PARTIAL DISCHARGE CHARACTERISTICS FOR DELAMINATION DEFECT OF EPOXY CAST RESIN POWER APPARATUS

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Abstract: For proper insulation design of epoxy cast resin power apparatus such as moulded transformers, it is important to consider defects that might exist at the interface between resin and conductor such as delamination. Accordingly, this paper aims to investigate partial discharge (PD) characteristics for micro gap delamination defect model of epoxy cast resin power apparatus. Atmospheric nitrogen was used as a typical filled gas inside the delamination of epoxy cast resin power apparatus and the results was compared with that of SF_6 gas filled delamination at epoxy GIS spacer. Electrical and optical PD measurements were carried out. PD inception voltage (PDIV) was measured for different delamination lengths, and then, PDIV was discussed in terms of the discharge mechanism. Following PDIV measurements, the PD activity for 10 minutes at PDIV and slightly higher voltage than PDIV were acquired in the form of PD light emission intensity, PD light emission image and PD current pulse. It was found that multiple PD events were detected only by PD light emission image and could not be detected by their current pulses as a result of very small magnitudes of PD current pulses. The effect of gap length and applied voltage on PD characteristics was investigated.

1 INTRODUCTION

The epoxy cast resin power apparatus such as moulded transformers have attracted wide interest due to their compactness and high dielectric strength in addition to environmental considerations [1]. In epoxy cast resin power apparatus, different insulation defects might exist in the moulding epoxy such as voids or delaminations. Existence of such defects would lead to partial discharge (PD) activity accompanying with degradation of the epoxy. This can subsequently cause eventual failure of the insulation system. Thus, it is crucial to investigate PD characteristics of such defects for the diagnosis purposes as well as risk failure assessment.

For void defect case, several studies have been performed for PD characteristics [2, 3]; with some focus on epoxy cast resin power apparatus [4]. The advancement in casting processes of epoxy resin could minimize voids during manufacturing process. However, under long time operation of cast resin transformers with thermal, mechanical and electrical stresses, delamination defect might be initiated at the interface between conductor and epoxy.

The ongoing research for delamination defect based PDs has been recently reported for gas insulated switchgears (GISs) with infiltrating SF_6 gas into the delamination area [5, 6]. These results discussed surface charge accumulation and its effects on PD behaviour in addition to the physical mechanisms of PD activity. On the other hand, as far as the authors know, few data are available concerning PD characteristics and mechanisms for delamination defect in cast resin power apparatus, especially with downsizing delamination lengths below 100 μm.

Accordingly, this paper aims to measure and analyze PD characteristics for delamination defect of epoxy cast resin power apparatus. First, PD inception voltage (PDIV) was measured and compared to the theoretical breakdown values. Then, PD characteristics were obtained for 10 minutes at PDIV and slightly higher voltage than PDIV. In order to deeply clarify and understand PD phenomenon, PD measurements were performed simultaneously in both electrical and optical forms. Finally, an attempt has been made to discuss PD mechanisms based on the obtained results and by comparing with PD characteristics of SF_6 gas filled delamination at epoxy GIS spacer.

2 EXPERIMENTAL SETUP

To investigate PD characteristics for delamination defect of epoxy cast resin power apparatus, an electrode setup simulating the delamination defect was built as shown in Figure 1. The high voltage electrode, which is a moulded type, was attached to the epoxy sample under study using vacuum

