CREEPING DISCHARGE CHARACTERISTICS IN SF_6/N_2 GAS MIXTURES UNDER SINGLE PULSE VOLTAGE WITH STEEP WAVE FRONT

H. Ueno[1*] , H. Shimada[1], S. Ka[1] and H. Nakayama[1]
[1]Univesity of Hyogo, 2167 Shosha, Himeji 671-2280, Japan
*Email: <ueno@eng.u-hyogo.ac.jp>

Abstract: Characteristics of a creeping discharge under pulse voltage application with various front durations in the range of 100ns to 10μs in SF_6/N_2 gas mixtures for needle-plane electrode configuration have been investigated. The unique creeping flashover characteristics under nonuniform field were observed clearly only in the negative polarity in our previous work. By increasing wave front steepness of applied pulse voltage, the uniqueness of creeping flashover characteristics becomes remarkably even though in the positive polarity as well as in the negative polarity. Namely, the positive creeping flashover voltage is comparable to that in SF_6 and it is reduced greatly by mixture of small amount of SF_6 for the pulse voltage application with 100ns wave front duration. However, no remarkable change in uniqueness in the negative polarity has been obtained. From the observation by high speed camera for creeping discharge behavior, charge distribution on the dielectric surface in progress of creeping corona extension should be one of important factor for the observed uniqueness in positive polarity.

1 INTRODUCTION

SF_6 gas has excellent dielectric insulating properties, and has contributed to the improvement of the reliability and miniaturization of the electric power apparatuses such as a GIS. However, a significant decrease of dielectric strength is induced under a nonuniform electric field by the existence of a protrusion on the conductor or a metallic impurity, or by invasion of a steep front surge. Moreover, recently the leakage of SF_6 is regulated like CO_2 due to the high global warming ability compared with that of CO_2 [1].

SF_6/N_2 mixed gas and high pressure N_2 gas have been very interested in the practical application as an insulating medium in place of SF_6 [2,3,4]. However, the dielectric insulation characteristics of SF_6/N_2 mixed gas under the nonuniform field have not been clarified. Especially, dielectric insulating properties for the system with a small gap have not been elucidated. From another viewpoint, an insulating system of the power apparatus consists of a solid dielectric and an insulating gas, because of supporting the conductor or coating the electrode by the insulators.

Creeping flashover characteristics in N_2/SF_6 mixtures have been investigated for composite insulating system with a narrow gap between the needle and the barrier in our previous work [5,6,7]. We have found that the negative creeping flashover voltage in N_2 (D=0%) is as high as that of SF_6 (D=100%), and the remarkable reduction of negative flashover voltage is induced by the small SF_6 gas mixture, and the flashover voltage has unique *V-t* characteristics.

To understand this uniqueness on flashover voltage in SF_6/N_2 gas mixtures under the nonuniform field, the field relaxation by the space charge and the accumulated charge should be considered as an important factor. As the primitive investigation, in this work, creeping discharge characteristics under steep-front pulse voltage on non-uniform field have been investigated.

2 EXPERIMENTAL DETAILS

Figure 1 shows electrode configuration used in this work. It is used for a borosilicate glass plate (thickness g=1mm) of 40mm×26mm as a dielectric barrier. A needle electrode was arranged on of the dielectric barrier and the counter plate electrode was arranged at the edge of the barrier. The distance between the needle and the plate electrode was fixed at l=7mm. A needle electrode with a 35 μs tip of curvature was set with the barrier surface. A counter plane electrode was set at the other side of the gap distance 7mm from the needle electrode. A filamentous steel wire with φ=0.9mm in the outer diameter was used as a back side electrode connected with the counter plane electrode. This electrode system was set up in a container made of brass, after it exhausted up to about 0.1Pa, and then it was filled with SF_6/N_2 gas mixture under the pressure of 0.1MPa to 0.3MPa.

