Surface Charge Accumulation and Partial Discharge Activity for Small Gaps of Electrode/Epoxy Interface in SF_6 Gas

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ABSTRACT

The electrical insulation reliability of solid spacers in Gas Insulated Switchgears (GISs) is an important issue to achieve a safe operation of such equipment. Among different phenomena, charge accumulation represents the most important matter that can degrade the overall performance of these insulation systems. For this respect, this paper discusses the contribution of partial discharge (PD) activity by ac voltage application to charge accumulation in the small gap at the electrode/epoxy interface as one of the weakest points in GIS solid spacers. The partial discharge inception voltages for non-accumulated charge case ($PDIV_0$) and after exposing to PD activity ($PDIV_n$) are measured among different gap lengths, simulating delamination at the electrode/epoxy interface. The PD activity is generated using applied voltage with $1.2 \times PDIV_0$ for all gap lengths examined in this study (50~500 μm). In these measurements, PDIV increased with increasing the number of PD pulses as a result of accumulated charges. The accumulated surface charge density is estimated using the boundary equations and is compared for the different gap lengths. The accumulated charge density was larger for the smaller gap lengths. Comparing PD parameters with accumulated charge density enabled us to identify that the number of negative and positive PD pulses is the main parameter that corresponds to charge accumulation process.

Index Terms — **Partial discharges, charge accumulation, electrode/epoxy interface, SF_6 gas insulation systems.**

1 INTRODUCTION

GAS insulated switchgears (GISs) have been widely used in electric power grids over the last 40 years. This imposes a necessity for dealing with insulation condition monitoring to increase reliability of such equipments. Epoxy spacers in GIS are critical component for safe operation of GIS. However, from the past experience and literature, it has been provided that good dielectric properties of epoxy spacers are strongly affected by surface charge accumulating on its surfaces [1, 2]. This motivated the interest of researchers allover the world to investigate the characteristics and predominant factors underlying various charge accumulation mechanisms in GIS [3-5]. Charges accumulating on solid insulators in ac GIS can be caused by field emissions [1], local field enhancement on particles or protrusions [5], or partial discharge activity [6, 7].

Defect types in GIS that mostly can be responsible for partial discharge based charge accumulation are particles adhered on a spacer surface and delamination at electrode/epoxy interface. For particles adhered on a spacer surface [8], it was found that 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

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influenced by successive PD. Then, PD characteristics became stable. On the other hand, for delamination at electrode/epoxy interface, few publications were reported for charge accumulation process, especially for delamination lengths *d* below 100 μm.

From this point of view, this paper assesses the impact of partial discharge activity on charge accumulation process for electrode/epoxy interface in SF_6 gas. First, PD inception voltage ($PDIV_0$) is measured for non-accumulated charge case. Then, the applied voltage is set at above PDIV condition to start PD activity. After each specified number of PD pulses, PD activity is stopped and PDIV is measured again. The difference in PDIV and corresponding accumulated charge density are obtained for the different gap lengths. Finally, a possible charging mechanism is proposed considering different gap lengths based on the observed experimental results.

2 EXPERIMENTAL ARRANGEMENT

2.1 GENERAL SETUP

Figure 1 shows the schematic diagram of the electrode system setup to simulate the delamination defect at the electrode/epoxy interface in SF_6 gas. The electrode setup consists of molded type high voltage electrode and ground plane electrode. The high voltage electrode is 60 mm in diameter and is molded using guard insulation with 90 mm diameter and the relative permittivity of 3.7. Molding high voltage electrode enabled to avoid edge discharge. The ground plane electrode is SUS304 and has an average surface roughness of 7.4 μm which is defined by the peak-to-peak height on the surface as obtained from microscope with 3D profile. A rectangular epoxy plate (100 mm × 100 mm × 5 mm thickness) with relative permittivity of 6.0 is placed between high voltage and ground electrodes. The small gap between the epoxy plate and ground electrode is provided using stack of thin dielectric films with each 25 μm thickness. Different gap lengths are considered in this study, ranging between 50 μm and 500 μm, simulating delamination at the electrode/epoxy interface. The gap is kept open to be able to control the gas type and the pressure in it.

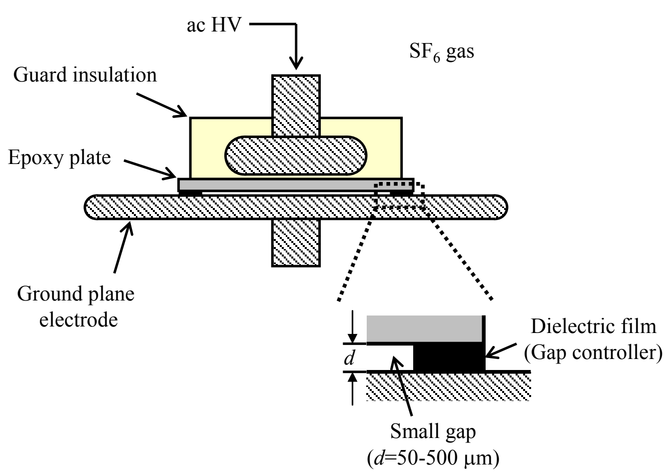

Figure 1. Schematic diagram of the electrode system setup to simulate delamination at the electrode/epoxy interface in SF_6 gas.