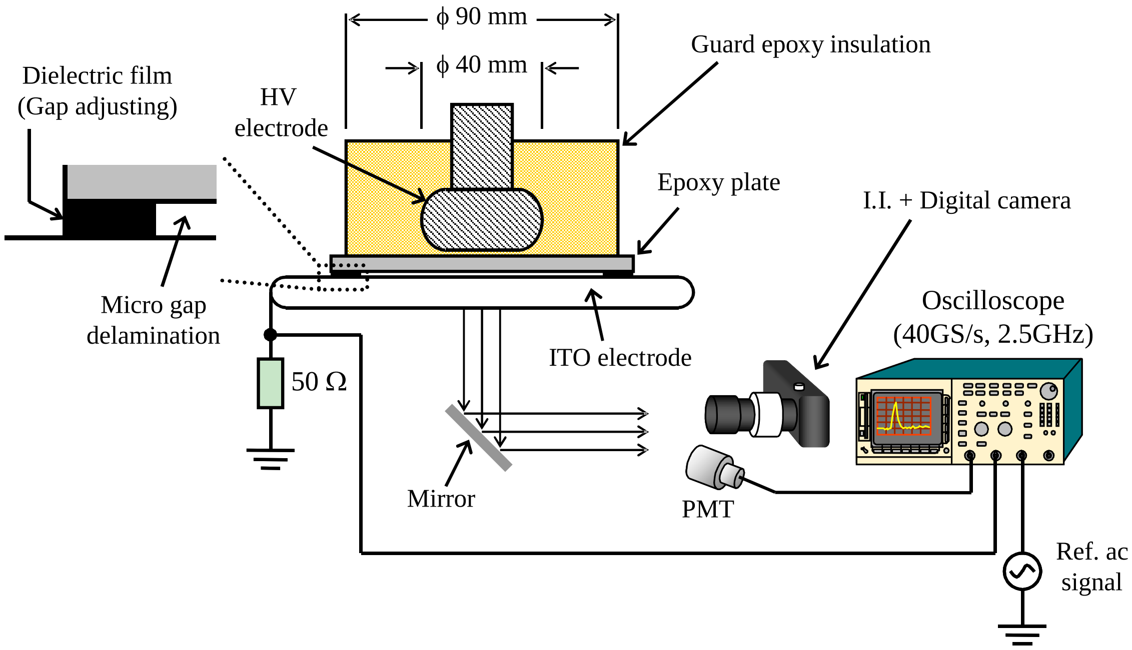

Figure 1: Experimental setup for measurement and analysis of PD pulses at delamination model of epoxy cast resin power apparatus

grease in order to avoid any voids at the physical interface. The ground electrode is of indium tin oxide (ITO) electrode which is transparent for PD observation in the visible range. The interface between ground electrode and epoxy sample was set away by a stack of thin dielectric films constituting a delamination. The delamination length was adjusted at 50 μm and 100 μm simulating possible delamination sizes in actual epoxy cast resin power apparatus. The delamination was filled with a nitrogen gas at atmospheric pressure because usually it is the gas used as the surrounding medium during the casting process.

A resistor of 50 Ω was inserted in series to the ground electrode to measure PD current. On the other hand, an optical system was set in order to acquire the optical emission from PD pulses. After emitted PD pulses passes through ITO electrode, a high reflectivity mirror is used to reflect the light emission into the detecting devices. The light emission signal was detected using a photomultiplier tube. The light emission image was observed by a digital camera coupled with an image intensifier. The shutter speed of the digital camera was adjusted 1/60 sec so that PD events over an entire cycle of the applied 60 Hz ac voltage can be captured. The detected PD current pulses and light emission signals were simultaneously measured using a large bandwidth digital oscilloscope (40 GS/s, 2.5 GHz). Also, a reference signal of the applied ac voltage was fed to the oscilloscope for the purpose of obtaining PD polarity and phase characteristics. All the measurements were carried out inside a shield room to increase the detection sensitivity of PD pulses. The detection sensitivity for PD current magnitude was 1.3 mA and the detection sensitivity of PD light emission signal was -0.4 arbitrary units.

3 RESULTS AND DISCUSSION

3.1 PD inception characteristics

PD inception voltages (PDIV) are measured and the corresponding PD inception electric fields (PDIE) are calculated at different values of delamination gap length, 100 μm and 50 μm. For each gap length, a new epoxy plate is used to avoid the effect of accumulated surface charges on PDIV as previously observed in case of SF_6 gas [7]. For PDIV measurement, ac voltage was increased in steps with 1 kV_{rms}/step. PDIV was determined if PD events were detected by current pulse measurements or light emission signals or even by light emission images. PDIV measurements were repeated 5 times for each gap length.

