A Study of Partial Discharge Patterns in Solid Insulations: The Role of Air Void Geometry in High Voltage Equipment

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Abstract- **Different materials—solid, liquid, and gaseous—are employed as insulation in high voltage electrical systems to guard against equipment failure. Because of the limitations of the production process, insulating materials typically always include certain contaminants. Additionally, these contaminants manifest as voids, fractures, poor conductor profiles, etc. It is frequently noted that there are air bubbles inside the insulating material, which is very undesirable as it creates a weak spot inside the insulator. Additionally, the insulation of high-voltage equipment eventually deteriorates as a result of the combined effects of chemical, electrical, and thermal stress. Therefore, a weak zone inside the insulator generates a partial discharge anytime high voltage stress occurs, which ultimately results in equipment damage.**

The PD activity of two distinct insulating materials— GLASS and GLASS PYREX—has been studied and compared in this work. An electrical circuit model is utilised for that. When the insulating material is subjected to a homogeneous electric field using a plane-plane electrode configuration, a tiny cylindrical void is assumed to be an impurity. Since the geometrical arrangement of the void substantially influences partial discharge, this analysis takes into account the relationship between apparent charge and void height and radius. Two solid insulating materials exhibit PD pulse magnitudes at various applied voltages. The MATLAB environment was used to complete the simulation.

I. INTRODUCTION

One crucial factor in assessing the effectiveness of power facilities is the electrical insulation of high-voltage power equipment [14]. HV power equipment is insulated using a range of insulating materials, including solid, liquid, and gaseous materials, as well as combinations of these [15]. Glass and Glass Pyrex are two examples of solid insulators that are frequently used in high-voltage power systems. Power engineers find it challenging to maintain the quality of such insulation because, in the manufacturing process, insulating materials frequently contain impurities in the form of cracks, voids (small air bubbles), poor conductor profiles, and other shapes. These impurities can be spherical, rectangular, cylindrical, elliptical, or any other geometric shape. Therefore, when high voltage stress is applied to such impurity-containing insulation, a weak spot inside the insulator is the cause of partial discharges, which gradually deteriorates the insulation quality utilised in high voltage equipment and ultimately results in equipment failure. Therefore, partial discharge detection and measurement are required to provide uninterrupted, dependable electric supply to consumers, including commercial, residential, and industrial.

Partial Discharge Basics

IEC (International Electro Technical Commission) standard 60270 defines a partial discharge as a localised electrical discharge that may or may not be next to a conductor and only partly bridges the insulation between conductors. Generally speaking, local electrical stress on the insulating surface causes partial discharges, which manifest as impulses, such as current and voltage impulses that last for less than a microsecond.

There are four different categories of partial discharges. a) Internal discharges: are the discharges located inside the dielectric volume in cavities or voids? b) Corona discharge: typically occurs when the field is not uniform. When the voltage is increased, the gas will initially experience a discharge at the sharpest points, where the electrodes are curved, or on

transmission lines. b) Surface discharge: took place at the dielectric material's contact, such as the gas/solid interface. D) Electrical stress discharge: This kind of discharge comes from a faulty point, such a metallic particle with a strong electric field, a tiny gas vacuum, or a sharp electrode edge. These discharges have the potential to produce ozone or UV radiation, which will then react with the surrounding dielectric substance and trigger breakdown, creating a new vacuum.

One of the primary causes of the continuous deterioration of electrical insulation and the equipment failure is the effect of partial discharge.

Electrical Equivalent Circuit for Partial Discharge Measurement

Figure 1 depicts the electrical equivalent circuit concept for partial discharge detection. It consists of a cylindrical void model of solid insulating material known as the test object (Ct), a measuring detector circuit (Zm), a measuring instrument (MI), a high voltage transformer (Vs), a high voltage measuring capacitor (Cm), a filter unit (Z), and a coupling capacitor (Ck). In order to measure PD, the parallel combination of resistor, inductor, and capacitor makes up the measuring detector circuit shown in this figure. ABC diagrams represent the solid insulating material's cylindrical void concept. The test item in this circuit indicates both the capacitance and the tiny capacitance. Ca stands for the capacitance of the remaining discharge-free insulation, Cb for the capacitance of the healthy dielectric in series with the cylindrical void, and Cc for the cylindrical void inside the solid insulating material. Additionally, when the AC voltage is applied to this circuit, the voltage across the cavity Cc is determined by
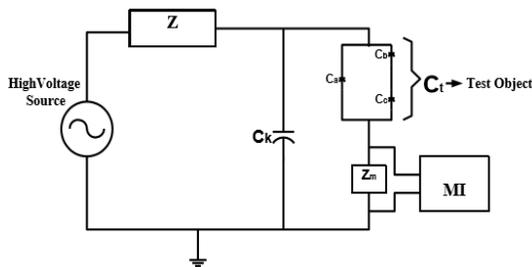

