Partial Discharge Phenomenon around a Triple Junction under DC Voltage in SF_6 Gas

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Abstract: In AC circuit gas insulated switchgears (GIS), DC voltage may be applied on spacer insulators and rod insulators due to residual voltage in busbars when the gas circuit breaker (GCB) or disconnecting switch (DS) opens. To improve the reliability of this DC voltage, it is necessary to clarify the partial discharge (PD) and creepage flashover (FO) phenomena occurring at around a triple junction (TJ) where a conductor, conductor-supporting insulator and adjacent insulating gas contact each other. In this study, we formed a TJ with voltage shield on fiber reinforced plastic (FRP), and investigate the V-t characteristics of both PD and FO under DC high voltage. As a result, we found that the gradient of the V-t curve was different between the two curves and the gradient for PD curve is steeper than that for FO. We estimated that the reason is that electric field relaxation caused by preceding multiple PD's gives the difference. We also found that the surface roughness of the FRP at TJ affects PD occurance distinctively, and the surface roughness of the FRP should be considered carefully in the design of high voltage electric appliances.

1. Introduction

Triple junctions (TJ) consisting of a conductor, conductor-supporting insulator and adjacent insulating gas are always formed in electric power apparatuses. Because the electric field is extremely high at a TJ, many studies have been performed on AC voltage and lightning impulse voltage in electric power apparatuses to determine the effect of PD. However, it does not seem that sufficient studies have been performed on DC voltage.

Electric field increase at a TJ can be restrained using the voltage shield against AC voltage or lightning impulse voltage. When DC voltage is applied, however, the electric potential distribution is changed from AC (immediately after application) to DC, and the effect of the voltage shield becomes invalid for the DC distribution.

Because DC voltage is applied when the gas circuit breaker (GCB) or disconnection switch (DS) is activated in the AC circuit GIS, it is important to determine PD leading to FO caused by application of DC voltage. Furthermore, as needs for the AC circuit UHV GIS increase and residual DC voltage becomes higher accompanied by an increase in the need for electric power in recent years, it has become important to clarify phenomena occurring at around a TJ.

In conventional studies, Hama and others applied lightning impulse at a TJ formed in the connection area between the tank and an insulating spacer in the AC circuit GIS, and clarified the relationship between PD and FO [1]. Nakanishi and others examined discharge from protrusions and electrostatic charge on creepage surfaces caused by application of DC voltage using epoxy resin, which is a material of insulating spacers [2]. Kaneko and others studied the effect of the permittivity on creepage surfaces of insulating spacers when DC voltage is applied [3]. The effect of a TJ and DC voltage on the GIS has been examined in this way in conventional studies, but the effect of DC voltage applied on a TJ has been examined in only a few studies.

In this paper, we report the results of observing PD and FO occurring at around a TJ when DC voltage is applied on fiber reinforced plastic (FRP) which is a material of insulating operation rods used in aGCB.

2. Test sample and electric field analysis

2.1 Test sample

Figure 1 shows a test sample. The test sample structure simulates a TJ of insulating rods in a GCB. We formed a TJ (R: 3 mm) using an aluminum electrode on a creepage surface of FRP used as insulating operation rods, and attached a shielding electrode on the outside. We attached the shielding electrode to prevent entering of equipotential lines in the AC distribution occurring immediately after DC voltage is applied.

We cut an FRP plate into a piece of 50 mm width, 40 mm height and 10 mm thickness of a fragment. The FRP is a laminated plate consisting of fiber layer and epoxy resin. In this experiment, we laid out the FRP piece so that the edgewise direction becomes vertical to the high-voltage electrode and grounding electrode.