The electrode setup is installed in a pressurized chamber filled with SF_6 gas where experiments are conducted at 0.1 MPa as shown in Figure 2. PD signals are detected with 50 Ω resistor. The detected PD signals were fed into a large bandwidth digital oscilloscope (20 GS/s, 4 GHz) and then analyzed by PD-Current Pulse Waveform Analysis (PD-CPWA) developed in [9]. In order to measure the first PD inception voltage, $PDIV_0$, the target ac high voltage with frequency 60 Hz is increased gradually until PD occurs. To avoid the effect of previously accumulated surface charges, a new epoxy sample is used in each experiment.

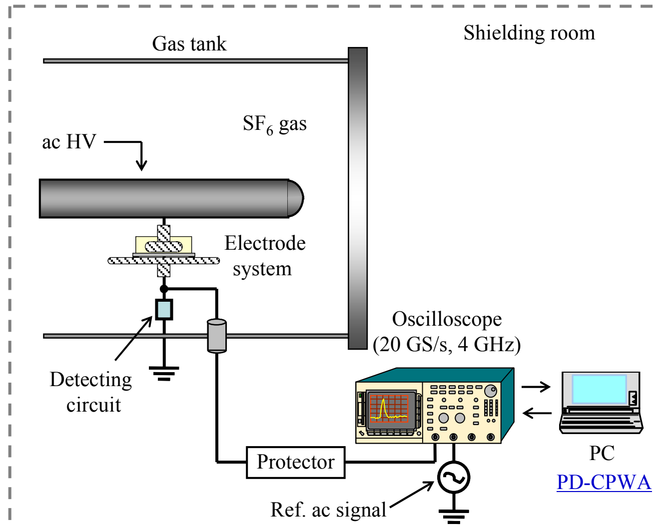

Figure 2. PD measurement system.

2.2 EXPERIMENTAL PROCEDURES

In the experimental procedures, the main goal is to examine the deviation of PDIV due to accumulated charges and also to acquire PD parameters during charging process. To accomplish this, the procedures illustrated in Figure 3 are introduced. First, PD inception voltage for non-accumulated charge case ($PDIV_0$) is measured. Then, to start PD activity and investigate the relevant charging process on the epoxy surface, the applied voltage is set at a certain value larger than $PDIV_0$, $1.2\times PDIV_0$, because around $PDIV_0$ condition, PD activity would stop due to the charge accumulation effect. After every 10,000 PD pulses counted by PD-CPWA, ac voltage is set to zero and then is gradually increased to obtain the new value of PDIV. This procedure is repeated ten times for each gap length. This means that total number of PD pulses reaches 100,000 pulses.

3 EXPERIMENTAL RESULTS

3.1 PARTIAL DISCHARGE (PD) INCEPTION CHARACTERISTICS

$PDIV_0$ before exposing to PD activity and the corresponding PD inception electric field ($PDIE_0$) in the gap space were obtained experimentally as a function of the gap length. Figure 4 shows these results. Also, in this figure, theoretical breakdown field strength for uniform fields in SF_6 gas given by the following equation are plotted [10].

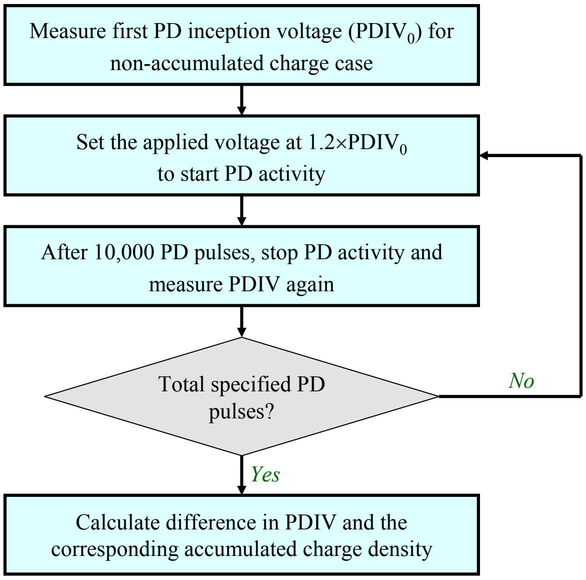

Figure 3. Experimental procedures to investigate charge accumulation process at epoxy surface in small gap.

$$\frac{E_b}{p} = \left(\frac{E}{p}\right)_0 + \frac{K}{27.7\,(pd)} \quad \text{[kV/cm]} \tag{1}$$

where E_b is breakdown electric field, d is the gap length, p is the gas pressure and $(E/p)_0 = 0.885$ V/cm-Pa.

