Modeling and Simulation of Partial Discharge Measurement for Defected Solid Dielectrics

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Abstract

Insulation system in high voltage power equipment is critical to the electric power system's reliability. As a result, it's important to evaluate its functioning in order to avoid the power system outage. The most essential phenomenon to be measured in the performance assessment of insulation diagnostics is partial discharge (PD). PD in solid dielectrics could occur due to the presence of a cavity or a crack within the insulating material which could be formed during manufacturing, installing or/and operating conditions. Since internal cavities are the main source of the PD activities, insulation system degradation could be happened. Consequently, a complete failure may be occurred. In this paper, PD simulation model is performed on a rubber insulating material with a changeable diameter of artificial cylindrical cavity. A COMSOL Multiphysics software is introduced as a Finite Element Analysis (FEA) tool for PD simulation model interlinked with MATLAB software in order to investigate the influence of cavity geometry on the PD behavior in the insulating material. Simulated results indicated that PD magnitude is strongly depending on changing the cavity size inside the insulating material.

Keywords: Partial discharge; Solid dielectrics; Cavity; Modeling; COMSOL Multiphysics

1 Introduction

Partial discharge (PD) is an internal or external electric spark occurrence that does not pass the distance among electrodes inside an electrical insulating material during electric field strength [1]. PD usually happens due to several defects such as internal small voids, cavities, or cracks inside the insulating material formed during the manufacturing process or during the operating service under electrical stress for a long term. Under operating conditions, the electric field inside the gaseous cavities exceeds the field of the insulating material and this returns to the higher permittivity of that dielectric material [2]. PD may occur if the electric field of the gaseous air in the void is enough to be large and the strength of the gas inside the void is increased [2-4]. During PD occurrence, the gas-filled cavity converts its insulation property to a conducted material causing decreasing the electric field inside the cavity to a lower value in a very small duration of time [5]. Since internal voids or cavities are the main sources of PD events, insulation degradation in the system could be happened and hence, a complete failure may be occurred [6]. As a result, monitoring of PD activities is very significant tool for evaluating the performance of the insulating system.

Several experimental detection methods have been used on the basis of both electrical and non-electrical techniques for detection, analyzing, and estimation of PD activities in solid dielectrics as described in [7, 8]. On the other hand, there are PD models that have been introduced to study the PD performance inside cavities in insulating materials. The abc-model is a traditional model that was used for simulation and modeling of PD mechanism inside solid dielectrics. In this model, the insulating material and the cavity are represented as capacitors [9]. Although this model has been used to clarify some observed experimental data, it is not realistic in describing the cavity discharge process [9, 10]. Recently, with emerging modern technology and upgrading of PD software models, Finite Element Analysis (FEA) software programs have been developed to model the PD behavior inside the dielectric materials and to understand the PD phenomena more deeply. This advanced tool is widely used for modeling of PD based on the geometry and the size of the cavity in solid dielectrics [1, 2, 6, 9, 11, 12, 13, 14]. The model introduced in [6] studied the PD events within a spherical cavity at variable applied voltages and frequencies and the simulated results were compared to the experimental data. In addition, the model developed in [1] studied the PD behavior on a cylindrical cavity within polycarbonate plates. Moreover, authors in [15] have developed a transmission-line matrix (TLM)-based simulation useful to investigate PD events in a transmission line. The proposed approach allows the predicting of the electromagnetic disturbances generated by the PD event, and the analysis of external field coupling, such as from intentional electromagnetic interference or lightning, which can add to the field stresses [15]. However, there is a shortage of usage of this advanced model on some applications such as outdoor insulators due to their complicated geometry as some researchers have studied only the distribution of electric field and electric potential on high voltage outdoor insulators [16-17].

In this work, a PD simulation model is performed on a rubber solid dielectric material with variable cylindrical cavity diameters. A COMSOL Multiphysics software is used as a FEA tool which is interfaced with MATLAB program software to simulate and model the PD events resulting from the cavities inside the rubber insulating material.

State the objectives of the work and provide an adequate background related to your work, avoiding a detailed literature survey or a summary of the results.

2 Materials and Methodology

In this study, a rubber dielectric sample is the test object. The samples under test were prepared with 5 cm diameter and 5 mm thickness as cleared in Figure 1(a). In order to obtain PD sources in the test samples, cylindrical cavities were introduced in the rubber samples with variable diameters as 2 mm, 4 mm, 6 mm, and 8 mm.

