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Partial Discharge in Solid Insulating Materials, Causes, Effects and Factors of Dependence -A Comparative Investigation

[1] Isha Pandit, [2] Ashish Kumar Sinha, [3] Prashant Kumar, [4] Ananda Shankar Hati
[1] M.Tech Scholar, Department of Mining Machinery Engineering, IIT (ISM) Dhanbad, India
[2, 3] Research Scholar, Department of Mining Machinery Engineering, IIT (ISM) Dhanbad, India
[4] Assistant Professor, Department of Mining Machinery Engineering, IIT (ISM) Dhanbad, India

Abstract**: -- Widespread use of heavy duty machinery in industrial setup has rendered the power supply and insulation network highly prone to various types and degrees of damages depending on the type and intensity of workload. Insulation damages generally lead to the production of partial discharges. This may be effectively used for online monitoring of insulation plant thereby leading to a substantial decrement in the unwanted downtime. In this context, the present work explores the various causes associated with the incurrence of partial discharges in an insulation system and consequent effects of the same. Furthermore, a comprehensive investigation has also been done regarding the factors on which amplitude of partial discharges depend, namely, supply voltage variation, changes in dimension (i.e. size) of void or impurity in the solid dielectric and variation in the number of voids (i.e. an amount of impurity) in the solid dielectric. Finally, a comparative investigation is done using three solid dielectrics which are mainly used in industries, i.e. epoxy resin, dielectric paper, and porcelain. The present work is based on a complete analytical study with the partial discharge model being developed in MATLAB/Simulink using high tension system in the range of 6 kV to 25 kV.**

I. INTRODUCTION

Insulation plays a vital role in determining the performance of power equipment in the industry. Off-late electric utilities have encountered substantial problems due to the ageing and deterioration of the high voltage power equipment owing to insulation breakdown in their operating service period, resulting in cost inherent and time consuming maintenance [1]. Therefore, it is particularly necessary to protect these equipments for the reliable operation. This requires a-priory diagnosis and performance assessment of an insulation system. A wide variety of insulations (solid, liquid, gas) have been used in the power equipments and literature review reveals that solid insulating materials have been used in the bulk. Detailed classification of solid insulating materials is shown in Fig.1. Furthermore, of the various known mechanisms of prospective insulation breakdown, the presence of internal defects formed during insulation manufacturing process such as cavities, voids, cracks, joints and delamination are of major concern [2].

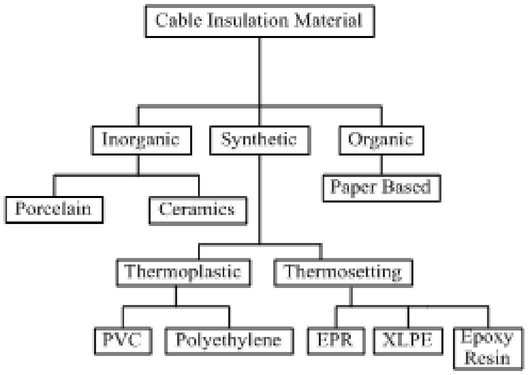

Fig.1. Types of solid insulating materials

These weak zones serve as an area for partial discharge (PD) to occur in material, which if persisted for long period of time, shall degrade the entire insulation [2]. As per the IEC (International Electro technical Commission) Standard 60270, Partial discharge is a localized electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor [3]. A sufficiently high value of electric field in the void (weak zone) and surpassing the breakdown strength of the gas in the cavity finally culminates into initiation of PD [4]. Under the influence of high electric field stress in the gas filled cavities (as the permittivity of void is less than the surrounding insulating material), the discharge initiates from one end of the defect and reaches the other end. Thus, PD only bridges the voids present and not the whole insulation. But in due course, repetitive discharges leads to progressive deterioration and huge energy loss in the system especially in the form of heat [5] [6] [7]. This thermal effect causes the insulation to deteriorate [8]. Further, during PD the gaseous environment changes its property from a non-conducting to a conducting one, thereby, resulting in the impulsive drop of electric field within the cavity [9]. The effect of PD within a cavity in high voltage insulation can be catastrophic and may conclude into fiasco of the entire system. Moreover, recurrence of PD causes progressive chemical deterioration of the insulating material. This chemical transformation may increase the conductivity of the cavity surface. This may further cause the pressure in the cavity to alter due to formation of gaseous by-products, subject to the gas content in the cavity and the material in the vicinity of the cavity [10]. Therefore, detection and quantification of PD is inevitable for safe, reliable and efficient functioning of power system [11]. Thus, the present work demonstrates analysis of the working behaviour of different solid insulating materials having void(s) in it. A high voltage ranging from 6KV-25KV is provided across the insulating material (epoxy resin, dielectric paper and porcelain), and magnitude of PD is recorded. Moreover, the dimension of void and the number of voids is increased, and the entire process is repeated. The entire analysis shall enable us to effectively design the insulation system of any power engineering equipment so as to detect and diagnose any disparity in the insulation system at an incipient stage. This will further aid in enhancing the production by achieving fault free working environment and reducing consequential damage. The present work is organized in five sections. Section 2 introduces the dependent factors which determine the prospect and extent of PD. Section 3 deals with the modelling of PD. Section 4 presents and encapsulates the results obtained for the tests run on different insulating materials having varying number and dimension of voids. Finally section 5 concludes the present work.

