Partial Discharge Detection at Delamination of Electrode/Epoxy Interface in GIS Spacers

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***Abstract*- Partial Discharge (PD) measurements are very promising for insulation condition monitoring in Gas Insulated Switchgears (GISs). However, for accurate PD detection and diagnosis, there is a need for better understanding of physical mechanisms behind PD activity. Accordingly, we have been investigating the PD characteristics and associated mechanisms for electrode/epoxy delamination of GIS spacers as one of the most serious defects in GIS. The gas pressure inside delamination usually changes from sub-atmospheric pressure, just after delamination initiates, to filled SF_6 gas pressure in the GIS tank, after SF_6 gas permeates into the delamination area. Therefore, in this paper, the PD activity at different gas pressures, from 0.02 MPa to 0.4 MPa, is acquired. The relative PD generation rate and its phase appearance are analyzed at different pressures and then discussed from the viewpoint of PD mechanism and PD detection. Experimental results show that, with increasing pressure, the peak of the PD generation rate shifts from around zero crossing like void-type discharge to around a peak of ac voltage, before PD pulses vanish at high pressure for the applied electric field stress. The obtained results could be useful for delamination diagnosis in GIS spacers.**

I. Introduction

Gas insulated switchgears (GISs) are exposed to different stresses such as mechanical, thermal, and electrical stresses under their operation conditions. These stresses are applied to the GIS spacers in different forms. One of these forms is the loss of adhesion at electrode/epoxy interface which leads to initiating delamination. Field experiences indicated that bulk dielectric failure of spacers can be attributed to delamination at the electrode/epoxy interface [1]. Usually an eventual failure of a GIS spacer due to delamination is preceded by partial discharge (PD) activity [2]. Therefore, an early detection of delamination is desirable in order to achieve high reliability of GIS.

When delamination initiates, the gas pressure inside the delamination area would be low. Hence, the SF_6 gas permeates into the delamination area resulting in gradual increase of gas pressure up to the gas pressure filled in a GIS. This process affects greatly the PD behavior inside delamination and should be considered in PD detection and diagnosis.

From this point of view, this paper aims to measure, analyze and detect PD pulses generated at electrode/epoxy delamination of a GIS spacer model. The model was built with adjustable gap lengths in order to simulate different delamination sizes in a GIS spacer. The pressure dependency of PD activity was investigated using the phase characteristics of the relative PD generation rate. The tendency of the relative PD generation rate for both negative and positive PD polarity was obtained and discussed from the viewpoint of initial electron generation mechanism.

II. Experimental Setup

The delamination defect at the electrode/epoxy interface in SF_6 gas was simulated with the electrode configuration described in Fig. 1. The electrode setup consisted of molded type high voltage electrode and grounded plane electrode. An alumina filled rectangular epoxy plate (100 mm × 100 mm × 5 mm thickness) with relative permittivity of 6.0 was attached to the high voltage electrode using vacuum grease to avoid any voids at the interface. The delamination was constituted by a stack of thin dielectric films inserted between epoxy plate and grounded plane electrode. Each dielectric film has a thickness 25 μm enabling to adjust the delamination gap at different lengths. The delamination gap length considered in this study is 50 μm. The electrode setup was installed in a pressurized chamber filled with SF_6 gas at 0.4 MPa. The delamination gap was kept open to allow controlling the gas pressure inside the

