Impulse Partial Discharge Characteristics and Their Mechanisms under Non-uniform Electric Field in N_2/SF_6 Gas Mixtures

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ABSTRACT

We have investigated impulse partial discharge (PD) and breakdown (BD) characteristics of a needle-plane gap in N_2/SF_6 gas mixtures under positive lightning impulse voltage application, and discussed their physical mechanisms. The 50% probability PD inception voltage ($PDIV_{50}$), leader discharge onset voltage (LOV) and BD voltage (BDV_{50}) were measured and analyzed as a function of gas pressure and SF_6 content. Experimental results revealed the stepwise propagation process of the impulse PD and enabled us to classify the impulse PD in N_2/SF_6 gas mixtures into two types, the streamer discharge and the leader discharge. We also discussed the impulse PD propagation mechanisms in terms of PD parameters such as propagation length, time interval and current pulse magnitude, and suggested a sequential relationship in the PD propagation process under non-uniform electric field.

Index Terms — **N_2/SF_6 gas mixtures, lightning impulse voltage, partial discharge, streamer, leader.**

1 INTRODUCTION

THE environmental problem of SF_6 gas has been regarded as a key issue in the field of high voltage engineering since the meeting of the Intergovernmental Panel on Climate Change/Conference of the Parties 3 (IPCC/COP3) in 1997 [1]. Though many studies have been carried out to search for new insulation gases as alternatives to SF_6 gas, it is N_2/SF_6 gas mixtures that are expected to be possible candidates in place of pure SF_6 gas [2]. N_2/SF_6 gas mixtures have excellent physical and chemical properties as well as much less global warming potential, lower cost, and lower liquefaction temperature, compared with pure SF_6 gas, while still retaining excellent electrical insulation performance [3, 4]. N_2/SF_6 gas mixtures as alternative substitutes for pure SF_6 gas may be applied not only for gas insulated switchgears (GIS) and gas insulated transmission lines (GIL), but also for gas insulated transformers (GIT).

The electrical insulation properties of N_2/SF_6 gas mixtures have generally been studied under uniform or quasi-uniform electric fields, but few studies so far have focused on conditions of non-uniform electric field. Non-uniform field characteristics like electrode irregularities and particles would be critical under commissioning tests and under operating conditions for determining the electrical insulation design. Especially, the impulse PD characteristics and their mechanisms leading to breakdown (BD) have not yet been elucidated under a non-uniform electric field in N_2/SF_6 gas mixtures.

From the above viewpoints, this paper discusses the positive impulse partial discharge (PD), leader discharge

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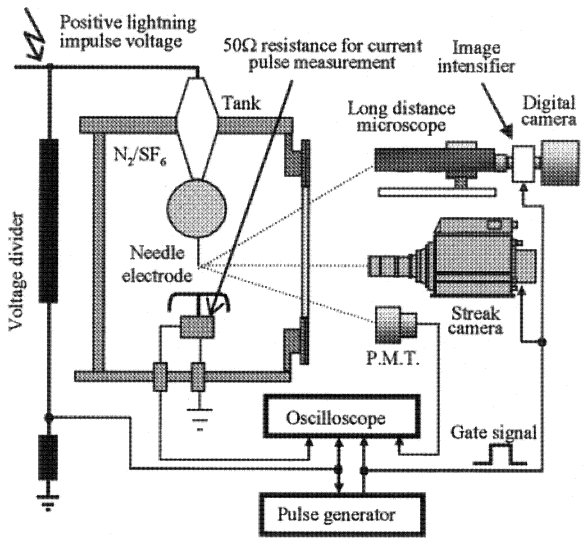

Figure 1. Experimental setup.

and BD characteristics of a needle-plane gap as a function of gas pressure and SF_6 content in N_2/SF_6 gas mixtures. In order to clarify the discharge mechanism of N_2/SF_6 gas mixtures, PD characteristics and mechanisms were investigated through the simultaneous measurement of current and light intensity pulse waveforms, streak and still light emission images of the impulse PD.

2 EXPERIMENTAL SETUP

Figure 1 shows the experimental setup. The experimental chamber was filled with N_2/SF_6 (SF_6 content: 0, 2, 5, 10, 20, 50, 100%) gas mixtures which are mixed in the tank by partial pressure at the total gas pressure of P = 0.1- 0.4 MPa. The term gas pressure here always indicates the total gas pressure. A needle electrode with a tip diameter of ϕ = 1 mm and a length of 20 mm was fixed on the sphere electrode. A plane electrode with a diameter of 30 mm was placed under the needle electrode. The gap length of the needle-plane electrode was 40 mm. Positive lightning impulse voltage was applied to the needle electrode and generated PD and BD. 50% probability PD inception voltage ($PDIV_{50}$) and BD voltage (BDV_{50}) were determined by the up-and-down method. In order to eliminate the influence of residual space charges, the time interval of voltage application was set to 6 minutes.