II. FACTORS AFFECTING PARTIAL DISCHARGE

The present section exhibits the dependent factors which influence the nature of dependence and the amplitude of partial discharge in a given insulating material.

2.1 Applied Voltage

An increase in the value of applied voltage enhances the amplitude of electric field which consequently increases the electron generation rate [12]. This causes an increase in PD magnitude. High voltages, generally ranging from 6kV to 25 kV are applied to the solid insulation model to observe PD activity due to the presence of void, and the same has been done in the present work to observe the PD characteristics using the MATLAB/Simulink.

2.2.Type of Insulating Material

An alteration in the nature of dielectric materials has an impact on the production of electric field due to the difference in the values of conductivity and permittivity of the different dielectric material which further has an impact on the nature and amplitude of PD [12].

In the present work, solid insulating materials like epoxy resin, dielectric paper, and porcelain have been investigated to observe the variation in PD.

Epoxy resin ($\varepsilon = 3.5$) is a thermosetting (irreversibly cured) compound which is extensively used in high voltage switchgear and insulation system of rotating machines [13].

Dielectric paper ($\varepsilon = 2.4$) is the most primitive and reliable insulating material used in high voltage cables. It is generally impregnated with a dielectric fluid (oil resin or synthetic fluid) so as to overcome the porosity issues [13].

Porcelain ($\varepsilon = 6$) is type of ceramic product which is baked at high temperatures to get vitreous properties (translucence and low porosity) which enables the excellent insulation characteristics of the same.

These dielectric materials are simulated using MATLAB/Simulink to observe the variation of PD for each of the different materials used in the sample model.

2.3 Variation In Void Size

In the insulation of power equipment, voids are one of the key factors which cause PDs. The variation in the size of these voids has prodigious influence on the characteristics of PD [14]. The lifetime of insulation depends on the size of void which is generally in inverse proportion, i.e. smaller size of void takes longer time to impair the insulation [12]. The behaviour of PD with different void size is also observed using MATLAB/Simulink in the present work.

III. PARTIAL DISCHARGE MODEL

The present section presents the model developed in MATLAB/Simulink for the measurement of PD for varying conditions, i.e. changes in the supply voltage, number and size of voids and for different dielectric materials as encapsulated in the previous section.

3.1. Electrical Equivalent Circuit for PD Measurement

As per the IEC (International Electro technical Commission) Standard 60270 [3], the equivalent circuit of a PD model consists of high voltage source, test object (a-b-c model), and a measuring instrument (MI). An insulation sample of epoxy resin, dielectric paper and porcelain of dimension (38×38×7.5) mm^3 are considered in the present work. Furthermore, a cylindrical void of radius (r) 3mm and height (h) 6mm is used as an impurity in the dielectric material.

Since, it is difficult to measure PD directly; therefore, apparent charge method is used in the present work. According to IEC Standard 60270, "*Apparent charge "q" of a PD pulse is that unipolar 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* [3].

