Partial Discharges and Associated Mechanisms for Micro Gap Delamination at Epoxy Spacer in GIS

Diaa-Eldin A. Mansour
Department of Electrical Engineering and Computer Science
Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

Hiroki Kojima, Naoki Hayakawa, Fumihiro Endo
EcoTopia Science Institute
Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

and **Hitoshi Okubo**
Department of Electrical Engineering and Computer Science
Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

ABSTRACT

For accurate detection and diagnosis of Partial Discharges (PDs) in Gas Insulated Switchgears (GISs), there is a need for better understanding of the physical mechanisms for the PD activity. Accordingly, we have been investigating the PD characteristics and associated mechanisms for electrode/epoxy delamination of GIS spacers as one of the severest 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 infiltrates into the delamination area. Therefore, in this paper, the PD activity at different gas pressures, from 0.02 to 0.4 MPa, is acquired. Delamination gap length at the level of 50 µm is considered, simulating possible size of actual delamination in a GIS spacer. The relative PD generation rate is analyzed regarding the phase characteristics at different pressures and then discussed from the viewpoint of PD mechanism in order to assess the possibility of delamination diagnosis in GIS spacers. Experimental results show that, PD parameters and phase characteristics change significantly with infiltrating SF_6 gas from the GIS tank into the delamination. The obtained results give a characterized feature for the delamination defect and can be useful for delamination diagnosis.

Index Terms — **Partial discharge, gas insulated switchgear, spacer, electrode/epoxy delamination, SF_6 gas, diagnosis.**

1 INTRODUCTION

INSULATION diagnosis of gas insulated switchgears (GISs) is of great importance in terms of preventing failures, and reducing maintenance cost. So, it is becoming highly demanded to build a diagnostic system that can detect, identify and locate any defect in the GIS insulation system [1, 2].

Although several insulation defects can exist in the GIS [3], it is considered that defects of a solid spacer are the critical ones that can initiate failure of GIS under normal ac operating stresses. Different defect types, such as contaminating particle, void, delamination, and so on, can be found in GIS spacers [4]. The possible defect types in GIS spacers are described in Figure 1. One of severe defects in a GIS spacer can be the micro gap delamination at the electrode/epoxy interface [4]. The advancement in epoxy casting for GIS spacers could eliminate delaminations during manufacturing process. However, under the operating conditions, GISs are exposed to different stresses such as mechanical, thermal and electrical stresses. These stresses are reflected on the GIS spacers in the loss of adhesion at electrode/epoxy interface which leads to initiating delamination. When delamination occurs, micro discharge traces would be generated at the electrode/epoxy interface leading to degradation [5], and finally could lead to dielectric failure of spacers [6]. This means that the detection of a delamination at an early stage is important to avoid

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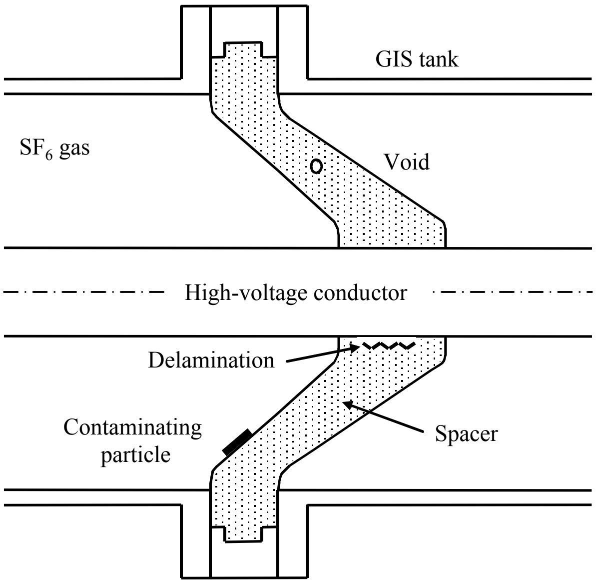

Figure 1. Possible defect types related to GIS spacers.

possible failure of GIS spacer.

Usually an eventual failure of a GIS spacer due to delamination is preceded by PD activity [7]. Therefore, understanding the physical mechanisms behind PD activity due to delamination is desirable for performing risk assessment of such defect. Previously, the phenomenon of surface charge accumulation was investigated [8]. Then, the charge accumulation effects on time transition of PD activity was clarified [9].