For both delamination gap lengths, detected PDIV values from current pulse measurements were coincided with that detected from optical measurements. Figure 2 shows the experimental values of PDIE for 100 μm and 50 μm as indicated by solid squares. Also, the theoretical Townsend breakdown criterion for Nitrogen gas with bare-bare electrode is depicted in this figure by a dashed line, which is deduced from Paschen's curve. It is evident that measured PDIE values matches with the theoretical values indicating that PDs are of Townsend-like mechanism. This is different than PD mechanism of SF_6 gas filled delamination, which matched with streamer breakdown criterion [7], as represented by hollow triangles in Figure 2. The deviation between experimental PDIE values and theoretical values, which is observed for both types of gas filled delamination, might be resulted from a small discharge volume, a lack of initial electrons and/or a surface roughness of electrode.

The Townsend-like mechanism of N_2 gas filled delamination can be explained by the effective secondary ionization which is attributed to the existence of a bare electrode on one side of the delamination. PD mechanism is different from the void defect case in which streamer-like is the driving mechanism for PDs and Townsend-like mechanism is only observed after surface resistivity decreased due to discharge by-products [8]. The PD mechanism was confirmed by obtaining the phase characteristics of a PD inception pulse as shown in Figure 3. In this figure, it is noticed that PD pulse at inception were observed at positive polarity of ac phase applied on the epoxy indicating that initial electrons for PD pulses are generated from the grounded bare cathode electrode, not the dielectric surface. For 100 μm gap, similar PD inception polarity was observed.

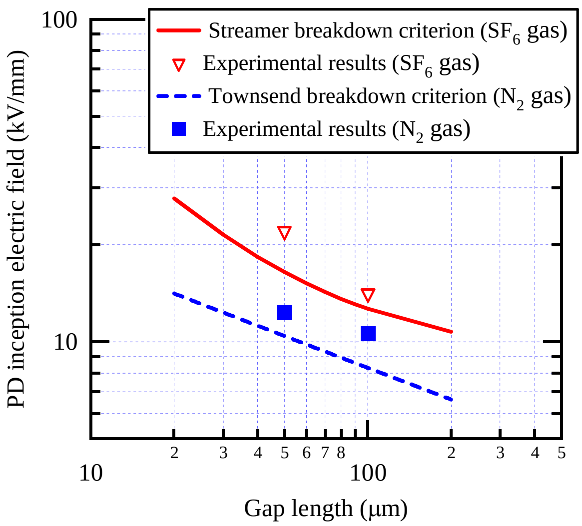

Figure 2: PDIE values for N_2 gas filled delamination and SF_6 gas filled delamination

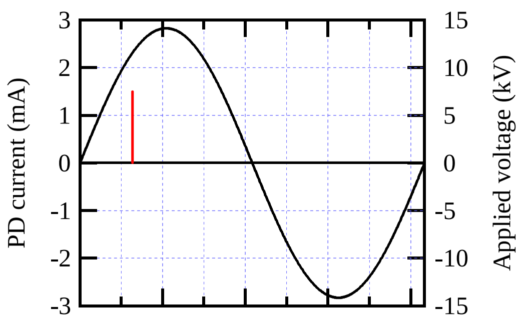

Figure 3: Phase characteristics of a PD inception pulse for N_2 gas filled delamination

The difference in PD mechanism between N_2 gas filled delamination and SF_6 gas filled delamination might be attributed to the effect of electronegativity of SF_6 gas. Streamer discharge occurs either in the case of a large number of initiatory electrons or at high field caused by overvoltage. With the existence of negative ions in SF_6 gas, the electron attachment plays a role as a deionization process and higher overvoltage would be needed to bring the gap into breakdown. At breakdown, the number of detached electrons would be high enough to develop a single avalanche into a streamer.

