Negative Synergistic Effect of SF_6/N_2 Gas Mixtures in Non-uniform Electric Field Under Lightning Impulse

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ABSTRACT

In recent years, SF_6/N_2 binary mixtures have been used as insulation in second generation gas-insulated metal-enclosed transmission lines mainly because of the greenhouse effect and diseconomy of SF_6. Though the synergistic effect of SF_6 is known in a uniform electric field, there is little understanding of the synergistic effect phenomenon with parameters in a non-uniform electric field under standard lightning impulse. A series of experiments were designed to increase our knowledge of this and the breakdown characteristics of SF_6/N_2 under multiple parameters show a negative synergistic effect. Our experimental results with negative lightning impulse demonstrated that the breakdown voltage of N_2 increased greater than with both SF_6 and its mixtures with increasing gas pressure. When the gas pressure exceeded 0.3MPa, the breakdown voltage of pure N_2 was higher than SF_6/N_2 gas mixtures and even exceeded the value of SF_6 at 0.5MPa. A normalization coefficient *h* was introduced in this research to evaluate the negative synergistic effect. Under negative lightning impulse the analytical results show that the negative synergistic effect increased with the augment of gas pressure. On the other hand, the synergistic effect was reduced with decreasing gas pressure under positive polarity impulse and it appeared to be a negative synergistic effect with the enhancement of field non-uniformity. The analysis of streamer discharge propagation indicates three reasons lead to the negative synergistic effect: similar streamer corona onset voltage, different space charge effect, and dissimilar discharge form of N_2 and SF_6/N_2 gas mixtures.

Index Terms — **negative synergistic effect, SF_6/N_2 gas mixtures, lightning impulse, normalization coefficient, space charge, streamer, leader**

1 INTRODUCTION

CURRENTLY, SF_6 is used as insulation in electric power system equipment and mainly because of its high dielectric strength, excellent arc extinguishing performance, and good chemical stability. However, this medium is harmful to the environment as it is an extremely potent greenhouse gas and the detrimental effect on the environment is increasing with increase in SF_6 consumption. According to the Kyoto Protocol in 1997, the consumption of SF_6 should be limited [1,2]. Another disadvantage of SF_6 is that its insulation performance is strongly influenced by non-uniform electric field. The effective ionization coefficient of SF_6 increases with increasing electric field; i.e., the dielectric property reduces with enhancement of the electric field. Also, the cost is high to use pure SF_6 in gas insulated metal-enclosed transmission lines (GIL) because of the large amount of SF_6 [3].

It is currently difficult to find a single gas to replace SF_6 and SF_6 gas mixtures have become a possible solution [4,5]. Corresponding characteristics of binary gas mixtures are variable based on insulation properties and mixing ratios, with both positive and negative synergistic effects [6,7]. SF_6/N_2 is one type of binary gas mixture with synergistic effects that are beneficial that may reduce SF_6 consumption [8]. SF_6/N_2 has promising applications as the purification of N_2 is simple and creates less pollution.

Research on gas mixtures SF_6 has been extensive since the 1970s and the breakdown characteristics of SF_6/N_2 under steady state voltage with a uniform electric field have been systematically studied, and the synergistic effect of these conditions has been analyzed in depth [9-11]. It is known that the breakdown voltage is related to the free electron spectrum breakdown temperature and the synergistic effect is affected by various factors such as waveform parameters [12, 13]. The discharge characteristics of SF_6/N_2 under lightning impulse has also been examined [14,15]. The synergistic effect of SF_6/N_2 is remarkable in a uniform electric field, but

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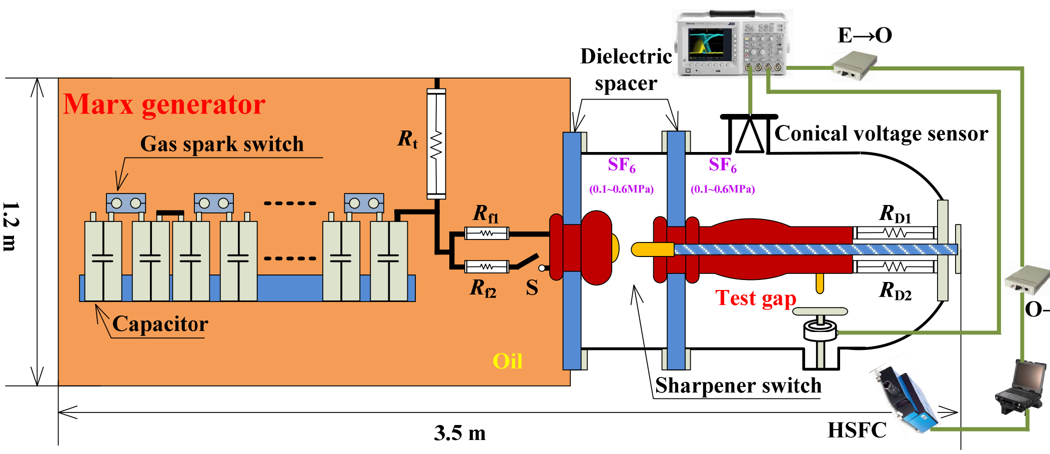

Figure 1. Structure of standard lightning impulse experiment platform.

characteristics of the synergistic effect in non-uniform electric fields are more complicated and poorly understood.

SF_6/N_2 has already been used in the second generation GIL, and the mixing ratio of SF_6 in GIL can range from 5~30% [16]. These issues require investigation on discharge characteristics of SF_6/N_2 with such mixing ratios.