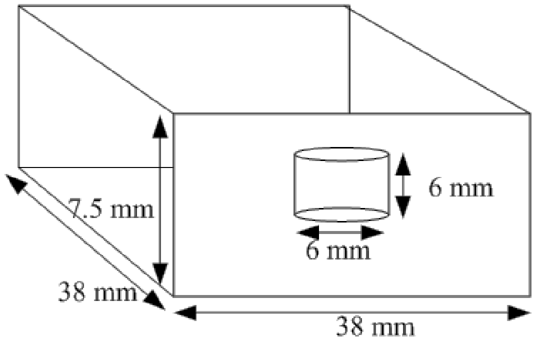

Fig.2. Cross-sectional view of the dielectric material

Therefore, electrically the whole sample can be represented by three-capacitor circuit model or `a-b-c' model representing an isolated cavity within a dielectric material as shown in Fig.2. [15], value of which can be calculated using (1)-(3) as,

$$C_a = \frac{\varepsilon * \varepsilon_r * (a-2r) * b}{c} \quad (1)$$

$$C_b = \frac{\varepsilon * \varepsilon_r * r^2 * \pi}{h} \quad (2)$$

$$C_c = \frac{\varepsilon * r^2 * \pi}{h} \quad (3)$$

$$(C_a >> C_b >> C_c)$$

Where, C_c is the cylindrical void present inside the solid insulation, C_b is to the capacitance of the remaining series insulation with the void C_c, C_a corresponds to the capacitance of the remaining discharge-free insulation of the rest of the solid insulator, *a* is length of the insulation sample, *b* is the width of the insulation sample, *h* is the height of void, and *r* is the radius of void [16].

Furthermore, voltage across the cubical void V_c is given by

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

The apparent charge transferred is calculated by [17]

$$Q = C_b * V_c \quad (5)$$

Here, high voltage source acts as the input which has low degree of background noise [18].

The coupling capacitor (C_k), as shown in Fig.3, returns a lower level of PD at a particular applied voltage when connected in series with the measuring system. This is highly undesirable practically. Therefore, for achieving a higher level of partial discharge, C_k and the measuring system must be connected separately while the measuring system is connected in series with the test object, as is shown in Fig.3.

In Fig.3, R_m, L_m, and C_m (Z_m) are the input impedances for the measuring system (3-phase R-L-C parallel branch). It determines the wave shape of the PD pulse. Furthermore, the test object (i.e. the a-b-c model) consists up of three capacitors: one connected in parallel with the other two which are connected in series. A measuring system is used to measure the PD pulses produced due to presence of void inside the test object. C_m is the measuring capacitor. When high voltage is applied across the test object, voltage across the dielectric V_a is rises in such a manner that there is a corresponding increase in voltage V_c across C_c. When V_c exceeds the inception voltage, which is the voltage across the sample at which discharges begin to occur, there is an off-set of PD in the void(s) [19]**.**

An occurrence of discharge bypasses C_c. This causes flow of a fast transient current in the circuit because of the voltage difference between the voltage source and voltage across C_b. Despite being simple, the present model can conveniently represent the transient state of the discharge event, i.e. the PD current pulse and apparent charge magnitude. These are represented as a function of time, which results from a voltage across the cavity due to discharge.

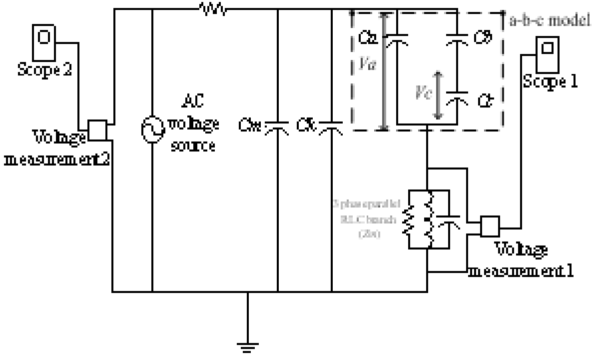

Fig.3. MATLAB Simulink model for PD measurement

Parameters Used For Simulation

Table 1 encapsulates the various parameters used for the design of simulation model as depicted in Fig. 3.

Table1 Parameters used for the design of simulation model of PD measuring circuit

PARAMETERS	SYMBOL	VALUE	UNIT

HV MEASURING CAPACITOR	C_m	1000	pF
COUPLING CAPACITOR	C_k	1000	pF
PERMITTIVITY	ε	8.85×10^-12	F/m
RELATIVE PERMITTIVITY	ε_r	Epoxy resin- 3.5 Dielectric Paper- 2.4 Porcelain-6	
RESISTANCE	R_m	50	Ω
INDUCTANCE	L_m	.6	mH
CAPACITANCE	C_m	.45	µF
Series Resistance	R	.0000001	Ω

IV. RESULTS AND DISCUSSION

The present section presents the results and discussions of the corresponding outcomes obtained when a high tension (HT) voltage in the range of 6 kV to 25 kV is applied across the solid insulation and maximum amplitude of PD pulses obtained under aforementioned circumstances.

