

Dependence of Partial Discharge Characteristics at Spacer Surface on Particle Size in SF₆ Gas Insulated System

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Abstract--A metallic particle appeared in a gas insulated switchgear (GIS) sometimes adheres on a solid spacer surface. If the adhered metallic particle is exposed to a surge high voltage, a breakdown (BD) may be induced. Therefore, it is eagerly demanded to diagnose its risk correctly under the service voltage by partial discharge (PD) measurement.

In this paper, particle-initiated surface PD characteristics were systematically studied in 0.4 MPa SF₆ gas by changing the sizes of particles. PD inception voltage (PDIV), temporal change of PD current and the PD pulse number were analyzed in detail. Furthermore, comparing with PD characteristics of particles in a gas gap, the influence of the solid insulator on the PD characteristics was clarified. It was found out that PD characteristics greatly changed with time owing to electric charges deposited on a spacer surface.

Index Terms--GIS, Partial discharges, Diagnosis, Particle, SF₆ gas.

I. INTRODUCTION

Though GIS is very reliable equipment, defects such as metallic particles sometimes influence its insulation reliability. Metallic particles lift off and move by the electrostatic force under the service voltage. And they have a chance to adhere on a solid insulator surface. Adhered particles continue to stay there for a long time by the electrostatic attraction. Under such a condition, when surge high voltages come into GIS, BD can be induced. PD usually appears at the service voltage and PD measurements are recognized as the most effective tool for finding particles in GIS. Many kinds of PD diagnostic methods have been applied to GIS, and their effectiveness has been reported [1-4]. To estimate the insulation reliability of GIS, the risk of particle-initiated PD must be assessed correctly. Though, many studies about particle-initiated PD have been conducted [5-10], the risk assessment based on PD mechanism has not yet been established.

In this paper, PD characteristics of various sizes of metallic particles on a spacer were systematically measured and analyzed under the service electric field strength. It was found out that PD characteristics markedly depended on the particle size. Moreover, PD characteristics were compared with those of protrusions in a gas gap, and their differences were clarified quantitatively.

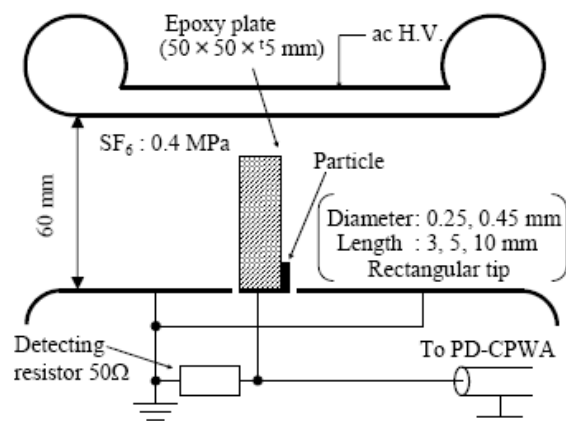


Fig. 1 Electrode

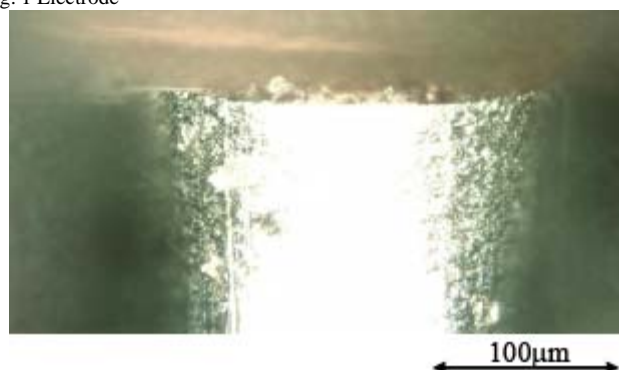


Fig. 2 Shape of a metallic particle tip (diameter : 0.25 mm).