By comparing the experimental results to the theoretical breakdown field strength in equation (1), where the value of constant K is known to be 10.5 for streamer criterion with uniform field gap in SF_6 gas as given by the following equation [11].

$$\int_0^x \bar{\alpha}\, dx = K \tag{2}$$

where $\bar{\alpha}$ is the effective ionization coefficient. It is evident that measured PD inception values for non-accumulated charge case matches with the theoretical values when the streamer criterion is applied. A deviation from theoretical

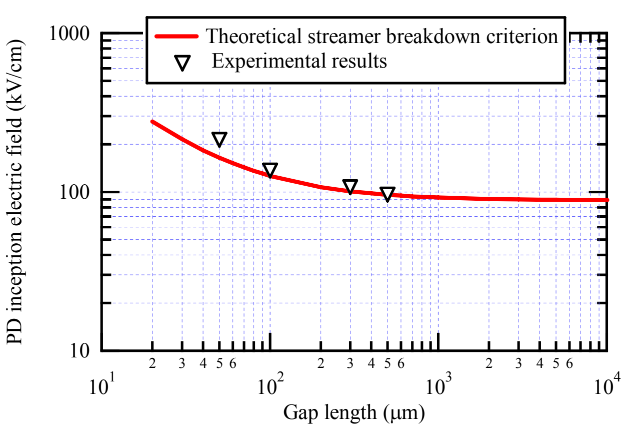

Figure 4. Experimental and theoretical PD inception electric field for different gap lengths of electrode/epoxy interface in SF_6 gas (p=0.1 MPa).

values is observed for gaps below 100 µm as a result of small discharge volume that consequently requires higher electric field to initiate avalanche.

Figure 5 shows the phase characteristics of a PD inception pulse and its current pulse waveform for 500 µm gap as an example. It is important to notice that the PD pulses at inception conditions for all examined gap lengths were observed at positive polarity of ac phase. This implies that, for PD inception, a streamer has started from the grounded plane bare electrode where the probability of extracting initial electron is higher than that from the epoxy surface.

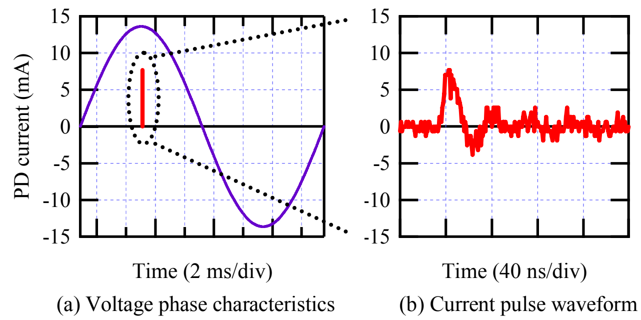

Figure 5. Voltage phase characteristics and current pulse waveform of PD inception pulse for 500 µm gap (p=0.1 MPa).

3.2 EFFECT OF SUCCESSIVE PD GENERATION ON PD INCEPTION VOLTAGE

When PD pulses are once generated at the small gap, charges due to PD will be accumulated on the dielectric surface of the interface. Then, the inception of subsequent partial discharges will be affected as a result of the change in electric field inside the gap. To investigate this effect, the variation of PDIV at the small gap is obtained after exposing to successive PD activity. For different gap lengths, PD pulses were produced at an ac applied voltage with 1.2×PDIV$_0$.

Figures 6 and 7 summarize PDIV measurement results with interval of PD activity equal to 10,000 PD pulses. For all tested gaps, PDIV increases as the number of generated PD pulses increases. However, PDIV tends to be saturated after several ten thousands of generated PD pulses.

For the case of 50 µm gap in Figure 7, the PDIV increased with the number of generated PD pulses until reaching 1.2×PDIV$_0$ which is the applied voltage used to generate PD pulses. At this moment, the applied voltage didn't generate more PD pulses and PD activity stopped. To clarify the differences in PDIV tendency with successive PD generation for 50 µm and 500 µm gaps, each graph is divided into three stages. These stages are decided based on the change in PD characteristics. First stage 1 corresponds to PD characteristics in the first period after voltage application while the second stage 2 corresponds to the intermediate change in PD characteristics. The third stage 3 is the last one when PD characteristics became stable. For each stage, the number of negative and positive PD pulses, expressed in the averaged pulse per second (pps), is obtained and the PD activity over several cycles is also captured as shown in Figure 6 for 500 μm gap and Figure 7 for 50 μm gap. The PD polarity is defined according to bare electrode polarity where PD streamer starts as will be discussed in section 4.

