PARTIAL DISCHARGE CHARACTERISTIC OF ELECTRICAL TREES IN POLYMERIC CABLE INSULATION

A Thesis submitted in partial fulfillment of the Requirements for the Award of the degree of

Master of Technology

In

Industrial Electronics

By

SUDHANSU SEKHAR BEHERA

ROLL No: 212EE5441

May, 2014

Department of Electrical Engineering
National Institute of Technology, Rourkela
Rourkela-769008, India
http//:www.nitrkl.ac.in

PARTIAL DISCHARGE CHARACTERISTIC OF ELECTRICAL TREES IN POLYMERIC CABLE INSULATION

A Thesis submitted in partial fulfillment of the Requirements
for the Award of the degree of

Master of Technology

In

Industrial Electronics

By

SUDHANSU SEKHAR BEHERA

Under the Guidance of

Prof. Subrata Karmakar

Department of Electrical Engineering
National Institute of Technology, Rourkela
Rourkela-769008, India
http//:www.nitrkl.ac.in

National Institute of Technology Rourkela

CERTIFICATE

This is to certify that the thesis entitled, **"Partial discharge characteristics of electrical trees in polymeric cable insulation"** submitted by **Sudhansu Sekhar Behera (Roll No. 212EE5441)** in partial fulfillments for the requirements for the award of Master of Technology Degree in Electrical Engineering with specialization in **"Industrial Electronics"** during 2012-2014 at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any degree or diploma.

Date: 02/05/2014

Prof. S. Karmakar

Department of Electrical Engineering
National Institute of Technology
Rourkela-769008

ACKNOWLEDGEMENT

I have been very fortunate to have **PROF. S. KARMAKAR**, Department of Electrical Engineering, National Institute of Technology; Rourkela as my project supervisor. I am highly indebted to him and express my deep sense of gratitude for his guidance and support. I am grateful to my supervisor, who gave me the opportunity to realize this work. He encouraged, supported and motivated me with much kindness throughout the work. In particular, he showed me the interesting side of the high voltage engineering and those of the highly interdisciplinary project work. I always had the freedom to follow my own ideas, which I am very grateful for him. I really admire him for patience and staying power to carefully read the whole manuscript. I am also grateful to our head of department, **PROF. A. K. PANDA**, who gave me the opportunity to work in this field.

I express my sincere gratitude to all the faculty members of the Department of Electrical Engineering, NIT Rourkela for their unparalleled academic support.

I render my respect to all my family members for giving me mental support and inspiration for carrying out my research work.

Date: 02/05/2014

Sudhansu Sekhar Behera
Roll. No.: 212EE5441
M. Tech (Regular)
Dept. of Electrical Engineering

CONTENT

ABSTRACT

The growth mechanism of electrical tree in high voltage and extra high voltage dielectric system is needed for early identification, in order to resist the complete insulation failure. In power system equipment, electrical tree formation prevention is very much crucial for reliable and long term operation of cable section. There are so many varieties of electrical tree structure can formed from a weak region or a imperfection site in cable insulation viz branch-type trees, bush-type trees and bush-branch type trees depending on the voltage applied. Electrical treeing was developed in a needle-plane geometry using 5µm tip radius hyperbolic needle shape and a 2 mm gap from the tip of the needle to plane electrode in polymeric samples. This project was conducted by simulations based work in order to understand the characteristics of electrical trees in solid dielectric materials. In this work, electrical tree formation mechanism in solid dielectric material was modeled using MATLAB environment and done experimental work in high voltage laboratory with the application of 100 kV AC source with 50 Hz supply voltage. After the experiment the sample was viewed under FESEM for observation of electrical tree growth. It was found that the FESEM was particularly useful for searching for electrical damage in the polymeric insulation material where treeing phenomena takes place.

LIST OF ABBREVIATION

Abbreviation	Acronyms
PD	Partial Discharge
HV	High Voltage
EHV	Extra High Voltage
XLPE	Crosslink polyethylene
SEM	Scanning electron microscope
FESEM	Field emission scanning electron microscope
CSM	Charge simulation method
GA	Genetic Algorithm

LIST OF SYMBOL

Symbol	Name of symbol
E	Electric field
E_c	Critical electric field
W_e	Electrostatic energy density
ϵ_0	Permittivity of the free space
ϵ_r	Relative permittivity
W_m	Mechanical energy density
σ	Mechanical stress
γ	Modulus of elasticity
G	Toughness
K_c	Critical crack number
E_{max}	Maximum electric field strength
V	Applied voltage
r	Needle tip radius
d	Gap between tip to ground electrode
q	Apparent charge
k	Coulomb constant

LIST OF FIGURE

LIST OF TABLE

CHAPTER 1

INTRODUCTION

Introduction

Literature review

Motivation and objective of the thesis

Organization of the thesis

Chapter 1

INTRODUCTION

1.1 INTRODUCTION

In recent year, XLPE cable is widely used for high voltage (HV) power system application such as power distribution and transmission lines up to 765 kV for its extremely good properties such as electrical, mechanical and thermal characteristics. When it is subjected to electrical stress its electrical properties deteriorate or degrade over the time similar to other type of insulating materials. One of the important causes for the long-term deterioration in case of polymeric insulating materials used in high voltage application is electrical tree. At the time high electrical stresses, the polymeric insulation undergoes localized degradation at stress enhancement due to contaminants within insulation interfaces. This degradation process is known as electrical treeing which is a tree like structure having numerous branching at the point of degradation. It has three phases such as tree initiation, tree propagation and at last final breakdown which is the final stage of the insulation failure. Electrical treeing is considered the most relevant mechanism of insulation breakdown in different solid insulating materials. Till now so many different methods have been given for the simulation of the short-lived propagation of electrical trees. Niemeyer et al was given a stochastic model for the electrical tree development assuming the conductive tree channels are collectively a local growth probability and relative to a certain power of the electric field [1].

The mechanism of electrical treeing in solid insulation was reported by many researchers that electrical tree is originating at points where different contaminants like impurities, bubbles, gas void, mechanical cracks or conducting projection cause extreme electrical and mechanical stress within small portion or local area of the dielectric materials. One of the main fundamental tools for the characterization of an insulation defect in case of insulation material is partial discharge (PD) measurement. It will provide early detection of electrical tree in various insulating medium. Electrical treeing is one of partial discharge phenomena in a dielectric system of XLPE insulated cable.

Overlay in one line, Partial discharge is the cause and electrical tree is the effect. Electrical treeing is not just the principle component for influencing the unwavering quality of cable insulation, additionally the last destructive condition of cable insulation working in the long time period. Once it is initiated, it would grow up and bring a severe damage and failure in daily life and the economy. The dielectric strength of XLPE is very high nearly about 1000 kV/mm but the actual operating voltage is very much lower than this value. In the electrical treeing process, the branching paths are known as degradation process which is caused mainly due to high voltage stress and their growth can be observed experimentally. Usually in case of high voltage (HV) and extra high voltage (EHV) power transmission cable system, electrical treeing phenomena are the main cause for cable failure. Recently, it has been identified that testing the underground cables in case of damage or defects, under the application of composite voltage formed due to AC/DC is more reliable compared to the AC/DC voltage test [2]. In this present work, an experimental and also simulation studies were carried out to recognize the growth dynamic process of electrical trees in underground XLPE cables under the AC power supply.

1.2 LITERATURE REVIEW

In the most recent century, when the high voltage engineering was presented for electrical power generation, transmission and distribution framework, an electrical trees sensation because of the Partial discharges have been perceived as a destructive hotspot for the solid insulation maturing in the high voltage power device. Diverse methods are created for identification, estimation and conduct investigation of electrical trees inside or outside of the solid polymeric insulation. Numerous creators have displayed their work about the discovery and estimation of electrical trees. Ramanujam Sarathi, Arya Nandini and Michael G. Danikas an endeavour has been made to recognize the partial discharges created because of the beginning and propagation of electrical trees receiving UHF method. And explained the various issues related to the electrical tree propagation in solid dielectric medium [3]. A. El-Zein, M. Talaat, and M. M. El Bahy given a proposed Model for Electrical Tree Growth in Solid Insulation. They have given another model for examining the electrical tree development in solid dielectric medium utilizing a hyperbolic needle-to-ground plane gap. The needle is installed in the dielectric medium. Tree shape characterized relying upon the electric field value. They have exhibited a model for re-enacting electrical tree development in a three dimensional field [4]. L. A. Dissado, J. M. Alison, J. V. Champion, S. J. Dood and P. I. Williams had given a report on The Propagation Structures of Electrical Tree in Solid Polymeric insulation. They have given two interchange methodologies to electrical tree propagation as per stochastic model that ascribe of tree structures to irregular probabilistic elements and in release avalanche model field variances are capable. It has been inferred that both models give the fractal structures of tree [5]. A. El-Zein, M. Talaat and M. El Bahy have given a Model of Simulation study for Electrical Tree in Solid Insulation Using CSM Coupled with GAs [6].

1.3 MOTIVATION AND OBJECTIVE OF THE THESIS

1.3.1 MOTIVATION

The presence of Partial discharge is a main problem for insulation deterioration of polymeric cable used in the underground cable system. It is seen that most of the cable insulations are manufactured with great care so that no impurity is added or remain in the insulation. But some small amount of impurity is always present during its manufacturing process. The impurities are appearing in the form of solid, liquid or gas. During the time of manufacturing process of such cable insulation the impurity is present in the form of air bubble and voids which creates a weak field inside the insulation. Most of the failure of such insulation occurs due to presence of PD at the weak zones with high voltage stress in the polymeric cable insulation. One of the primary reasons of the dielectric degradation of the XLPE cable framework is known as the electrical treeing. Electrical treeing is not just the primary variable influencing the unwavering quality of cross-linked polyethylene (XLPE) cable protection, additionally the final destructive form of cable protection working in the long run.

1.3.2 THE MAIN OBJECTIVE OF THE THESIS

The important objectives are

- To study the growth mechanism of electrical trees in high voltage XLPE polymeric insulation.

- Early Identification of PD in the solid dielectric insulation system in order to resist the complete dielectric insulation failure of the cable.

- Characterization of electrical tree formation in different applied voltages in MATLAB simulation environment.

- Experimentally, visualize the insulation degradation by the application of high electric field in solid XLPE insulation specimen.

- PD prevention is crucial to guarantee reliable and long term operation of the high voltage electrical appliances.

1.4 ORGANIZATION OF THESIS

This thesis sorted out into seven separate chapters including an introduction

Chapter 1: This chapter incorporates the introduction, motivation & objective of the thesis. It likewise contains the writing review subject on electrical treeing polymeric insulation protection and association of the thesis.

Chapter 2: This Chapter describes the concept of electrical trees and the necessity of electrical trees detection in XLPE cable insulation, its classification and the effects of electrical treeing in solid cable insulation and also its growth characteristics.

Chapter 3: This chapter discussed about a numerical model of electrical tree growth which includes the tree growth under electrical stress, under mechanical stress and both combined stress and also calculates the electric field stress.

