PRESSURE DEPENDENCE ON PARTIAL DISCHARGE IN WEDGE AIR-GAP FORMED BY INSULATED COATING CONDUCTORS

Hirotaka Torii, Satoshi Matsumoto

Graduate School of Engineering and Science, Shibaura Institute of Technology

Contact E-mail Address: torii-hirotaka@fujielectric.com

ABSTRACT

This paper describes the partial discharge voltage of resin molded coils simulating transformer or generator windings. Experiments were carried out to clarify the relationship between air pressure and partial discharge voltage of the wedge gap formed by insulated coating.

To explain the experimental results, calculation model was constructed for the wedge air gap. Experimental and calculated results were consistent with the error less than 15%, we have confirmed the validity of our calculation method.

1. INTRODUCTION

Transformers and rotating machines generally use the molded coil as excitation winding. The molded coil generally uses insulating coated round conductors. In case of resin impregnation is insufficient, wedge-shaped air gaps remain between the coated conductors. When potential difference between adjacent coated conductors increases, partial discharge occurs in wedge shaped air-gap parts composed of between conductors. Partial discharges damage the insulation coating, eventually leading to short-circuit. In order to prevent the occurrence of partial discharge, this wedge air-gap parts are vacuum-impregnated with a resin. If the resin impregnation is insufficient, wedge air-gap remains as reduced-pressure space. Air gap part becomes the generation of starting point in the partial discharges [(4)], therefore insulation performance of the entire molded coil is dependent on the air gap condition.

Several studies have been reported that partial discharge voltage is lower in impregnation failure mold coil than non-molded coil [(1)]. It is presumed that one of the reasons for this phenomenon is lowering pressure in the air gap by vacuum casting operation [(2)]. To clarify the relationship between gas pressure and partial discharge voltage in the wedge-shaped air gap, we have carried out the insulation model experiment and constructed the calculation model.

2. EXPERIMENT

In this chapter, we show experimental sample configuration and method for measuring the partial discharge characteristics of the wedge gaps.

2.1 Experimental sample

Figure 1 shows experimental sample configuration using acrylic pipe as inner mold. This acrylic pipe is 100mm in outer diameter and 500mm in height. We have wound 20 turns coated conductor in spiral configuration around the acrylic pipe, and wrapped insulating sheets around the coated conductor, and wound 20 turns coated conductor in spiral configuration around the insulating sheets. Outer conductor was voltage application side, inner conductor was earth side. For this experimental sample, we have defined space between the coated conductor and the insulation sheet as the wedge-shaped gap, and examined partial discharge voltage in wedge-shaped gap. As the materials used for the experimental samples, we describe the specifications of the coated conductor and insulating sheet. The conductor material is cupper, and diameter is 0.96 mm. The coating material is polyester resin, and thickness is 0.02 mm, and relative permittivity is 4.0.

The Insulation sheets are three types, table 1 shows these materials and thickness and relative permittivity.

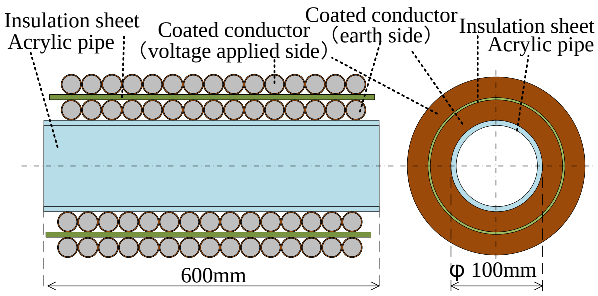

Fig.1 Experimental sample configuration.

Table 1 Insulation sheet materials.

Insulation sheet	Thickness	Relative Permittivity
PET (Polyethylene terephthalate)	0.19 mm	3.3
NOMEX (Aramid fiber sheet)	0.18 mm	3.1
HTH (Polyester Nonwoven fabric)	0.20 mm	2.4

We have selected insulation sheets so as to change relative permittivity. Thickness of the insulating sheet was adjusted by change in the number.

2.2 Experimental method

Figure 2 shows test circuit. Partial discharge voltage was measured by the case of inner conductors are set to ground potential and outer conductors are applied AC high voltages. Test sample was placed in the chamber that is adjusted to pressure 0.1 ~ 1.0MPa, and generated partial discharge by applying alternating voltage. This test procedure firstly increase voltage until generating stable partial discharge, and then the voltage is held for 1 minute, and finally gradually decreases the voltage until extinguishing partial discharge. We have measured extinction voltage of partial discharge as a partial discharge voltage.