For 500 μm gap case in Figure 6, in the first stage, the number of negative PD pulses is larger than the number of positive PD pulses. In the second stage, the reduction in the number of negative PD pulses and the increase in the number of positive PD pulses occur. However, the number of negative PD pulses is still larger. In the third stage, the number of negative and positive PD pulses became comparable to each other.

For 50 μm gap case in Figure 7, in the first stage, the number of negative PD pulses is extremely larger than that of positive PD pulses. In the second stage, the number of negative PD pulses decreased but still the difference between the number of negative and positive PD pulses is very large.

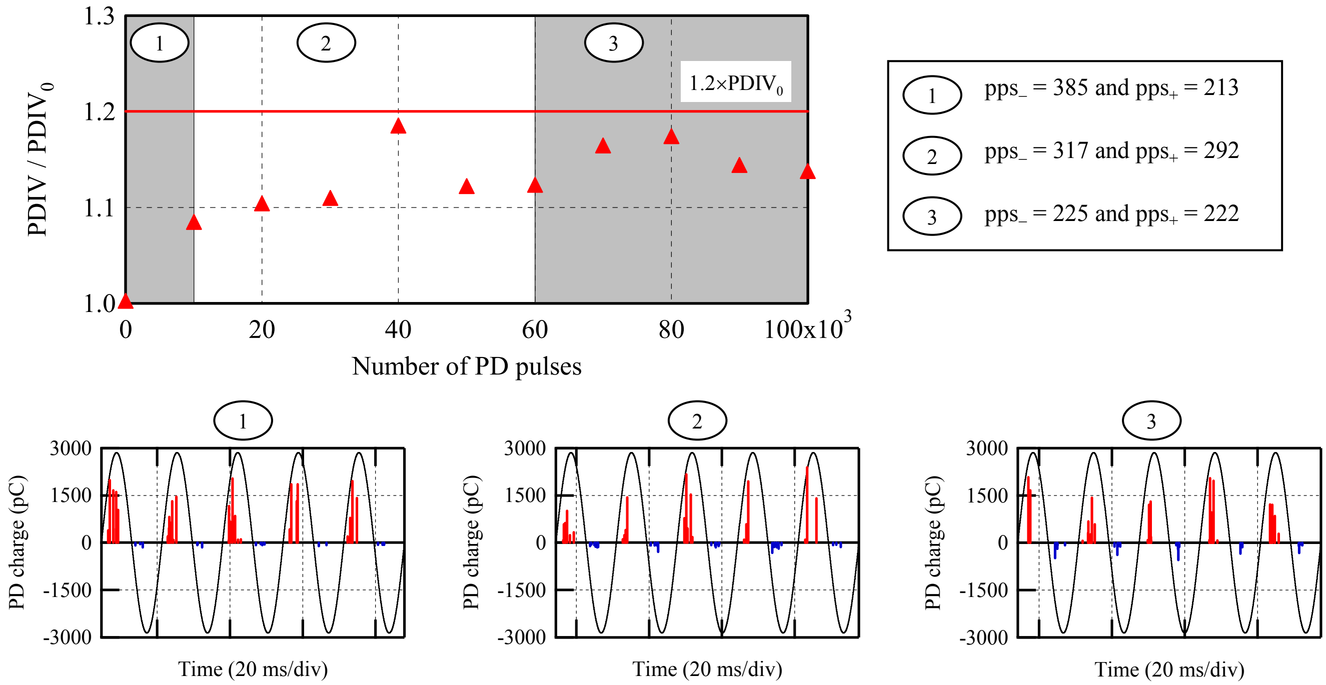

Figure 6. Dependence of PDIV on successive PD exposure of epoxy samples for 500 μm gap case.