The objective of this research was to focus on the discharge characteristics of SF_6/N_2 in a highly non-uniform field under lightning impulse.

2 EXPERIMENTAL SETUP

2.1 SYSTEM

A fully enclosed experimental platform was set up in the laboratory to simulate the actual structure of GIL to investigate discharge characteristics of SF_6/N_2 under lightning impulse. As shown in Figure 1, the Marx generator, immersed in transformer oil, generates standard or non-standard lightning impulse by adjusting the wave front resistor, wave tail resistor and sharpener switch. The test gap between high voltage bus and test chamber can simulate slight-to-highly non-uniform electric fields.

The experimental measurement system showed in Figure 2 consists of three parts: conical voltage sensor, coaxial integrator and digital oscilloscope. A double shielded cable was used to connect the coaxial integrator and oscilloscope [17]. This measurement system has great response characteristic within 5ns, and the combined measurement uncertainty is less than 5% [18,19].

Needle-plane electrode system was chosen as the experimental electrodes in this research which represent the highly non-uniform electric field simulating a protrusion on high voltage bus in GIL. The electrodes, shown in Figure 3, are stainless steel which has a good ablation resistance. The radius curvatures of needle electrodes are 2 and 1 mm, respectively. In addition, the plane electrode is designed as a Rogowski electrode with a 300 mm diameter. The distance between needle and plane electrodes is 33 mm. According to simulation by Ansoft, the non-uniform coefficient f (defined as the ratio of maximum electric field strength E_{max} to the average electric field strength E_{av}) was 14.0 and 24.3, respectively.

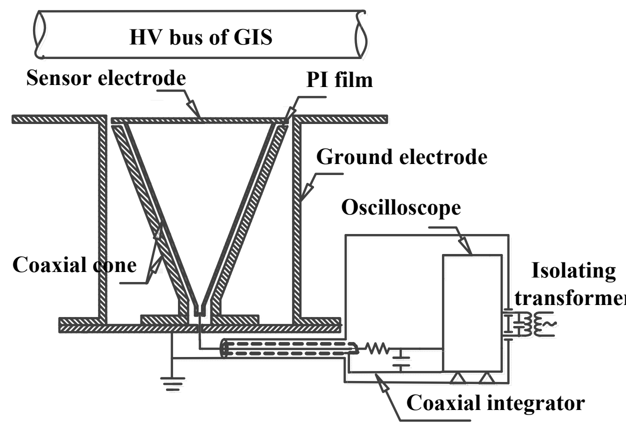

Figure 2. Structure of experiment measurement system.

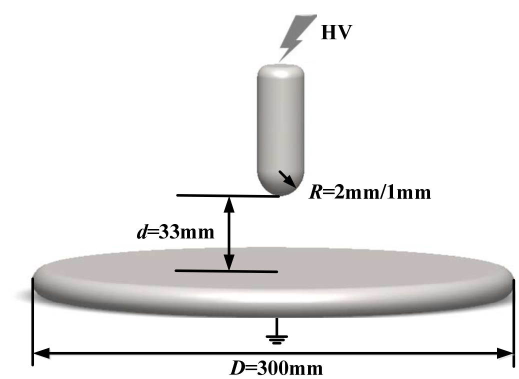

Figure 3. Arrangement of experimental electrodes.

2.2 METHOD

First, the experimental chamber was placed under vacuum and then filled with pure N_2 gas and left for more than 12 hours to dry the chamber. Next, the chamber was reduced to less than 100 Pa and then filled with the experimental gas. Both SF_6 and N_2 were both treated as ideal gases within experimental conditions, meaning that Dalton's law was applicable to determine gas concentrations of mixing ratios [8, 20]. Dalton's law is as follows:

$$\frac{n_A}{n_B} = \frac{P_A}{P_B} \tag{1}$$

where n represents the moles of pure gas and P is the partial pressure of each gas.

The chamber was first filled with the lower content gas (SF_6) to ensure accurate control of mixing ratios [20] and the experiments on the gas mixtures were initiated after 24 hours.

The experiments were conducted using the up-and-down method. The 50% breakdown voltage under standard lightning impulse was calculated from more than 30 replications of valid test values. Considering the dielectric strength recovery of gas mixtures, the time interval between adjacent experiments was no less than 10 min. Tektronix digital oscilloscope (model DPO4104) was connected to a central control computer via fiber to record the output waveform.

3 RESULTS

3.1 BREAKDOWN CHARACTERISTICS INFLUENCED BY GAS PRESSURE

The experimental breakdown results using R=2 mm needle-plane electrodes are documented in [27]. The research described here is a comprehensive examination of the negative synergistic effect in a highly non-uniform electric field and the relevant discharge characteristics are documented. Figure 4 shows the 50% breakdown voltage of SF_6/N_2 gas mixtures with gas pressure with R=2 mm needle-plane electrodes. The results demonstrate that the breakdown voltage of has a linear correlation with gas pressure under positive impulse and no N shape characteristic is seen [21]. This result demonstrates that the influence of space charge is weak, and there is no significant corona stabilization effect.