However, one of the most important processes that affect greatly the PD behavior inside delamination and should be considered in PD detection and diagnosis is the change in gas pressure inside the delamination due to infiltrating SF_6 gas into the delamination area. When delamination initiates, the gas pressure inside the delamination area would be low. Hence, the SF_6 gas infiltrates into the delamination area resulting in gradual increase of gas pressure up to the gas pressure filled in a GIS.

From this point of view, this paper aims to measure, analyze and detect PD pulses generated at electrode/epoxy delamination of a GIS spacer when the gas pressure is changed. A spacer model was built with 50 μm delamination gap length, in order to simulate micro delamination lengths 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. Finally, the physical mechanisms behind PD activity were proposed based on the obtained results.

2 EXPERIMENTAL SETUP

2.1 ELECTRODE CONFIGURATION AND PARTIAL DISCHARGE MEASUREMENT SYSTEM

The delamination defect at the electrode/epoxy interface in SF_6 gas was simulated with the electrode configuration described in Figure 2. The electrode setup consisted of a molded high-voltage electrode and a grounded plane electrode. The diameter of the high voltage electrode is 60 mm and the diameter of the guard epoxy insulation is 90 mm with relative permittivity of 3.7. 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 the epoxy plate and the grounded plane electrode. Each dielectric film has a thickness 25 μm enabling to adjust the delamination gap at different lengths. In this study the delamination gap length is adjusted to 50 μm. The electrode setup was installed in a pressurized chamber filled with SF_6 gas. The delamination gap was kept open to the tank in order to adjust the SF_6 gas pressure inside the 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 [10].

2.2 EXPERIMENTAL PROCEDURES

The experimental procedures are divided into two parts as shown in Figure 3. In the first part, PD inception voltage (PDIV) and the corresponding PD inception electric field (PDIE) are measured at different values of gas pressure before exposing the epoxy sample to long term PD activity. That is

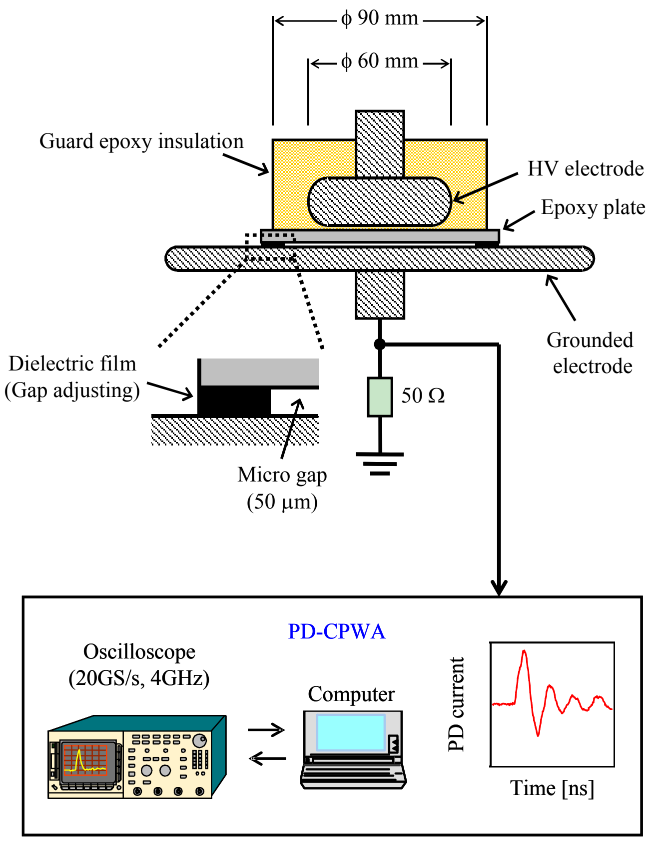

Figure 2. Experimental configuration for measurement and analysis of PD pulses at electrode/epoxy delamination in SF_6 gas.

because accumulated surface charges due to long term PD activity affect greatly PDIV and PDIE measurement results [8]. At the PDIV measurement, ac voltage was gradually increased with a rate 0.1 kV_{rms}/sec. In the second part of experimental procedures, PD activity is acquired for each step of gas pressure. For a delamination, the surface charging occurs within few minutes of PD activity [9]. This means that in an actual delamination, the surface charging would occur at low gas pressure and would be effective at other gas pressures. Consequently, in this study, the PD characteristics are acquired and analyzed at each gas pressure 10 minutes after ac voltage was stepped up to the applied voltage, where stable PD activity is attained.

