Simulation of Partial Discharge Phenomenon Under Various Applied Voltage Amplitude

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Abstract

Major direct and indirect causes of air pollution include energy generation and consumption. Emissions from power plants can pollute the air over a long-distance and have wide-ranging consequences. Data on the effects of power generation on air pollution provide a wealth of evidence. As a result, research into power generation and related phenomena are crucial. The Partial Discharge (PD) phenomenon causes insulation degradation, which, if left unattended, may trigger electrical breakdown due to repetition of PD events. PD modeling is crucial as to develop a PD measuring and detection system to assess the condition of the insulation system. A Finite Element Solver program is being used in this project to simulate the Finite Element Analysis (FEA) model. Through the modeling process, electric field distribution in a cavity and a dielectric material can be observed, which influences the PD characteristics under high applied voltage. PD phenomenon is further understood by implementing parameters such as free-electron supply, inception field, and extinction field using MATLAB with Livelink and simulated through three different voltage steps, namely 10kV, 14kV, and 18kV.

Keywords Partial Discharge, finite element analysis, MATLAB with Livelink, high voltage insulators

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INTRODUCTION

Partial Discharge (PD) is a discharge event that happens that partially bridges the electrodes in high voltage insulators (Afrouzi 2015). The occurrence of PD signifies degradation or aging in an insulation system (Illias et al. 2011b). Partial discharge, if not being dealt with, might lead to the formation of an electrical tree or even electrical breakdown. According to the insulation and electrode configuration, PD discharges could be happening in cavities surrounded by solid dielectrics, which can be categorized into three categories (Pan and Zeng, 2018): internal (cavity) discharge, surface discharge, and corona discharge.

Among the three PD discharges, internal discharge is the most common type of discharge and is considered a threat to the insulation system. It induces signals on a level that is detectable by power equipment (Pan et al., 2019). It is also a stepping-stone for more intense discharge types like sparks which may lead to ultimate insulation breakdown (Pan et al. 2011).

Internal discharge happens when a gas breakdown takes place in the cavity surrounded by liquid or solid dielectric. Streamer development, as well as the relationship between streamer and cavity walls, can be found during internal discharge. Surface discharge, on the other hand, occurs along the surface of the dielectric (Pan et al., 2011). Surface discharge happens due to a large tangential component of the electric field, where streamer development and dielectric dominate. Corona discharge takes place in the region around a conductor and involves streamer development. This project will focus on cavity discharge as it includes both processes.

In the real world, the PD measurement system is being used to evaluate the dielectric condition of HV equipment in power systems, which includes the detection of electrical trees in the insulation (Illias et al. 2015). Data collected during testing are being compared to the measurement values of specific insulation cables to ensure quality standards. The dielectric is then grouped as either new, strongly aged, or faulty, with maintenance and repair schedules being planned (Afrouzi et al., 2022).

Researchers have been proposing reports on the modeling of PD in cavities in dielectric insulation by using Finite Element Analysis (FEA) software. The benefit of using this software is that the parameters which will affect the occurrence of a PD phenomenon can be analyzed (Callender et al., 2018). With that being said, this project will simulate the PD phenomenon by modeling an FEA model using a Finite Element Solver software and, in the latter part, integrate it using MATLAB to simulate PD events under different voltage levels.

METHODOLOGY

To start off, the model is simplified so that the dielectric material chosen is non-dispersive, meaning its related permittivity does not vary with frequency. A Space Dimension of the 2D model is chosen for modeling. AC/DC physics is used to compute electric field, current, and potential distributions under a time-dependent study are used to observe the relationship between electric field distribution along the cavity and dielectric material at each time step.

Geometry is considered in which it acts as a dielectric material, two spherical cavities, and a voltage terminal, respectively. The material properties are defined separately. The cavity is chosen to be air-filled with defined property values, whereas a filled epoxy resin (X238) is chosen as the dielectric material with defined property values. A copper-typed conductor is chosen to mirror real-world situations.