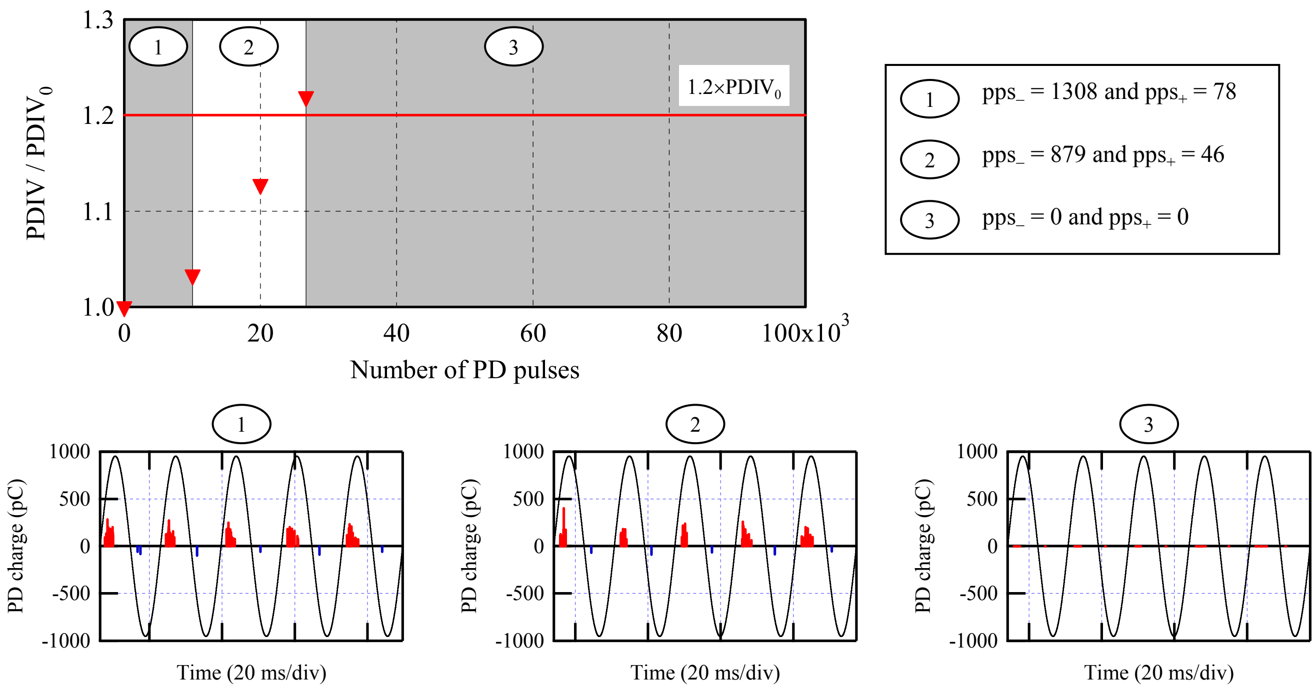

Figure 7. Dependence of PDIV on successive PD exposure of epoxy samples for 50 μm gap case.

Finally, in the third stage, PD activity stops where PDIV attains the applied voltage used to generate PD pulses. This phenomenon of PD disappearance implies that detection of delamination with a micrometer gap may not be possible by using PD measurements due to charge accumulation effect. However, it is expected to detect such delamination lengths for the short time after PD occurrence or at higher electric field.

On the other side, it must be emphasized that, the time of charge decay process is investigated to check its effect on the experimental results. To carry out this, PDIV was measured as a function of time in the absence of applied voltage after epoxy surface is exposed to 100,000 PD pulses as shown in Figure 8 for 100 μm gap case as an example. The PDIV decreased rapidly after one hour but after several hours the PDIV was kept at the constant value larger than $PDIV_0$. So, the time of charge decay was relatively large compared to the time of experiment and consequently the charge accumulation results would not be affected by the charge decay process.

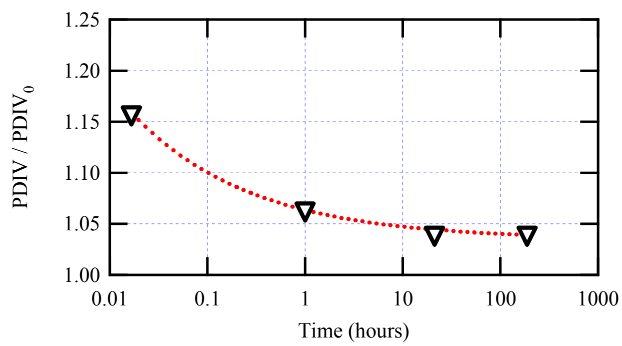

Figure 8. PDIV variation as a function of time for 100 μm gap without exposure to PD activity.

3.3 ACCUMULATED CHARGE EFFECT AND CHARGE DENSITY

Generally, the accumulated charge has an influence on PD inception and propagation characteristics. For PD propagation characteristics, this influence is understood from the pulse sequence analysis [12]. On the other hand, in this paper, in order to better understand the influence of accumulated charge on PD inception, a qualitative analysis of electric field distribution in the gap between the epoxy and electrode can be addressed. The resultant electric field E_g in the gap is composed of two contributing fields. The first contributing field is due to the applied stress E_a. The second contribution, E_q, is associated with the surface charges left by PD activity. Then E_g can be expressed for the gap as:

$$E_g = E_a + E_q \tag{3}$$

Here E_g represents the critical field strength inside the gap which is considered fixed for the same gap. In this case increasing PDIV at the positive polarity of applied voltage, as was shown in section 3.1, indicates that the electric field E_a, which is required to bring the gap to breakdown, become higher and consequently E_q should be opposite to E_a. This means that the majority of accumulated charges on the epoxy surface must be of negative polarity.