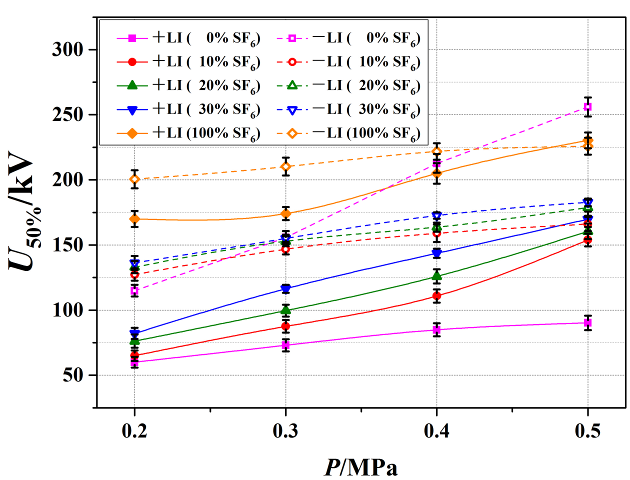

Figure 4. The relationship between 50% breakdown voltage and gas pressure under lightning impulse with R=2 mm needle-plane electrodes

Figure 4 also shows that the 50% breakdown under positive lightning impulse voltage of SF_6/N_2 increases as with increasing SF_6 content. But the experimental result is unlike that in a quasi-homogeneous electric field; dU/dP changes little with variation of mixing ratio in the non-uniform electric field. In a quasi-homogeneous electric field, dU/dP increases as the concentration of SF_6 increases due to increasing $(E/P)_0$ [22]. In addition, the value of dU/dP in a quasi-homogeneous electric field is more obvious than that in highly non-uniform electric field. In a quasi homogeneous electric field, dU/dP of the gas mixtures ranges from 130 to 160 kV/bar, and is about 50 kV/bar for pure N_2 gas [23, 24]. In highly non-uniform electric fields, dU/dP of gas mixtures ranges from 20 to 40 kV/bar, and is just 10 kV/bar for pure N_2 gas. These values indicate that the increase of electric field non-uniformity weakens the influence of gas pressure on the breakdown voltage. The local electric field concentration has a significant effect on the breakdown voltage. For example the initial electron is generated easily, and a streamer is more likely to transform to leader in highly non-uniform electric fields, resulting in a significant reduction in the breakdown voltage. This relationship demonstrates that the decrease in the mean free path with the augment of gas pressure has little contribution to the increase in breakdown voltage.

The breakdown voltage versus gas pressure presents a significant tendency of saturation under negative lightning impulse, especially for pure SF_6. The breakdown voltage of SF_6/N_2 gas mixtures with low SF_6 concentrations is not close to the value for pure SF_6 gas; a different relationship from that in quasi homogeneous electric field. That relationship indicates that the synergistic effect is weak. It is worth noting that the 50% breakdown voltage of pure N_2 gas is higher than the value of gas mixtures when the gas pressure exceeds 0.3 MPa, and even higher than the value of pure SF_6 when gas pressure is 0.5 MPa, indicating a negative synergistic effect. The dU/dP of pure N_2 gas is 50 kV/bar, significantly higher than the value of SF_6/N_2 and the value of dU/dP approaches the corresponding value in a quasi homogeneous electric field, but it is greater than that value under positive polarity.

Figure 5 illustrates the relationship between the 50% breakdown voltage of SF_6/N_2 gas mixtures and gas pressure with R=1 mm needle-plane electrodes. It indicates that the breakdown voltage of SF_6/N_2 is linearly correlated with gas pressure under lightning impulse. Also, dU/dP of gas mixtures is around 10 kV/bar with different mixing ratios under positive polarity impulse, dissimilar to the value with R=2 mm needle-plane electrodes. The breakdown voltage of N_2 is higher than the breakdown voltage value of SF_6/N_2 with low mixing ratio. This relationship may be due to the transformation to leader with the intensification of the electric field. Non-uniformity leads to the reduction of breakdown voltage of gas mixtures, similar to the situation with R=2 mm rod-plane electrodes under negative polarity. The characteristics of breakdown are similar for negative lightning impulse to that with R=2 mm needle-plane electrodes under negative polarity, but the breakdown voltages are closer with different percentages of SF_6. The synergistic effect is weaker, and the negative synergistic effect appears at a lower gas pressure.

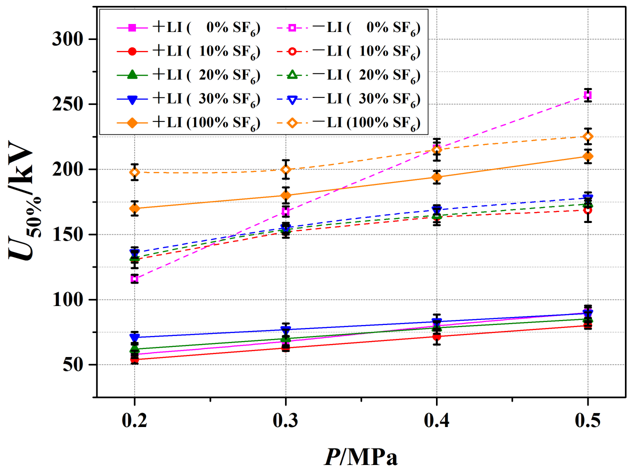

Figure 5. The relationship between 50% breakdown voltage and gas pressure under lightning impulse with R=1 mm needle-plane electrodes.