PD current pulse waveforms were measured by a digital oscilloscope (1 GHz, 2 GSamples/s) through a current pulse measuring 50 Ω resistance, together with the applied impulse voltage waveform. The PD sensitivity in our experimental setup is a few tens pC by PD current detection. The still image and the intensity of PD light emission were observed using a digital camera with an image intensifier (I.I.) and a photomultiplier tube (P.M.T.), respectively. The streak image of PD light emission was recorded by an ultra high-speed streak camera (time resolution < 250 ps) to observe the propagation process of the impulse PD. These electrical and optical signals of PD phenomena were simultaneously and synchronously obtained using a

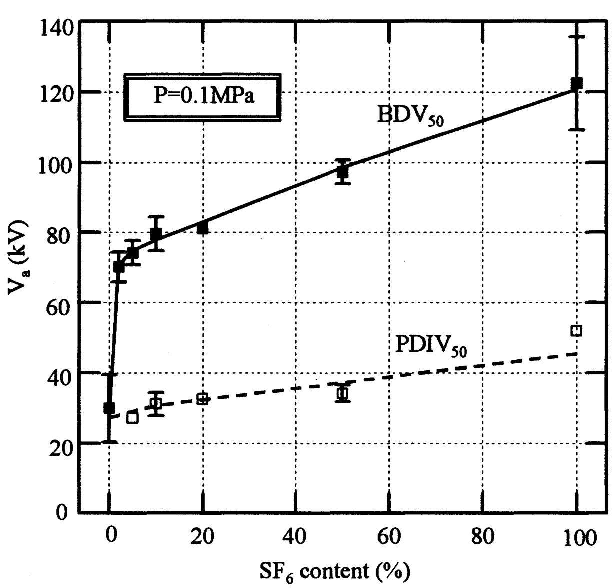

Figure 2. Positive impulse $PDIV_{50}$ and BDV_{50} as a function of SF_6 content in N_2/SF_6 gas mixtures at P = 0.1 MPa.

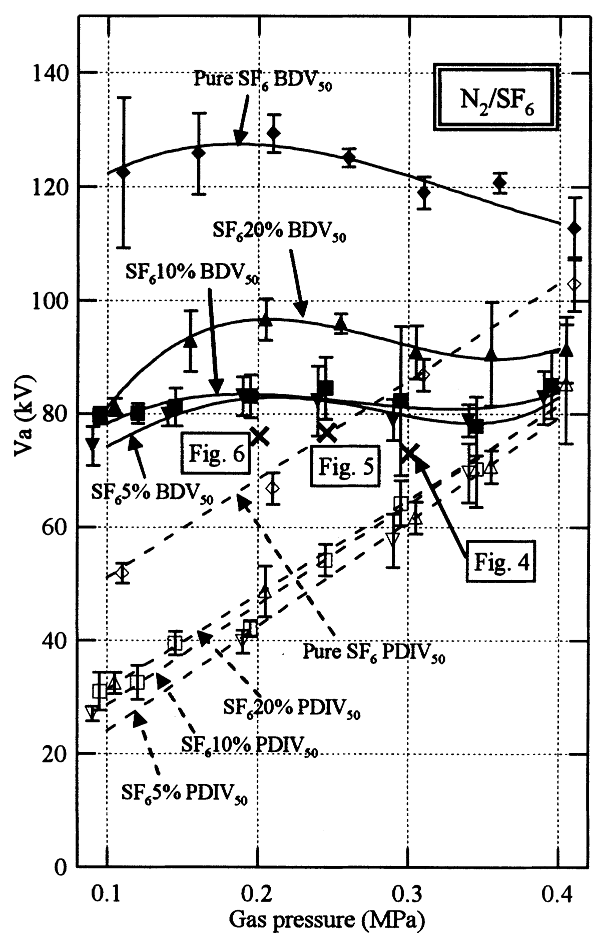

Figure 3. Positive impulse $PDIV_{50}$ and BDV_{50} as a function of gas pressure for different SF_6 content in N_2/SF_6 gas mixtures.

high-speed electrical shutter and a gate signal from a pulse generator with the time resolution of nanosecond order. In order to synchronize these signals, the time delays of the cable propagation and the measuring instruments were measured and compensated by adjusting the cable length and the trigger setting of the pulse generator. All experiments were carried out at room temperature.