The electric potential distribution in the dielectric is described by the PD model simulated, which results in the equation below (Illias et al. 2011a):

$$\nabla \cdot D = p_f \qquad (1)$$

$$\nabla \cdot J_f + \partial p_f / \partial t = p_f \qquad (2)$$

where D is the electric displacement field, p_f the free charge density or unpaired charge density and J_f is the free current density. The equation is further derived if the dielectric is a non-dispersive, linear isotropic material with an instantaneous polarization that is exposed to a slowly varying field:

$$\nabla \cdot D = \nabla \cdot (\varepsilon E) = -\nabla \cdot (\varepsilon \nabla V) \qquad (3)$$

based on (3), (2) is rewritten as:

$$\nabla \cdot -\sigma \nabla V - \nabla \cdot \varepsilon \nabla \partial V \partial t = 0 \qquad (4)$$

The finite element analysis software is being used to solve (4), whereby boundary conditions are being set to solve electric potentials.

For streamer type PD, the inception field, E_{inc} depends on the cavity geometry, gas pressure, dielectric permittivity, and the characteristic ionization process within the gas is derived from the critical avalanche criterion (Pan and Zeng, 2018) and is one of the important parameters when dealing with the internal discharge process. The expression is shown below:

$$E_{inc} = (\frac{E}{p})_{cr} p[1 + \frac{B}{(pd_{cav})^n}] \qquad (5)$$

where (E/p)cr is the pressure-reduced critical field at which α = η, α is the gas ionization coefficient, η is the gas attachment coefficient, p indicates the gas pressure within the cavity, B, n are constants, and d_{cav} indicates the cavity height parallel to the applied field. If the cavity is full of air, (E/p)cr = 25.2 VPa-1m-1, B = 8.6m$^{0.5}$Pa$^{0.5}$ and n = 0.5.

In this model, the cavity inception voltage is obtained by looking at the voltage across the cavity center when the electric field is the same as (5). When cavity voltage is larger than the inception voltage, it is possible to have a free electron present to start an ionization avalanche. The number of free electrons available to start a PD in the cavity per unit time, $N_{est}(t)$ is represented with the equation below:

$$N_{est}(t) = N_{et}(t) \exp |\frac{U_{cav}(t)}{U_{inc}}| \qquad (6)$$

As charge magnitude depends on the voltage drop across the cavity during PD, N_{PD} is dependent on the cavity's voltage magnitude at the time of previous PD occurrence. Hence it can be represented as:

$$N_{PD} = N_{ed0} |\frac{U_{cav}(t_{PD})}{U_{inc}}| \qquad (7)$$

However, like charges on cavity surface may become trapped in shallow traps and decay through charge movement into deeper traps, N_{ed} can be represented as:

$$N_{ed}(t) = N_{PD} \exp[-(t - t_{PD})/\tau_{trap}] \qquad (8)$$

When the cavity voltage, U_{cav} exceeds the inception voltage, U_{inc} The total electron generation (EGR) rate is represented by the probability of discharge, P:

$$P = 1 - e^{-N_e dt} \qquad (9)$$

Several boundary conditions are determined in this model. The outer boundaries are chosen to be ground. The middle circle is chosen to be a voltage source terminal sourced by a sinusoidal voltage waveform of 50Hz and a variation of 10kV, 14kV, and 18kV. A mesh size of the fine is chosen so that more details can be observed from the model.

Table 1: Parameters used in the simulation

Definition	Symbol	Value	Unit
Frequency	f	50	Hz
Cavity diameter	dcav	0.006	m
Material diameter	dmat	0.06	m
Applied voltage	appvolt	10, 14, 18	kV
Material Permittivity	ermat	4.4	F/m
Cavity permittivity	ercav	1	F/m
Initial extinction field	Eext0	0.89	kV/mm
Initial inception field	Einc0	3.3	kV/mm

A time-Dependent study is used to compute the results. A time range of (0,0.01,1)s is chosen. The electric potential, electric field norm, and electric potential can be observed under results selection. Several settings such as color range and coloring style are tuned to better observe the electric potential and electric field distribution. 1D plot graphs are being added to plot the relationship between electric field norm with time-based on the cut line drawn.

