

Simulation of Partial Discharges in Solid Dielectric Material: A Study on PD Magnitudes to the Parallel and Perpendicular Axis of a Cylindrical Cavity

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Abstract — The assessment of partial discharges (PDs) gives important information pertaining to the reliability of the high voltage power equipment. PDs occur in weaker regions like voids, cracks, and imperfections present inside the insulation. The PD is generally accepted as the predominant cause of long term degradation and failure of electrical insulation. Simulation environment is a significant approach towards the study of PD mechanism. In this paper, simulations of partial discharge with the single void whose axis parallel and perpendicular to the electric field was analyzed. The analysis has been carried out on characteristic parameters like PD magnitude, partial discharge inception voltage (PDIV) and apparent charge with respect to the geometric parameters of the void and also under different stress conditions. This study acknowledges the influence of PD activity inside the solid dielectric material. The relationship of PD magnitude with respect to the axes of the cavity in the direction of the electric field was compared. The computed and simulation results were presented.

Keyword— Partial Discharges, Solid Insulation, Cylindrical Void, Apparent Charge.

I. INTRODUCTION

Electrical insulation is a very significant but weakest part of high voltage (HV) apparatus. It is also termed as the heart of HV apparatus which predicts the integrity of the equipment. PD is a localized electrical discharge that only partially bridges the insulation between the conductors and which can or cannot occur adjacent to a conductor. PDs are in general a consequence of local electrical stress concentrations in the insulation or on the surface of the insulation. Generally such discharges appear as pulses of duration of much less than 1 μ s. [1, 2].

When there is an increase in applied voltage, the electric stress across the insulation will be higher which leads to discharge in cavities when it exceeds the PDIV. This process may weaken the insulation strength, ultimate degradation leads to breakdown at last during the normal operating conditions. This will emphasize the study of PD Mechanism in solid insulation system of the HV apparatus.

PD in due course of time reduces the strength of insulation leading to a total or partial failure or breakdown of the insulation [3]. The evaluation of the PD inside the high voltage apparatus like rotating machine insulation[4] widely use epoxy resin, gives valuable information about the higher stress region and imperfections in the fabrication. PD will be categorized into several types of discharge phenomena which depends on the location of its occurrence: internal discharges occurring in voids or cavities within solid dielectrics, surface discharges appearing at the boundary of various insulation materials, corona discharges occurring in gaseous dielectrics in the presence of inhomogeneous fields and formation of discharge channels in the form of treeing in solid dielectrics. When the deterioration bridges the high voltage electrode to that of ground electrode leads to the complete failure of the insulation [5, 6].

Various research works has been carried out on PD in cavities inside the solid insulation extensively. With reference to IEC standard 60270, PD measurement is mainly done with the apparent charge as a vital parameter. To compute the apparent charge, an equivalent circuit has been developed for modelling of PD is a familiar approach. Several PD models have been developed in order to study its behaviour based upon capacitance concept and electromagnetic theory [7, 8]. The capacitive equivalent circuit for the study of PD behaviour in solid dielectrics was developed by Gemant & Philippoff in 1932 widely known as capacitance model or a-b-c model [8,9]. Pederson's PD model is based on the streamer type which includes the charge induced on the measuring electrode [7, 10]. PD Model with cylindrical void has been developed to analyze the PD characteristic parameters with respect to variation in frequency of the voltage applied to the insulation [11]. However, the geometric parameters of the void present in the dielectric does not considered as a significant one. The simulation model of cylindrical void enclosed in the solid dielectric wherein void axis parallel to the

direction of the electric field was proposed in [12]. The conceptual idea and the schematic representation about a cylindrical cavity enclosed in a solid insulation with its main axis perpendicular to the applied electric field have been considered [8].

In this paper, with an aid of simulation model [12], an analysis is carried out on the PD characteristic parameters in a single cylindrical void viz. (1) with its axis parallel to the applied electric field and (2) with its axis perpendicular to the applied electric field. The PD behaviour has been interpreted with the aid of capacitance model. Variations in the values of the capacitances in the equivalent circuit were computed. The PD characteristics were deliberated from the simulation results. The PD magnitudes were investigated for the two different position of the axis of cylindrical cavity in the direction of the electric field.