The ac applied voltage with frequency 60 Hz is adjusted such that the electric field in the delamination gap becomes in the range of the expected electric field stress for a delamination at a GIS spacer. The operating electric field stress of a GIS spacer is usually 2.5-5 kV_{rms}/mm [4, 11]. Since the delamination gap length is very small compared to the epoxy spacer, 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 the intermediate value 24 kV_{rms}/mm by setting the applied voltage at 28 kV_{rms}.

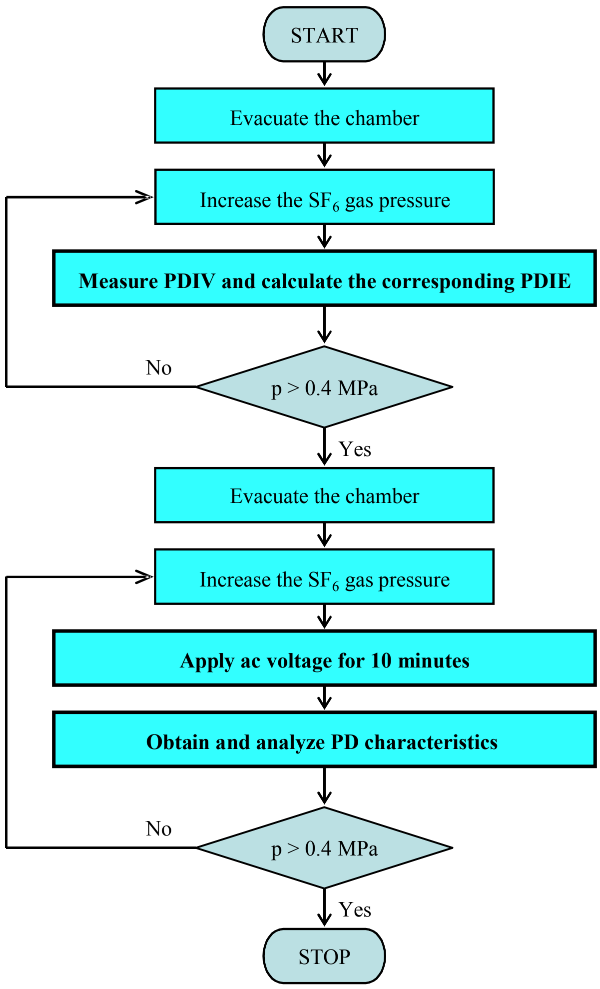

Figure 3. Experimental procedures for measuring PD characteristics.

3 EXPERIMENTAL RESULTS

3.1 PARTIAL DISCHARGE INCEPTION VOLTAGE

The measured PD inception voltage (PDIV) at different values of SF_6 gas pressure inside the gap is shown in Figure 4. Also, the corresponding PD inception electric field in the delamination (PDIE) is calculated. It is found that PDIE increases linearly with the rise of pressure. At all pressure values, PD inception occurs at the negative polarity and around the peak of the ac applied voltage. The voltage polarity in this paper is referred to the grounded bare electrode. 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 SF_6 gas [12], it is found that the critical E/p equals to 110 V/(Pa m), where E is the electric field and p is the gas pressure. The well known value of critical E/p in SF_6 gas equals to 89 V/(Pa m) even under low pressure cases [13]. This indicates that the high critical E/p in this study might be attributed to the small discharge volume in the delamination.

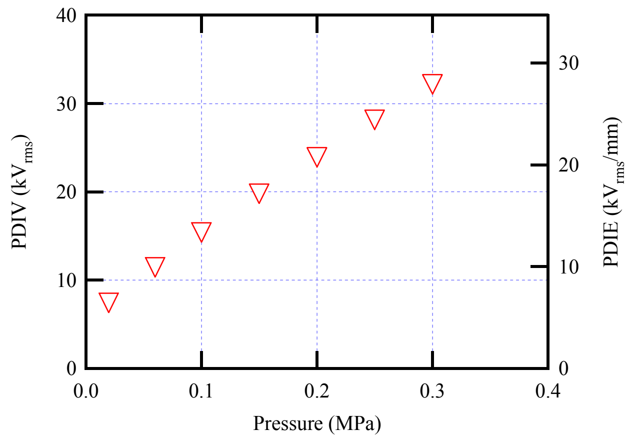

Figure 4. PD inception characteristics for electrode/epoxy delamination with 50 μm gap in SF_6 gas.