A model of PD is introduced using COMSOL Multiphysics program as a FEA tool which interfaced with MATLAB software. The geometry of the model is carried out in two dimensional (2D) axial symmetric depending on the test object of Figure 1(a). The model consists of four main parts; a homogenous insulation material (rubber), a cylindrical cavity with 2 mm, 4 mm, 6 mm, and 8 mm diameters, a cavity surface of 0.1 mm thickness, and two copper electrodes as cleared in Figure 1(b).

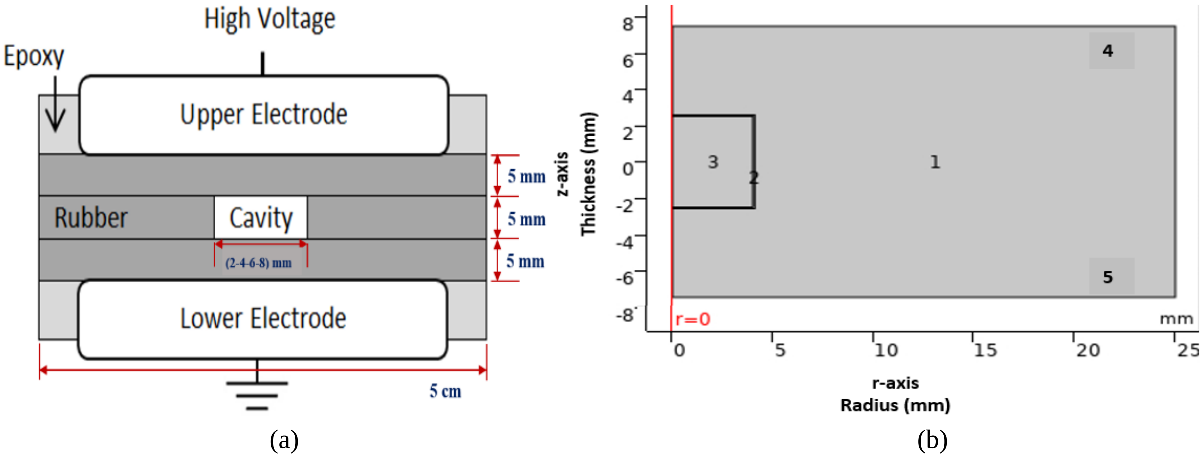


Figure 1: (a) Schematic diagram of PD model with cylindrical cavity, and (b) 2D geometry of the model in COMSOL program (1: insulation material, 2: cavity surface, 3: cavity, 4: potential electrode, 5: grounded electrode)

After adding the data for all used materials from COMSOL library or by manual, boundaries for each section are created. The upper copper electrode is set as boundary potential (V= Vapp. Sin (100πt)) and the lower electrode is set as boundary ground (V = 0). After that, the meshes in the model are refined to obtain more accurate results [2].

In this model, it is assumed that the insulation material (rubber) is homogeneous and the PD events occur at the cavity center due to the strongest concentration of the electric field inside the center of the cavity [2, 11]. The electric potential and electric field distributions through the developed model are solved by equation (1) [1, 11, 14] by choosing ‘electric current (ec)’ from ‘AC/DC module’. For sinusoidal applied voltage, time dependent study is selected to be used for solver settings.

$$\nabla \cdot \left[-\sigma\nabla V - \frac{\partial}{\partial t}(\varepsilon_o \varepsilon_r \nabla V) \right] = 0 \qquad (1)$$

Where: V is the electric potential, σ is the conductivity, ε_o is the vacuum permittivity, and ε_r is the relative permittivity.

3 PD Conditions

In this model, two necessary conditions are required for PD occurrence in a cavity [1, 2, 9, 11, 12, 14, 18, 19]; the first condition is the electric voltage in the void shall be greater than the intensity of the breakdown of the gas which corresponds to the cavity inception voltage (V_{inc}), and the second condition is that free electrons must be available enough inside the cavity to start an electron avalanche process. So, the first condition can be achieved by testing that the cavity voltage (V_{cav}) is greater than the voltage inception (V_{inc}) that required to initiate PD event. For the second condition, free electrons in the cavity in this study are obtained only from cavity surface emission as in [1, 1١] depending on the electron generation rate (N_e) according to equation (2) [1, 11, 14].

$$N_e(t) = N_{e0}\exp(|V_{cav}(t)/V_{inc}(t)|) \qquad (2)$$

Where: V_{cav} is the voltage across the cavity center, V_{inc} is the inception voltage to initiate PD event, and N_{e0} is a constant.