Fig.4 shows the PD pulse, maximum output for an input voltage of 10 kV as and when it occurs inside the void of solid insulation, epoxy resin in the present case. A clear increase in the amplitude of PD is further recorded on the increase of supply voltage up to 25 kV, as can be seen from Table 2 to Table 6.

Furthermore, similar tests have also been carried out using dielectric paper and porcelain as an insulating medium and the results of PD output are shown Table 2 to Table 6.

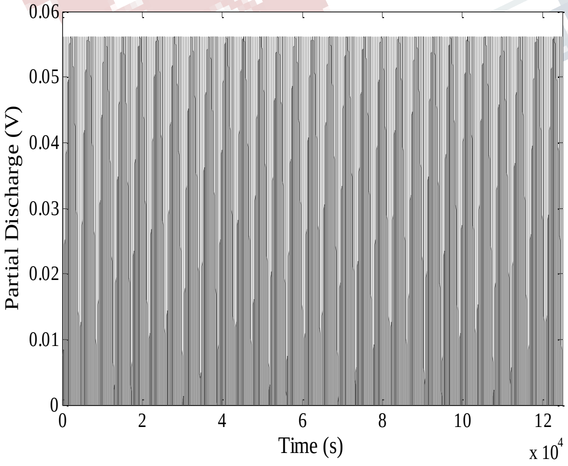

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Fig.4. PD amplitude for a. epoxy resin, material having single void subjected to 10kV.

The results as Tabulated in Table 2 to Table 6 have further been encapsulated graphically in Fig.5.

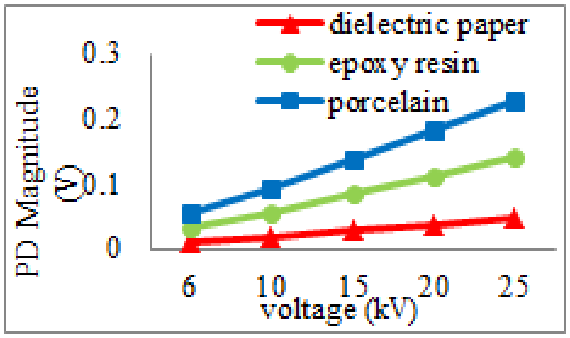

Fig.5. Variation of PD magnitude with voltage for epoxy resin, dielectric paper & porcelain.

Based on the interpretation of Fig.5, it is concretified that there is a definite increase in the amplitude of PD with an increase in the amplitude of supply voltage. While the results shown in Fig.4 and Fig.5 are for an impurity of dimension 3mmx6mm, it is essential to study the changes in the amplitude of PD for a certain insulating material when the size of impurity present in the void changes. In the present work, the void dimensions have been varied in the range of 3mmx6mm to 3.4mmx6.4mm and the results have been recorded correspondingly. Fig.6 shows the PD output waveform for epoxy resin as an insulating material for a void size of 3.2mmx6.2mm for a supply voltage of 10 kV.

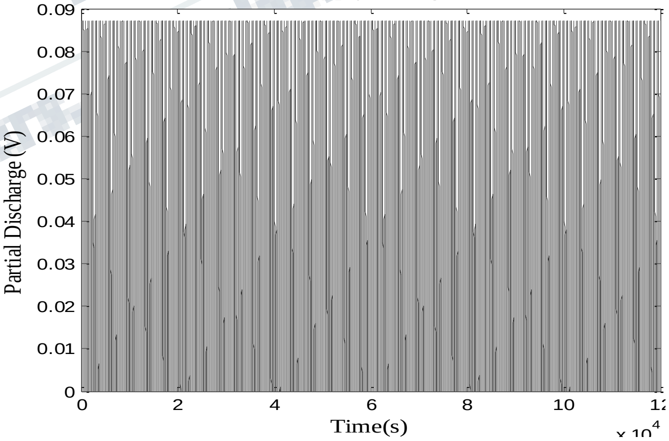

Fig.6. PD amplitude with epoxy resin paper insulating material having single void subjected to 10kV with increased dimension of 3.2×6.2 mm.

From the results depicted thus far, it is concluded that the value of PD amplitude increases with increase in the dimensions of impurity present in the dielectric. Further experiments have also been carried out for an increase in void size up to 3.4mmx6.4mm for different solid dielectrics and the results are represented graphically in Fig.7.

