Charge Accumulation Effects on Time Transition of Partial Discharge Activity at GIS Spacer Defects

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ABSTRACT

The partial discharge (PD) measurements are considered as the most important tool for condition monitoring of Gas Insulated Switchgears (GISs). However, if spacer surface is involved in PD activity, charge accumulation process greatly affects the time transition of PD characteristics. This paper investigates this effect considering the defect types of delamination at the electrode/spacer interface and metallic particles adhered to the spacer surface as the most serious defects that can lead to major failure. Two different electrode configurations were built to simulate the two defect types. The PD characteristics were measured and analyzed from immediately after voltage application up to several minutes where steady state characteristics have been obtained. As a result, it was found that the generation rate of PD pulses changed considerably with time for both defect types. This tendency of PD characteristics has been discussed considering the effect of charge accumulation. Comparing these effects for negative and positive PD enabled to clarify the similarities and differences in the charge accumulation effect for both defect types which can contribute to the defect type identification in GIS. It was found that the effects of charge accumulation on the electric field strength for the delamination defect case as well as on the ionization volume for the metallic particle case were the responsible parameters for the different PD tendencies.

Index Terms — **Partial discharges, charge accumulation, spacer, gas insulated switchgear, delamination gap, metallic particle.**

1 INTRODUCTION

INTEREST in insulation condition monitoring and diagnosis in gas insulated switchgears (GISs) aims principally to achieve high reliability of such equipment [1]. Partial discharge (PD) measurement is usually used for this purpose [2]. In particular, PD measurements have been investigated for identification of defect type and size in GIS [3, 4]. Generally, PD inception and propagation characteristics are changed by the local electric field at defects. If a dielectric surface is involved in the PD activity, changes in PD characteristics may occur even over a short time scale as a result of charge accumulation on the dielectric surface from previous PD events [5]. In GIS, this phenomenon occurs if the defect type is related to a solid insulating spacer. It is expected that understanding the effect of charge accumulation on PD activity will be helpful in PD diagnosis of an actual GIS.

Different defect types that can be related to solid spacers in GIS are voids, delamination at the interface, and particles on surfaces [6]. The role of charge accumulation in PD activity initiated at voids has been extensively investigated by many researchers [7, 8]. However, less attention has been paid for the other two types especially for a delamination defect due to the experimental difficulties in building micro gap structure

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required to simulate actual delamination gap lengths in a GIS spacer which are usually below 100 μm.

From this point of view, in this paper, the effect of charge accumulation on PD activity for electrode/epoxy delamination defect is explored and compared to that for metallic particles adhered to the spacer surface. This effect is observed from the time transition of PD generation rate over 10 minutes from just after voltage application. To simulate the two defects, different electrode configurations were built and set in a GIS model. The tendency in the generation rate for positive and negative PD is investigated for both defects to enable extracting the certain features of partial discharges that can be affected by accumulated charges. Finally, to clarify the charge accumulation process, surface potential measurements are carried out after voltage application and then, the modification in local electric field is analyzed and discussed for both defect types.

2 EXPERIMENTAL ARRANGEMENT

2.1 ELECTRODE CONFIGURATION

Two electrode configurations were built to simulate the different defect types related to solid insulating spacers as shown in Figures 1 and 2. Both electrode setups were installed in a pressurized chamber filled with SF_6 gas where experiments were conducted.

Figure 1 shows the electrode system setup to simulate the delamination defect at the electrode/epoxy interface in SF_6 gas. The electrode setup consisted of molded type high voltage electrode and grounded plane electrode. The high voltage electrode was molded to prevent discharges at the electrode edge. The high voltage electrode diameter is 60 mm and the molding insulation diameter is 90 mm with relative permittivity of 3.7. The grounded plane electrode was made of SUS304 with average surface roughness of 7.4 μm. An alumina filled rectangular epoxy plate (100 mm × 100 mm × 5 mm thickness) with relative permittivity of 6.0 was sandwiched between high voltage and grounded electrodes. A stack of thin dielectric films with each 25 μm thickness was used to adjust the gap between the epoxy plate and grounded electrode. This made it possible to change the gap length from direct contact to very small gap length, 50 μm, in order to simulate delamination at the electrode/epoxy interface in a GIS spacer. The dielectric film was set away from the discharge area to avoid its interaction with PDs. The gap was kept open to be filled with the same gas and pressure inside the chamber. Actually, when a delamination suddenly occurs, the gas pressure in the delamination gap could be below or equal to atmospheric pressure and then the SF_6 gas would permeates gradually from the GIS tank into the delamination gap. For this reason, in this study, SF_6 gas at 0.1 MPa is considered for the time transition of partial discharge activity at the initial stage of delamination occurrence.

For metallic particles adhered to the spacer surface, electrode system setup is shown in Figure 2 with enlarged shape of the tip of a metallic particle. An epoxy plate filled with alumina was placed in the parallel-plane electrodes of a 60 mm gap length. The relative permittivity is 6.0. A square-cut metallic particle was fixed at the triple junction between the epoxy plate, the grounded electrode, and SF_6 gas. The particle material was made of aluminum. Different particle sizes were used with diameters of 0.25 mm and 0.45 mm, and length L 3 mm. The pressure of SF_6 gas was 0.4 MPa in this case. For both electrode setups, ac high voltage with 60 Hz was applied.