3 IMPULSE PARTIAL DISCHARGE INCEPTION AND BREAKDOWN CHARACTERISTICS

Figure 2 shows the positive impulse $PDIV_{50}$ and BDV_{50} as a function of SF_6 content in N_2/SF_6 gas mixtures at P = 0.1 MPa. $PDIV_{50}$ increased linearly with the SF_6 content. On the other hand, the BDV_{50} increased drastically with the SF_6 content; the BDV_{50} reached 240% of that in

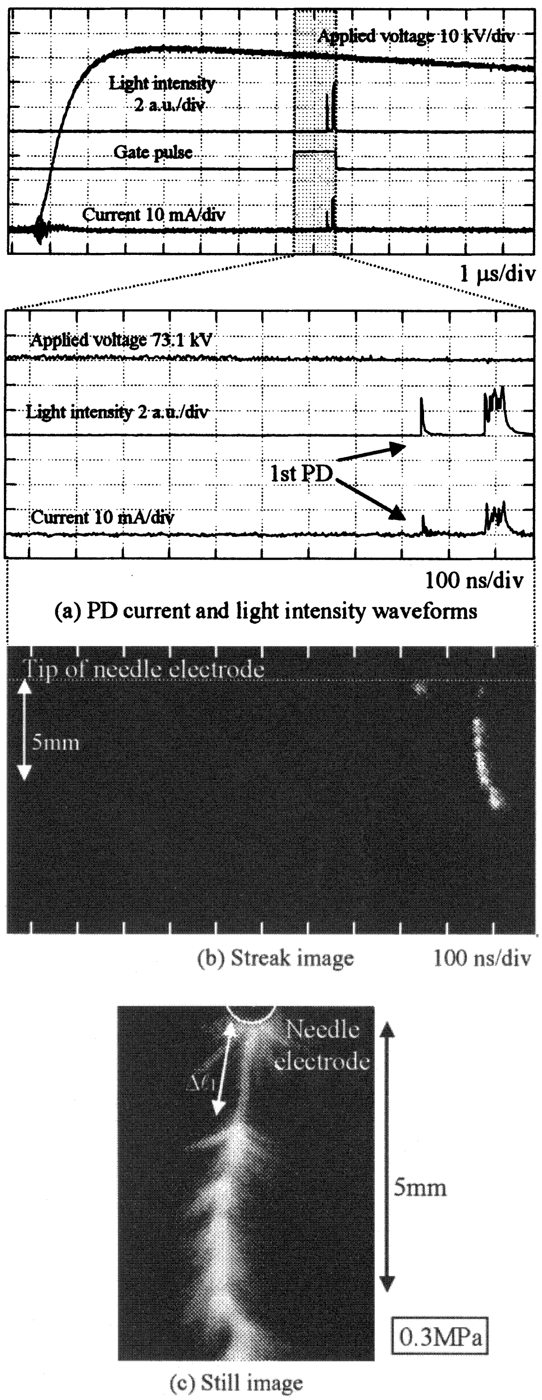

Figure 4. PD current, light intensity, streak and still images for impulse voltage application of 73.1 kV at 0.3 MPa. (10% SF_6).

