Partial Discharge Inception Voltage Measurement and Its Estimation by Volume-Time Theory for SF6/PET Insulated Wedge Gap under Impulse Voltage

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PARTIAL DISCHARGE INCEPTION VOLTAGE MEASUREMENT AND ITS ESTIMATION BY VOLUME-TIME THEORY FOR SF_6/PET INSULATED WEDGE GAP UNDER IMPULSE VOLTAGE

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Abstract: Insulation properties of SF_6 gas gap formed at the wedge gap of gas-insulated transformer has not been investigated well. So, the authors aim to study characteristics of partial discharge inception voltage (PDIV) of the wedge gap formed by two electrodes wrapped with polyethylene terephthalate (PET) film to simulate wedge gap insulation system of the gas-insulated transformer coil insulation. Applying a given magnitude of impulse voltage to a set of the electrode systems, discharge generation probability is obtained at different pressures (0.10, 0.22, 0.50 MPa) of SF_6 gas. Partial discharge (PD) signal occurring at the wedge gap is detected using a number of 1 kΩ resistors connected in series of the electrode systems. An attempt is made to interpret these results in terms of the Volume-Time theory. It was found that the Volume-Time theory can explain the measured discharge inception probability quantitatively.

1 INTRODUCTION

SF_6 is used as an insulator for gas-insulated transformer due to excellent insulation properties such as high partial discharge inception voltage (PDIV). As electric power demand is increasing in metropolitan areas, recommendation to use an underground substation has arisen in urban areas which have insufficient space for constructing a new substation. Under the circumstances, gas-insulated transformer fulfils such demand due to incombustibility and non-explosive nature. Additionally, the equipment in the substation needs downsizing to increase the capacity in a limited space in metropolitan areas, allowing reduction of SF_6 amount and cost. On the contrary, downsizing of gas-insulated transformer (GIT) arises a new issue that SF_6 wedge gap coated polyethylene terephthalate (PET) film used as insulation of the winding of GIT faces high electric field, increasing PD occurrence probability. Thus, understanding the insulation properties of the SF_6/PET wedge gap in GIT is important to make rational insulation design by quantitatively evaluating the PD inception characteristics leading to downsizing GIT. From the viewpoints, this paper deals with PDIV of the SF_6/PET insulated wedge gap under an impulse voltage application. An attempt is also made to interpret the PDIV results in terms of the Volume Time theory.

2 EXPERIMENTAL

2.1 Sample structure

Figures 1 (a) and (b) illustrate two types of plane-rod electrodes systems with different rod diameter φ to simulate insulation coating SF_6 gas micro-gap; i.e. rod electrode RE 25 and RE 5 with φ of 25 and 5 mm, respectively. Namely, RE 25 and RE 5 consist of 22 μm thick polyethylene terephthalate (PET) film coated plane electrode with 50 and 25 mm in diameter, respectively. Accordingly, the electrode system used lies in a category of insulator-gap-insulator (IGI) system. Note that a sheet of PET film was adhered firmly to the rod electrode by pushing it with an acrylic board.