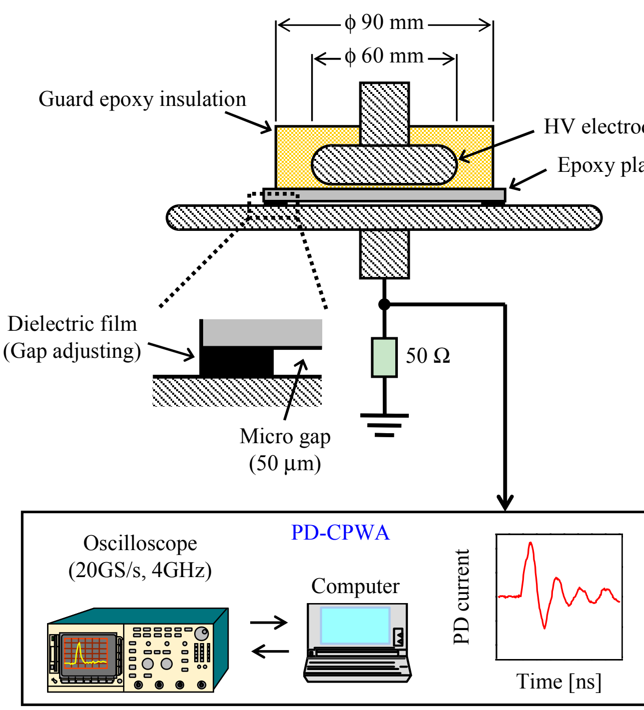


Fig. 1. Experimental configuration for measurement and analysis of PD pulses at electrode/epoxy delamination in SF_6 gas

delamination. The generated PD pulses were detected using 50 Ω resistor and then were analyzed using PD-Current Pulse Waveform Analysis (PD-CPWA) developed in [3].

III. Experimental Results

A. Partial discharge inception characteristics

The PD inception voltage (PDIV) is measured at different values of SF_6 gas pressure inside the gap. Then, the corresponding PD inception electric field (PDIE) is calculated as shown in Fig. 2. The gap length is 50 µm. It is found that PDIE increases with the rise of pressure. At all pressure values, PD inception occurs at the negative polarity of the grounded electrode and around the peak of ac voltage. Therefore, for PD inception, an initial electron is generated from the grounded bare plane electrode. By fitting PDIE to the theoretical breakdown field strength for streamer criterion [4], it is found that the critical E/p equal to 110 V/Pa m (E is the electric field and p is the gas pressure). This value is higher than the theoretical value 89 V/Pa m which might be attributed to the small discharge volume for delamination case.

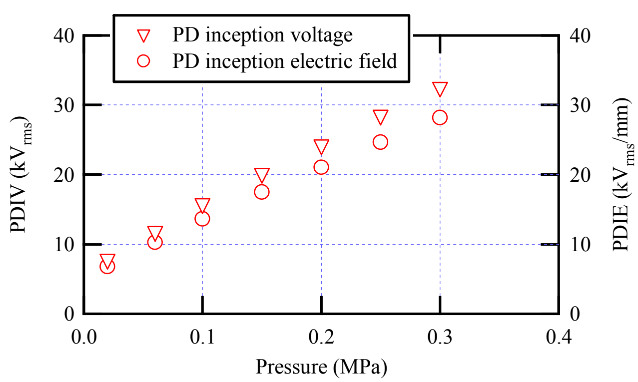
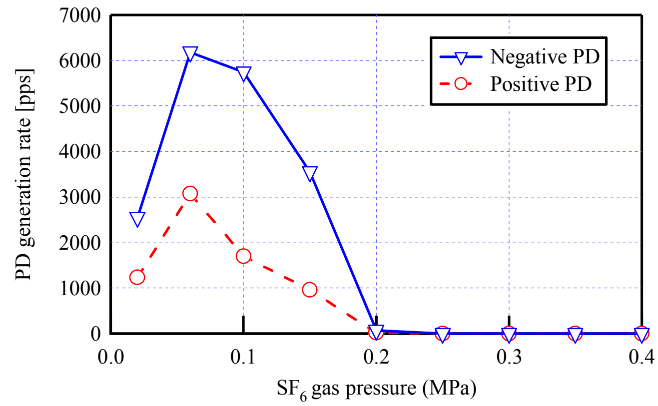


Fig. 2. PD inception characteristics for electrode/epoxy delamination with 50 µm gap in SF_6 gas

