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# FDM based Stochastic PD Simulation Model considering the effect of Supply Voltage Harmonics at different Void Locations

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## ABSTRACT

*During the last few decades researchers have been working on simulation of PD patterns and have been trying to know the effect of different parameters on such patterns. In this work a simulation model based on Finite Difference Method (FDM) is developed, where critical field intensity for partial discharge occurrence ($E_c$), residual field intensity ($E_r$) and critical field intensity for discharge propagation along the void surface ($E_s$) are considered as significant model parameters. In this paper, a rectangular parallelepiped void is considered to be placed within a plane-plane electrode system. PD simulations for two significant locations of void inside the dielectric are carried out for particular $E_c$, $E_r$ and $E_s$, considering stochastic occurrence, extinction and propagation of PD. Different proportions of harmonics were added to the sinusoidal supply voltage to study the effect of supply harmonics on PD patterns. Different shapes of PD patterns (phase resolved plots), angle of inception and extinction of PD, amount of charge that is released during PD, are studied and reported in this paper.*

***Key words— Discharge Channel, Finite Difference Method, Partial Discharge Simulation, Phase Resolved Plot and Supply Voltage Harmonics.***

## I. INTRODUCTION

Imperfections are often present in the insulations used in electric power apparatus due to some manufacturing defect. The imperfections act as weak parts of an insulator and are responsible for Partial Discharge (PD). Degradation of insulating material at the location of the void and also at the interface between electrode and insulating material is aggravated due to the charge released during PD [1]. The statistical variation of released charge amplitude and shape of PD pattern was studied in [2]. Turtle-like or rabbit-like PD patterns have been observed for void in [3] & [4] .The effect of material ageing on PD patterns was observed in the study of [6, 14]. The turtle-like pattern was found considering the effect of time lag of PD and the rabbit-like pattern was obtained when probability of occurrence of the first PD after the change of pulse polarity was assumed to be less than that of other pulses. Variable discharge area was responsible for rabbit like PD pattern, reported in [8] & [16]. Surface conductivity also plays an important role for rabbit like PD pattern, which was established in [9].

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Authors of [11] reported that the rabbit like PD pattern may be due to temperature of the void surface. Influence of supply voltage harmonics on phase resolved PD plot was intensively studied in [10], [13] & [18].

In order to understand PD inception-extinction mechanism, shapes of PD patterns, amount of charge released during PD and above all, the stochastic nature of PD, one should first compute the electric field distribution within the specimen. In this work Finite Difference Method (FDM) is used for electric field computation. Phase resolved plots, which directly reflect the shapes of PD patterns, have been obtained and reported in this paper. Turtle-like PD pattern, symmetrically distributed in positive and negative half cycles of the supply voltage waveform has been obtained when the void was placed at the centre of the dielectric. Unsymmetrical PD pattern has been found when the void is considered to be placed in contact with the electrode. By changing the amount of different harmonics in the supply voltage, split nature phase resolved plots are also obtained.

## II. CHARGE RELEASED DURING PD

Partial discharge takes place when the net electric field intensity across the void surfaces in the direction of the applied field exceeds the critical field intensity for partial discharge occurrence and the stochastic condition for discharge are satisfied simultaneously. Charge released during a PD can be expressed as

$$Q = \varepsilon_{r2}\varepsilon_0 A(E - E_r) \tag{1}$$

A is the area of that part of the void surface where discharge can propagate during a particular discharge, which is also defined as discharge area. $\varepsilon_{r2}$ is the relative permittivity of gas inside the void. E is the field intensity between the void surfaces at the time of PD occurrence and $E_r$ is the residual field intensity.

## III. MODEL USED FOR SIMULATION

In this model the dielectric is considered to be placed between a plane-plane electrode system. A rectangular parallelepiped void is placed within the dielectric as shown in Fig.1.