Figure 2 indicates a typical experimental setup. A single pulse voltage with a front time duration of T_f=100ns~10μs was applied between the upper needle electrode and the counter plane electrode. Applied voltage waveform and corona light emission were recorded using an oscilloscope (Yokogawa, DL-1540, 200MS/s, 150MHz) through a high-voltage probe (Iwatsu, HV-P30, DC-50MHz) and a photomultiplier (Hamamatsu Photonics, 931A, wavelength 300-650 nm), respectively. Corona onset voltage and flashover voltage were taken as instantaneous values at the first detection of corona light emission and flashover on the wave front.

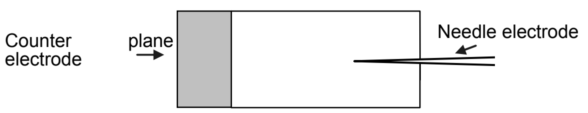
Corona extension and creeping discharge development were captured using a high-speed digital framing camera with a maximum amplification of 7000 (Hadland Photonics, IMACON468) and a CCD camera with high-speed gated image-intensifier (maximum amplification of 200,000) (Hamamatsu Photonics, C4346).

Here, the time decay constant of surface potential on the borosilicate glass barrier (volume resistivity $\rho_v=10^{12}$ Ω·m, dielectric constant ε_r =7) is estimated to be about 1 minute. To prevent influence of the residual charge on the barrier by the corona, voltage application interval for the present experiments in series was to be 1 minute or more. The charge decay of the surface of the barrier in front time duration of applied voltage can be ignored. Therefore, experimental results and effects are expected to be same in the case of epoxy resin used for GIS.

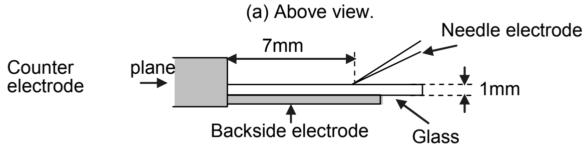
3 EXPERIMENTAL RESULTS

3.1 Influence of SF_6 Content and Wave Front Steepness on Flashover Voltage

Figure 3 shows SF_6 content dependence of flashover voltage for a single pulse voltage with a front time duration of T_f=100ns and 1.5μs. In the case of positive polarity, the flashover voltage in 3% SF_6 mixture decreased from that in N_2. By further increasing SF_6 gas content, the flashover voltage increased with increasing SF_6 gas content.



(a) Above view.



(b) Side view.

Figure 1: Electrode configuration.

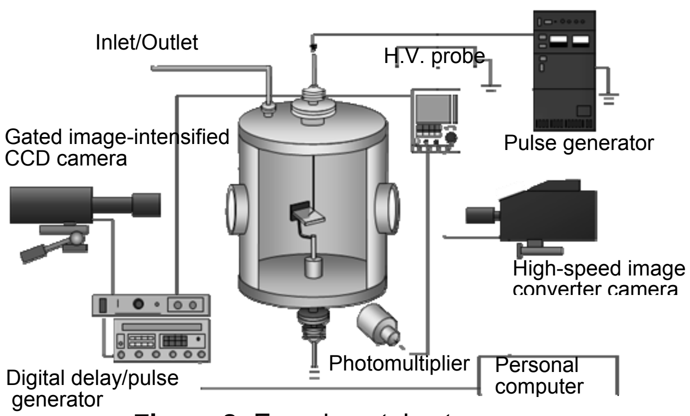
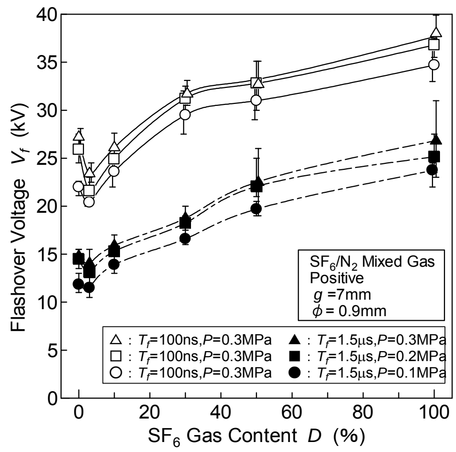


Figure 2: Experimental setup.