3.2 PD activity

The first kind of PD activity considered in this study is PD generation characteristics for 10 minutes at applied voltage equal to PDIV. The reason of applying voltage for 10 minutes is to get stable PD characteristics after surface charging occurs. PD activity was acquired in the form of PD light emission signal using photomultiplier tube (PMT), PD light emission image using image intensifier with digital camera and PD current pulse.

Figure 4 shows typical waveforms of the applied voltage, PD current pulse and PMT signal for 100 μm gap. It is clear that few number of PD pulses,

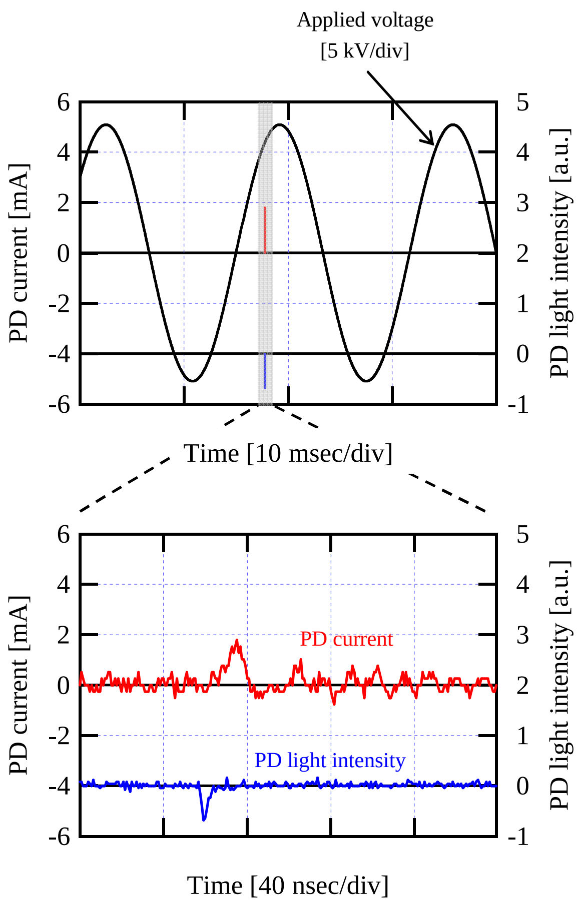

Figure 4: Phase characteristics and waveforms of a typical PD event for 100 μm delamination gap (V_a = 1.0×PDIV)

at most one pulse per cycle, were detected by their PD current magnitudes or even by their PMT signals. However, captured light emission image indicated that several PD pulses per cycle were observed as shown from the PD light emission image in Figure 5. So, it is evident that multiple of PD pulses fall below the trigger level of oscilloscope and can not be detected when using current pulse measurements or PMT signals on oscilloscope. This is attributed to the small discharge magnitude and light intensity of PD pulses corresponding to Townsend-like mechanism. The maximum PD charge obtained for 100 μm gap was 33 pC and for 50 μm gap was 14 pC which was smaller than in SF_6 gas [9]. The non-detection of PD pulses in case of N_2 gas filled delamination would affect delamination diagnosis based on PD activity in epoxy cast resin power apparatus, while PD activity in SF_6 gas filled delamination could be used for delamination diagnosis in GIS [5].