Figure 1. Electrical equivalent circuit model of cylindrical void in solid insulating material

$$V_c = V_a \times C_b / (C_a + C_b) \qquad (1)$$

where the voltages across Ca, Cb, and Cc are, respectively, Va, Vb, and Vc. During the PD activity within the solid insulator, the apparent charge "q" that accumulates across the test item is monitored. This q, which is observable at terminals A and B, is computed using the formula provided by [3].

$$Q = C_b \times V_c \qquad (2)$$

A. Pedersen has proposed a model based on the idea of induced charge (charges induced on the electrode terminals of the system), as capacitance models might produce very unsatisfactory results because they cannot account for all the pertinent empty factors [2]. This model allows the apparent charge q for a tiny cylindrical vacuum to be expressed as follows:

$$Q = S \times V \times \varepsilon_0 \times \varepsilon_r \times (E_i - E_l) \times \Delta z \qquad (3)$$

where $\varepsilon 0$ is the permittivity of the free space, εr is the relative permittivity of the dielectric, Ei is the inception field for streamer inception, El is the limiting field for ionisation, and delZ is the reciprocal of space between the two electrodes (1/d). Furthermore, S is the void geometric factor, and V is the volume of the cylindrical void, which is determined by the formula $\pi r2h$, where r is the radius and h is the height of the cylindrical void. As recommended by Pederson for non-attaching gases [2], the amount (Ei - El) can be computed using the following formula:

$$\frac{E_i}{p} = \frac{E_l}{p} \cdot \left(1 + \frac{B}{\sqrt{2ap}}\right) \qquad \dots (4)$$

Where B is constant characteristic of gas in the void, a is the radius of cylindrical void and p is the pressure of gas in the void.

$$E_l/p \text{ (for air)} = 24.2/pa.m. \qquad \dots\dots (5)$$

Table 1Parameters used for simulation of Partial Discharge

SI No.	Para-Meter	Symbol	Default Value	Dimension

1	Gap Spacing between electrodes	D	0.02	m
2	Relative Permittivity Of dielectric (for glass)	E_{r1}	3.5	
3.	Relative Permittivity Of dielectric (for glass Pyrex)	E_{r2}	4.8	
4	Permittivity of free space	ε_0	8.852 x 10^{-12}	F/m
5	Constant Characteristics of gas	B	8.6	$Pa^{0.5}\ m^{0.5}$
6	Pressure	P	10^5	N/m^2

Description of Simulink Model for Partial Discharge Detection

A basic dielectric test object or high voltage power equipment may be used as the test object. The electrical PD detection technique for the basic inquiry is based on the visibility of PD current or voltage pulse across the test object. In order to ascertain the basic parameters of a PD pulse, a basic capacitor-equivalent circuit with a cylindrical void is used for this task. The cylindrical vacuum located inside the solid insulation is represented by capacitance Cc in the equivalent circuit of a capacitor. The remaining series insulation with vacancy Cc is represented by Cb. Additionally, Ca stands for the capacitance of the remaining solid insulator's discharge-free insulation. According to the size of the void in solid insulating samples, such as glass and glass polymer, a cylindrical void with a height of 1 mm and a radius of 1 mm is used in a cube sample (30 x 30 x 30) in this model most of the time (Ca>>Cb>>Cc). As seen in the image below, the void is situated in the middle of the insulating sample.
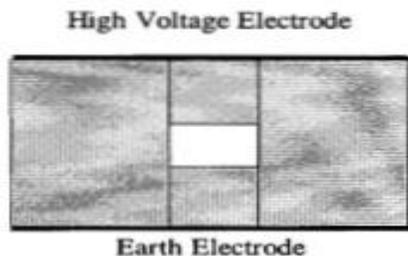