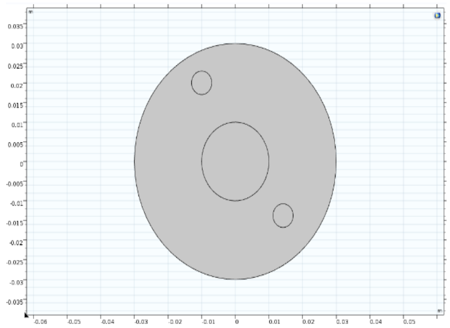


Figure 1: 2D FEA model

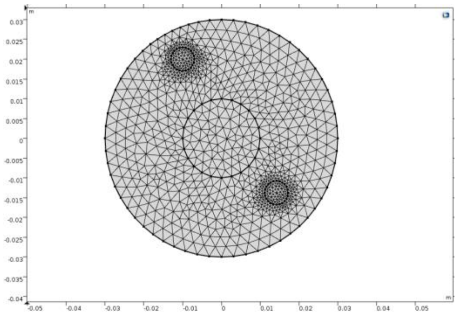


Figure 2: Meshed interface with boundary

LiveLink with MATLAB is being used to connect COMSOL Multiphysics server API to the MATLAB scripting environment. By using LiveLink, the model function library GUI and certain model functions such as mphlibrary are enabled.

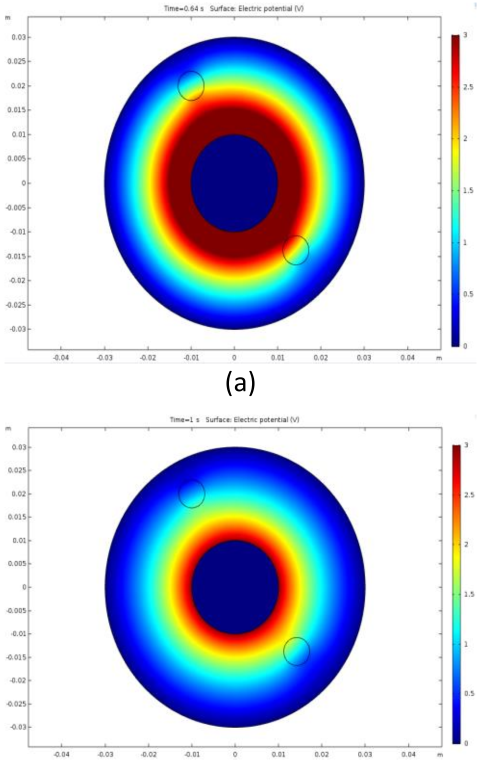
Parameter values, boundaries, material properties, geometries, and studies are being defined here. Next off, additional parameters and equations are being defined to integrate them into the model in order to satisfy the conditions for PD to occur. To ease the simulation, boundary conditions are being updated at several stages, and the model is solved by using solver sequence syntax. Parameters are being updated and obtained at several points throughout the stages to be used to simulate PD occurrence at different applied voltage amplitude levels.

Boundary conditions and material properties are also updated. The program updates the parameters at each time step. In the inception field, E_{inc}, is being updated by using the inception voltage equation (5). As equation (5) requires pressure within the cavity, the temperature in the cavity, T_cav is being extracted from the field model to update the equation.

If the cavity field, E_{cav}, is bigger than the inception field, E_{inc}, and there is an initial electron for ionization avalanche, then PD will occur. The electric field plots and the temperature in the cavity are obtained if it's the first PD.

RESULTS AND DISCUSSION

It is noted that the electric field is proportional to electric potential. Under normal conditions, the electric field decreases when it is further away from the voltage source. It is also noted from Figure 7 that when there is a presence of a cavity, the electric field is higher in the cavity compared to the absence of a cavity.