II. EXPERIMENTAL METHODS

Figure 1 shows an experimental setup. An epoxy plate filled with alumina was placed in the parallel-plane electrodes of a 60 mm long gap. A metallic particle (diameter: 0.25, 0.45 mm, length: 3, 5, 10 mm, rectangular cut) was fixed at the triple junction between the epoxy plate, the grounded electrode and SF₆ gas. The tip shape of a metallic particle was rectangular (Fig. 2). Material of a particle was aluminum (0.25 mm diameter) and copper (0.45 mm diameter). SF₆ gas pressure was 0.4 MPa. Ac high voltage was usually gradually increased to the experimental value. In this conventional method, PD appeared and space charges from PD were deposited on the spacer surface during voltage increase. Deposited charges greatly influence PD characteristics at the target voltage. To prevent this, the target ac voltage was applied by only one-step in this experiment. This one-step

method can simulate the moment when a particle adhered to the spacer surface under the operational condition. As the service electric field strength of GIS is 2.0 ~ 2.5 kV_{rms}/mm, the applied ac voltage was 120 kV_{rms}.

All PD current pulses were sequentially measured with the ultra-high speed PD-CPWA (PD current pulse waveform analyzing system) [11]. PD-CPWA could obtain not only the waveforms of PD current pulses, but also the PD behavior from PD inception to BD. The PD detection sensitivity is 0.1 pC. The obtained waveforms of PD current pulses could be analyzed in terms of the peak value, di/dt, the rise time, the fall time of each PD current pulse, the time interval of subsequent PD current pulses and so on.

Table 1. PD inception voltage in various experimental condition

Particle diameter [mm]	Particle length [mm]	PDIV [kV _{rms}]	
		Particle condition	
		Surface case	Gas gap case
0.25	3	60	75
	5	48	58
	10	19	31
0.45	3	100	120

III. EXPERIMENTAL RESULTS

A. Partial Discharge Inception Voltage

Table 1 shows PD inception voltage (PDIV) of various particles on an epoxy plate surface (surface case) and in a gas gap (gas gap case). In the gas gap case, an epoxy plate was removed in Fig. 1. As a particle became thin and long, PDIV decreased. In all sizes of particles, PDIV of the surface case was about 20 ~ 30 % lower than that of the gas gap case.

B. Time Dependence of Partial Discharge Activities

Figure 3 shows sequential PD pulses at 0, 5, and 30 sec after the voltage application of 120 kV_{rms} (diameter : 0.45 mm, length : 3 mm). The voltage polarity is expressed as the polarity of a metallic particle tip. PD initiated at several cycles after the voltage application. Negative PD appeared constantly at most cycles, but positive PD did not. Until about 10 cycles after the voltage application, few positive PD appeared. At about 10 ~ 20 cycles after the voltage application, positive PD appeared at nearly half of cycles. After that, positive PD appeared in most cycles. Thus, PD activities changed greatly within 20 cycles after the voltage application. After 20 cycles, PD activities became stable. The other sizes of particles showed similar changes of PD activities.

