Temporal Development of Partial Discharge and Its Application to Breakdown Prediction in SF_6 Gas

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Abstract- **We measured the temporal change of partial discharge (PD) characteristics leading to breakdown in SF_6 gas for ac voltage application. At the final stage close to the breakdown, positive PD pulses with relatively high magnitude began to take place in the phase region near the applied voltage peak. This event was interpreted in terms of the change of PD type in SF_6 gas from streamer to leader. Optical observation also revealed that PD type transition occurred. With the results considered, the mechanisms of PD were discussed.**

Moreover, we discussed the possibility of breakdown prediction in GIS. An attempt was made to find a breakdown prediction parameter which characterized the change of PD type: the ratio R_L of maximum charge to the average charge of PD pulses appearing in the phase region near the peak in positive half cycle. It was found that R_L allowed to predict the time to breakdown successfully within the error of 4 ~ 20 %.

I. INTRODUCTION

Since SF_6 gas insulated swichgears (GIS) have been widely used in high voltage substations, a reliable and efficient diagnosis technique for insulation performance of GIS is strongly required [1]. There could exist various defects in GIS, such as conductor roughness, metallic particles, voids in spacers, and so on. Among them, metallic particles is the most typical insulation defect and one of the severest situation in GIS. These defects may give rise to partial discharge (PD), leading to breakdown. It has been required to elucidate the relationship between PD characteristics and breakdown for preventive maintenance of operating GIS [2]. However, it is insufficient to interpret physical breakdown processes in order to predict breakdown in GIS with high reliability [3]. Thus, understanding the fundamental phenomena is necessary to improve PD measurement and diagnosis techniques. Especially to assess actual insulation performance of GIS and to predict the breakdown, it is important to clarify how PD characteristics change from its inception to breakdown for different applied voltages or with time for an ac voltage application [4-7].

From the above points of view, we have been constructing a computer-aided PD measuring and diagnosis system on the basis of understanding PD phenomena in SF_6 gas [8-10]. In the previous reports, we tried to distinguish PD characteristics between in SF_6 gas and in air [8], and quantitatively investigated PD characteristics from its inception to breakdown in SF_6 gas [9, 10]. In this paper, we measure the temporal change of PD characteristics to breakdown in SF_6 gas for needle-plane electrode configuration for ac voltage application using the developed computer-aided PD measuring system. An attempt is also made to interpret the temporal change of PD characteristics in terms of the change of PD type. We also perform optical observation of PD light emission to discuss the change of PD type from its inception to breakdown. Moreover, we investigate the possibility of breakdown prediction by introducing a breakdown prediction parameter R_L which characterizes the change of PD type.

II. EXPERIMENTAL

Figure 1 shows a model GIS and a test circuit for measuring PD in SF_6 gas. A needle electrode to simulate a metallic particle in GIS was fixed on the high voltage conductor. In the experiments, we used the needle electrode made of aluminum with 5 mm in length and 0.25 mm in

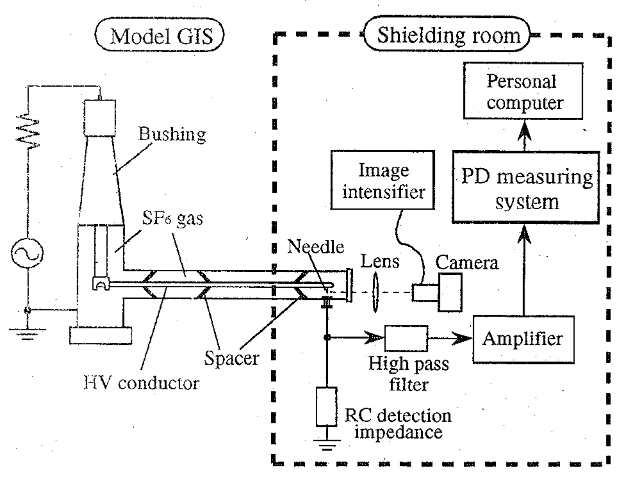

Fig.1 Model GIS and experimental setup.

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diameter. The needle tip was cut off horizontally. A plane electrode made of stainless steel was placed under the needle electrode. The gap length between the needle and plane electrodes was set at 7.0 mm. SF_6 gas with 0.4 MPa of pressure was filled in the model GIS. Light emission around the needle tip was taken with optics consisting of lenses, an image intensifier and a camera to observe PD type. The computer-aided PD measuring system allowed the phase-resolved measurements of PD characteristics [8].