Expression (2) is very simple for electron generation rate based on Ritchardson-Schottky law [14, 20]. Sometimes the number of free electrons is poor for starting electron avalanche. So, the electron generation rate and PD occurrence are considered as a stochastic process [1]. Consequently, the probability (P) of generating a free electron in the cavity in a time step (dt) is assumed to be $N_e(t)dt$ according to equation (3) [1, 11, 14].

$$\mathrm{P} = N_e(\mathrm{t})dt \qquad (3)$$

Then the obtained value can be compared to a random number (R) which is distributed between 0 and 1 (0< R < 1). At each time step there is a possibility of PD occurrence if $V_{cav} > V_{inc}$ and P > R.

Since the time of the discharge is very short almost in a few nanoseconds, the electric potential in the cavity drops sharply within a short time period [11]. After a PD event, the electric potential in the cavity is decreased causing the free electrons to lose their accelerated energy and the conductivity and the current decrease in the cavity. When the electric voltage in the cavity reduced to become less than the extinction voltage (V_{ext}), the PD activity stopped [2].

In this current study, PD activity in the cavity is modeled dynamically by increasing the conductivity of the cylindrical cavity according to equation (4) [1, 14].

$$\sigma_{cav} = \begin{cases} \sigma_0 \boldsymbol{e}^{\left(\left|\frac{V_{cav}}{V_{inc}}\right| + \left|\frac{I_{cav}}{I_0}\right|\right)} & \mathit{during\ discharge} \\ \sigma_0 & \mathit{no\ discharge} \end{cases} \qquad (4)$$

Where: σ_0 is the initial cavity conductivity at no discharge, I_{cav} is the current across the cavity and I_0 is the initiating current at an electron avalanche onset

The current in the cavity during discharge can be calculated according to equation (5) [1, 14].

$$I_{cav} = \begin{cases} \iint \boldsymbol{J.ds} & \mathit{during\ discharge} \\ 0 & \mathit{no\ discharge} \end{cases} \qquad (5)$$

Where: $\boldsymbol{J}$ is the current density through the cavity.

Finally, the physical charge value (q) due to PD event is calculated according to the equation (6) [2, 14].

$$q = \int_t^{t+dt} I_{cav}(t)\, dt \qquad (6)$$

Figure (2) shows a flow chart of the modeling PD steps from preparing COMSOL interfaced with MATLAB software to obtaining the charge magnitude across a certain number of cycles.

