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X-ray Irradiation Induced Discharge of Spherical Void in Epoxy Resin

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***Abstract*—It is crucial for proper insulation design of cast resin transformer to consider voids and delamination which might exist in cast molding process and/or under long-term operation because of several surface boundaries between resin and conductor. Should such defects in the insulation system exist, it would lead to reduction of the life of the apparatus. In this report, we investigate the relation between the void size and apparent charge of partial discharge (PD) occurring in a model simulating the insulation system of cast resin transformer. It is also important to determine necessary PD detection sensitivity of PD test in a factory as well as in a field. In addition, we investigate X-ray irradiation induced discharge of spherical void in epoxy resin. Physical consideration of the effect of X-ray irradiation on void discharges in epoxy resin was also made. Time lag of void discharges in epoxy resin was also made with attenuation of X-ray irradiation dose considered.**

Keywords-component; cast resin transformer; partial discharge; X-ray irradiation; discharge time lag

I. Introduction

In cast resin transformer using solid insulation system, variety types of interface exist such as resin to conductor etc. If some defects such as voids and delamination should exist in the insulation system, the insulation performance might degrade resulting in the failure of the transformer. From this viewpoint, it is great importance to exclude and detect such defects in manufacturing process. A technology for detecting such small defects in the cast resin transformer has not been established yet, and empirical methods for detecting the defects are still used. More than 30 years have passed since cast resin transformers were initially put into practical use in fields. In that sense, it is strongly required to establish a confirmation method of healthy conditions in cast resin transformer and improve the confirmation precision. For ensuring reliability of the apparatus, it becomes crucial how defects such as voids in the insulation material can be detected in the manufacturing process and in operation as well. Besides, from the viewpoint of insulation diagnostics, insulation design and tests, the authors aim fundamental change and establishment of measurement system with high sensitivity of PD control and detection technique.

There have been so far a lot of reports which deal with internal void discharges in epoxy resin from both experimental and theoretical viewpoints [1-6]. Nevertheless, complete understanding of the void discharge mechanism and its application to the cast resin transformer still seems to be insufficient. We aim to elucidate fundamental behaviors of partial discharges occurring in a closed void artificially fabricated in epoxy resin which simulates the solid insulation system of cast resin transformer. In the previous report [1], we investigated and compared PD characteristics (the apparent charge Q_a versus the void diameter $2a$) in the void using the two different types of physical models for internal void PD by calculation. The calculated relation between the discharge time lag and the void size was also discussed. Experimental investigation was made on the effect of X-ray irradiation to the epoxy resin on PD inception voltage (PDIV) characteristics. It was found that both PDIV and PD elimination voltage (PDEV) decreased with increasing the X-ray irradiation to the epoxy resin sample with the spherical void.

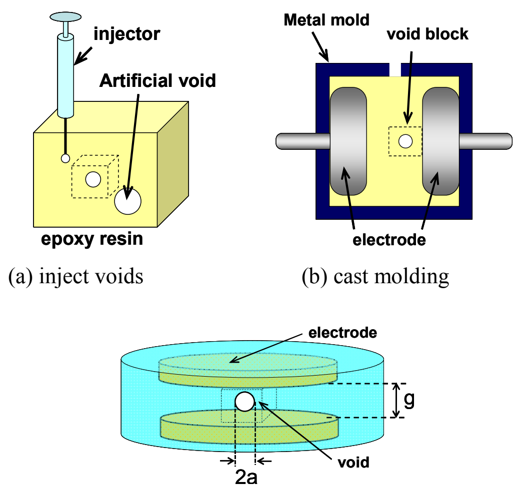
In this report, we experimentally investigate the effect of X-ray irradiation on fundamental PD behaviors in a spherical void of epoxy resin such as the relation between the void size and apparent charge of PD, and the relation between PD inception voltage and the void size, and the phase resolved characteristics. Time lag of void discharges in epoxy resin was also measured with X-ray irradiation. Physical consideration of the effect of X-ray irradiation on the characteristics of void discharges in epoxy resin was also made with considering attenuation of X-ray irradiation dose by copper plate inserted between X-ray generation source and the epoxy resin sample.