III. PD CHARACTERISTICS UNDER LONG TIME AC VOLTAGE APPLICATION

A. PD Characteristics from Inception to Breakdown

As an example of quantitative analysis by the PD measuring system, Fig. 2 shows the maximum PD charge q_{max+} and q_{max-} per one ac half cycle for positive and negative PD pulses, respectively, as functions of SF_6 gas pressure and applied voltage V_a. This figure displays the quantitative transition of q_{max} from PD inception (PDIV) to breakdown (BD) for different gas pressures. At any pressure, the first PD occurs in the negative half cycle (negative PDIV). As V_a rises further, PD pulses also occur in the positive half cycle (positive PDIV). It is also seen that q_{max+} sharply increases with a rise of V_a, whereas q_{max-} increases slowly. We confirmed that breakdown always took place in a positive half cycle (BD). Thus, there exists such a remarkable polarity difference in the maximum charge q_{max} between positive and negative PD pulses.

B. Temporal Change of PD Characteristics

PD characteristics were measured several times under a constant ac voltage application for long time till breakdown. Breakdown occurred after the average time of 254 and 145 min for V_a = 50 and 55 kVrms, respectively. Figure 3 shows a typical result of temporal change of PD characteristics for V_a = 55 kVrms and time to breakdown t_B = 149 min. As seen in Fig. 3, the magnitude of PD pulses grows as the time goes on even though the applied voltage is kept constant. Especially, in Fig. 3 (f), positive PD pulses with relatively higher magnitude begin to take place in the phase region of the applied voltage peak. The result indicates that the increase in positive PD pulse may directly lead to breakdown. In fact, breakdown proved to occur at the positive half cycle for all cases. In other words, the magnitude of positive PD pulses may be closely related to breakdown.

Figure 4 shows the change of appearance of the needle electrode tip with transition time under the same conditions as those in Fig. 3. As seen in Fig. 4, the needle tip edge gets round gradually owing to the melting by PD. This change of the needle tip shape leads to the change of

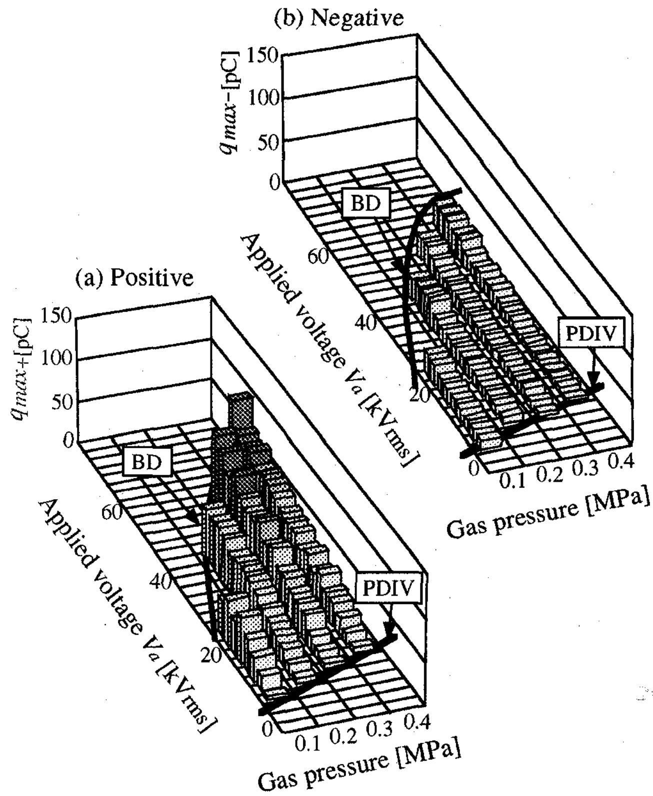

Fig.2 Maximum PD charge q_{max} as functions of SF_6 gas pressure and applied voltage.