Chapter 4: This chapter contains physical approach for the dielectric specimen and flow chart model for simulation project and investigation of the created model has been talked about.

Chapter 5: This chapter contains the simulation results and its discussion.

Chapter 6: In this chapter experimental setup is used for detection of electrical trees using the needle-plate electrode system in XLPE cable and about the FESEM that has been used for the study of experimental results are shown in figure.

Chapter 7: Finally this chapter concludes the project work and scope for the future work is discussed in brief.

CHAPTER 2

CONCEPT OF ELECTRICAL TREES

Introduction

Necessity of detection of electrical trees in XLPE cable

Classification of electrical trees

Effect of electrical trees in polymeric insulation

Chapter 2
CONCEPT OF ELECTRICAL TREES

2.1 INTRODUCTION

Now a day in all over world, polymeric insulated cables are widely used for the rapid development in solid dielectric manufacturing techniques. The polymeric cables are very much popular for HV and EHV application. The main polymer insulation material used for cable insulation is XLPE, due to its good electrical and mechanical properties. But at the time of production there is any manufacturing defects such as gas voids, bubbles, mechanical cracks, impurity those are influencing aging and breakdown process in cables when they are utilized within useful environment and electrical treeing phenomena is for the most part in charge of the XLPE cable's insulation failures. In the process of electrical treeing, tree shape degradation paths which are formed mainly due to high electric field stress in polymer and we can observe the tree shape experimentally. Thus, an electrical tree defined as pre-breakdown phenomena by which formation of degradation channels in solid polymeric insulation due to high electrical stress. The path formed by this process look like tree shaped hollow channels.

2.2 NECESSITY OF ELECTRICAL TREE DETECTION IN SOLID INSULATION

The process of manufacturing polymeric insulation structure involves several stages starting from selection and preparation of raw material, processing of raw material and also thermal or chemical treatment. The whole process provides a good electrical insulation to the high voltage system. But practically it is very difficult to achieve a perfect insulation because during the manufacturing process, there is some impurity contaminants may present that influence insulation failure followed by breakdown which is hazardous to mankind and economy. Due to the above reason electrical tree finding and observation is mandatory for forecasting of insulation life span in high voltage and extra high voltage system appliances.

2.3 CLASSIFICATION OF ELECTRICAL TREE

The electrical trees are categorized according to their channel patterns (a) Branch type electrical tree (b) Bush type electrical tree (c) Branch-bush type electrical tree [7].

(a) BRANCH TYPE ELECTRICAL TREE

Electrical tree generated under low voltage usually 6 kV to 10 kV having the characteristics of branch type because of less number of conducting channel under the application of weak electric field. The conducting channels are growing from needle tip to grounding electrode and progress rapidly.

Figure 2.1 Branch type electrical trees at 9 kV [8]

(b) BUSH-BRANCH TYPE ELECTRICAL TREE

Electrical tree generated under medium voltage usually within 11 kV to 17 kV having the characteristics of bush-branch type because of less number of conducting channel followed by more number of conducting channel under the application of applied electric field. The conducting channels are growing from needle tip to grounding electrode and progress rapidly with respect to time.

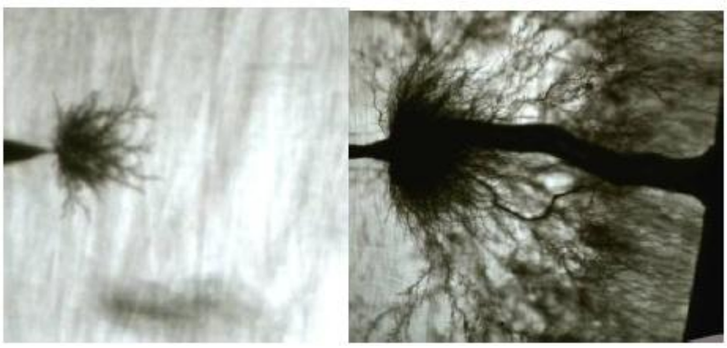


Figure 2.2 Bush-branch type electrical trees at 12 kV [8]

(c) BUSH TYPE ELECTRICAL TREE

Electrical tree generated under high voltage usually above 18 kV having the characteristics of bush type because of more number of conducting channel under the application of a greater electric field. The conducting channels are growing from needle tip to grounding electrode and progress slowly. The diameter of the bush type tree increases slowly with respect to time.

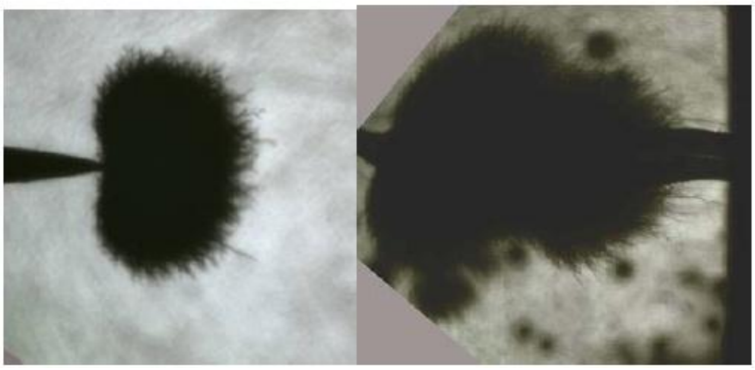


Figure 2.3 Bush type electrical trees at 18 kV [8]

2.4 EFFECT OF ELECTRICAL TREE IN POLYMERIC INSULATION

The formation of electrical tree in the dielectric basically consists of three different phases. These are inception, propagation and final breakdown. On first stage i.e. in the inception stage, damage gathers at the current range where defects are available. In propagation stage, number of branching channels begins from that defect territory and spreads over the dielectric. The tree propagation structure comprises of hollow channels and its development includes the inflammation of electrical discharges in existing channels. Despite the fact that the electric field stress has an essential part in driving the development, however in auxiliary, mechanical stress has additionally been demonstrated to influence the tree structure. At last, in breakdown stage, the channels have bridged the gap between the tips of inception to the ground electrode [9].

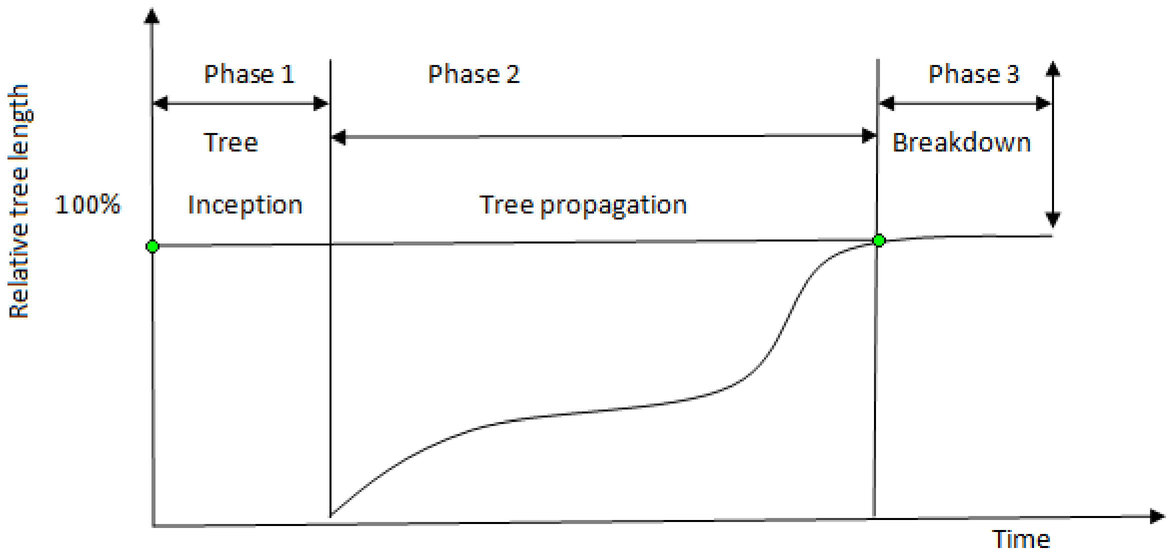


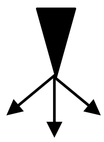
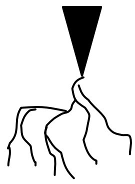
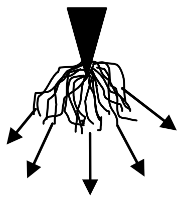
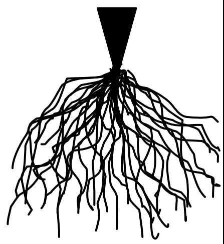
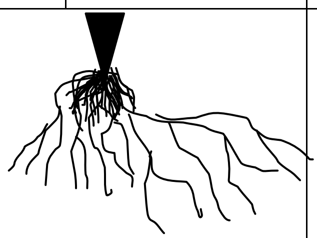
Figure 2.4 Electrical tree growth characteristics of polymeric insulation

The effect of tree generation crack begins in a solid insulating medium. At the time the strain energy deliver more than that required to overcome the dielectric strength of materials. As a result electrical breakdown and insulation failure takes place.

2.5. ELECTRICAL TREE GROWTH PHASE CHARACTERISTIC

The electrical tree growth phase can be explained by the tree growth rate characteristic. Table 2.5 show the electrical tree propagation process in an insulation sample where the double structure of electrical tree goes through all the growth phases such as initiation, propagation and final breakdown [10].

Table 2.5: The double structure dispersion process of electrical tree

Item Growth Phase	Electrical tree structure changing process In the process	 In the end	Growth characteristics
1. Electrical tree initiation phase			1. Electrical tree initiated at needle tip when charge injection and extraction to insulation. 2. Initiation of a single branch
2. Electrical tree propagation phase			1. Charge injection and extraction to dielectric from conducting channel. 2. The Dense branching electrical tree appears
3. The double structure formation phase			1. Growth of channels is rapid. 2. The insulation broken down and failure occurred.

CHAPTER 3

ELECTRICAL TREE GROWTH NUMERICAL MODEL

Proposed model of electrical tree

Electric field calculation

Chapter 3

ELECTRICAL TREE GROWTH NUMERICAL MODEL

3.1 ELECTRICAL TREES FORMULATION UNDER ELECTRICAL STRESS

In case of Electrical tree, each spark filament is taken as one crack [11]. Very high electric field (E) will produced at the tip of the filament which will give rise to mechanical stress.

W_e is known as the electrostatic energy density at the tip of the crack.

$$W_e = \frac{1}{2}\epsilon_{\circ}\epsilon_r E^2 \qquad (1)$$

Where$\epsilon_{\circ}$: Permittivity of the free space

ϵ_r: Relative permittivity of the insulating medium

3.2 ELECTRICAL TREES FORMULATION UNDER MECHANICAL STRESS

The strain energy density (W_m) is given as

$$W_m = \frac{\sigma^2}{2\gamma}\ \mathrm{J}/m^3 \qquad (2)$$

Where σ is known as mechanical stress and γ is known as modulus of elasticity.