II. Experiments

A. Sample Preparation

In this study, we fabricated an electrode system consisting of parallel plane electrodes molded with epoxy resin (ER). Figure 1 illustrates fabrication process of epoxy cast molding electrode. Epoxy resin was formed by mixing chief material (Epicoat 816B: Mitsubishi Chemical Co.) and hardner (Epicure 113: Mitsubishi Chemical Co.). Note that Epicoat 816B is formed in such a way as bisphenol A type liquid epoxy resin

(Epicoat 828) is made low-viscosity by mixing with reactive dilution agent. The epoxy resin prior to hardening was fully mixed and degassed in vacuum. A number of spherical voids with various diameter were formed in ER prior to hardening with a syringe (Fig.1 (a)), and then curing of the ER was made. After the curing, ER was cut into small blocks with a spherical void inside using an electric cutter. A thus obtained block was adhered on the one side of an electrode by epoxy resin (Fig.1(b)). During the adhesion process, special care was taken in order not to form new and unwanted void space at the interface between the block and the electrode. Next, the electrode adhered with the void included block and a new counter electrode were made parallel and molded by the same ER to form the electrode system (Fig.1 (c)) with sufficient degassing process. The disk-shape electrodes with 25 mm in diameter were made with brass. The distance g between the two electrodes was set as 3 mm. The void size (diameter $2a$) used in experiments was 0.21, 0.29, 0.49, 0.61 and 0.65 mm. The void size was measured with an optical microscope in the precision of 0.01 mm.



(a) inject voids
(b) cast molding
(c) completed electrode
Figure 1 Sample preparation.

B. PD Measureing Circuit with X-ray Irradiation Source

Figure 2 shows experimental setup for X-ray induced PD measurements. The experimental setup consists of the fabricated mold electrode sample with a void, PD measuring circuit ac high voltage transformer and X-ray generation source. An X-ray module (Matsusada Precision XM10-60-05, maximum output 10 W, X-ray tube voltage 10~60 kV, current 33~166 μA; a driving voltage source dc 24 V was used) was utilized to generate X-ray, which was irradiated to the specimen from outside of a test vessel in the direction parallel to the surface of the specimen. The distance between the X-ray module and the center of a void in ER sample was 60 mm. All experiments X-ray was continuously irradiated during the ac voltage application.

A signal produced with ac signal generator (NF Circuit Design Block Co., WF1974) was increased and simultaneously amplified with a precision power amplifier (NF Circuit Design Block Co., 4520A) and a transformer. The output ac high voltage at 60 Hz was applied at a rise rate of 150 V_{rms}/s to the electrode system through a 20 kΩ current limiting resistor. A coupling capacitance of 1000 pF was connected in parallel with the sample. PD pulse signal was detected with a detecting impedance (Japan Measuring Instrument Co.: DI-21) connected between the coupling capacitance and the earth. The detected signal was amplified with a 400 kHz tuning type PD measuring device CD-6 (Japan Measuring Instrument Co.) and recorded with an oscilloscope (LeCroy Japan Co.: Wave Surfer 62Xs-A, 2.5 GS/s, 600 MHz). It is noticed that the PD measuring system allowed PD detection sensitivity 3 pC. The applied voltage was increased up to the voltage (PDIV) at which the first PD signal with charge magnitude q_a above 5 pC was detected with the measuring devices. This measuring process was repeated twelve times. PDIV was determined by averaging ten results without maximum and minimum PDIV values among the twelve times experiments. To avoid unwanted discharges, the entire electrode system was immersed in insulating liquid.

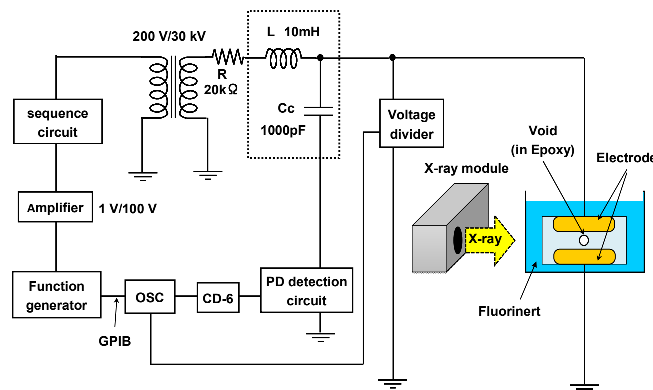


Figure 2 Experimental setup.