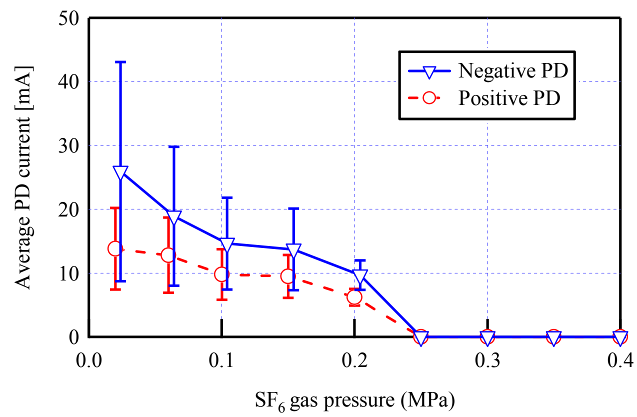
B. Pressure dependency of partial discharge activity

The PD activity was acquired at different values of SF_6 gas pressure inside the gap. The delamination gap length was adjusted at 50 µm. The operating electric field stress of a GIS spacer is usually 2.5~5 kV_{rms}/mm [5]. Hence, the expected electric field stress for a delamination at a GIS spacer can be estimated 2.5~5 kV_{rms}/mm times 6.0 (the relative permittivity of epoxy), i.e. the expected electric field will be 15~30 kV_{rms}/mm. In the present study, the electric field in the delamination gap was fixed at 24 kV_{rms}/mm by setting the applied voltage at 28 kV_{rms}.

After voltage application, the PD activity changes greatly with time due to the charging phenomena on the epoxy surface [6]. Therefore, in this study, the PD characteristics are acquired and analyzed after several minutes of voltage application where stable PD activity is attained.



(a) PD generation rate



(b) Average PD current magnitude

Fig. 3. Pressure dependency of PD activity for electrode/epoxy delamination with 50 µm gap in SF_6 gas (Electric field = 24 kV_{rms}/mm)

The dependence of PD generation rate and average PD current magnitude on gas pressure is shown in Fig. 3 for both PD polarities. The polarity is expressed as the polarity of the grounded bare electrode at the delamination. The PD generation rate is expressed as pulses per second (pps) and the average PD current magnitude is expressed as mA.

As can be seen in Fig. 3a, the negative PD generation rate increased from 2500 pps to 6200 pps when SF_6 gas pressure grew from 0.02 MPa to 0.06 MPa, whereas the positive PD generation rate increased from 1200 pps to 3100 pps. Then, the PD generation rate for both polarities reduced with the rise of gas pressure higher than 0.1 MPa until PD activity completely stopped at gas pressure of 0.25 MPa. In spite of that the tendency of PD generation was similar for negative and positive PD polarities; the generation rate of positive PD was smaller than that of negative PD.

For the average PD current magnitude shown in Fig. 3b, it was found that the PD current magnitude for both PD polarities reduced continuously as the gas pressure increased from 0.02 to 0.2 MPa before stopping of PD activity at 0.25 MPa. For negative PD pulses, average PD current magnitude reduced from 26 mA at 0.02 MPa to 10 mA at 0.2 MPa. Similar to the PD generation rate, there was a difference in PD current magnitudes between negative and positive PD.

C. Analysis of relative partial discharge generation rate

The transition of PD activity with pressure is analyzed using the characteristics between the ac voltage phase (ϕ) and the relative number (n) of PD pulses as a useful way to represent PD behavior over multiple cycles of ac voltage. To construct the plot, the ac voltage phase is divided to intervals with each 10° spacing. The PD pulses generated in a certain time frame are counted at each phase interval and represented as a percentage of the total PD pulses.

The ϕ-n distribution obtained for different gas pressures are given in Fig. 4 with 50 μm delamination gap. For the sub-atmospheric gas pressures in Fig. 4a and Fig. 4b, PD pulses appeared around the zero-crossing of the applied voltage. This is similar to the pattern of a void-type discharge [7]. For the gas pressures 0.1~0.2 MPa in Fig. 4c, 4d and 4e, the phase characteristics of PD pulses shifted to around the peak of the applied voltage. For all aforementioned cases, the relative generation rate for negative PD is higher than that for positive PD. Finally, at the pressure 0.25 MPa or higher, PD activity completely stopped as shown in Fig. 4f. These results suggest that the PD activity changed from void-type discharges to gap discharges with the pressure increase in the delamination gap.