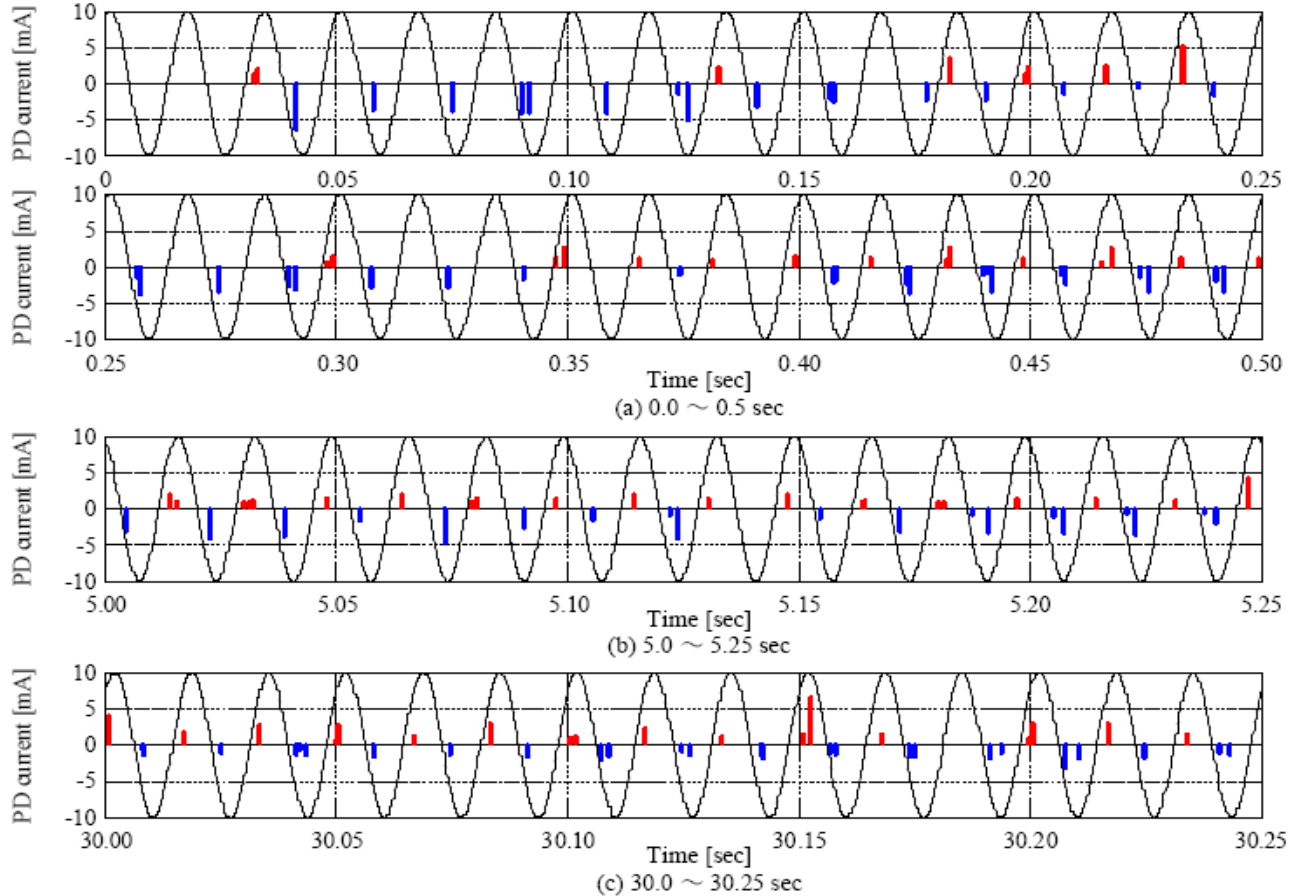


Fig. 3 Temporal behavior of PD pulses (surface case, diameter : 0.45 mm, length : 3 mm, 120 kVrms).

Figure 4 shows time dependence of PD current (diameter : 0.45 mm, length : 3 mm). Circles before 1 sec are expressed as the mean value for 10 cycles, whereas the other circles are expressed as the mean value for 1 sec. Bars show the standard deviation. Negative PD current decreased with time. However, positive PD current was nearly constant. Negative PD current decreased rapidly in 1 sec, and after that it decreased slowly.

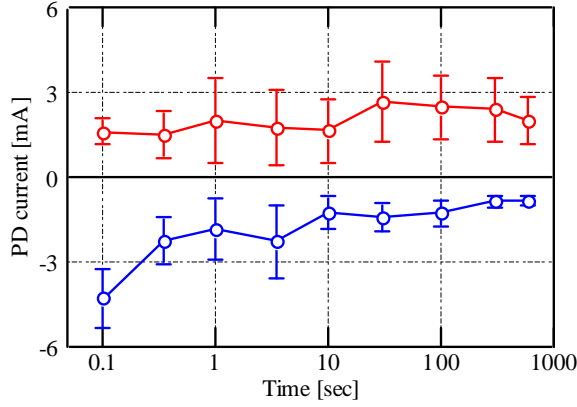


Fig. 4 Temporal change of PD current
(surface case, diameter : 0.45 mm, length : 3 mm, 120kV_{rms}).