3.2 BREAKDOWN CHARACTERISTICS INFLUENCED BY MIXING RATIO

The relationship between the 50% breakdown voltage of SF_6/N_2 and mixing ratio under lightning impulse with R=2 mm needle-plane electrodes is shown in Figure 6. The synergistic effect under positive polarity impulse is clearly noted at relatively high gas pressure. For example, the breakdown voltage of SF_6/N_2 with 10% mixing ratio is more than 1.7 times the voltage of pure N_2 gas at 0.5 MPa. The synergistic effect obviously weakens when gas pressure is decreased, and starts to transform to the linear relationship. A negative, weak synergistic effect appears at 0.2 MPa. The characteristics are more complicated for negative lightning impulse. The synergistic effect can hardly be observed, and the negative synergistic effect appears obviously when gas pressure exceeds 0.2 MPa. This result means that the breakdown voltage of gas mixtures is lower than the corresponding value in a linear relationship. These results demonstrate that the sensitivity of SF_6 to the non-uniformity of the electric field which is not necessarily reduced by adding N_2 gas. It is important to note that the insulation strength of pure N_2 gas is greater than this property for SF_6 gas with high gas pressure under negative lightning impulse.

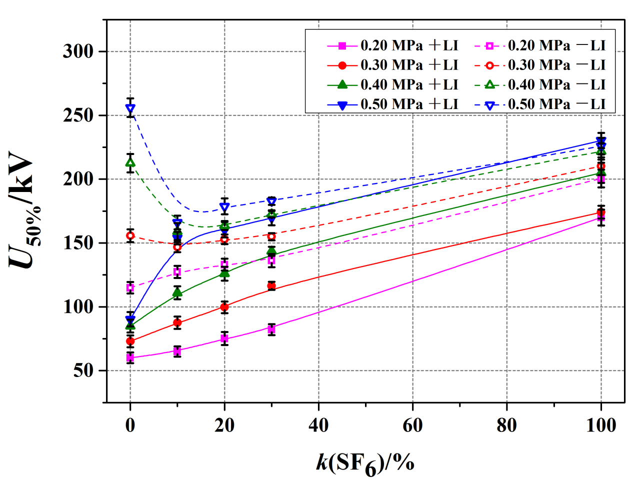

Figure 6. Breakdown voltage versus mixing ratio under lightning impulse with R=2 mm needle-plane electrodes.

The breakdown voltage of SF_6/N_2 versus mixing ratio under positive and negative lightning impulse with R=1 mm needle-plane electrodes (Figure 7) demonstrates that the negative synergistic effect is weak with different gas pressures. It also shows that the sensitivity of SF_6 to the non-uniformity of the electric field does not decrease by adding N_2 gas. This is in addition to the intensification of the electric field non-uniformity. The breakdown voltage of SF_6 with R=1 mm needle-plane electrodes is very similar to the value with R=2 mm under positive polarity (Figure 6). The breakdown voltage of gas mixtures with low content of SF_6 decreases significantly with the enhancement of the electric field non-uniformity, leading to the negative synergistic effect. The phenomenon with R=1 mm needle-plane electrodes under negative polarity shown in Figure 7 is similar to the R=2 mm, illustrating that the negative synergistic effect is significant at high gas pressures.

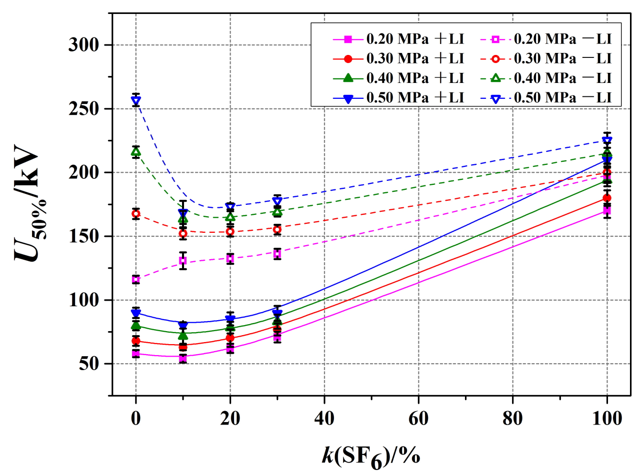

Figure 7. Breakdown voltage versus mixing ratio under lightning impulse with R=1 mm needle-plane electrodes.

4 DISCUSSION

4.1 NORMALIZATION COEFFICIENT H

The synergistic effect coefficient C is widely used in the evaluation and analysis of the synergistic effect [25, 26]. This method on evaluating the synergistic effect and linearity is effective. However, this method can neither be used in evaluating the negative synergistic effect nor under the condition that the difference in breakdown voltage between the two gas compositions is relatively small, in which case the error of synergistic effect coefficient C would increase significantly. Considering the limitation of the method mentioned above, the normalization coefficient h was used for evaluating the negative synergistic effect of SF_6/N_2 gas mixtures in this paper [27]. The definition of this normalization coefficient h, Equation (2):

$$h = \frac{(U_m - U_2) - k(U_1 - U_2)}{0.5(U_1 + U_2)} \quad 0 < k < 1 \tag{2}$$

$$h = 0 \quad k = 0 \text{ or } 1$$

The breakdown voltages of gas mixtures compositions are expressed as U_1 and U_2, where U_m represents the breakdown voltage of the binary gas mixture and k represents the mixing ratio which is the content of pure gas. If h=0, the relationship between U_m and k would be linear. The value of h represents the degree of the synergistic effect, which means the synergistic effect exists if h>0 and a negative synergistic effect exists if h<0. Based on the normalization coefficient h, the synergistic effect of gas mixtures in different conditions can be normalized and compared.