They are initiated some extra area during crack which is known as toughness (G) and produced by energy per unit area and considering a mechanical crack the strain energy density is greater than toughness.

i.e. $\frac{\sigma^2}{2\gamma} > \mathrm{G}$

3.3 TREES UNDER COMBINED MECHANICAL AND ELECTRICAL STRESS

The mechanical stress induced by existing electric field (E) will be

$$\sigma = \frac{1}{2}\epsilon_{\circ}\epsilon_{r}E^{2} \tag{3}$$

After adding the strain energy (W_m) with the electrostatic energy (W_e) we can get total energy (W) regarding volume [12].

$$W = \left[\frac{\sigma^2}{2\gamma} + \frac{1}{2}\epsilon_o\epsilon_r E^2\right]\pi r^2 dl \tag{4}$$

Where r is the crack radius

But under the application of breakdown field, $W_m >> W_e$.

Therefore, $$W = [\frac{\sigma^2}{2\gamma}]\pi r^2 dl$$

$$= [\frac{\frac{1}{4}{\epsilon_0}^2{\epsilon_r}^2E^4}{2\gamma}]\pi r^2 dl$$

$$= [\frac{{\epsilon_0}^2{\epsilon_r}^2E^4}{8\gamma}]\pi r^2 dl \tag{5}$$

By considering a tubular shape crack having distance dl, it can overcome the crack deformation energy (W_f) and crack surface energy (W_s) of the crack. So, the total energy must be higher than ($W_s + W_f$).

Where, $$W_s = 2\pi \mathrm{rG}\, dl \tag{6}$$

$$W_f = \pi r^2 \gamma\, dl \tag{7}$$

From the above equation (5), the total energy is proportional to E^4

So, $$\mathrm{W} \propto E^4$$

At critical electric field (E_c) if this energy considered as the critical energy (W_c) then it will reached for tree initiation.

$$W_C = \frac{\pi r^2 E_c^4 \epsilon_0^2 \epsilon_r^2}{8\gamma} dl_0 \quad (8)$$

And

$$\frac{W}{W_c} = \left(\frac{E}{E_c}\right)^4 = k \quad (9)$$

By applying an equal volume criterion, $\pi r_0^2 dl_0$ is taken equal to $\pi r^2 dl.$ At critical electric field E_c, dl_0 is consider as crack length and r_0 is crack radius and energy destroy factor denoted as k which is constant.

In this approach the volume of one crack $=\frac{1}{3}\pi r^2 h$ and total volume of the destroyed volume with radius R is $\frac{4}{3}\pi R^3$ .In destroyed volume, the number of cracks covers the entire volume of bush type tree and in destroyed volume having spherical shape, the total number of cracks (K) with radius R_d will be

$$K = \frac{\frac{4}{3}\pi {R_d}^3}{\frac{1}{3}\pi {r_0}^2 R_d} = 4\left(\frac{R_d}{r_0}\right)^2 \quad (10)$$

In 3- Dimensional space for bush type tree, the number of k in collapse zone is

$$k = 0.064K = 25.6$$

But in 2- Dimension, the critical number of cracks (K_c) for bush tree is

$$k_{c} = \sqrt[3]{K} = 2.944$$

But substituting this value in equation (9) we can get

$$\frac{W}{W_c} = k_c$$

And

$$\frac{E}{E_C} = \sqrt[4]{k_c} = 1.31$$

From the above analysis, we conclude that

$\frac{E}{E_C} < 1.31$ Indicates a branch type tree

$\frac{E}{E_C} > 1.31$ Indicates a bush type tree [13]

3.4 ELECTRIC FIELD CALCULATION

The electric field strength in needle-plane electrode by assuming no space charge around the tree tip approximately can be [14],

$$E_{max} = \frac{2V}{rln\ (1+\frac{4d}{r})} \tag{11}$$

Where E_{max} = Maximum electric field strength

V = Applied voltage at the needle tip

r = Needle-tip radius

d = the space between the needle tip to ground electrode

When the electric field value reaches at 4 MV/cm at that time the electric field competent to overtake the mechanical strength and crack starts. This electric field is known as a critical electric fieldE_c.

$$V = \frac{1}{4\pi\epsilon_0}\frac{q}{r} \tag{12}$$

Where q is the apparent charge and r is radius of the point charge

$$q = 4\pi\epsilon_r\epsilon_0 Vr \tag{13}$$

$$= 32\ \pi\epsilon_r Vr \times 10^{-12}$$

And $\epsilon_0 = 8.85 \times 10^{-12 F/m}$ is known as permittivity of the free space

Electric field at every point charge

$$\text{E} = \frac{1}{4\pi\epsilon_0\epsilon_r}\frac{q}{r^2} \tag{14}$$

Where $K = \frac{1}{4\pi\epsilon_0} = 8.98 \times 10^9$ is known as coulomb constant

CHAPTER 4

CONSIDERATION FOR A NEW MODEL

Physical approach for dielectric specimen

Assumptions taken for tree propagation

Flowchart model for tree structure

Chapter 4

CONSIDERATION FOR A NEW MODEL

4.1 PHYSICAL APPROACH FOR DIELECTRIC SPECIMEN

Considering a dielectric material having dimension $20\ mm \times 5\ mm$ is divided into several 100 layers, each layer having $50\ \mu m$ contains random number of voids with random location in a two dimension specimen depending upon the value of voids by using binomial distribution function. Here we are choosing one simulated needle having hyperbolic shaped, with radius $r = 5\ \mu m$ and $\mathrm{d} = 5\ mm$. Where 'r' is the needle tip radius and 'd' is the separation gap between the metallic needle tip and ground electrode.