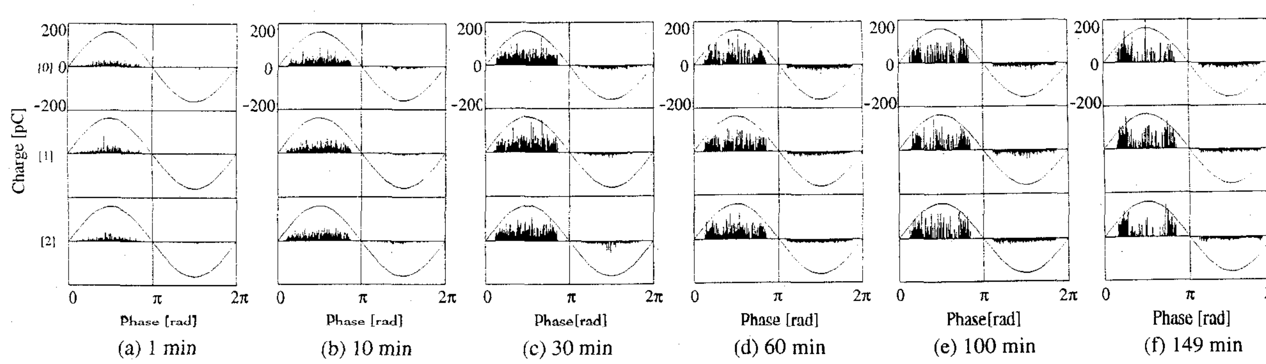

Fig.3 PD phase characteristics during long time ac voltage application.
Applied voltage V_a = 55 kVrms, time to breakdown t_B = 149 min.

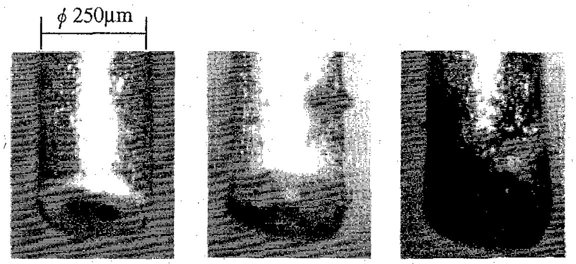

Fig.4 Change of needle electrode tip with transition time of ac voltage application.

PD characteristics and PD type; these phenomena will be discussed section IV.

C. Transition of PD Mechanism for Long Time PD Characteristics

We try to interpret the change of PD characteristics leading to breakdown for long time ac voltage application to the needle electrode as follows: it seems in Fig. 3 that negative PD pulses change only slightly, while positive ones with relatively higher magnitude begin to take place in the peak region of the applied voltage phase at the final stage close to the breakdown. This event can be interpreted in terms of the change of PD mechanism in SF_6 gas from streamer to leader corona.

Figure 5 depicts a schematic illustration of temporal change of PD characteristics and breakdown process, together with the relation between breakdown voltage V_B, PD inception voltage V_i and SF_6 gas pressure P. In Fig. 5 (a), at the initial stage immediately after voltage application, the measuring point A(V_a, P_a) lies in the corona stabilization region between V_B and V_i, so that PD occurs without breakdown. Discharge type of the positive PD is streamer corona. As the time goes on, the tip radius of the needle gets larger as shown in Fig. 4, resulting in the enlargement of streamer corona region. Figure 5 (b) shows the middle stage, where the leader inception voltage level is lower than the measuring point. At this stage, leader corona begins to emerge near the peak phase region of the positive half cycle. Figure 5 (c) shows the final stage just before breakdown where the breakdown curve is close to the measuring point. A number of PD pulses due to leader corona occur together with streamer corona pulses. Because of further enlargement of the needle tip radius, the measuring point crosses the breakdown voltage curve, where the propagating leader corona leads to breakdown. The above interpretation for transition of PD mechanism can be verified by the experimental results of PD characteristics, as will be shown in the next section .

IV. TRANSITION OF PD CHARACTERISTICS AND PD TYPE IN SF_6 GAS

Figure 6 shows the light emission of PD and the corresponding PD phase characteristics for different SF_6 gas pressures and applied voltage V_a at the needle tip radius R = 500 μm and the gap length g = 25 mm for PD observation with the optics including the image intensifier. It is found from Fig. 6 that both the intensity and area of luminous region increase with rising V_a. The observed results of the light emission are consistent with the PD phase characteristics; i.e. both the repetition rate and magnitude of PD pulses increase with rising V_a as shown in Fig. 6. When V_a exceeds 60 kVrms, a few filamentary bright lines begin to emerge out of the sphere-like luminous region. It is also evident that the length of the filamentary lines increases as V_a rises. These results indicate that PD mechanism has changed with V_a as shown in Fig. 5.