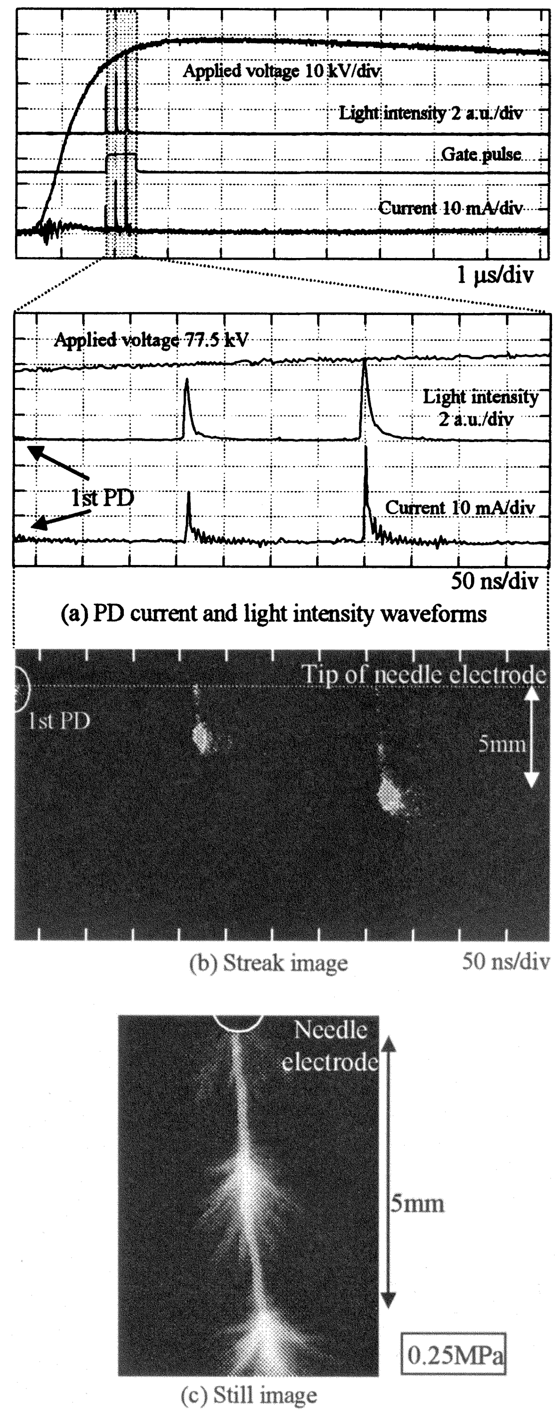

Figure 5. PD current, light intensity, streak and still images for impulse voltage application of 77.5 kV at 0.25 MPa. (10% SF_6).

pure N_2 gas and 60% of that in pure SF_6 gas with only 2% addition of SF_6 gas, and hence exhibited a strong synergistic effect.

Figure 3 shows the positive impulse $PDIV_{50}$ and BDV_{50} as a function of gas pressure for different SF_6 content in N_2/SF_6 gas mixtures. $PDIV_{50}$ increased linearly with the gas pressure, whereas the BDV_{50} exhibited non-linear characteristics with the gas pressure; a maximum at P = 0.20 - 0.25 MPa and a minimum at P = 0.30 − 0.35MPa. Such non-linear characteristics of BDV_{50} are attributed to the transition from streamer discharge to highly conductive leader discharge in electronegative gases at high gas pressure. Therefore, it is important to investigate the leader discharge characteristics in order to elucidate the impulse PD and BD mechanisms in N_2/SF_6 gas mixtures. Thus, we focused on the impulse leader discharge inception and propagation characteristics for different gas pressure and SF_6 content in N_2/SF_6 gas mixtures.

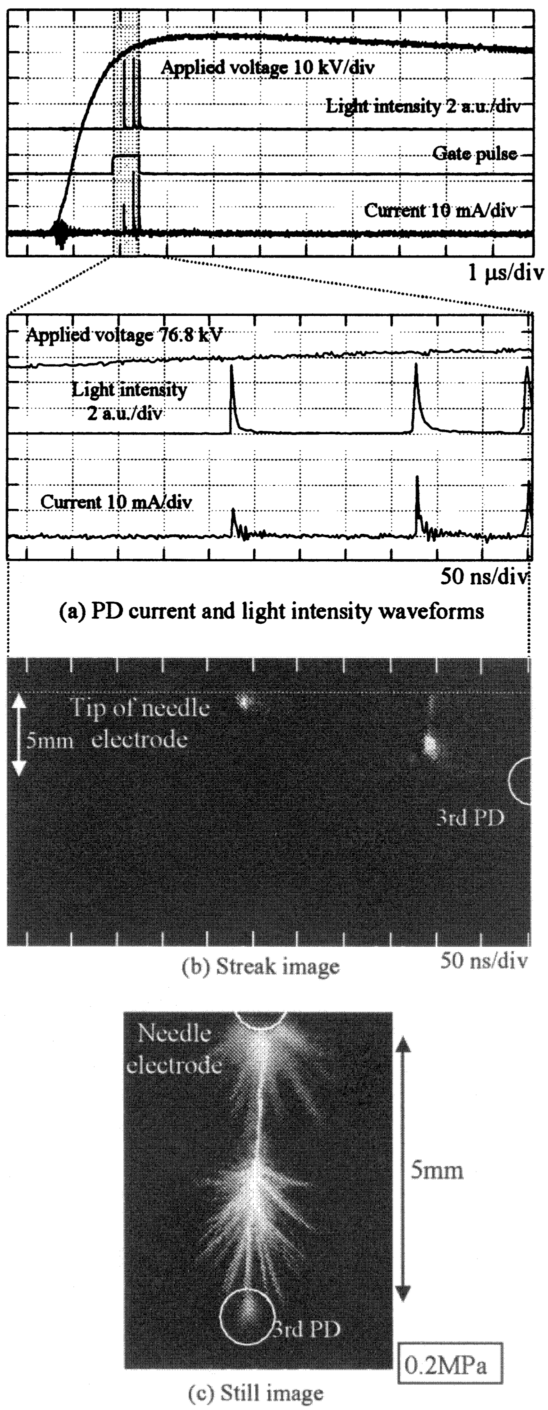

Figure 6. PD current, light intensity, streak and still images for impulse voltage application of 76.8 kV at 0.2 MPa. (10% SF_6).