2.2 Electric field analysis of test sample structure

We confirmed the equipotential line distribution of the test sample using the electric field analysis

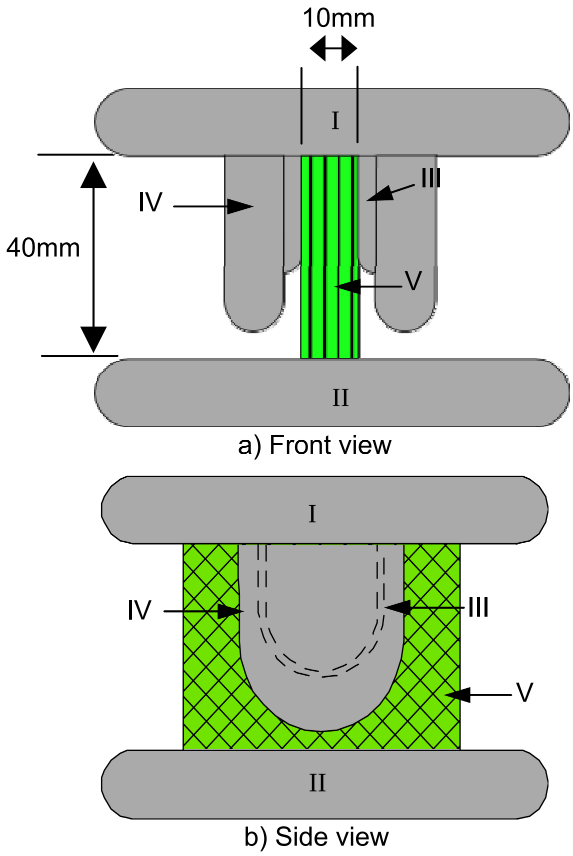


Fig.1 Specimen and Electrodes
I. H.V electrode, II. Ground electrode,
III. Triple junction electrode, IV. Shield electrode, V. Specimen

software adopting the finite element method. Figure 2 shows the analysis result.

a) shows the AC equipotential line distribution immediately after DC voltage is applied (t ≈ 0), and b) shows the DC equipotential line distribution when an infinite time has passed after DC voltage is applied (t → ∞).

In the AC distribution, the equipotential line density is higher at the shielding electrode tip than at the TJ. On the other hand, in the DC distribution, the equipotential line density is higher at the TJ. We could examine PD and FO in a process where the electric field at the TJ increases accompanied by the change of equipotential lines from the AC distribution to the DC one.

3. Experimental setup and procedure

Figure 3 shows the experimental setup configuration. For detecting PD, we laid out two photomultiplier tubes (PMT) and one patch antenna to eliminate measurement errors caused by noise. The PMT C9546-04 (manufactured by Hamamatsu Photonics K.K.) is highly resistant to exogenous noise, but may amplify electrons caused by cosmic rays inside the PMT during measurement over a long time, and may output a false signal as if it had detected light due to PD. The patch antenna can detect electromagnetic waves generated by minute

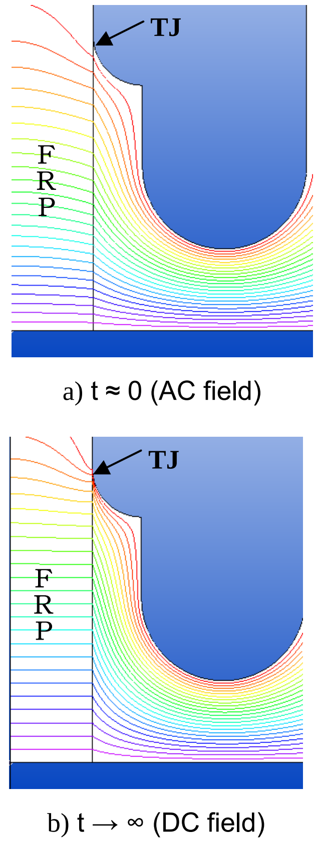


Fig.2 Equipotential line distribution

PD, but it is sensitive to exogenous electromagnetic noise. Accordingly, we handled the signal as a indication of true PD occurance only when both the PMT and the patch antenna detected it simultaneously.

The PMTs were attached to the outside of the experimental container in such a way that the entire TJ can be seen through an acrylic transparent window. The patch antenna was laid out inside the experimental container to reduce electromagnetic noise. The patch antenna has a frequency responce in 1.8 GHz band for detecting PD [4].

