Partial Discharge Characteristics for Small Gap of Electrode/Epoxy Interface in SF_6 Gas

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Abstract- **To achieve a safe operation of Gas Insulated Switchgears (GISs), the reliability of electrical insulation is one of the fundamental importance. For this respect, there is an urgent need for better understanding of partial discharge (PD) mechanisms at different locations in GIS. In the current work, the PD inception characteristics at electrode/epoxy interface at insulating spacer in GIS, which represents one of the most critical defects in GIS, are obtained and investigated with different gap lengths, 50~500 µm. Partial discharge inception voltage (PDIV) and electric field (PDIE) are measured and analyzed regarding PD inception mechanism in SF_6 gas. Also the dependence of PDIV on repetitive number of PD pulses is obtained and discussed from the viewpoint of accumulated charge on the epoxy surface.**

I. 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. Epoxy spacers in GIS are critical component for safe operation of GIS. Therefore, there is an increasing demand for evaluating insulation reliability in GIS. However, epoxy insulators are susceptible to localized degradation resulting in generation of partial discharge (PD) pulses leading to breakdown [1, 2].

The PD originates either in gas-filled voids in the solid insulator or in delamination at interfaces [3]. Although there have been significant improvements in the processing and handling of materials, GIS manufacturing and installation techniques, it is difficult to eliminate all problems at interfacial region between high voltage electrode and epoxy spacer. Especially form the view points of long time GIS operation, electric stress at the interface can be critical for determining the lifetime of electrical insulation performance. Thus it is important to know how the interfaces behave under operating stresses. The electrical stress needed to initiate PD in the interfacial gap depends on several factors, for example, gap size, gas pressure and charge accumulated on epoxy surface. The understanding of different processes governing the PD phenomena initiating at the electrode/epoxy interface in SF_6 gas is crucial for the design and dimensioning of GISs.

PD inception voltage (PDIV) and electric field (PDIE) are key factors to evaluate the strength of insulating materials and systems. In addition, the successive number of PD pulses would change the accumulated charge on the dielectric surface and hence, modify the local electric field and could change PDIV.

From this point of view, this paper concentrates on the investigation of PD inception characteristics for electrode/epoxy interface in SF_6 gas with small gaps considering the accumulated charge effect. The electric field reduction in the gap resulted from surface charge is calculated and the corresponding charge density is obtained and compared among different gap lengths.

II. Experimental Setup

A schematic diagram of the electrode system setup is illustrated in Fig. 1. To simulate the delamination at the electrode/epoxy interface in SF_6 gas, a parallel plane electrode is used and installed in a pressure chamber. The high voltage electrode is 60 mm in diameter and is molded using guard insulation with 90 mm diameter and relative permittivity of 3.7. The ground plane electrode is SUS304 with average surface roughness of 7.4 µm. A rectangular epoxy plate (100 mm × 100 mm × ^{t}5 mm) 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. The gap is kept open to be able to control the gas type and pressure in it.

Experiments are conducted in a gas tank filled with SF_6 at 0.1 MPa. PD signals are detected with 50 Ω resistor and then are acquired through a large bandwidth digital oscilloscope (20GS/s, 4GHz). 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.

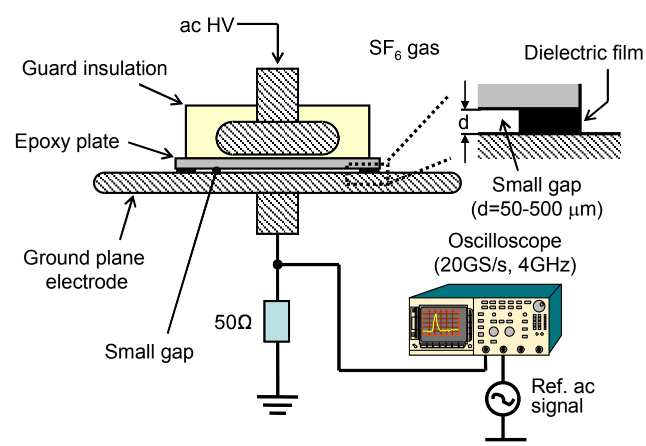


Fig. 1. Schematic diagram for simulating small gap with electrode/epoxy interface in SF_6 gas

To examine the effect of accumulated charge on epoxy surface, PD pulses are generated at applied voltage equal to $1.2 \times PDIV_0$ and PD pulses are counted using the digital oscilloscope until 10,000 pulses is attained. After exposed to 10,000 PD pulses, ac voltages are gradually increased from zero and PDIV is obtained again. This procedure is repeated ten times for each gap length. This means that total number of PD pulses reaches 100,000 pulses.