III. Results of X-ray Irradiated Void Discharges

Figure 3 shows typical example of discharge waveform detected with CD-6 for a void included sample with 0.65 mm in diameter. Figure 4 shows experimental result of PDIV as a function of X-ray irradiation intensity (output power of X-ray module) for the epoxy resin slab specimen with the void of 0.29 mm in diameter. It is evident in the figure that PDIV decreases with increasing the X-ray module output (i.e. X-ray intensity irradiated to the specimen).

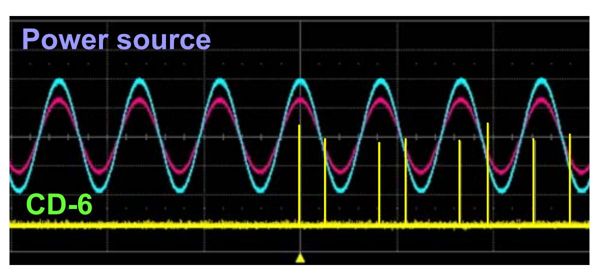


Figure 3 Detected waveform of ER sample containing a void of $2a$= 0.65 mm in diameter (5 pC/div, 20 ms/div)

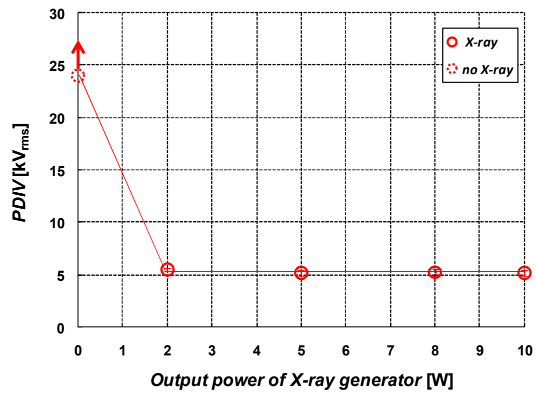
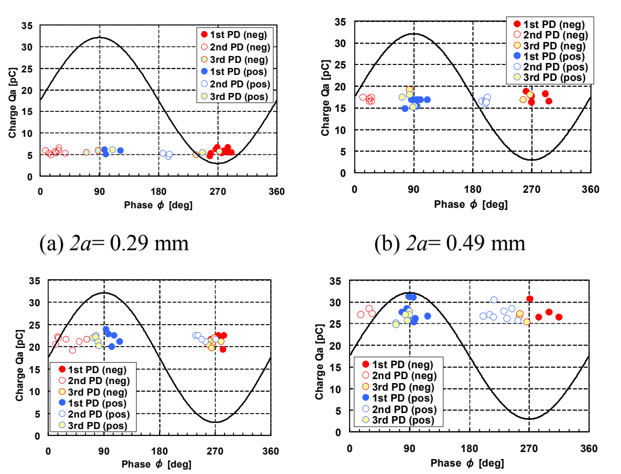


Figure 4 Relationship between output of X-ray generator and PDIV for epoxy resin specimen with void diameter $2a$= 0.29 mm.

A. PD Characteristics with X-ray Irradiation

Figure 5 shows the relation between phase angle of PD pulse occurrence and apparent charge (ϕ-q pattern) for molded electrode sample with various void sizes. Note that all PD pulses appearing in an oscilloscope frame (sampling time: 0.1 s) in twelve times experiments are plotted in each figure. As can be seen, as the size of the void increases, both charge q and the repetition rate increases. It should be noticed that most of PD pulses occur in the vicinity of the phase angle 90 and 270^o.



