Partial Discharge Modeling by Simulink

Kehinde Oluwaseyi Ehineni

Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the Degree of

Master of Science
in
Electrical and Electronic Engineering

Eastern Mediterranean University
September 2014
Gazimagusta North Cyprus

Approval of the Institute of Graduate Studies and Research

Prof. Dr. Elvan Yilmaz
Director

I certify that this thesis satisfies the requirements as a thesis for the degree of Master of Science in Electrical Engineering.

Prof. Dr. Hasan Demirel
Chair, department of
Electrical and Electronic Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Electrical and Electronic Engineering

Asst. Prof. Dr. Suna Bolat
Supervisor

Examining Committee

1. Assoc. Prof. Dr. Hasan Demirel
2. Asst. Prof. Dr. Rasime Uyguroglu
3. Asst. Prof. Dr. Suna Bolat

ABSTRACT

The presence of partial discharges (PD) is one of the most conspicuous signs of defects and ongoing defection of insulation in electrical equipment. In this study, partial discharges (PD) are simulated by adopting the classical PD model. In the literature, different models for partial discharges have been presented. The capacitive void model has been effectively instrumental in the study of void breakdown and its generated transients. As an alternative to this, the induced charge concept is been introduced expressing strong criticism against the capacitance modeling of voids.

The aim of the study is to use this concept to examine partial discharges in solid insulators with Simulink. A model is created that can effectively represent the existence of a void in an XLPE cable, implemented in MATLAB Simulink and simulated. The effect of the conductor-void proximity on the magnitude of discharge is verified as well as the effect of void sizes. The simulated results are compared with other Simulink models created in other literatures.

By this study, it is possible to get one step closer to understand the physics behind partial discharge phenomena.

Keywords: Partial Discharge, Void, Induced charge concept, Simulink.

ÖZ

Elektriksel yalıtımının bozulması sürecinin ve yalıtım hatasının en göze çarpan göstergelerinden biri Kısmi Boşalmalardır (KB). Bu çalışmada, kısmi boşalmaların benzetimi klasik KB modelinin uyarlanmasıyla gerçekleştirilmiştir. Literatürde, kısmi boşalmalar için farklı modeller sunulmuştur. Kapasitif model, katı yalıtkan içindeki boşlukta meydana gelen boşalmanın yarattığı geçici durumları incelemek için, çok uzun zamandır kullanılmaktadır. Boşluğun kapasitif modeline bir alternatif olarak, kapasitif modeli eleştiren endüklenmiş yük kavramı ortaya sürülmüştür.

Bu çalışmanın amacı, Simulink ile katı yalıtkan içindeki boşluklarda meydana gelen kısmi boşalmaların bu kavramla incelenmesidir. Bir XLPE kablo içindeki boşluğu etkin bir şekilde yansıtan bir model oluşturulmuş ve MATLAB Simulink kullanılarak benzetimi yapılmıştır. İletken – boşluk yakınlığının ve boşluk boyutunun boşalma şiddetine etkisi incelenmiştir. Benzetim sonuçları, literatürdeki diğer benzetim çalışmalarıyla karşılaştırılmıştır.

Bu araştırma yardımıyla, kısmi boşalma olaylarının arkasındaki fiziksel mekanizmayı anlamaya bir adım daha yakınlaşılmıştır.

Anahtar Kelimeler: Kısmi boşalma, Boşluk, Endüklenmiş yük kavramı, Simulink.

DEDICATION

Dedicated to my Family

ACKNOWLEDGEMENT

My sincere gratitude goes to the Lord Almighty, the reason why I am here. He gave me life without which nothing could have been possible. I will forever be indebted also to my parent, Mr. and Mrs. Ehineni, who despite financially intimidating my program was, they sacrificed everything, you are the best parent in the world mum and dad. To my beautiful and loving fiancée, Yemisi Oluwaseye, thank you so much for your support, you were really my electrical engineering shock absorber, to my siblings and my fiancée's siblings and parent, thanks a million.

To my supervisor, Assistant Prof Suna Bolat, you are indeed the best teacher I have ever met for a very long time, you were more than a supervisor to me, you were God-sent to me, thanks for everything hocam. May God bless you beyond measures.

To my family in Cyprus, Pooya Ferdosipour, Bethesda Family, Scripture miners I want to say thank you for the warmth you gave me here in Cyprus.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

A	Capacitor plate area
C_k	Coupling capacitor
C_m	Measurement capacitor
C_p	Capacitor parallel with the void
C_{scor}	Corrected capacitor in series with the void
C_{void}	Void capacitance
D_{ins}	Insulation Diameter
$\vec{E}_a$	Electric field of air filled gap
E_c	Electric field of the conductor
$\vec{E}_{in}$	Electric field of the insulation
$\vec{E}_{out}$	Electric field of the outside environ of the capacitor.
I_c	Conductor current
$\vec{J}_c$	Current density
K_{ef}	Correction factor
l_v	Void Length
Q_c	Conductor charge
R_p	Resistance associated with C_p
R_{scor}	Resistance associated with C_{scor}
Rv1	Detector circuit
R_{void}	Void resistance
r_v	Void radius
t_v	Void width

v_i^-	Crest of the discharge in the negative cycle
v_i^+	Crest of the discharge in the positive cycle
v_r^-	Trough of the discharge in the negative cycle
v_r^+	Trough of the discharge in the positive cycle
XLPE	Cross-linked polyethylene
μ	Dipole moment
σ_c	Conductor conductivity
ε_0	Permittivity of free space
ε_r	Relative permittivity of XLPE
Ω	Void volume

Chapter 1

INTRODUCTION

1.1 Problem Statement

The insulation of power equipment is very essential and it plays an important role in the efficient and effective delivery of the equipment. Insulation degradation and breakdown had been an intense challenge for power system infrastructures most especially for high voltage. This has been one of the major reasons for the reduction in efficiency, increase in power loss and outages over the years; hence the study of partial discharge is a vital aspect of electrical power engineering.

Insulators usually contain impurities and air bubbles present giving rise to Partial Discharge (PD) when subjected to high or intense electrical stress. This is a major failure of insulators. Eventually, this may lead to a breakdown of the electrical power system. The adequate knowledge of the activity, occurrence, type and mode of partial discharge helps in its prevention and effective management. One of the effective ways of understanding partial discharge activity is through void simulations. This is done by creating a model that can perfectly represent a true-life scenario.

In this study, a void located within the insulation of an XLPE cable model is created and simulated using a four-capacitor PD model. The void position is varied for three points within the insulation and void size is varied from 0.5 mm to 1 mm. At each case partial discharge current and voltage are simulated, the effect of void size and location are observed.

1.2 Objective of the thesis

1. To understand the concept of partial discharge and its activity in a void located in a medium voltage XLPE cable.
2. To calculate the capacitances in the void.
3. To develop an adequate model suitable enough to represent a partial discharge.
4. To observe the partial discharge occurrence in the void at different points within the insulation.

1.3 Organization of the thesis

The thesis is divided into five chapters: Chapter one introduces the research work as well as the aim and the objectives, Chapter two contains a review of literature by other researchers on partial discharge, it also gives more basic concepts for better understanding of partial discharge, Chapter three contains the methodology used in the research which involves how the void model is created and simulated, Chapter four consists of the results from the simulations for the varied void positions and dimensions. Finally, Chapter four concludes the thesis and gives recommendation for further studies.

Chapter 2

LITERATURE REVIEW

2.1 Background

Partial Discharge (PD) is a discharge occurrence across/within a part of an insulating material of two conducting electrodes, without causing a total bridge in the gap. The occurrence of PD is initially confined to a localized part of the insulating material but a repetition of occurrence could lead to an total breakdown as a result of constant continuous insulation deterioration and degradation. This is a major concern in the protection and utilization of high voltage power equipment. Insulation defects, discontinuity and impurity are the major causes of PD [1]. Partial discharges, as defined by IEC60270, are localized dielectric discharges in a partial area of an electrical dielectric insulation system under electric field stress.

Initiation of activities of partial discharge could be triggered in electrical equipment when there is deterioration with age of the insulation, an over-stress of its thermal and electrical properties or when the installations are not properly done. Partial discharge could also occur on distribution system due to mechanical production errors causing defects on the cables thereby creating a void.

2.2 Partial Discharge Occurrence

Partial discharge occurrence can be at any part of insulation, where the breakdown strength of that portion of the insulating material is exceeded by its electric field [2].

