MODELING OF BREAKDOWN VOLTAGE OF SOLID INSULATING MATERIAL USING ARTIFICIAL NEURAL NETWORK

Debashis Mishra (109EE0284)

Department of Electrical Engineering
National Institute of Technology Rourkela

MODELING OF BREAKDOWN VOLTAGE OF SOLID INSULATING MATERIAL USING ARTIFICIAL NEURAL NETWORK

A Thesis submitted in partial fulfilment of the requirements for the degree of

Bacelor of Technology

in

Electrical Engineering

By

Debashis Mishra
Roll No.109EE0284

Under the Supervision of
Prof. Sanjeeb Mohanty

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA
राष्ट्रीय प्रौद्योगिकी संस्थान, राउरकेला
PIN-769008
ODISHA, INDIA

Dedicated TO

BhagawanShriShirdiSai Baba

&

My beloved Parents

DEPARTMENT OF ELECTRICAL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA- 769 008
ODISHA, INDIA

CERTIFICATE

This is to certify that the thesis report titled "***Modelling of Breakdown Voltage of a Solid Insulating Material using Artificial Neural Network***", submitted to the National Institute of Technology, Rourkela by **Mr. Debashis Mishra, Roll No**: **109EE0284** for the award of **Bachelor of Technology** in Electrical Engineering, is a bonafide record of research work carried out by him under my supervision and guidance.

The candidate has fulfilled all the prescribed requirements.

The thesis report which is based on candidate's own work, has not submitted elsewhere for a degree/diploma.

In my opinion, the draft report is of standard required for the award of a **Bachelor of Technology** in Electrical Engineering.

Supervisor
Department of Electrical Engineering
National Institute of Technology
Rourkela – 769 008 (ODISHA)

ACKNOWLEDGEMENTS

This work was carried out at the Department of Electrical Engineering, National Institute of Technology, Rourkela, Orissa, under the supervision of Prof. Sanjeeb Mohanty.

I would like to express my sincerest gratitude to Prof. Sanjeeb Mohanty for his guidance and support throughout my work. Without him I will never be able to complete my work with this ease. He was very patient to hear my problems that I am facing during the project work and finding the solutions. I am very much thankful to him for giving his valuable time for me.

I would like to express my sincere thanks to Prof. A.K Panda, Prof. K.B Mohanty and Prof. B.Chitti Babu for their precious suggestions and encouragement to perform my project work.

My special thanks to all my friends who did their thesis computational work in Simulation & Computing Lab, of Electrical Engineering department and providing me good company in the lab. And I would like to thank my friends who helped me in completing my thesis in time.

I thank God for giving me the chance to pursue my academic goals and a wonderful, complete life full of amazing people.

Finally, hearty thanks to my family member for their sacrifice that encouraged me to proceed with the work.

Debashis Mishra

ABSTRACT

The voids or cavities within the solid insulating material during manufacturing are potential sources of electrical trees which can lead to continuous degradation and breakdown of insulating material due to Partial Discharge (PD). To determine the suitability of use and acquire the data for the dimensioning of electrical insulation systems breakdown voltage of insulator should be determined. A major field of Artificial Neural Networks (ANN)) application is function estimation due to its some useful properties, such as, non-linearity and adaptively especially when the equation describing the function is unknown. In this project, the breakdown voltage due to PD in cavities for five insulating materials under AC conditions has been predicted as a function of different input parameters namely the thickness of the insulating sample 't,' the thickness of the void 't_1' diameter of the void 'd' and relative permittivity of materials ε_r by using the ANN model. The requisite training data are obtained from experimental studies performed on a Cylinder-Plane electrode. The voids are artificially created with different measures. Detailed studies have been carried out to determine the ANN model parameters which give the best results. On completion of training, it is found that the ANN model is capable of predicting the breakdown voltage $Vb = f(t, t_1, d, \varepsilon_r)$ very efficiently and with a small value of Mean Absolute Error. The system has been predicted using MATLAB.