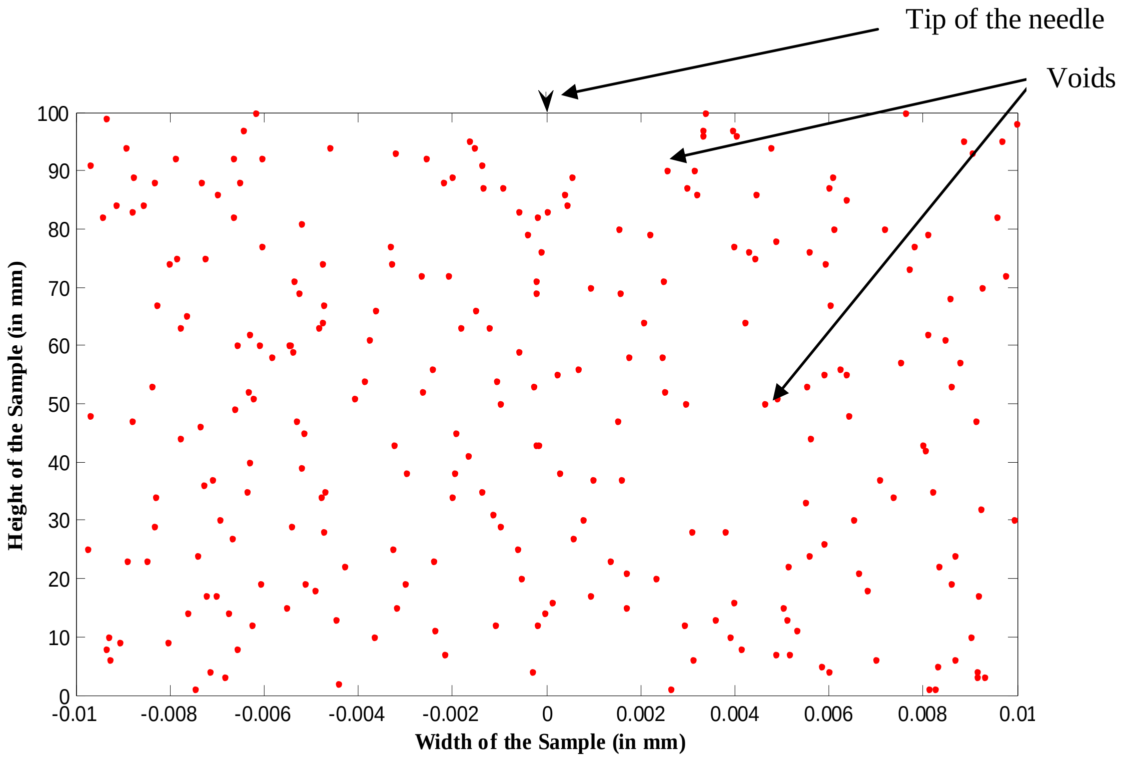


Figure 4.1 Model for air bubbles distribution in dielectric specimen

4.2 CONDITIONS FOR ELECTRICAL TREE PROPAGATION

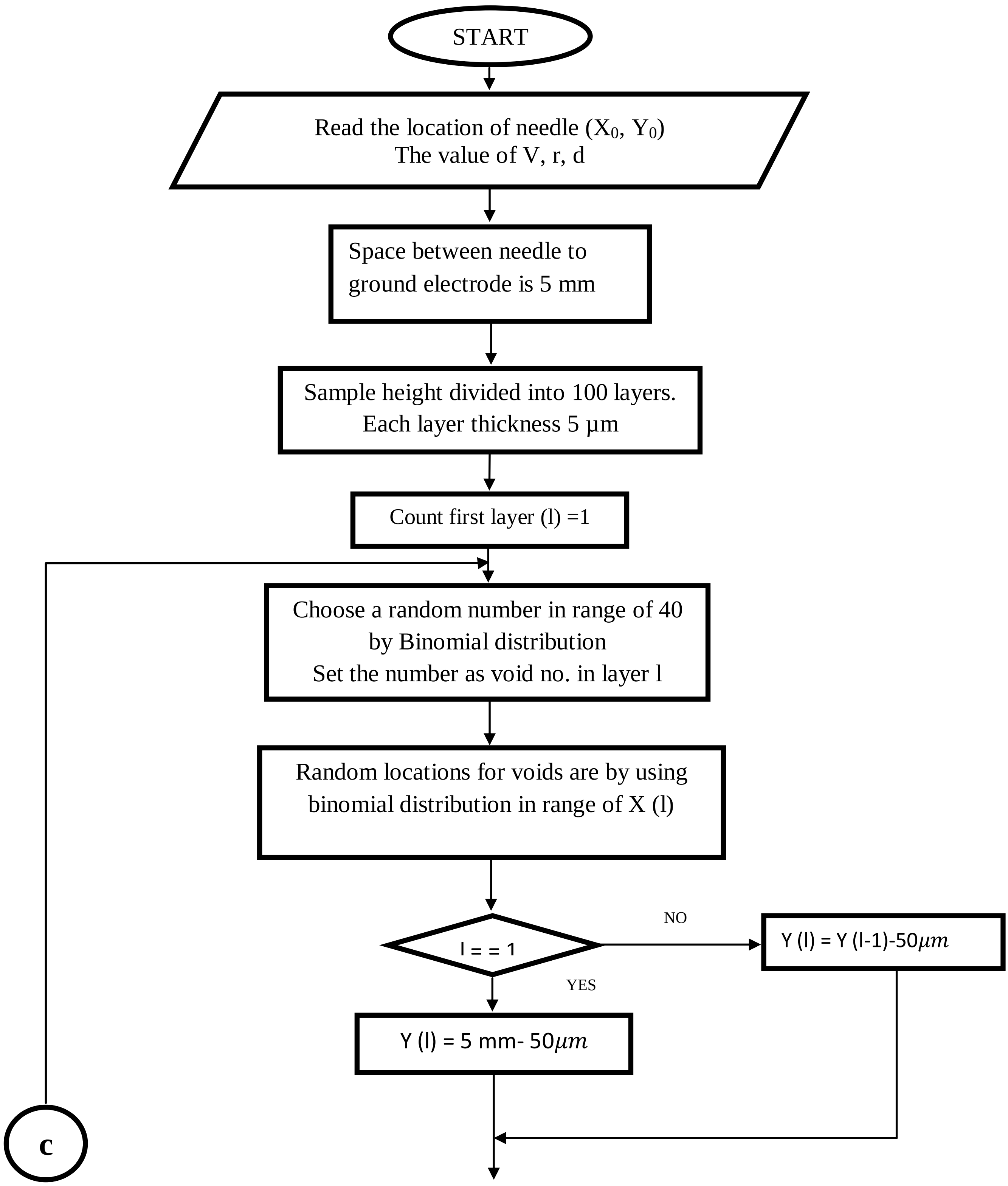
4.2.1 BRANCH TYPE ELECTRICAL TREE

- When the electric field reaches at 4 MV/cm, tree inception starts and formation of branching begins [12].
- At $\frac{E}{E_c} = 1$ one branch will form. If $\frac{E}{E_c} = 1.189$ two crack paths will added. When $\frac{E}{E_c} \geq 1.31$ more than two crack path will add [20].
- The electric tree starts at needle tip having a high electric field to the nearest defect which is in minimum distance.
- In next step tree tip, which is previously formed have the highest electric field and branching will be formed from tree tip to nearest void. This process continued until the total breakdown occurs.

4.2.2 BUSH TYPE ELECTRICAL TREE

In bush type tree case complete breakdown of dielectric material occurs and at that time $\frac{E}{E_c} \geq 1.31$.

4.3 FLOWCHART MODEL FOR SIMULATION PROGRAM



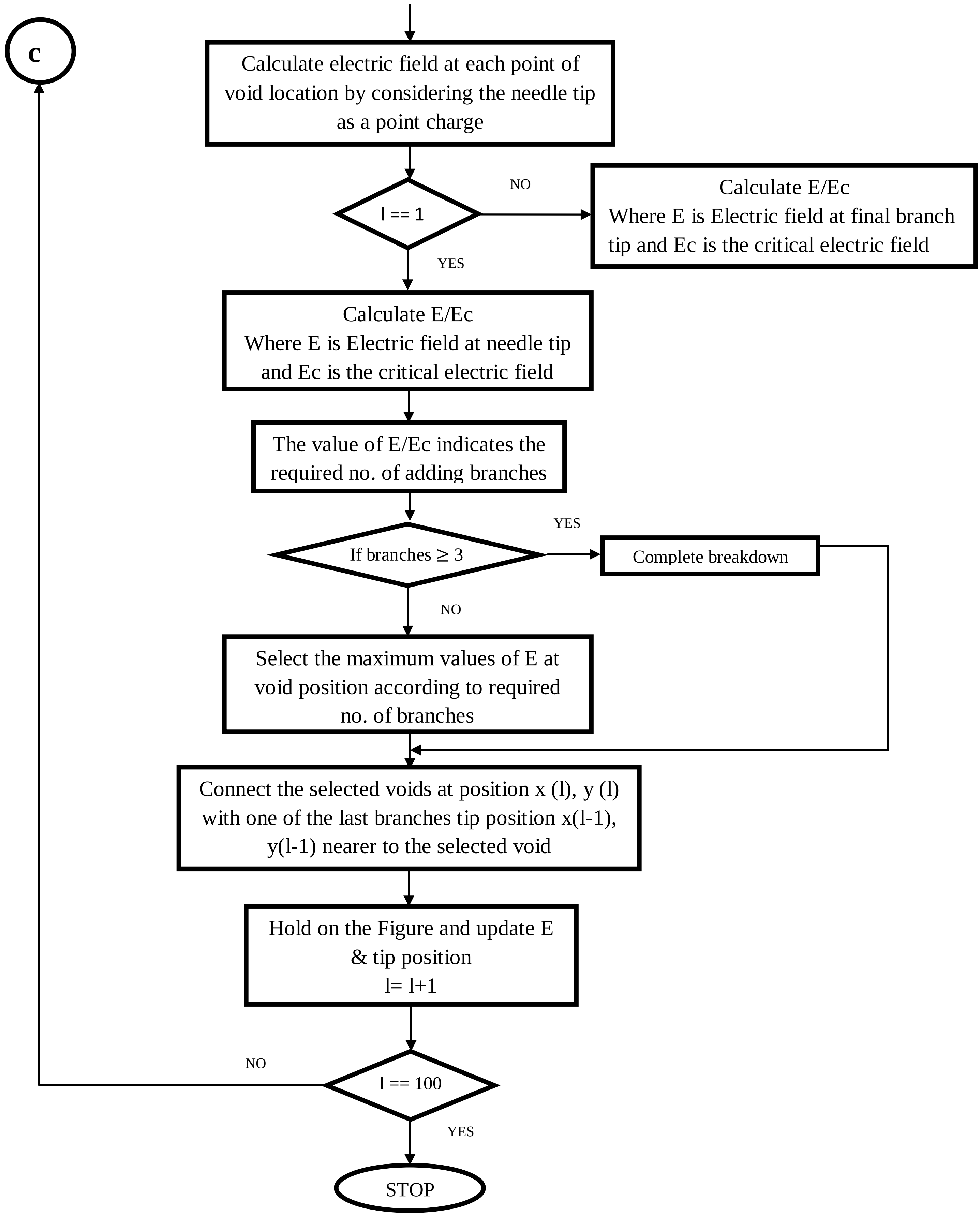


Figure 4.2 Flow chart model of electrical tree simulation program

CHAPTER 5

SIMULATION RESULT AND DISCUSSION

Branch type Electrical tree

Bush type Electrical tree

Chapter 5
SIMULATION RESULT AND DISCUSSION

In this proposed simulating program, gives the predicting electrical tree growth behavior in a solid insulation sample which is shown in figures. From these figures, the tree pattern in different voltages will predict. The growth of electrical trees was simulated by means of two dimensional numerical models. The newly introduced algorithm is based on the charge simulation method (CSM) along with genetic algorithm (GA) in one or more homogeneous media [15, 16]. Two main types of treeing, Branch-type and Bush-type trees were simulated in respect to their shape and voltage dependency. To simulate the electrical tree activity inside the polymeric insulation sample having dielectric constant $\epsilon_r = 2.3$ and the dimension of the horizontal axis is 20 mm and the vertical axis is 5 mm are taken in consideration by MATLAB programming.

5.1 BRANCH TYPE ELECTRICAL TREE

The electric tree starts at needle tip having a high electric field to the nearest defect which is in minimum distance. Formation of branching or channel starts when an electric field reaches a value 4 MV/cm generally known as critical value. At the time of formation of branches in one direction other branches considered dead without any charge during simulation [17].