The normalization coefficient h for R=2 mm needle-plane electrodes is calculated and shown in Figure 8. Under positive polarity impulse, the synergistic effect is enhanced with gas pressure, and a weak negative synergistic effect can be observed at 0.2 MPa. In contrast to the result shown in Figure 6, the degree of the synergistic effect in different gas pressures, or mixing ratios, can be obtained intuitively. As shown in Figure 8, the negative synergistic effect is significant at high gas pressure under negative polarity impulse. However, the degree of the negative synergistic effect would be enhanced with increasing gas pressure according to the decrease of h. The normalization coefficient h is basically zero at 0.2 MPa, which means a linear relationship exists.

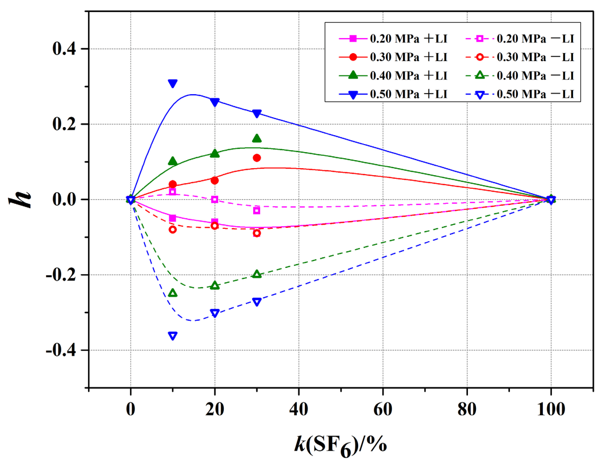

Figure 8. Normalization coefficient h versus mixing ratio with R=2 mm needle-plane electrodes.

Figure 9 shows the normalization coefficient h of R=1mm needle-plane electrodes. The negative synergistic effect can be observed obviously in SF_6/N_2 under positive impulse, and its degree is hardly relevant to the gas pressure. The characteristics of normalization coefficient h with R=1mm needle-plane electrodes is similar to that R=2mm under negative polarity, which means the negative synergistic effect becomes more significant as gas pressure increases, and the linear relationship appears at 0.2MPa. The results indicate that the gas discharge process of SF_6/N_2 under two polarities is quite different, and it affects the change of the synergistic effect significantly.

4.2 NEGATIVE SYNERGISTIC EFFECT

The negative synergistic effect is shown to exist with SF_6/N_2 in a highly non-uniform electric field. This draws the conclusion that dU/dP of pure N_2 gas is much greater than that of SF_6 and its mixtures under negative lightning impulse. This phenomenon can be illustrated in three aspects, streamer corona onset, space charge, and discharge form respectively.

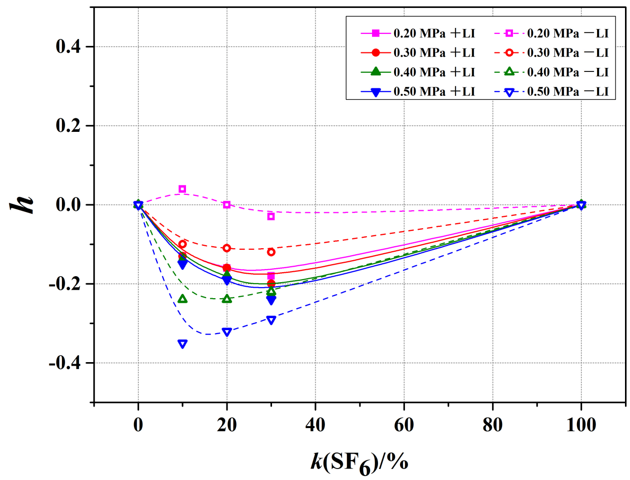

Figure 9. Normalization coefficient h versus mixing ratio with R=1 mm needle-plane electrodes.

First of all, the growth rate of effective ionization coefficient $\overline{\alpha}$ in SF_6 gas is greater than N_2 with the enhancement of the electric field non-uniformity. Equation (3) and Equation (4) show the effective ionization coefficients $\overline{\alpha}$ of SF_6 and N_2 separately. N_2 gas is a non-electronegative gas ($\eta = 0$) and its ionization coefficient α equals to the effective ionization coefficient $\overline{\alpha}$ in pure N_2 [22, 28].

$$\frac{\overline{\alpha}}{P} = 27.7\left(E/P - 88.5\right) \tag{3}$$

$$\frac{\alpha}{P} = 6600\exp\left[-215/\left(E/P\right)\right] \tag{4}$$

The unit of $\frac{\overline{\alpha}}{P}$ and E/P is $\mathrm{mm \cdot MPa^{-1}}$ and $\mathrm{kV \cdot (mm \cdot MPa)^{-1}}$, respectively. Considering the ionization energy of SF_6 is approximately equal to N_2, the effective ionization coefficient of SF_6/N_2 $\overline{\alpha}_m$ can be calculated using Equation (5) [28].

$$\overline{\alpha}_m / p = k\left(\overline{\alpha}_{SF6} / p\right) + \left(1-k\right)\left(\alpha_{N2} / p\right) \tag{5}$$

Based on Equations (3) to (5), the partial discharge inception voltages of these gases are similar in highly non-uniform electric field. By the same token, the streamer corona onset voltage defined as U_{st} of SF_6/N_2 is close to that of N_2.