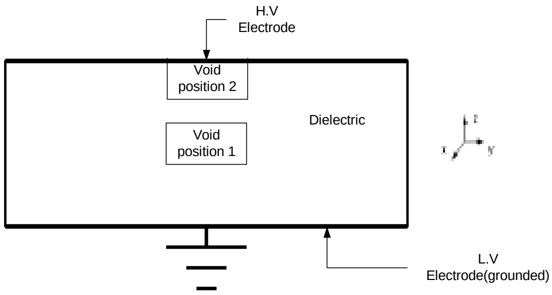


**Fig.1. Electrode-insulator-void configurations considered for PD simulation.**

The mesh used in the simulation is a three dimensional one of size (40×40×10) units. The electrode separation is taken as 10 units. One unit in the mesh corresponds to 0.25mm. The void dimension is taken as (12×12×2) units. Two different locations for the void have been chosen. Position-1 is at the center of the dielectric and position-2

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is in contact with the live electrode. The relative permittivity of the insulating material ($\varepsilon_{r1}$) and that of the gas inside the void ($\varepsilon_{r2}$) are chosen as 4 and 1 respectively. The peak value of the applied sinusoidal voltage is taken as 20kV at 50 Hz.

## IV. FINITE DIFFERENCE MODELLING

To compute the electric field distribution using FDM, at first the total three-dimensional zone of interest (total volume of the dielectric & void) is discretised suitably into a mesh. Potential of any node (x, y, z), except those nodes lying on the insulation-void interface, can be expressed in terms of the potentials of the connected nodes. The corresponding discrete form of Laplace's equation at that node (x, y, z), considering equal nodal distances can be written as

$$v_{x,y,z} = [v_{x+1,y,z} + v_{x-1,y,z} + v_{x,y+1,z} + v_{x,y-1,z} + v_{x,y,z+1} + v_{x,y,z-1}]/6 \quad (2)$$

The potential at any interfacial point (x, y, z) on the void surface having no free charge can be expressed as follows.

$$v_{x,y,z} = [v_{x+1,y,z} + v_{x-1,y,z} + v_{x,y+1,z} + v_{x,y-1,z} + (2\varepsilon_{r2}\varepsilon_0 v_{x,y,z+1} + 2\varepsilon_{r1}\varepsilon_0 v_{x,y,z-1})/(\varepsilon_{r1}\varepsilon_0 + \varepsilon_{r2}\varepsilon_0)]/6 \quad (3)$$

Similarly in presence of any accumulated charge due to PD, the potential at any point (x, y, z) on the void surface can be written in the following way

$$v_{x,y,z} = [v_{x+1,y,z} + v_{x-1,y,z} + v_{x,y+1,z} + v_{x,y-1,z} + (h\sigma_{x,y,z} + 2\varepsilon_{r2}\varepsilon_0 v_{x,y,z+1} + 2\varepsilon_{r1}\varepsilon_0 v_{x,y,z-1})/(\varepsilon_{r1}\varepsilon_0 + \varepsilon_{r2}\varepsilon_0)]/6 \quad (4)$$

where $\sigma_{x,y,z}$ is the surface charge density and $h$ is the nodal distance.

The boundary conditions for field calculation are as follows.

(a) For the live electrode, $v = V_m Sin\omega t$

(b) For the grounded electrode, $v$ is zero

(c) Electric field on the four sides of the specimen, i.e. on x-z and y-z planes, was considered to be linear.

The field distribution before and after PD were calculated by equations (2), (3) & (4) respectively. The PD charge is equal to the difference between the induced charge on the void surface before and after PD. If the conductivity of the void surface and that of the insulating material were neglected, the charge distribution would not change until the next PD. The field intensity changes with the AC voltage, and the next PD occurs when the field intensity across the void met the condition for discharge. The actual PD pattern was simulated when the above steps are carried out at every 0.1 degree of the sinusoidal voltage waveform for several cycles.