(a)

(b)

Figure 3: Simulation of electric potential at the time (a)0.64s (b)1.00s

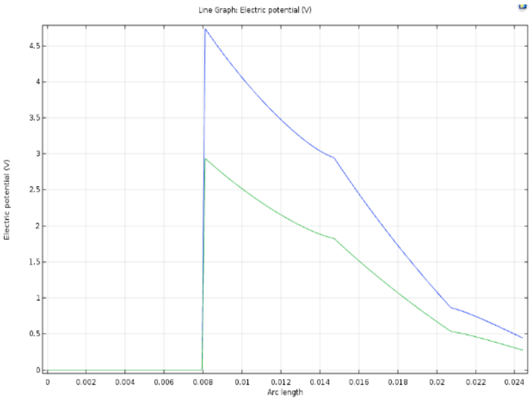
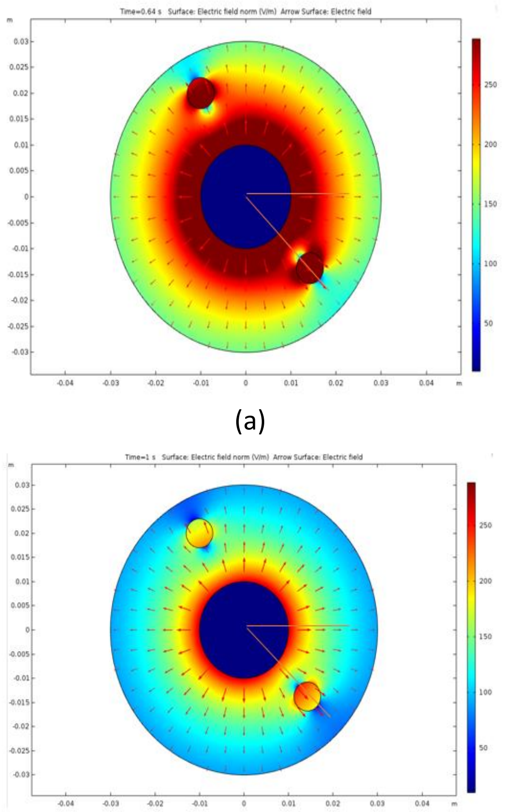


Figure 4: 1D plot of electric potential at time (green color curve - 0.64 and blue color curve - 1.00s)



(a)

(b)

Figure 5: Simulation of electric field distribution of field model with the cut line at the time (a)0.64s (b)1.00s

This actually encourages the occurrence of the PD phenomenon in cavities as one of the conditions for PD to happen is that the electric field exceeds the breakdown strength of dielectric material, which in the meantime, exceeds a critical value. Another condition for PD occurrence is the availability of free electrons that may induce an ionization avalanche. In HV conditions, this is especially common due to a high voltage being transmitted through long distances. High voltage will induce a high electrical field norm. When the transmission medium is being sourced by a strong acceleration in the electrical field, the free electrons may collide with atoms in the transmission medium, ionizing them while releasing more free electrons. This may induce a chain reaction that causes an ionization avalanche in the meantime, satisfying both PD conditions.