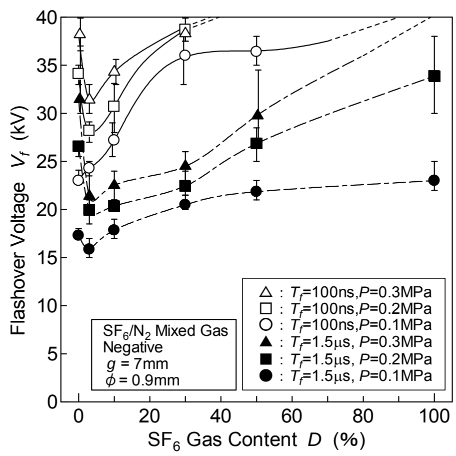
The decreased of flashover voltage induced by small SF_6 mixture was enhanced by reduction of wave front steepness from T_f= 1.5μs to T_f=100ns. In the case of negative polarity, the flashover voltage was higher than that in the case of positive polarity as well-known; furthermore the reduction of flashover voltage by small SF_6 admixture was also observed like as in the positive polarity. Especially, reduction of flashover voltage was markedly under the pressure of P=0.2 and 0.3Mpa, however, no remarkable enhancement of reduction of flashover voltage was not appeared by increasing wave front steepness.

In our previous work, we reported remarkable reduction of flashover voltage induced by small SF_6 admixture in N_2 only for the negative polarity. In the present work, such a reduction of flashover voltage was observed for the positive polarity, and it was enhanced by increasing wave front steepness of applied pulse voltage. It may associate with creeping corona extension behavior and time lags of discharge.

To clarify influence of wave front steepness on reduction of flashover voltage induced by small SF_6 mixture in N_2 in detail, flashover voltage – time characteristics have been investigated by changing wave front duration of applied voltage of T_f=100ns



(a) Positive polarity.



(b) Negative polarity.

Figure 3: SF_6 gas content dependence of flashover voltage

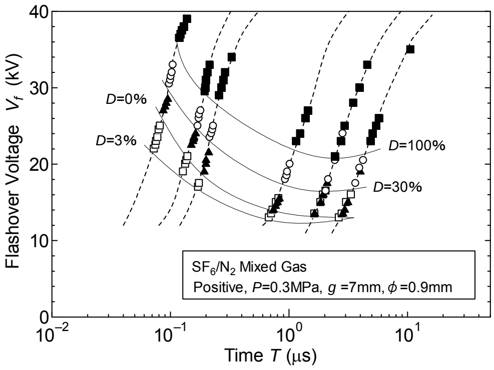
~ 10μs. Figure 4 shows flashover voltage – time characteristics for the various SF_6 content. For easy recognition of characteristics, lower limit of flashover voltage for each wave front is indicated a solid curve as a guidance.

In the case of positive polarity, flashover voltage increased with reduction of wave front duration of applied voltage (increase of front steepness) in all investigated SF_6 gas contents. Flashover voltage in N_2 (D=0%) increased markedly by reduction of wave front duration comparing those in SF_6 content of D=3~100%. So that the reduction of flashover voltage by SF_6 addition was enhanced by increasing front steepness. On the other hand, in the case of negative polarity, change in flashover voltage in N_2 (D=0%) by reduction of wave front duration was not so remarkable in comparison with that in 3%-SF_6.