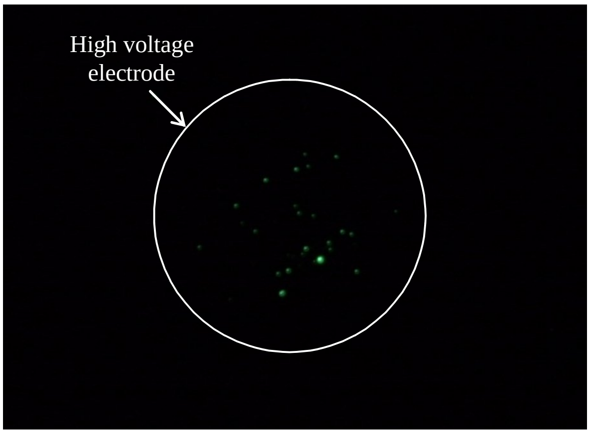

Figure 5: PD light emission image for 100 μm delamination gap (V_a = 1.0×PDIV)

3.3 Effect of delamination gap length

In order to investigate the effect of delamination gap length on PD characteristics, the distribution of PD current magnitudes for 100 μm and 50 μm gap at applied voltage of PDIV was obtained as shown in Figure 6. To construct the plot, the number of PD pulses corresponding to each value of PD current magnitudes was counted over the 10 minutes of voltage application. Since the detection sensitivity for PD current magnitude is 1.3 mA, the distribution of PD current magnitudes started beyond this value. For 100 μm gap, the distribution of PD current magnitudes extended until 3.84 mA, while, for 50 μm gap, the distribution of PD current magnitudes extended until 2.05 mA. The total number of electrically detected PD pulses was about 2000 pulses for 100 μm gap and about 100 pulses for 50 μm gap. It is evident that, for 50 μm gap, few number of PD pulses were detected and their PD current magnitudes were lower. However, by observing the PD light image for 50 μm gap, which is exhibited in Figure 7, it is found that multiple of PD events were generated per cycle similar to the case of 100 μm gap in Figure 5. This means that more PD pulses were not detected for smaller gap case. This can be explained by the few collisions for each electron crossing the gap for smaller gap lengths, resulting in low maximal PD current magnitude.