III. Partial Discharge Inception Characteristics

$PDIV_0$ before exposing to PD activity and the corresponding $PDIE_0$ in the gap space were obtained experimentally for different gap lengths as illustrated in Fig. 2. The PD pulses at inception conditions were observed at positive polarity of ac phase.

In the case of SF_6 gas, the breakdown field strength in uniform fields is given by the following formula [4]:

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

where E_b is breakdown electric field, d is the gap length, $(E/p)_0$ = 0.885 V/cm-Pa and K is constant. For the Townsend mechanism K is determined by the secondary ionization coefficient γ and the numerical value of K in this case ranges from 8 to 10. For the streamer mechanism K is determined by the critical avalanche length required to develop to streamer and is given by the following equation:

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

where $\bar{\alpha}$ is the effective ionization coefficient. As proposed by Raether [5], the transition from avalanche to streamer generally occurs when the combined space charge field and externally applied field lead to intense ionization and excitation of the gas molecules in front of the avalanche head.

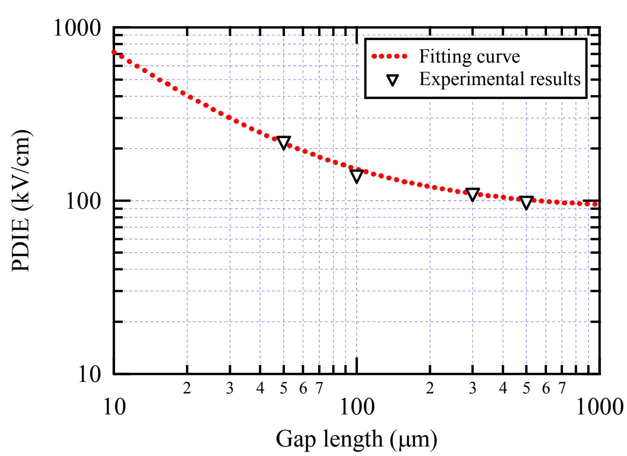


Fig. 2. Experimental PDIE results and its fitting curve corresponding to breakdown field strength in SF_6 gas

The number of space charges at the avalanche head determines the value of K in equation (2). It has been reported in the literature that the values of K corresponding to streamer criterion in SF_6 gas ranges from 10.5 to 18 [6].

To obtain the value of K matching with the experimental results and indicate the possible PD criterion, the experimental results are fitted according to equation (1). The value of K is found to be 17.5 suggesting that the PD criterion is streamer type.