4 IMPULSE LEADER DISCHARGE INCEPTION AND PROPAGATION CHARACTERISTICS

We observed the propagation process of positive impulse PD from its inception to extinction. Figures 4, 5 and 6 show the applied voltage, PD current and light intensity pulse waveforms, streak and still light emission images in $N_2 90\%/SF_6 10\%$ gas mixtures for positive impulse voltage application of 73.1 kV, 77.5 kV and 76.8 kV at P = 0.3 MPa, P = 0.25 MPa and P = 0.2 MPa, respectively, where those corresponding measuring points (applied voltage, gas pressure) were designated by "×"symbols and labels (Figure 4, Figure 5 and Figure 6) in Figure 3. In the PD current and light intensity waveforms in Figures 4a, 5a and 6a, multi-peak pulses were measured, which corresponded to the impulse PD. Together with the streak image of the PD light emission in Figures 4b, 5b and 6b, the impulse PDs were verified to propagate stepwise [5]. The first pulse with brush-like PD corresponded to the streamer discharge extending from the needle electrode, whereas the subsequent pulses corresponded to the leader discharge. The stepwise propagation of the impulse PD due to the streamer/leader transition was also confirmed in N_2/SF_6 gas mixtures with different SF_6 contents. Such discrimination of streamer and leader discharge in the impulse PD propagation is consistent with those in the references [6, 7].

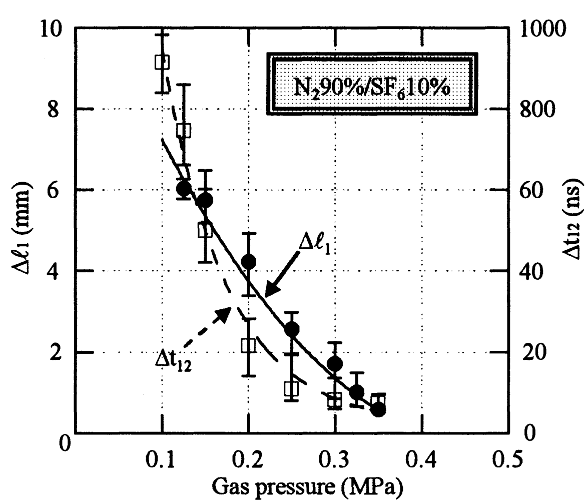

Figure 7. PD step length $\Delta \ell_1$ and time interval Δt_{12} as a function of gas pressure in $N_2 90\%/SF_6 10\%$ gas mixtures.

The still images in Figures 4c, 5c and 6c also confirmed the stepwise propagation of the impulse PD, where the leader discharge with a relatively long step length was followed by subsequent streamer discharge with the brush-like PD at the tip of the previous leader discharge. At high gas pressure, the step length $\Delta \ell$ and the time interval Δt of the subsequent leader discharge were shorter than those of the first. On the other hand, at lower gas pressure, the step length $\Delta \ell_1$ of the first PD and the time interval Δt_{12} between the first and the second PD were almost the same. Figure 7 shows $\Delta \ell_1$ and Δt_{12} as a function of gas pressure. $\Delta \ell_1$ and Δt_{12} decreased remarkably at P = 0.1 − 0.25 MPa and kept the low value at P = 0.25 − 0.35 MPa, which might be related to the appearance of the leader discharge.

5 CLASSIFICATION OF IMPULSE PARTIAL DISCHARGE TYPE

Figures 8a − 8d show the leader discharge onset voltage (LOV) together with the $PDIV_{50}$ and BDV_{50} of Figure 3 as a function of gas pressure for different SF_6 contents in N_2/SF_6 gas mixtures. LOV was defined as the minimum value of the applied voltage where multi-peak pulses with the stepwise PD propagation were observed, as was shown in Figures 4, 5 and 6. These results enabled us to classify the impulse PD in N_2/SF_6 gas mixtures into either streamer discharge or leader discharge. Comparing Figures 8a − 8d, the leader discharge area became larger with the increase in gas pressure and SF_6 content, whereas the streamer discharge area became smaller in N_2/SF_6 gas mixtures. These results are attributed to the enhancement