The PMTs were connected to the oscilloscope DPO7254 (manufactured by Tektronix), and the patch antenna was also connected to the

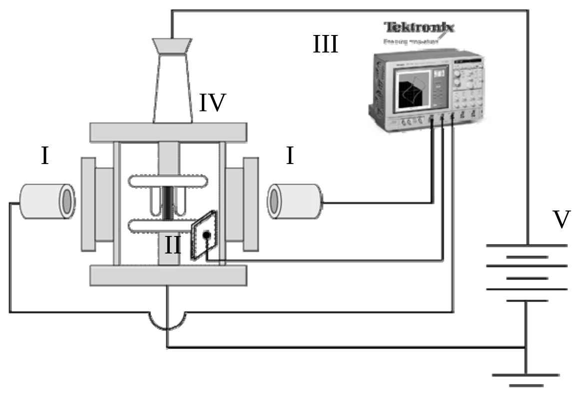


Fig.3 Experimental setup
I. PMT, II. Patch antenna, III. Osc. IV. Bessel, V. DC power supply

oscilloscope by way of the amplifier ZX60-3018G-S (manufactured by Mini-Circuits).

Data was recorded with the oscilloscope set in the fast-frame mode so that all PD waveforms could be acquired from the instant of voltage application on the test sample until FO.

The test sample was laid out in the experimental container of 300 mm in diameter and 500 mm in height in which SF_6 gas at 0.5 MPa-abs was charged, and constant DC voltage was applied. The test sample was replaced after FO occurred onece.

4. Experimental results

4.1 Fundamental feature of PD and FO

Figure 4 shows the V-t curve of PD. We performed the experiment using 2 to 10 samples at each DC voltage of 30, 50 and 80 kV. The curve shows the time of PD was observed for the first occurrence of PD after start of application of DC voltage at each samples.

Figure 5 shows the V-t curve of FO. The line shows the V-t curve of the first PD described in Fig. 4 .

Solid diamonds show the time of occurrence, and open diamonds indicats that PD or FO did not occur before the plotted time. The numbers on marker's own shoulder is indicated piled-up numbers of the data.

The shortest PD inception time was approximately 1,600 seconds at 30 kV, 220 seconds at 50 kV, and

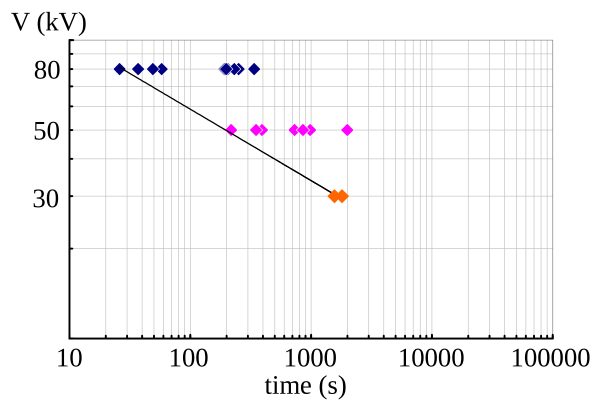


Fig.4 V-t curve of partial discharge

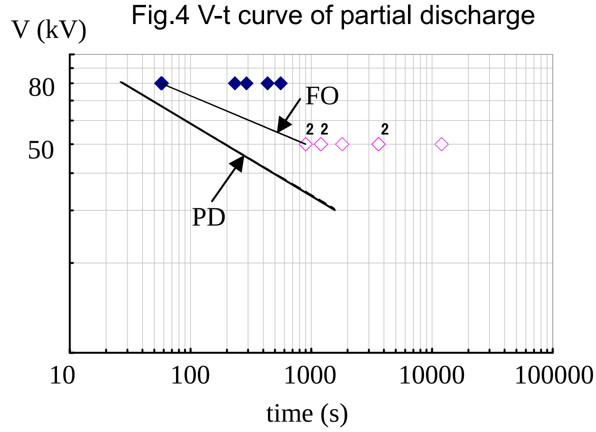


Fig.5 Comparison of V-t curve of partial discharge and creepage flashover

30 seconds at 80 kV. These times are connected to make the solid line in Figure 4.

The shortest FO time was approximately 60 seconds at 80 kV. FO did not occur, though 50 kV was applied from as little as for 900 seconds to as much as for 10800 seconds.

In Figure 5, we assumed as the FO characteristics the curve made by connecting PD in 60 seconds at 80 kV and in 900 seconds at 50 kV, and compared the FO characteristics with the PD characteristics. As a result, we found the trend that the time difference between PD and FO becomes smaller as the applied voltage becomes higher.