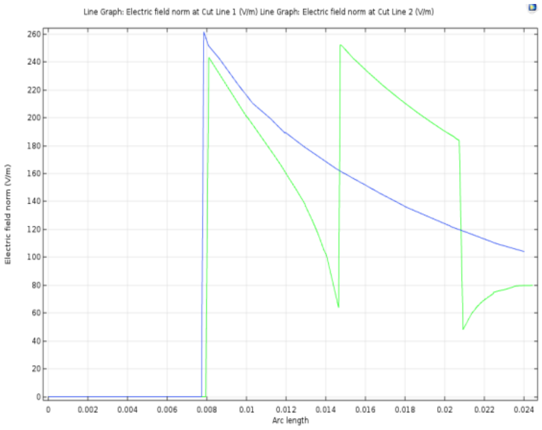
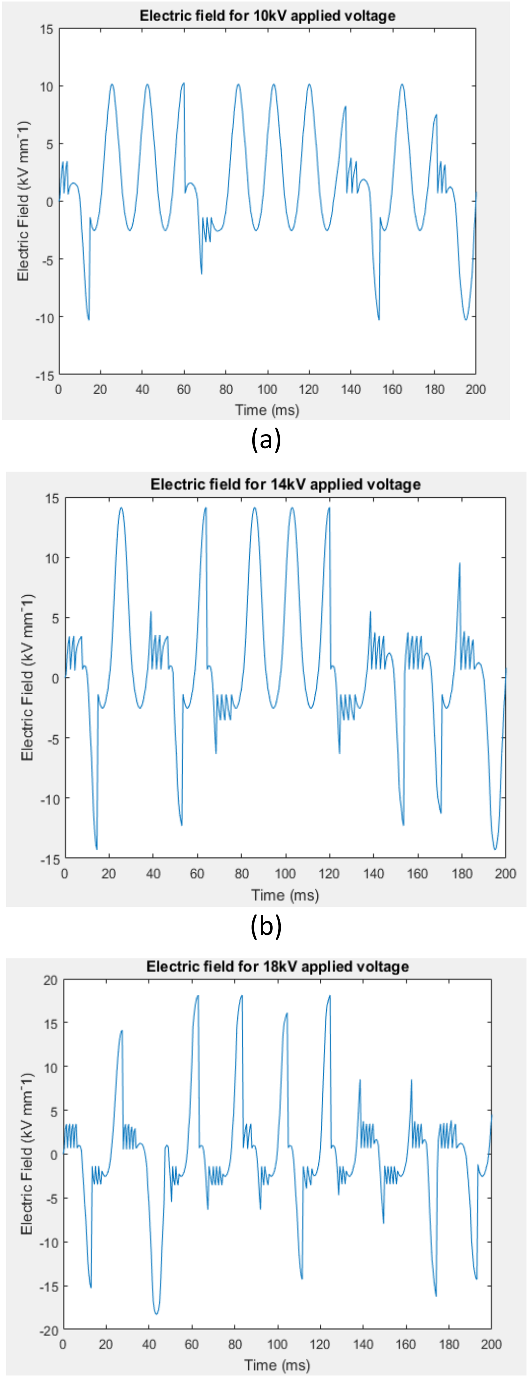


Figure 6: Simulation of electric field norm of field model at Cut Lines in Figure 29 (blue curve – without passing through the cavity and green curve – passing through a cavity)

Figure 7 shows the cavity field plot as a function of applied voltage amplitude with time. Before a PD event, the cavity field, $\mathrm{E_{cav}}$Is the same as the initial cavity field. After a PD occurrence, $\mathrm{E_{cav}}$ will decrease due to the charge accumulation of the surface of the cavity, which is the opposite polarity of $\mathrm{E_{cav}}$. As the polarity of $\mathrm{E_{cav}}$ changes and is the same as the field on the cavity surface, $\mathrm{E_{cav}}$ is enhanced, meaning $\mathrm{E_{cav}}$ may exceed the initial cavity field.

By observing the time between 5ms and 15ms in Figure 8, it is noticed that PD does not occur immediately as $\mathrm{E_{cav}}$ exceeds $\mathrm{E_{inc0}}$. This is due to having no free initial electron available for ionization avalanche. This occurrence is due to statistical time lag.