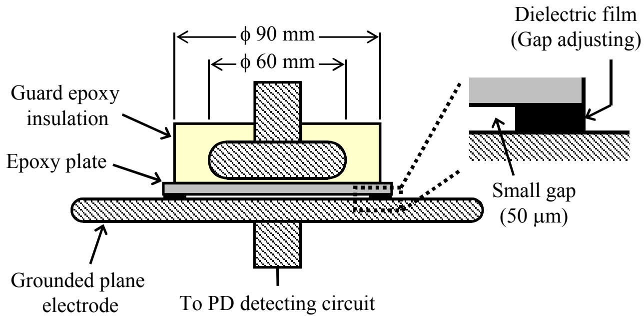


Figure 1. Electrode system setup to simulate delamination at the electrode/epoxy interface in SF_6 gas (Delamination defect).

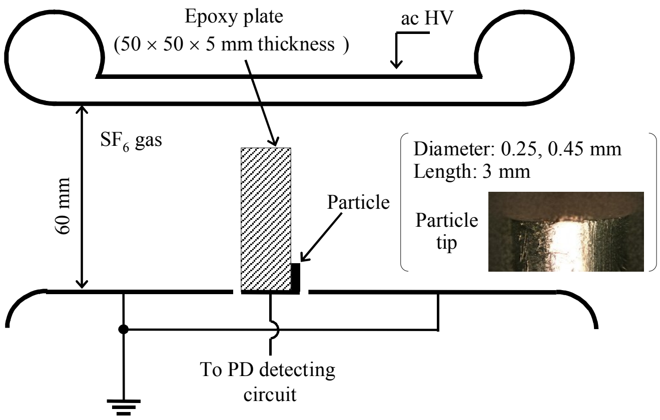


Figure 2. Electrode system setup for metallic particles adhered to the spacer surface in SF_6 gas (Metallic particle defect).

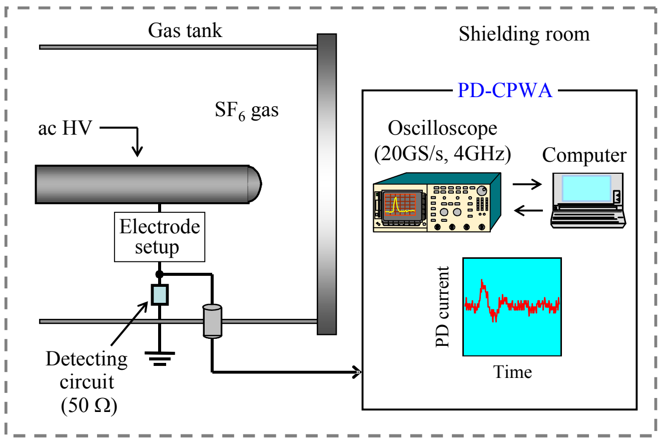


Figure 3. PD measurement system.

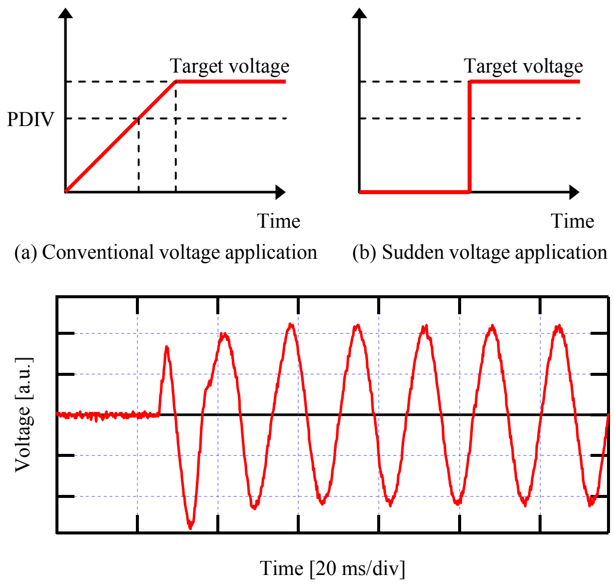
2.2 PARTIAL DISCHARGE MEASUREMENT SYSTEM

After the electrode setup was installed in a pressurized chamber filled with SF_6 gas, the PD measurement system was established as shown in Figure 3. PD current pulses were detected with 50 Ω resistor. The detected PD pulses were fed into a large bandwidth digital oscilloscope (20 GS/s, 4 GHz). All PD current pulses were then analyzed sequentially by PD-Current Pulse Waveform Analysis (PD-CPWA) developed in [9]. By PD-CPWA, the transition of PD current and number of PD pulses over the time could be obtained.

2.3 VOLTAGE APPLICATION

In order to measure the PD inception voltage (PDIV), the target ac high voltage with frequency 60 Hz has been increased gradually until PD occurs. However, for investigating temporal change of PD characteristics, in this paper, the target ac voltage is applied suddenly to prevent PD occurrence and charge accumulation during voltage increasing process. Figure 4 shows the conventional and sudden voltage application method with typical ac waveform for sudden voltage application.