II. DISCHARGE ACTIVITY IN A VOID

The design of insulation must meet out the vital requirements like evaluation of the electric stresses with which the insulation can able to withstand, and also the behaviour of such insulation medium when it is subjected to applied electric stresses. Insulation coordination reveal about the close agreement between the electric stresses developed on the insulation and the dielectric strength of the insulating medium [13].

Solid insulation with imperfections or voids leading to PD can be represented by an equivalent circuit as shown in Fig. 1. In the equivalent circuit, C_c corresponds to capacitance of the void; C_b is the capacitance of the insulation in series with C_c and C_a is capacitance of the void-free healthy part of the insulation parallel to void. When the applied voltage is increased, a critical value is reached across C_c and a discharge takes place across it. Because the voids are filled with the gas whose breakdown strength is lower than the solid insulation.

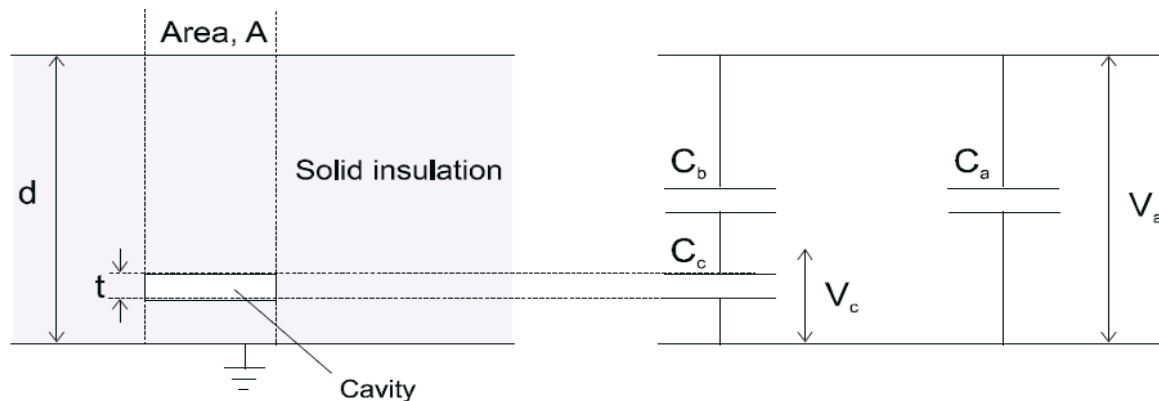


Fig. 1. Capacitance model of a cavity in solid insulation

The condition for the capacitance model shown in the Fig. 1 should be $C_c \ll C_b \ll C_a$. The capacitance C_a is computed by the expression given in the equation (1)

$$C_a = \frac{\epsilon_0 \epsilon_r A}{d} \quad (1)$$

where, ϵ_0 - permittivity of the free space ($= 8.854 \times 10^{-12}$ F/m), ϵ_r - Permittivity of the solid insulating material, A - area between the electrodes and d - distance between the electrodes. The relative permittivity of the gas is 1, hence the capacitance of the void is given by the equation (2) and the capacitance of the insulation in series with C_c using the equation (3)

$$C_c = \frac{\epsilon_0 A}{t} \quad (2)$$

$$C_b = \frac{\epsilon_0 \epsilon_r A}{d-t} \quad (3)$$

where, t - thickness of the void. The voltage across the cavity can be expressed by the equation (4) as

$$V_c = \frac{C_b}{C_c + C_b} V_a \quad (4)$$

where, V_a - voltage across the capacitance C_a . Substituting (2) & (3) in (4) results in equation (5) with

$$V_c = \frac{V_a}{1 + \frac{1}{\epsilon_r} \left(\frac{d}{t} - 1 \right)} \quad (5)$$