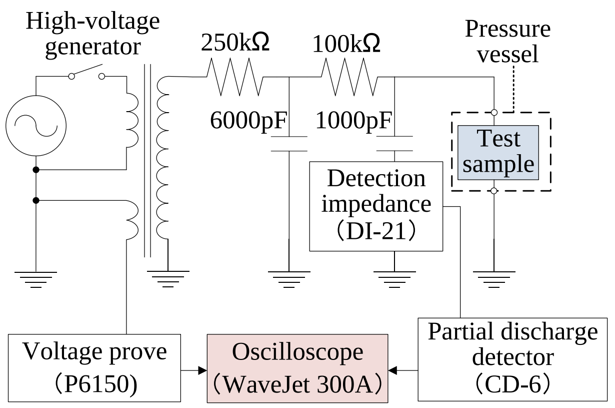

Fig.2 Test circuit.

3. CALCULATION METHOD

In this chapter, we describe the generation point and conditions for the partial discharge, and develop the expression for the equation to obtain partial discharge voltage. This calculation method consists of three steps. Firstly, we calculate electrical field intensity and gap distance between each point of insulation coated surface and insulation paper in wedge air-gap part. Secondly, we obtain discharge voltage at the each point by substituting the electrical field intensity and gap distance to Paschen curve approximation formula. Lastly, we define minimum value of these discharge voltages as a partial discharge voltage at wedge air-gap part.

3.1 Outline

Figure 3 shows the partial discharge model of the wedge gap. Potential difference is generated between upside and downside of the coated conductors. The wedge gap between coated conductors would occur ionizing collisions, it might lead to discharge. If discharge can't break insulation sheet and insulating coating, the discharge phenomenon periodically repeat generation and extinction following potential difference variation. This intermittent discharge is referred to as the partial discharge. Formation condition of partial discharge is electric field which can cause ionizing collisions and the number of ionizing collisions which can cause streamer transition. The number of ionizing collisions depend on the number of molecules along the discharge paths. The number of molecules is determined by product of gap length and gas pressure. A rise of gas pressure increase the number of molecules in same volume, but shorten the mean free path. If the mean free path is shortened, it requires larger electrical field strength to cause ionizing collisions. Therefore, a rise of gas pressure is not always to increase the discharge voltage. An extension of gap length increase the number of molecules, but decrease electric field strength at the same potential difference. The wedge gap has variety for the gap length, the shorter gaps are around contact point between the coated conductor and the insulation sheet, longer gaps are around contact point of adjacent the coated conductor. Accordingly, discharge points in wedge gap are moved by gas pressure and the sample configurations. Therefore, we estimate discharge voltages in all the gap lengths, and consider the lowest discharge voltage in all the gap lengths as discharge voltage of the wedge gap. Specifically, we set up calculating formulas to obtain generation electric field and discharge electric field in all the gap lengths, and find discharge voltage value by solving this simultaneous equations.

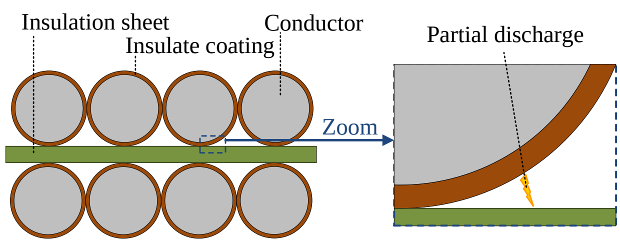

Fig.3 Partial discharge generation point.

3.2 Generation electric field calculation

This section describes the calculus equation of electric field strength in each gap length. We considered this calculus equation based on the assumption that coated conductors is symmetrical to insulation sheet. Figure 4 shows calculation region and its simplified model.

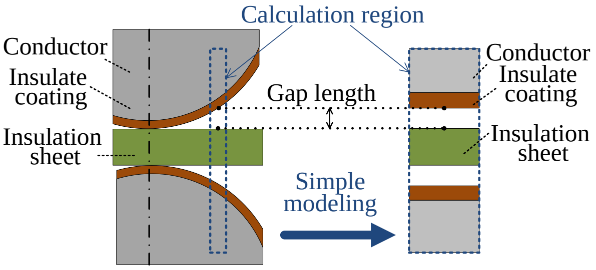

Fig.4 Calculation region and its simplified model.