For the delamination defect, two different voltages were applied to change the local electric field at the delamination gap. These applied voltages (V_a) are 1.0 and 1.3 times PDIV which is 14.5 kV_{rms}. In case of a metallic particle defect, the applied voltage V_a was set at 120 kV_{rms} to give the same



(a) Conventional voltage application (b) Sudden voltage application

(c) Typical waveform of sudden voltage application

Figure 4. Voltage application method

Table 1. PDIV and its fraction of V_a for various particle sizes on an epoxy plate surface (V_a = 120 kV_{rms})

Particle length [mm]	Particle diameter [mm]	PDIV [kV_{rms}]	V_a/PDIV
3	0.25 mm	60	2.0
	0.45 mm	100	1.2

operating electric field of actual GIS (2.0 kV_{rms}/mm). Therefore, to obtain different local electric fields at the particle tip, different particle sizes were used as mentioned in section 2.1. Table 1 shows PDIV of various particle sizes and the corresponding ratio of applied voltage V_a to PDIV. As a particle became thick, PDIV increased.

3 TEMPORAL CHANGE OF PARTIAL DISCHARGE CHARACTERISTICS

3.1 PARTIAL DISCHARGE ACTIVITY JUST AFTER VOLTAGE APPLICATION

Figure 5 shows the condition of PD generation immediately after sudden voltage application for delamination defect and metallic particles defect. The voltage polarity is expressed in terms of the polarity of the grounded electrode for the delamination defect and in terms of the particle tip for the metallic particle defect. For both defects, the PD polarity is defined according to the PD type which is negative streamer at positive applied voltage and positive streamer at negative applied voltage. The voltage is applied suddenly at time t = 0.

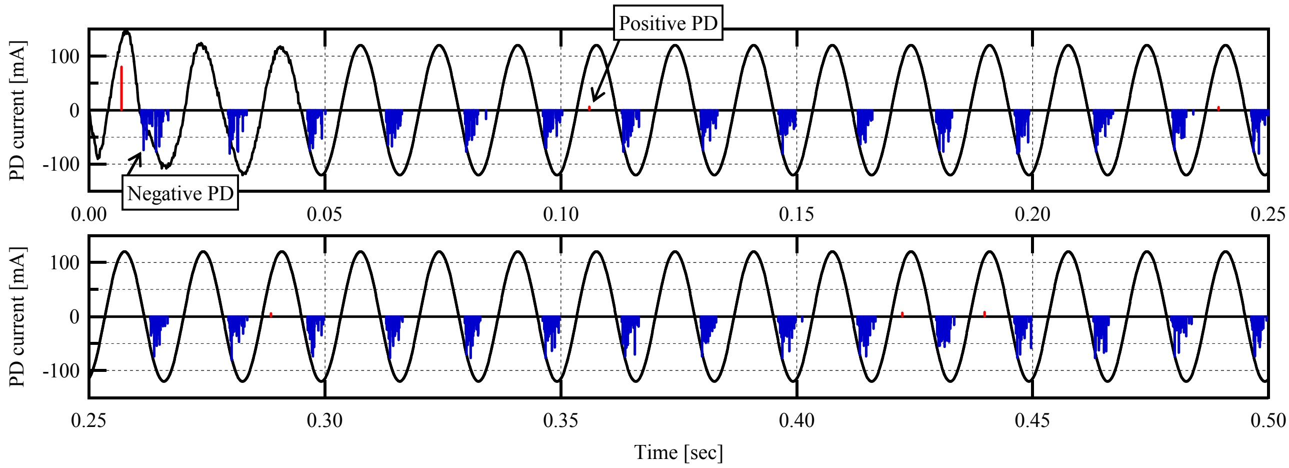
For the delamination defect in Figure 5a, negative PD pulses appeared constantly at all cycles, but positive PD did not, except that an initial large positive PD pulse during transients immediately after switching on. At about t = 0.1 s, positive PD pulses started to appear but the number of their PD pulses and the magnitude of PD current are much smaller than negative ones. Positive PD pulses increased gradually and it takes more than 2 s until it appears at most cycles. Similar tendencies are obtained for other applied voltages.

For the metallic particle defect in Figure 5b, negative PD pulses appeared at most cycles. At about t = 0.1 s after the voltage application, positive PD pulses appeared at most cycles. At about t = 0.3 s after the voltage application, positive PD pulses appeared at nearly all cycles. It is evident that PD activities change greatly within the first few seconds after the voltage application. This change takes shorter duration compared to the case of delamination defect.