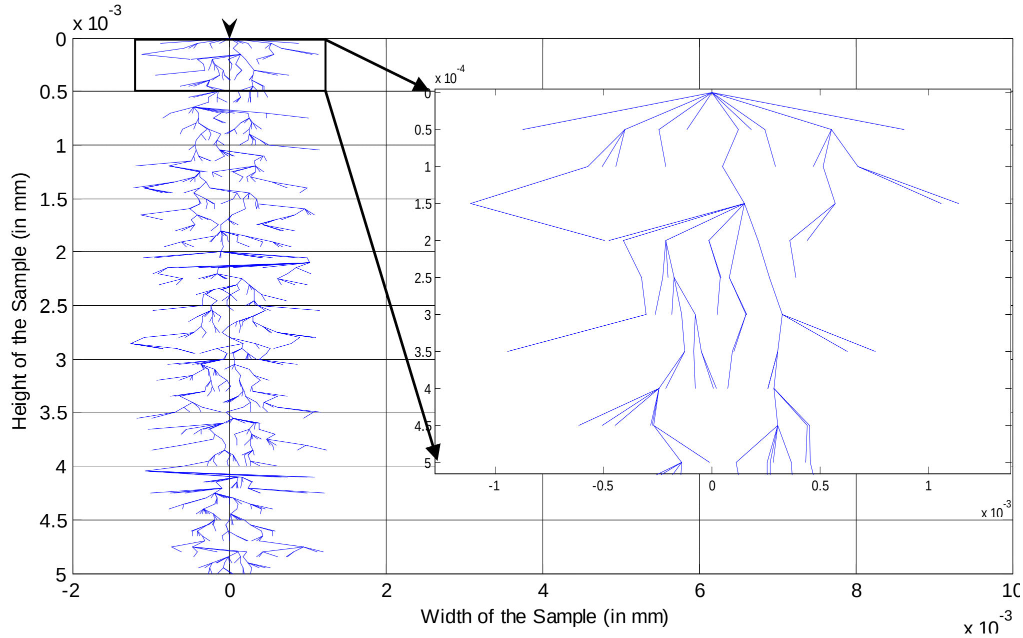


Figure 5.1 Branch type electrical tree at 5 kV applied voltage

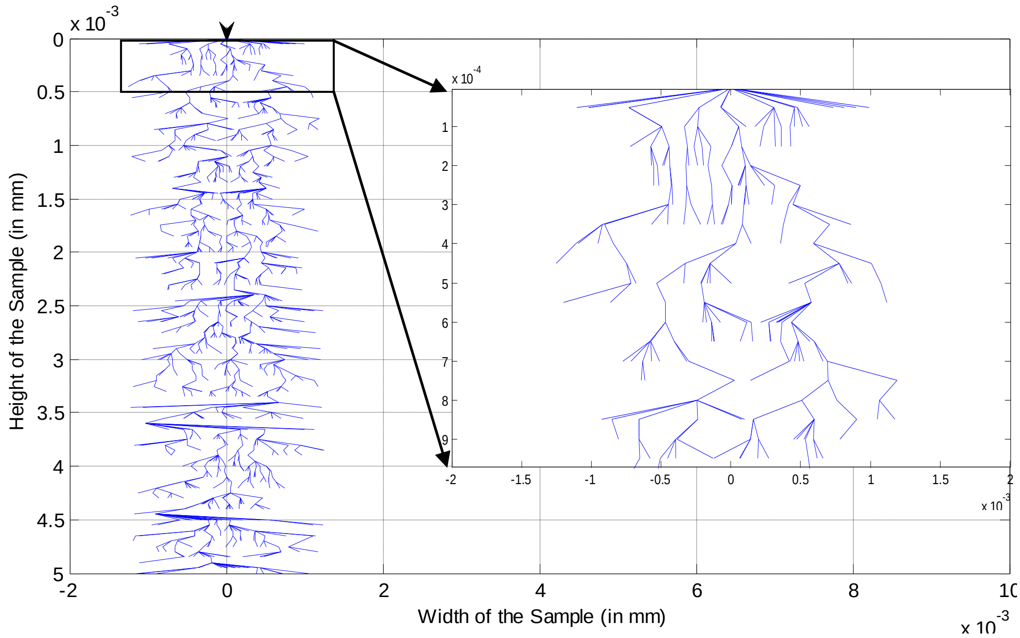


Figure 5.2 Branch type electrical tree at 8 kV applied voltage

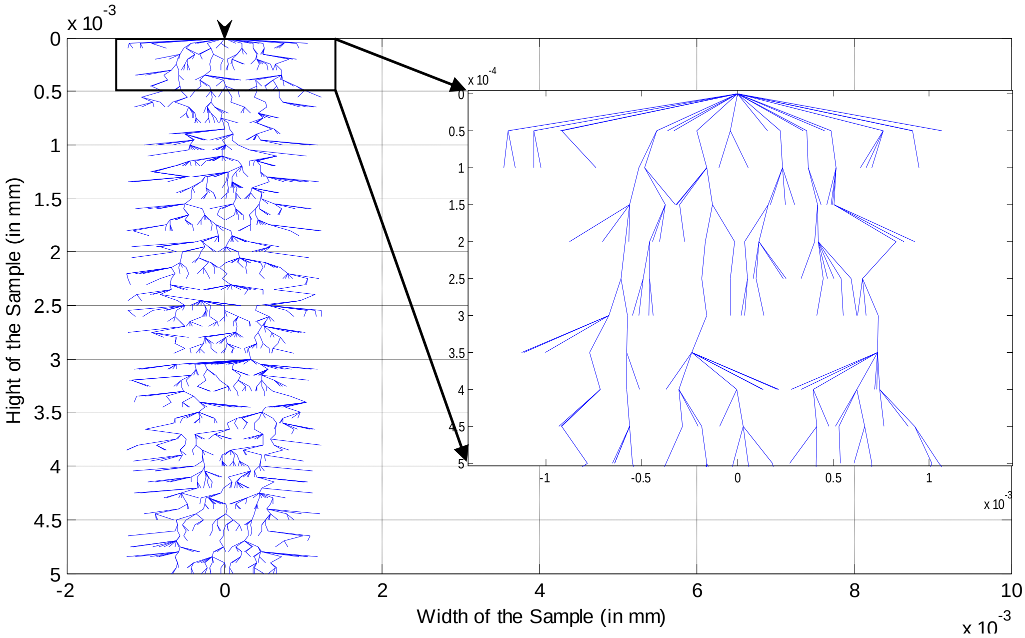


Figure 5.3 Branch type electrical tree at 10 kV applied voltage

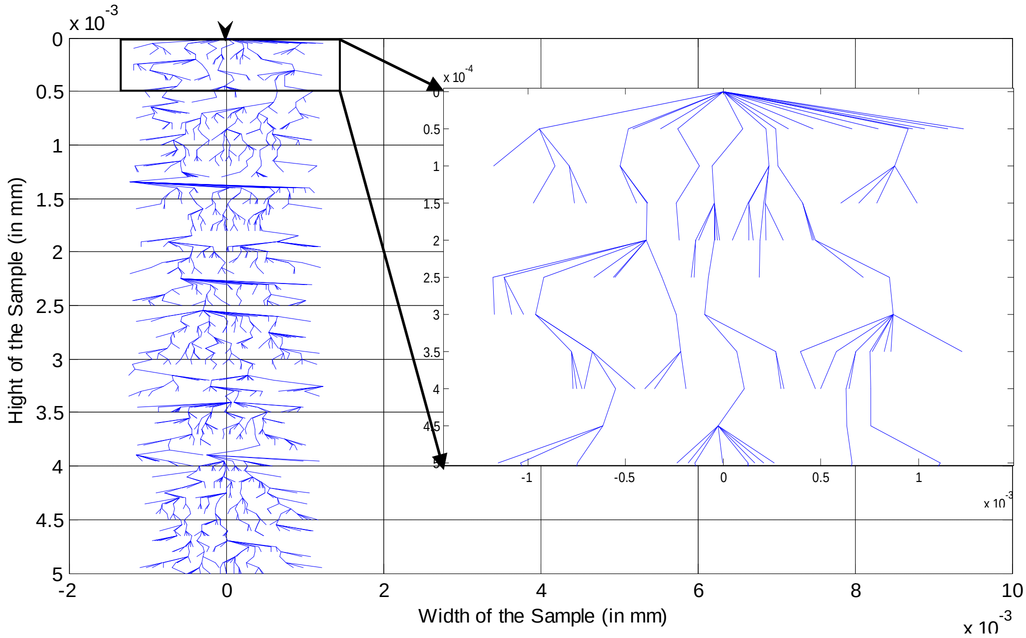


Figure 5.4 Branch type electrical tree at 12 kV applied voltage

In Fig. 5.1 the supplied voltage of 5 kV and corresponding with its tree pattern is shown and likewise increasing applied voltage such as 8 kV, 10 kV, 12 kV simulate the tree pattern. The entire simulated tree has been zoomed from (0-0.5) mm in height and -0.2 mm to 0.2 mm in width for visualizing tree pattern clearly and understanding the mechanism of formation of electrical tree channel.

In Figure 5.1, from the tip of needle 9 numbers of branches are formed i.e. at that point the critical electric field ratio $\frac{E}{E_c} \geq 1.31$ and in next layer 3 channels are added with 2 numbers of branches which are previously formed where $\frac{E}{E_c} \geq 1.31$ and single channel is added with 3 branches from previous layer where $\frac{E}{E_c} = 1$ and 4 branches can't added any further branches due to the insufficient critical electric field (E_c).

In Figure 5.2, from the tip of needle 12 numbers of branches are formed i.e. at that point the critical electric field ratio $\frac{E}{E_c} \geq 1.31$ and in next layer 4 channels are added with a single branch which are previously formed where $\frac{E}{E_c} \geq 1.31$ and 2 channels are added with 4 branches from previous layer where $\frac{E}{E_c} = 1.189$ and 6 branches can't added any further branches due to the insufficient critical electric field.

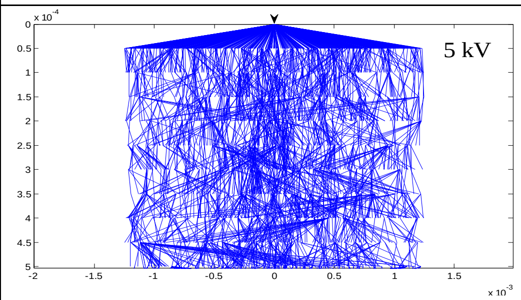
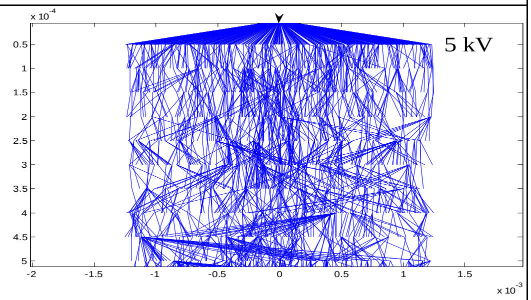
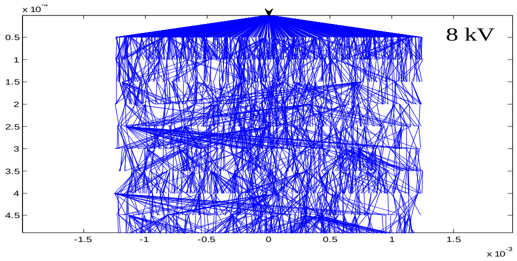
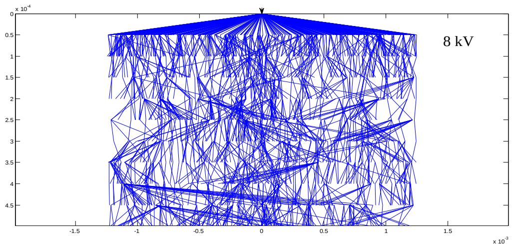
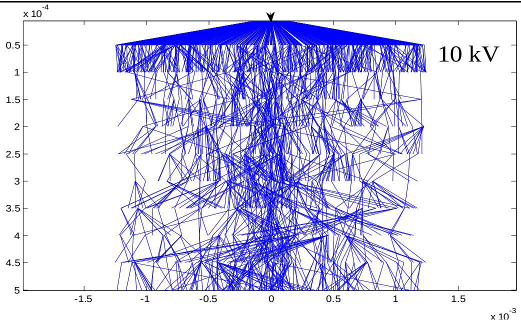
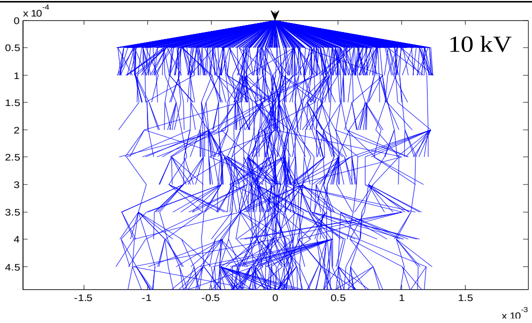
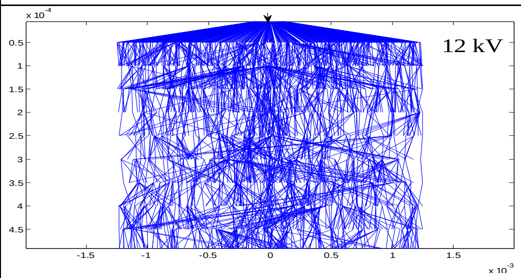
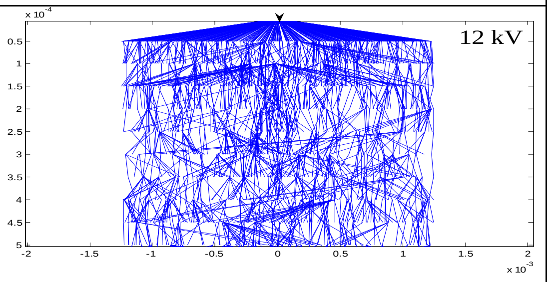
In Figure 5.3, from the tip of needle 17 numbers of branches are formed i.e. at that point the critical electric field ratio $\frac{E}{E_c} \geq 1.31$ and in next layer 3 channels are added with a single branch which are previously formed where $\frac{E}{E_c} \geq 1.31$ and 2 channels are added with 4 branches from previous layer where $\frac{E}{E_c} = 1.189$ and 6 channel are added with 6 branches from previous layer where $\frac{E}{E_c} = 1$ and 6 branches can't added any further branches due to the insufficient critical electric field.