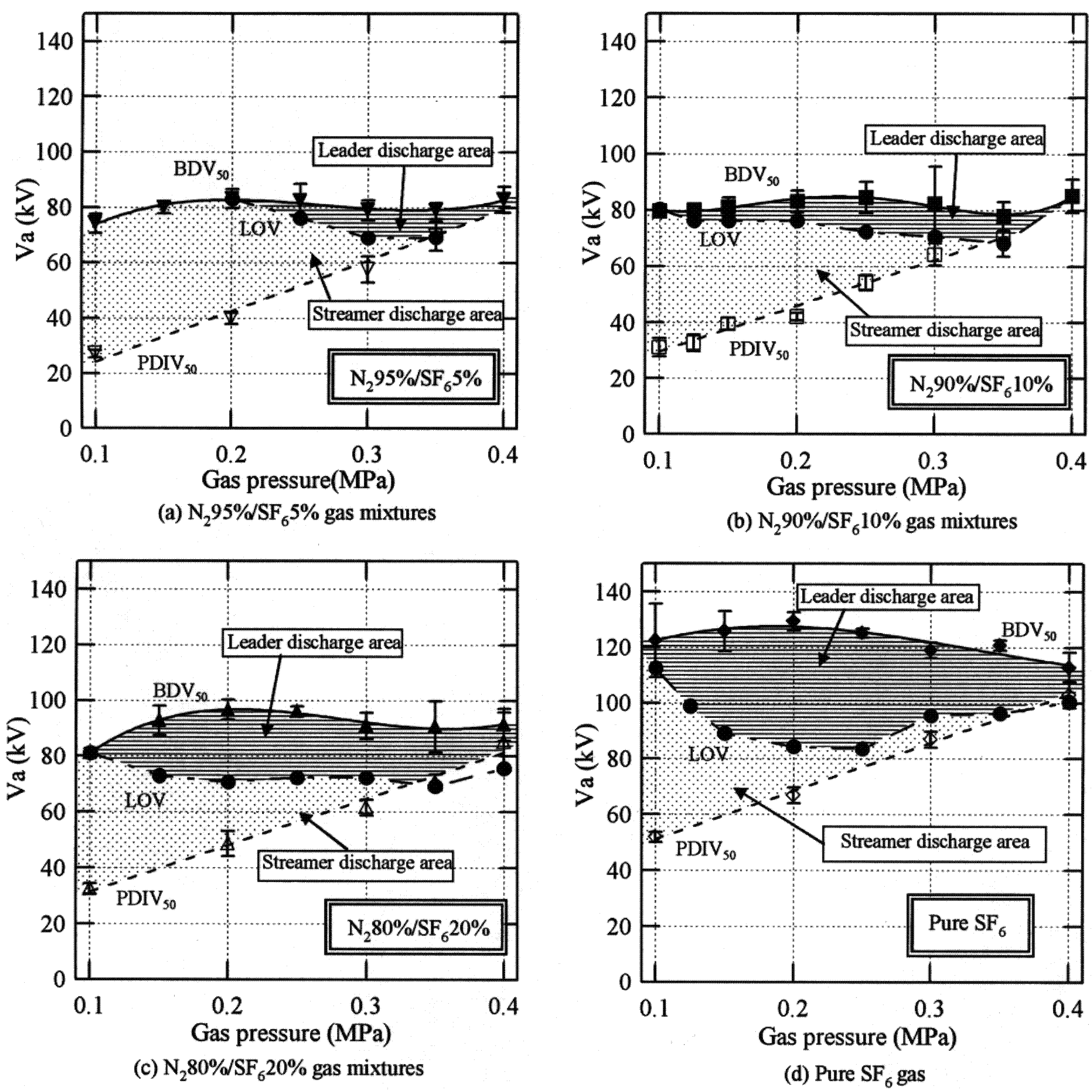

Figure 8. Classification of impulse PD type in N_2/SF_6 gas mixtures. a, $N_2 95\%/SF_6 5\%$ gas mixtures; b, $N_2 90\%/SF_6 10\%$ gas mixtures; c, $N_2 80\%/SF_6 20\%$ gas mixtures; d, Pure SF_6 gas.