Table of Contents

NOMENCLATURE

AC	Alternating Current
ANN	Artificial Neural Network
BPA	Back Propagation Algorithm
BV	Breakdown Voltage
EBA	Experimental value of Breakdown Voltage
E_{tr}	Mean Square Error
E_{ts}	Mean Absolute Error
m	Number of Iteration
MFNN	Multilayer Feed forward Neural Network
MAE	Mean Absolute Error
N_h	Number of Hidden Neurons
α	Momentum Factor
η	Learning Rate Parameter of BPA
PD	Partial Discharge
η_2	Learning Rate Parameter of LMS algorithm
w_{aj}	Weight connected between hidden layer and input layer of MFNN.
w_{bj}	Weight connected between output layer and hidden layer of MFNN
SC	Soft Computing
PE	Processing Element
w	Weight vector

b	Bias term
α_i	Lagrange multipliers
ε_r	Relative permittivity
C	Cost function

LIST OF FIGURES

Figure No **Page No**

LIST OF TABLES

Table No **Page No**

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

In modern times, industry, research laboratories and much power system are using high voltages for wide variety of applications. And with ever increasing demand of electrical energy the power system is expanding both in size and complexities. To get the modern civilization such applications play the vital role. The generating capacities of power plants and transmission voltage are on the increase because of their inherent advantages.So it's very much essential to know the property of the insulation material for optimum solution in terms of cost and insulating capability. The power transfer capability of the system becomes four times if the transmission voltage is doubled and the line losses are also relatively diminished. Consequently it becomes a stronger and economical system. In our country India we already using 400 KV lines in operation and 800 KV lines are being planned. In big cities, for the distribution voltages we are using the conventional transmission voltages (110 kV–220 kV etc.) because of increased demand. A system (transmission, distribution, switchgear, insulator etc.) designed for 400 kV and above using conventional insulating materials is both bulky and expensive and, therefore, latest insulating materials are being investigated to bring down both the cost and space requirements. On insulating materials the electrically live conductors are supported and sufficient air clearances are provided to avoid flashover or short circuits between the live parts of the system and the grounded structure. At times, a live conductor is to be immersed in an insulating liquid to bring down the size of the container and at the same time provide sufficient insulation between the grounded container and. the live conductor.The quality of a solid insulation is adjudged in several ways, out of these, the breakdown voltage continues to evoke a lot of interest to the Electrical Engineers in general and High Voltage Engineers in particular. Hence, it is extremely important to develop solid insulating materials with excellent breakdown strength and any attempt at modelling the phenomenon with the presence of void would go a long way in assessing the insulation quality.

Under normal working conditions, insulation steadily loses its dielectric strength and overvoltage capacity because of general aging as well as due to local defects appearing in the form of voids in the insulation during manufacture, particularly in extruded and cast type insulation. The quality of a solid insulation is judged in several ways, such as, hydrophobicity, electroluminescence, crystallization kinetics, hydrothermal, breakdown voltage etc.

1.2 BREAKDOWN OF SOLID INSULATING MATERIALS

Fothergill [1] has very clearly differentiated between the breakdown and degradation of a solid non conducting material. According to him, the breakdown is an event that is sudden and catastrophic and the insulation cannot withstand the service voltage following the breakdown. The degradation, on the other hand takes place over a period. It increases the probability of breakdown and decreases the breakdown voltage. Erosion and pit formation are vital in the degradation process and are followed by tree formation and/or final dielectric failure. The degradation process after a period of hours to weeks, leads to breakdown. Well-designed insulation system operated within the scope of various design parameters, should not breakdown or degrade. Both these processes are irreversible. Table 1.1 shows some differences between degradation and breakdown for a solid insulating material.

TABLE 1.1 DIFFERENCES BETWEEN DEGRADATION AND BREAKDOWN FOR A SOLID INSULATING MATERIAL

Features	**Breakdown**	**Degradation**
Effect	Catastrophic insulation cannot be used afterwards	Leads to breakdown, reduces breakdown voltage
Speed	Fast occurs in << 1s	Hours, years
Evidence	Direct observation normally by eye	Observation would require microscope
Examples	Intrinsic, Thermal, Electromechanical, Electrochemical, Partial Discharge in cavities	Electrical Trees, Water trees