Clearly, U_{st} is proportional to the gas pressure P, which means the slope of U_{st}-P in SF_6/N_2 gas mixtures is higher and close to that of N_2. On the other hand, the effect of space charge on the discharge process is distinct in different situations. The diameter of the SF_6 molecule is large, and the molecular weight is much greater than N_2. Compared to N_2, the drift rate of ions generated by SF_6 ionization or electron attachment is lower, and the drive speed is lower as well. Thus, under high gas pressure, the space charge around the needle electrode is difficult to form as a homogeneous space charge layer, which can improve the distribution of the electric field near the needle electrode. On the contrary, ions ionized by N_2 can drift and diffuse outward easily because of their lighter mass, leading to a larger stable space charge layer, which demonstrates the improvement of the electric field distribution would be more effective over a wide range of gas pressures. That explains the N-curve characteristic of pure N_2 that appears at a higher gas pressure. In order to illustrate the difference between the space charge of SF_6 and N_2, the radius of the streamer corona is analyzed qualitatively through a theoretical calculation.

The streamer propagates only when the electric field E exceeds the critical value E_{cr} [29]:

$$E \geq E_{cr} \tag{6}$$

For simplicity, the spherically symmetric gap, with sphere electrode of radius r_0 at potential U_0 was used to simulate the actual electrodes structures [30]. Assuming the geometric configuration of the streamer corona is a spherical shell with radius r_c, and the internal electric field is equal to E_{cr}.

$$E \equiv E_{cr} \qquad \text{for} \quad r_0 \leq r \leq r_c \tag{7}$$

The radius of streamer corona could be calculated by the following equations as [26]:

$$U_0 = \int_{r_0}^{r_c} E_{cr} dr + \int_{r_c}^{\infty} E(r) dr \tag{8}$$

$$r_c = 0.5(\frac{U_0}{E_{cr}} + r_0) \tag{9}$$

E_{cr} depends on gas pressure and pressure-independent gas property $(E/P)_0$ as follows [28, 31]:

$$E_{cr} = (E/P_0)_0 gP \tag{10}$$

$$\begin{aligned} (E/P_0)_0 &= 88.5\text{kV/(mmgMPa)} && \text{for } SF_6 \\ (E/P_0)_0 &= 20\text{kV/(mmgMPa)} && \text{for } N_2 \\ (E/P_0)_0 &= 56.4\text{kV/(mmgMPa)} && \text{for } 10\%SF_6/N_2 \end{aligned} \tag{11}$$

The critical value $(E/P)_0$ for N_2 is estimated due to the internal electric field in streamer corona, which approximates to 10-20 kV/(mm·MPa). Some of the aforementioned equations are different from the literature [32,33], but the results have shown to be equivalent. It is easy to calculate the streamer corona radius of N_2, which is greater than SF_6 and its mixtures under the same applied voltage. This conclusion agrees to the discussion about space charge above. As the analysis mentioned above is based on a simplified model in steady state, the type and polarity of applied voltage should be discussed.

Under lightning impulse, the voltage rate-of-rise is high, so the migration time of ions is short and that makes the space charge effect between SF_6 and N_2 more evident. As the gas pressure rises, the obstacle to the diffusion of space charge in SF_6 leads to smaller streamer corona radius and more intensive space charge near the needle electrode. This inhibition effect of gas pressure on the diffusion of space charge in N_2 would be weaker than SF_6. It demonstrates that the corona stabilization effect with N_2 is more significant than SF_6 and its mixtures in highly non-uniform electric field. Considering the effect of rise time on space charge, the equivalent action voltage U_e is introduced to replace U_0 in Equation (9):

$$U_e = \frac{\int_{t_{eff}} U(t)\mathrm{d}t}{t_e} \tag{12}$$

$$r_c = 0.5(\frac{U_e}{E_{cr}} + r_0) \tag{13}$$

The effective action time t_{eff} represents the time which the applied voltage affects the formation of space charge. The equivalent action voltage U_e would decrease with shorter wave front time.

The influence of the voltage polarity on this phenomenon is noticeable, as shown in Figure 10. As the polarity of the needle electrode is positive, electrons would enter the needle electrode quickly and positive charge would gather in the head of streamer which abates the electric field of the streamer. This strengthens the electric field in front of the head of streamer, and results in the development of streamer. Compared with the negative polarity impulse, the radial size of streamer corona under positive impulse is much smaller, and the effect of corona stabilization is weaker. As the polarity of needle electrode is negative, the streamer corona would be formed quickly in the area of high electric field near the needle electrode. According to the large number of electron avalanches around tip of the needle electrode, the distribution of streamer corona is dispersive, which gives the same result as increasing the electrode radius of curvature, thereby weakening the electric field in front of the streamer. It also demonstrates a larger radial size of streamer corona under negative impulse, and the effect of corona stabilization is more obvious. That is to say, E_{cr} is higher under negative polarity voltage than positive, and E_{cr} should be modified in Equation (13) according to the applied voltage polarity. Therefore, the corona stabilization effect of SF_6 and N_2 would be weakened under positive polarity, and it also decreases the breakdown voltage of N_2 due to the decreased corona stabilization effect, which explains why the negative synergy effect is inconspicuous under positive impulse.

In addition, gas discharge from N_2 and SF_6/N_2 gas mixtures are much different. As for N_2, due to this small gap distance d (d=3.3 cm), the leader propagation would not appear.

Therefore, the discharge form of pure N_2 is streamer propagation. Meanwhile, the discharge form of SF_6 and its mixtures in non-uniform electric field would change from streamer to leader propagation. Under the current experimental conditions, the streamer-leader propagation was already observed in SF_6/N_2, as shown in Figure 11.