3.2 PRESSURE DEPENDENCY OF PARTIAL DISCHARGE ACTIVITY

The dependence of PD generation rate and average PD current magnitude on gas pressure is shown in Figure 5 for both PD polarities. The PD generation rate is expressed as pulses per second (pps).

As can be seen in Figure 5a, PD generation rate shows a peak at 0.06 MPa for both negative and positive PD, and PD activity stopped at gas pressure of 0.25 MPa. The PD generation rate was smaller at positive PD than at negative one. The average PD current magnitude in Figure 5b reduced to zero as the gas pressure increased from 0.02 to 0.25 MPa. Similar to the PD generation rate, there was a difference in PD current magnitudes between negative and positive PD.

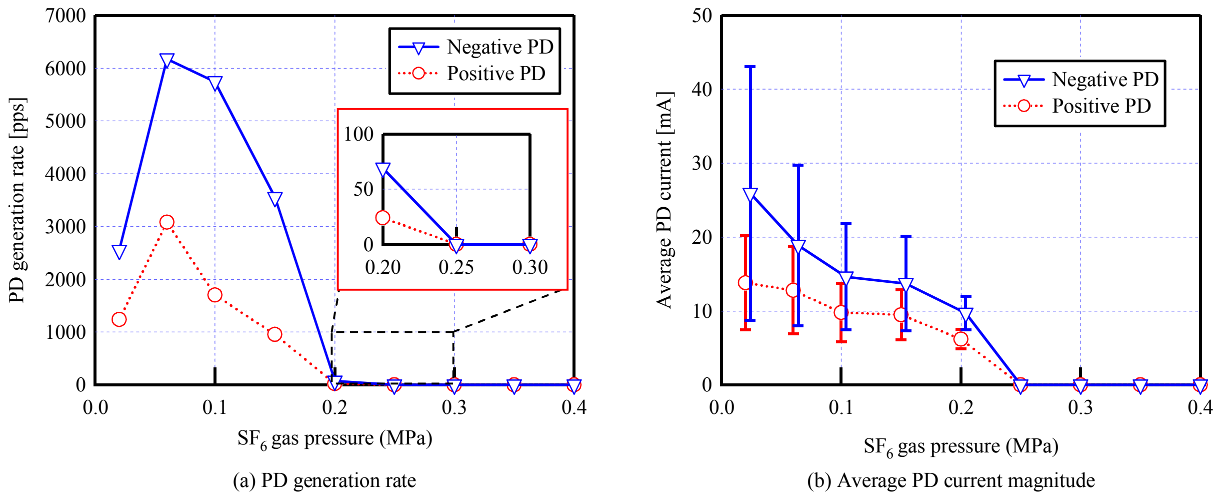

Figure 5. Pressure dependency of PD activity for electrode/epoxy delamination with 50 μm gap in SF$_6$ gas (Electric field = 24 kV$_{rms}$/mm).