4.2 Effect of roughness of creepage surface of FRP for PD

We evaluated the effect of the FRP surface roughness on the PD and FO time. We used same FRP, and prepared test samples of 3 μm (N = 2) and test samples of 28 μm (N = 8) in R_z (Value of Ten-Point Height of Irregularities).

Figure 6 shows the result when 80 kV was applied. We found that the PD inception time is shorter as the surface is rougher.

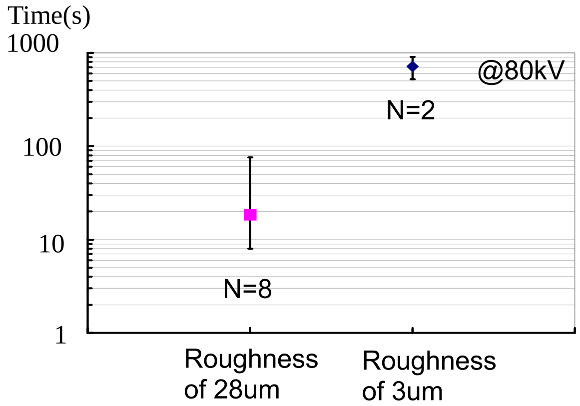


Fig.6 Dependence on surface roughness of FRP@80kV of PD inception time

4.3 Phenomenon of PD and FO under DC voltage

We applied 60, 70 and 80 kV, and observed the cumulative number of PD occurrences and PD occurrence time until FO.

We use test samples different from that used in Subsections 4.1 and 4.2 to make experiment easier. We shortened the shielding electrode, and changed the FRP piece length from 40 mm to 35 mm to apply a higher electric field and shorten the PD inception time. We adopted 28 μm as the surface roughness (R_z). We performed the experiment 3 to 7 times at each voltage, and found that the trend was same at every voltage. Figure 7 shows one experimental result, and the characteristics are described below.

PD occurred 10 times at 60 kV after start of voltage application. PD occurred 11 times at 70 kV, and FO occurred in approximately 200 seconds. PD

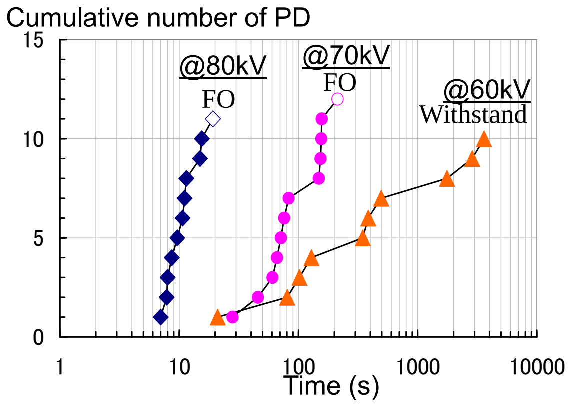


Fig.7 Dependence on applied voltage of cumulative number of PD and PD inception time

occurred 10 times at 80 kV and FO occurred in approximately 20 seconds. At the 60kV, FO did not occur even after voltage was applied continuously for 1 hour.

At 80 kV, PD occurred in 6 seconds for the first time after start of voltage application, and PD occurred consecutively at almost a constant interval in up to 12 seconds after start of voltage application. A longer time passed until the next occurrence of PD, and then PD occurred twice consecutively. After PD occurred the 3rd time, FO occurred.

At 70 kV, PD occurred 5 times consecutively in 60 to 80 seconds after start of voltage application, a longer time without PD passed, PD occurred 4 times consecutively in 150 seconds and later, and then FO occurred after more than 200 seconds passed.

The same trend was also seen at 60 kV. Though FO did not occur finally, PD occurred consecutively 3 times within 1 hour. The time interval between consecutive PD occurrences was longer as the applied voltage was lower.

5. Discussions

5.1 Fundamental feature of PD and FO

As described in Subsection 2.2, the electric field at a TJ under DC voltage increases as time passes. PD occurs at a location around a TJ where the streamer condition that the number of electrons builds up to10^8 is satisfied.

As described in Subsection 4.1, we think that the gradient of the V-t characteristics of FO is low-pitched because of the effect of relaxation of the electric field around a discharge point caused by space charge. The space charge occurred by PD of the same polarity as the applied voltage is accumulated on the FRP surface due to the extremely high surface resistance of FRP, and the electric field around a discharge point is relaxed. The effect is larger as the voltage is lower, and the time delay after PD inception until FO becomes larger.