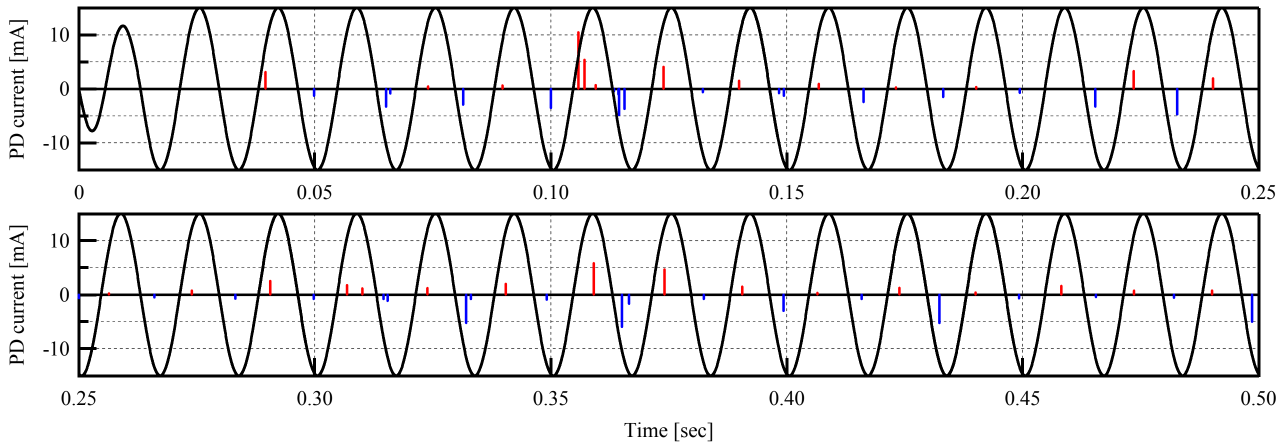
3.2 TIME TRANSITION OF PARTIAL DISCHARGE CHARACTERISTICS

Figure 6 shows the time dependence of number of PD pulses expressed in pulses per second (pps) when different applied voltages (1.0×PDIV and 1.3×PDIV) were applied on the electrode setup of delamination defect. In these figures, the number of PD pulses is obtained using measured data with fixed time duration. The time duration of measured data is chosen 2 s and 0.6 s for 1.0×PDIV and 1.3×PDIV, respectively.

For the number of PD pulses at 1.0×PDIV shown in Figure 6a, the number of negative PD pulses was about 400 pps directly after voltage application. This number increased to a maximum value of 470 pps before reducing to a very few number of PD pulses after about 5 minutes. The positive PD pulses at 1.0×PDIV didn't appear at all. For the case of 1.3×PDIV shown in Figure 6b, negative and positive PD



(a) Delamination defect case (V_a = 1.3×PDIV)

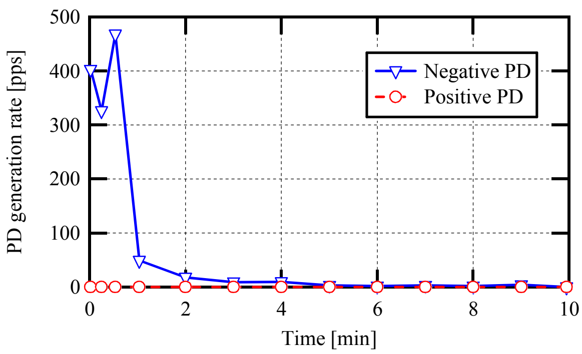


(b) Metallic particle defect case (ϕ = 0.45 mm, L = 3 mm, 1.2×PDIV)

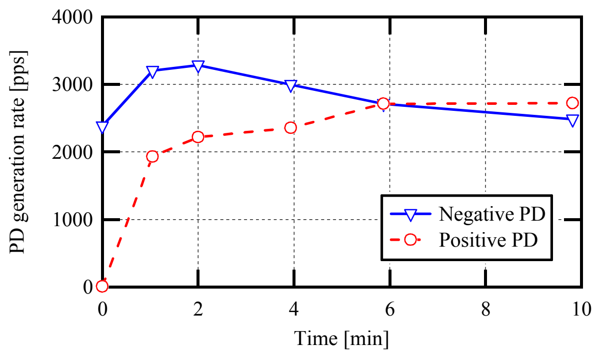
Figure 5. Temporal change of PD pulses just after voltage application

pulses appeared. The number of negative PD pulses increased from about 2400 to about 3200 pps before reducing to a steady state value 2500 pps after about 5 minutes. But the number of positive PD pulses continued to increase drastically after voltage application until reached a steady state value of about 2700 pps after the same mentioned time (5 minutes). As evident from these figures, the time transition of PD generation rate exhibits different tendencies for negative and positive PD pulses and the higher the over voltage ratio against PDIV, the larger the generation rate of positive PD pulses to the negative PD pulses. Similar tendencies in time transition of PD generation rate are obtained for higher applied voltages [10].