There have been several models of partial discharge proposed by researchers but the simplest and most deterministic is the three-capacitance equivalent circuit. It was introduced more than 50 years ago and was further reduced into a class of piece-wise isometric in [3] is as shown below:

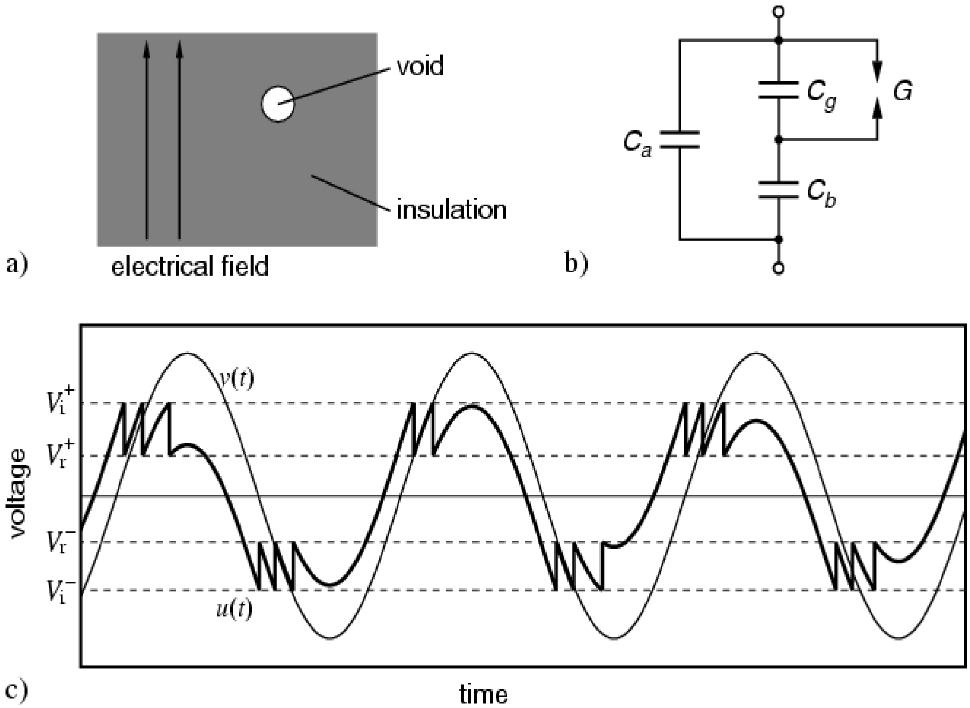

Figure 2.1: PD explanatory model due to void

In the Figure 2.1 above, (a) is a schematic diagram indicating the presence of a void in an insulation system under an electric stress. Discharges take place exclusively within the void. (b) shows capacitive model circuit, here the gap is labelled G and the capacitors C_g, C_a and C_b are used to represent the presence of the void, and the remaining aspects of the insulation respectively. Lastly, (c) is a graph of the discharge voltage compared to the applied voltage. The voltage between the gap G is indicated by the thick line. At the time when it attains the point $\mathbf{V}_i \pm$, where the discharge reaches its peak and the value of this discharge discretely changes to $\mathbf{V_r} \pm$ The applied voltage is denoted by v(t) [4].

2.3 Causes of partial discharge

Partial discharge might be caused by different sources. .

2.3.1 PD caused by voids

Partial discharge occurrences within an insulating material are always triggered within voids filled with gas in the dielectric. Because the surrounding dielectric has a permittivity greater than the void, the electric field across dielectric distances is less than the electric field across the void. If the electric stress across this void rises beyond the inception field of the corona for the gas in the void, a partial discharge occurrence in the void is initiated [5].

PD occurrence could also be along the surface of solid insulators. This happens if the surface electric field becomes high to the extent that it can cause a breakdown on the surface of the insulator. This usually is observed on insulators of overhead lines, especially times of when the humidity is very high that causes insulation contamination.

2.3.2 Irregular surfaces on insulating material

Sharp points and edges usually cause a concentration of electric field intensity and if an insulating material happens to have such irregularities, this will cause the electric field at these non-homogeneous points to increase. That may lead to a partial discharge if it exceeds the tensile strength of the insulating material which might be resulted in a total breakdown eventually.

2.3.3 Bubbles in liquid insulation

Bubbles may trigger high electric field in a liquid insulation and thereby causing a partial discharge. For example in transformer oil, such protracted and incessant partial discharge could lead to the eventual break down of the void.

2.3 4 Coronal Discharges

Coronal discharges occur as a result of ionization of fluid surrounding an electrically energized conductor. The discharge appears in a glow of blue around extreme edges of an high voltage carrying conductors [6].

Figure.2.2: Corona effect on power lines [7]

2.3.5 Manufacturing inefficiency

The insulation material might suffer damage or defect with time due to either ageing or third party. This might result in a partial discharge.

Also during the process of manufacturing due to inefficiency or mistakes, there could be presence of air or gas bubbles in the insulating material, which is one of the major reasons for imperfection in the insulation material. This imperfection due to the presence of the bubble (either gas or air) might be in several geometric forms, for example, it could be in rectangular shapes, spherical shapes, cylindrical shapes etc. Irrespective of the shape of occurrence, this manufacturing defect serves as an impurity within the insulating material and it in turn creates a weakness in the insulating materials; this weakness is one of the major reasons for high voltage equipment PD occurrences [8]. Partial discharge is initiated when the electric field intensity exceeds the breakdown strength of gas located in void [9]. Ambient conditions such as humidity, pressure and temperature could also trigger PD occurrences.

2.4 Effect of partial discharge

PD activities cause insulating material deterioration, which eventually may lead to electrical breakdown. PD effects within high voltage cables and equipment usually cause a lot of damage to the system and might result in a total breakdown of the equipment.

2.4.1 In solid dielectric

In solid dielectrics, PD activities cause teeing; a formation of several, partially branching channels of conducting discharge. Repetition of such discharges may lead to irreversible mechanical and chemical degradation of the insulating material. Such damage may occur as a result of the energy dissipated due to UV light of the discharges, high energy electron or ions, ozone interaction with the void wall and cracking that occur during chemical breakdown processes when gases are liberated at a high pressure. It should be noted that the electrical conductivity of the dielectric material surrounding the voids is increased due to the chemical transformation of the dielectric. As this happens, the electrical stress in the unhampered gap region increases, causing acceleration in the whole breakdown process. Some dielectrics are more resistive to PD damage such as inorganic dielectrics like glass, mica and porcelain, compared to organic and polymer dielectric.

2.4.2 Paper insulation

Partial discharges in paper-insulated cables always start as a negligible small hole penetrating the paper windings adjacent to the outer sheath or electrical conductor. A repetition of discharges due to un-hindered progress in the PD activities eventually lead to a total change in chemical composition of the paper layers affected and dielectric fluid. The insulation begins to be subjected to high tension or stress as these activities continue, leading to further growth of the damaged region, resistive heating along the path formed by the tree, and then tracking. All these activities eventually lead to a breakdown or even electrical explosion as time goes by.

2.5 Concept of the induced charge

The concept of the induced charge was first introduced by Crichton G. C, Karlsson P. W. and Pedersen while creating a PD model called Pedersen's model. The model established a relationship between PD transients and the distributed charges created in the space between the electrodes and also between the charge in the space and the charge induced on the electrode [10]. The induced charge is defined as the difference between the charge found on the electrode after PD have occurred and the charge that would have been on it if the PD has not occurred [8, 11].

The sources of these induced charges are hence the charges, which as a result of this partial-discharge activity, are distributed within voids located throughout the whole system.

If a discharge in a void with surface S is considered, the discharge will result in the deployment of the surface making the surface charge density σ to reach a value where the electric field across the void will reduce until the discharge process is complete [12].

Using super-position principle, the induced charge related to the charge distribution on the surface S can be expressed in the form.

$$q = - \int_S \lambda \sigma \mathrm{d}S \tag{2.1}$$

where, q is the induced charge related to the charge distribution on surface S of the void, λ is a dimensionless scalar function and it depends on the position of dS only. The boundary conditions are λ = 1 at the electrode on which q is distributed, λ = 0 at all other electrodes, σ is the surface charge density while **S** is the void surface. The Dipole Moment of μ of the charges deposited on void surface S is given by

$$\vec{\mu} = \int_S \vec{r} \sigma \mathrm{d}S \tag{2.2}$$

Where $\vec{r}$ is the radius vector that locates the position of the surface element $\mathrm{d}S$.

The induced charge which arises from the dipole is given by

$$Q = - \vec{\mu}.\vec{\nabla}\lambda \tag{2.3}$$

2.6 The Transients Related To Induced Charges

The properties considered and measured are the applied voltage and the current pulses even though the observable transients are related inherently to the induced charges.

In [12], Crichton et al explains that the potential drops to U - ΔU where U is initial voltage and ΔU voltage change and as result, the charge on the electrode is given as Q + ΔQ, where ΔQ is the charge that is being sent to the electrode. Therefore by using the Green's reciprocal theorem [5], expression for this potential drop can be obtained.

$$(\mathrm{U} - \Delta U)\mathrm{Q} = \mathrm{U}(\mathrm{Q} + \Delta\mathrm{Q}) + \int_s v\sigma \mathrm{d}S \qquad (2.4)$$

where v is the scalar potential at the surface element dS for the discharge-free situation.

Since

$$\mathrm{V} = \lambda\mathrm{U} \text{ and } \mathrm{Q} = \mathrm{CU} \qquad (2.5)$$

Hence,

$$-\int_s v\sigma \mathrm{d}S = \mathrm{C}\Delta U + \Delta\mathrm{Q} \qquad (2.6)$$

Therefore,

$$\mathrm{q} = \mathrm{C}\Delta U + \Delta\mathrm{Q} \qquad (2.7)$$

$\mathrm{C}\Delta U$ can become much larger than ΔQ if the impedance in this circuit becomes too large discharge associated current. This will in turn make ΔQ become negligible in the equation since $\mathrm{C}\Delta U >>> \Delta\mathrm{Q}$. Therefore the induced charge q can be written as

$$\mathrm{q} \approx \mathrm{C}\Delta U \qquad (2.8)$$

2.7 The Theory of Void in Electrical Insulation

A void can be referred to as a cavity or a portion within an insulation system where the insulation property is discontinuous or absent. [11-17]. This cavity within the insulation poses a threat to the electrical equipment as it makes it vulnerable at that point. Void is one of the major causes of partial discharges, eventual insulation breakdown and cable failure.

Several researches have proved the relationship with void existence within insulation and its effect on durability of the insulation system as well as its performance. This study also covers the effect of the proximity of void in an XLPE insulated cable with respect to the conductor and the effect of void size on the PD magnitude. In addition, Steven M et al in [9] argued that void existence within an insulation system causes a high increase in the energy storing capacity of the electric field between the conductors. Concluding that void size and density has a significant influence on the dielectric capacitance.