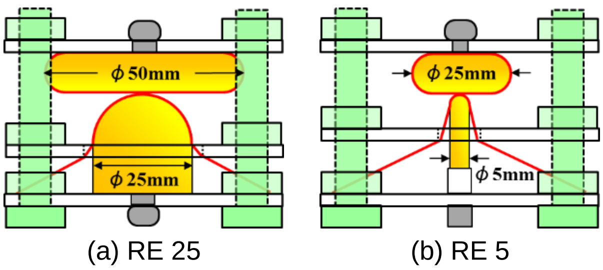


Figure 1. Structure of electrode system

2.2 Experimental

Figure 2 shows a circuit for measuring PDIV by applying an impulse voltage. Ten samples were placed on a rotary table in a steel chamber with connecting each sample earth side. Figure 3 shows appearance of the samples placed in the chamber. The pressure inside the chamber was vacuumed to 3000 Pa by a rotary pump. Then, SF_6 gas was filled in the chamber till the pressure reached a given level. One shot of impulse voltage of given value V_i with rise and fall times of 2.7 and 60 μs respectively was applied to the one sample. PD current was detected with a resistor of 1 kΩ connected to the rotary table and recorded by an eight channel oscilloscope (Teledyne-Lecroy, HDO8108, 2.5 GS/s, 1 GHz). At the same time, applied impulse voltage divided by a high-voltage probe (Tektronix, P6015A, damping ratio 1000:1, 75 MHz) was measured with the oscilloscope. PD of a sample was detected on applying one shot of impulse voltage of a given magnitude V_i. This sequence of the test was carried out for ten samples by rotating the rotary table. Here, let discharge generation probability P_i be defined as N/10, where N represents the number of samples with accompanying PD. The above mentioned experiments were also carried out at different applied voltages and gas pressures after heaving all the samples in the chamber for 24 hours.

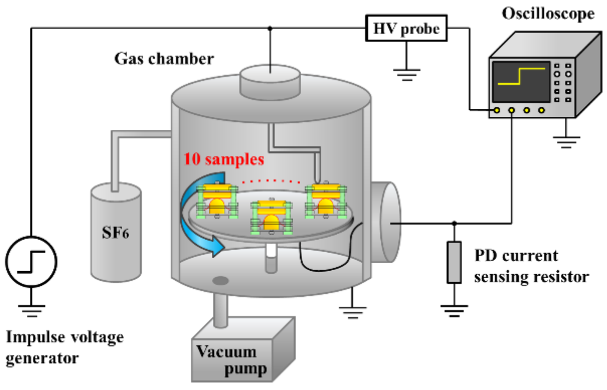


Figure 2. Measurement circuit

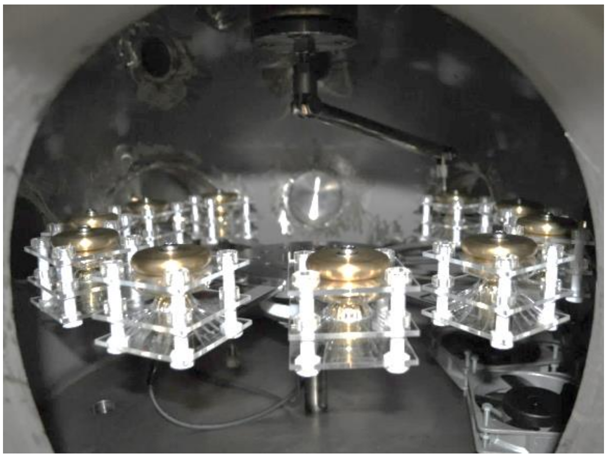


Figure 3. Appearance of samples in the chamber

3 RESULT AND DISCUSSION

3.1 Experimental results

Figure 4 shows example of a current waveform detected from an electrode system with 25 mm φ of the rod by applying one shot of impulse voltage 2.0 kV. It can be seen in the figure that PD occurs at about 8 µs after the initiation of the voltage application. Figures 5 (a) and (b) show measured P_i as a function of V_i in RE 25 and RE 5, respectively, by applying single shot impulse voltage at different SF_6 gas pressures. It is evident from the figures that PD generation voltages at a same given P_i increase with increasing SF_6 gas pressure.