Since the gap region under study is micro region as compared to whole area, we assumed that gap shape is parallel plate and electric field is equal distribution. In this assumption, target gap region can be regarded as dissimilar dielectric multilayer plate electrode. The electric field strength E_{gap}(d) in gap length d is given by

$$E_{gap}(d) = \frac{V_0}{1.0\times\left(\frac{2\times a}{\varepsilon_a}+\frac{b}{\varepsilon_b}+\frac{2\times d}{1.0}\right)}, \quad (1)$$

where V_0 is applied voltage, ε_a is relative permittivity of the coating material, ε_b is relative permittivity of the insulation sheet, a is thickness of the coating material, b is thickness of the insulation sheet, d is length of the target gap.

3.3 Discharge electric field calculation

This chapter describes the calculus equation of electric field strength required for the discharge generation. In order to approximate a uniform electric field in the gap, we used Paschen's law. It is an experimental law that represents relationships between the discharge voltage V_{fo} of under uniform electric field and product of the gas pressure P and the gap length d. We carried out curve-fit along Paschen's law graph data [3], fitting equation is given by

$$V_{fo} = \frac{C\times(P\times d+A)}{B\times ln(P\times d+A)-D}, \quad (2)$$

where A, B, C and D are constant parameters. The constant parameters used three pattern in a range of product of P and d, is shown in table 2. The fitting equation curve and measured data are with an uncertainty of 4 percent in the range of 200＜ $P\times d$ ＜ 10000000.

Table 2 Constant parameters of Pachen's law fitting equation under the stipulation that voltage unit is "kV", pressure unit is "Pa" and distance unit is "mm".

	A	B	C	D
P×d ＜ 600	1109	203	0.0167	1421
600 ＜ P×d ＜ 30000	1109	233	0.0580	1417
30000 ＜ P×d	1109	196	0.0337	1422

Figure 5 shows relationship graph of the discharge voltage and product of the gas pressure P and the gap length d by the fitting equation curve and the measured data on reference [3].

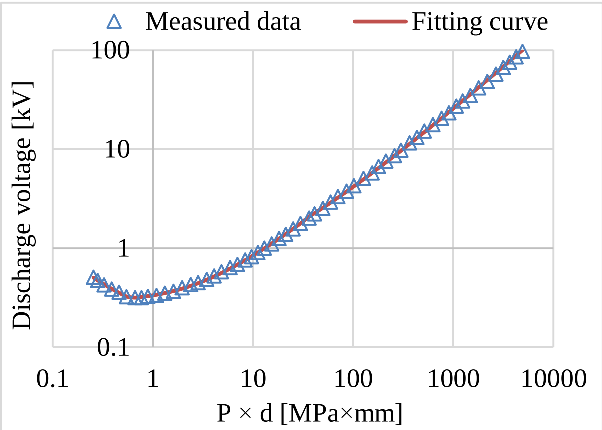

Fig.5 Relationship graph of the discharge voltage and product of the gas pressure P and the gap length d by the fitting equation curve and the measured data.

3.4 Discharge voltage calculation

Both sides of the equation (2) is divided by d, electric field E_{fo}(P, d) leading to the discharge is given by

$$E_{fo}(P,d) = \frac{V_{fo}}{d}\frac{C\times\left(p+\frac{A}{d}\right)}{B\times ln(p\cdot d+A)-D}. \quad (3)$$

If P and d as fixed values, discharge voltage at a gap point is V_0 under the stipulation that E_{gap}(d) and E_{fo}(P, d) become equal. The simultaneous equation of Equation (1) and (3) is given by

$$V_{gfo} = \frac{C\times\left(p+\frac{A}{d}\right)\times\left(\frac{2a}{\varepsilon_a}+\frac{b}{\varepsilon_b}+2d\right)}{B\times ln(p\cdot d+A)-D}, \quad (4)$$

where V_{gfo} is discharge voltage at a gap point. Equation (4) can calculate the discharge voltage of an arbitrary gap length of the fixed gas pressure. We calculated the discharge voltages of all the gap lengths, and regard the minimum discharge voltage as the discharge voltage of the wedge gap.

4. DISCUSSION

In this chapter, we shows the discharge voltage characteristics of the wedge gap, and compare the experimental results with the calculation results, and consider the validity and the error cause of the calculation model of discharge phenomenon in the wedge gap.

4.1 Comparison of measurement with calculation

Figure 6 shows relation between partial discharge voltage and insulation sheet thickness, and figure 7 shows relation between partial discharge voltage and gas pressure.