(a) $2a$= 0.29 mm (b) $2a$= 0.49 mm

(d) $2a$= 0.61 mm (e) $2a$= 0.65 mm

Figure 5 ϕ-q pattern for molded electrode system with various void sizes

Figure 6 shows PDIV and charge q_a of firstly observed PD pulse as a function of the void diameter $2a$ with X-ray power 5 W. Each symbol and bar represent the average and maximum and minimum for the twelve experiments without maximum and minimum values. It is obvious in the figure that PDIV decreases and q_a increases with an increase in the void diameter. The obtained quantitative relation between q_a and the void size is expected to be used for estimating the void size in the insulation system of a cast resin transformer from measured PD charge. Further investigation is under way on this subject.

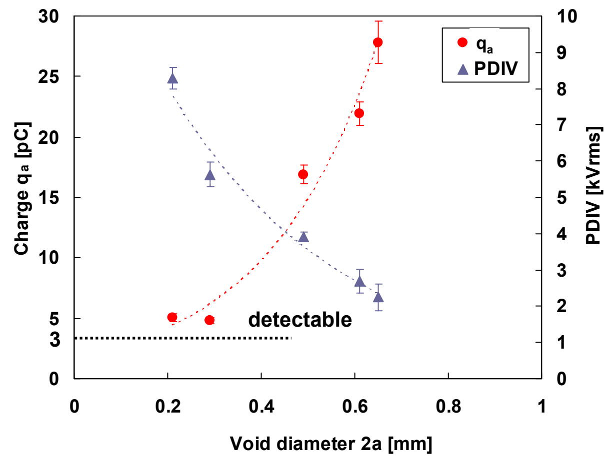


Figure 6 PD inception voltage and charge of firstly observed PD pulse as a function of the void diameter $2a$. (X-ray: 5 W)

B. Discussion on Phase resolved PD Characteristics

As shown in Fig.3, it should be noted that a firstly observed PD pulse occur near the positive or negative peak instantaneous voltage and then the next PD pulse occurs at the vicinity of the zero cross phase within one sinusoidal cycle. Once the first PD pulse and the second pulse occur, such a sequence of PD events (i.e. two pulses in the same one ac voltage cycle) were found to repeatedly or intermittently continue. The obtained feature of the phase-resolved PD characteristics can be interpreted in terms of the extremely shorten time lag in void discharge brought by X-ray irradiation. In other words, the experimental results can be explained by promotion of initial electron supply in the void volume by direct ionization caused by X-ray irradiation or field emission from the void surface.

The above experimental results and consideration are consistence with simulation result obtained by T.Okamoto et al. [6] , who calculate phase-resolved PD pattern using integration equation that the probability distribution expressing PD pulse occurrence fluctuation obeys on the basis of Whitehead's equivalent circuit model for PD in void in dielectric material. Namely, the present experimental results with X-ray irradiation seem to agree well with the simulated results obtained for very short time lag of discharge.

IV. DISCHARGE TIME LAG WITH X-RAY IRRADIATION DOSE ATTENUATION CONSIDERED

A. Simulation Conditions for Void Discharge Time Lag with X-ray Irradiation Dose Attenuation

In this chapter, we show results on the time lag of void discharge initiation with considering X-ray irradiation dose attenuation by copper plate. Figure 7 illustrates configuration of simulation model to estimate the attenuation of X-ray dose reaching a spherical void. For simplicity, ER is assumed to be methacrylate resin. Dose by X-ray source was measured as 33 Gy/s at a position 1 cm apart from the source under the conditions of X-ray tube voltage 60 kV, tube current 0.1 mA. In the figure, r, d_1 and d_2 represent distance between X-ray source and the center of a void, that between the surface of ER and the void center, and thickness of a copper plate, respectively. The X-ray linear attenuation coefficient of air and copper is referred as $\mu_{Air} = 0.042$, $\mu_M = 35.70\,\mathrm{m}^{-1}$. These values are estimated by assuming that photon energy emitted from the X-ray generation source at the tube voltage 60 kV is 30 keV and using mass attenuation constant at the above value [7]. Multiplication of the mass attenuation constant with the density [8] of air (20 degree C, 1 atm) and methacrylate allows estimation of μ_{Air} and μ_M, respectively.