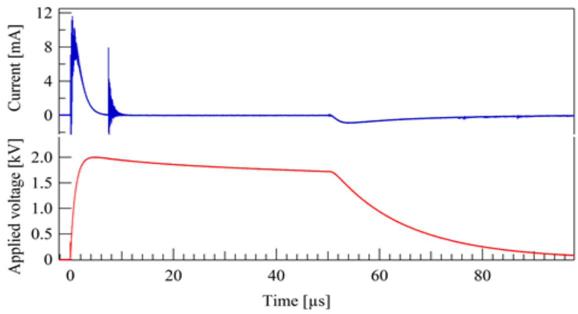
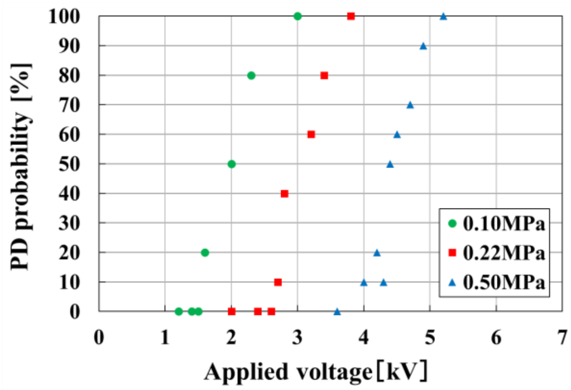
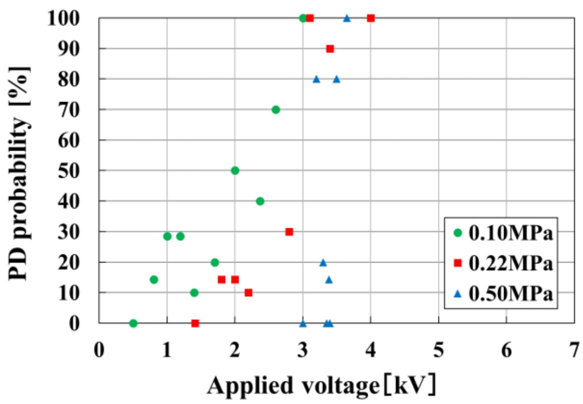


Figure 4. Current signal in RE 25 and applied voltage



(a) RE 25



(b) RE 5

Figure 5. Measured discharge generation probability P_i at each applied voltage V_i (0-peak value) of two types of electrode systems for different gas pressures

3.2 Estimation of PD probability by Volume-Time theory

Next, an attempt was made to explain measured P_i by Volume-Time theory [1]-[6]. This theory allows us to calculate generation probability P caused by initial electrons by considering a time and spatial change of the electric field distribution so as to provide discharge inception probability at a given applied voltage. Generation mechanism of initial electrons in SF_6 gas is generally considered to be due to electron detachment from negative ions in SF_6 gas. For electrode surface covered by solid insulating material, initial electrons are also released into the gas gap from the solid insulator surface. Hence, P is expressed as equations (1)-(3) considering the electron detachment from negative ions in SF_6 gas and the electron emission from PET film surface [6].

$$P = 1 - \exp\left[-\int_0^t (V_w + S_w) dt \right] \quad (1)$$

$$V_w = \int_{V_{cr}} \frac{dn}{dt}\left(1 - \frac{\eta}{\alpha}\right) dV \quad (2)$$

$$S_w = \int_{S_{cr}} \frac{di}{dt}\left(1 - \frac{\eta}{\alpha}\right) dS \quad (3)$$

where: P = Generation probability of initial electrons
dn/dt = Expected generation number of initial electrons due to electron detachment from negative ions in SF_6 gas (/mm^3 μs)
di/dt = Expected generation number of initial electrons due to electron emission from the PET film surface (/mm^2 μs)
V_{cr} = Critical volume (mm^3)
S_{cr} = Critical area (mm^2)
α = Ionization coefficient
η = Attachment coefficient

A term of (1-α/η) represents attachment of released electrons by SF_6 molecule. The effective ionization coefficient α-η and α are empirically expressed by equations (4) and (5), respectively [2] [8].

$$\frac{\alpha - \eta}{p} = 26.2\left(\frac{E}{p} - 87.8\right) \quad (4)$$

$$\frac{\alpha}{p} = 24\frac{E}{p} - 1320.1 \quad (5)$$

where: E = Electric field at the gas gap (kV/mm)
p = Gas pressure (MPa)

3.2.1 Consideration of transition process of initial electrons to discharge

Discharge occurrence needs generation of initial electrons to repeat impact ionization leading to a streamer (discharge path). Therefore, P_i can be calculated by integrating the generation probability P of initial electron over the region (critical volume V_{cr}) where the initial electrons can develop into the streamer. Generally, Schumann's equation governs the streamer transition as expressed by equation (6) [3] [6].

$$\int_{x_{cr}} (\alpha - \eta) dx = K \quad (6)$$

where: x_{cr} = Path length along electric force line
K = Number of impact ionization