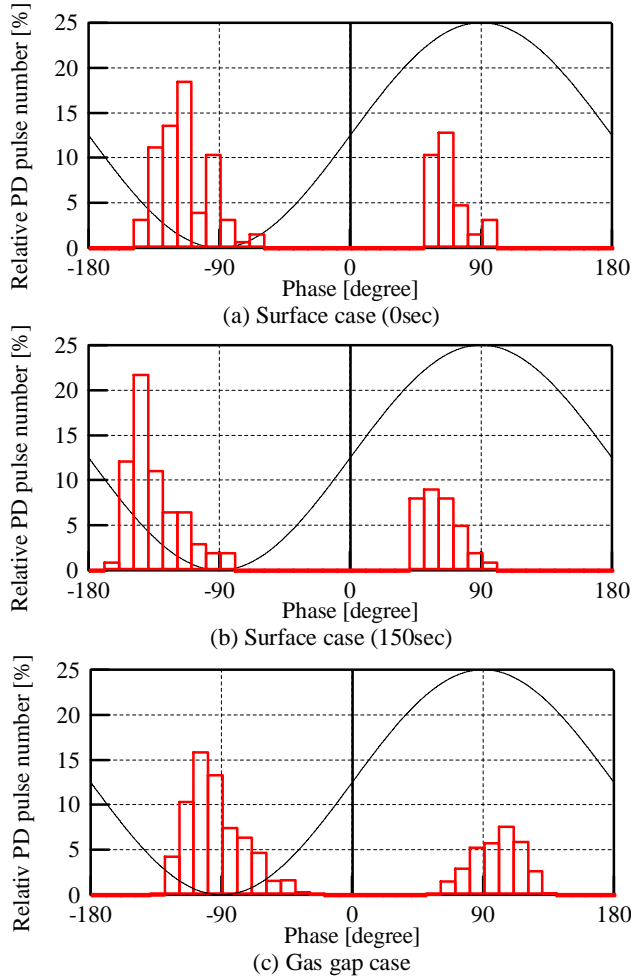


Fig. 5 PD pulse number – voltage phase ($\phi - n$) characteristics
(diameter : 0.45 mm, length : 3 mm, 120 kV_{rms}).

Figure 5 shows time dependence of the $\phi - n$ characteristics between the voltage phase (ϕ) and the PD pulse number (n) (diameter : 0.45 mm, length : 3 mm). Sinusoidal curves show the applied voltage. The PD pulse number shows pulses appeared in 1sec, and was plotted as the relative value in Fig. 5. At 0 sec (Fig. 5 (a)), many PD appeared near the peak of the applied voltage at both negative and positive polarities. This tendency was nearly equal to that in the gas gap case (Fig. 5 (c)). However, at 150 sec (Fig. 5 (b)), the distribution of the negative PD pulses shifted to the early phase side, and many PD appeared in the early phase and the PD pulse number decreased near the voltage peak.

C. Dependence of PD Characteristics on Particle Diameter

Figure 6 shows the dependence of PD characteristics on the metallic particle diameter (length : 3 mm). Circles show positive PD, and triangles show negative PD. Solid lines correspond to the surface case, and broken line to the gas gap case. Figure 6 (i) shows the characteristics immediately after the voltage application. Figure 6 (ii) shows the characteristics at the time when PD characteristics were stable (300 sec after the voltage application). PD current became large as the particle diameter was large (Fig. 6 (a)). This tendency was observed at 300 sec, too. On the other hand, in the gas gap case, only negative PD appeared and PD current didn't change between different particle diameters.

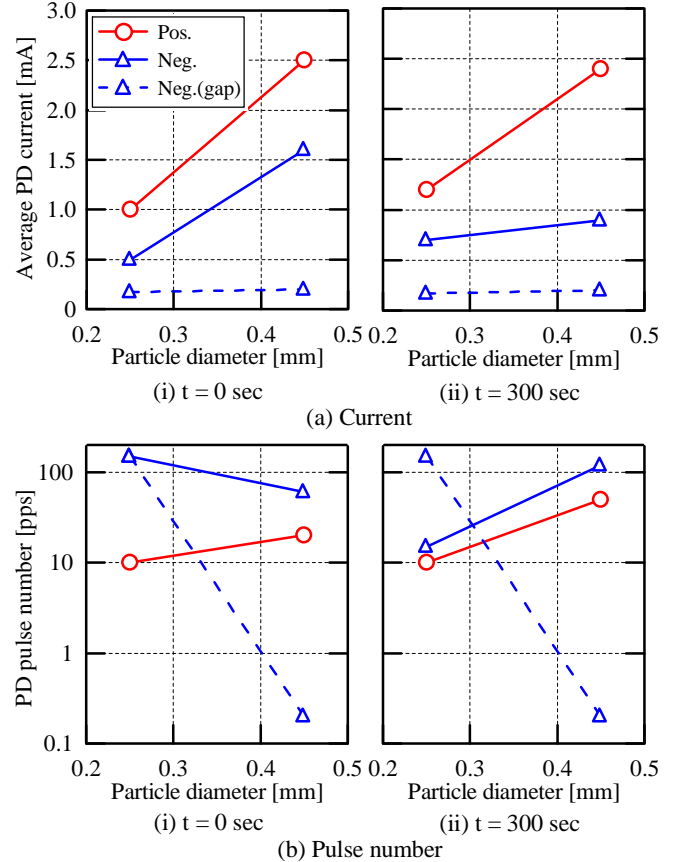


Fig. 6 Dependence of PD characteristics on particle diameter
(length : 3mm, 120 kV_{rms}).