One of the major causes of void in an insulation system is during manufacturing process. Below is shown an void equivalent circuit.

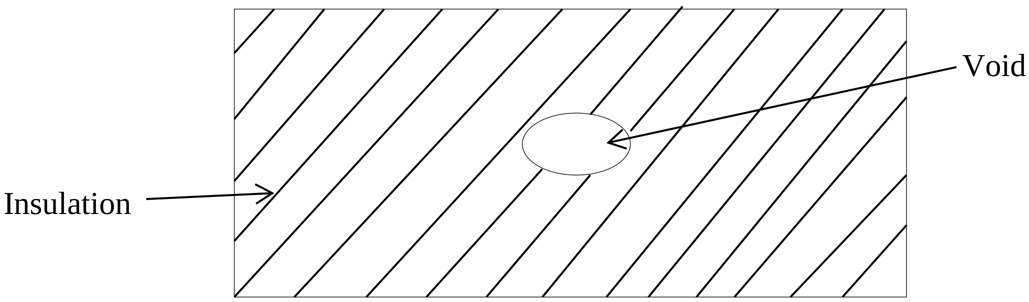

Figure 2.3: A schematic diagram of a void in an insulation system [10].

Figure 2.4 below shows a void capacitive equivalent network circuit, where Ca and C_b are the insulation healthy parts, C_v denote the void capacitance, V_a and V_b, are the potentials across the healthy parts and V_d is the void respectively. It has been earlier noted that at the inception of an applied voltage V_i, PD occur as soon as the void breakdown strength is exceeded by the electric field intensity within it. The discharge causes charge q_v accumulation on the void surface, therefore, the void voltage is given as $V_v = \frac{q_v}{C_V}$ and it is in opposition to V_d.

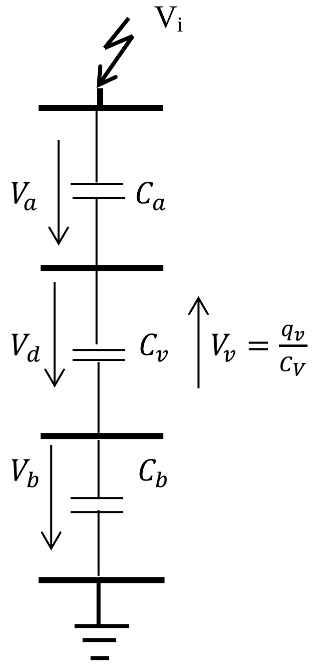

Figure 2.4: Capacitive equivalent network circuit of a void [11]

In an attempt to mathematically explain the void induced charge, G. C. Crichton et al [12, 14] while considering a small dimensional ellipsoidal void with an effective uniform field due to its small dimension concluded that the PD occurs when the void field attains the value inception E_i causing a decomposition of the void surface charge and a decrease in its internal field. They also noted that this PD will come to an end as soon as the reduction of the internal field attains a value E_i. It was also assumed that void internal field stays uniform and that the whole part of the void takes part in the discharge process. Based on the afore-mentioned assumptions, the dipole moment μ of the distribution of charges remaining on the void surface is stated below.

$$\mu = \frac{8\pi\varepsilon}{3A}\left[\overrightarrow{E_0} - \left(1 + \frac{abcA(\varepsilon_0 - \varepsilon)}{2\varepsilon}\right)\overrightarrow{E_l}\right] \tag{2.9}$$

where a,b and c are the void semi-axes, $\overrightarrow{E_0}$ is the field when the internal field and the field of inception becomes equal, $\overrightarrow{E_l}$ is the value the field is reduced to when the discharge comes to an end while ε_0 is the permittivity of the vacuum, ε is the dielectric permittivity and finally A is an introduced parameter and its given below integrally as:

$$A = \int_0^{\infty} \frac{ds}{(a^2+S)^{\frac{3}{2}}\,(b^2+S)^{\frac{1}{2}}(C^2+S)^{\frac{1}{2}}} \tag{2.10}$$

A dimensionless parameter K is also introduced and it is given as:

$$K = \frac{2}{abcA} \tag{2.11}$$

If (2.10) and (2.11) are substituted in (2.9), the dipole moment is obtained as

$$\mu = \left(\frac{K}{h}\right)\Omega\varepsilon\left(\overrightarrow{E_\iota} - \overrightarrow{E_l}\ \right) \tag{2.12}$$

where $\Omega = \left(\frac{4\pi}{3}\right)abc$ which is the volume of the void.

and h is also dimensionless parameter introduced by G. C. Crichton et al and it is given as

$$h = \frac{K\varepsilon_r}{1 + (K-1)\varepsilon_r} \tag{2.13}$$

where ε_r is the relative permittivity. Since the induced charge arising from the dipole have been found to be given as;

$$q = -\mu.\vec{\nabla}\lambda \tag{2.14}$$

Substituting equation (2.12) into equation (2.14), the induced charge is then found to be

$$q = -\left(\frac{K}{h}\right)\Omega\varepsilon\left(\overrightarrow{E_\iota} - \overrightarrow{E_l}\right)\vec{\varepsilon}\lambda_{\ 0} \tag{2.15}$$

where $\lambda_{\ 0}$ is a Laplace equation solution for the dimensionless scalar function λ in equation (2.14) which is given as$\vec{\nabla}.\left(\varepsilon\vec{\nabla}\lambda\right) = 0$. Hence, equation (2.15) gives a simplified calculation for the induced charge as stated by G. C. Crichton et al.

However, it should be noted that the void is considered to be spheroid at a point where b = a, it is stated that if $x = \frac{b}{a}$, for an oblate spheroid, x >1 and the dimensionless parameter K for such is given in terms of arctan and ln functions as seen below:

$$K = \frac{u^3}{(1+u^2)(u - \arctan u)} \tag{2.16}$$

where $u = \sqrt{(x^2 - 1)}$

If we consider a capacitor of parallel plate insulated at both ends and filled with air in the middle as explained in [13] and shown in Figure 2.5 below:

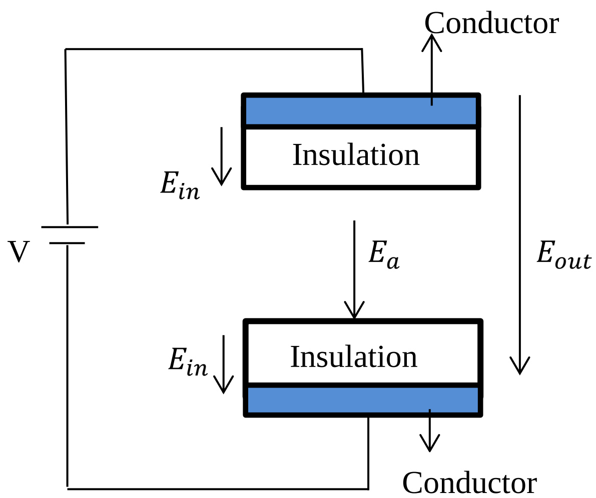

Figure 2.5: Air filled parallel plate capacitor

The electric field of air E_a, electric field of the outside E_{out}, electric field of the insulation at both ends E_{in} are mathematically related as follows:

$$\vec{E}_{out} = 2\vec{E}_{in} + \vec{E}_a \tag{2.17}$$

But if we now consider a conductor to be occupying the middle of the insulators instead of air, the electric field E_a will pass through the conductor and this would cause a movement of the conductor free electrons in the electric field opposite directions. This movement produces a current density J_c which can be mathematically stated in relation to E_a as follows;

$$\vec{J}_c = \sigma_c \vec{E}_a \tag{2.18}$$

Therefore,

$$\vec{J}_c = \sigma_c \overline{(\vec{E}_a - \vec{E}_c)} \tag{2.19}$$

σ_c is the conductor conductivity while $\vec{E}_c$ is the electric field produced in the conductor as a result of the electron movement in opposite direction as shown in Figure 2.6 and this is in opposition to $\vec{E}_a$ causing a reduction in $\vec{J}_c$ until it eventually attains zero making;

$$\vec{E}_{out} = 2\vec{E}_{in} \tag{2.20}$$

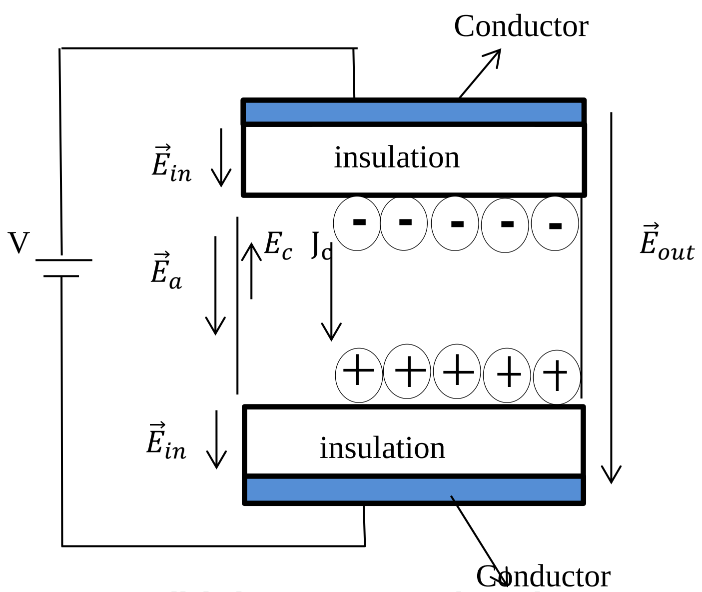

Figure 2.6: Parallel plate capacitor with conductor.

Conclusively, this means that the conductor electric field will disappear while the insulation will now have the electric field $\vec{E}_{out}$.