For the metallic particle defect, the electric field distribution is first calculated around the tip of each size of metallic particles as shown in Figure 7. The electric field calculation was performed under applied voltage of 120 kV_{rms}. The electric field of the tip of metallic particle with a diameter



(a) Applied voltage = 1.0×PDIV



(b) Applied voltage = 1.3×PDIV

Figure 6. Time transition of PD generation rate for delamination defect

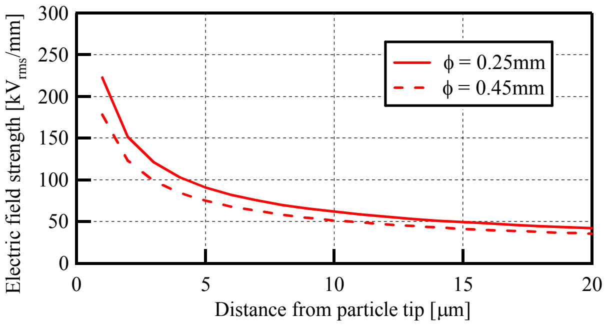
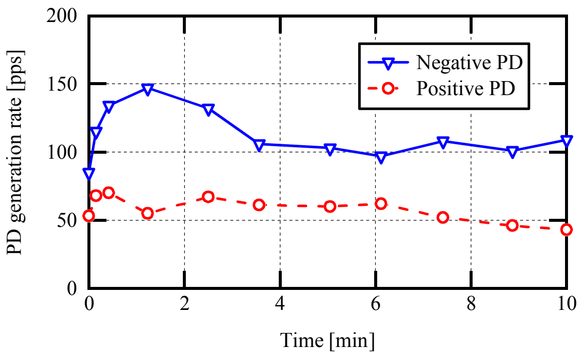


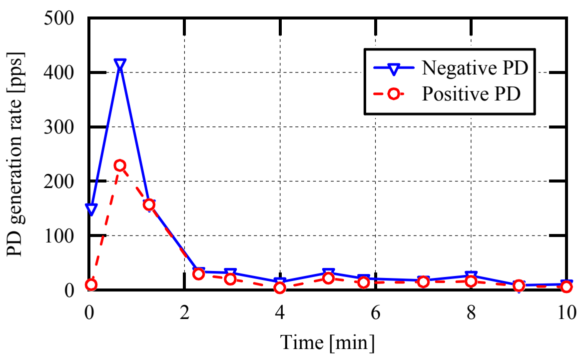
Figure 7. Electric field distribution around particle tip (120 kV$_{rms}$)

of 0.25 mm and length of 3 mm is stronger than that with a diameter of 0.45 mm and length of 3 mm.

The time dependence of PD generation rate corresponding to different particle sizes is shown in Figure 8. The number of PD pulses at all particle sizes increases immediately after voltage application, then decreases and becomes almost constant. In the case of Figure 8a, with a diameter of 0.45 mm and length of 3 mm, the period until number of PD pulses tends to decrease is longer than that in the case of Figure 8b, with a diameter of 0.25 mm and length of 3 mm. Also it is important to note that when the particle becomes thinner, where the electric field becomes stronger, the generation rate of positive PD pulses to the negative PD pulses increases exhibiting similar tendency to the delamination defect case. However, in inverse to the delamination defect case, the time



(a) ϕ = 0.45 mm, L = 3 mm (1.2×PDIV)



(b) ϕ = 0.25 mm, L = 3 mm (2.0×PDIV)

Figure 8. Time transition of PD generation rate for metallic particle defect.

transition of PD generation rate exhibits similar tendencies for negative and positive PD pulses. These tendencies are also confirmed for longer particles [11].

Generally speaking for the obtained results, the negative and positive PD pulses have approximately similar tendency for the metallic particle case and different tendency for the delamination case. This is considered to be resulted from the initial electron generation mechanisms which represent with the charge accumulation the main factors affecting PD activity, as will be further detailed in the next sections.

4 CHARGE ACCUMULATION PROCESS

4.1 DISTRIBUTION OF ACCUMULATED SURFACE CHARGES

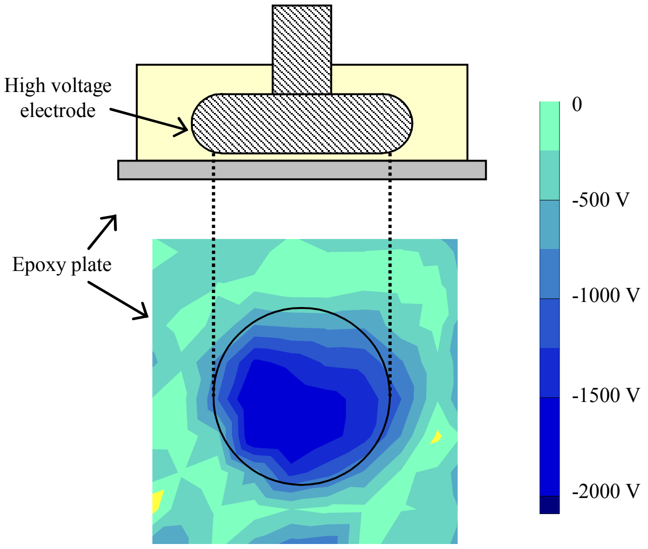
Obtaining the distribution of accumulated surface charges is the first step to analyze the effect of charge accumulation on the local electric field. The electric charge of an epoxy samples was removed by cleaning them with ethanol or by using new samples. The charge free initial state has been verified by measuring the surface potential of a sample.