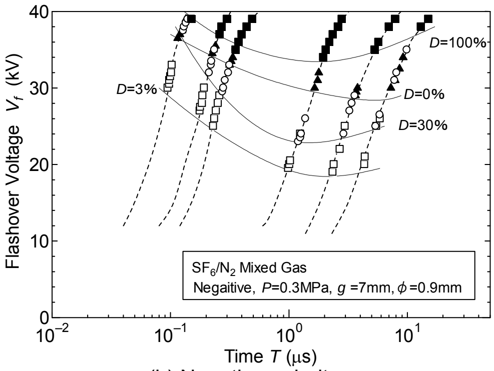
From the investigation of voltage – time characteristics, decrease of flashover voltage becomes large by reduction of wave front duration. It may suggest that discharge formative time lag and/or creeping discharge behavior are related with such unique phenomena on SF_6 content dependence of flashover voltage.

3.2 Corona Onset Voltage and Corona Light Emission

Corona onset voltage for the various conditions has been investigated. Corona onset voltage is shown in Figure 5. In the both polarities, corona onset voltage increased very slightly with increasing SF_6 content lower than 50% though the positive corona onset voltage was higher than negative one. Reduction of corona onset voltage by addition small SF_6 (D=3%), as observed on flashover voltage, was not obtained. Furthermore, there is no significant change by reduction of wave front duration in this SF_6 content region. Only in the pure SF_6 (D=100%), corona onset voltage for

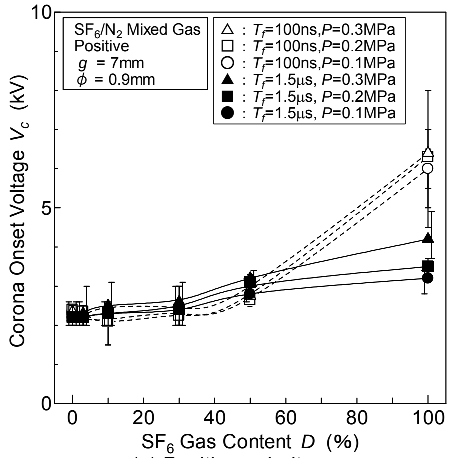


(a) Positive polarity.

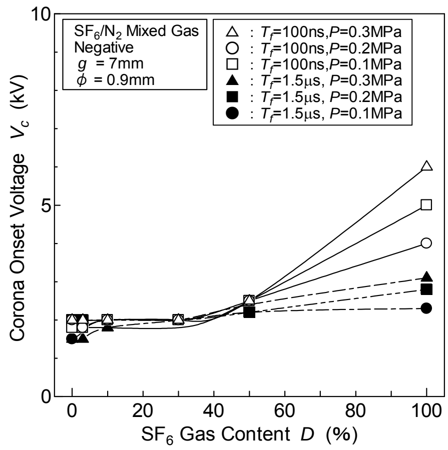


(b) Negative polarity.

Figure 4: V - t characteristics (P=0.3MPa).

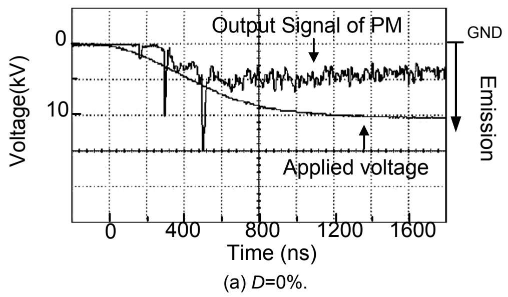


(a) Positive polarity.

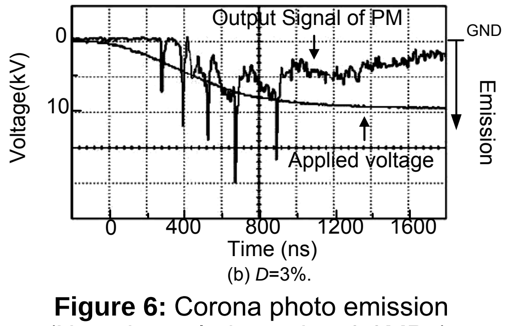


(b) Negative polarity.

Figure 5: SF_6 gas content dependence of corona onset voltage



(a) D=0%.