## V. MODEL FOR PD OCCURRENCE AND EXTINCTION

In this model, the stochastic behavior of PD is expressed in two different ways as mentioned below:

(a) The stochastic nature of Partial Discharge occurrence is modelled in the following way

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$$P(E) = f(E) \quad (E > E_C)$$
$$= 0 \quad (E \le E_C) \tag{5}$$

where P (E) is the probability for partial discharge occurrence in the void when the field intensity across the void is E, f(E) is a chosen function of E, $E_c$ is the critical field for partial discharge occurrence. In this work it is assumed that the probability of PD occurrence is a sigmoid function of ($E$-$E_c$), i.e. higher the difference between E and $E_c$, higher is the probability of PD at E. Accordingly f (E) is expressed in the following way

$$f(E) = 1/[1 + K_{sig} \times e^{(-k(E-E_c))}] \tag{6}$$

In this simulation, k is suitably chosen as 1.5, the value of the sigmoid parameter ($K_{sig}$) has been varied according to the location of the void. When the void is placed at position 1, the value of $K_{sig}$ is chosen as 100 irrespective of the surface from which discharge channel initiates. For position 2 of the void, $K_{sig}$ is chosen as 100 when the discharge channel initiates from the bottom insulating surface and it is 1 when it initiates from the top conducting surface. In this study the critical field ($E_c$) for partial discharge occurrence is chosen as 5.5 kV/mm. This critical field value is chosen considering Paschen's curve with the assumption that the pressure and temperature of the gas inside the void are 760mm/Hg and 20$^o$C, respectively.

(b) Once the electric field intensity in the direction normal to the void surface exceeds $E_c$ and the probabilistic condition for PD occurrence is also satisfied, discharge channel initiates from one surface of the void and moves towards the opposite surface of the void as shown in Fig.2. It is assumed that after reaching the opposite surface of the void, the discharge channel propagates along the void surface (in the direction perpendicular to the applied field) in those directions where the electric field intensity is greater than the critical field intensity for discharge propagation along the void surface ($E_s$). Accordingly, discharge area is defined as the area on the two opposite surfaces of the void, where the released charge can instantaneously propagate during a discharge.

(c) Partial discharge extinguishes when the field intensity after a PD across the void reduces to a value $E_r$ (residual field intensity). It is stated in [4] that $E_r$ is not a constant and its value varies between 0.2$E_c$ and 0.5$E_c$. In this work, to introduce the stochastic nature discharge extinction process the following expression for residual field has been introduced

$$E_r = E_{ro} + B.N_r \tag{7}$$

Where $N_r$ is a random number distributed uniformly between 0 and 1, B is a constant and $E_{ro}$ is the average residual field intensity in the discharge channel. The values of those two variables are found to be 1.925 and 0.825, respectively.

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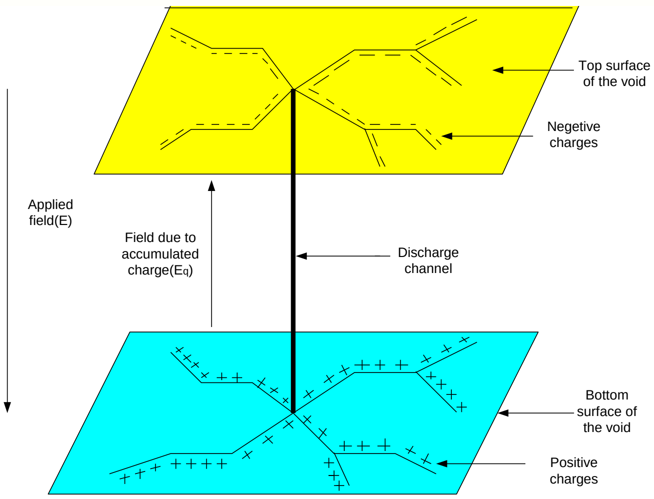


**Fig.2. Propagation of discharge channel on the void surfaces.**

## VI. SIMULATION RESULTS AND DISCUSSIONS

The time period (T=20ms) of the applied sinusoidal voltage is divided into 3600 discrete time intervals such that each time interval is equal to 0.1 degree or 5.55 µs. Results in the form of phase resolved plots have been obtained after acquiring data for hundred cycles, which show the effect of $E_s$ and probability distribution function on PD at two different positions of void.