The characteristics of PD occurrence explained in subsection 4.3 and V-t curve in subsection 4.1 are discussed below based on a simple equivalent

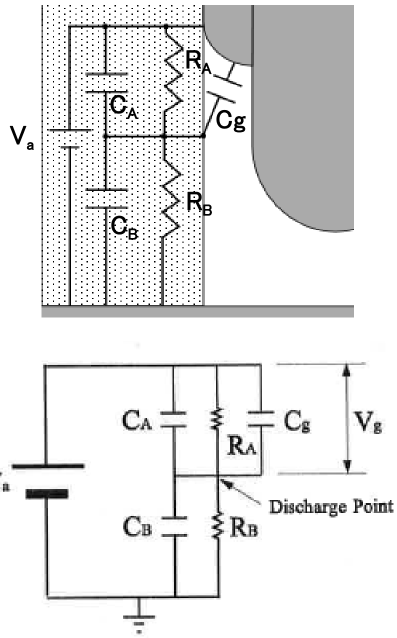


Fig.8 Equivalent circuit for PD at around a TJ

circuit model for discharge point.

We examined relaxation of the electric field around a discharge point using the equivalent circuit shown in Fig. 8. Here, the Discharge Point indicates the position where a partial discharge occurred on the FRP surface, "R_A" and "R_B" is the surface resistance of FRP above and below the Discharge Point, and "C_A" and "C_B" indicate the capacitance of FRP above and below the Discharge Point. "Cg" is the capacitance of the gap between the TJ electrode and the FRP surface. "Vg" is the gap voltage. When this equivalent circuit is dissolved for "Vg", the Eq. (1) is obtained. Figure 9 shows the temporal change of "Vg" plotted against the applied voltage.

$$V_g = \alpha V_a \left\{ 1 + \frac{\beta}{\alpha} \exp(-\frac{t}{\tau}) \right\} \quad (1)$$

$$\alpha = \frac{R_A}{R_A + R_B} \quad (2)$$

$$\beta = \frac{C_A}{C_A + C_g + C_B} - \alpha \quad (3)$$

Here, "Va" indicates the applied voltage, "α" indicates a value determined by the resistance as shown in the Eq. (2), and "β" indicates a value determined by the capacitance and resistance as shown in the Eq. (3). When the relaxation of the electric field at the gap caused by PD is not taken into consideration, the gap voltage increases monotonously as time passes, as shown in Fig. 9.

On the other hand, when relaxation of the electric field around a discharge point caused by PD is taken into consideration, Fig. 10 is obtained. Figure 10 shows an image obtained by supposing that the gap voltage reaches the PD inception voltage, and

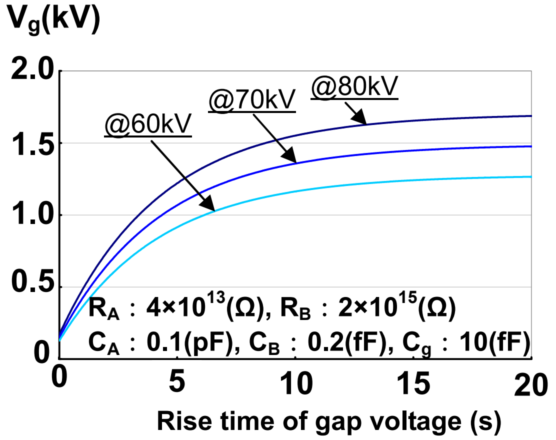


Fig.9 Results of calculation of equivalent circuit.

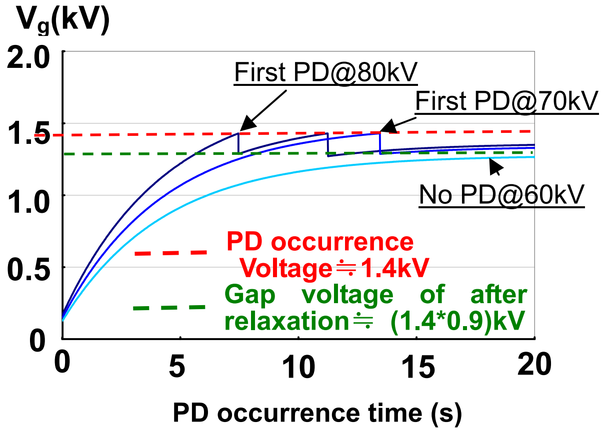


Fig.10 Results of calculation of equivalent circuit considered relaxation of electric fields near the TJ by PD.

the electric field is relaxed at a constant ratio by the space charge that was occurred by PD.