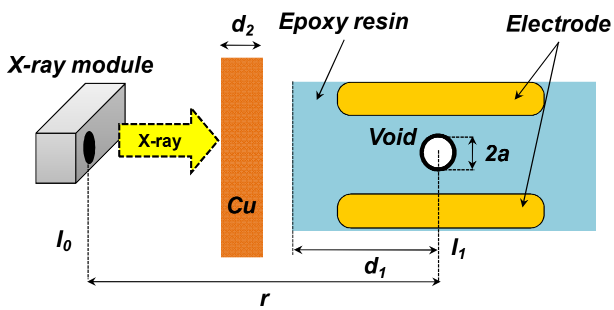


Figure7 Configuration for X-ray irradiation and attenuation dose estimation.

Here, it is assumed that energy of photons emitted from the X-ray source is uniform as parallel beam, and that materials dealt here (air, copper, and methacrylate resin) have also uniform attenuation characteristics. It is generally known that the interaction between the photons emitted from X-ray source and material causes X-ray dose to decay in an exponential manner with the distance or thickness. Besides, if the X-ray generation source is considered to be a point light source, the dose decays in inverse proportion to the square of the distance. Thus, when X-ray exposure radiation dose of the X-ray source is I_0 [Gy/s], that inside the void is I_1 [Gy/s], namely transmitted amount of dose, can be expressed by the following equation

$$I_1 = \frac{I_0}{r^2} e^{-\mu_{Air}(r-d)-\mu_M d} \qquad (1)$$

Furthermore, when q [C/kg] is charge generated in the surrounding air with unit mass by photons emitted from the output of the source, n is the number of electrons per unit charge, ρ_{air} is the density of air, then the discharge time lag t_{inc} can be derived by the following equation, by assuming that the time required for supplying one electron in the void space is t_{inc}

$$t_{inc} = \left[\frac{BI_0}{r^2} \cdot q \cdot n \cdot e^{-\mu_{Air}(r-d_1-d_2)-\mu_M d_1 - \mu_{Cu} d_2} \cdot \frac{\pi}{6} (2a)^3 \rho_{Air} \right]^{-1} \qquad (2)$$

Here, calculation was conducted using the following values: I_0 = 10.89 Gy/s, r= 61 mm, d_1= 17.5 mm, d_2 is the thickness of the copper plate, the regenerate coefficient B = 1 (d_2 = 0 mm), 9.7 (d_2 = 1 mm), 19.3 (d_2 = 2 mm), $q = 2.98\times10^{-2}$ C/kg, $n = 6.24\times10^{18}$ C^{-1}. The dose attenuation coefficient of copper , epoxy and air were set as μ_{Cu} = 9671 m^{-1}, μ_M = 35.7 m^{-1} and μ_{Air} = 0.042 m^{-1}, respectively.

B. Comparison of Experiments and Simulation on Void Discharge Time Lag with X-ray Irradiation

Measurements of the time lag t_{inc} of the void discharge were conducted for the configuration shown in Fig.7 with X-ray irradiation at 5 W of the source by applying voltage 1.2 times of PDIV. Figure 8 shows calculated t_{inc} as well as experimental results as a function of the void diameter 2a for different copper plate thickness. It is noticed in the same figure that theoretical and experimental results without X-ray irradiation obtained by L.Niemeyer [3] are also plotted. Symbol and bar of t_{inc} for d_2=1 and 2 mm represent the average and maximum and minimum of ten data among twelve experiments excluding the maximum and minimum values. It is found from the figure that the theoretically obtained t_{inc} agrees well with experimental ones. It is also evident that as the diameter of the void increases, the time lag greatly decreases. The results can be interpreted in terms of increase in PD generation probability due to the initial electron supplied from radiation ionization in the void volume caused by X-ray dose.