For both the delamination defect and the metallic particle defect, surface potential measurements were performed after the epoxy surfaces were exposed to PD activity for 10 minutes as shown in Figure 9. For the delamination defect, the charge distribution is uniform around the surface below high voltage electrode as shown in Figure 9a. This implies that PD occurs all over the epoxy surface. However, for the metallic particle defect, the charging area expands only around the particle tip with decreasing the charge density as shown in Figure 9b. For both defects, the accumulated charges develop with PD activity. For the delamination defect, this is proved from the change in PD inception electric field until a steady state characteristics have been obtained when a balance between charge accumulation and charge neutralization occurs [12]. For the metallic particle defect, the development of accumulated charges is confirmed from the surface potential measurements after 1 minute and 10 minutes of voltage application [11].

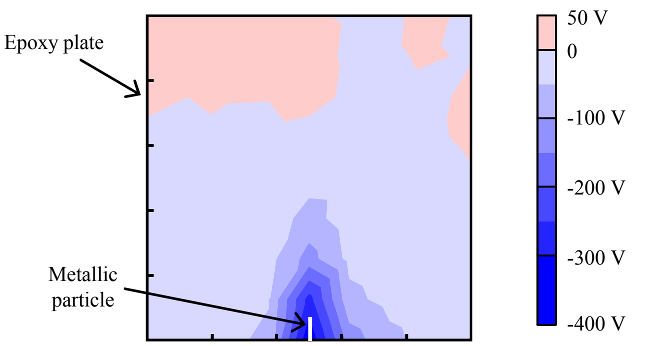
4.2 ANALYSIS OF CHARGE ACCUMULATION EFFECT ON THE ELECTRIC FIELD

PD activity is affected by the electric field at the PD location, i.e. by accumulated charges on the epoxy surface. Hence, it is important to investigate the effect of accumulated surface charges on the electric field. The electric field at the PD location is composed of two components. The first component E_a is generated by the externally applied voltage. The second component E_q is associated with the surface charges accumulated by PD activity which generates local dc field. To obtain the resultant electric field dependence on accumulated charge density, a simplified calculation is carried out based on the charge distribution obtained in Figure 9.

For the delamination defect, the applied electric field is uniform and also the charge distribution on the epoxy surface is uniform. Thus, the equations of uniform electric field distribution and the equations of boundary conditions at



(a) Delamination defect (50 μm gap, 1.3×PDIV)



(b) Metallic particle defect (ϕ = 0.45 mm, L = 3 mm, 1.2×PDIV)

Figure 9. Surface potential measurements on the epoxy plate after exposing to PD activity for 10 minutes.

molding insulation / epoxy boundary and epoxy / gas boundary were used to obtain the local electric field as follows:

$$V_a = E_m d_m + E_e d_e + E_g d_g \quad (1)$$

$$\varepsilon_e E_e - \varepsilon_m E_m = 0 \quad (2)$$

$$\varepsilon_g E_g - \varepsilon_e E_e = q_s \quad (3)$$

where V_a is the applied voltage, E_m, E_e and E_g are the electric field component in the molding insulation, epoxy and gas gap respectively, d_m, d_e and d_g are the molding insulation thickness, epoxy thickness and gap length respectively, ε_e, ε_m and ε_g are the dielectric constant of epoxy, molding insulation and SF_6 respectively, q_s is the accumulated charge density on the epoxy surface considering that the charge distribution is uniform. Based on these equations, the resultant electric field dependence on accumulated charge density is obtained as shown in Figure 10, when the polarity of grounded electrode is positive. The range of −50 to 50 μC/m^2 charge density was chosen, according to our previous results for charge density estimation from PDIV measurements which was found about −20 ~ −45 μC/m^2 [12]. As evident in Figure 10, the resultant

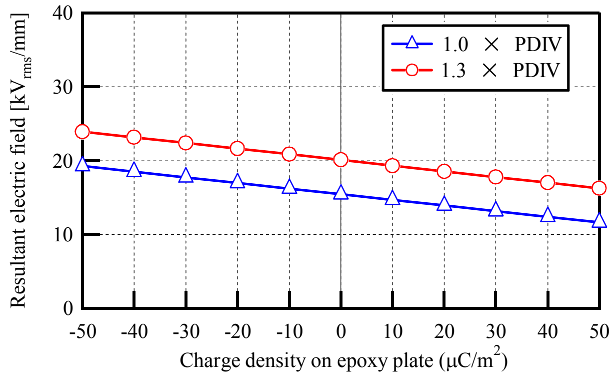


Figure 10. Change of local electric field strength by the accumulated charges on the epoxy surface for delamination defect.

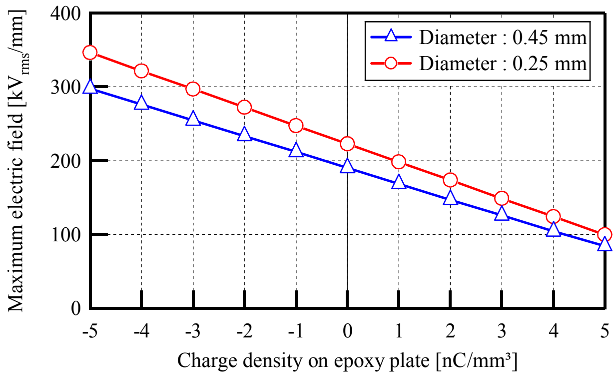


Figure 11. Change of maximum electric field strength by the accumulated charges on the epoxy surface for metallic particle defect (L = 3 mm).

electric field strength was influenced by the accumulated charge. When the polarity was the same between the accumulated charge and grounded electrode, the resultant electric field weakened. When the polarity was opposite, the resultant electric field strengthened.