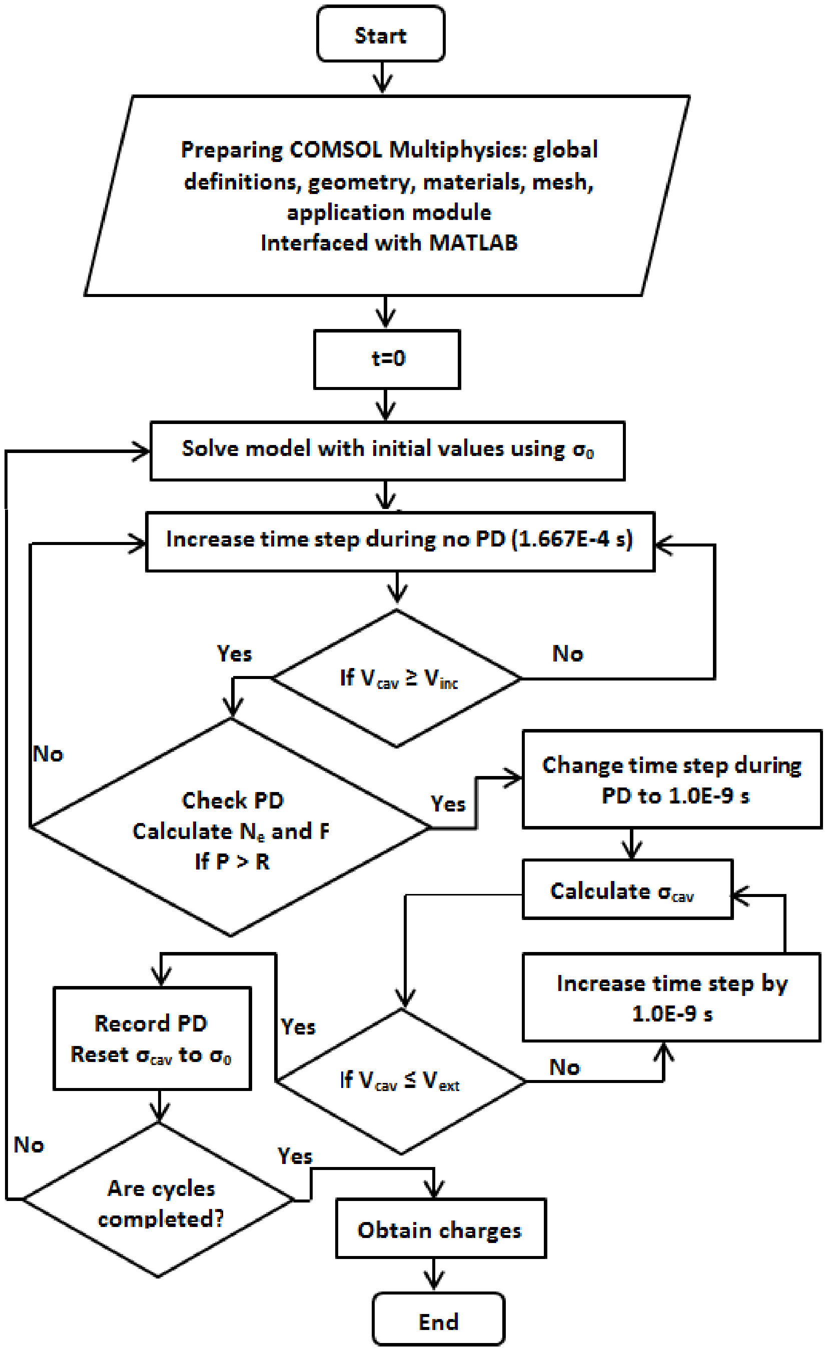


Figure 2: Flowchart model steps

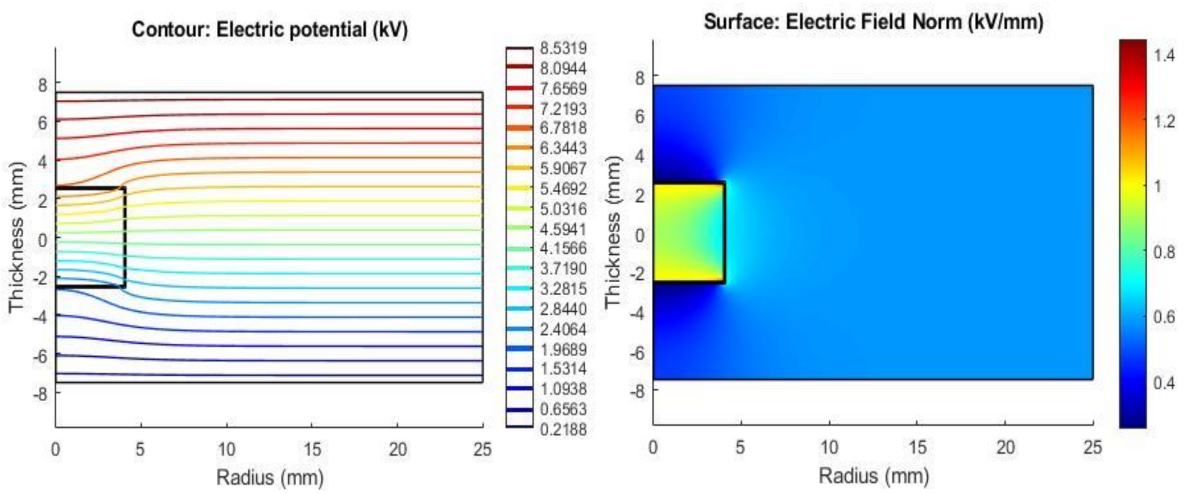
4 Results and Discussion

The parameters that used in this model are assumed as shown and described in Table 1 represented in a MATLAB interactive menu at the beginning run of the model. Also, it has been assumed that the inception voltage is to be around 5.45 kV, 5.23 kV, 5.01 kV, and 4.82 kV for cavity diameters 2 mm, 4 mm, 6 mm, and 8 mm respectively.