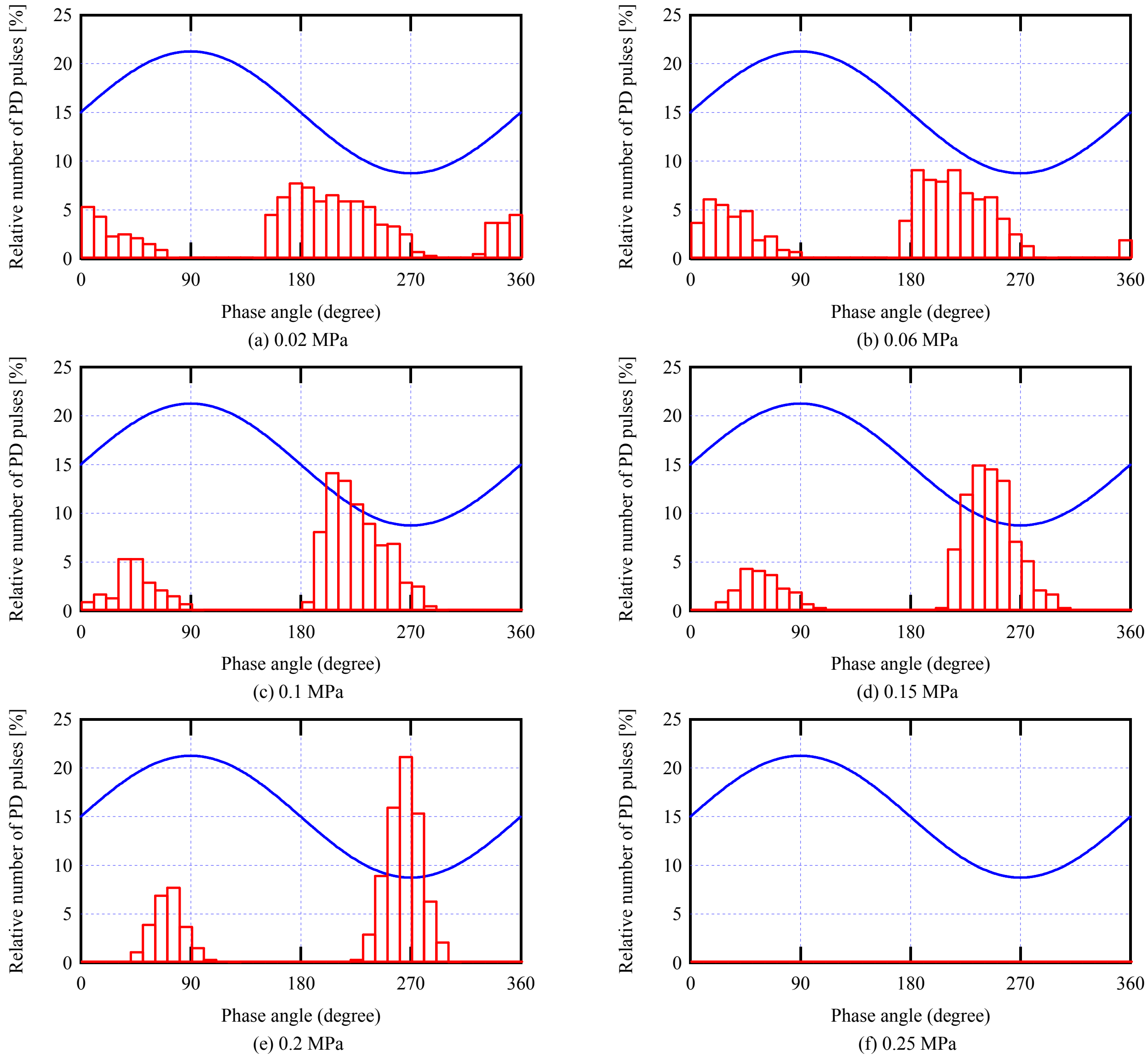

Figure 6. Change of ϕ-n distribution with SF$_6$ gas pressure for electrode/epoxy delamination with 50 μm gap (Electric field = 24 kV$_{rms}$/mm).

3.3 PHASE CHARACTERISTICS OF 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 shown in Figure 6. To construct the plot, the ac voltage phase is divided every 10 degrees. 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. By these plots, PD behavior over multiple cycles of ac applied voltage could be represented in a useful way.

From the ϕ-n distribution in Figure 6, it is found that, for the sub-atmospheric gas pressures in Figures 6a and 6b, PD pulses appeared around the zero-crossing of the applied voltage. For the gas pressures 0.1-0.2 MPa in Figures 6c, 6d and 6e, the phase characteristics of PD pulses shifted to around the peak of the applied voltage. Finally, at the pressure 0.25 MPa or higher, PD activity completely stopped as shown in Figure 6f. It is notably to mention that these tendencies in PD phase characteristics were also observed for other delamination gaps like 25 µm gap [14]. For all aforementioned cases of gas pressures, the relative generation rate for negative PD is higher than that for positive PD.