It is evident that the apparent charge (q) of a PD pulse is having significant part in life expectancy of the HV insulation system. As per IEC standard 60270, it is that charge which, if injected within a very short time between the terminals of the test object in a specified test circuit, would give the same reading on the measuring instrument as the PD current pulse itself. The apparent charge is usually expressed in picocoulombs (pC). The apparent charge is not equal to the amount of charge locally involved at the site of the discharge, which cannot be measured directly [1]. The apparent charge of a discharge is given by the equation (6)

$$q_a = C_b \Delta V_C \tag{6}$$

where, ΔV_C is the voltage across the void [4]. The apparent charge of an air-filled cavity relating the field after a discharge to the minimum field required for the discharge is given by the equation (7) as

$$q = k\Omega\varepsilon_0\varepsilon_r(E_i - E_l)\nabla\lambda_0 \tag{7}$$

where, k is a geometric factor of the void, Ω is the volume of the void, $E_i - E_l$ is the difference between the minimum breakdown field and the minimum field necessary to sustain a discharge and $\nabla\lambda_0$ is the reciprocal of the distance between the electrodes[7,14,15]. The minimum breakdown field is expressed approximately by the equation (8)

$$E_i = \left(\frac{1+8.6}{\sqrt{2ap}}\right) 24.2p \tag{8}$$

where, p – pressure in Pascals and a – radius of the void in metres. The limiting field after the discharge as the function of pressure is given by

$$E_l/p = 24.2 \text{ V/ Pa.m} \tag{9}$$

The change in field upon discharge for an air filled cavity is

$$E_i - E_l = 147.2\sqrt{(p/a)} \tag{10}$$

For the capacitance model, the PDIV can be calculated [5] by the relation

$$PDIV = 26.5pt + 0.55 \tag{11}$$

where, p is the pressure in the void in atm and t is its thickness in cm.

III.MEASUREMENT OF PARTIAL DISCHARGES

A cylindrical void within the solid dielectric is considered. The void is defined as a 6mm diameter placed in the middle of the insulation sample of dimension 38mm x 38mm x 7.5mm as represented in the Table I.

TABLE I
DIMENSION OF VOID MODEL WITH SOLID SAMPLE

Insulation Sample (Rectangular Solid)			Cylindrical Void	
Length (l)	Width (b)	Height (s)	Radius (r)	Height (h)
38mm	38mm	7.5mm	3mm	6mm

The cylindrical void model with its axis parallel[12] and perpendicular [8] to the applied electric field is shown in the Fig 2. & 3. respectively.

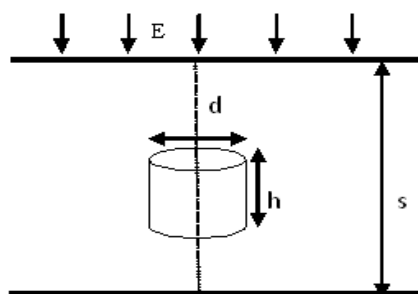


Fig. 2. Model of a cylindrical void within a solid insulation shows its axis parallel to the applied electric field

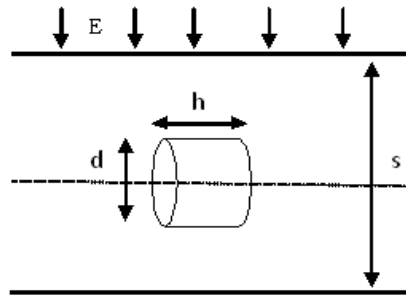


Fig. 3. Model of a cylindrical void within a solid insulation shows its axis perpendicular to the applied electric field

Partial discharge measurement is a proactive qualitative assessment tool which alarm about the forthcoming insulation failure. There are various test circuits to measure the PD [1]. In this paper, an equivalent circuit with respect to the PD measuring circuit shown in the Fig.4. is considered and modelled with simulink[12] to study the PD characteristics parameters.