For the metallic particle defect, since the applied electric field is non-uniform, the finite element calculation was carried out to obtain the electric field dependence on accumulated charge density as shown in Figure 11. In this case, the maximum electric field was plotted instead of the resultant electric field. Since the electric field at the particle edge is infinity, the maximum electric field is taken at 0.3 μm apart from the particle edge. In this calculation, it was assumed that charges were accumulated in the region of 5 mm in length and 200 μm in depth based on the measured surface potential in Figure 9b. The calculation was also carried out when the polarity of metallic particle tip is positive like the delamination defect case. It is observed that the effect of the polarity of accumulated charge on the electric field is similar to the delamination defect case.

5 DISCUSSION

As highlighted from the experimental results, the PD parameters change greatly with time after voltage application for both delamination and metallic particle cases. Furthermore, the PD parameters depend on the local electric field at the PD location which is influenced by charges accumulated on the epoxy plate surface. At the initial stage of voltage application, charges were accumulated with certain polarity and then, part of these charges was neutralized by charges with the opposite polarity. These processes caused remarkable change in PD generation rate. However, when the ac voltage was applied for a long time, a balance between charge accumulation and charge neutralization occurred and PD activity became stable. These phenomena are discussed in details in [12]. In spite of that charge accumulation was observed for both defect types, there are main certain differences between the two cases regarding the charging effect.

5.1 ROLE OF INITIAL ELECTRON GENERATION AND IONIZATION VOLUME

The initial electron is a necessary condition for PD generation. The source of such electron is different for negative and positive PD pulses [13]. For negative PD pulses, initial electron is generated from the electrode surface, i.e. the grounded electrode for the delamination defect case and the particle tip for the metallic particle case. For positive PD pulses, initial electron is generated from the gas gap, i.e. the delamination gap for the delamination defect case and the gas region at the vicinity of the particle tip for the metallic particle case. This explains why negative PDs occur more than positive PDs just after the voltage application. After initial electron is released, it will start an avalanche as large as the critical size to develop a streamer. The probability of PD initiation depends on the probability p_1 of initial electron generation as well as the probability p_2 that the generated electron yields an avalanche of the critical size to be detected or satisfy the streamer criterion.

For the delamination defect case, the probability p_1 depends on the field emission for negative PD and the existence of negative ions for positive PD. Thus, for the non-accumulated charge case and same delamination length and area, the probability p_1 depends only on the electric field. Moreover, the probability p_2 depends on the electric field. Therefore, at higher electric field, PD generation rate increases for both PD polarities in Figure 6. In this case, the modification of electric field due to accumulated charge takes time and then, the time needed to obtain stable PD generation rate becomes longer, about 5 minutes, as shown in Figure 6.

For the metallic particle case, where the electric field is non-uniform, there is another phenomenon referred as the ionization volume that affects the probability p_1 of PD initiation. The ionization volume is defined as the region in the gas gap around the particle tip where the electric field E is higher than the critical electric field E_{cr} [14]. The ionization volume affects both PD polarities in the same tendency but with different abilities. For negative PD pulses, a number of initial electrons are emitted from the particle tip by the field emission, and so, p_1 approaches unity. Then, the ionization volume affects only the probability p_2. But, for positive PD pulses, the ionization volume affects both probabilities p_1 and p_2. When the electric field becomes higher, the ionization volume grows resulting in the increase in PD generation rate of negative and positive PD polarities in Figure 8. In this case, the effect of charge accumulation on the ionization volume appears shortly, less than 2 minutes, and fast change toward stable PD characteristics occurs as illustrated in Figure 8.

5.2 ROLE OF CHARGE ACCUMULATION

Another important difference in the charging effect is the tendency of negative and positive PD generation rate among the both defects. As previously mentioned, the PD polarity for both defects is defined according to the PD type which is negative streamer at positive applied voltage and positive streamer at negative applied voltage. For negative PD pulses, the generation rate decreased for both defects. However, for positive PD pulses, the generation rate increased after 10 minutes for delamination defect in Figure 6b and decreased for metallic particles defect in Figure 8. This is explained by considering the role of charge accumulation.