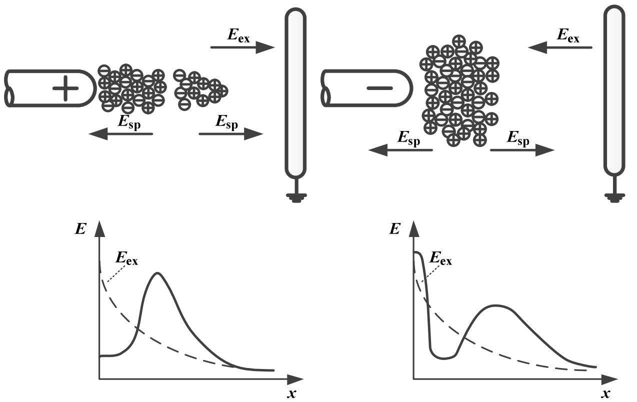

Figure 10. The influence of polarity to the streamer corona radial dimension.

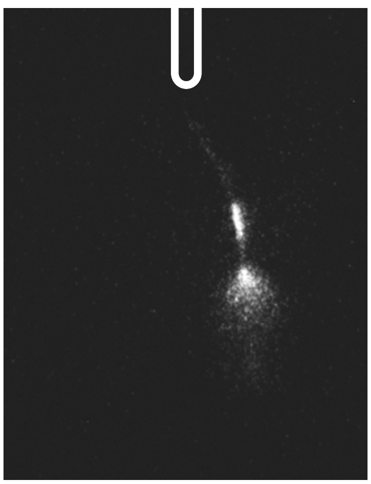

Figure 11. Discharge propagation of SF_6/N_2 under negative lightning impulse with R=1mm needle-plane electrodes.

Figure 11 depicts the discharge propagation of SF_6/N_2 under negative impulse with R=1 mm needle-plane electrodes. The streamer propagation is in the head of discharge channel and it can be seen that there are multiple streamer channels that are dispersed. The leader propagation that can be seen in the middle of the discharge channel is thin and bright. The mechanism of leader inception is the stem mechanism, because that the charge of branched streamer channels feeds into single stem [34].

The distinction of the form of the discharge between N_2 and SF_6/N_2 also can be shown by the discharge time delay and streamer length with different mixing rations of SF_6/N_2. The discharge time delay versus gas pressure with R=1 mm needle-plane electrodes under negative impulse is shown in Figure 12. It is worth noting that the time delay of N_2 is higher than SF_6 and its mixtures, and there is no significant difference between the discharge time delay of SF_6 and its mixtures. The result indicates that the discharge process of N_2 is different from SF_6 and its mixtures. Since the electric field strength at the tip of needle is much higher than the average field, the statistical time delay is short, and the discharge time delay mainly depends on the formation time delay. As for N_2, the breakdown process is completed by the streamer reaching the opposite electrode. The streamer would be affected by the space charge during its growth, which leads to the inhibition of streamer growing forward, so the formation time delay increases. In SF_6 and its gas mixtures, the appearance of leader makes electric field strength of streamer area in front of leader increase, so the speed of streamer growth is accelerated by the electric field. It causes that the formation time delay is significant shorter than N_2 which just depends on the streamer process. So the result of discharge time delay demonstrates the discharge process of N_2 and SF_6/N_2 is certainly different.

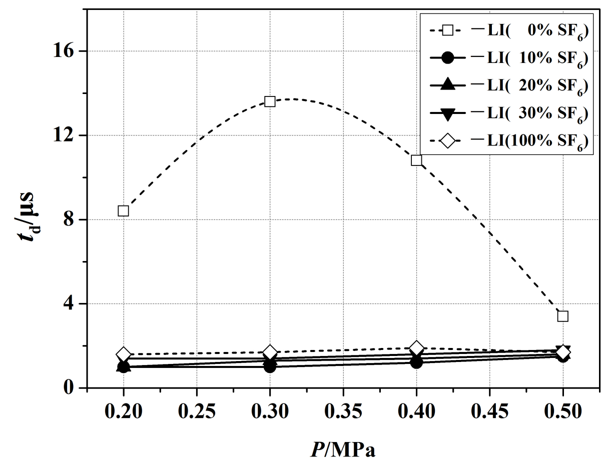

Figure 12. Discharge time delay versus gas pressure with R=1mm needle-plane electrodes under negative lightning impulse.

The maximum length l of streamer could be calculated from the following equation [35]:

$$\int_0^l (E(x) - E_{cr})dx = 0 \tag{14}$$

The length l of streamer with R=1 mm needle-plane electrodes under negative impulse is calculated as an example, which is shown in Figure 13. It is noted that the streamer length of pure N_2 is obviously greater than SF_6 and its mixtures with different gas pressure. And the streamer length of pure N_2 is near the gap distance between electrodes (3.3cm), which proves that the discharge process of N_2 is streamer propagation. As for SF_6/N_2 gas mixtures, the streamer length is nearly equal to that of pure SF_6 and quite short compared with the gap distance.

The result demonstrates that the discharge process consist of not only streamer propagation, and when the streamer length is not enough to cause breakdown, the leader propagation transformed from streamer appears and leads to breakdown. Same with the result of discharge time delay, the streamer length also demonstrates the discharge process of N_2 and SF_6/N_2 gas mixtures is different indeed.