(b) D=3%.

Figure 6: Corona photo emission (Negative polarity and P=0.3MPa).

T_f=100ns was enhanced by decreasing front duration from T_f= 1.5μs.

Figure 6 shows corona light emission in D=0% and D=3% for the negative polarity at wave front of applied pulse of T_f=1.5μs. Corona light emission in D=0% was observed impulsively. Impulsive corona emission increased by 3%-SF_6 addition. This impulsive corona light emission will associate with creeping corona extension behavior, so it is considered that this difference in emission behavior suggests unique phenomena observed in the present work are associated with creeping corona extension depending on wave front duration, SF_6 gas content and polarity.

3.3 Creeping Corona Extension

From the above-mentioned results, to clarify the relationship among the unique creeping flashover characteristics, wave front steepness and corona extension behavior, the corona extension processes for various wave front durations have to be investigated. Especially, corona development from corona onset to creeping flashover should be observed. Time-resolved images of corona extension progressed at the wave front of applied voltage were taken, using ultra-high speed camera because it is considered that difference of corona extension causes the difference of flashover voltage. Figure 7 show extension behavior at P=0.3MPa in the negative polarity in which condition the reduction of flashover voltage induced by small SF_6 addition is observed. Here, exposure time for corona image capture by using high speed camera was set at 100ns for T_f= 1.5μs and 10ns for T_f=100ns, instantaneous voltage upon capture of image is indicated below each image (Frame).

Figure 7(a) shows corona extension behavior for the SF_6 gas content of D=0% (pure N_2) at T_f= 1.5μs. After first corona observation at Frame 1, the corona development was suppressed seen in Frame 2, and then the corona with strong emission extended radially in Frame 3, but its corona did not reached at the counter electrode. By increasing applied voltage in Frames 4 and 5, corona extended further and flashover occurred. On the other hand, the first corona generation at the needle tip was observed in Frame 1 of Figure 7(b), and then the corona grew gradually by increasing applied voltage as seen in Frame 2 ~ 5. Corona extension behavior at T_f=100ns is indicated in Figures 7(c) and (d). The behavior is essentially same as that observed at T_f=1.5μs, however, the corona extended strongly and radially compared with that observed at T_f= 1.5μs.

From observation of corona extension, corona extension was suppressed tentatively in D=0%. It is considered that creeping discharge characteristics in N_2 (D=0%) are unique, which may associated with field relaxation induced by accumulated charges on the barrier. On the contrary, corona extension behavior in D=3% is greatly different from that in D=0%. Namely, impulsive corona development is observed by 3%-SF_6 addition, which is typical behavior in SF_6 under the non-uniform field. This fact suggests that the unique creeping flashover characteristics caused by accumulated charge distribution and charge density on the barrier depending on SF_6 content.