For the delamination defect case in Figure 12, when negative charges were accumulated, the local electric field E_q caused by accumulated charges is in reverse direction to the applied electric field E_a for negative polarity. Thus, the resultant electric field weakens. The reduction of electric field due to negative accumulated charges is well known on composite insulation systems [15] and for the delamination defect case, it is confirmed by measuring the PD inception electric field before and after PD activity as previously investigated [12]. Consequently, the probability p_2 becomes lower and the PD generation rate decreases. On the other side, the charge accumulation has an inverse effect on positive PD pulses. When negative charges were accumulated, two effects exist. The first effect is that negative charges can be a source for initial electron generation. The second effect is that the

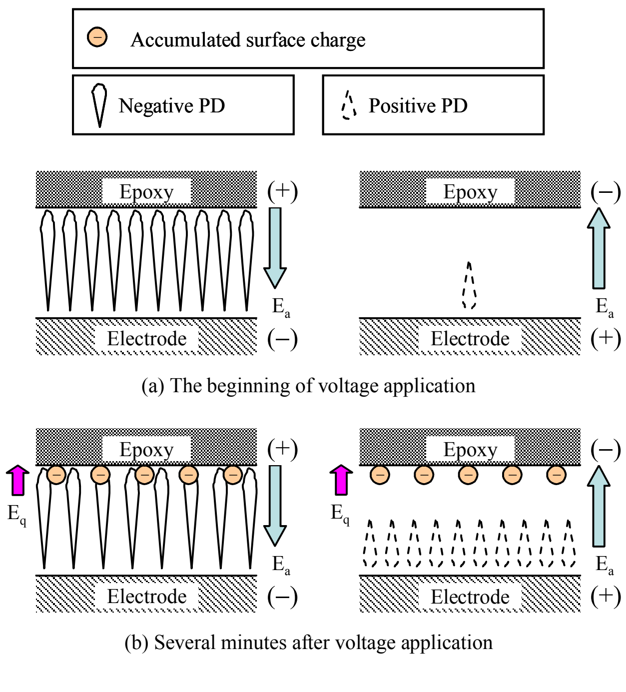


Figure 12. The role of accumulated charges on the epoxy surface in partial discharge activity for delamination defect.

resultant electric field strengthened where E_q and E_a are in the same direction. Both these effects act towards increasing the probability p_1 of positive PD initiation.

For the metallic particle case in Figure 13, after the charges have been accumulated on the epoxy surface, electric field is mitigated by the electric field E_q. Then, the ionization volume decreases as confirmed from the light emission images at the beginning and end of voltage application which are shown in Figure 13. The reduction of ionization volume causes generation rate of both PD polarities to be lower after 10 minutes. By understanding this role of surface charge accumulation in PD activity for both defects, the PD diagnosis of GIS must be performed.

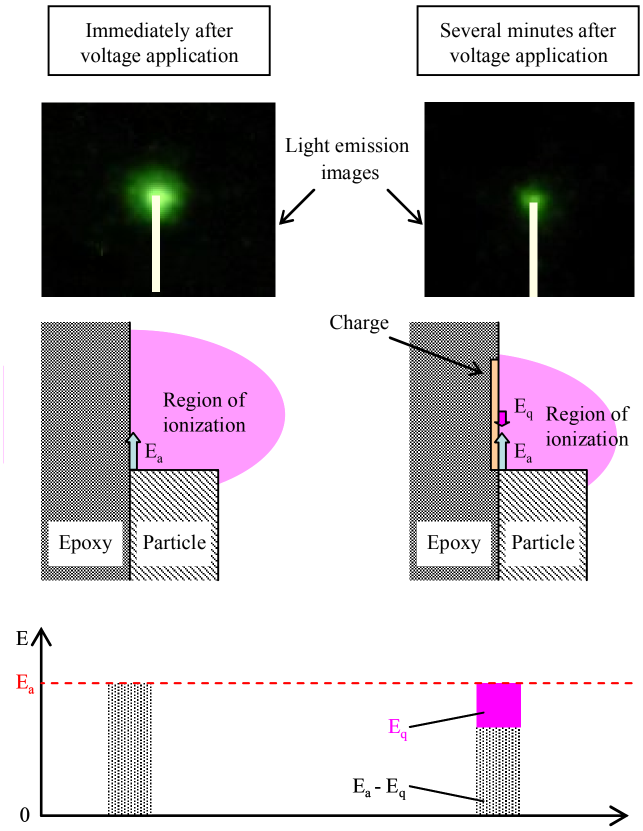


Figure 13. The role of accumulated charges on the epoxy surface in partial discharge activity for metallic particle defect.

6 CONCLUSIONS

The role of accumulated surface charge in partial discharge activity for GIS spacers has been clarified in this paper. Both delamination defect and adhered metallic particle defect were considered. The time transition of their PD characteristics was obtained after sudden voltage application and discussed from the viewpoint of charge accumulation effect. As a result the following findings were concluded:

(1) PD activity changes greatly at the first few minutes just after voltage application for both defects due to the effect of accumulated charges on the epoxy surface.

(2) For the delamination defect case, the accumulated charge polarity is estimated as negative. Thus, the resultant electric field weakened for negative PD pulses and its PD generation rate decreased. For positive PD pulses, the PD generation rate increased where the resultant electric field strengthened and also the accumulated negative charges can act as a source of an initial electron.

(3) For the metallic particle case, the PD generation rate is affected by the ionization volume. Therefore, when charges are accumulated on the epoxy surface, the electric field is mitigated and the ionization volume decreases. This caused the reduction of the PD generation rate for both polarities.

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