From the current- current density relation equation;

$$I = \iint \vec{J} . \overrightarrow{ds} \tag{2.21}$$

Inserting equation (2.19) into the above equation, we get the equation for the physical current flowing through the conductor, it is given as follows:

$$I_c = \iint \sigma_c \overrightarrow{(\vec{E}_a} - \vec{E}_c) . ds \tag{2.22}$$

Where the conductor field and the conductor charge are related as follows:

$$Q_c = \iint \varepsilon_0 \vec{E}_c \ . \vec{d}_s \tag{2.23}$$

By solving the above and substituting it into equation (2.22), the conductor current, I_c is given as follows:

$$I_c = \sigma_c \, A E_a \, e^{\frac{\sigma_c t}{\varepsilon_0}} \tag{2.24}$$

Here, A is the capacitor plate area.

Chapter 3

METHODOLOGY

3.1 The Partial Discharge (PD) Model

One of the most appropriate and highly potent ways to investigate and understand the nature, activities, impart and influence of PD on an insulating material is by creating appropriate precise model [16]. This has proved effective through successful results over the years. The model should be able to represent physically the insulating material and the PD activity. This has helped even in the classification of partial discharges as well has given more in-depth knowledge in understanding the physics behind PD occurrences and impart [17].

Several PD models have been proposed by different researchers. The first model which can be referred to as the simplest model was the capacitive model proposed by Gemant and Philippoff in 1932 [15]. The model is shown in Figure 3.1. It comprises of three capacitors where one of the capacitors is used to represent the void where the discharge takes place, a switch is connected across this void to control voltage flow and to initiate breakdown. Several other models have been created owing to the criticisms this model faced but most of the proposed models were modifications of the capacitive model [18] and then comparison was made [19].

One of such criticism is that of Crichton, Karlsson and Pedersen in [12] criticizing the capacitive model arguing that there is absence of capacitance change during discharge process of the capacitive model. They later introduced the induced charge concept method as an alternative and modification of the capacitive model.

Since for a PD to occur, the covering insulation must be strong enough to withstand a total breakdown thereby limiting the occurrence of the discharge to a localized part of the insulation where its dielectric strength have been exceeded.

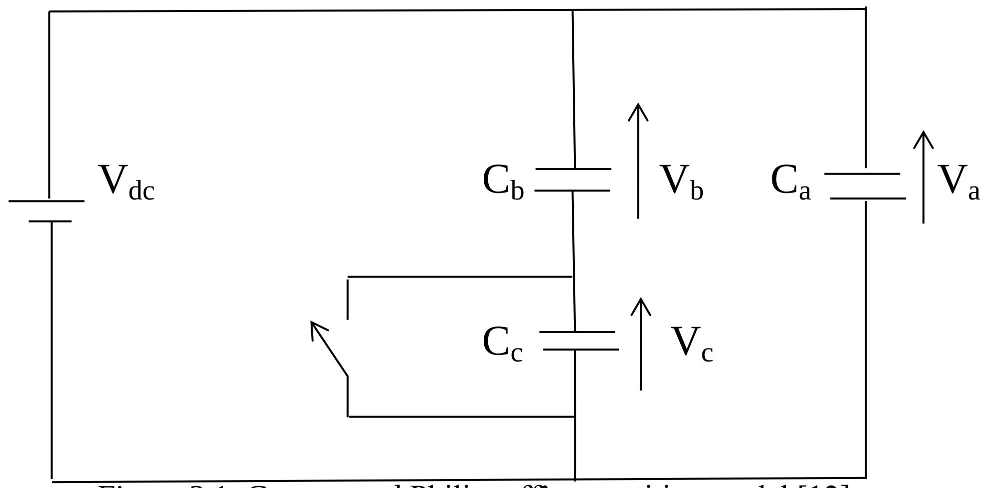

Figure 3.1: Gemant and Philippoff's capacitive model [12]

The model used in the study shown in Fig 3.2 is also a modification of the capacitive model, the model used takes remnant charges into account, these are the charges believed to be dissipated due to former PD activities in the void as suggested by Y. Z. Arief et al in [15].

This model is presented in Figure 3.2. The void and the insulations are represented by capacitors and resistors. The value of these capacitors and resistors were later determined through calculations in Sections 3.3 and presented in Table 3.1 of Section 3.4.

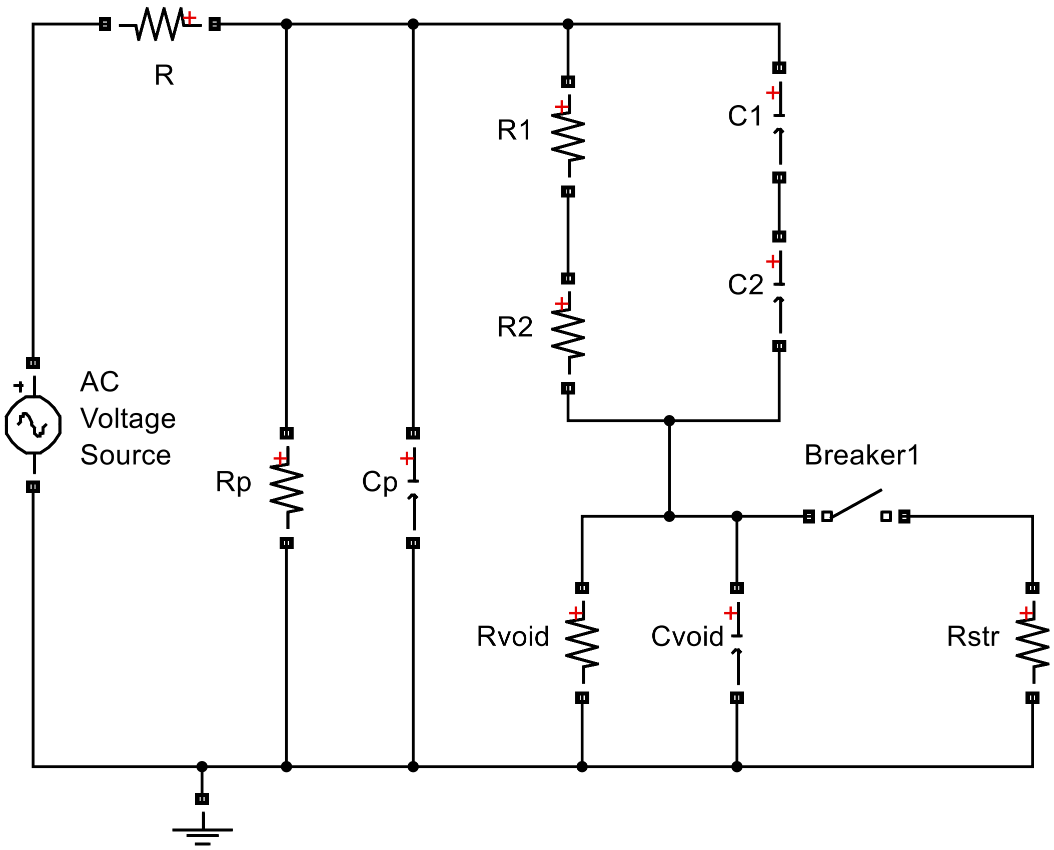

Figure 3.2: The void model

Where Cp represent the insulation of the cable at other point apart from where the void is located, Rp is that insulation related resistance, C1 and C2 are the insulations around void, they are in series with the void while R1 and R2 are their corresponding resistances, Cvoid is the capacitance associated with the void while Rvoid is the associated void resistance and Rstr signifies the void discharge.

3.2 Explanation of the void in an XLPE cable.

The considered void is one in an aluminum conductor XLPE cable as shown in Figure 3.3, which is incorporated into the circuit model in Figure 3.2.