Fig.3 & Fig.4 show the phase resolved plots with a particular value of $E_c$ and $E_s$ at void position 1 and 2 respectively. It may be observed from these two phase resolved plots that the positive and negative parts of discharge are almost symmetrical in position 1 of the void and it is asymmetrical in position 2 of the void. As per equations (1), (5), (6) & (7), the fluctuation in the released charge magnitude is due to probabilistic nature of discharge inception, extinction and propagation for a particular value of $E_c$, $E_r$ & $E_{s.,}$ In position 1 of the void, as the two opposite surfaces of the void are same insulator, the probability distribution function for PD occurrence from each of these surfaces are considered to be the same. Therefore, the positive and negative discharges in the phase resolved plots remain symmetrical.

The shape of the phase resolved plot in Fig.3 is almost like a turtle, as it was experimentally observed in [3]. In the case of position-2 of the void, the two opposite surfaces of the void are not identical. One surface is a conductor and the other is an insulator. So, the probability distribution function for PD occurrence from each of these surfaces is not the same. In this simulation, it is considered that the probability for PD occurrence at any particular field is higher when the initial electron for discharge inception comes out from the conducting surface of the void rather than the insulating surface. As a result, field at the time of discharge in the direction perpendicular to the applied field also becomes low and accordingly, the probability of discharge to propagate far away from the discharge site would decrease. This leads to release of charge of less magnitude. It is totally opposite when discharge initiates from the insulating surface of the void placed at position-2. Therefore, the

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released charge magnitude is also comparatively high, which makes the phase resolved plot in Fig.4 asymmetrical in nature as it was observed experimentally in [8]. Apart from this, when the discharge initiates from the conducting surface, the time lag between two consecutive discharges also gets decreased due to higher probability of discharge, which makes the discharges more frequent and consequently, the points on the negative half cycle of the phase resolved plots in Fig.4 becomes denser w.r.t that in the positive half cycle.

The problem of harmonic influence is common to all measurements based on acquisition of phase resolved partial discharge images. This study is also crucial for proper identification and classifications of PD patterns. To make a comparative study between the PD patterns due to presence of different harmonics in the supply, particular percentage of different odd harmonics were mixed in phase with the original sinusoidal supply in such a way that the peak value of the mixed wave remains same as that of the original waveform. Phase resolved plots for void at position-1 have been presented in Figs 6, 7, and 8, when the supply voltage consists of fundamental plus 10% of 3rd, 5$^{th}$ and 7$^{th}$ harmonic respectively. For all these cases not much variation were observed in the peak value of the released charge but the shape of the PD patterns gets changed from the conventional turtle-like pattern**.** It can be observed from Fig.5a, due to the presence of 10% 3$^{rd}$ harmonic in the supply, the slope of the resultant voltage does not change much compared to the original supply voltage. As a result not much variation was observed in the corresponding phase resolved plot in Fig.6. Moreover, due to flat topped nature of the supply voltage, discharges extinguish much before the peak of the supply voltage is reached. Therefore, the angular span of discharge was found to be less in comparison to that in Fig.4. With the addition of 5$^{th}$ and 7$^{th}$ harmonic respectively, the shape of the phase resolved plots shown in Fig.7 & Fig.8 starts changing. Further increase of harmonics in the supply changes the shape completely and the phase resolved plots become split in nature.

It can be observed from Fig.5b that due to presence of 25% 3$^{rd}$ harmonic, the slope of the voltage wave in the initial part becomes comparatively high and the peak comes prior to the peak of original waveform. Due to greater rate of change of voltage, the probability of partial discharge to take place at a higher field increases. As a result, number of discharges with higher magnitude increases, which is also evident from Fig.9. It can also be observed from the same figure that PD extinguishes much before the voltage phase angle reaches peak as a result PD pulses exist in a narrow angular span in comparison with that found in Fig.3. The resultant voltage waveform shows three peaks and two valleys in a half cycle when the original wave was mixed with 25% 5$^{th}$ harmonic and four peaks and three valleys when added with 25 % of 7$^{th}$ harmonic. And a consequence, number of split part in the phase resolved gets increased. The split nature phase resolved plots which are obtained in this simulation are almost similar to the experimental results reported in [13] & [18].