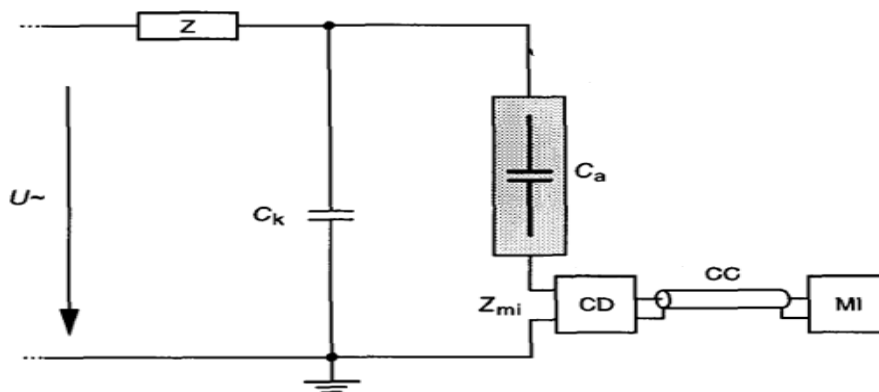


Fig. 4. PD measuring circuit in which coupling device is in series with the test sample

$U\sim$ - high voltage source, Z - input filter, C_k - coupling capacitor, C_a - capacitance of the test sample, Z_{mi} - impedance of the measuring system, CC - connecting cable, CD - coupling device, MI - measuring instrument.

IV RESULTS AND DISCUSSIONS

The calculation of the three different capacitance values in the equivalent circuit of the test sample can be done using the equations (1), (2) & (3). The capacitance values are computed for cylindrical geometry of the void for the two different positions of the void represented in the Table II. The capacitance values are determined for the two different conditions viz (i) by keeping the height of the void constant with the variation in its diameter and (ii) for an equal value of height and diameter of the void.

TABLE II
COMPUTED VALUES OF CAPACITANCES OF THE TEST SAMPLE WITH VOID

Model	C_a (F/m ²)	C_b (F/m ²)	C_c (F/m ²)
Void axis parallel to E	5.02×10^{-12}	5.84×10^{-13}	4.17×10^{-14}
Void axis perpendicular to E	3.77×10^{-12}	2.19×10^{-13}	

Fig.5 shows the theoretical PDIV with the varying product value of gas pressure and gap spacing. The curve obtained is linear one. Increase in value of thickness of the void will increase the PDIV with a constant pressure value.

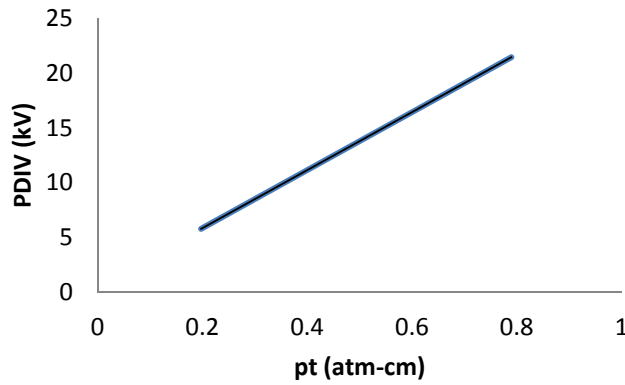


Fig. 5. Variation of PDIV with (pt)

The apparent charge for an air filled cavity is computed using the equation (7) and its variation with the height and radius of the void was shown in the Fig.6 & 7 respectively. The pressure value is taken as 100kPa. The change in the field ($E_i - E_l$) will be decreasing with increase in the value of the void radius. It is learnt that the number of voids with different geometric shapes present within the solid dielectrics cause high stress concentration.