Table 1: *Definition of Used Parameters in the Model.*

Symbol	Value	Description
V_{app}	30 kV	Test voltage
f	50 Hz	Rated frequency
V_{ext}	2 kV	Extinction voltage
E_{mat}	4	Relative permittivity of dielectric material
E_{rcav}	1	Cavity permittivity
E_{rs}	4	Cavity surface permittivity
E_{cu}	1	Copper permittivity
S_{mat}	1×10^{-13} S/m	Conductivity of rubber material
S_{cav}	1×10^{-15} S/m	Cavity conductivity
S_s	1×10^{-13} S/m	Conductivity of cavity surface
S_{cu}	5.813×10^{7} S/m	Conductivity of copper
S_{cavmax}	1×10^{-4} S/m	Max. cavity conductivity
N_{e0}	650 1/s	Initial electron generation rate
I_0	1×10^{-10} A	Initiation current at an electron avalanche onset

Figures (3-6) show the distribution of the electric potential and electric field in the rubber material and the cavity in case of 8 mm diameter, for example, before and after the occurrence of PD in the cavity. It has been observed from Figure (3) that the electric field inside the cavity is larger than that in the surrounding rubber material because of the higher dielectric constant of the rubber material. Therefore, the electric field on the top and bottom of the surface wall of the cavity nearest to the electrodes is low because the applied electric field is perpendicular to the surface of the cavity [2]. This observation can be noticed from Figure (4) which shows the electric field performance through the z-axis (thickness) before PD event.



(a) (b)

Figure 3: (a) Electric potential and (b) electric field distribution before PD event.

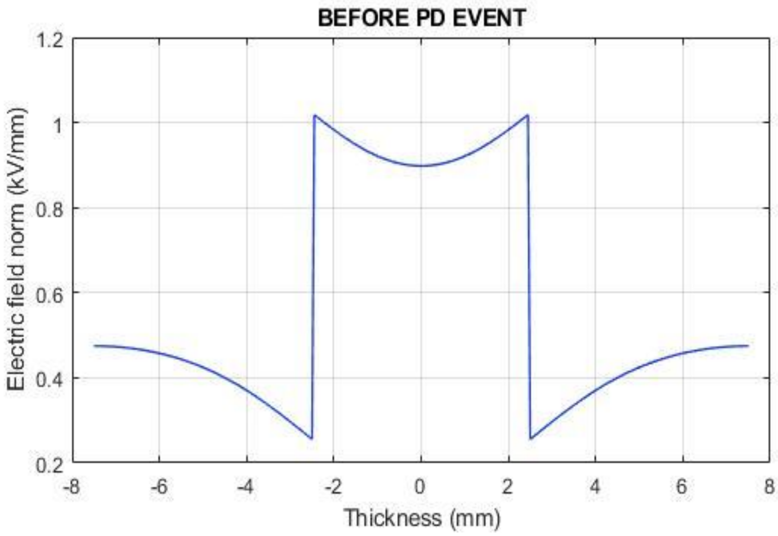
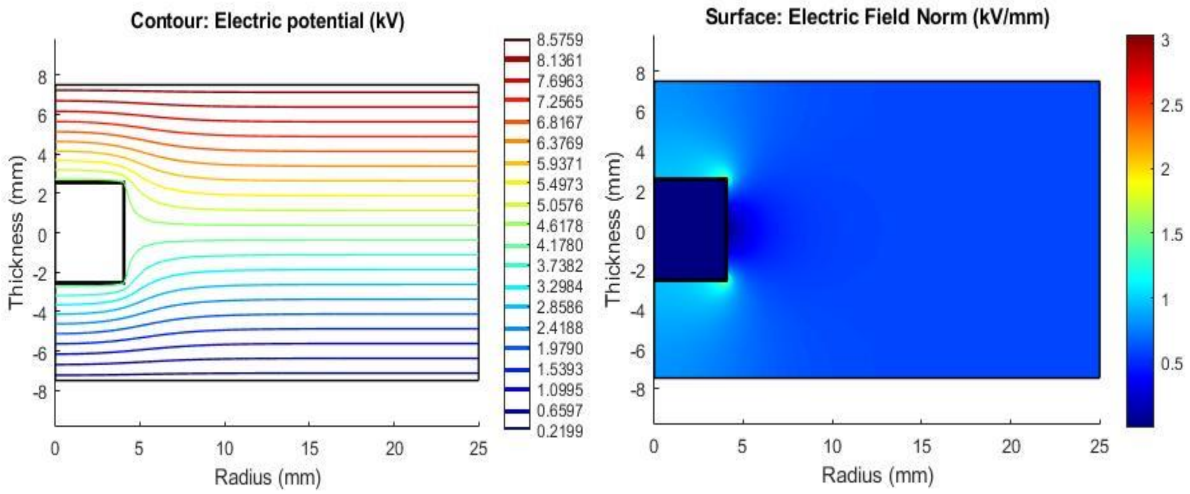