This study of partial discharge due to presence of supply harmonic is further extended for void at position-2. It can be found from Table1 and Table2 that the average charge released per half cycle for different harmonic content is greater when the void is located in position-2 rather than in position-1. Phase resolved plot for position-2 of the void have been obtained and presented in Fig.12 when the supply voltage contain the 25% 5$^{th}$ harmonic. The phase resolved plot is asymmetrical in nature as usual. Table1 and Table2 also show irrespective

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of the location of void, very small variation in the released charge magnitude per half cycle with the addition of same percentage of different harmonics with the supply voltage.

Phase resolved plot in Fig.13 is due to combined effect of 3rd, 5th & 7th (Fig.7c) harmonics was also obtained for position- 1 of the void, which reveals discharges with higher magnitude in the initial part of the phase resolved plot compared to that in the later part of the supply voltage waveform. This phase resolved plot almost resembles a rabbit with sharp ear, which also tally with the experimental observation as reported in [8] & [9]. Therefore, it can be concluded that presence of different harmonics in the supply voltage can be one of the reasons behind 'rabbit-like' phase resolved plot.

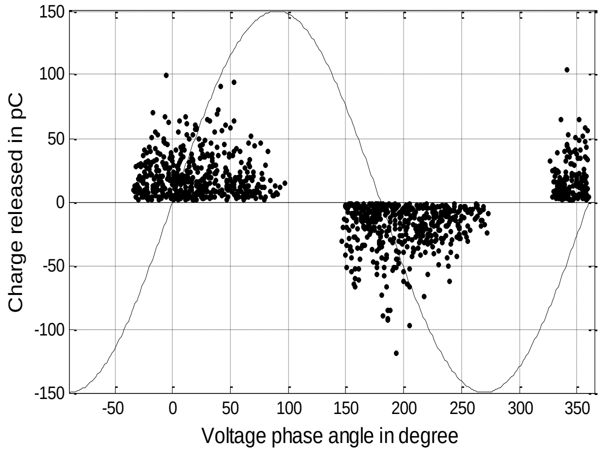


**Fig.3. Phase resolved plot for $E_s$=0.5 kV/mm when the void is at position-1.**

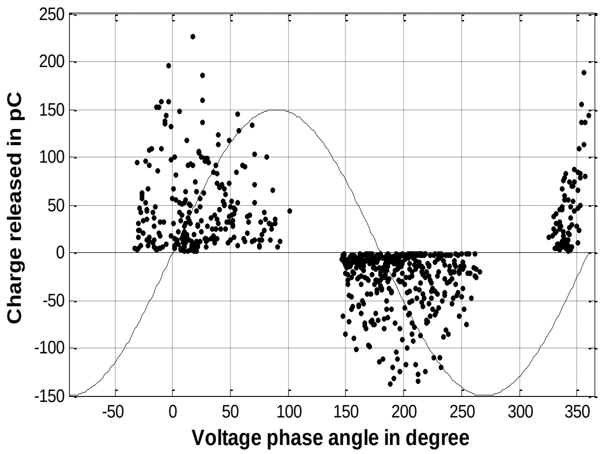


**Fig.4. Phase resolved plot for $E_s$=0.5 kV/mm when the void is at position-2.**

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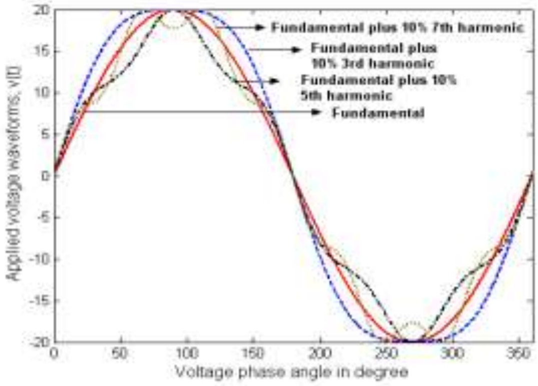