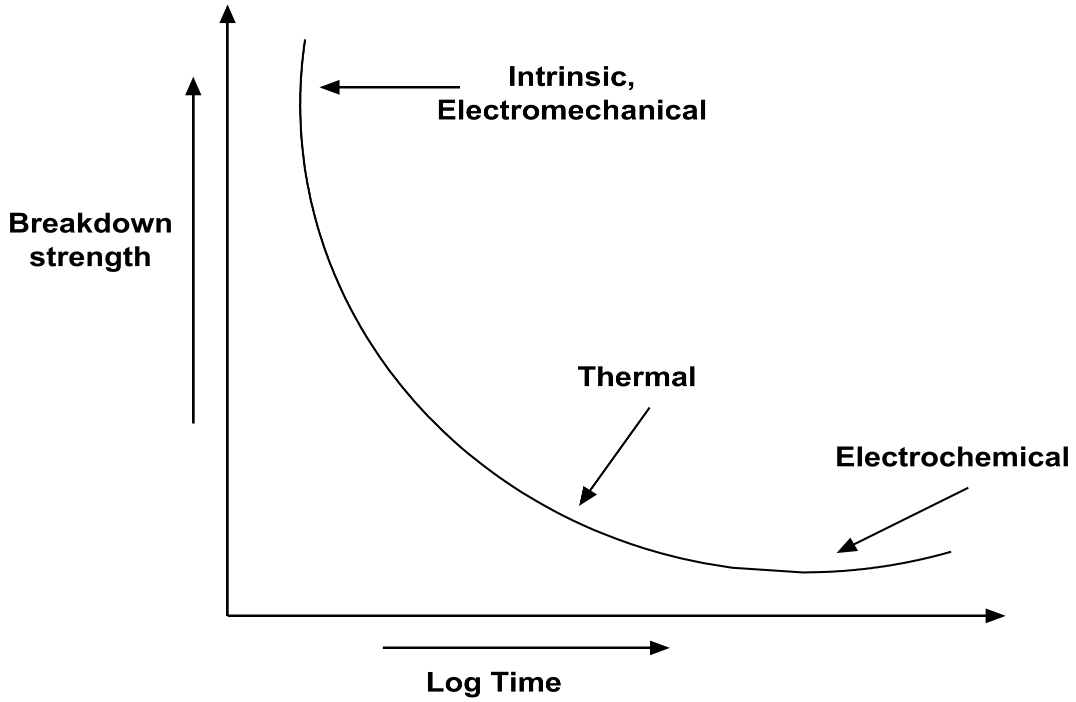


FIG.1.1 VARIATION OF BREAKDOWN STRENGTH AFTER THE APPLICATION OF VOLTAGE

The breakdown of solid dielectrics is an event that is sudden and catastrophic. Breakdown occurs in a time duration which is very much less than a second [2]. Basically, breakdown of solid insulating materials occur due to intrinsic, electromechanical [3], multi-stress aging [4] or failure due to treeing and tracking, relative humidity [5], thermal, electrochemical, partial discharges (PD) in the cavities [6].

1.2.1 INTRINSIC BREAKDOWN

When voltages are applied only for short durations of the order of 10^{-8} s the dielectric strength of a solid dielectric increases very rapidly to an upper limit called the intrinsic electric strength. By experimentally, this highest dielectric strength can be obtained only under the best experimental conditions when all extraneous influences have been isolated and the value depends only on the temperature and structure of the material. It is recorded that 15 MV/*cm* for polyvinyl-alcohol at -196^0C is the maximum electrical strength. The obtainable range of maximum strength is from 5MV/cm to 10MV/cm.

The presence of free electrons plays the vital role in intrinsic breakdown which are capable of migration through the lattice of the dielectric. Mostly, a few number of conduction elections are present in solid dielectrics, with some structural imperfection and small amount of impurities. The molecules or impurity atoms or both act as traps for the conduction electrons up to certain ranges of electric fields and temperatures. Exceeding these ranges, more electrons along with trapped electrons are instantly released, and these electrons take part in the conduction process. Depending on this principle, two types of intrinsic breakdown mechanisms have been proposed and they are (a) Electronic Breakdown and (b) Avalanche or Streamer Breakdown.

1.2.1.1 ELECTRONIC BREAKDOWN

As mentioned earlier, intrinsic breakdown is assumed to be electronic in nature because it occurs in time of the order of 10^{-8}s.The initial density of conduction (free) electrons is very large, and electron-electron collisions take place. When electric field is applied on, electrons gain energy from the field it cross the forbidden energy gap from the valence to the conduction band. When this process is repeated continuously, more electrons become available in the conduction band, finally leading to breakdown.