Figure 2 Solid dielectric with internal void

And the capacitance of the solid insulation sample is calculated by the formula:

$$C_a = \frac{\varepsilon_0 \times \varepsilon_r \times (a - 2b) \times b}{c} \qquad (6)$$

$$C_b = \frac{\varepsilon_0 \times \varepsilon_r \times r^2 \times \pi}{c - h} \qquad (7)$$

$$C_c = \frac{\varepsilon_0 \times r^2 \times \pi}{h} \qquad (8)$$

With the applied voltage of 5 KV and frequency of 50 Hz to the insulation sample, calculated value of capacitance is given by : $C_a = 9.2925 \times 10^{-13}$ F

$C_b = 3.595 \times 10^{-15}$ F

$C_c = 2.7803 \times 10^{-14}$ F

In this calculation the value of the high voltage equipment and the void model for measurement of PD has been taken as per the values shown in table 1 and table 2 respectively.

Table 2 Specification of Different Components and Their Values Used for Simulation

SI. NO.	COMPONENTS	VALUE/RATING
1	HV Transformer	0.23/5 KV,50 KVA
2	HV measuring capacitor	200/1500 pF
3	HV Coupling Capacitor	1000 μF
4	Detector circuit Resistance	50Ω
5	Detector Circuit inductance	0.63mH
6	Detector Circuit Capacitance	0.47μF

II.. RESULTS AND DISCUSSION

In order to investigate partial discharge activity in the cylindrical vacuum, two insulating materials— GLASS and GLASS PYREX—are utilised in this work. A high voltage of 0–30 KV is placed between the electrodes in order to examine the PD activity within the solid insulation model that was built because of the cylindrical void. Since the geometrical arrangement of the void in solid insulation strongly affects partial discharge, this research takes into account the relationship between apparent charge and void radius as well as void height.
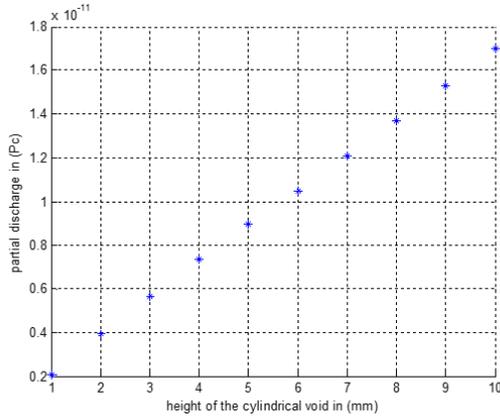
Fig 4.1 The relation between apparent charge and height of the cylindrical void