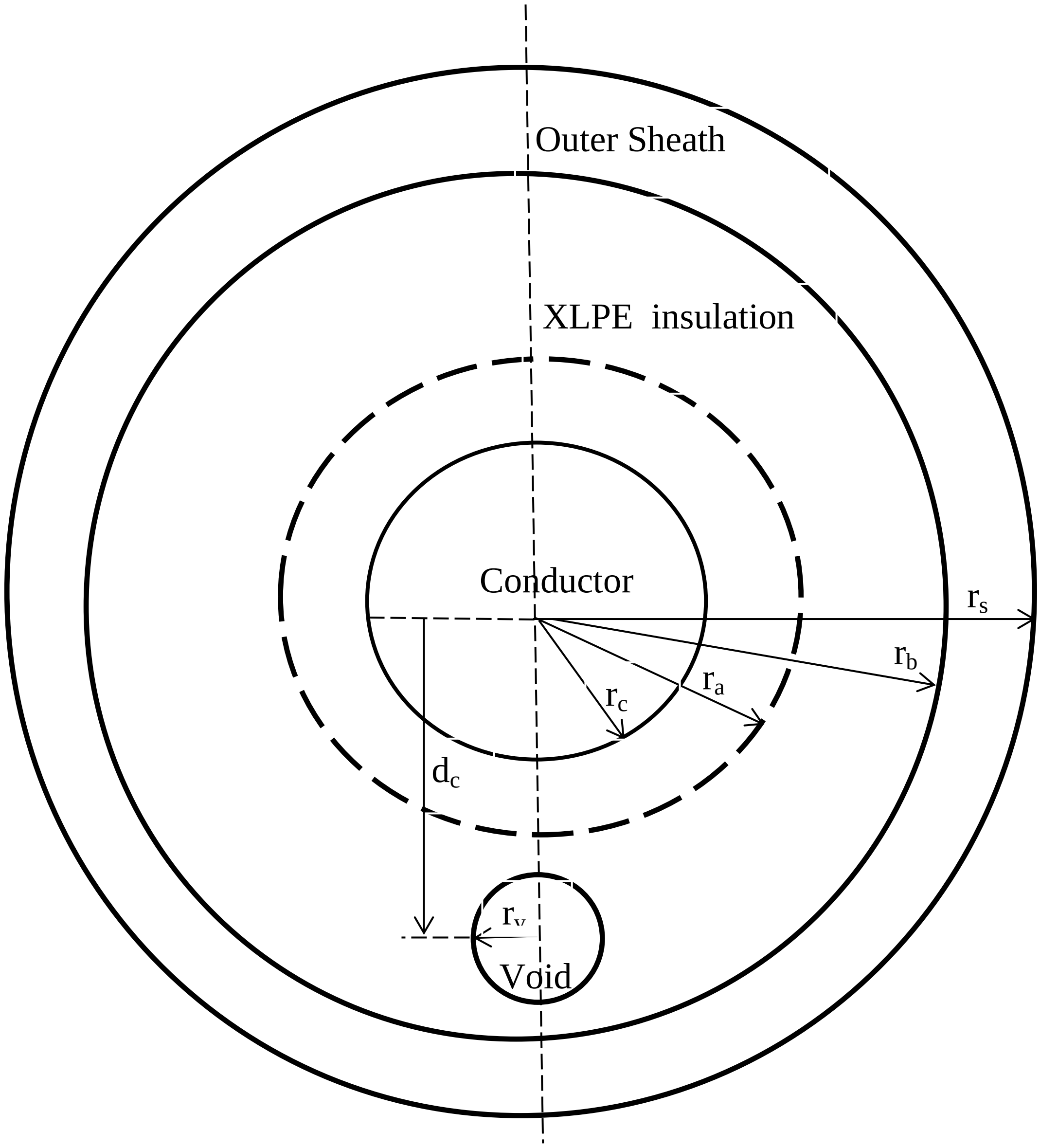

Figure 3.3: Cross-sectional area of an XLPE cable indicating the void location between the core and outer-sheath [14]

where, d_c is the distance between the void and the conductor, r_c is the radius of the conductor, r_a is the distance between the conductor core and the conductor sheath, r_b is the distance between the conductor core and insulator sheath while, r_s is the distance between the conductor core and the cable outer-sheath, r_v is the radius of the void.

The void is assumed to be located in the insulator part and the parameters were calculated for different location points of the void within the insulation as well as for different void sizes. The points considered are as follows:

(1) Close to the conductor but very far from the outer-sheath.

(2) In-between the conductor and the outer-sheath.

(3) Close to the outer-sheath but far from the conductor.

Firstly, the parameters of the void location are calculated using the XLPE cable data sheet. The electrical characteristics are also calculated as proposed in [14] in order to accurately implement the void PD simulation in MATLAB.

Based on the void parameter analysis, the electrical characteristics of the void and the insulation such as capacitances and resistances are calculated as proposed in [15-16] and [18]. The calculations are carried out for the different void positions within the insulation using the following equations gotten from carefully examining the cross-sectional area of a XLPE cable.

3.3 Calculation of parameters

3.3.1 Major Parameters

r_c = 5.5 mm

r_s = 18.5 mm

r_x = r_c + Void location (this was varied for different points)

D_{ins} = 4 mm (insulation thickness)

$$K_{ef} = \frac{3\epsilon_r}{1+2\varepsilon_r} \text{ (correction factor)} \tag{3.1}$$

Where ε_r is the relative permittivity of XLPE = 2.645.

K_{ef} as suggested by Stratton in [20] is a dimensionless correction factor that amplifies the electric field in an ellipsoid void in relation to the insulating material. It is pertinent to note that the void presence obviously causes irregularities in the uniformity of the electric field within the void and this situation as such affects the calculation. The correction factor is used to correct the influence of this on the calculated results [18].

3.3.2 Radial distances

$$r_a = r_c + d_c - \left(\frac{r_v}{2}\right) \tag{3.2}$$

and

$$r_b = r_c + d_c + \left(\frac{r_v}{2}\right) \tag{3.3}$$

where r_v is the void radius and d_c is distance between the conductor and the void.

3.3.3 Resistances

The equations for the resistances

$$R_1 = \left(\frac{1}{\sigma_{ins}} + \frac{r_x}{t_v l_v}\right) \ln\left(\frac{r_a}{r_c}\right) \tag{3.4}$$

$$R_2 = \left(\frac{1}{\sigma_{ins}} + \frac{r_x}{t_v l_v}\right) \ln\left(\frac{r_s}{r_b}\right) \tag{3.5}$$

where t_v is the width of the void, l_v is the length of the void which are taken to be 1mm each and d_c is the distance between the conductor and the insulation as shown in Figure 3.3. The resistances R_1 and R_2 are arranged in the circuit to be in series; therefore, to further simplify the circuit, their equivalent resistance is calculated and then divided by the correction factor by the expression given below:

$$(R_1 + R_2)\, {K_{ef}}^{-1} \tag{3.6}$$

The resistance of the void, R_{void} is also calculated through the equation given below:

$$R_{void} = \left(\frac{1}{\sigma_{ins}} + \frac{r_x}{t_v L_v}\right) \ln\left(\frac{r_a}{r_b}\right) \tag{3.7}$$

where σ_{ins} is the insulation conductivity which is given as $7x10^{-17}$ mho/m

It is pertinent to note that the void resistance R_{void} does not need to be corrected using the equation (3.10). The reason is because the modification has been accounted for during derivation of its equation as noted in [18].

3.3.4 Capacitances

$$C_1 = \frac{\varepsilon_0 l_v t_v}{r_x \ln\left(\frac{r_a}{r_c}\right)} \tag{3.8}$$

$$C_2 = \frac{\varepsilon_0 l_v t_v}{r_x \ln\left(\frac{r_b}{r_a}\right)} \tag{3.9}$$

Where ε_0 is the permittivity of space with the value $8.854x\ 10^{-12}$ [F/m]

The equivalent values of the two capacitances in parallel connections

$$C_{scor} = \frac{C_1 C_2}{C_1 + C_2}\ K_{ef} \tag{3.10}$$

Where the capacitor in parallel to the void is given as

$$C_p = \frac{2\pi\varepsilon_{ins} L}{\ln\left(\frac{r_s}{r_a}\right)} \tag{3.11}$$

Where $\mathcal{E}_{ins}$ is the relative permittivity of the XLPE insulation and its given as 2.645.

$$C_{void} = \frac{\varepsilon_0 l_v t_v}{r_x \ln\left(\frac{r_b}{r_a}\right)}\ K_{ef} \tag{3.12}$$

3.4 Values Obtained

The calculations are made for the different void locations within the insulation and the result obtained is given in tabular form in Table 3.1.

Table 3.1: Calculated parameters for the considered void locations

Calculated Parameters	Void distances from conductor				
	1.5 mm	2.0 mm	2.5 mm	3.0 mm	3.5 mm
C_p (F)	$2.69x10^{-10}$	$2.69x10^{-10}$	$2.69x10^{-10}$	$2.69x10^{-10}$	$2.69x10^{-10}$
R_p (Ω)	$1.24x10^{15}$	$1.24x10^{15}$	$1.24x10^{15}$	$1.24x10^{15}$	$1.24x10^{15}$
C_{scor} (F)	$1.045x10^{-14}$	$9.54x10^{-15}$	$8.76x10^{-15}$	$8.11x10^{-15}$	$7.53.x10^{-15}$
R_{scor} (Ω)	$3.2x10^{19}$	$3.51x10^{19}$	$3.82x10^{19}$	$4.13x10^{19}$	$4.44x10^{19}$
C_{void} (F)	$1.86x10^{-14}$	$1.85x10^{-14}$	$1.85x10^{-14}$	$1.85x10^{-14}$	$1.85x10^{-14}$
R_{void} (Ω)	$1.00x10^{11}$	$1.0015x10^{11}$	$1.0015x10^{11}$	$1.0015x10^{11}$	$1.0015x10^{11}$
R_{str} (Ω)	$10x10^{3}$	$10x10^{3}$	$10x10^{3}$	$10x10^{3}$	$10x10^{3}$
C_{str} (F)	$1.86x10^{-15}$	$1.85x10^{-15}$	$1.85x10^{-15}$	$1.85x10^{-15}$	$1.85x10^{-15}$

3.5 Simulink Model

The model used in the simulation is shown in Figure 3.4. It is modified version of the capacitive model and the models proposed in [14-16].

where C_{scor} is represent the insulation around the void and it is in series in the void in this model. It has being corrected by a correction factor K_{ef} as proposed in [12] and R_{scor} is the corresponding resistance, C_{void} is the capacitance of the void itself where R_{void} is its resistance.

The breaker is switched once to implement the discharge at an applied voltage of 25 kV for 50 Hz. Then the PD current and voltage as well as the applied voltage waveform are observed by the use of oscilloscope. The model was implemented in MATLAB Simulink is given in figure 3.4.