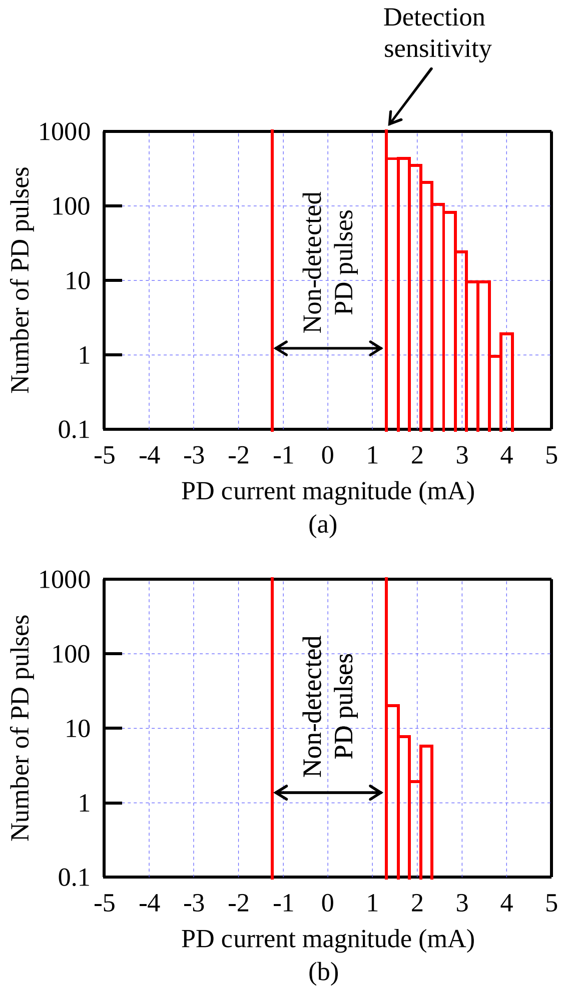

Figure 6: Distribution of PD current magnitudes: (a) 100 μm gap (b) 50 μm gap

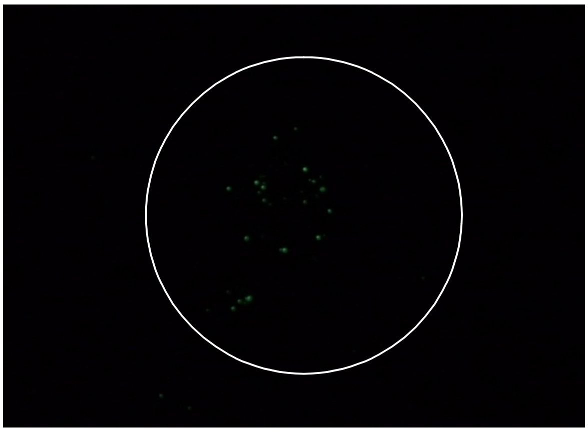

Figure 7: PD light emission image for 50 μm delamination gap (V_a = 1.0×PDIV)

It is important to point out that there are no detected PD pulses for the negative polarity of the applied ac voltage for both gap lengths as shown in Figure 6. This might be attributed to the absence of initial electrons from the dielectric surface and even initial electrons become available after charge accumulation, the higher work function of the dielectric surface limits the secondary ionization leading to non-detectable PD current magnitudes.

3.4 Effect of applied voltage

In order to investigate the effect of applied voltage on PD generation characteristics, PD light emission images were used, since not all PDs are detected by current pulse measurements or PMT signals. For each gap length, the applied voltage was set slightly higher than PDIV value and kept for 10 minutes. For 100 μm gap, the applied voltage was set at 1.1×PDIV, and for 50 μm gap, the applied voltage was set at 1.2×PDIV.

Figures 8 and 9 show PD light emission images obtained at 100 μm and 50 μm gap lengths, respectively. The first observation from these figures is the diffused luminous pattern of emitted light spots, which is similar to the luminous pattern of Townsend-like mechanism in [8]. Therefore, it can be said that Townsend-like mechanism is still applicable at the higher settings of the applied voltages. The second observation from Figures 8 and 9 is the higher number of PD pulses compared to that at 1.0×PDIV in Figures 5 and 7, respectively.

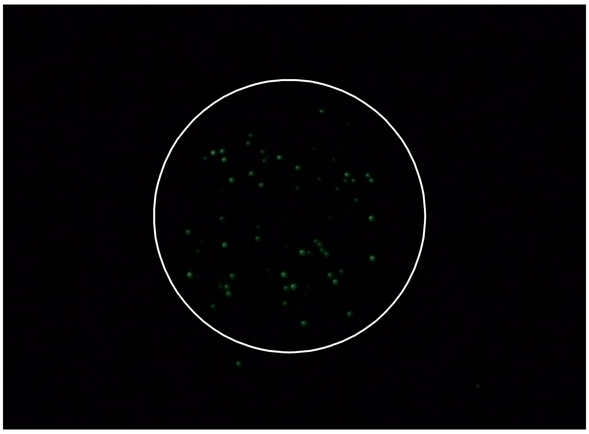

Figure 8: PD light emission image for 100 μm delamination gap (V_a = 1.1×PDIV)

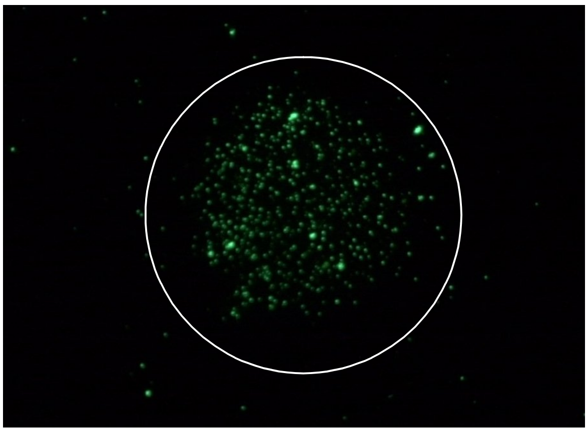

Figure 9: PD light emission image for 50 μm delamination gap (V_a = 1.2×PDIV)