**Fig. 5a**

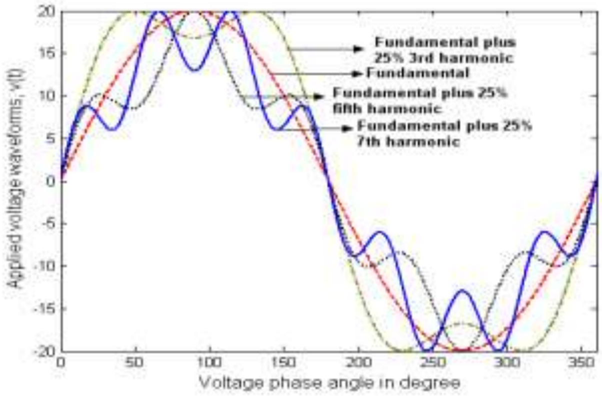


**Fig.5b**

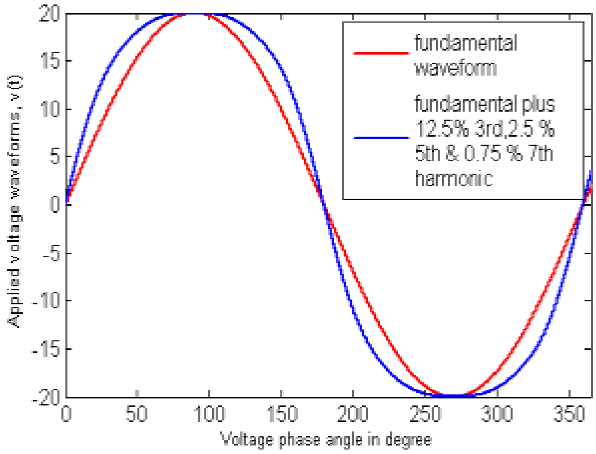


**Fig.5c**

**Fig.5. Applied voltage waveforms for different percentage of harmonic content.**

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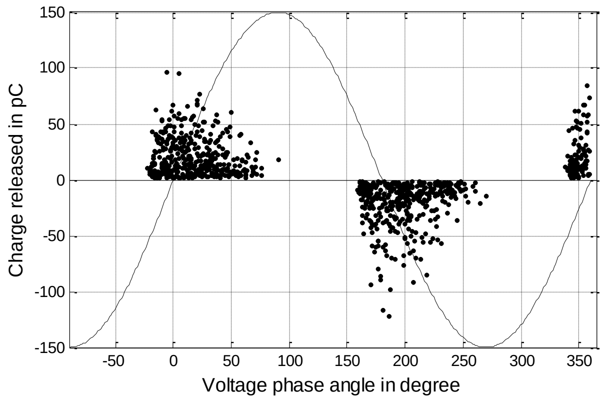