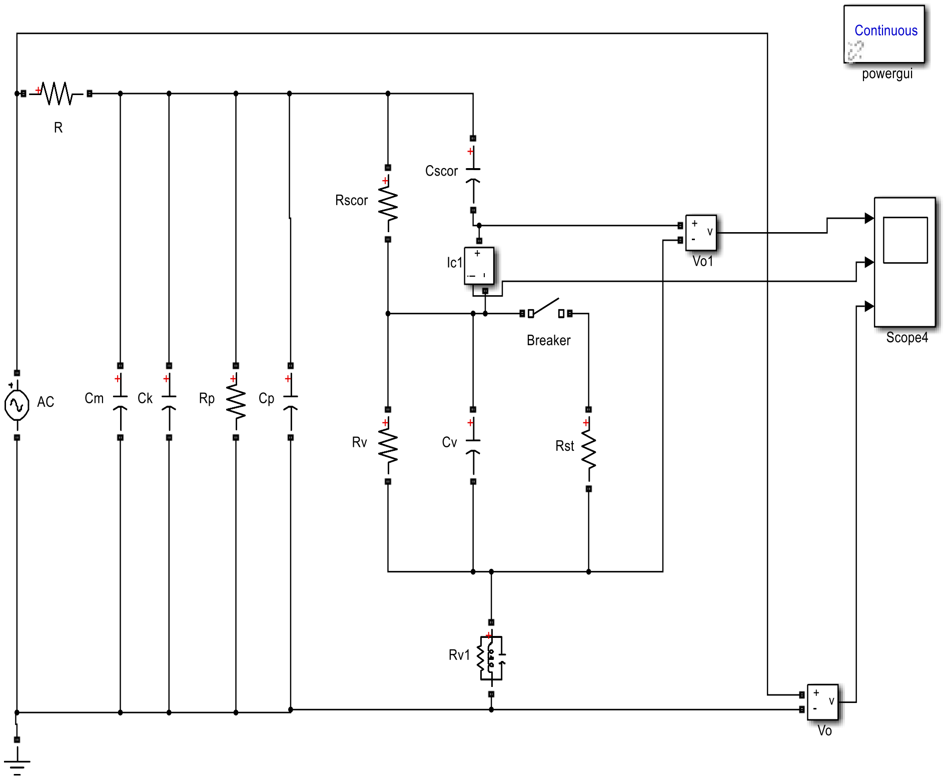

Figure 3.4: Model configuration in MATLAB simulink.

In this model, a real life experiment scenario was considered in order to have a perfectly simulated discharge and a reliable output, this is the reason for the use of coupling capacitor C_k, a high voltage measuring capacitor C_m and a detector device Rv1 represented by an RLC parallel connection, these are required for a standard PD experiment case as stated in [6,11], here the values of Cm and C_k are given as 100pF and 1000μF respectively while the values of the detector device represented by RLC branch are given as follow R=50Ω , L = 0.63mH and 0.47μF.

The scope shows the waveforms of the applied voltage, PD voltage and PD current for effective comparison.

Chapter 4

RESULT AND DISCUSSIONS

4.1 Simulation Result for different void location result

The simulation was ran for 0.07 sec, with an applied voltage of 25 kV, frequency of 50Hz while ode23tb (stiff/TR-BDF2) solver with a variable step-size and non-adaptive algorithm configuration in MATLAB Simulink.

The resulting simulations for the different void locations are shown below. The locations considered are 1.0mm, 1.5mm, 2.0mm, 2.5mm and 3.0mm distances from the conductor.

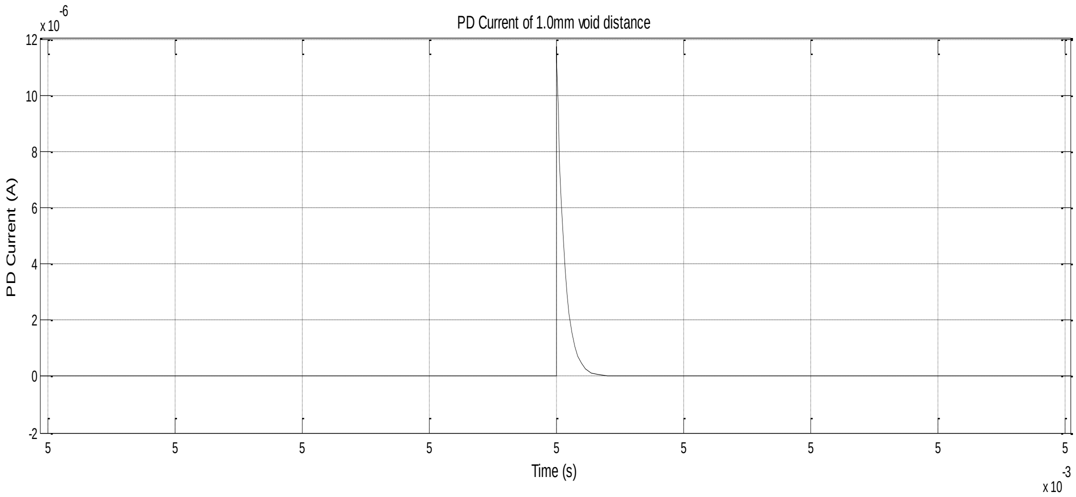

Figure 4.1: PD Current result for 1.0 mm void distance location.

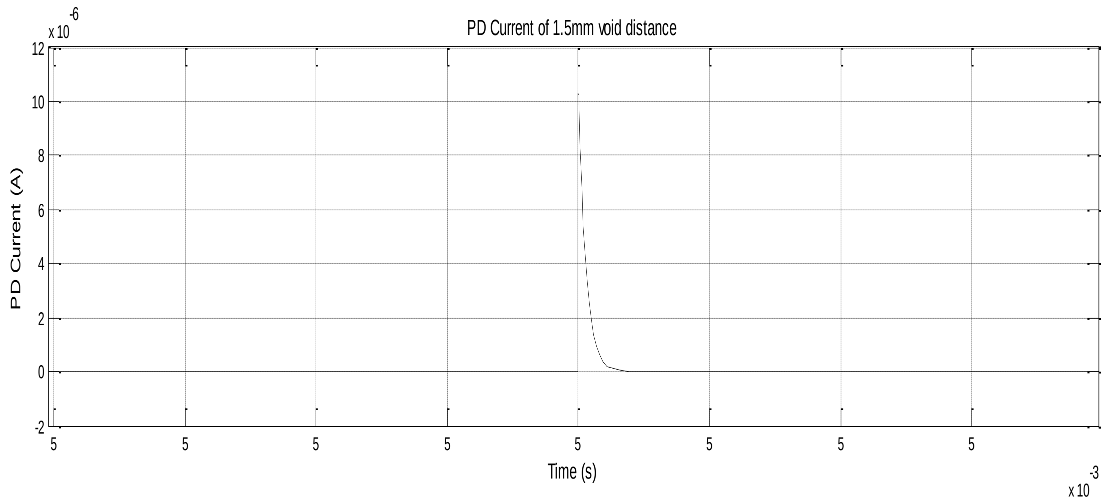

Figure 4.2: PD Voltage result for 1.5mm void distance location.

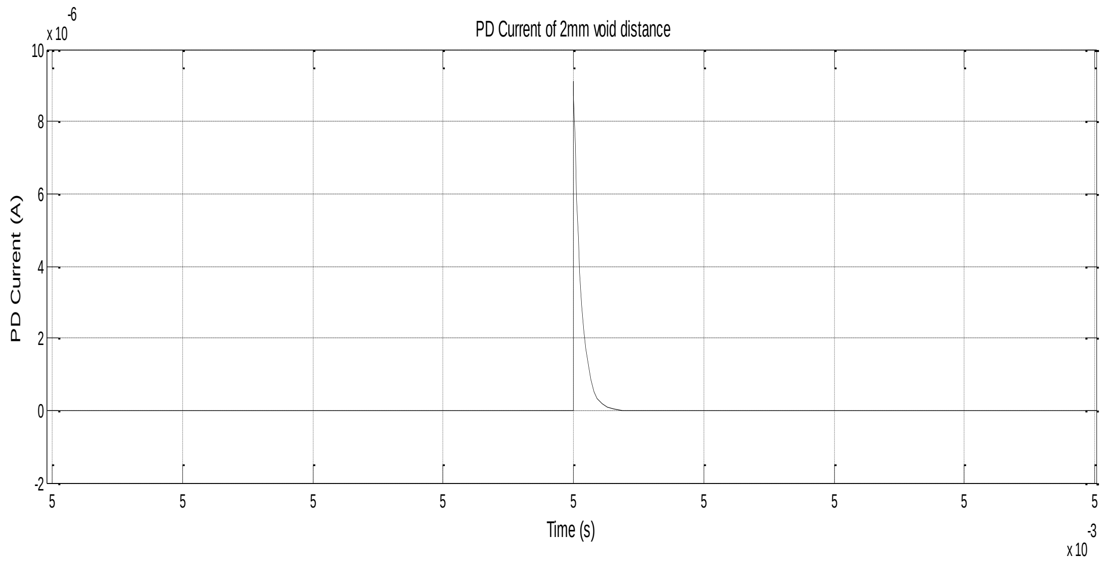

Figure 4.3: PD Current result for 2.0mm void distance location.

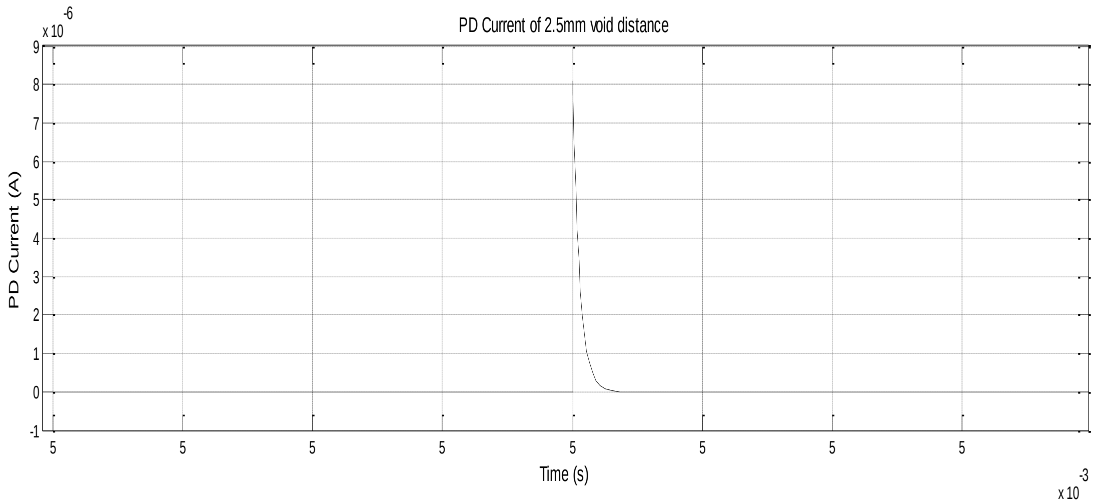

Figure 4.4: PD Current result for 2.5mm void distance location.