Quantitatively, the increase in number of PD pulses was analyzed in Figure 10 for each condition of the applied voltages and gap lengths in case of both types of gas filled delamination. In this figure for N_2 gas filled delamination, the number of emitted light spots from light emission image was approximately counted and multiplied by 60 cycles to get number of PD pulses expressed in pulses per second (pps). For 100 μm gap, the number of PD pulses increased from about 1500 pps at PDIV to about 3000 pps at 1.1×PDIV. For 50 μm gap, the number of PD pulses increased from about 1400 pps at PDIV to about 22000 pps at 1.2×PDIV. The increase in the number of PD pulses can be explained by the increase in the probability of initial electron generation from the grounded bare electrode at higher electric field. In addition, at higher electric field, some PD pulses would be initiated from the epoxy surface as a result of accumulated surface charges. Comparing the results to that of 50 μm gap in SF_6 gas filled delamination, it is clear that the number of PD pulses was higher for N_2 gas filled delamination. This is because in the case of SF_6 gas filled delamination, a streamer discharge extends along the epoxy surface resulting in surface charging at a certain location and decrement in the local electric field below inception condition at this location.

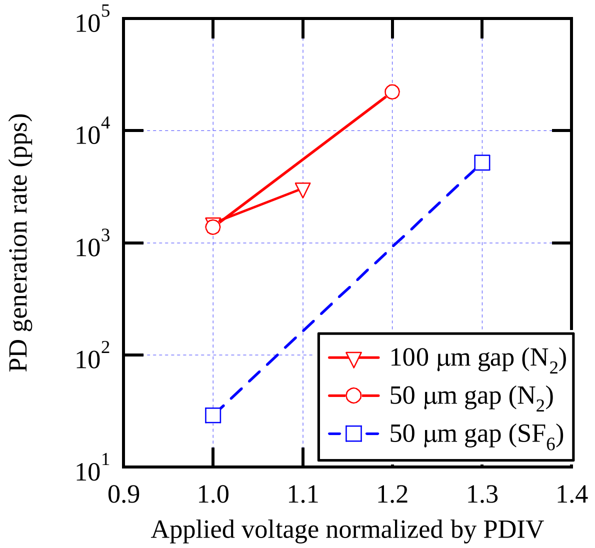

Figure 10: Number of PD pulses versus applied voltage for different delamination gap lengths in N_2 and SF_6 gas filled delamination.

4 CONCLUSION

The partial discharge (PD) characteristics for delamination defect model of epoxy cast resin power apparatus have been investigated using optical and electrical measurements. It was found that PDIV values match with theoretical values of Townsend-like mechanism as a result of the existence of an electrode on one side of the delamination. With Townsend-like mechanism, multiple of PD pulses had small discharge magnitudes that were only detectable by PD light emission images. Inversely to N_2 gas filled delamination of epoxy cast resin power apparatus, streamer mechanism was the main mechanism for SF_6 gas filled delamination at epoxy GIS spacer. The discharge magnitude was higher in the case of SF_6 gas filled delamination. The small discharge magnitude of PD pulses in case of N_2 gas filled delamination would affect delamination diagnosis based on PD activity in epoxy cast resin power apparatus.

The effect of delamination gap lengths and applied voltages on PD characteristics was investigated. With decreasing the gap length, more PD pulses became non-detectable as a result of few collisions for each electron crossing the gap inducing low maximal PD current magnitude. For long and short gap lengths, there were no detected PD pulses for the negative polarity of the applied ac voltage. With increasing the applied voltage slightly higher than PDIV, the luminous pattern was still similar to Townsend-like mechanism. In addition, with increasing the applied voltage, the number of PD pulses increased for both gap lengths. For N_2 gas filled delamination the number of PD pulses was higher than that for SF_6 gas filled delamination as a result of streamer discharge extension along the epoxy surface in the later case.

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