In Figure 5.4, from the tip of needle 17 numbers of branches are formed i.e. at that point the critical electric field ratio $\frac{E}{E_c} \geq 1.31$ and in next layer 3 channels are added with a single branch which are previously formed where $\frac{E}{E_c} \geq 1.31$ and 6 channels are added with 6 branches from previous layer where $\frac{E}{E_c} = 1$ and 10 branches can't added any further branches due to the insufficient critical electric field.

5.2 BUSH TYPE ELECTRICAL TREE

For a statistical analysis, electrical tree pattern of 30 and 20 simulations were superimposed at 5 kV, 8 kV, 10 kV, 12 kV applied voltages and displayed in Table 5.2. Generally electrical trees at higher voltage stress needs less time for electrical breakdown [18].

Table 5.2 Comparison between 30 and 20 times iteration of simulated trees

<table>
<tr><th rowspan="2">Applied Voltage</th><th colspan="2">Number of Iteration</th></tr>
<tr><th>30</th><th>20</th></tr>
<tr><td>5 kV</td><td></td><td></td></tr>
<tr><td>8 kV</td><td></td><td></td></tr>
<tr><td>10 kV</td><td></td><td></td></tr>
<tr><td>12 kV</td><td></td><td></td></tr>
</table>

By comparing 30 and 20 times number of iteration of simulating tree under the application of different voltages concluded that by increasing the iteration the number of channel increases corresponding with applied voltage. The time required for computer simulation program of 30 number of iteration is more than 20 number of iteration.

From the above analysis, it is concluded that with increase in supply voltage the number of initial channel increases. The number of initial cracks which determines the electrical tree growth and depends upon the energy level of the electric field stress at the tip of the needle relative to the critical electric field E_c.

- For Branch type tree

  When, $K_c = 1$ i.e. $\frac{E}{E_c} = 1$ at that time one crack will form.

  When, $K_c = 2$ i.e. $\frac{E}{E_c} = 1.189$ at that time two cracks formed.

- For Bush type tree

  When, $K_c = 2.949$ i.e. $\frac{E}{E_c} \geq 1.31$ at that time more than two cracks formed.

The shape of electrical trees is separating in choosing the life of electrical insulation subject to this type of degradation. Case in point a bush tree may not prompt breakdown sooner than a branch tree which may be organized at a higher electric field.

In this model, electrical tree propagation which is firstly depend on voids location in the insulation medium, combines with the electrical field distribution in the medium to explain the local area damage features encircling the tree tip, and enables this action of compressive to predict the electrical tree growth.

The present model has the ability to quantitatively forecast the electrical tree enlargement shape with different types of tree patterns.

CHAPTER 6

EXPERIMENTAL SET UP FOR ELECTRICAL TREE OBSERVATION

Introduction

Sample preparation

Experimental set up

Experimental results

Chapter 6

EXPERIMENTAL SET UP FOR ELECTRICAL TREE OBSERVATION

6.1 INTRODUCTION

In this experimental study a commercial 33 kV XLPE cable and a needle-plane electrode system used to analyze the electrical tree growth. We are providing AC high voltage 50 Hz supply to the test sample and observed the fractal dimension of electrical tree by using FESEM.

6.2 COMMERCIAL 33kV XLPE CABLE

In this experiment, all sample specimens were taken from a commercial 19/33 kV three core XLPE insulated armored cable having aluminum conductors 35 mm in diameter and 8.80 mm insulation thickness as shown in Figure 6.1. Mainly for the underground distribution purpose this type of cables are used.

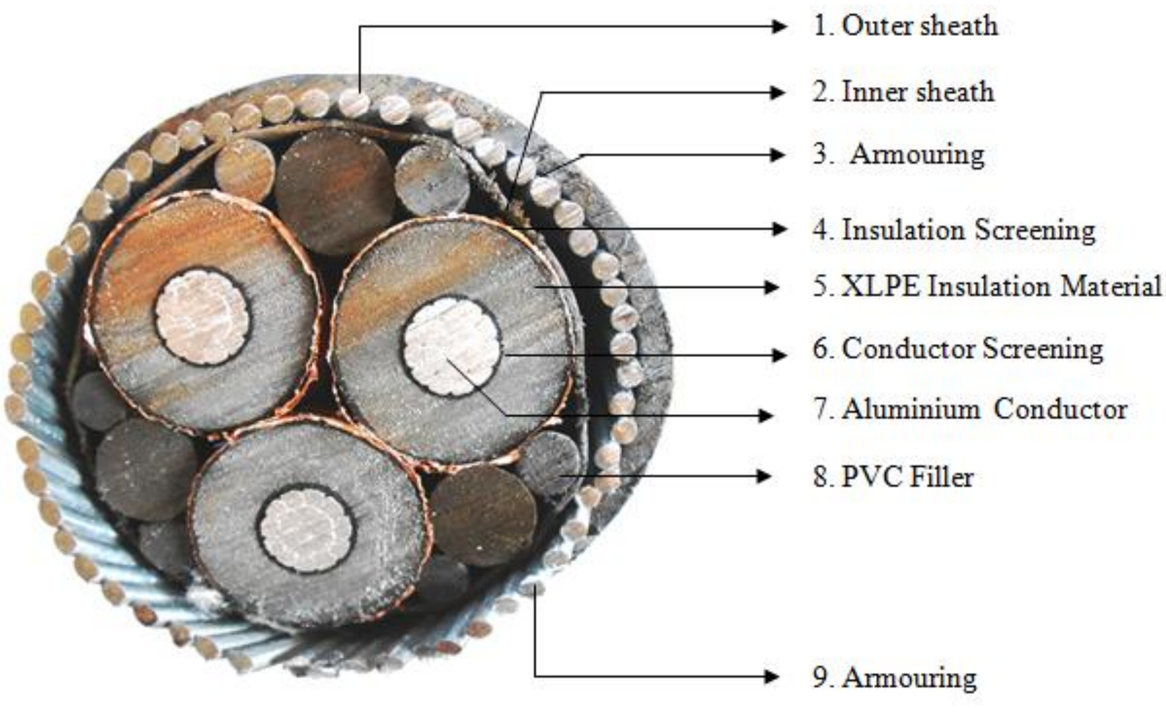


Figure 6.1 Cross-sectional view of commercial 33 kV XLPE cable

6.2.1 PHYSICAL PARAMETER OF XLPE CABLE

Size (cross-sectional area) in Sqmm	Nominal Insulation thickness in mm	Minimum inner sheath thickness in mm	Flat strip armour			Round wire armour		
			Nominal armour strip dimension in mm	Minimum outer sheath thickness in mm	Approx. overall cable dia. in mm	Nominal dia. Of armour wire in mm	Minimum outer sheath thickness in mm	Approx. overall dia. Of cable in mm
25	8.80	0.70	4×0.80	2.36	64	3.15	2.52	69
35	8.80	0.70	4×0.80	2.52	67	3.15	2.68	72
50	8.80	0.70	4×0.80	2.52	69	3.15	2.68	75
70	8.80	0.70	4×0.80	2.68	73	3.15	2.84	78
95	8.80	0.70	4×0.80	2.84	77	3.15	3.00	82

6.2.2 ELECTRICAL PARAMETER OF XLPE CABLE

Size (cross-sectional area) in Sqmm	Aluminium		Capacitance of Cable (Approx.) $\mu F/Km$	Normal current rating for Aluminium Conductor		
	Max. Conductor DC Resistance at $20^{\circ}C$ (Ohm/Km)	Approx. Conductor AC Resistance at $90^{\circ}C$ (Ohm/Km)		Ground (Amps)	Duct (Amps)	Air (Amps)
25	1.20	1.54	0.10	90	85	110
35	0.868	1.11	0.11	110	100	130
50	0.641	0.820	0.12	130	115	155
70	0.443	0.567	0.14	160	140	190
95	0.320	0.410	0.15	190	170	230

6.2.3 GENERAL PROPERTIES OF XLPE CABLE

Properties		XLPE Cable
Rated temperature(℃)	Normal	90
	Overload	130
	Short circuit	250
Tensile strength (kg/mm^2)		1.9
Elongation (%)		200-350
Volume resistivity at 20℃ ($\Omega.cm$)		10^{18}
Dielectric constant, 1kHZ		2.3
Dielectric strength (kV/mm)		20
Aging resistance	100℃	Excellent
	120℃	Excellent
	150℃	Good
Resistant to heat deformation		Good
Solvent resistance		Good
Resistance to weather		Good
Resistant to oil		Excellent
Resistant to organic chemical		Excellent
Resistant to inorganic chemical		Excellent

By the process of cross-linking, the thermoplastic characteristics of polyethylene can be converted into a stable thermosetting compound. In between parallel chains of polyethylene molecules perpendicular molecular bonds are formed by the process of cross linking and two dimensional polymeric structures converted into a three dimensional structure. As a result this compound exhibits all superior properties than polyethylene.

6.2.4 PROCESS INVOLVED IN CROSS-LINKING METHOD

In cross-linking process carbon atoms of same or different polyethylene chains are attached together to form three dimensional molecular structures. These cross-linking bonds may be directly between carbon to carbon or a chain between two or more carbon atoms. The cross-linking process of polyethylene can be taking place in different steps; such as Initiation, Propagation, Bonding and Termination [19].

Initiation:

The first step involves the generation of free radicals by the process of chemical reaction or energy radiation. Decomposition of the initiators is mainly peroxides or hydrogen atom abstracts generated by energy radiation process.

(1) Decomposition of peroxide

$$ROOR \longrightarrow 2RO^*$$

$$RO^* + PH \longrightarrow ROH + P^*$$

(2) High energy radiation

$$PH \xrightarrow{hv} H^* + P^*$$

Propagation:

Free radicals and atmospheric oxygen will react to form peroxide radicals and cross-linking takes place after a series of reaction like this.

$$P^* \xrightarrow{O_2} POO^*$$

$$POO^* + PH \longrightarrow POOH + P^*$$

Bonding:

Network formation starts when P* added on both sides,

$$POOH \longrightarrow OH^* + PO^*$$

$$PO^* + PH \longrightarrow POH + P^*$$

Termination:

Due to the presence of impurities and additives, termination takes place;

$$P^* + P^* \longrightarrow P - P$$

$$POO^* + POO^* \longrightarrow POOP + O_2$$

$$PO^* + H^* \longrightarrow PH$$

6.2.5 CHEMICAL CROSS-LINKING METHOD

Peroxide cross linking is the most common method for polyethylene cross-linking. In this process, organic peroxide is used as initiator. The chemical reaction involves the formation of Crosslink polyethylene is shown in Figure 6.2.