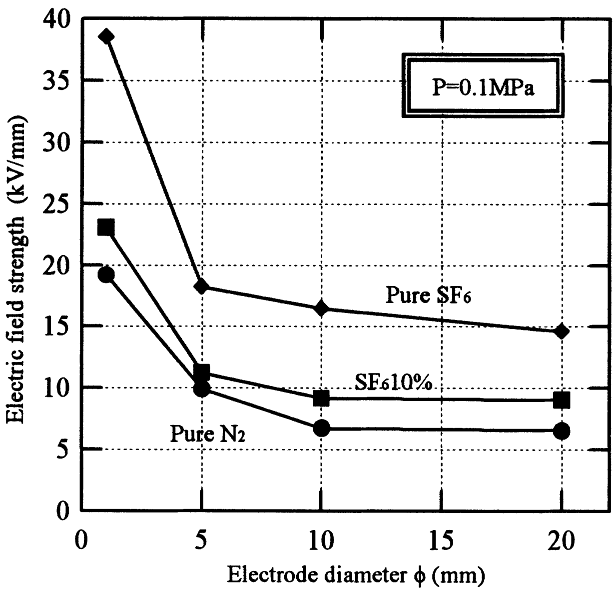

Figure 9. Positive impulse $PDIE_{50}$ as a function of electrode diameter in N_2/SF_6 gas mixtures at P = 0.1 MPa.

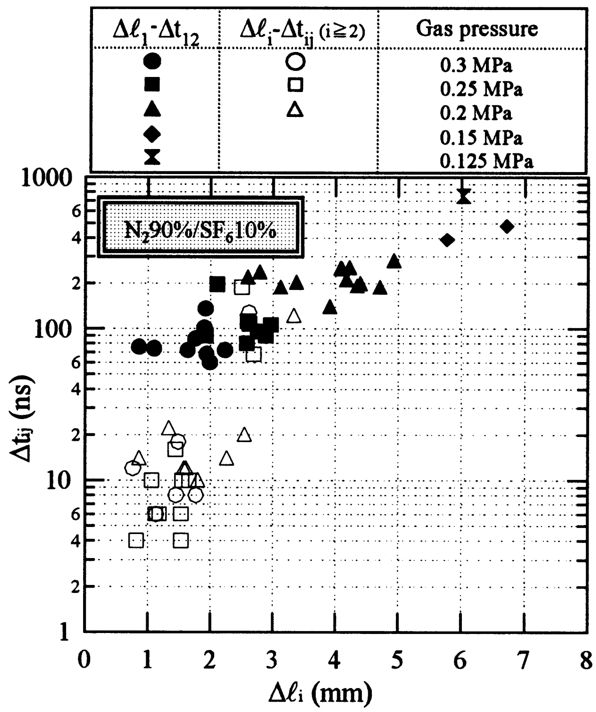

Figure 10. Relationship between step length $\Delta \ell_i$ and time interval Δt_{ij} of consecutive PD pulses in $N_2 90\%/SF_6 10\%$ gas mixtures.

of electronegativity in N_2/SF_6 gas mixtures with the higher SF_6 content and gas pressure, which could induce the shrinkage of the leader column and the activation of the streamer/leader transition.

Such classification of impulse PD type has been clarified as a significant characteristic in pure SF_6 gas [8], however it has not been previously reported in N_2/SF_6 gas mixtures. Figures 8a − 8d will contribute as a guideline for electrical insulation design of environmentally-benign power apparatus with N_2/SF_6 gas mixtures.

Figure 9 shows the 50% probability PD inception electric field strength ($PDIE_{50}$) of the needle (ϕ = 1 mm)-plane gap system together with rod(ϕ = 5, 10, 20 mm)-plane gap system in pure N_2 gas, $N_2 90\%/SF_6 10\%$ gas mixtures and pure SF_6 gas, respectively. The $PDIE_{50}$ for smaller tip diameter (ϕ) sharply increased because of the lack of initial electrons associated with the decrease in the critical volume under impulse voltage application [6]. This is the reason why the $PDIE_{50}$ obtained from Figures 3 and 8 were 2.2 - 4.4 times higher than the critical electrical field strength (E_{cr}) under non-uniform electric field. The $PDIE_{50}$ for larger tip diameter gradually decreased, which can be regarded as an area effect.

6 IMPULSE PARTIAL DISCHARGE PROPAGATION MECHANISMS

In this section, the stepwise propagation mechanism of the impulse PD is discussed through the relationship between PD propagation length $\Delta \ell_i$ at the i-step, time interval Δt_{ij} (j = i+1) of successive PD pulses and PD current pulse height I_j, where the definition of each parameter can be seen in Figures 4, 5 and 6.