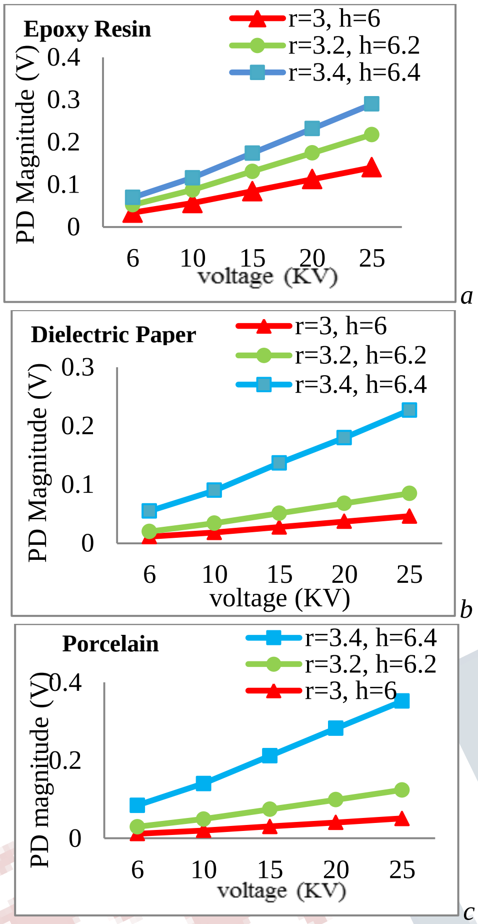

Fig.7. PD magnitude variation with varying dimensions of one void for a. epoxy resin, b. dielectric paper, and c. porcelain.

The results, as shown in Fig.7 clearly suggest that there is a definite increase in the amplitude of PD for an increase in the dimensions of the impurity. Furthermore, it is also seen that porcelain returns the maximum value of PD as compared to epoxy resin and dielectric paper when subjected to similar supply voltage and size of impurities.

Moreover, further tests have also been carried out for the same materials with increased number voids (up to 2 nos. of voids). Fig.8 shows the PD of epoxy resin for a 2 nos. of voids having dimensions of 3mmx6mm for a supply voltage of 10 kV. Furthermore, similar tests have also been carried out for dielectric paper and porcelain as insulating materials and the results thus obtained for PD amplitude have been represented graphically in Fig.9. A close observation of Fig.9 reveals that the magnitude of PD exhibits a gradual increase with increase in the number of voids (i.e. increase in the level of impurity). Furthermore, it is also observed that value of PD is lesser for the case of porcelain as compared to the corresponding values of other dielectric materials. This difference is even more evident for the presence of higher impurity levels in the dielectric as compared to the lower values of the same.

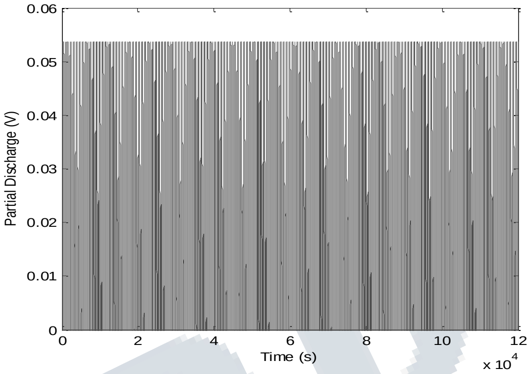

Fig.8. PD amplitude with epoxy resin insulating material having two voids subjected to 10kV.