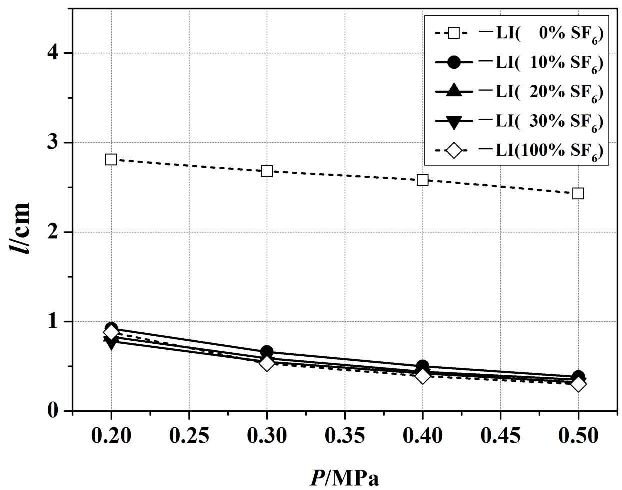

Figure 13. Streamer length versus gas pressure with R=1mm needle-plane electrodes under negative lightning impulse.

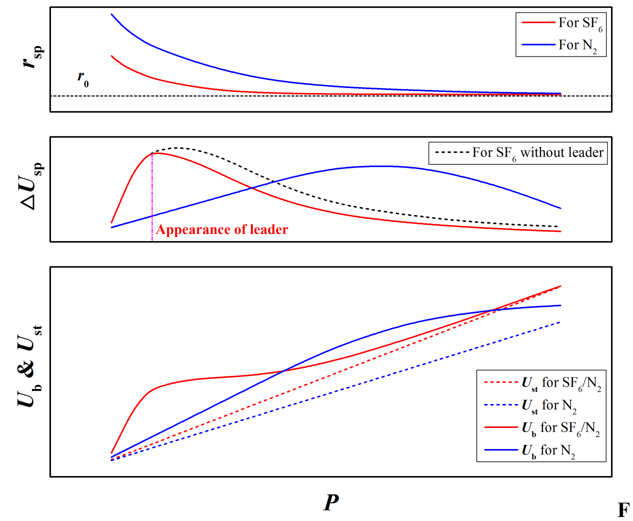

Figure 14. The difference of breakdown voltage U_b between N_2 and SF_6/N_2.

According to the previous analysis, the radial size of streamer corona in SF_6 is small and the charge is dense, which makes the root of streamer channel easily heated. Before the streamer channel reaching opposite electrode, the thermal ionization appears at the root of streamer channel, and then transforms to leader. The degree of ionization and conductance are increased, and the axial field strength significantly reduced as 3-4 kV/cm, which makes the electric field of streamer area in front of leader increases, and generates new streamers, then the leader channel would grow. With the increase of voltage, the leader channel grows throughout the gap, and the breakdown process is completed. Therefore, the appearance of leader process would significantly reduce the average breakdown electric field strength of gap, which causes the decrease of the breakdown voltage. In another word, the effect of space charge on breakdown with streamer propagation would be influenced by the appearance of leader propagation. The breakdown voltage U_b can be calculated by the streamer corona onset voltage U_{st} added the influence of space charge on breakdown voltage $\triangle U_{sp}$:

$$U_b = U_{st} + \Delta U_{sp} \tag{15}$$

Combining the analysis above, Figure 14 illustrates the difference of breakdown voltage between pure N_2 and SF_6/N_2 qualitatively. The streamer corona onset voltage U_{st} increases linearly with the rise of gas pressure, and the slope of U_{st}-P with SF_6/N_2 gas mixtures is higher and close to that with N_2. Due to the density and volume of space charge, the influence of space charge on breakdown voltage $\triangle U_{sp}$ would increase first and then decrease with the rise of gas pressure. The radius of space charge in N_2 is greater than SF_6/N_2, so the range of gas pressure with space charge effect is much wider in N_2. However, the space charge around needle electrode in SF_6/N_2 is denser than N_2, which means that the corona stabilization effect of space charge is more significant at low gas pressure. When the leader propagation appears, the influence of space charge on breakdown voltage is depressing because of the high conductivity of leader channel. In another word, $\triangle U_{sp}$ would reduce with the appearance of leader. The analysis mentioned above can explain the breakdown voltage U_b of pure N_2 could be higher than SF_6/N_2 even SF_6 within the certain range of gas pressure and dU/dP of pure N_2 gas is greater than that of SF_6 and its mixtures, which is shown in Figure 14. That is the reason for the appearance of negative synergistic effect with SF_6/N_2 in highly non-uniform electric field.

5 CONCLUSION

In this paper, the breakdown characteristics and negative synergistic effects of SF_6/N_2 mixtures at low SF_6 concentrations in a highly non-uniform electric field under standard lightning impulse were studied through experiments with two electrode configurations. The results show that the dU/dP of N_2 is significantly higher than both SF_6 and its mixtures under negative lightning impulse. When the gas pressure exceeds 0.3 MPa, the breakdown voltage of N_2 is higher than SF_6/N_2 gas mixtures, and voltage even exceeded the value of pure SF_6 at 0.5 MPa. The normalization coefficient h is introduced to evaluate the negative synergistic effect. The results showed that the synergistic effect decreased with decreasing gas pressure under positive polarity impulse with R=2 mm needle-plane electrodes, and it becomes a negative synergistic effect with the enhancement of electric field non-uniformity. It is worth noting that the negative synergistic effect appears under negative impulse, and it becomes more significant with increase of gas pressure. The negative synergistic effect was caused by similar streamer corona onset voltage, different space charge effect, and discharge form.

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