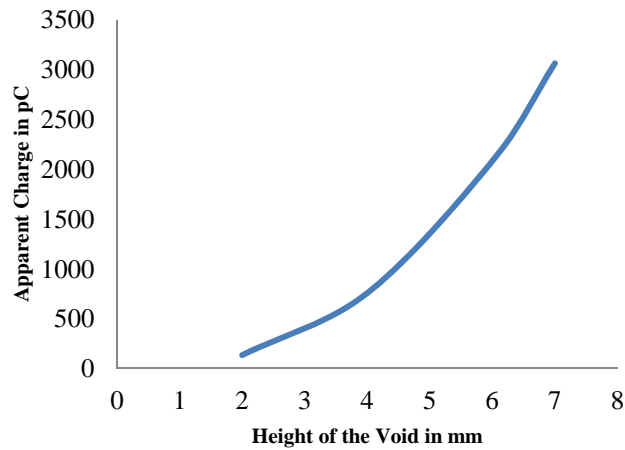


Fig. 6. Variation of apparent charge with height of the void

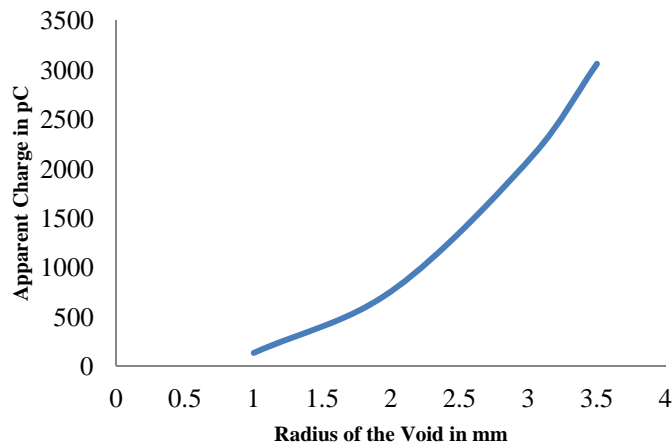


Fig. 7. Variation of apparent charge with radius of the void

A high voltage source between 6 kV and 30 kV has been applied across the sample insulation to learn the PD characteristics. Fig.8. shows the variation of the PD pulse magnitude occurring inside the void of solid insulation for the applied voltage of 8 kV. Maximum PD pulse magnitude has been extracted for the range of

applied voltage mentioned. Fig. 9. represents the maximum PD magnitude for the various applied voltages. There is an increase in the magnitude of PD pulse with the increase in the applied voltage. The comparison of the PD magnitude for the various applied voltages is depicted in the Fig.10 for the void model represented in the Fig. 2. & Fig. 3.