**Fig.6. Phase resolved plot for supply with 10% 3rd harmonic when the void is at position-1 and $E_s$=0.5 kV/mm.**

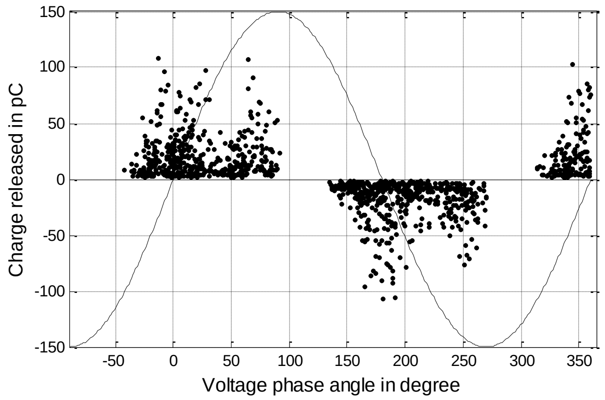


**Fig.7. Phase resolved plot for supply with 10% 5th harmonic when the void is at position-1 and $E_s$=0.5 kV/mm.**

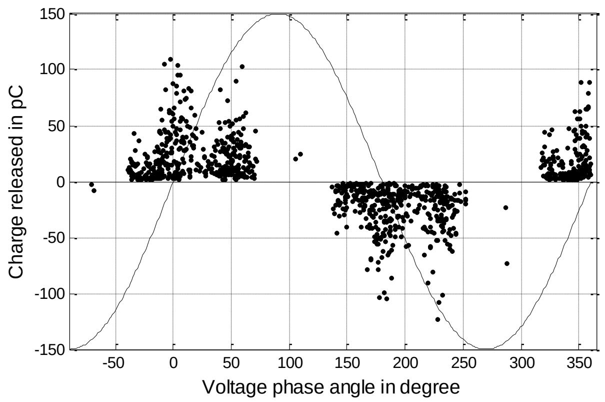


**Fig.8. Phase resolved plot for supply with 10% 7th harmonic when the void is at position-1 and $E_s$=0.5 kV/mm.**

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**Table1**. **Variation of average charge released per half cycle for different harmonic content in the supply voltage, when the void is at position-1 and $E_s$=0.5 kV/mm.**

| % harmonic content | Average charge released per half cycle in nC |
|---|---|
| 25% 3rd harmonic | 9.58 |
| 25% 5th harmonic | 9.52 |
| 25% 7th harmonic | 9.61 |

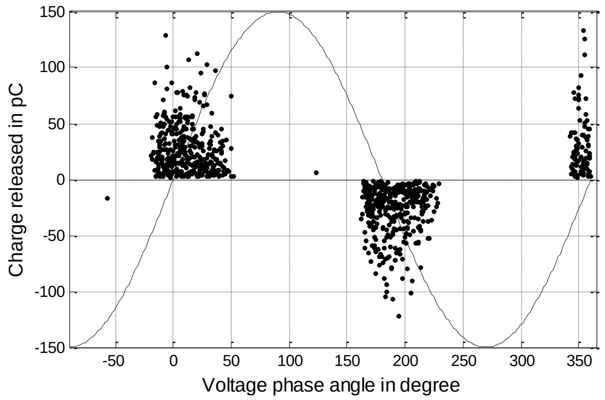


**Fig.9. Phase resolved plot for supply with 25% 3rd harmonic when the void is at position-1 and $E_s$=0.5 kV/mm.**

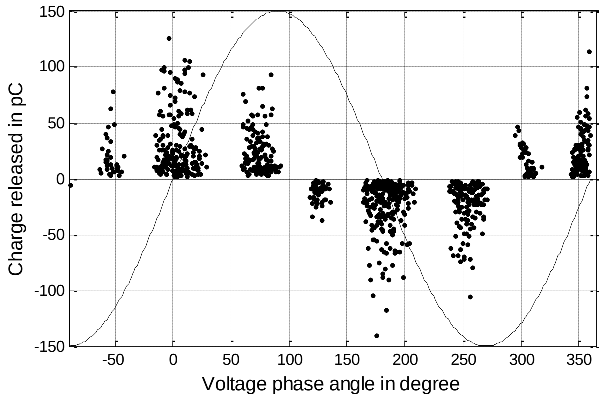


**Fig.10. Phase resolved plot for supply with 25% 5th harmonic when the void is at position-1 and $E_s$=0.5 kV/mm.**

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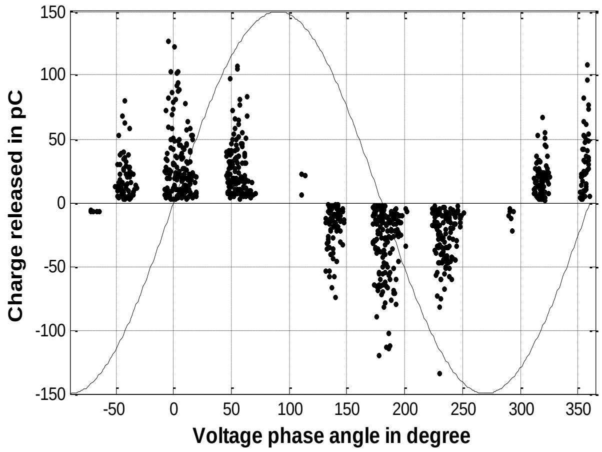