For simplicity, it is assumed that x_{cr} equals the gas gap length. K events depending on gas is set to 18 for SF_6 gas [3]. Note that the critical volume V_{cr} and critical area S_{cr} are, respectively, the gap volume and surface area of the coated earth electrode where the volume and area satisfies equation (6) and α-η>0; i.e. Initial electrons emitted into critical volume can grow to streamer. Figures 6 and 7 show thus calculated V_{cr} as a function of instantaneous voltage V_{ai} for RE 25 and RE 5, respectively. In the figures, the large V_{cr} indicates that the initial electrons are likely to be transferred to the discharge; i.e. In the RE 25 electrode system, the generated initial electrons are more likely to grow into a streamer.

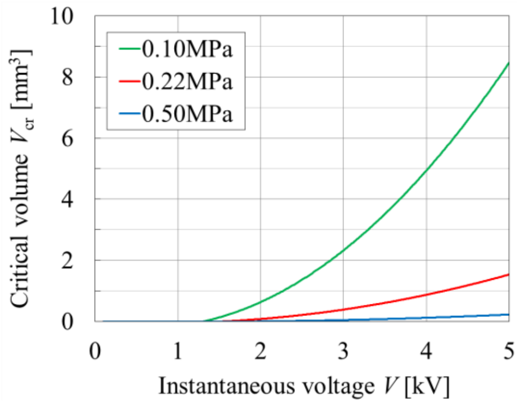


Figure 6. Critical volume with instantaneous voltage dependence at RE 25

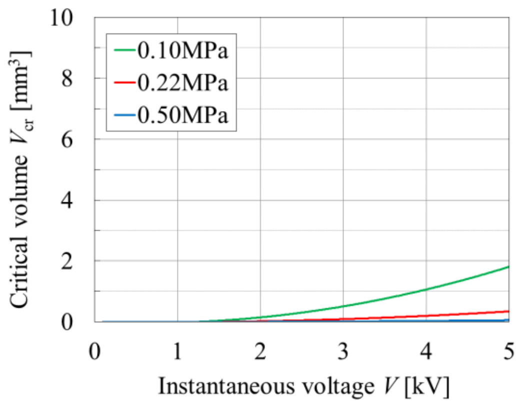


Figure 7. Critical volume with instantaneous voltage dependence at RE 5

3.2.2 Initial electron detachment from negative ions in gas gap

A term of *dn/dt* in equation (2) is given by product of the ion density n^- of SF_6^- and detachment coefficient k_d [2] [5] [6] as expressed by equation (7).

$$\frac{dn}{dt} = k_d \times n^- \qquad (7)$$

where: k_d = Detachment coefficient (/μs)
n^- = Ion density of SF_6 (ions/cm^3)

Here, detachment coefficient k_d depends on the overvoltage ratio E/E_{cr} (see Fig. 8), and the critical electric field E_{cr} of SF_6 is 87.8 kV/mm/0.1MPa [8]. It is assumed that n^- is 1500 ions/cm^3/0.1MPa [5]. Figure 9 shows calculated *dn/dt* as a function of *E* at different *p*. It can be seen in the figure that electrons are less likely to detach from SF_6^- ions with increasing SF_6 gas pressure. The results provide interpretation of the experimental result shown in Figure 5 that PDIV increased with increasing SF_6 gas pressure.