The curves in Figures 9 and 10 show changes in the voltage at the gap at 80, 70 and 60 kV. The PD inception voltage is 1.4 kV when 80 kV is applied, 1.3 kV when 70 kV is applied, and 1.2 kV when 60 kV is applied.

The gap voltage increase ratio is highest at 80 kV because it is in proportion to the applied voltage. Because the gap voltage increases fast, it reaches the PD inception voltage at an early stage of the rising edge. PD occurs at the gap where the voltage reaches the PD inception voltage, then the gap voltage drop low due to the space charge occurred by discharge.

The increase ratio is high at the gap voltage rising edge. As a result, the gap voltage reaches the PD inception voltage again in a short time, and PD occurs. This phenomenon occurs around a discharge point, and PD occurs consecutively as shown in Figure 7.
When the applied voltage is lowered to 50 kV, 30 kV, etc., the gap voltage increase ratio becomes lower before reaching the PD occurrence voltage. As a result, a longer time is required until the gap voltage lowered by the space charge reaches the PD occurrence voltage again. Accordingly, the consecutive PD occurrence time and the time without PD until next consecutive PD occurrence become longer as the applied voltage is lowered. At a voltage (30 kV, for example) at which the gap voltage does not reach the PD inception voltage even in the DC steady state, PD does not occur at infinite time.

5.2 Effect of roughness of creepage surface of FRP for PD

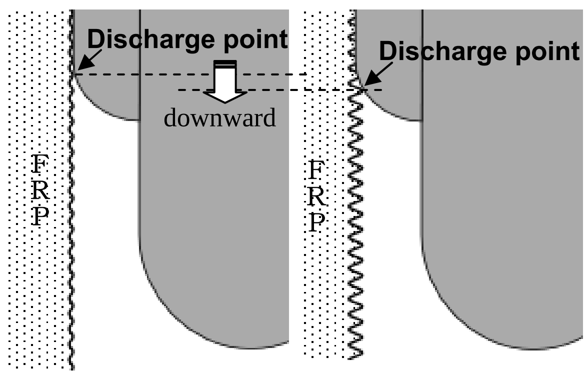
In this section, the effect of surface roughness shown in Fig.6 is discussed. It is considered that three major factors determine PD occurrence time at discharge point: the position or the detailed shape of discharge point, the resistance of FRP surface and concentration of electric field at minute projections. Figure11 shows the effect of surface roughness of FRP schematically: (a) smooth surface and (b) rough surface.

In the case of FRP with rough surface, discharge point downward from TJ. And the rate of increase of the electric field at the discharge point is faster as its position approach the end of shield electrode. Accordingly, in the case of the rough surface, PD is occurred shorter time than that of the smooth surface.

Secondly, surface resistance around the discharge point affects the PD occurrence time. The resistance of the FRP surface tends to be low in the case of roughness surface [2]. The lower resistance makes time constant smaller.

Finally, Electric field concentrates on a dielectric projection in the same phenomenon as a metal conductor. Accordingly, the concentrations on the projection of the FRP should be also considered.

The reviews of these ideas will be investigated by the experiments and electric field analysis.



a) smooth surface b) rough surface

Fig.11 difference of TJ location

6. Conclusions

We observed PD at around a triple junction under DC high voltage, and found the following:

(1) The time leading to both PD and FO occurrence varies depending on the applied

voltage.
The time difference between the PD inception and the FO becomes smaller as the applied voltage becomes higher.

(2) PD's occur intermittently. The time intervals are estimated to be determined by the relaxation of the electric field caused by the space charge created by proceeding PD around a discharge point.

(3) The surface roughness of FRP gives considerable effect to the PD occurrence characteristics under DC voltage. The surface roughness should be carefully taken into consideration in the design of electric appliances.

7. REFERENCES

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