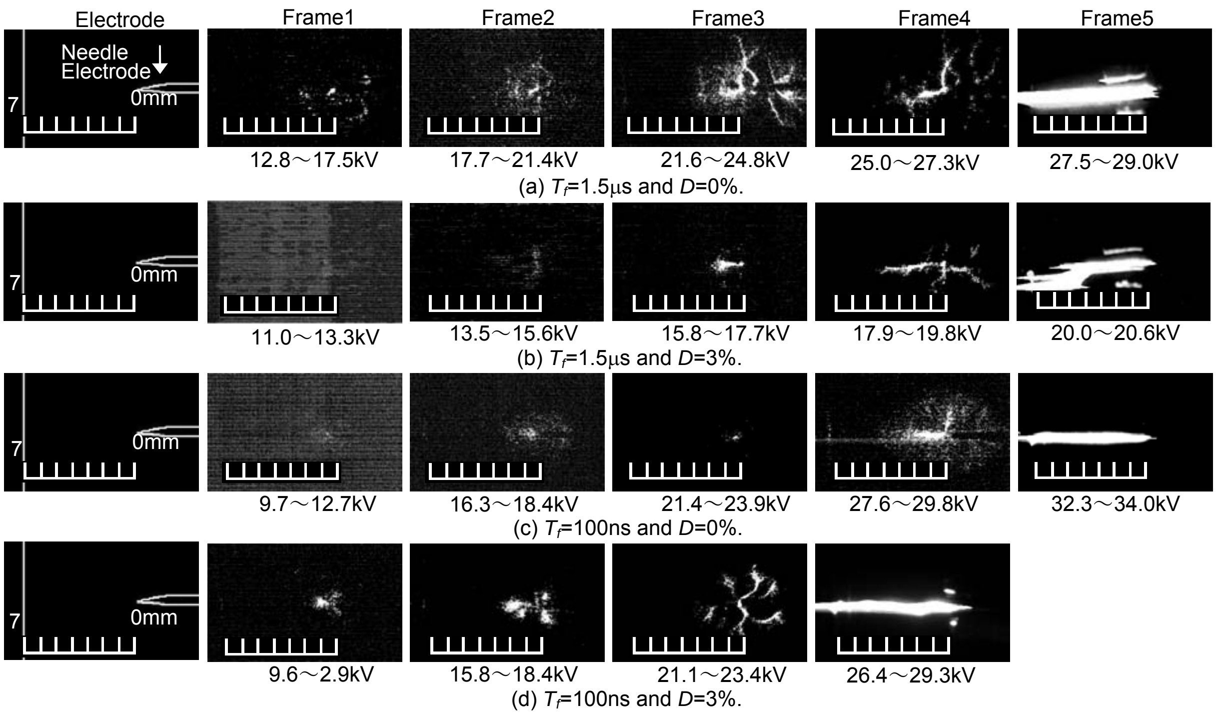


Figure 7: Behavior of corona extension observed with high speed camera (Negative polarity and P=0.3MPa).

4 DISCUSSION

4.1 Creeping Flashover Behavior at Small SF6 Content

From the investigation of SF_6 gas content dependence of creeping flashover voltage in SF_6/N_2 gas mixture, the flashover voltage has minimal at low SF6 gas content. On the other hand, thus uniqueness has not observed on corona onset voltage. So the above-mentioned unique behavior should be associated with creeping corona extension process.

Broad corona light emission, strong emission on the barrier surface and its suppression were appeared on the corona extension observation given in Figures 6 and 7 in N_2 (D=0%). This fact interpreted as follows. Charges generated by ionization near the needle tip are accumulated on the barrier surface with increasing applied voltage. Corona extension is suppressed tentatively by the field relaxation induced by those accumulated charge.

However, impulsive corona emission increases by small SF_6 addition seen in Figure 6, leading to repetition of corona extension and suppression on the barrier in short periods. Furthermore, creeping corona gradually develops along the backside electrode without any suppression by small SF_6 addition.

Electron attachment coefficient for electrons with energy of 2eV is 3～4 order of magnitude lower than that for electron with energy of 1eV, leading to lower dielectric strength under the non-uniform field in SF_6 gas. By admixture of SF_6 into N_2, negative ions are generated by attachment of low energy electrons induced by collision with N_2 molecule near the needle tip. Therefore, the field relaxation effect by the accumulated charge on the barrier is reduced, leading to easy creeping corona development. In addition, photo-ionization is effective at low SF_6 content. It means that electron supply increases and corona development is enhanced [8]. In the case of further SF_6 content, electron attachment effect of SF_6 molecules is essentially dominant, so that creeping flashover voltage in SF_6 (D=100%) is higher than that in N_2 (D=0%). The above-mentioned process results in reduction of flashover voltage by small SF_6 addition.

4.2 Polarity Effect on Creeping Corona Extension

Reduction of flashover voltage is enhanced by increasing wave front steepness in positive polarity. On the other hand, it is not clearly observed in negative polarity. Flashover voltage is affected by corona extension behavior, so that polarity difference in creeping corona development on the barrier has been investigated by using image-intensified CCD camera (ICCD).