It is generally recognized that as V_a increases, the discharge type of positive PD changes from streamer to leader corona at a constant pressure [3, 5]. Further increase

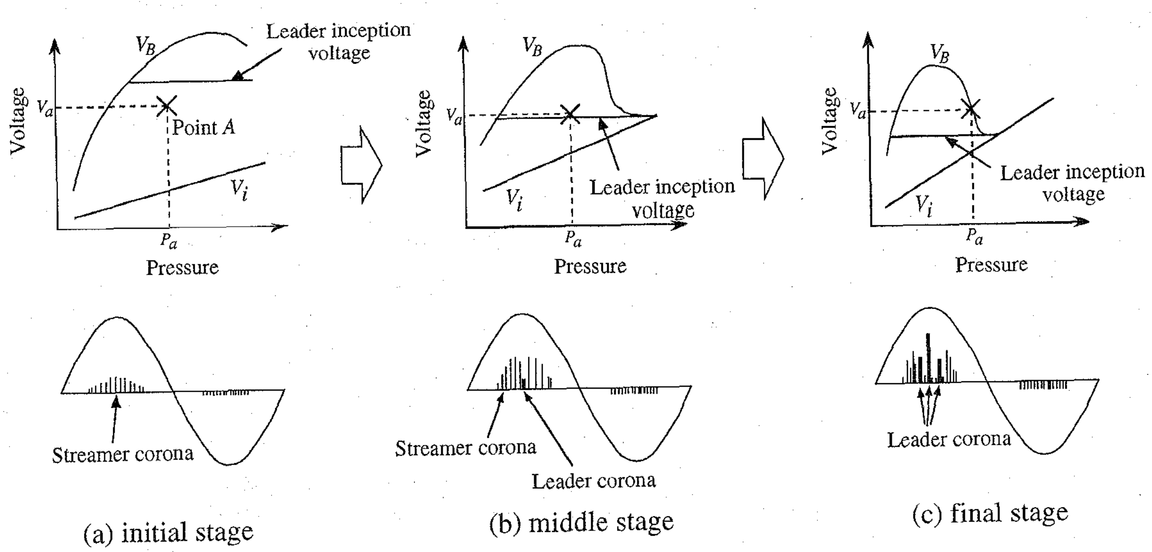

Fig.5 Schematic illustration of temporal change of PD characteristics and breakdown process.

in V_a causes the leader to extend longer length resulting in breakdown. With both the present experimental results and the above reports considered, we believe that the filamentary bright lines and the sphere luminous part represent leader and streamer corona, respectively.

It is also evident from Fig. 6 that the light intensity of the sphere luminous part at 0.4 MPa is weaker than that at 0.2 MPa, and the number of filamentary lines at 0.4 MPa is more than that at 0.2 MPa. These results are interpreted in terms of weaker corona stabilization effect for 0.4 MPa resulting in the lower breakdown voltage than that for 0.2 MPa. In other words, the streamer corona occurring at 0.2 MPa causes the corona stabilization effect to act more strongly. As a result, the breakdown voltage at 0.2 MPa becomes larger than that at 0.4 MPa because of more effective field relaxation near the needle tip.

Next, we estimate the field strength at corona tip from the length of light emission observed from Fig. 6 with an aid of numerical field calculation. Figure 7 shows thus obtained electric field strength Ec at the corona tip as a function of applied voltage for different gas pressures. It is found that Ec coincide comparatively with critical field Ecr = 89 V/m·Pa of SF_6 gas at 0.1 - 0.2 MPa. Note that the critical field for each pressure is drawn by doted line in the figure. The region to which the light emission extends depends on Ecr of SF_6 gas, i.e. the corona stabilization effect determines the region. Whereas at 0.3 - 0.4 MPa, Ec is lower than Ecr for the higher V_a. The results indicate that leader corona propagates beyond the region determined by Ecr of the streamer corona. Further propagation of leader corona leads to breakdown. As a consequence, the optical observation revealed that the corona stabilization works more effectively with increasing the streamer corona radius. It is also found that the results of the light emission and PD characteristics for different V_a and P shown in Fig. 6 are consistent with those of the temporal change of PD characteristics in Figs. 3 and 5.