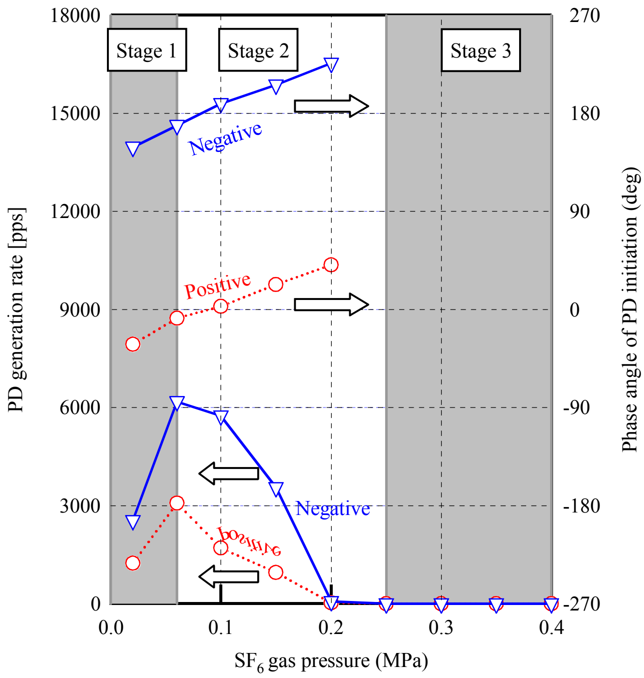

Figure 7. Transition of PD behavior with gas pressure in the delamination.

4 DISCUSSION

As a general remark from the experimental results reported in section 3, there is a change in PD characteristics with increasing the SF_6 gas pressure in the delamination gap. In particular, the analysis of relative PD generation rate seems to have a significant meaning regarding the physical mechanisms behind PD activity. Furthermore, there is a difference in PD generation rate between negative PD and positive PD. This is considered to be resulted from the difference in initial electron generation mechanism for both polarities.

4.1 PRESSURE EFFECT AND ASSOCIATED MECHANISMS OF PD ACTIVITY

The pressure dependence of PD parameters in Figure 5 and the corresponding relative number of PD pulses in Figure 6 can be attributed to two effects. The first effect is the pressure dependence of dielectric strength of SF_6 gas. The second effect is the range of voltage phase over which PD inception conditions are met, i.e. the instantaneous electric field is higher than the critical electric field.

At first, based on the experimental results, the PD behavior can be divided into three stages as shown in Figure 7 which illustrates the transition of PD generation rate and phase characteristics with gas pressure. The phase appearance used in this figure is the starting phase angle at which PD pulses start to appear for both polarities. The Stage 1 corresponds to PD characteristics at low gas pressure where PD generation rate increases with increasing the gas pressure and PD pulses appears around zero crossings of applied voltage. The Stage 2 corresponds to PD characteristics at gas pressures 0.06-0.25 MPa where PD generation rate decreases with increasing the gas pressure and PD pulses shifted beyond zero crossings. Finally, in the Stage 3, PD activity stops.

The explanation of PD characteristics and corresponding mechanisms for each stage are shown in Figure 8. For the Stage 1 in Figure 8a, it is clear that the dielectric strength of SF_6 gas was low due to the low gas pressures in the delamination. This could increase PD current magnitude at low pressures as in Figure 5b where PD across the gap can develop along the epoxy surface, causing the electric field inside the delamination to fall to zero. In this case, PD pulses appeared around zero-crossing of applied voltage (Figure 6a).

With increasing the pressure in the Stage 2, the dielectric strength of SF_6 gas became higher. This resulted in small PD current magnitude as in Figure 5b where extension of PD pulses along the epoxy surface was short. In this case, single PD event was localized and did not affect the electric field at other places. This means that PD pulses can appear at multiple locations as given from PD phase characteristics which were shifted beyond zero-crossing in Figure 6b. Multiple PD locations could increase the PD generation rate at 0.06 MPa as described in Figure 8b. With multiple PD locations, the main parameter that affect PD generation rate and phase characteristics is the range of phase angle 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 Figures 6c, 6d and 6e and also PD generation rate reduced as described in Figure 8c.