**Fig.11. Phase resolved plot for supply with 25% 7th harmonic when the void is at position-1 and $E_s$=0.5 kV/mm.**

**Table2. Variation of average charge released per half cycle for different harmonic content in supply voltage, when the void is placed in contact with the live electrode (position-2)**

| % harmonic content | Average charge released per half cycle in nC |
|---|---|
| 25% 3rd harmonic | 11.1 |
| 25% 5th harmonic | 11.0 |
| 25% 7th harmonic | 10.8 |

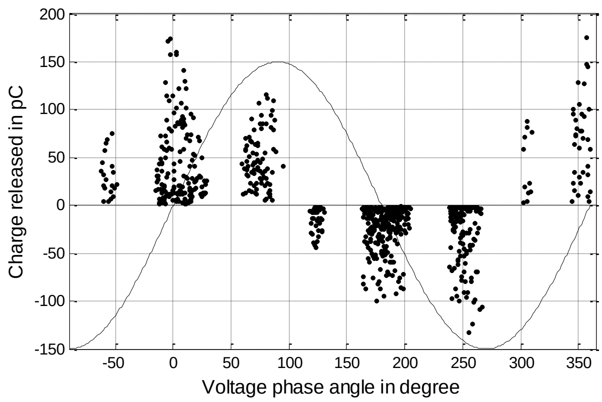


**Fig.12. Phase resolved plot for supply with 25% 5th harmonic each when the void is at position-2 and $E_s$=0.5 kV/mm.**

The results obtained from the above modelling and simulation in terms of phase resolved plots resemble the shapes (turtle-like) found by the authors of [3] & [6]. The split natured phase resolved plots obtained in this

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paper due to presence of supply harmonics also tally with the experimental observation by the authors of [12] & [13]. Simulation results considering the presence of particular harmonics in the supply gives a pattern close to a rabbit, which is almost similar to those observed experimentally in [8] & [9]. Phase resolved plots with asymmetrical discharges in positive and negative half cycles have been obtained when the void is placed in contact with the live electrode, which is almost similar to that obtained by the authors of [8] in their experiment.

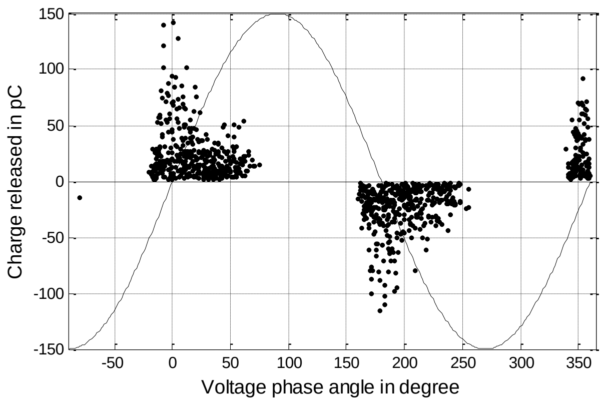


**Fig.13. Phase resolved plot for $E_s$=0.5 kV/mm, when the void is at position-1and the supply contain 12.5% $3^{rd}$ , 2.5% $5^{th}$ and 0.8% $7^{th}$ harmonic.**

## VII. CONCLUSION

This simulation model provides information about inception, extinction and shape of PD patterns for different locations of void where time lag between two consecutive discharges is assumed to be determined by the charge distribution on the void surface and the effect of charge migration in gas is neglected. The effects of supply voltage harmonics and the location of the void on PD patterns were also studied in details. The turtle-like, rabbit-like and split natured PD patterns obtained in this simulation closely tally with the experimental results of previous researchers, which also validates this PD simulation model. In future, PD current pulses may be analyzed to detect the dominating frequency components within it.

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