Figure 4: Cross-section plot of the electric field along the z-axis (thickness) before PD event

Furthermore, in Figure (5) after PD occurrence, the electric field across the cavity seems to be less than that of the surrounding rubber material because of the dynamic motion of electrons inside the cavity [2]. In addition, the electric field on the top and bottom of the cavity surface closest to the electrodes is high. This can be also observed from Figure (6) showing the electric field behavior through the z-axis (thickness) after PD event.

After PD occurrence, charges accumulate on the surface wall of the cavity producing an opposite electric field which decreases the electric field inside the cavity [2].



(a) (b)

Figure 5: (a) Electric potential and (b) electric field distribution after PD event.

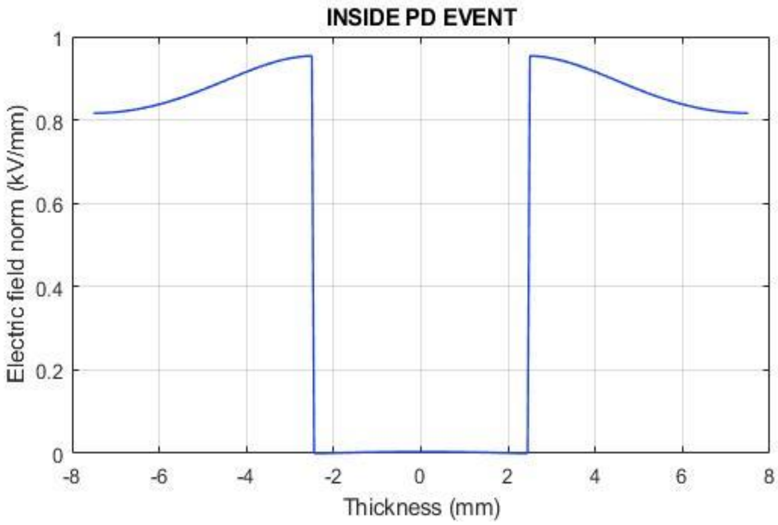


Figure 6: Cross-section plot of the electric field along the z-axis (thickness) after PD event

Figures (7-10) show the simulation of V_{app}, V_{cav}, V_{inc}, V_{ext}, and charge magnitude against the phase angle during one cycle for 2 mm, 4 mm, 6 mm, and 8 mm cavity diameters. Initially, the cavity voltage starts from zero with the applied voltage, and then it exceeds as the applied voltage increases. When the cavity voltage arrives to the inception voltage and more released electrons are available radiated from the surface of the cavity, the PD can occur. Immediately after PD occurrence, the cavity voltage drops sharply until reaching to the extinction voltage where the discharge stops. Increasing the cavity conductivity causes the voltage inside the cavity again to be increased and the discharges repeated. It has been seen from these figures that, PD occurs immediately when the cavity voltage reaches to the inception voltage due to the availability of free electrons for a PD to occur. This process is repeated in the two half cycles of the applied voltage and continues untill stopping the applied voltage. Therefore, increasing the cavity diameter increases the PD repetition rates of occurrence and increases the maximum PD magnitude. Also, it has been observed that with increasing cavity diameter, PD occurs at earlier time and this returns to the availability of electrons from the cavity surface at earlier time.