V. BREAKDOWN PREDICTION IN SF_6 GAS

In the previous section, we quantitatively investigated the transition of PD characteristics from its inception to breakdown using the PD measuring system and the optical arrangement. With all the results considered, an attempt will be made to predict the time to breakdown viewed from the transition of PD characteristics. In other words, we try to predict breakdown by observing the change of the discharge type of PD occurring in positive half cycle from streamer to leader corona finally leading to breakdown as shown in Figs. 5 and 6. We propose a breakdown prediction parameter R_L which characterizes the change of PD characteristics near the peak in the positive half cycle; R_L is defined as follows:

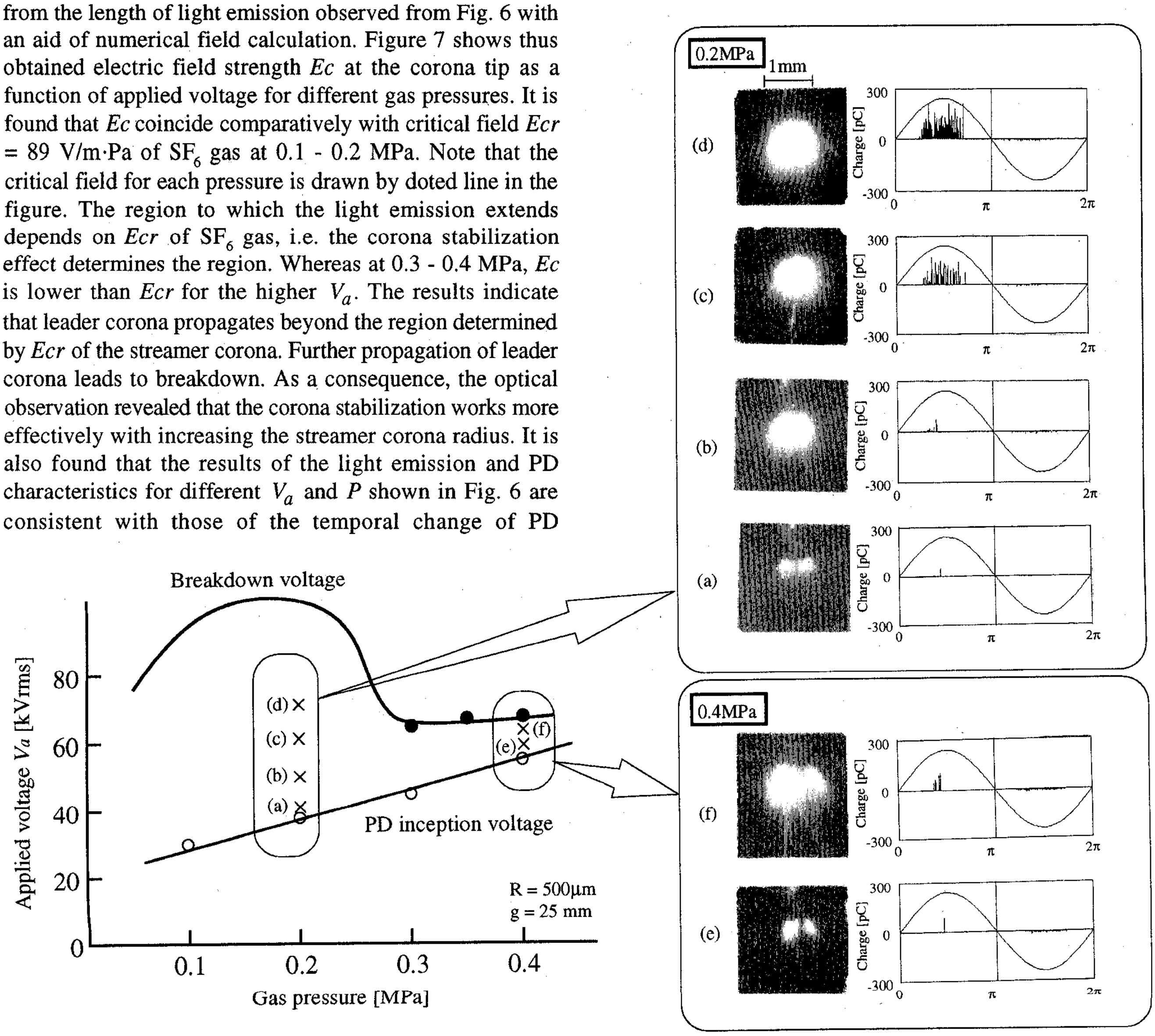

Fig.6 Light emission of PD and PD phase characteristics for different V_a at 0.2 and 0.4 MPa.