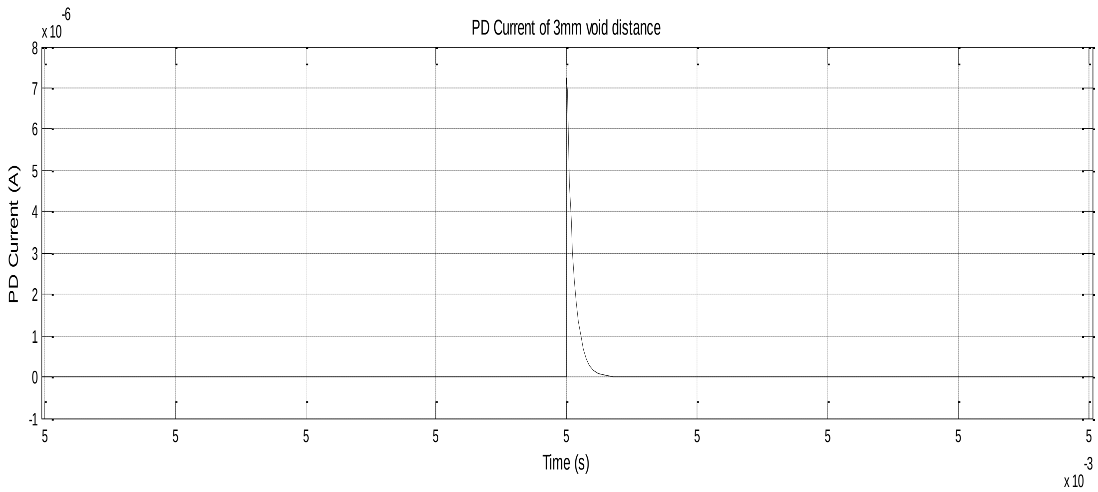

Figure 4.5: PD Current result for 3.0mm void distance location.

The amplitude of each PD current with respect to its void distances from the conductor is given in tabular form in table 4.1 while the graph comparison is given in the figure 4.6.

Table 4.1: PD current of each void distances from the conductor.

Void Distances	PD Current
1.0mm	$1.17x10^{-5}$
1.5mm	$1.03x10^{-5}$
2.0mm	$9.01x10^{-6}$
2.5mm	$8.10x10^{-6}$
3.0mm	$7.24x10^{-6}$

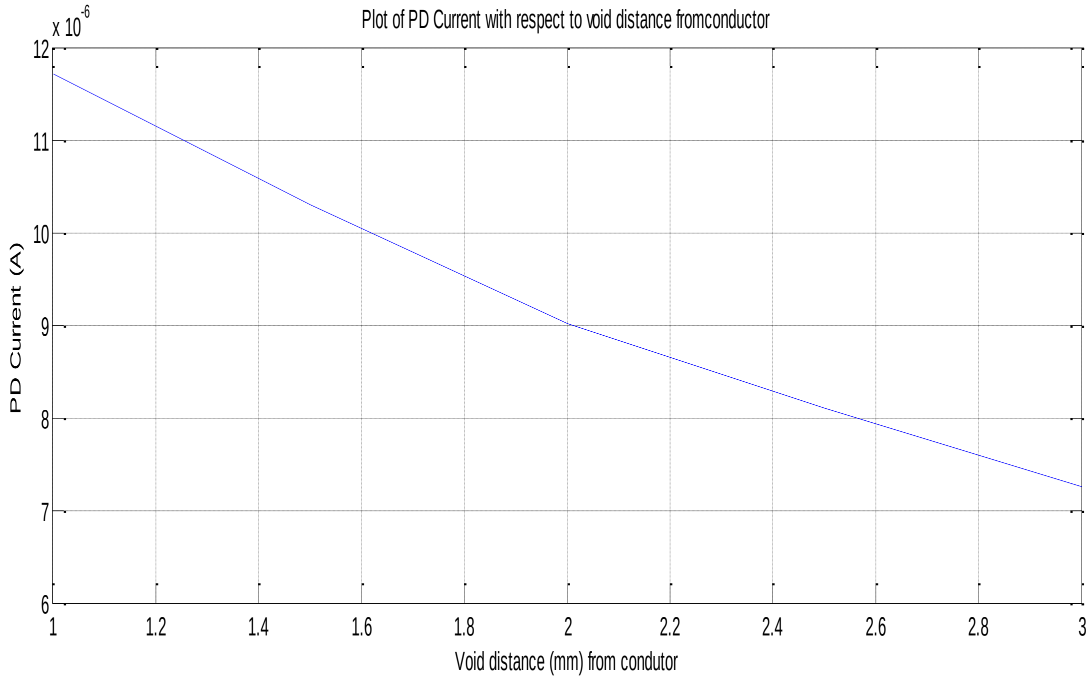

Figure 4.6: Plot of PD Current for varied void distances

It can be rightly noted that there are significant differences in the simulation results under the influence of the same applied voltage. It is observed that the PD current amplitudes are higher when the void is closer to the core of the conductor and it reduces as the void position moves farther from the conductor. It can be conclusively said that PD occurrence in the insulation is a function of the proximity of the void to the conductor.

4.4 Simulation result of PD current compared with different void sizes

Different void sizes were considered during the simulation and the simulation result for the PD current observed are considered and compared. The graph for the observed result is plotted and it is shown in Figure 4.7 below:

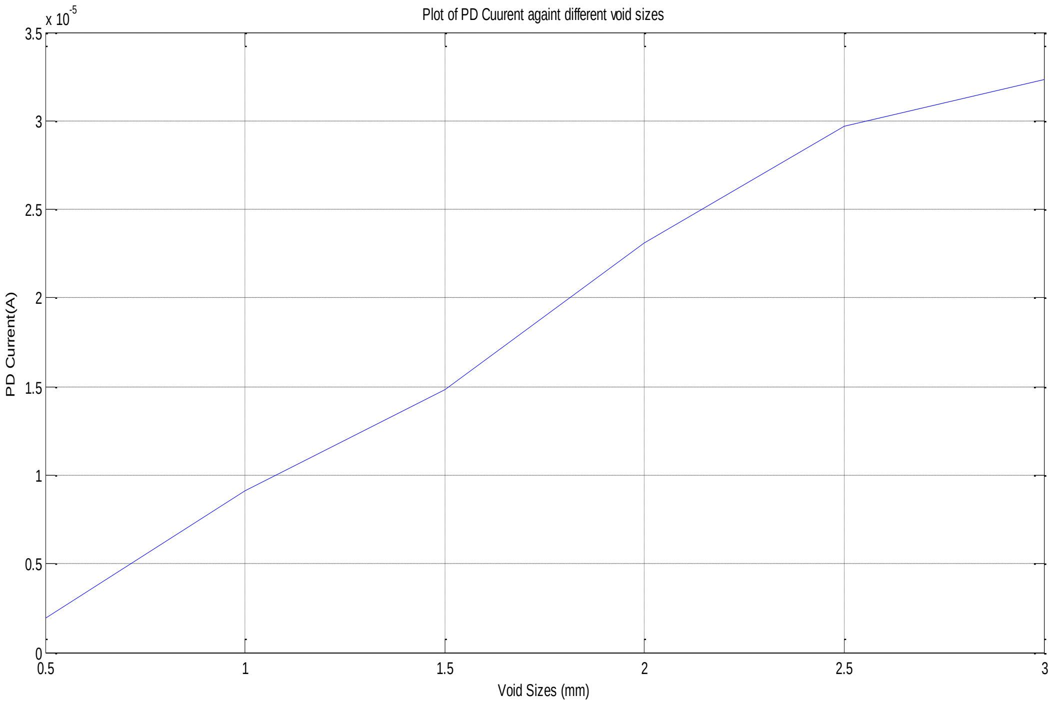

Figure 4.7: PD current against void sizes

From the graph, it is seen that as the void size is increased, the current discharge increases as well, it is concluded here that change in the void size contribute significantly to the discharge magnitude which agrees with researches already done on PD.