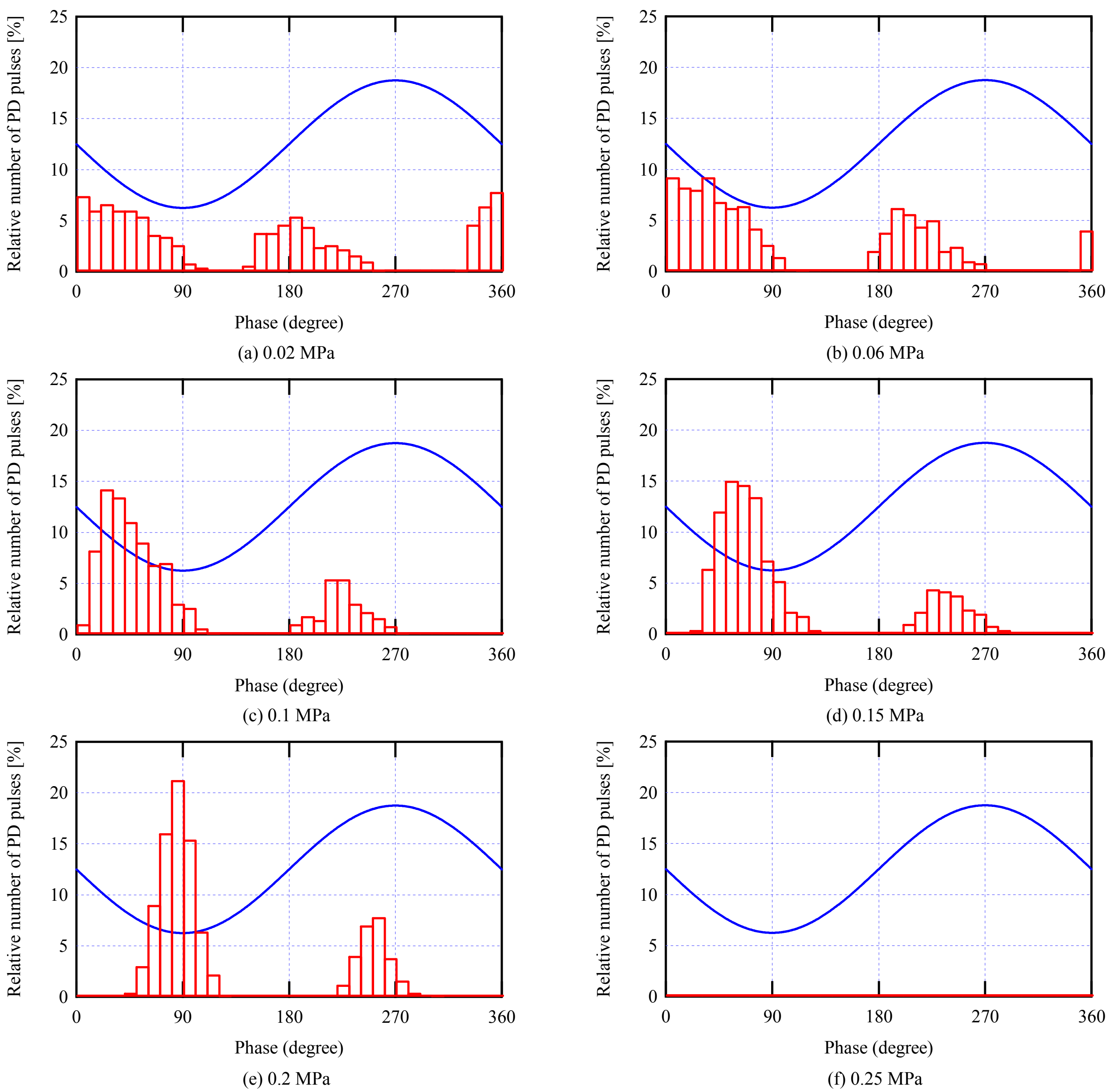


Fig. 4. Change of ϕ-n distribution with SF_6 gas pressure for electrode/epoxy delamination with 50 μm gap (Electric field = 24 kV_{rms}/mm)