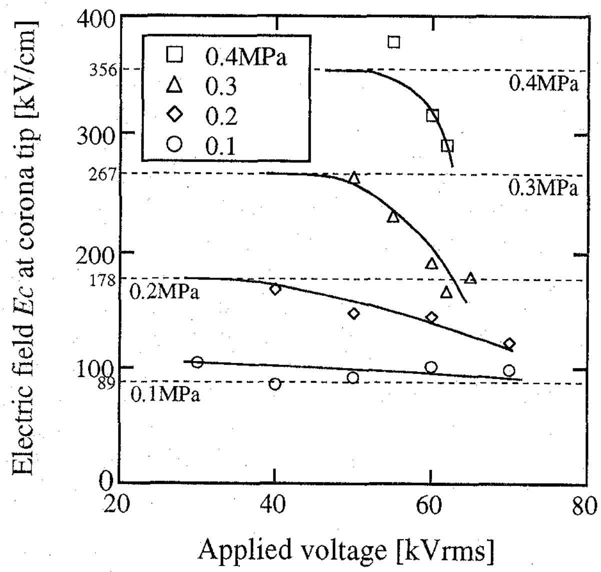

Fig.7 Electric field Ec at corona tip as a function of applied voltage. (Dotted line indicates the critical field strength.)

$$R_L = \frac{q_{\max+(60^\circ-120^\circ)}}{\bar{q}_{+(60^\circ-120^\circ)}} \qquad (1)$$

R_L is the ratio of the maximum charge q_{max+} to the average charge $\bar{q}_+$ of positive PD pulses both of which take place in the voltage phase region between 60° and 120°. In other words, R_L indicates how different the magnitude of PD pulses is in the designated phase region. Figure 8 shows the breakdown prediction parameter R_L as a function of time normalized by each time to breakdown t_B for all the experimental conditions. As seen in Fig. 8, the change of R_L with t/t_B falls into a universal curve for most cases in spite of the slight scattering. As approaching to the breakdown, R_L rises from 5 to 11. The solid line in Fig. 8 indicates the approximated curve experimentally obtained as follows;

$$R_L = \exp(1.50 + 0.908 \times t/t_B) \qquad (2)$$

Hence, there is the possibility that equation (2) permits to predict the time to breakdown t_{BP} by watching the change of R_L. Using equation (2), we calculated the prediction time to breakdown t_{BP} from the normalized time t/t_B when R_L = 10; i.e. it is assumed in our experimental conditions that the threshold value of R_L for breakdown is set at R_L = 10. For example, the time calculated from R_L = 10 is 138 min, while t_B = 149 min for V_a = 55 kVrms. As a result, t_{BP} = 155 min is predicted by equation (2); the error between t_B and t_{BP} is 6 min (4 %) for the actual time to breakdown. Table 1 summarizes the results of breakdown prediction for most cases. As seen in Table 1, watching the change of R_L with time permits a correct prediction of the time to breakdown within the error of 4 ~ 20 %.

Table 1 Error between time to breakdown t_B and prediction time to breakdown t_{BP}.

Applied voltage V_a [kVrms]	Time to breakdown t_B [min]	Prediction time to breakdown t_{BP} [min]	Error [%]
50	234	186	20
	274	227	17
55	118	108	8
	147	137	7
	149	155	4
	167	184	10

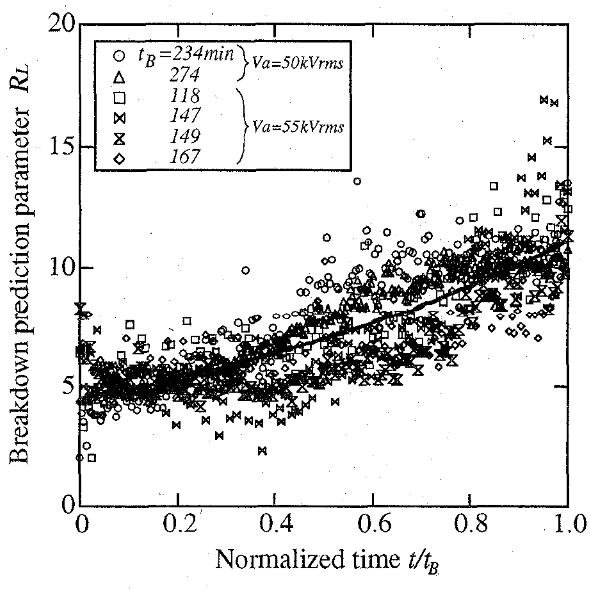

Fig.8 Breakdown prediction parameter R_L as a function of normalized time t/t_B.