The pulse number of negative PD at 0 sec was nearly equal between the spacer and the gas gap cases (Fig. 6 (b) (i)). At 0 sec, when particles became thick, the pulse number of negative PD decreased, and that of positive PD increased. At 300 sec, the pulse number of negative PD at 0.25 mm diameter in the surface case became one tenth of that at 0 sec. But the pulse number of negative and positive PD increased at 0.45 mm diameter. As a result, the pulse number increased when particles became thick. These characteristics were extremely different from those in the gas gap case. The reason of these tendencies will be discussed in the next chapter.

IV. DISCUSSIONS

A. Partial Discharge Inception Voltage

PDIV was dominated by the electric field strength near the metallic particle tip. The electric field strength differed between the particle lengths (Fig. 7 (a)). The particle diameter was 0.25 mm and the applied voltage was 120 kV_{rms} in Fig. 7. Intensity of electric field strength decreased rapidly as the distance from the particle tip became large. It extremely concentrates near the particle tip as a metallic particle becomes long. The maximum field strength in the surface case is about twice of that in the gas gap case (Fig. 7 (b)). When the particle diameter became large from 0.25 to 0.45 mm, the electric field strength was weakened by about 70 %. These tendencies corresponded well to the difference in PDIV in Table 1.

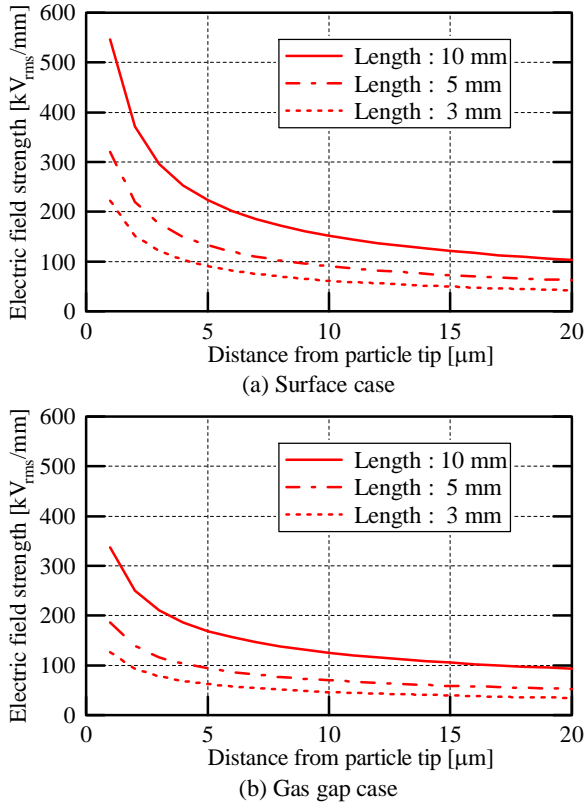


Fig. 7 Electric field distribution near a particle tip (diameter : 0.25 mm, 120kV_{rms}).

B. Time Dependence of Partial Discharge Activities

(B-1) PD inception characteristics

Though the applied voltage (120 kV_{rms}) was higher than PDIV (Table 1), no PD appeared in several cycles after the voltage application. On the other hand, in the conventional method of the voltage application, PD appeared at the instance when the applied voltage reached the target value higher than PDIV. This difference in the PD inception between two methods was considered to be caused by the number of initial electrons for PD generation.

In the conventional method, many PD appeared during the voltage increase up to the target value. So, sufficient electrons were provided at the moment when the applied voltage reached the target value. However, in the one-step method, the number of electrons near the particle tip was too small to initiate PD. Therefore, it took several cycles to initiate PD. After that, as many electrons were supplied by previous PD, PD appeared continuously.

(B-2) Temporal change of PD characteristics

PD appearance is closely related to the electric field strength near the metallic particle tip. Furthermore, the electric field strength is influenced by charges accumulated on the epoxy plate surface. At several cycles after the voltage application, a small number of charges were accumulated, and the distribution of the accumulated charge changed greatly every time PD appeared. When the ac voltage was applied for a long time, many PD appeared and the quantity of the accumulated charge became sufficient not to be influenced by successive PD. Then, PD characteristics became stable. Therefore, PD characteristics were greatly influenced by the duration of the applied voltage.