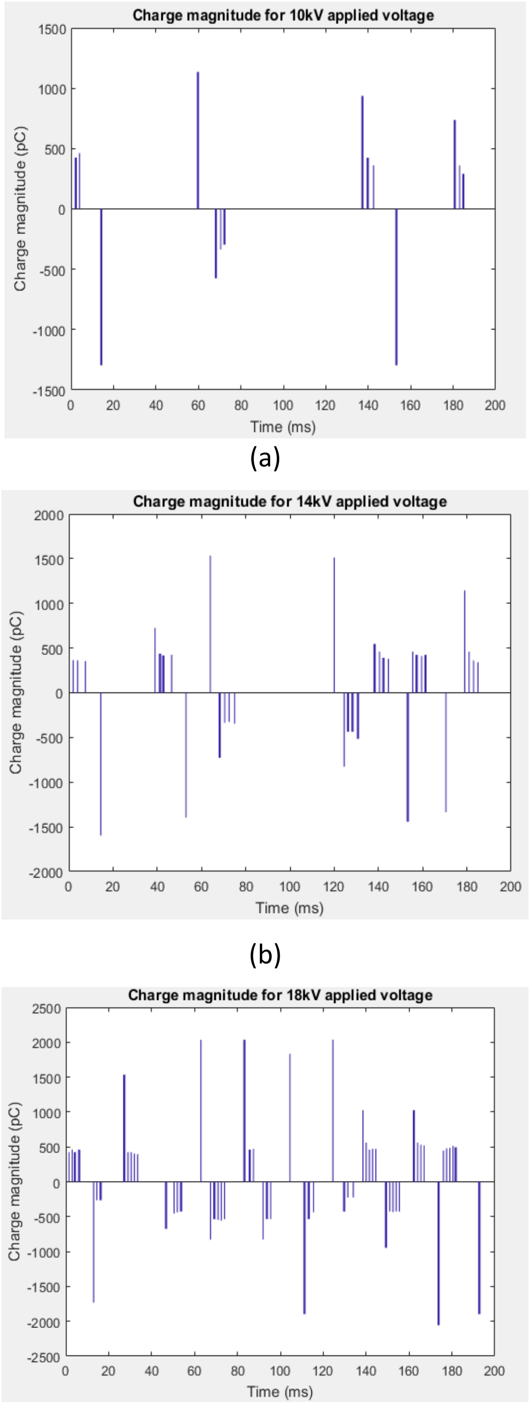


(a)

(b)

(c)

Figure 7: Cavity field for (a)10kV (b)14kV (c)18kV applied voltage



(a)

(b)

(c)

Figure 8: Charge magnitude for (a)10kV (b)14kV (c)18kV applied voltage

The time lag for the first PD is usually long because electrons are harder to be released from the cavity surface, which is due to the lack of electrons being accumulated on it.

Since electrons will be available after the ionization avalanche, after the first PD, there will be some free electrons from the previous PD being left on the surface. Hence, the time lag after the previous PD will be shorter as there are more free electrons being available during the next PD occurrence. Because of this, the statistical time lag influences the number of PDs per cycle.

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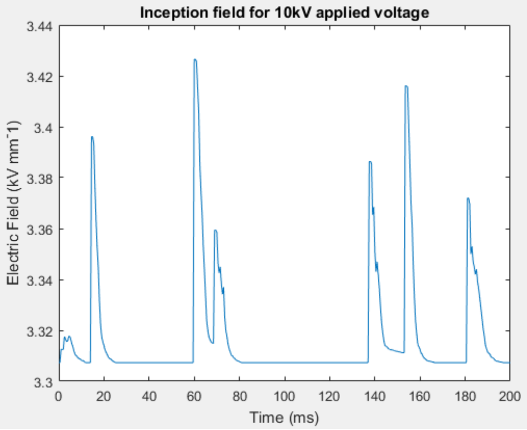
Table 2: Simulation of charge magnitude for different voltages

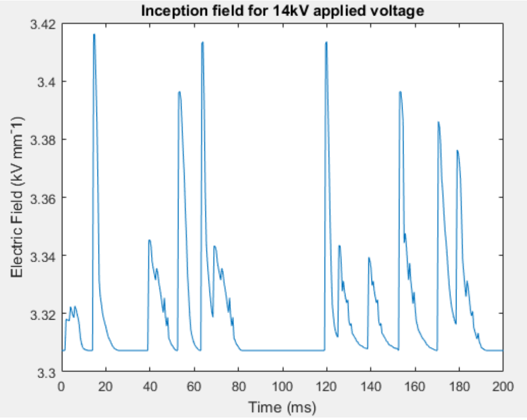
Applied voltage (kV)	**10**	**14**	**18**
Total PDs per cycle	2.1	2.6	5.6
Total charge magnitude per cycle (pC)	1599	2184	3082
Mean charge magnitude (pC)	601	613	584
Maximum charge magnitude (pC)	1381	1557	2106
Minimum charge magnitude (pC)	251	251	252

By comparing the results for 10kV, 14kV, and 18kV applied voltage, it is observed that as the applied voltage magnitude is increased, the total electron generation rate due to volume ionization is higher.