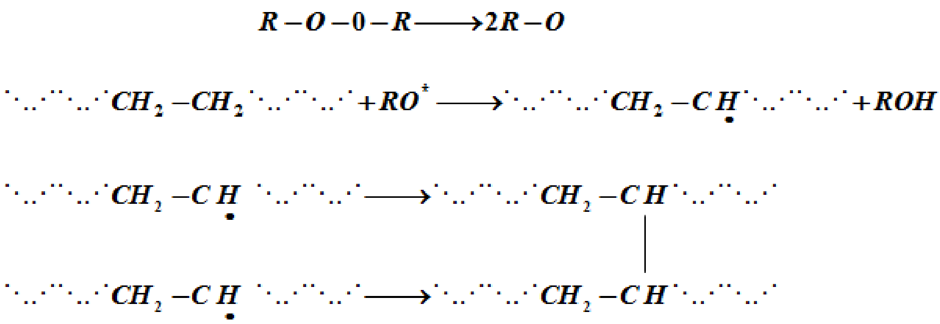


Figure 6.2 Schematic representations for cross linking of polyethylene

Polyethylene compound converted to a XLPE compound by cross-linked the long molecular bonds to form a network structure is shown in Figure 6.3.

Polyethylene Compound

XLPE Compound

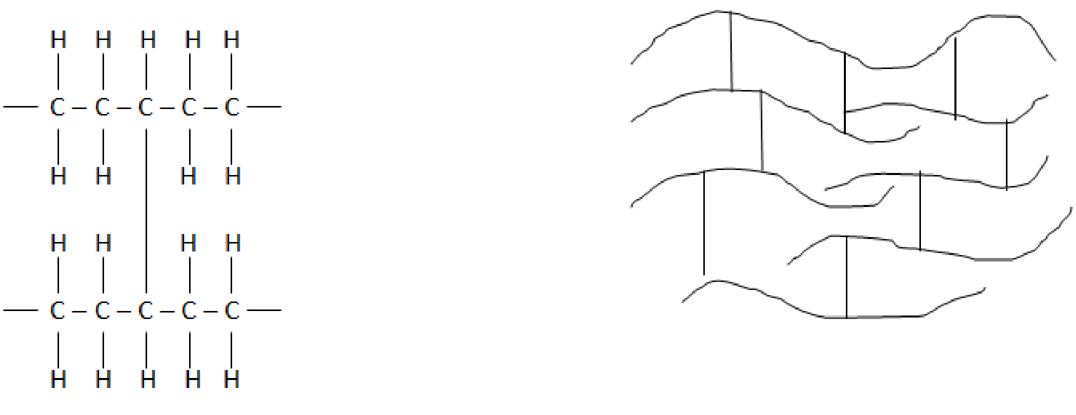


Figure 6.3 Molecular structure of Crosslink polyethylene

6.3 SAMPLE SPECIMEN AND PREPARATION

A commercial 33 kV high voltage XLPE cable was taken for the sample preparation. The extruded semiconductor layer, i.e. insulation screening above the XLPE material have been separate before the experiment. The cable insulation was cut cross-sectional like hollow disc having a thickness of 4 mm shown in Figure 6.4. The electrode generally a stainless steel metallic needle having point-plane geometry with tip radius curvature of $5 \pm 1\ \mu m$ .the needle electrode was inserted into the sample after the specimen was heated to $140^0 C$ for approximately 20-25 minutes to minimize mechanical stress and residual stress around the needle tip region and after inserting needle cooled down in room temperature for 5 hours shown in Figure 6.4. The extruded semiconducting conductor screening layer was not removed during the process because it provides good contact with XLPE insulation with the ground electrode.

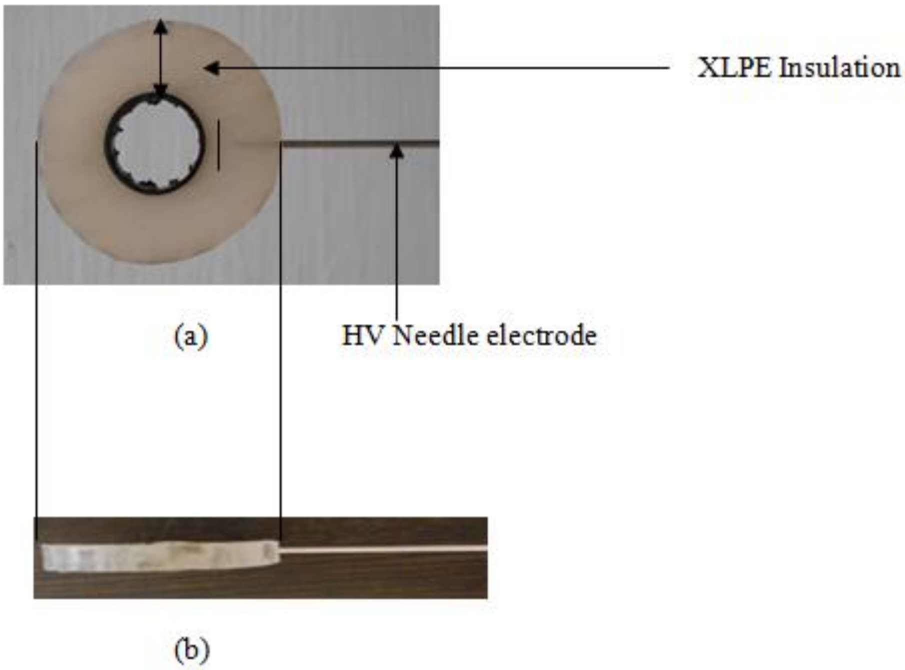


Figure 6.4: (a) Cross-sectional schematic diagram of specimen (b) Side view of sample with metal needle electrode

6.4 EXPERIMENTAL SETUP

The experiment equipment system used for the electrical treeing test is shown in Figure 6.5. The main equipments are 230 V/100 kV HV transformer, needle-plane electrode system, field emission scanning electron microscope (FESEM) and HV testing chamber. During the experiment the sample was kept in transformer oil to control the temperature i.e. cooling purpose and another thing is that to prevent flashover or external discharge. The experiment was conducted at room temperature and samples were tested at 10 kV, 12 kV, 15 kV, 20 kV rms AC voltages stress and observed the fractal structure of electrical tree growth under FESEM.

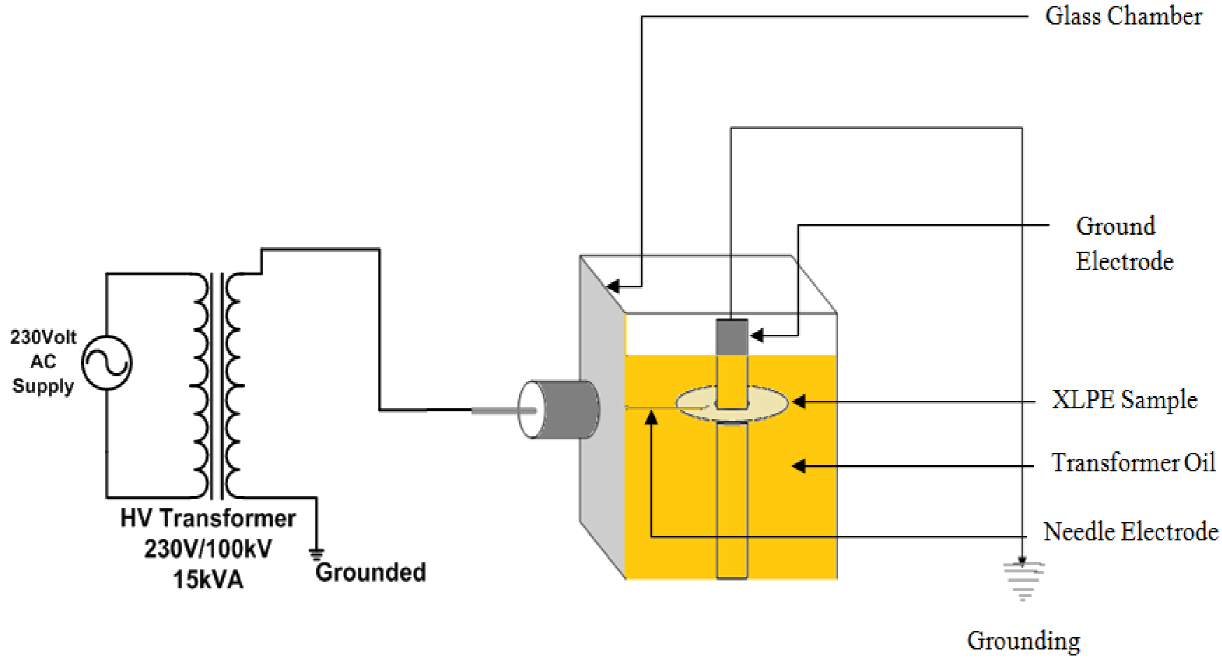


Figure 6.5 Schematic diagram of experimental setup

6.4.1 HIGH VOLTAGE AC SOURCE

The high voltage AC supply was generated by using 230 V/100 kV, 15 kVA discharge free test transformer. By using a capacitive divider, the supply AC voltage was measured and in regular interval of time the supply voltage was increased up to a certain limit as per required test voltage level.

6.4.2 NEEDLE-PLANE ELECTRODE SYSTEM

In this experiment, electrical trees were generated by using needle-plane electrode system which was made by a glass chamber containing one sharp metal needle electrode and one ground electrode and both fixed with XLPE insulation sample. The sample was inserted in transformer oil for preventing corona or external discharge and helps to maintained temperature balanced. After providing the required amount of voltage to the sample, it was observed under the field emission scanning electron microscope (FESEM).

6.4.3 FIELD EMISSION SCANNING ELECTRON MICROSCOPE

The FESEM facilitates ultra-high resolution micro structural characterization and analysis of insulation, ceramic and metallic samples. FESEM provides elemental and also topographical information at magnification of 10 X to 300,000 X with unlimited depth of field. FESEM produced clear, less distorted image with spatial resolution 1.4 nm @ 1 kV with compared to SEM.

