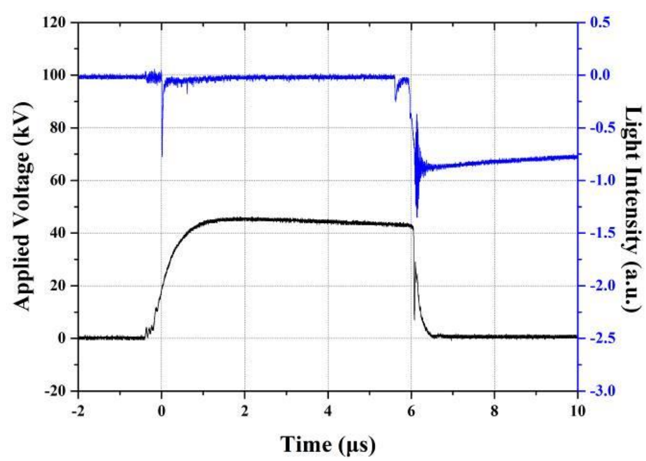
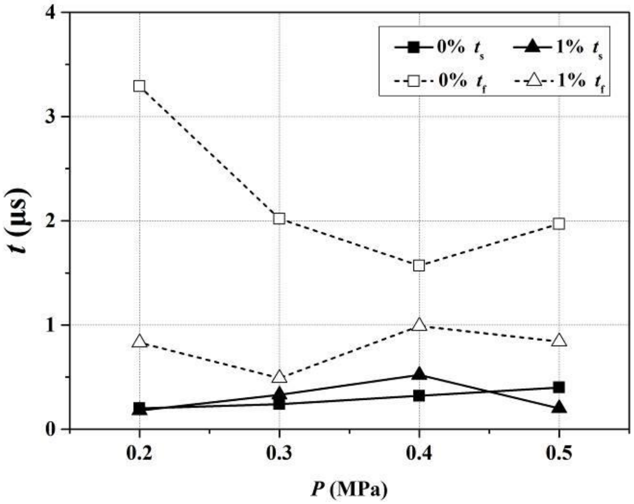
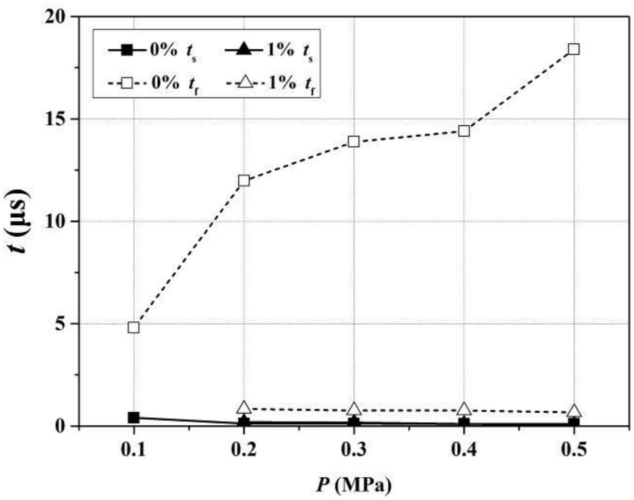


Fig. 4. The first streamer corona burst of pure N_2 under positive lightning impulse via PMT



(a) Positive lightning impulse



(b) Negative lightning impulse

Fig. 5. The discharge time delay characteristics of pure N_2 (0%) and 1% SF_6/N_2 gas mixtures under positive and negative lightning impulse

of pure N_2 is quite long, and would decrease significantly by adding trace of SF_6 into N_2. The difference is more remarkable under negative lightning impulse. The results demonstrate that the distinction of discharge propagation exists between two types of gases.

Considering the electronegative of SF_6, the discharge propagation should be hindered to some extent. However, the formative time delay of pure N_2 is much longer than that of SF_6/N_2 gas mixtures. It can be judged that the discharge form would transform by adding trace of SF_6. The discharge form is streamer propagation in pure N_2, and the formative time delay is long for formation of streamer. Add trace of SF_6, the streamer propagation would transform to streamer-leader step propagation. The appearance of leader leads to the acceleration of discharge propagation. That is why the formative time delay shortens significantly. The transformation of discharge form would probably cause the negative synergistic effect in non-uniform electric field.

IV. Conclusions

In this paper, the discharge characteristics of SF_6/N_2 gas mixtures with low mixing ratio in non-uniform electric field under lightning impulse were studied. The results demonstrate that the negative synergistic effect appears, that is the breakdown voltage of pure N_2 is higher than that of SF_6/N_2 gas mixtures at high gas pressure. In addition, the discharge time delay was analyzed through Laue plot and PMT. The analysis results indicate that the formative time delay of N_2 is much longer than that of 1% SF_6/N_2 gas mixtures. That is to say, the streamer propagation with N_2 transforms to streamer-leader step propagation by adding trace of SF_6.

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