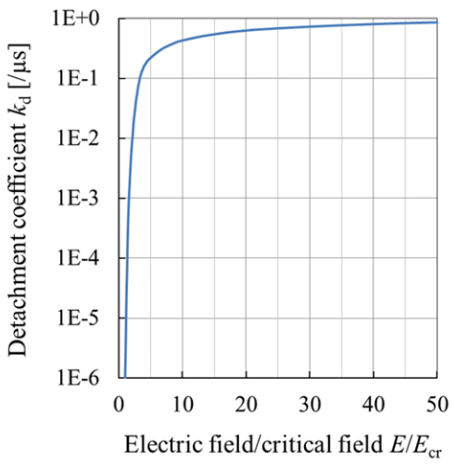


Figure 8. Detachment coefficient k_d as a function of overvoltage ratio E/E_{cr}

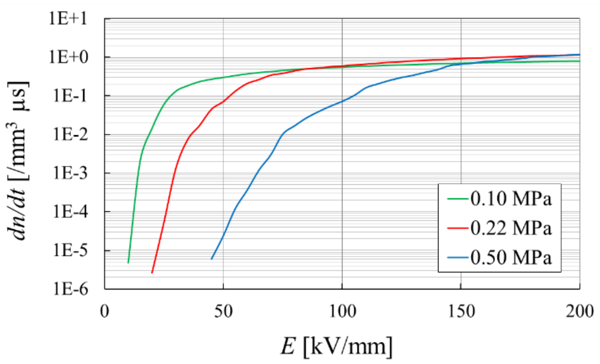


Figure 9. Calculated *dn/dt* as a function of electric field *E* at different gas pressure *p*

3.2.3 Initial electron emission from solid insulator surface

The calculation assumes that electrons trapped in PET film surface are emitted by field emission, so that *di/dt* in equation (3) can be expressed by Fowler-Nordheim field emission process as given in equation (8) [8].

$$\frac{di}{dt} = \frac{e^3(\beta E_i)^2}{8\pi h(e\varphi_D)} \exp\left[-\frac{8\pi\sqrt{2m}}{3he\beta E_i}(e\varphi_D)^{\frac{3}{2}}\right] \qquad (8)$$

where: e = Electron charge (C)
m = Electron mass (kg)
h = Plank's constant (m^{2}kg/s)
E_i = Electric field applied to PET (V/m)
φ_D = Potential barrier height (eV)
β = Field enhancement factor

In the calculation, φ_D and β are assumed to be 1.55 eV and 14, respectively. Note that the trap depth of PET is reported to be 1.55 eV by a quantum chemical calculation [9]. Figure 10 shows calculated *di/dt* as a function of *E*. It is evident from the figure that *di/dt* increases sharply with increase in *E* above 100 kV/mm. As shown in Fig. 9, while the electron detachment from SF_6^- ions decreases with increase in *p*, P_i in Fig. 5 increases sharply at 0.50 MPa. The sharp increase of P_i in high gas pressure can be interpreted in terms of dominant electron emission from the PET surface.

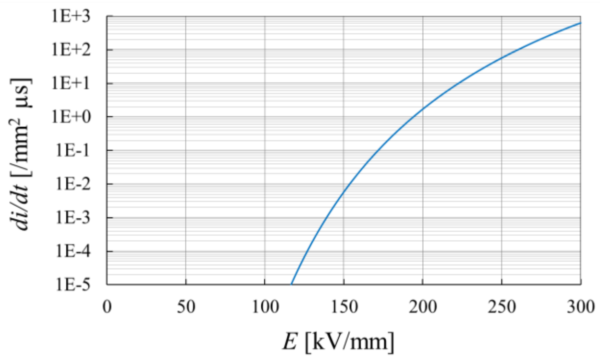
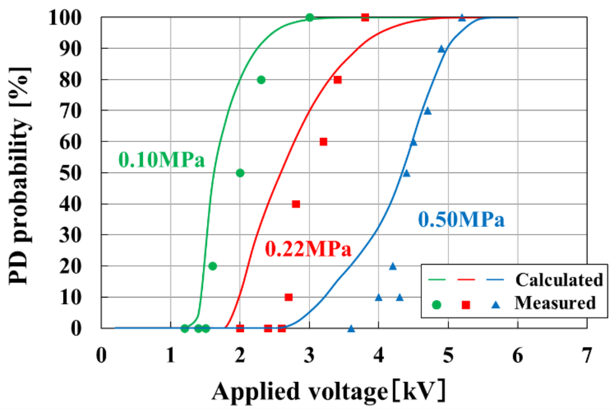