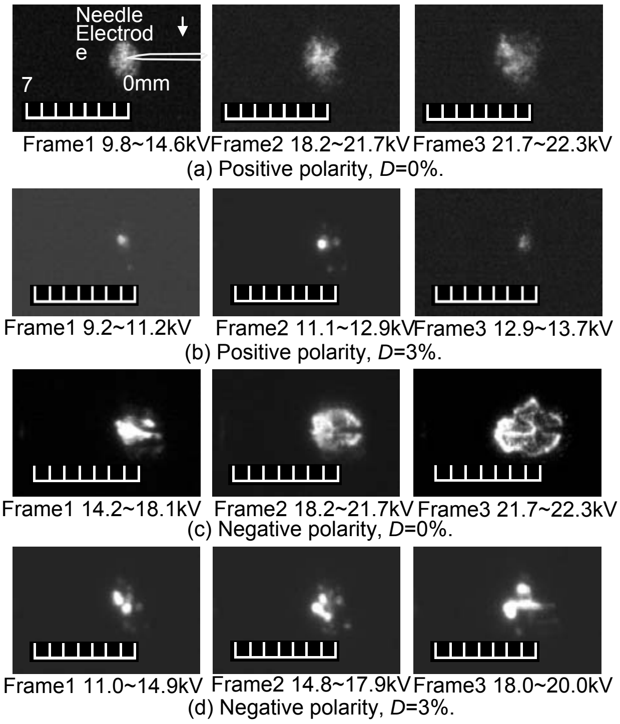


Figure 8: Corona extension images with ICCD camera (T_f=100ns and P=0.3MPa).

Figure 8 shows corona growth behavior at wave front duration of T_f=100ns under the pressure of P=0.3MPa. For the case of positive polarity in N_2 (D=0%), corona generation at needle tip was observed seen in Frame 1 of Figure 8(a), and then corona grew radially on the barrier surface as indicated in Frames 2 and 3. On the contrary, corona growth region became narrow and corona emission near the needle tip was intense by small SF_6 addition in Figure 8(b). Corona growth behavior in negative polarity is very different from that in positive polarity. Especially, corona with intensive emission in N_2 extended widely on the barrier surface compared with that in positive polarity.

It is considered that the field relaxation in negative polarity by accumulated charge originated by creeping corona is effective in comparison with that in positive polarity in N_2 (D=0%). On the corona growth process upon increasing applied voltage at wave front, electrons supplied from high field region near the tip of creeping corona drift to barrier surface, because electric field is intensified by backside electrode. Therefore, ionization is active and a large number of residual positive charges are accumulated on the barrier, so that field relaxation is strongly effective.

On the other hand, number of charge accumulated on the barrier in positive polarity is lower than that in the negative polarity because of inverse of electric field direction. Furthermore, field relaxation effect will be dominant in negative polarity rather than effect induced discharge time-lag, so that flashover voltage in negative polarity did not change so remarkable with reduction of wave front duration of applied voltage. And reduction of flashover voltage induced by small SF_6 addition is strongly depends on the polarity and wave front steepness.

5 CONCLUSION

In the present work, characteristics of a creeping discharge under pulse voltage application with various front durations in SF_6/N_2 gas mixtures for needle-plane electrode configuration have been investigated. By increasing wave front steepness of applied pulse voltage, the uniqueness of creeping flashover characteristics becomes observed remarkably even though in the positive polarity as well as in the negative polarity. Namely, the positive creeping flashover voltage is comparable to that in SF_6 and it is reduced greatly by mixture of small amount of SF_6 for the pulse voltage application with 100ns wave front duration. From the observation by high speed camera for creeping discharge behavior, charge distribution on the dielectric surface in progress of creeping corona extension should be one of important factor for the observed uniqueness in positive polarity.

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