This causes a higher number of PDs per cycle, a higher total charge magnitude, and a higher maximum charge magnitude as the voltage is increased. The increased number of PDs per cycle in 18kV compared to 14kV and 10kV applied voltages is due to a higher PD repetition rate in 18kV applied voltage. The increase of maximum charge magnitudes in 18kV compared to lower applied voltages is due to the drop in cavity voltage during PD. However, it is observed that the minimum charge magnitude is almost the same between the three applied voltage steps, meaning that it is not affected by the change in voltage.



(a)



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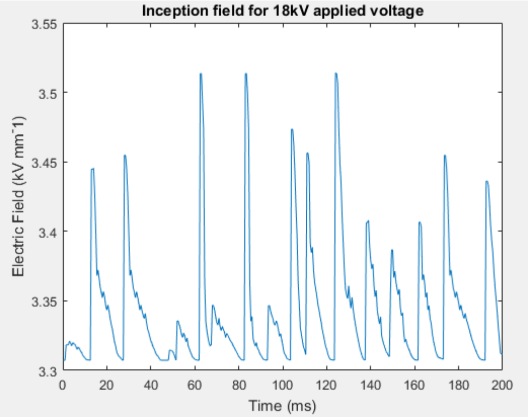

(c)

Figure 9: Inception field for (a)10kV (b)14kV (c)18kV applied voltage

As the voltage increases, the total EGR increases, causing the effect of charge decay to become more prominent as the surface charge on the cavity tends to move faster, causing charge recombination, which results in an increased charge decay rate, meaning that in 18kV applied voltage the charge decay rate is higher, resulting in a higher amount of surface charges, which in turn results in faster movement of surface charges, higher EGR and higher charge magnitude.

Furthermore, since the EGR increases at higher voltages, the chances of having more free electrons increase, causing the statistical time lag between consecutive charges to decrease, which may affect PD to happen earlier in the phase of higher applied voltages. The decrease in statistical time lag compared to lower applied voltages will cause more PDs per cycle. However, they will have lower charge magnitudes. As the voltage increases, the average temperature rise in the cavity also rises due to a larger total charge per cycle in higher applied voltage. In 18kV applied voltage, as discharge occurs with a large charge magnitude, the cavity temperature increases following the charge magnitude. After the discharge, as the cavity temperature is high, it does not recover immediately to its initial temperature. Before the next discharge occurs, causing the inception field be higher when the next PD is set to occur. The reason for cavity temperature to be higher in higher applied voltage is higher due to the higher number of PDs per cycle, which is due to the higher electron ionization rate.

Several parameters are important in affecting a PD characteristic. This includes the inception field, the extinction field, the electron generation rate, charge decay as well as cavity temperature. Ultimately, the parameters above will vary as the voltage applied varies.

CONCLUSION

It is noted that the electric field distribution surrounding the model influences PD characteristics. The occurrence of PDs is also influenced by conditional parameters such as the inception field, extinction field, as well as the existence of free electron supply. By varying the applied voltage amplitude, it is noticed that the PD occurrences vary. This is due to the changing of an electric field, which may affect the inception and extinction voltages as well as the number of initial free electrons in the cavity. When the applied voltage amplitude is higher, the electron generation rate is higher, meaning the number of charges in the cavity, as well as the temperature in the cavity, becomes an important factor that will affect the PDs per cycle. PDs are a nuisance to the transmission medium, as they may ultimately cause an electrical breakdown. From the simulation, it is observed that the electric field increases drastically when reaching the cavity surface and decreases when leaving, meaning cavities are prone to PD occurrences. Hence, simulation and modeling of PD are especially important to understand the cause of it and to prevent it from happening. Future work may include simulation of PD occurrences for different shapes of cavities, such as conical. A comparison of the PD phenomenon in two cavities within a dielectric material can also be considered.

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