Figure 10. Calculated *di/dt* as a function of *E*

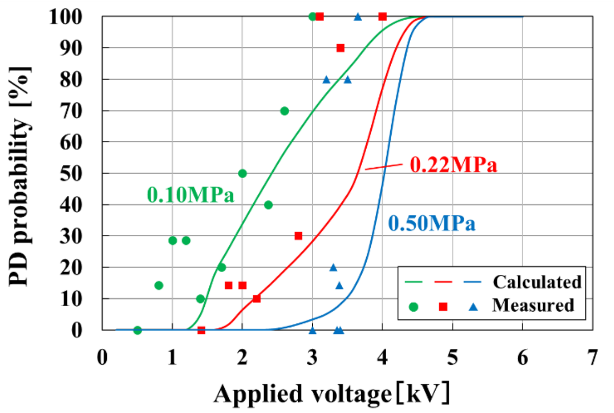
4 ANALYSIS RESULT AND DISCUSSION

Figures 11 (a) and (b) show thus calculated discharge generation probability P_i as a function of applied voltage V_i (0-peak value) at RE 25 and 5, respectively, for different SF_6 gas pressures as well as the experimental results. Note that solid lines in the figures represent P_i vs V_i calculated by the Volume-Time theory. Here, let PDIV be the voltage at which the expected number of the initial electrons generated within the critical volume becomes 1; i.e. let PDIV be defined as V_i when P_i is 63.2%. Figures 12 (a) and (b) show measured and calculated PDIV for different pressures for RE

25 and 5, respectively. It is obvious in these figures that measured results almost agree with calculated ones. In other words, it is concluded that P_i against V_i can be explained in terms of the initial electrons generated from negative ions in SF_6 gas and the PET film surface and transition process of initial electrons to discharge. The theory provides reasonable examination for the result that P_i of RE 25 is more likely to increase with V_i than that of RE 5 in terms of larger V_{cr}. Furthermore, the theory allows us to explain that P_i at 0.5 MPa increases sharply with V_i in terms of promoted electron emission from the PET surface by E exceeding 100 kV/mm.

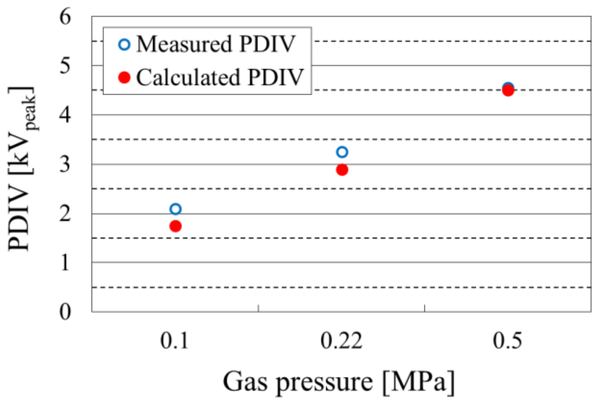


(a) RE 25

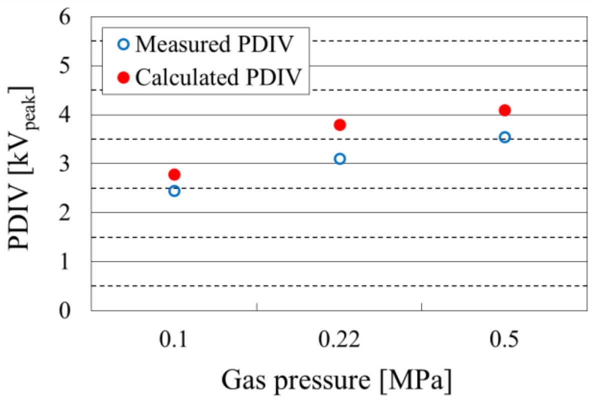


(b) RE 5

Figure 11. Measured and calculated discharge generation probability P_i at each applied impulse voltage V_i (0-peak value)



(a) RE 25



(b) RE 5

Figure 12. Measured and calculated PDIV at each gas pressure p

5 CONCLUSION

For the purpose of downsizing the GIT, discharge generation probability P_i as a function of applied impulse voltage V_i of the IGI electrode system was measured and its analytical study was conducted. It is concluded that P_i against V_i can be explained in terms of initial electrons generated from negative ions in SF_6 gas and the PET film surface and transition process of the initial electrons to discharge. Finally, the Volume-Time theory and Schumann's equation provide reasonable examination for the experimental result.

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