IV. Effect of Successive PD Generation on Inception Conditions

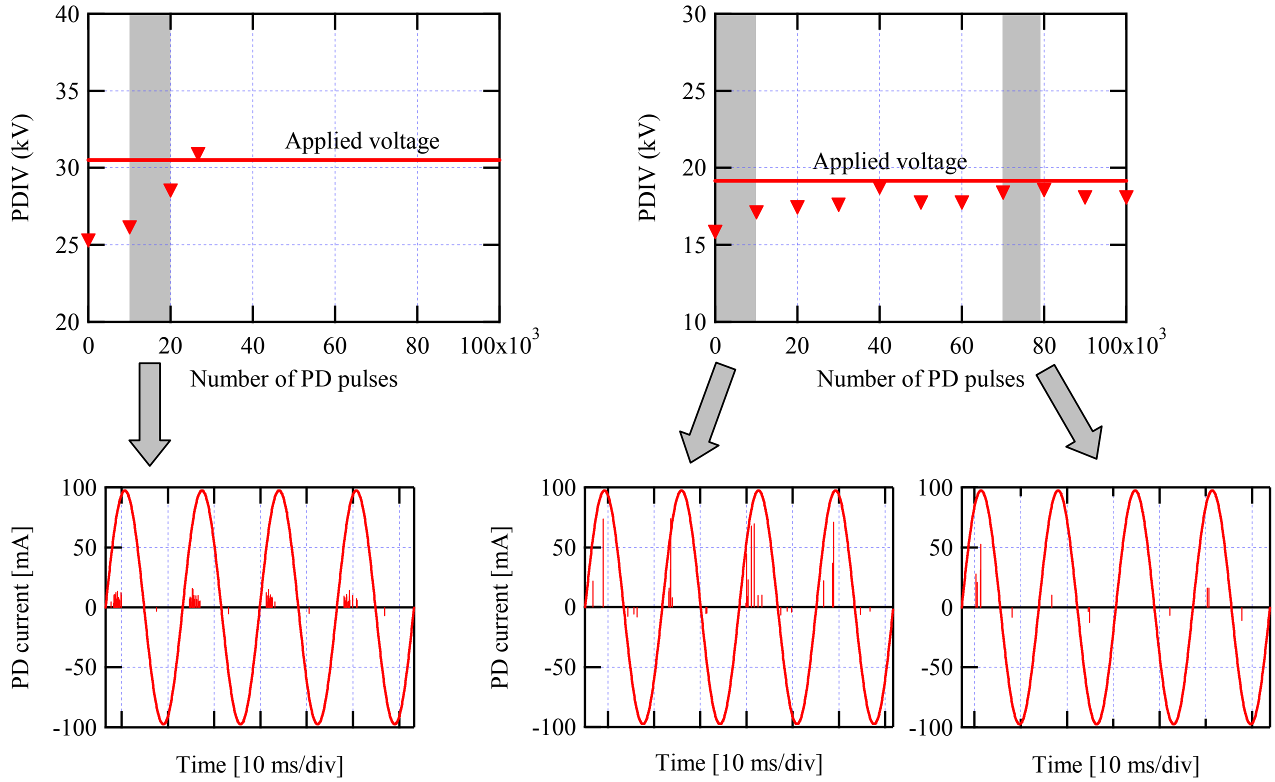
The inception of a partial discharge is a process affected by the charge carriers accumulated by previous discharge events. To investigate this effect, the PDIV dependence on the number of PD pulses is obtained and analyzed for small and large gaps as shown in Fig. 3. The applied voltage used to generate PD pulses is equal to 1.2 times of $PDIV_0$. At all examined values of gap lengths, PDIV increases with increasing the number of PD pulses until reaching a saturated value after several ten thousands of PD pulses. This saturated level increased for smaller gap lengths. To clarify the saturation phenomenon of PDIV with successive PD generation, the PD activity over several cycles are captured at the beginning of PD generation and after PDIV saturation happened as shown in Fig. 3(b). It is noticed that at the beginning of PD generation, the pulse per second (pps) and PD current of positive PD pulses were larger than that of negative PD pulses. This resulted in more negative charge to reach at epoxy surface. On the opposite side, after PDIV saturation occurs, the pps and PD current of positive PD pulses decreased resulting in less charge to be accumulated on the epoxy and consequently, balance between charge accumulation and charge neutralization.

For the case of 50 μm gap in Fig. 3(a), the PDIV increased with the number of PD pulses until reaching $1.2 \times PDIV_0$ which is used to generate PD pulses. At this stage the applied voltage didn't generate more PD pulses. This can be explained by the large number of positive pps which is responsible for charge accumulation process. The average (pps) measured here was 520 pps for 500 μm gap and 1240 pps for 50 μm gap. This phenomenon of PD disappearing implies that detection of delamination with micro meter length may not be possible due to charge accumulation effect.

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_{ag}. 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:

$$E_g = E_{ag} + E_q \tag{3}$$

Here E_g represents the critical field strength required to bring the gap to breakdown which is considered fixed for the



(a) 50 μm gap (b) 500 μm gap

Fig. 3. Dependence of PDIE on successive PD exposure of epoxy samples for small and large gaps

same gap. Increasing PDIV in this case and consequently PDIE indicates that the majority of accumulated charges on the epoxy surface are negative charges resulting in the direction of E_q opposite to that of E_{ag}. The increase in PDIV will be explained in details in the next section considering the accumulated charge density and the parameters by which this accumulated charge may be influenced.

On the other side, the process of accumulated charge diffusion is investigated. PDIV was measured as a function of time in the absence of applied voltage after epoxy sample is exposed to 100,000 PD pulses. The PDIV decreased rapidly after one hour but after several hours the PDIV is saturated at constant value larger than $PDIV_0$. So, the time of charge diffusion was relatively large compared to the time of experiment and consequently the charge accumulation process would not be affected by the charge diffusion.