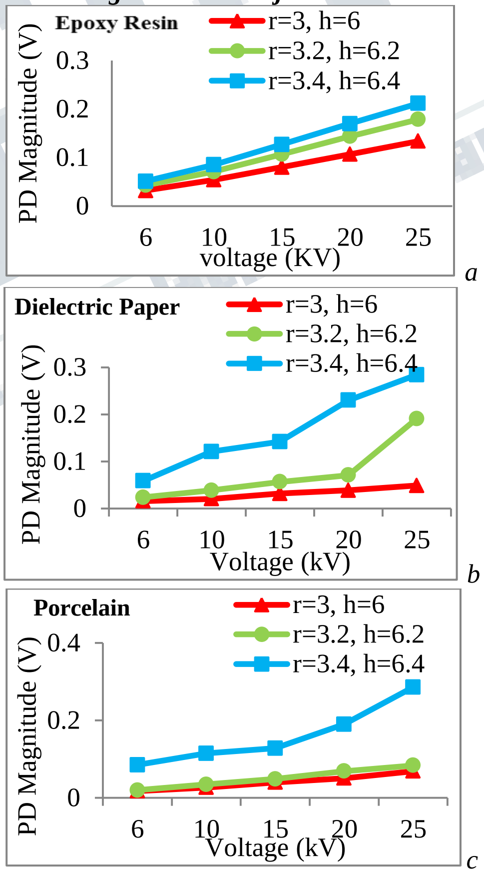

Fig.9. PD variation for a.epoxy resin, b.dielectric paper, and c.porcelain with two voids & varying dimensions and voltage.

These results are further encapsulated in Table 2 to Table 6. They further highlights the claims made thus far.

Table 2 PD for different dielectric materials with varying size and number of voids at 6 kV supply voltage

	6 kV SUPPLY VOLTAGE					
	1 VOID			2 VOIDS		
Dimension (mm)	3x6	3.2x6.2	3.4x6.4	3x6	3.2x6.2	3.4x6.4
Epoxy Resin	0.034	0.0523	0.0695	0.038	0.059	0.072
Dielectric paper	0.011	0.02	0.055	0.016	0.024	0.059
Porcelain	0.01	0.02	0.01	0.018	0.02	0.09

Table 3 PD for different dielectric materials with varying size and number of voids at 10 kV supply voltage

	10 kV SUPPLY VOLTAGE					
	1 VOID			2 VOIDS		
Dimension (mm)	3x6	3.2x6.2	3.4x6.4	3x6	3.2x6.2	3.4x6.4
Epoxy Resin	0.056	0.087	0.116	0.058	0.091	0.123
Dielectric paper	0.018	0.034	0.09	0.021	0.0388	0.121
Porcelain	0.02	0.03	0.134	0.027	0.04	0.12

Table 4 PD for different dielectric materials with varying size and number of voids at 15 kV supply voltage

	15 kV SUPPLY VOLTAGE					
	1 VOID			2 VOIDS		
Dimension (mm)	3x6	3.2x6.2	3.4x6.4	3x6	3.2x6.2	3.4x6.4
Epoxy Resin	0.09	0.131	0.174	0.08	0.121	0.184
Dielectric paper	0.028	0.051	0.1368	0.032	0.057	0.142
Porcelain	0.03	0.05	0.02	0.04	0.05	0.13

Table 5 PD for different dielectric materials with varying size and number of voids at 20 kV supply voltage

	20 kV SUPPLY VOLTAGE					
	1 VOID			2 VOIDS		
Dimension (mm)	3x6	3.2x6.2	3.4x6.4	3x6	3.2x6.2	3.4x6.4
Epoxy Resin	0.1124	0.18	0.232	0.127	0.184	0.24
Dielectric paper	0.04	0.07	0.18	0.039	0.071	0.23
Porcelain	0.04	0.06	0.027	0.05	0.07	0.19

Table 6 PD for different dielectric materials with varying size and number of voids at 25 kV supply voltage

	25 kV SUPPLY VOLTAGE					
	1 VOID			2 VOIDS		
Dimension (mm)	3x6	3.2x6.2	3.4x6.4	3x6	3.2x6.2	3.4x6.4
Epoxy Resin	0.1405	0.218	0.29	0.144	0.279	0.292
Dielectric paper	0.05	0.09	0.227	0.049	0.191	0.28
Porcelain	0.05	0.07	0.034	0.069	0.084	0.29

V. CONCLUSION

Healthy working of insulation is indispensable for achieving a fault free working environment. In this regard, the present work showcases the behaviour of three different insulating materials namely epoxy resin, dielectric paper and porcelain in terms of partial discharge magnitude. Additionally, partial discharge magnitudes for the above mentioned solid dielectrics are also tested under varying conditions of supply voltage, void size and quantity. Based on the results obtained is finally concluded that the magnitude of partial discharge shows direct dependence on supply voltage. Furthermore, an increase in the dimensional statistics of the void (i.e. impurity in the dielectric) reflects as an increase in the magnitude of partial discharge. Finally, a quantified increase in number voids also result in an increase in amplitude of partial discharge. It is also concluded based on the present work that porcelain as a dielectric material is more desirable in places prone to higher impurity levels. The present work intends to provide a bird's eye view to prospective readers so as to comprehend the topic at hand.

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