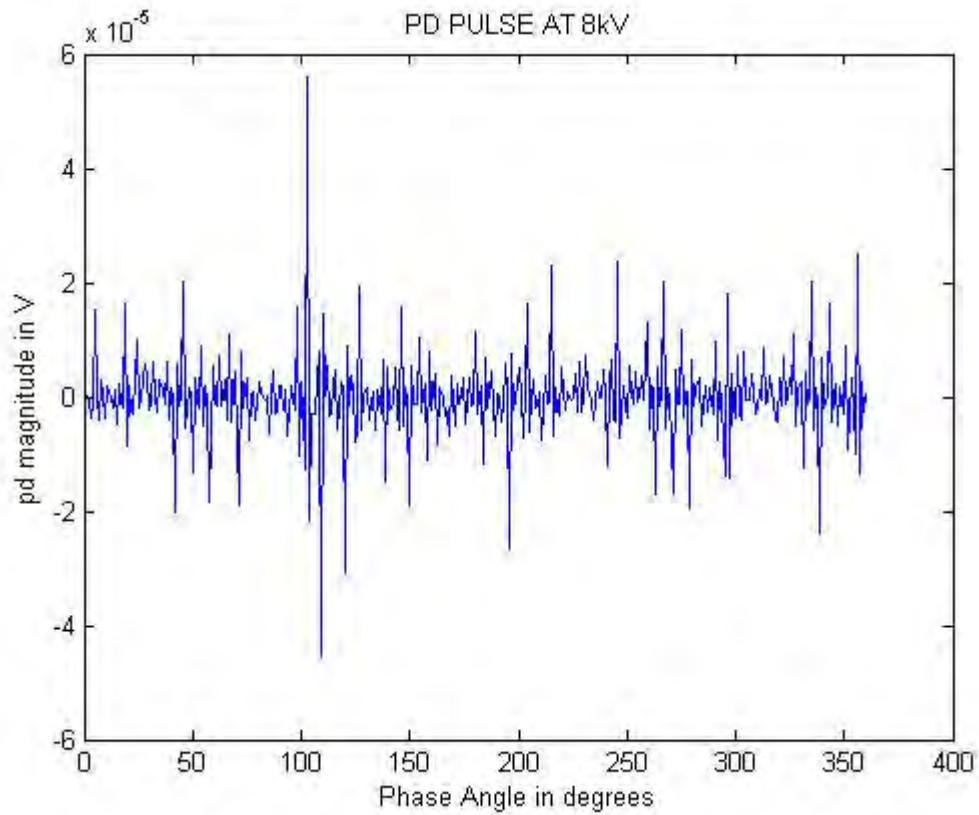


Fig. 8. Simulation result of the variation of PD magnitude with the phase angle

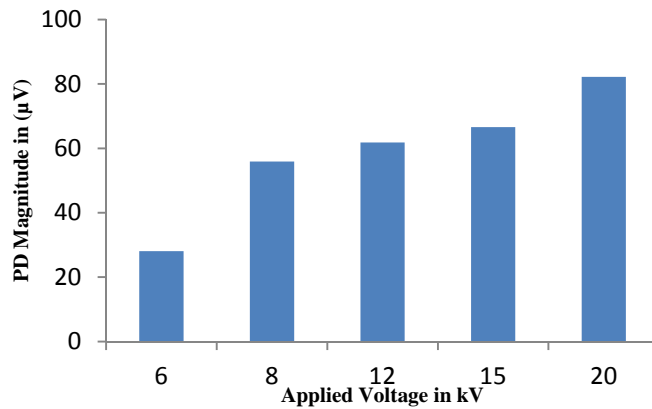


Fig. 9. Variation of PD magnitude with different applied voltage for the model shown in Fig.2

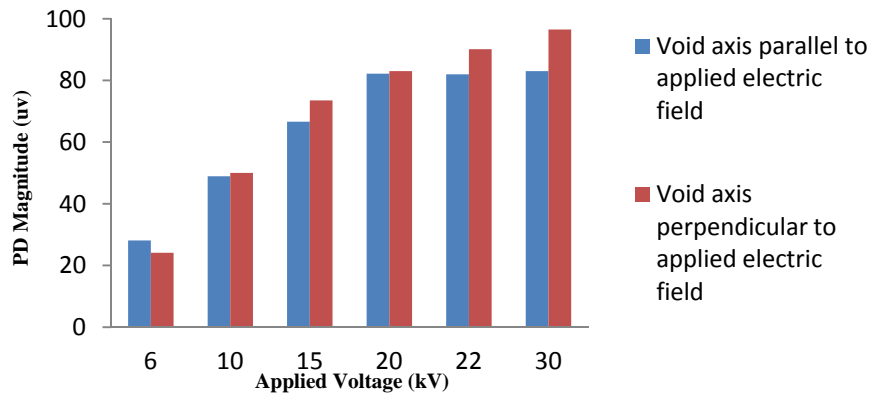


Fig.10. Comparison of PD magnitudes with different applied voltage for the model shown in Fig 2 and Fig 3.

V CONCLUSION

PD model and its simulation help to describe the behaviour of PDs inside the solid insulation. The PD model involves various parameters to evaluate the magnitude of discharges. This paper explains the shape of cylindrical void and its behaviour with the variation in the applied voltage. It has understood that the PD magnitude is high for the higher value of the applied voltage for the void axis perpendicular to the applied electric field. This comparison enables the assessment and assurance of the quality of the insulation. This simulated study also depicts the role of void axis with its relationship on PD magnitudes. Better understanding of PD mechanism will avoid the failure and defects of the solid insulation. Hence the life expectancy, reliability and integrity of the high voltage equipments will be ensured.

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