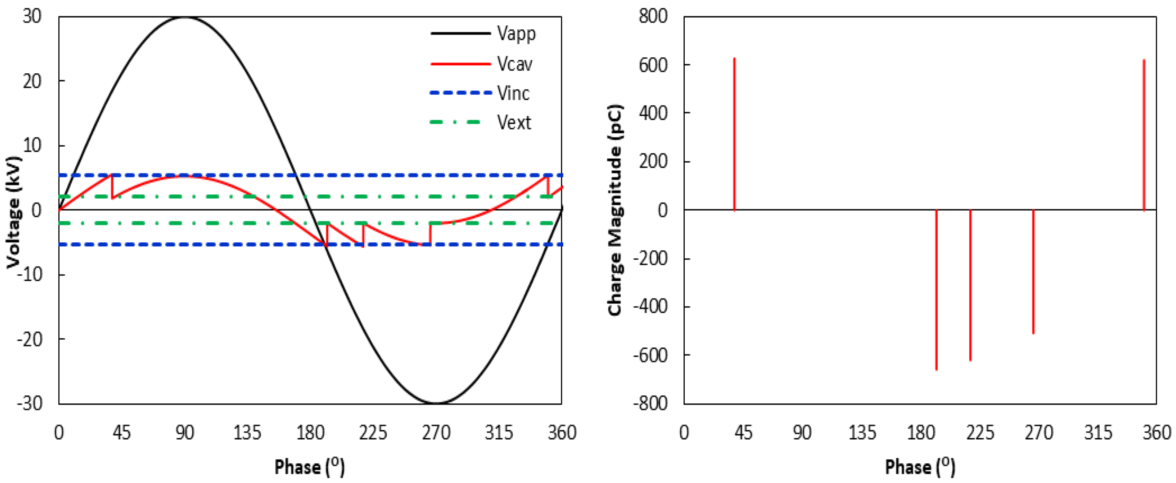


Figure 7: Voltage at cavity and PD magnitude with phase angle for one-cycle at 2 mm cavity diameter

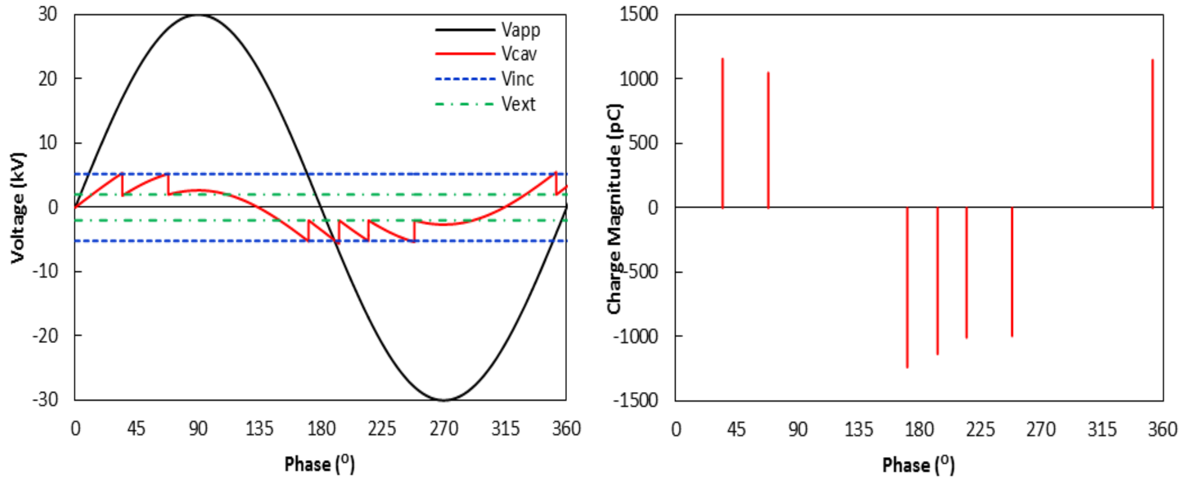


Figure 8: Voltage at cavity and PD magnitude with phase angle for one-cycle at 4 mm cavity diameter