Since charge accumulation greatly affects the PD inception, it is important to estimate surface charge density q_s on the epoxy surface after exposing to PD activity. In this study, the surface charge density q_s on the epoxy surface is calculated from the new PDIV measured after charge accumulation and from the equation of boundary condition between epoxy and SF_6 gas given by:

$$\varepsilon_g E_g - \varepsilon_e E_e = q_s \tag{4}$$

where ε_g and ε_e are the dielectric constant of SF_6 and epoxy respectively; E_g and E_e are the electric field component in the gap and epoxy; q_s is the accumulated charge density on the epoxy surface considering that the charge distribution is uniform as concluded from surface potential measurements [13]. In this case, the accumulated charge density is treated as a net value made up of the total positive and negative charges.

The accumulated charge density q_s is calculated after each 10,000 PD pulses and plotted as shown in Figure 9. The results of the different gap lengths examined are recorded. It is noticed that the curves for gap lengths 100~500 μm retains almost the same shape. In these cases, a constant charge density seems to be reached after about 40,000 PD pulses. The constant level is found to be around 20 μC/m^2. On the other hand, an examination of Figure 9 indicates that, for 50 μm gap, the charge density increases rapidly until PD activity stops. The final charge density after PD stopping is found to be 45 μC/m^2.

As illustrated in Figure 10, the values of charge density increase with decreasing the gap length when applying the same percentage of $PDIV_0$ ($1.2\times PDIV_0$) to generate PD pulses. In this figure, the charge density reached at the end of PD exposure is plotted against the gap length. The changes observed between different gaps suggest the dependence of

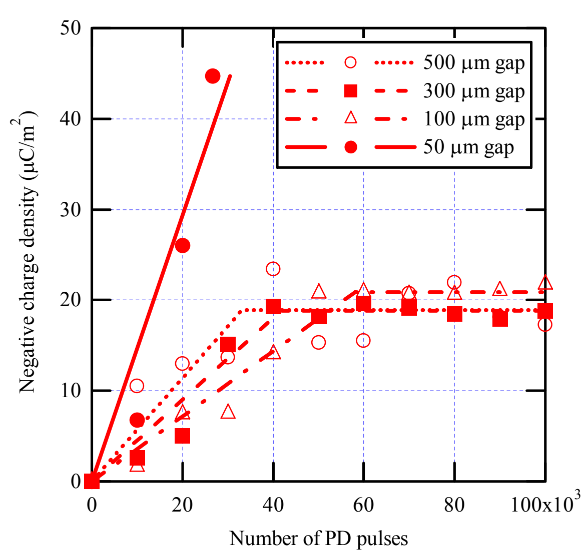

Figure 9. Accumulated charge density as a function of PD pulses for different gap lengths under $1.2\times PDIV_0$ voltage application.

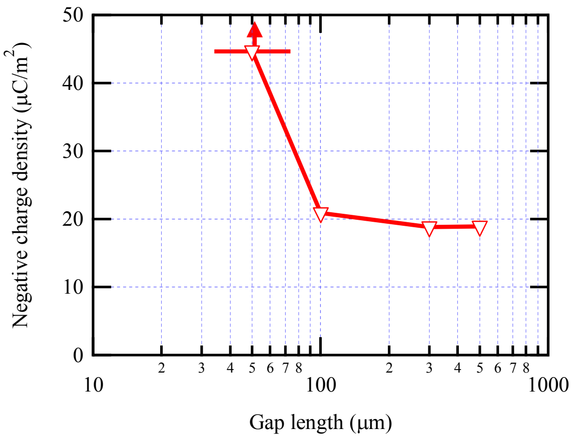

Figure 10. Dependence of accumulated charge density on the gap length.

accumulated charge density on the number of negative PD pulses which is larger for smaller gaps. This process will be discussed in details in the next section.

4 DISCUSSIONS

The PD polarity is defined according to ground side bare electrode polarity where streamer propagation begins. This means that negative type PD appears during the positive half cycle of the applied voltage and positive type PD appears during the negative half cycle of the applied voltage. When the gap length decreases, the number of PD pulses increases during the positive half cycle of the applied voltage. This suggests that the initial electron is generated from the ground bare electrode where higher electric field is applied. On the other side, during the negative half cycle of the applied voltage, the number of PD pulses decreases for smaller gaps. This suggests that the initial electron is generated from the gas gap where the probability of initial electron generation becomes lower. From these mechanisms of initial electron generation, it is clarified that possible PD type is considered to be negative streamer and positive streamer during the positive and negative half cycles respectively. This consideration is also supported by the difference in PD charge which is larger for negative type PD.