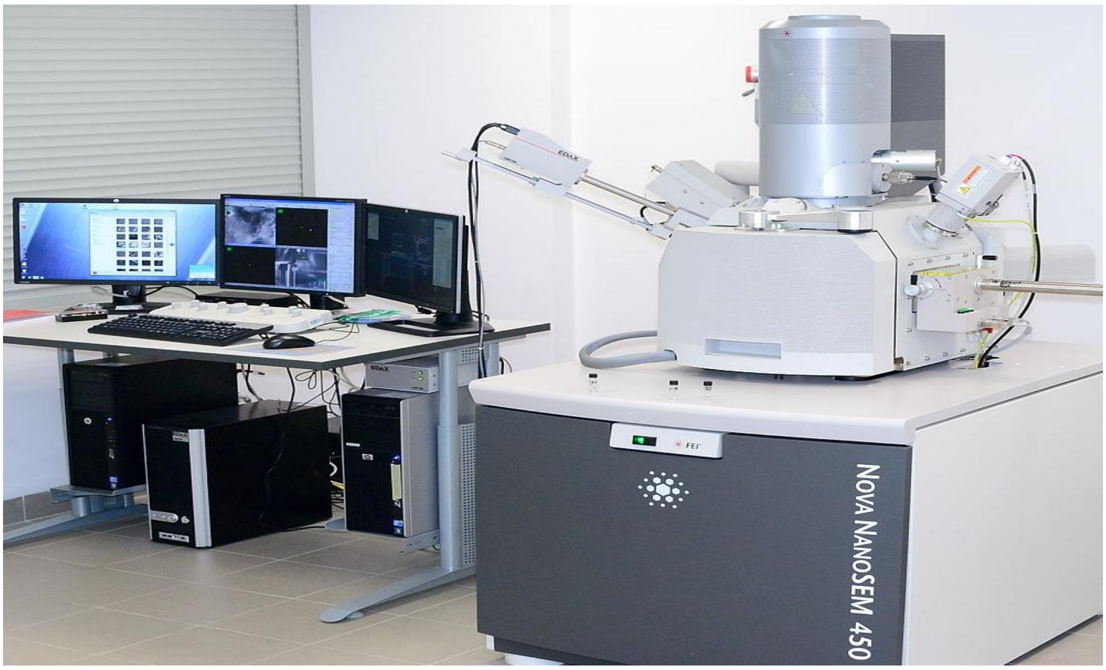


Figure 6.6 Field emission scanning electron microscope (FESEM) set up

APPLICATION

- Analysis of microstructure in nano to micrometer range.
- Cross-sectional analysis of film thickness and construction details of semiconductor device.
- Determination of structure, uniformity and elemental composition mapping.

6.5 RESULTS AND DISCUSSION

To understand the electrical treeing phenomena practically inside the 33 kV XLPE cable insulation was examined by supplying 12 kV AC voltage stress 50 Hz frequency for 5 minutes at the needle tip and keeping the gap between the needle tips to ground electrode was 2 mm. After the experiment the sample was viewed under FESEM for observation of electrical tree growth.

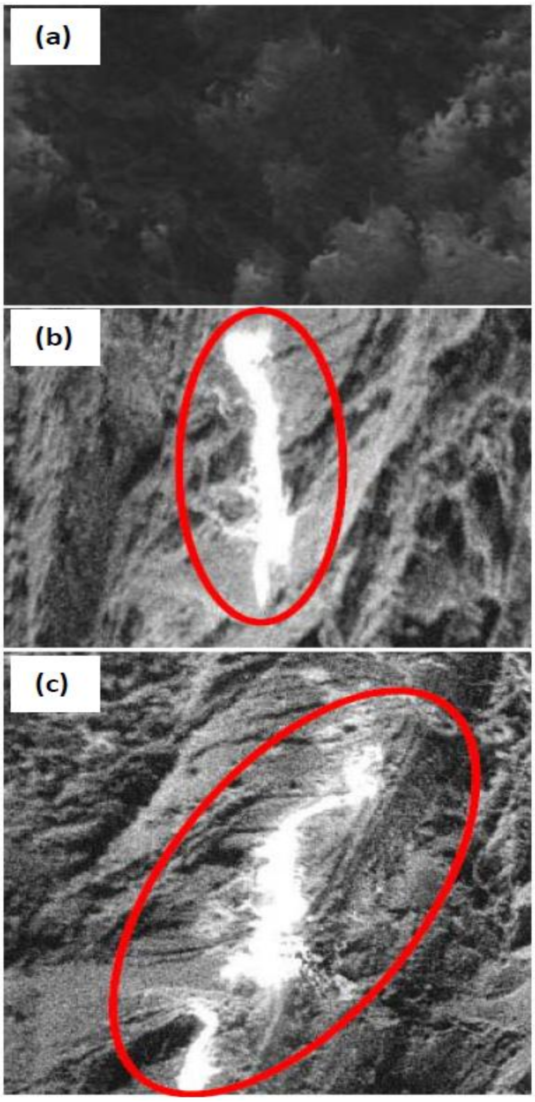


Figure 6.7 XLPE sample viewed under FESEM at 400 X magnification (a) New sample without Testing (b) Tested sample after time 3 minutes (c) Tested sample after time 5 minutes

It was found that the FESEM was particularly useful for searching for electrical damage in the polymeric insulation material where treeing phenomena takes place. Due to the propagation of tree channel, the polymeric insulation morphology changes due to the presence of impurities. FESEM studied carried out to determine the morphology of the XLPE insulation after the application of electrical stress. Three XLPE sample were tested by varying time period before testing, second one is after 3 minutes and third one is after 5 minutes, keeping supply voltage constant i.e. 12kV and viewed under FESEM as shown in Figure 6.7 (a), Figure 6.7 (b) and Figure 6.7 (c) respectively. By increasing time period the tree channel increases as shown in Figure 6.7.

CHAPTER 7

CONCLUSION AND SCOPE FOR THE FUTURE WORK

Conclusion

Scope for future work

Chapter 7

CONCLUSION AND SCOPE FOR THE FUTURE WORK

7.1 CONCLUSION

The above model indicates the structure of electrical tree growth, which is critical to calculating the time period of solid polymeric insulation and presented by combining both mechanical and electrical stress successfully. By introducing a new critical ratio of E/E_c which indicates the electrical tree shape, $E/E_c < 1.31$ indicates to branch-type tree and $E/E_c > 1.31$ to bush-type tree. For predicting tree growth behavior one must consider the void distribution and the effect of electrical field stress in a practical solid insulating material under the application of high voltages. This proposed model has the capability to predict the electrical tree growth quantitatively having different tree patterns. Some experimental results have been given to study the morphology of the solid insulation under FESEM after the formation of electrical tree.

7.2 SCOPE FOR FUTURE WORK

In the present study different tree patterns have been studied under the application of high voltages. This study is kindly helpful to identify the tree pattern with respect to aging.

The present research work would be further carried out

- By detecting the tree process inside the solid polymeric insulation using different detection technique and by condition monitoring for increase the reliability and life span.
- Prediction of the effect of high temperature and frequency on the electrical tree growth rate.
- To develop Artificial Intelligence (AI) software to diagnose electrical treeing faults in solid insulation.

REFFERENCES

[1] L. Niemeyer, L. Pietronero and H. J. Wiesmann, "Fractal dimension of dielectric breakdown" *Phys. Rev. Lett.,* vol. 52, pp.1033–1036, 1984.

[2] Grzybowski, S. McMelllon, R, R. "Electrical Breakdown Strength of XLPE Cables under Combined ac-dc Voltage". 9th ISH, Paper No. 1086, Graz, Austria, August, 1995.

[3] R. Sarathi, A. Nandini and M. G. Danikas, "Understanding Electrical Treeing Phenomena in XLPE cable Insulation Adopting UHF Technique". IEEE Trans. Of Electrical Engineering, Vol. 62, No. 2, 2011.

[4] A. El-Zein, M. Talaat, and M. M. El Bahy. "A Numerical Model of Electrical Tree Growth in Solid Insulation" under review for publication in IEEE Trans. Dielectric and Electrical Insulation,Vol. 16, No. 4, August 2009.

[5] L. A. Dissado, S. J. Dood, J. V. Champion, P. I. Williams and J. M. Alison. "Propagation of Electrical Tree Structures in Solid Polymeric Insulation". IEEE Trans. Dielectric and Electrical Insulation, Vol. 4, No. 3, pp. 259-279, June 1997.

[6] A. El-Zein, M. M. El Bahy, and M. Talaat. "A Simulation Model for Electrical Tree in Solid Insulation Using CSM Coupled with GAs" IEEE Annual Report CEIDP, pp. 645-649, October 2008.

[7] A. Xie, X. Zheng and G. Chen, "Investigations of Electrical Trees in the Inner Layer of XLPE Cable Insulation Using Computer-aided Image Recording Monitoring", IEEE Transactions on Dielectrics and Electrical Insulation Vol. 17, No. 3; June 2010.

[8] Wei Wang, Heng Sui, Yanlong Yu, Yankun Wu and Guanghui Chen, "The growth of electrical tree and its PD in inner and outer layer of 110 kV XLPE cable insulation" under publication in IEEE Trans. Power and Energy Engineering, August 2012.

[9] A. L. Barclay and G. C. Stevens, "Statistical and Fractal Characteristics of Simulated Electrical Tree Growth", IEE 6th Intern. Conf. Dielectric Materials, Measurements and Applications, pp. 17-20, 1992.

[10] X. Q. Zheng and G. Chen, "Propagation Mechanism of Electrical Tree in XLPE Cable Insulation by Investigating a Double Electrical Tree Structure", IEEE Trans. Dielectr. Electr. Insul. Vol. 15, pp. 800-807, 2008.

[11] J. C. Fothergill, "Filamentary Electromechanical Breakdown", *IEEE Trans. Elec. Ins.*, Vol. 26, No. 6; pp. 1124-1129, December 1991.

[12] A. El-Zein, "Effect of Extrusion Pressure on Polyethylene Cable Insulation Treeing", *9th Inter. Symposium on High Voltage Eng. (ISH)* Austria; pp. 1018-1_1018-4, 1995.

[13] A. El-Zein, M. M. El Bahy, and M. Talaat, "Types of Electrical Trees in Solid Insulation under Electrical and Mechanical Energy Basis", IEEE, 12th International Middle-East Power System Conference (MEPCON), pp. 80-84, 2008.

[14] L. A. Dissado. "Review Understanding Electrical Trees in Solids: from Experimental to Theory". IEEE Trans. On Dielectric and Electrical Insulation, Vol. 9, No. 4, pp. 483-497, August 2002.

[15] N. H. Malik. "A Review of the Charge Simulation Method and its Applications". IEEE Transactions on Electrical Insulation, Vol. 24 No. 1, pp. 3-20, February 1989.

[16] M.M. Abouelsaad and M.M. El Bahy. "Accurate Field Computation of Needle-Plane Gaps using an Optimized Charge Simulation Method". IEEE CEIDP, pp. 506 -509, 2000.

[17] K. S. Bromley, L. A. Dissado and J. C. Fothergill. "Local Field Calculations for Electrical Trees in Point-Plane Geometry". IEEE Annual Report - CEIDP, pp. 304-307, Minneapolis, October, 1997.

[18] T. Farr, R. Vogel sang, K. Froehlich: "A new deterministic model for tree growth in polymers with barriers", Conference on Electrical Insulation and Dielectric Phenomena, CEIDP 2001, Kitchener, Ontario, Canada.

[19] S. M. Tamboli, S. T. Mhaske and D. D. Rale, "Crosslinked Polyethylene" , Indian Journal of Chemical Technology, Vol. 11, pp. 853-864, November 2004.

[20] A. El-Zein, M. Talaat, and M. M. El Bahy. "A New Method to Predict The Electrical Tree Growth in Solid Insulation" under review for publication in IEEE Trans. High Voltage Engineering.