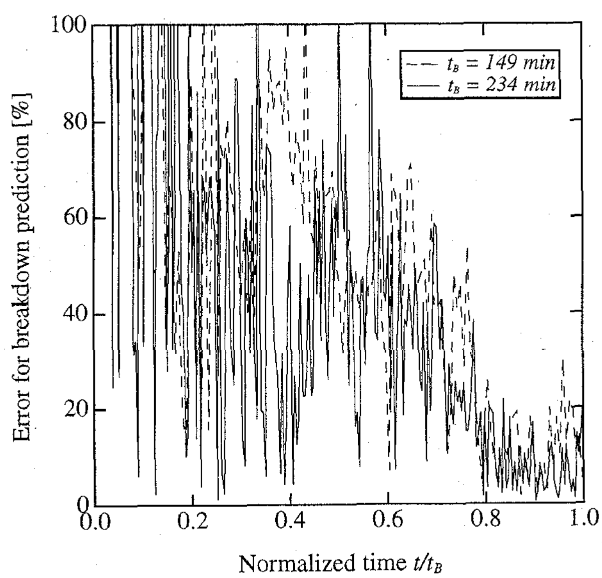

Fig.9 Error for breakdown prediction with R_L as a function of normalized time. V_a = 55 kVrms, t_B = 149 min.

Figure 9 shows the error between t_B and t_{BP} as a function of time for t_B = 234 min and t_B = 149 min. As seen in Fig. 9, the error falls with time, i.e. the precision of the breakdown prediction is improved as the time approaching to breakdown. At the final stage close to breakdown (t/t_B = 0.8 - 1.0), breakdown is predicted with an error less than 20 %. Consequently, R_L is regarded as a useful parameter to predict time to breakdown in SF_6 gas. Moreover, it is also expected that combining other PD statistical parameters with R_L will highly enhance the breakdown prediction probability.

VI. CONCLUSION

We investigated PD in SF_6 gas for assessing the insulation performance in GIS. We measured the temporal change of PD characteristics to breakdown for ac voltage application at a given constant SF_6 gas pressure. As time went on, the magnitude of PD pulses increased. Especially, at the final stage close to breakdown, positive PD pulses with relatively higher magnitude began to take place in the phase region near the applied voltage peak. This event was interpreted in terms of the change of PD type in SF_6 gas from streamer to leader. This consideration was also confirmed by observing the change of light emission related to PD type with the optics consisting of lens, and an image intensifier. Experimental results revealed that PD type changed from streamer to leader with a rise of applied voltage.

Moreover, we investigated the possibility of breakdown prediction in GIS; an attempt was made to find a breakdown prediction parameter which characterizes the change of PD type: the ratio R_L of the maximum charge to the average charge of positive PD pulses occurring near the peak in positive half cycle. As approaching to breakdown, R_L rose from 5 to 11 in the approximated curve for most cases. When R_L was used as a breakdown prediction parameter, the time to breakdown could be successfully predicted within the error of 4 ~ 20 %. Thus, we suggested the possibility that R_L will allow the breakdown prediction in SF_6 gas for metallic particle defect.

VII. REFERENCES

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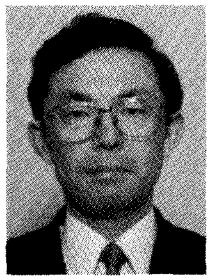

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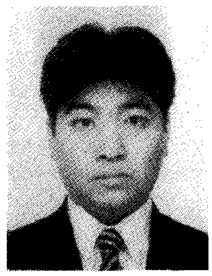

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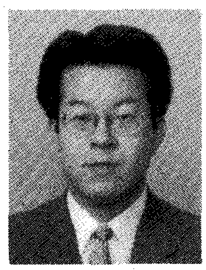

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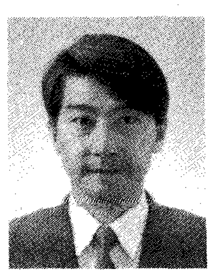

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