V. Accumulated Charge Effect and Charge Density

The accumulated charge on a solid insulator surface is one of the critical parameters that can reduce the insulation performance [7]. Therefore, it is important to grasp charge amounts on an insulator surface exposed to PD activity. In our study, the charge density on the epoxy surface is calculated from the new PDIV measured after charge accumulation and from the equations of boundary conditions given by:

$$\varepsilon_g E_g - \varepsilon_e E_e = \rho_s \quad (4)$$

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; ρ_s is the accumulated charge density on the epoxy surface considering that the charge distribution is uniform. 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 ρ_s is calculated after each 10,000 PD pulses and plotted as shown in Fig. 4. The results of the different gap lengths examined are recorded. It was noticed that the curves have the same shape. However, the values of charge density increase with decreasing the gap length. The changes observed between different gaps attest the dependence of charge accumulation density on electric field. On the other hand, an examination of Fig. 4 indicates that a saturation state seems to be reached after about 40,000 PD pulses for the different gaps. The saturation level was found to be 19 μC/m^2 for 500 μm gap, 19 μC/m^2 for 300 μm gap and 21 μC/m^2 for 100 μm gap. For 50 μm gap the final charge density after PDIV reached $1.2\times PDIV_0$ was found to be 45 μC/m^2.

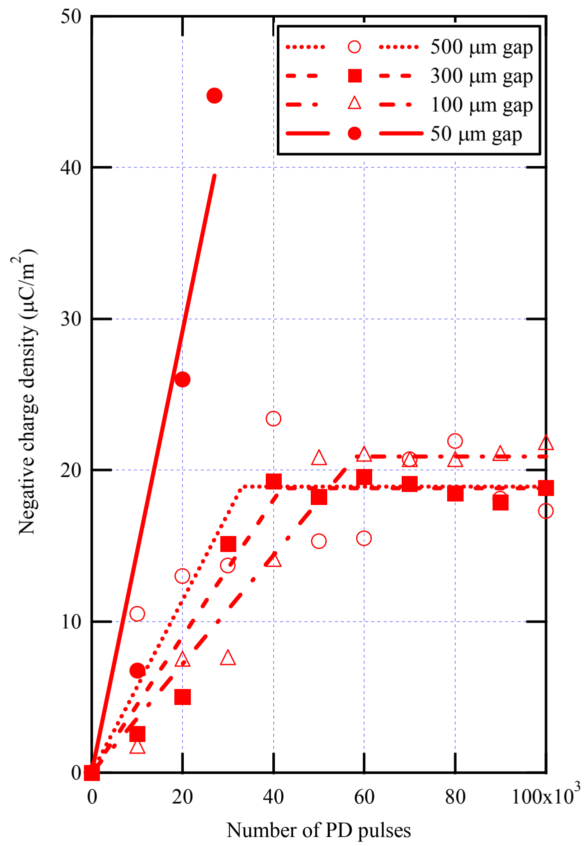


Fig. 4. Accumulated charge density as a function of PD pulses for different gap lengths

The charge density saturated at the end of PD exposure, after 100,000 PD pulses, is plotted against the gap length as shown in Fig. 5. For 50 μm case, the charge density at stopping generation of PD pulses is used. From this it is evident that decreasing the gap length and applying the same percentage of $PDIV_0$ ($1.2 \times PDIV_0$) to generate PD pulses results in an increase in charge density magnitude and, in turn, increase the applied voltage required to incept PD.

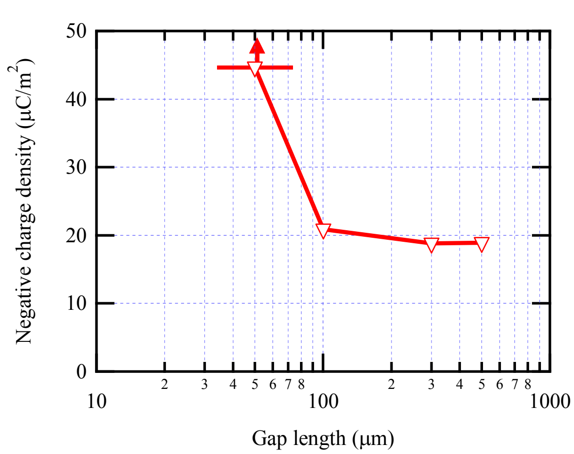


Fig. 5. Dependence of accumulated charge density on the gap length

VI. Conclusions

Partial discharge inception characteristics were measured and analyzed with a wideband (4 GHz, 20 GS/s) measuring instrument for electrode/epoxy interface in SF_6 gas with different gap lengths. The $PDIV_0$ and $PDIE_0$ at the first PD inception 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 streamer criterion for spark formation. The PD inception appeared at positive half cycle of ac phase at epoxy covered electrode.

The effect of accumulated surface charge on PD inception is investigated and the following items are concluded:

- 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 is negative type.
- The accumulated charge density calculated for different gap lengths indicated that for smaller gap lengths, the charge density on the epoxy surface increases using applied voltage with $1.2 \times PDIV_0$ to generate PD pulses. The charge density was 20~50 $\mu C/m^2$.
- For 50 μm gap with 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 micro meter length.

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