4.4 Comparison with the simulations of other research works

There have been several models created and simulated to represent PD in a void, the result in this research work is compared with two of these models, the models are; a model created by Achillides Z et al in [17] and a model created by Farhad H et al in [18], the models are given as follows;

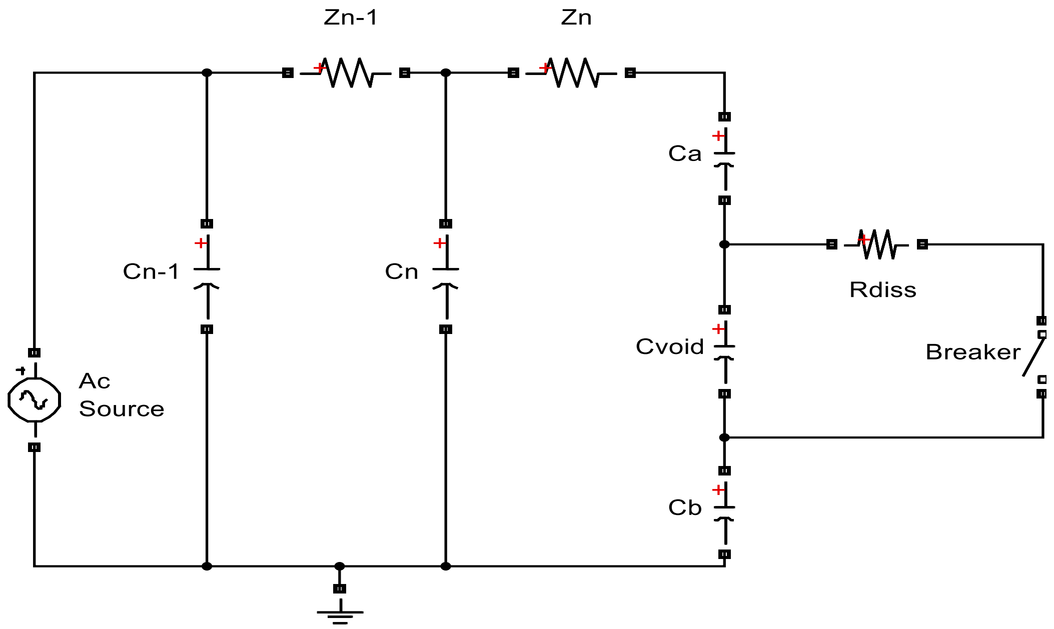

Figure 4.8: Achillides Z et al model [17]

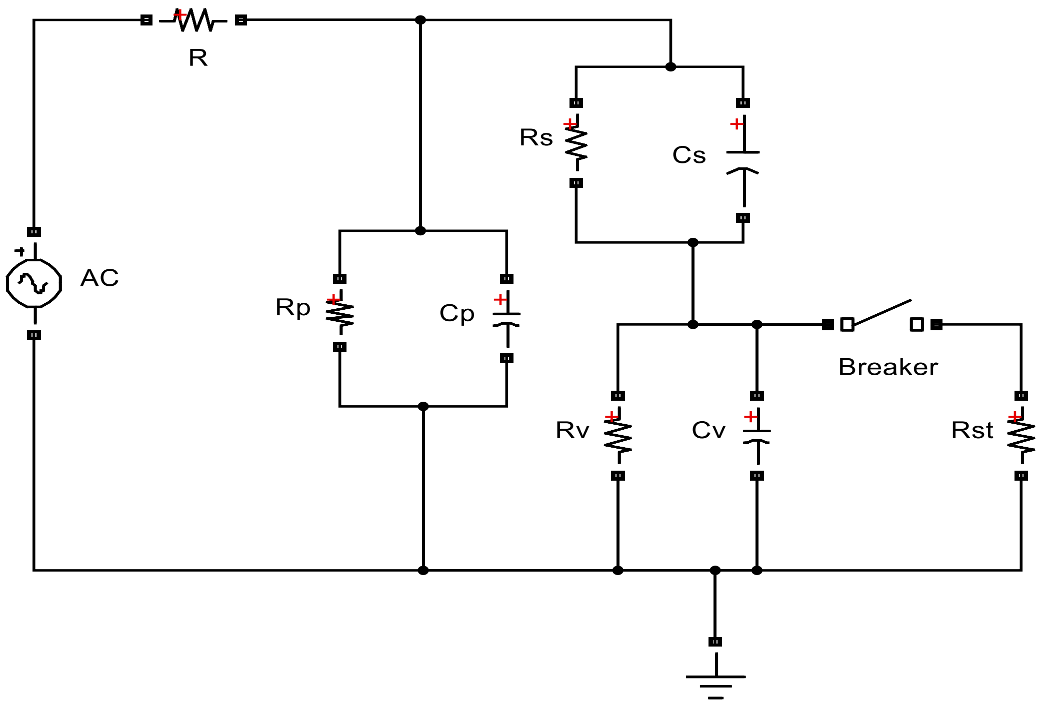

Figure4.9: Farhad H et al model [18]

The resulting PD currents and voltage of the two models were compared with the results of the thesis, the amplitudes of the PD current of Achillides Z et al model is found to be 1.435×10^{-4}A while the PD current for Farhad H et al model is found to be 6.549×10^{-5}A compared to the PD current of the thesis model which was found to be 1.89×10^{-5}A.

The major differences between the model used in the thesis and the compared model is the real life experimental scenario considered in the model which involves the use of the coupling and measuring capacitors as well as the detector device, This makes the model results to be much more reliable as proved in [20].

Chapter 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

This research work has been able to successfully investigate the activities of PD in a void located at different points within the insulation of an XLPE cable. A useful and efficient model is developed and its electrical parameters are calculated using the geometric characteristics of the void in the cable. The void sizes and distances were also varied in order to analyze PD occurrence and activities at different void locations and sizes. It is noted that the void sizes and proximity to the conductor has a significant effect on the PD activity.

5.2 Future Works

For further in-depth study and understanding, it is recommended that different void shapes and geometry be considered. The PD activities could also be investigated using other types of insulators. It is possible that the PD characteristics could be investigated using different frequencies as well. The applied voltage frequency used in this work is 50 Hz.

The void simulation can also be integrated into a distribution network to see its effect. The switching times could also be increased to see the effect of repeated PD occurrence in the void. In addition to the above, aside MATLAB which was used in the thesis other computer application programs could be used to simulate the activities of PD in an insulation system.

REFERENCES

[1] HVPD, *"An Introduction to partial Discharge"* Retrieved from http://www.hvpd.co.uk/technical, Feb 2014.

[2] OMICRON, *"Partial Discharge Analysis"* Retrieved from https://www.omicron.at/en/products/power-transformer/diagnosis/partial-discharge-analysis, Feb 2014.

[3] Partial Discharge Academy, *"What is Partial Discharge"* Retrieved from http://www.partial-discharge-academy.com/what-is-partial-discharge,Feb 2014.

[4] Suzuki H., Aihara K. & Okamoto T., "Complex behavior of a simple partial-discharge model.", *Europhys. Lett*, Vol 66, No 1, p.28. 2004.

[5] Danikas M.G., Papagiotopoulos D.. "Partial discharges in solid insulation cavities: A theoretical analysis and a comparison with experimental results", *Facta Universitatis, Ser.: Elec. Energy*., Vol. 15, No. 3, pp. 385-398, 2002.

[6] Edin H., *Partial Discharges Studied with Variable Frequency of the Applied Voltage.* Sept 14, Stockholm, Sweden : Kungl Tekniska Högskolan, TRITA-EEK-0102., 2001.

[7] Corona effect on power system, *Retrieved from http://www.electrical4u.com/* August, 2014.

[8] Danikas M.G., George E. V., “The case of Pedersen's theory to model partial discharges in cavities enclosed in solid insulation: a criticism of some of its aspects from an electrical engineer’s and from a physicists' point of view’ *Journal of electrical engineering,* vol. 52, no. 5-6, 2001, 166-170.

[9] Steven M. & David A. Horvath “microscopic void detection as a prelude to predicting remaining life in electric cable insulation” *International Topical Meeting on Nuclear Plant Instrumentation, Controls, and Human-Machine Interface Technologies(NPIC&HMIT 2000),* Washington, DC, November, 2000.

[10] Gabe P.E. & Alex G. “Partial discharge theory and technologies related to medium voltage electrical equipment”, *Institute of Electrical And Electronic Engineers IAS 34th Annual Meeting,* 2000.

[11] Asima S & Karmakar S. “Simulation of Partial Discharge in High Voltage Power Equipment” *International Journal on Electrical Engineering and Informatics* - Vol 3,No 2, 2011.

[12] Crichton G.C., Karlsson P. W. & Pedersen A., “Partial discharges in ellipsoidal and spheroidal voids”, *IEEE Trans. Electrical Insulation,* Vol. 24, pp. 335–342, 1989.

[13] Pedersen A., “Partial Discharges in Voids in Solid Dielectrics. An Alternative Approach”, *1987 Annual Report – Conf. on Elect. Insulation and Di- electric Phenomena, IEEE Publication*, pp. 58-64, 1987.

[14] Achillides Z., ,Kyriakides E. & Georghiou G .E., “Partial Discharge Modeling: An Improved Capacitive Model and Associated Transients along Medium Voltage Distribution Cables”, *Dielectric and Electrical Insulation., IEEE Transactions*, Vol.20, Issue. 3, pp. 770 – 78, 2013.

[15] Achillides Z.,, Kyriakides E.,& ,Georghiou G.E, “Partial Discharges and Associated Transients: The Induced Charge Concept versus Capacitive Modeling”, *IEEE Transactions on Dielectrics and Electrical Insulation* Vol. 15, No. 6; December 2008.

[16] Arief Y. Z., Izzati W. A, & Adzis Z.” Modeling of Partial discharge mechanism in solid di-electric materials”, *International Journal of Engineering and Innovative Technology (IJEIT)* Volume 1, Issue 4, 2012.

[18] Farhad H., Esmaeel K. & Mohammad S. “Comprehensive 3-capacitors model for partial discharge in power cables”, COMPEL: *The international Journal for Computation and Mathematics in Electrical and Electronic Engineering*, Vol 31, No 2, 2012 pp 346-368.

[19] Niemeyer L., “A generalized approach to partial discharge modeling*”, IEEE Trans. Dielectric and Electrical Insulation*, Vol.2, pp.510–528, 1995.

[20] McAllister I. W. & Crichton G.C. “Analysis of the temporal fields in lossy dielectric media”, *IEEE Trans. Electric Insulation*., Vol. 26, pp. 513–528, 1991.