4.1 CHARGE ACCUMULATION PROCESS

From the viewpoint of charge accumulation, the important factor is the behavior of space charges in the streamer channel after reaching epoxy surface. For the dielectric/electrode interface mode, the propagation of streamer through the gap is associated with landing on the insulator surface [14] where space charges are moving in the gap according to the resultant electric field strength as shown in Figure 11. This means that, for negative PD pulses, negative charges move toward the insulator surface and some of these charges reach the surface and then are accumulated after the PD event as illustrated in Figure 11a. For positive PD pulses as shown in Figure 11b, positive charges move toward the insulator surface and then, these charges neutralize some of the previously accumulated negative charges. Therefore, it is considered that the number of negative and positive PD pulses is one of the main parameters that can relate to charge accumulation process.

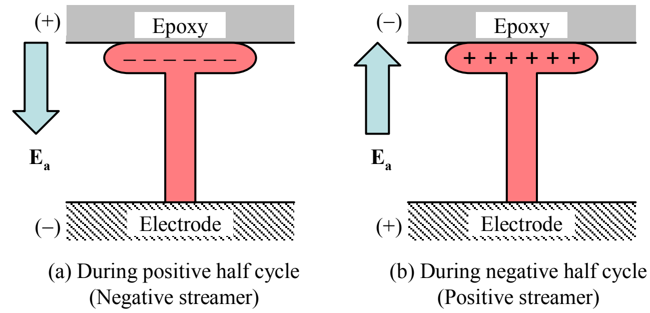

Figure 11. Landing of partial discharge on insulation surface and charge accumulation process.

4.2 EVOLUTION OF ACCUMULATED CHARGES WITH PD ACTIVITY

As highlighted from the experimental results, the PDIV increased after exposing to PD activity and, in turn, the accumulated charge density increased. This increase mainly corresponds to change in the number of negative PD pulses with respect to that of positive PD pulses. Figure 12a and Figure 12b describe the temporal change of PD activity and its correlation to charge accumulation process for 500 μm and 50 μm gaps. The stages used here correspond to those in Figures 6 and 7, respectively, based on PD characteristics. It is important to point out that the measured average pulse width for a certain gap length is approximately the same at the beginning and end of PD activity. Consequently, it is assumed that there would be no transition in PD mechanisms, unlike the case of dielectric bounded voids filled with air [15].

For 500 μm gap as shown in Figure 12a, the number of negative PD pulses at the first stage is about two times that of positive PD pulses. This causes charge accumulation process with negative polarity to be predominant and consequently, rapid change in PDIV. After 10,000 PD pulses, during the second stage, the number of negative PD pulses decreases due to the reduction of the net stress, $E_a - E_q$, in the gap. However, it is still larger than the number of positive PD pulses. So, the charge accumulation process continues but with slow rate, as indicated from the small changes in PDIV. At the third stage, after about 60,000 PD pulses, the number of negative and positive PD pulses decreases to a steady state value. At this stage, the number of PD pulses at both polarities becomes similar, resulting in balance between charge accumulation and charge neutralization. Then, the PDIV is approximately kept constant.

For 50 μm gap case as shown in Figure 12b, the number of negative PD pulses is three or more times that for 500 μm gap case and is extremely larger compared to the number of positive PD pulses of the same gap. These characteristics continued in the first and second stages causing a surface charging rate to be fast, and consequently PDIV increased notably until reached 1.2×PDIV$_0$ where PD activity is stopped in the third stage. When PD activity is stopped during the positive half cycle, the probability of initial electron generation from the gas gap became very low and PD activity is stopped also during negative half cycle.