For GLASS

Fig 4.2 the relation between apparent charge and radius of the void

For GLASS

It is also studied that, since PD sources are not accessible so apparent charge is an important factor for the measurement of PD in high voltage power equipment. The relation between apparent charge and height of the cylindrical void is shown in fig 4.1 for GLASS. In this graph it is very clear that as we increase the height of the cylindrical void from 0.001 mm to 0.10 mm, the apparent charge will increase from 2.0583 PC to 16.99 Additionally, it has been established that apparent charge plays a significant role in measuring PD in high voltage power equipment since PD sources are not readily available. Figure 4.1 for GLASS illustrates the relationship between the height of the cylindrical void and perceived charge. It is evident from this graph that the apparent charge will rise from 2.0583 PC to 16.999 PC when the height of the cylindrical vacuum increases from 0.001 mm to 0.10 mm. Figure 4.3 illustrates that for glass pyrex, the apparent charge will rise from 8.8679 x 10-14 PC to 18.61 x 10-14 PC when the height of the cylindrical void increases from 0.001 mm to 0.10 mm. 9 PC. Figure 4.3 illustrates that for glass pyrex, the apparent charge will rise from 8.8679 x 10-14 PC to 18.61 x 10-14 PC when the height of the cylindrical void increases from 0.001 mm to 0.10 mm. The simulation results show a linear relationship between the apparent charge curve and the height of the cylindrical vacuum.
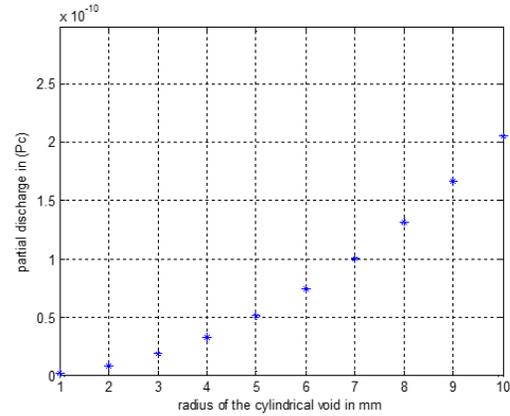
This paper also examines the relationship between the cylindrical void's radius and perceived charge. Figure 4.2 for glass makes it evident that the apparent charge will rise from 2.0583 PC to 205.83 PC when the void's radius increases from 0.001 mm to 0.10 mm. Similarly, for GLASS PYREX, as seen in fig. 4.4, the apparent charge will rise from 8.867 X 10-14 PC to 11965 x 10-13 when the radius of void increases from 0.001 mm to 0.10 mm. Thus, it is evident that in the cylindrical vacuum model, perceived charge likewise depends on radius. The simulation results also show that there is a linear relationship between the apparent charge curve and the radius of the cylindrical vacuum.
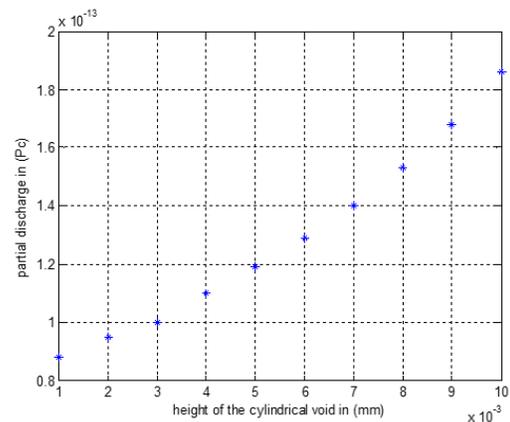

Fig 4.3 The relation between apparent charge and height of the void
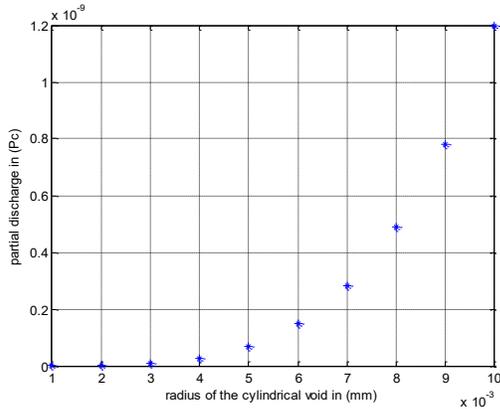
For GLASS PYREX

Fig 4.4 The relation between apparent charge and radius of the void

For GLASS PYREX

The amplitude of the PD pulse is determined by the following equation:

$$V = \frac{q}{C_a + C(1 + \frac{C_a}{C_k})} \times (e^{-t/2Rm}) \times \cos(\omega t)$$

4.1

Where V represents the amplitude of PD amplitude, q

$$w = \sqrt{\left(\frac{1}{Lm} - \frac{1}{4R^2 m^2}\right)}$$

denotes for apparent charge,

$$m = \frac{C_a \times C_k}{C_a + C_k} + c.$$

C_k denotes for coupling capacitor, Ca denotes the capacitance of rest of the discharge free insulation, Rm denotes for resistance of the detector circuit for the measurement of PD

In this study, a MATLAB Simulink model is taken into consideration inside the solid insulating medium to simulate the partial discharge activity. An rising voltage of 0–30 KV is supplied between the void models in order to detect the PD activity inside the solid insulator. It is believed that no partial discharge peak amplitude was discovered between cylindrical void models above the applied voltage of 5 KV. The field intensity within the void does not surpass the breakdown strength of the gas in the void below the applied voltage of 5 KV. Additionally, a modest partial discharge amplitude appears when the high voltage between the void model increases However, the existence of a cylindrical vacuum inside the solid

insulation causes the first peak amplitude to be detected at the applied voltage of 5 KV partial discharge. This indicates that the field intensity within the vacuum is greater than the gas breakdown strength at the applied voltage of 5 KV, and a partial discharge pulse is seen, as seen in fig. 4.6.
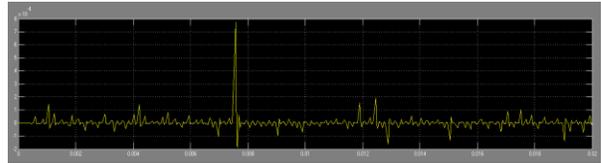