Figure 10 shows the relationship between $\Delta \ell_i$ and Δt_{ij} in $N_2 90\%/SF_6 10\%$ gas mixtures at P = 0.125 − 0.3 MPa. Δt_{ij} increased with the increase in $\Delta \ell_i$, which may be interpreted by that it took long time to enhance the electric field strength at the tip of a previous PD channel with a long propagation length. In addition, $\Delta \ell_1$ and Δt_{12} of the first PD were longer than $\Delta \ell_i$ and Δt_{ij} of the subsequent PDs for i > = 2. This result may be explained by the fact that the electric field strength at the tip of the needle electrode for the first PD was smaller than that at the tip of the subsequent PD channels for i > = 2, because of the difference in tip diameter. Δt_{ij} decreased with $\Delta \ell_i$ as the gas pressure increased, where PD propagation was suppressed in the electronegative gases with high density.

Figure 11 shows the relationship between Δt_{ij} and I_j. I_j increased with the increase in Δt_{ij}, which may be attributed to the weaker corona stabilization effect after a longer Δt_{ij} from scattered positive ions around the needle electrode [9].

A similar relationship between $\Delta \ell_i$, Δt_{ij} and I_j was also confirmed in $N_2 95\%/SF_6 5\%$ and $N_2 80\%/SF_6 20\%$ gas mixtures. The other significant correlation than those between $\Delta \ell_i$, Δt_{ij} and I_j was not obtained in the PD parameters such as the rise time and fall time of PD current pulse waveform, etc. These results suggest the relationship between propagation length $\Delta \ell_i$, time interval Δt_{ij} and current pulse magnitude I_j; Δt_{ij} are determined by $\Delta \ell_i$ and also have an influence on I_j. With the repetition of such a sequential relationship in PD parameters, the

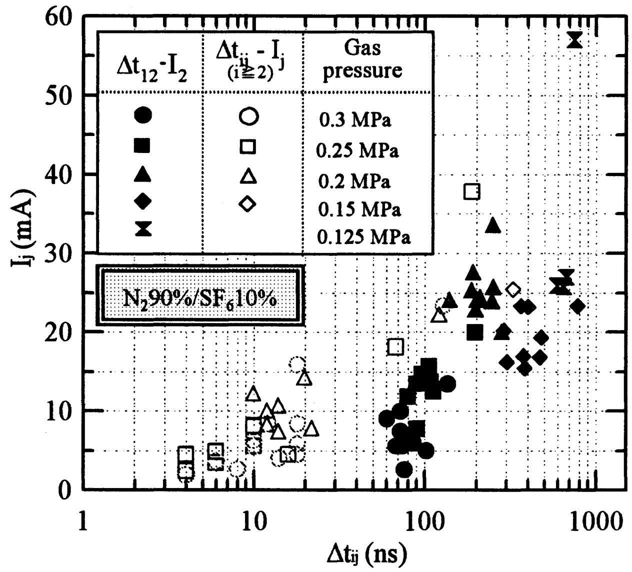

Figure 11. Relationship between time interval Δt_{ij} and current I_j of consecutive PD pulses in $N_2$90%/$SF_6$10% gas mixtures.

impulse PD would propagate stepwise in N_2/SF_6 gas mixtures.

7 CONCLUSIONS

IN this paper, the PD inception and propagation characteristics and their mechanisms in N_2/SF_6 gas mixtures under positive lightning impulse voltage application were investigated as a function of gas pressure and SF_6 gas content. The main results obtained are summarized as follows:

1. Impulse BDV_{50} exhibited the strong synergistic effect under non-uniform electric field; BDV_{50} reached 240% of that in pure N_2 gas and 60% of pure SF_6 gas by only 2% addition of SF_6 gas. Impulse $PDIV_{50}$ showed essentially no synergistic effect and a near proportional increase as the SF_6 content increased.

2. Impulse PD type in N_2/SF_6 gas mixtures was quantitatively classified into two types, streamer discharge or leader discharge, as a function of gas pressure and SF_6 content. The leader discharge area became larger with the increase in gas pressure and SF_6 content, whereas the streamer discharge area became smaller. This is attributed to the enhancement of electronegativity in N_2/SF_6 gas mixtures with the higher SF_6 content and gas pressure, which induced the shrinkage of the leader column and the activation of the streamer/leader transition. $PDIE_{50}$ for smaller electrode tip diameter was higher than critical electrical field strength (E_{cr}) because of the lack of initial electrons associated with the decrease in the critical volume.

3. Impulse PD propagation mechanisms were interpreted in terms of PD parameters such as propagation length $\Delta \ell_i$, time interval Δt_{ij} and current pulse magnitude I_j; Δt_{ij} are determined by $\Delta \ell_i$ and also have an influence on I_j. With the repetition of such a sequential relationship in PD parameters, the impulse PD would propagate stepwise in N_2/SF_6 gas mixtures.

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