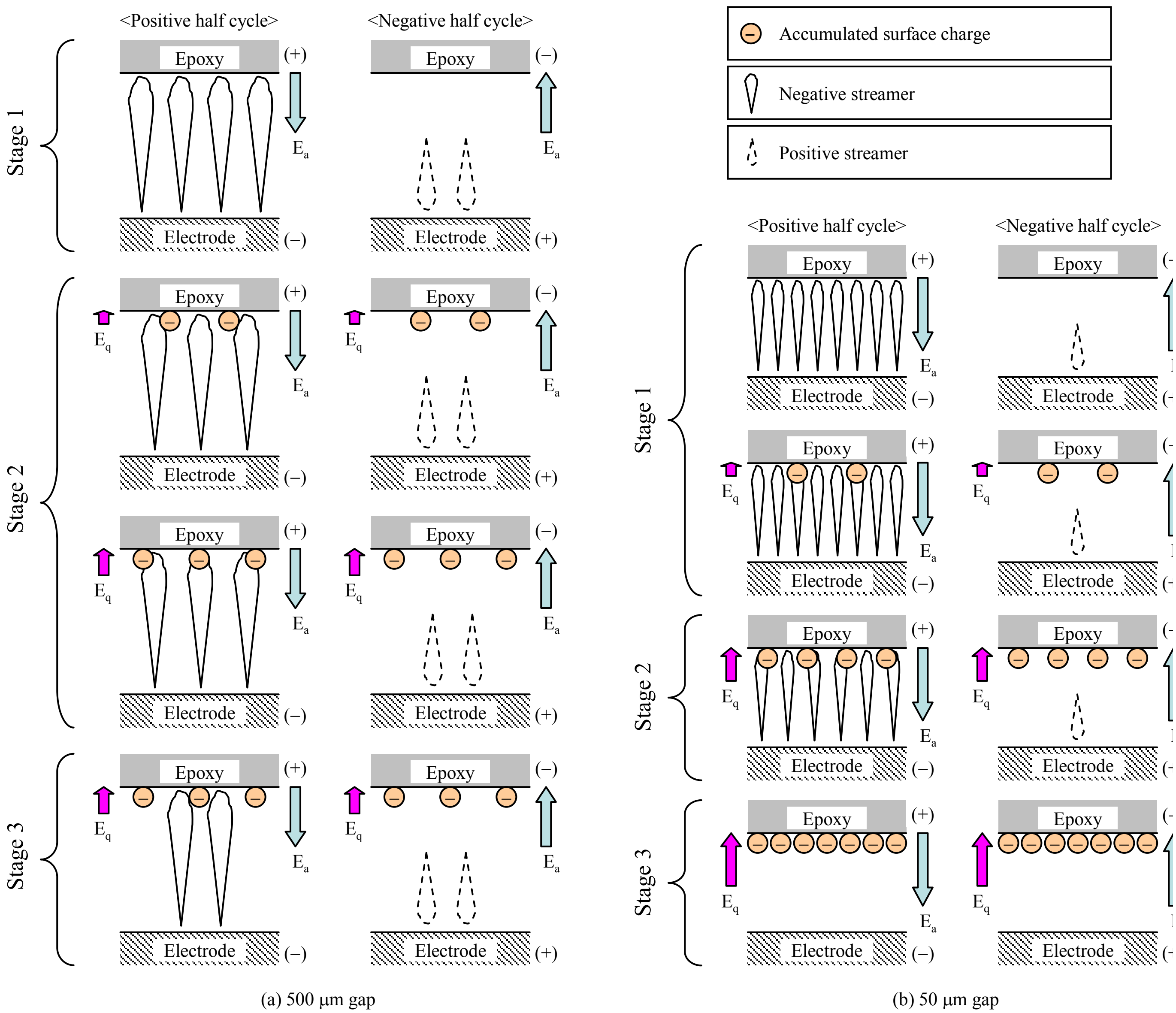

Figure 12. Evolution of accumulated charges with PD activity for different gap lengths.

5 CONCLUSIONS

The contribution of partial discharge (PD) activity to charge accumulation in the small gap at the electrode/epoxy interface in SF_6 gas is discussed in order to provide some useful points for reliable operation of gas insulated switchgears. The important parameters that affect the charge accumulation process are investigated. First, $PDIV_0$ and $PDIE_0$ for non-accumulated charge case were obtained for gap lengths 50, 100, 300 and 500 μm and discussed from the viewpoint of discharge inception mechanism. It is indicated that the PD inception mechanism matches with the theoretical values when the streamer criterion is applied. The PD initiated at positive half cycle of ac voltage at the epoxy covered electrode.

The change of PDIV and consequently accumulated charges after exposing to PD pulses was measured and the following items were concluded:

(1) For different gap lengths, PDIV increases with increasing the number of PD pulses until reaching a saturated value after several ten thousands of PD pulses. This is resulted from the accumulated charges which produce local electric field inside the gap. The increase in PDIV implies that the accumulated charge has negative polarity.

(2) The accumulated charge density calculated for different gap lengths indicated that the charge density on the epoxy surface is larger for smaller gaps, when using applied voltage with $1.2\times PDIV_0$ to generate PD pulses. The charge density ranged from 20~50 μC/m^2.

(3) For 50 μm gap with delamination area about 60 mm in diameter and applied voltage $1.2\times PDIV_0$, the PD pulses vanished after 27,000 pulses due to charge accumulation effect. This indicates that charge accumulation may limit detection of delamination defect with micrometer gap length at GIS spacer.

(4) It is considered that the number of positive and negative PD pulses is the main parameter that can be related to charge accumulation process.

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