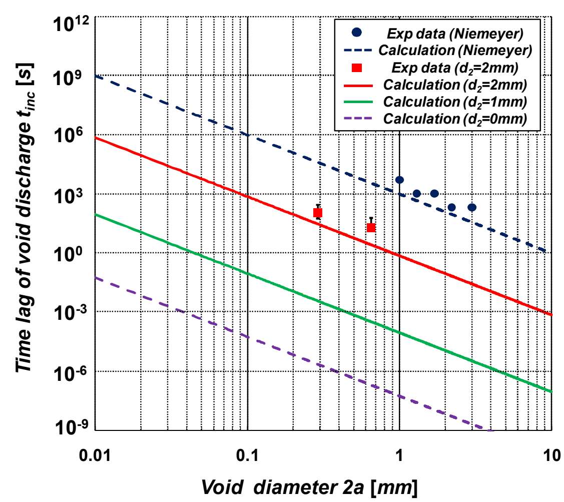


Figure 8 Time lag of void discharge as a function of void size for different thickness of copper plate. (r = 61 mm, d_1 = 17.5 mm)

As shown, it is found that X-ray irradiation to the ER sample with a spherical void allows the discharge time lag to greatly be reduced. Further investigation is underway on the dependences of the distance between the X-ray source and the void, the amount of the dose radiation, the thickness of the copper on the discharge time lag. These considerations will lead to the control and precise detection PD in the insulation system of cast resin transformers.

V. Conclusions

In this report, we experimentally investigate the effect of X-ray irradiation on fundamental PD behaviors in a spherical void of epoxy resin such as the relation between the void size and apparent charge of PD, and the relation between PD inception voltage and the void size, and the phase resolved characteristics. Time lag of void discharges in epoxy resin was also measured with X-ray irradiation. It was found that a firstly observed PD pulse occur near the positive or negative peak instantaneous voltage and then the next PD pulse occurs at the vicinity of the zero cross phase within one sinusoidal cycle. It was also found that X-ray irradiation to the ER sample with a spherical void allows the discharge time lag to greatly be reduced. Physical consideration of the effect of X-ray irradiation on the characteristics of void discharges in epoxy resin was also made with considering attenuation of X-ray irradiation dose by copper plate inserted between X-ray generation source and the epoxy resin sample.

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References

[1] M.Hikita, M.Kozako, H.Takada, M.Higashiyama, T.Hirose, S.Nakamura, and T.Umemura, "Partial Discharge Phenomena in Artificial Cavity in Epoxy Cast Resin Insulation System," Intern. Symp. on Electrical Insulation 2010, pp.660-664, San Diego, USA June 2010.

[2] G.C.Crichton, P.W.Karlsson and A.Pedersen, "Partial Discharges in Ellipsoidal and Spheroidal Voids", IEEE Transactions on Electrical Insulation, Vol.24, No.2, pp.335-342 (1989)

[3] F.Gutfleisch and L.Niemeyer, "Mesurement and Simulation of PD in Epoxy Voids", IEEE Transactions on Dielectrics and Electrical Insulation, Vol.2, No.5, pp.729-743 (1995)

[4] H. Illias, G. Chen and P. L. Lewin: "Modelling of Surface Charge Decay in a Spherical Cavity within a Solid Dielectric Material Using Finite Element Analysis", 16th International Symposium on High Voltage Engineering 2009, E-18 (2009).

[5] H. A. Illias, G. Chen, P. L. Lewin: "Measurement and Modeling of Partial Discharge Behavior in Spherical Cavity within a Solid Dielectric Material as a Function of Cavity Diameter", 2010 International Conference on Solid Dielectrics, Potsdom, Germany, July 4-9, E2-04 (2010)

[6] T.Okamoto, T.Takahashi, S.Miyazaki, and T.Kuraishi, "An Integral Equation for Analysis of Partial Discharge Characteristics for Asymmetric Electrode Condition", Proc. Of the 41th Sympo. on Electrical and Electronic Insulating Materials and Applications in Systems, IEE Japan, S1-2, pp.123-128 (2010)

[7] Japan Isotope Association : "ISOTOPE HANDBOOK", Maruzen Corporation, p.41-42 (1984)

[8] National Astronomical Observatory of Japan : "SCIENTIFIC CHRONOLOGY", Maruzen Corporation, p.444, 448 (1998)