Finally, with the rise of gas pressure to 0.25 MPa in the Stage 3, the PD activity extinguishes as shown in Figure 8d. 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

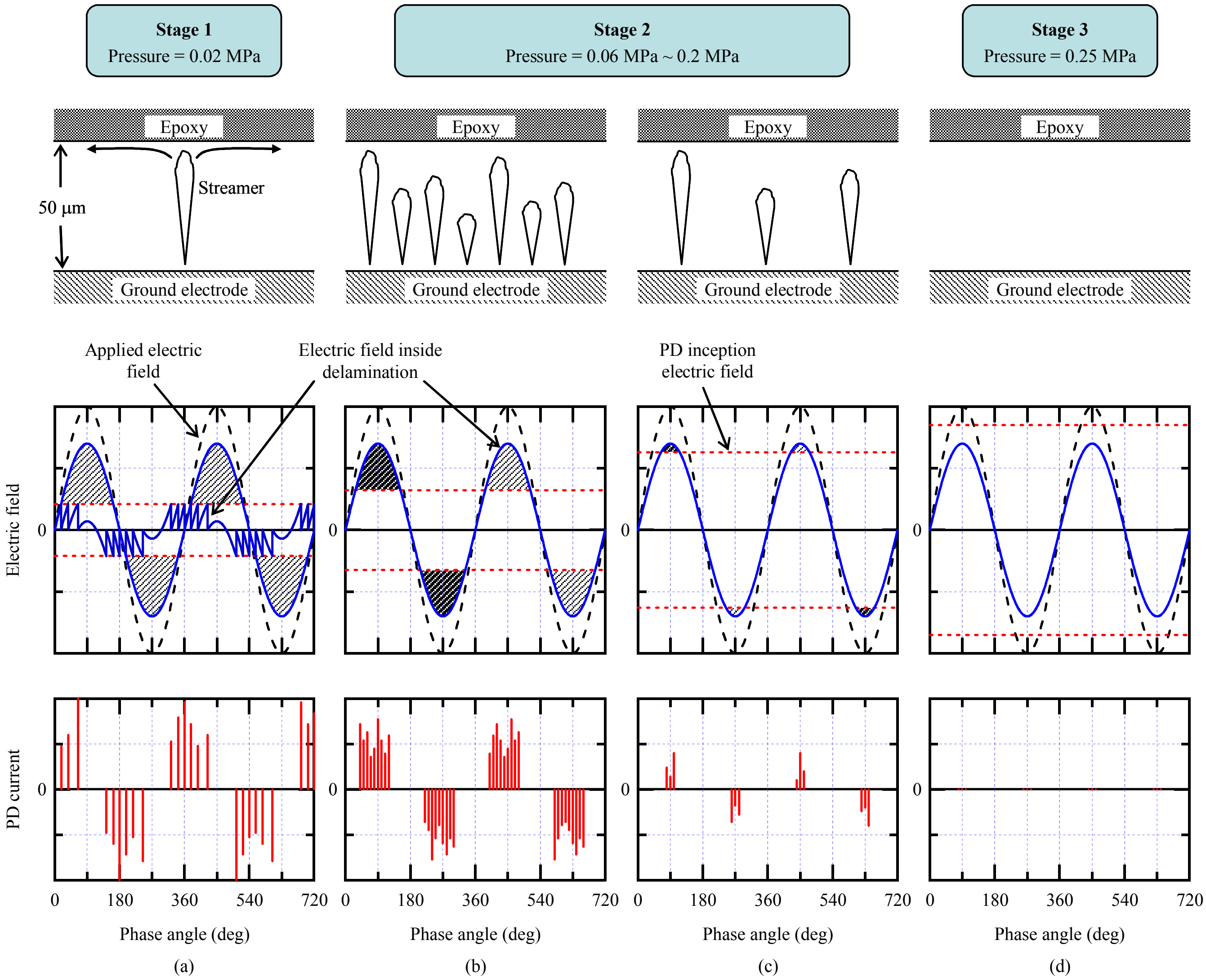

Figure 8. Schematic illustration of PD activity with increasing the gas pressure in the delamination gap.

PD activity for electrode/epoxy delamination will be limited by the rise of SF_6 gas pressure in the delamination gap.

The aforementioned tendencies in PD parameters and phase characteristics are specific features for the delamination defect with SF_6 gas infiltration. Consequently, considering these tendencies together with their physical mechanisms can be helpful for diagnosing a delamination defect in GIS spacers.