IV. Discussions

A. Difference between negative and positive PD activity

As described in Fig. 3, there is a difference in PD generation rate between negative PD and positive PD. This is considered to be resulted from the initial electron generation mechanism. For negative PD, initial electrons are generated from the grounded bare electrode. Thus, the rate of avalanche initiation should be quite high as soon as the critical electric field is reached. On the other hand, initial electrons for positive PD are generated as a result of the negative charges accumulated on the epoxy surface during the previous negative PD events [6]. This could reduce the probability of release of avalanche-initiating electron for positive PD generation. As a result, positive PD generation rate is lower (Fig. 3a). With the rise of gas pressure to 0.25 MPa, the PD activity extinguishes. This is because PD inception and/or extinction electric fields reach beyond the applied electric field inside the delamination, 24 kV_{rms}/mm. Consequently, it is important to point out that PD activity for electrode/epoxy delamination will be limited by the rise of SF_6 gas pressure in the delamination gap.

B. Pressure effect and physical mechanisms of PD activity

The pressure dependence of PD parameters in Fig. 3 and the corresponding relative number of PD pulses in Fig. 4 are attributed to two effects. First effect is the over-voltage factor above PD inception voltage. Second effect is the range of voltage phase over which inception conditions are met, i.e. the instantaneous electric field is higher than the critical electric field.

For the over-voltage factor, it is clear that at low gas pressures the over-voltage factor was high, e.g. about 3.5 times PDIV for 0.02 MPa. This could increase PD current magnitude at low pressures as in Fig. 3b where PD pulses across the gap can develop to a surface discharge along the epoxy surface, causing the electric field across the delamination area to fall to zero. Then, all the delamination area can act as a single void. In this case, PD pulses appeared around zero-crossing similar to void-type discharges (Fig. 4a).

With increasing the pressure, the over-voltage factor became lower. This resulted in small PD current magnitude as in Fig. 3b where propagation of PD pulses along the epoxy surface was short. In this case, single PD event could not affect the electric field along the delamination area; only affected the electric field at its location. This means that the delamination area can act as multiple voids, and void-type PD did not become dominant as given from PD phase characteristics which were shifted beyond zero-crossing in Fig. 4b. Multiple PD could increase the PD generation rate until 0.06 MPa in Fig. 3a.

With multiple PD locations, the main parameter that affect PD generation rate and phase characteristics is the range of voltage phase over which the instantaneous electric field is higher than PDIE. It is evident that this range decreases with the rise of gas pressure where PDIE becomes higher. This caused a narrow range of voltage phase where PD activity was recorded for higher gas pressures as in Fig. 4c, 4d and 4e and also PD generation rate reduced in Fig. 3a. Considering these tendencies in PD parameters and phase appearance together with their physical mechanisms can be helpful for diagnosing a delamination defect in GIS spacers.

V. Conclusions

An experimental study of partial discharge (PD) detection for electrode/epoxy delamination in SF_6 gas has been undertaken. The electrode configuration was built with 50 μm delamination gap length. The use of ϕ-n distribution together with pressure dependency of PD parameters enabled to clarify the physical mechanisms behind PD behavior. The obtained results can be summarized as follows:

(1) For all examined pressures, the PD generation rate is different for positive and negative PD polarity due to the differences in initial electron generation mechanism.

(2) At the first portion of SF_6 gas pressure, 0.02 MPa ~ 0.06 MPa, the PD generation rate increases due to the change of PD mechanism from void-type discharge to multiple location discharge. At pressures higher than 0.06 MPa, the PD generation rate decreases due to the reduction of phase range over which the instantaneous electric field is higher than PD inception electric field.

(3) The average PD current magnitude decreases continuously with the rise of pressure due to the reduction in the over-voltage above PD inception.

(4) The PD activity stops when the pressure in the delamination becomes 0.25 MPa. This indicates that PD activity will be limited by the rise of SF_6 gas pressure for the applied electric field stress.

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