Fig 4.6 The observed partial discharge pulse at 5 KV (for glass)
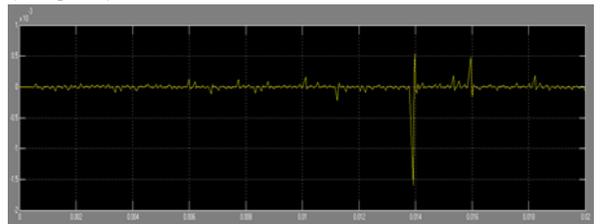

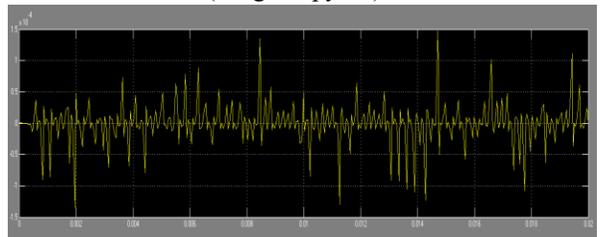Fig 4.7 The observed partial discharge pulse at 5 KV (for glass pyrex)

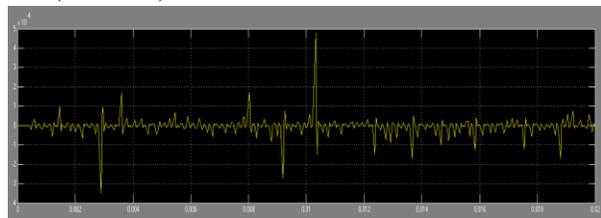Fig 4.8 The observed Partial Discharge pulse at 10 KV (for Glass)

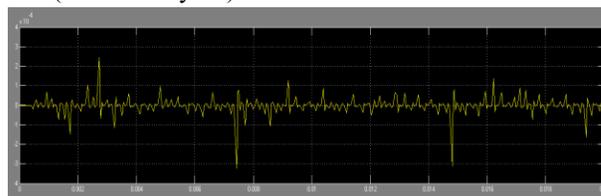Fig 4.9 The observed Partial Discharge pulse at 10 KV (for Glass Pyrex)

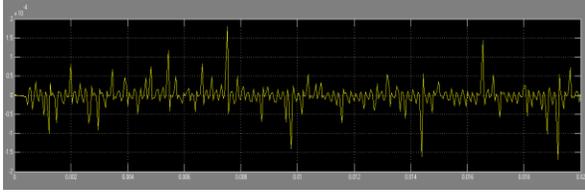Fig 4.10 The observed Partial Discharge pulse at 15 KV (for Glass)

Fig 4.11 The observed Partial Discharge pulse at 15 KV (for Glass Pyrex)

III. CONCLUSION

In a system with high voltage power the primary causes of insulation failure in high voltage power equipment are partial discharges, which must be closely watched to prevent an early power system network collapse. Here, a Simulink model based on MATLAB has been created to effectively explain the partial discharge activity inside the solid insulation. The overall shape of the void inside the solid insulation model (Glass and Glass Pyrex sample) has a significant impact on the PD activity inside the solid insulation. Additionally, when the applied voltage inside the solid insulation sample increases, so does the partial discharge. This article compares the change in air void geometry for high voltage power equipment with partial discharges in solid insulation (Glass and Glass Pyrex). For the same applied voltage and void structure, it is discovered that the glass sample exhibits a greater magnitude of partial discharge than the glass pyrex. Higher permittivity materials often have lower partial discharge initiation voltages. The properties of the produced PDs have been examined using the created SIMULINK model and the parameters that were computed for the Glass and Glass Pyrex samples. Additionally, power engineers will find this study very helpful in forecasting the quality of insulation used for high voltage power equipment. In order to determine the PD activity and create a comparison study of partial discharge, this current work can potentially be expanded in the future to include additional insulating materials that are often used in high voltage power equipment.

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