4.2 DIFFERENCE BETWEEN NEGATIVE AND POSITIVE PD ACTIVITY

The initial electron is a necessary condition for PD generation. The source of such electron is different for negative and positive PD pulses [15]. In the delamination case, when the electrons are generated from the grounded bare electrode, the PD pulses are negative. Thus, the rate of avalanche initiation should be quite high as soon as the critical electric field is reached. On the other hand, for positive PD, initial electrons for the first avalanche are generated from the insulating epoxy as a result of the negative charges accumulated on the surface during the previous negative PD events [9]. Since initial electrons for the first avalanche of positive PD are generated from the insulating epoxy, the probability of positive PD generation could be reduced. As a result, positive PD generation rate is lower than negative one (Figure 5a).

5 CONCLUSIONS

Partial discharge (PD) behavior for electrode/epoxy delamination in SF_6 gas has been investigated based on an experimental study. The use of ϕ-n distribution together with pressure dependency of PD parameters enabled to discuss the physical mechanisms behind PD behavior. The obtained results can be summarized as follows:

(1) At Stage 1 of SF_6 gas pressure, 0.02 MPa, PD pulses appear around zero-crossings of applied voltage where PD across the gap propagates along the epoxy surface. With increasing the gas pressure, PD pulses shift beyond zero-crossings where extension of PD pulses along the epoxy surface is short and then, PD could be generated at multiple locations in the delamination gap.

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

(3) The average PD current magnitude decreases with the rise of gas pressure due to the increase in the dielectric strength of SF_6 gas and the corresponding reduction in PD extension along the epoxy surface.

(4) For all stages of gas pressures, the PD generation rate is lower for positive PD polarity than that for negative PD polarity due to the difference in initial electron generation mechanism.

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Diaa-Eldin A. Mansour (S’06) was born in Tanta, Egypt on 31 December 1978. He received the B.Sc. and M.Sc. degrees in electrical engineering from Tanta University, Tanta, Egypt, in 2000 and 2004, respectively. Since 2000, he has been with the Electrical Power and Machines Department, Faculty of Engineering, Tanta University, Egypt. Currently, he is working towards the Ph.D. degree at Nagoya University, Nagoya, Japan. His research interests are insulation diagnosis of electrical power equipments, partial discharge measurements, and high voltage engineering.

Hiroki Kojima was born on 7 December 1975. He received the Ph.D. degree in 2004 in energy engineering and science from Nagoya University. Since 2004, he has been at Nagoya University and presently he is an Assistant Professor of Nagoya University at the EcoTopia Science Institute. Dr. Kojima is a member of IEE of Japan.

Naoki Hayakawa (M’90) was born on 9 September 1962. He received the Ph.D. degree in 1991 in electrical engineering from Nagoya University. Since 1990, he has been at Nagoya University and presently he is a Professor of Nagoya University at the EcoTopia Science Institute. From 2001 to 2002, he was a guest scientist at the Forschungszentrum Karlsruhe/Germany. Prof. Hayakawa is a member of IEE of Japan.

Fumihiro Endo (M’78) was born on 25 November 1945. He received the Ph.D. degree in 1989 in electrical engineering from Osaka University. He joined Hitachi, Ltd., Japan in 1968 and was a Chief Researcher of Power & Industrial Systems R & D Laboratory, Hitachi, Ltd. He had been engaged in R & D of high-voltage engineering. He has been a Guest Professor of Nagoya University at the EcoTopia Science Institute since 2005. Prof. Endo is a member of IEE of Japan and a vice-president of IEED in Japan.

Hitoshi Okubo (M’81) was born on 29 October 1948. He received the Ph.D. degree in 1984 in electrical engineering from Nagoya University. He joined Toshiba Corporation, Japan in 1973 and was a manager of high voltage laboratory of Toshiba. From 1976 to 1978, he was at the RWTH Aachen, Germany and the TU Munich, Germany. In 1989, he became an Associate Professor of Nagoya University at the Department of Electrical Engineering and presently he is a Professor of Nagoya University at the Department of Electrical Engineering and Computer Science. Prof. Okubo is a member of IEE of Japan, VDE and CIGRE.