(B-3) ϕ - n characteristics

In Fig. 5, PD characteristics changed with time. But the characteristics at 0 sec were similar to those in the gas gap case. These mean that ϕ - n characteristics were not influenced by the epoxy plate at the moment of the voltage application. As a very small quantity of charges was accumulated around the particle tip, it was supposed that PD was dominated by the applied electrostatic field strength. On the other hand, after a large quantity of charges was accumulated (Fig. 5 (b)), the accumulated surface charge greatly affected the electric field distribution.

Figure 8 shows the influence of the accumulated surface charge on the maximum electric field strength (length : 3 mm). In this calculation, it was assumed that charges were accumulated in the region of 5 mm in length and 200 μm in depth in the epoxy plate. Positive charge density is in the same polarity as the metallic particle tip. The maximum electric field strength was greatly influenced by the accumulated charge. When the polarity was the same between a charge and a particle, the maximum electric field strength weakened.

When the polarity was opposite, the maximum strength increased. Therefore, PD could appear at a low voltage (early phase) under the accumulation of the charge in

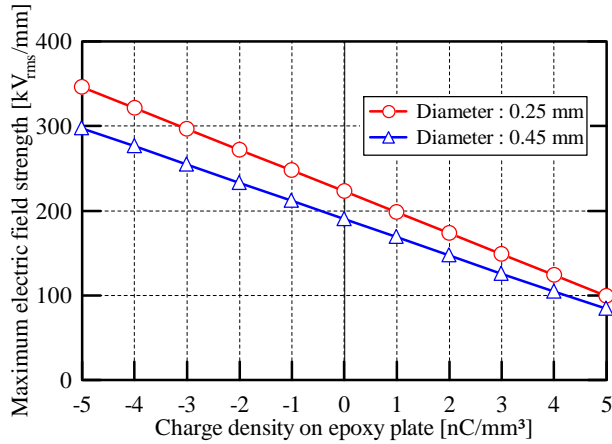


Fig. 8 Change of maximum electric field strength by surface charge accumulated on an epoxy plate (length : 3 mm, 120 kV_{rms}).

the opposite polarity. After the PD appearance, the accumulated charge turned to the same polarity as the applied voltage. And then the electric field weakened. So, PD did not appear at the next voltage peak. These caused the shift of $\phi - n$ characteristics into the early phase, as was shown in Fig. 5 (b).

C. Dependence of PD Pulse Number on Particle Diameter

When a particle became thick from 0.25 to 0.45 mm, the PD pulse number decreased immediately after the voltage application, and then, after that, increased (Fig. 6 (b)). These tendencies were explained by the charge deposition.

At 0 sec, (Fig. 6 (b) (i)), a quantity of charges deposited near the particle tip was too small to affect the electric field strength. So, the electric field strength was determined by the applied electric field strength (Fig.7 (a)). However, at 300 sec (Fig. 6 (b) (ii)), a large quantity of charges was accumulated, and it affected the electric field strength. This effect became large as a particle was thin. So, the influence on the PD pulse number was larger at 0.25 mm diameter than at 0.45 mm one.

V. CONCLUSIONS

PD characteristics of various metallic particles on the epoxy plate were measured and analyzed using the ultra-high speed measurement system. Temporal change of PD characteristics and dependence of PD characteristics on the particle size were discussed. The following results were obtained.

- (1) The electric field strength near the metallic particle tip was intensified extremely when a metallic particle was fixed on the epoxy plate. And PDIV decreased by about 20 ~ 30%.
- (2) PD didn't appear in several cycles after the voltage application even if the applied voltage was much higher than PDIV. Temporal change of PD characteristics was extremely large immediately after the voltage application.
- (3) The $\phi - n$ characteristics shifted from the voltage peak to the early phase side when the duration of the applied voltage became long.

- (4) PD current increased with the particle diameter. PD pulse number depended on the particle diameter and time. Immediately after the voltage application, the PD pulse number decreased with metallic particle diameter. However, after several minutes, the PD pulse number started to increase with the particle diameter.
- (5) Complex PD characteristics of different sizes of particles were qualitatively explained with the surface charges accumulated on the epoxy plate near the particle tip.

VI. REFERENCES

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