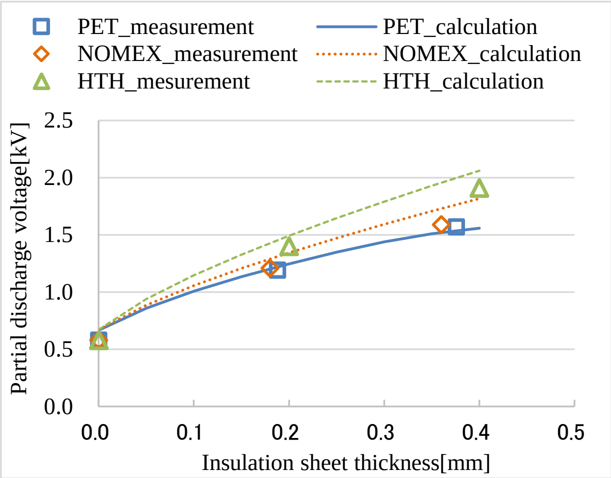

Fig.6 Relation between partial discharge voltage and insulation sheet thickness.

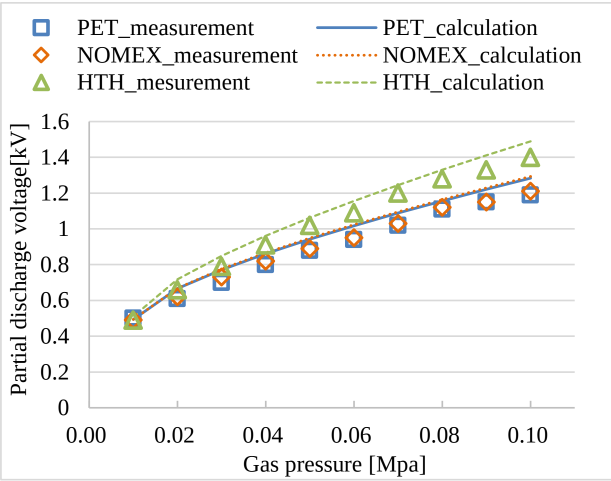

Fig.7 Relation between partial discharge voltage and gas pressure.

The partial discharge voltage has risen along with increasing the insulation sheet thickness, and with increasing the gas pressure, and with decreasing relative permittivity. This changing trends are consistent with the measured data and calculated curve, thus we has determined that the calculation model could be modeled discharge phenomenon under the wedge gaps. We consider the effects of insulation sheet thickness and relative permittivity is due to the action that the burden voltage of gap is reduced under same applied voltage. In this experimental conditions, we consider the effects of pressure is due to became easier to occur discharge by shortening of the mean free path. If the gas pressure is reduced more, we guess the discharge voltage reverse the downward trend.

4.2 Error cause

The calculated values were 0.2～9.8% larger than the measured values. We presume the largest error cause is to underestimate the electric field strength in the wedge gap. We assumed that coated conductors is symmetrical to insulation sheet, however the conductors position shift slightly in fact. In this actual conductor position, electric field strength rise in one side of the gaps by leaving the difference in the gap length with the insulating sheet upside and downside. As a practical matter, since all of the conductor arrangement can not be exactly grasped, we consider that the fundamental solution of this error factor is especially difficult. Other major error factors are three. First, the approximation of the direction of the discharge path is perpendicular to the insulating sheet. Second, the approximation of the electric field distribution of the discharge path is equality. Third, the changes in the electrode arrangement by insulation sheet compressed by winding force.

5. CONCLUSION

We have constructed the discharge voltage calculation method in the wedge gap, and elucidated the relation between the discharge voltage and the gas pressure. Since the partial discharge voltage in the wedge gap have become calculable under the condition of arbitrary gas pressure, we have made it possible to assess the risk of partial discharge generation by impregnation failure.

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Hirotaka Torii received the B.E. (2005) and M.E. (2007) degrees in Electrical engineering from Shibaura Institute of Technology. He is currently pursuing the Ph.D, also working in Fuji electric Co., Ltd.

Satoshi Matsumoto received the M.Eng. and Dr. degrees in electrical engineering from the University of Tokyo in 1981 and 1984, respectively. In 1984, he joined Toshiba Corporation. He has been a Professor in the Department of Electrical Engineering of Shibaura Institute of Technology since 2007. He is a Senior Member of IEEE and IEEJ.