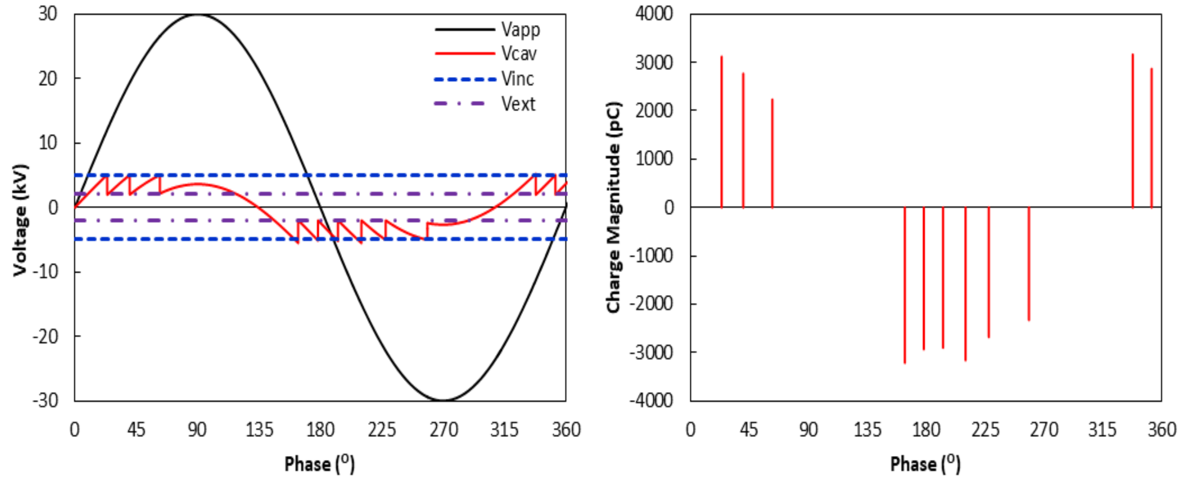


Figure 9: Voltage at cavity and PD magnitude with phase angle for one-cycle at 6 mm cavity diameter

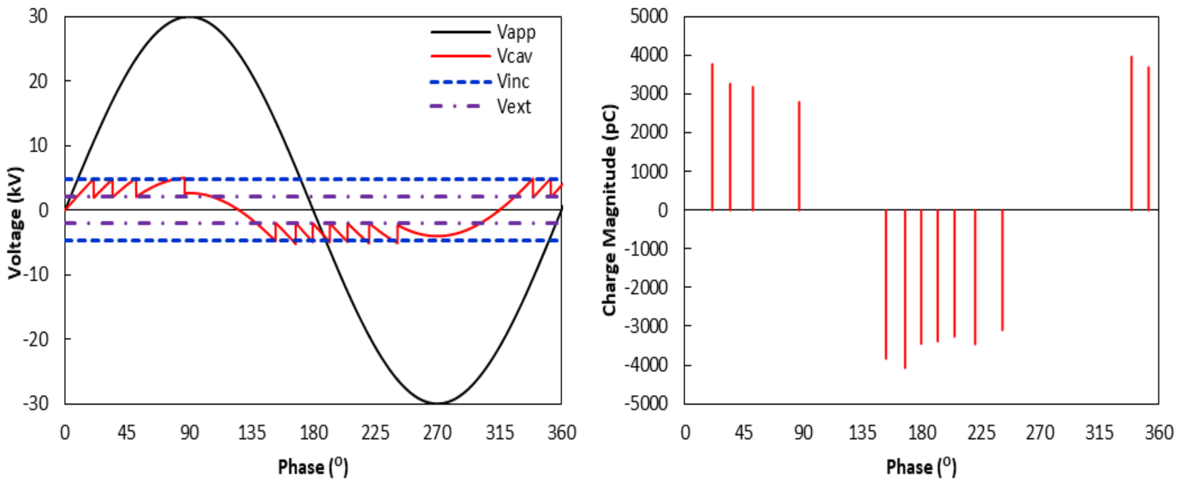


Figure 10: Voltage at cavity and PD magnitude with phase angle for one-cycle at 8 mm cavity diameter

5 Conclusions

In this research, modeling and simulation of partial discharge is applied to a rubber sample with a variable cavity diameter to discuss the influence of cavity diameter on the behavior of PD activities. PD simulated model is developed using COMSOL Multiphysics interfaced with MATLAB software for extending a deeper understanding of PD occurrence inside a cavity. The simulated model studies the distribution of the electric potential and electric field inside the cavity in case of before and after occurrence of PD. Therefore, simulation results indicated that the PD magnitude and PD repetition rate increase with increasing cavity diameters and PD occurs at earlier time for large cavity diameter because of the availability of released electrons emitted from the surface of the cavity at earlier time. These results will be compared to an experimental work for the same test object in the next publications.

6 Declarations

6.1 Study Limitations

None.

6.2 Funding source

None.

6.3 Competing Interests

None.

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