1.2.1.2 AVALANCHE OR STREAMER BREAKDOWN

Avalanche or Streamer Breakdown is similar to breakdown in gases due to cumulative ionization. Free electrons gain sufficient energy above a certain electric field and cause liberation of electrons from the lattice atoms by collisions. Under certain uniform field conditions, if in the specimen the electrodes are embedded, breakdown will occur when an electron avalanche bridges the electrode gap.

An electron under the dielectric, starting from cathode will drift towards the anode and during this motion profits energy from the field and loses it at collisions. When the energy gained by an electron exceeds the lattice ionization potential and an additional electron will be liberated due to collision of the first electron. This process repeats itself and resulting in the formation of an electron avalanche. When the avalanche exceeds a certain critical size then breakdown will occur.

In practice, breakdown does not occur by the single formation of avalanche itself, but it occurs as a result of so many avalanches formed within the dielectric and extending step by step through the entire full thickness of the material. This can be easily demonstrated in a laboratory by applying an impulse voltage between point-plane electrodes with point embedded in a transparent solid dielectric such as perspex.

1.2.2 ELECTROMECHANICAL BREAKDOWN

When solid dielectrics are put into high electric field, failure happens due to electrostatic compressive forces which can exceed the mechanical compressive strength. If the thickness of the specimen is d_0 and it is compressed to a thickness d under an applied voltage V, the electrically developed compressive stress is in equilibrium if

$$\varepsilon_0 \varepsilon_r \frac{V^2}{2d^2} = Y \ln\left[\frac{d_0}{d}\right] \tag{1.1}$$

Where Y is the Young's modulus.

$$V^2 = d^2 \left[\frac{2Y}{\varepsilon_0 \varepsilon_r}\right] \ln\left[\frac{d_0}{d}\right] \tag{1.2}$$

Mechanical instability occurs when $d/d_0 = 0.6$.

Substituting this in Eq 1.2, the largest apparent electric stress before breakdown,

$$E_{\max} = \frac{V}{d_0} = 0.6\left[\frac{Y}{\varepsilon_0 \varepsilon_r}\right]^{\frac{1}{2}} \tag{1.3}$$

The above equation is only approximate if Y depends upon the mechanical stress. When subjected to high stresses then the elasticity theory does not stand good and plastic deformation has to be taken into account.

1.2.3 BREAKDOWN DUE TO TREEING AND TRACKING

When a solid dielectric subjected to electrical stress for long time fails, two kinds of visible markings are observed on the materials. They are:

(a) the presence of a conducting path across the the insulation;

(b) a mechanism where leakage current passes through the conducting path leading to the formation of spark. Insulation degradation occurs as a result of these sparks.

The spreading of spark during tracking, in the form of branches of a tree is called treeing.

Consider a system of solid dielectric having a conducting film and a couple of electrodes on its surface. The conducting film often is formed due to moisture. Applying voltage, the film starts conducting, as a result generating heat, and the surface starts becoming dry. The conducting films become apart due to drying, and so sparks are drawn damaging the surface. Organic insulating materials such as paper and Bakelite, the dielectric carbonizes at the regions of sparking, and the carbonized regions act as conducting channels resulting in increased stress over the rest region. This is a cumulative process, and insulation failure takes place when carbonized tracks bridge the distance between layers of Bakelite and similar dielectrics built of laminates. On the other hand treeing occurs due to the erosion of materials at the tips of the spark. Erosion results in roughening of the surfaces, hence becomes a source of contamination. This causes more conductivity resulting either in forming a conducting path bridging the electrodes or a mechanical failure of the dielectric.

1.2.4 THERMAL BREAKDOWN

The breakdown voltage of a solid dielectric must increase with its thickness. But this is true only up to a fixed thickness above which the heat generated in the dielectric due to the current determines the conduction.

When electric field is applied on a dielectric, conduction current, flows through the material. The current heats up the specimen and the temperature increases. The heat generated is transferred to the surroundings by conduction through the dielectric and radiation from its outer surface.

Equilibrium is reached when the heat needed to raise the temperature of the dielectric, plus the heat radiated out, equals the generated heat.

This of huge importance to practicing engineers, as most of insulation failures in high voltage power apparatus occur due to thermal breakdown. Thermal breakdown sets up an upper bound for increasing the breakdown voltage when the thickness of insulation is increased. For a given loss angle and the applied stress, heat generated is proportional to the frequency hence thermal breakdown is much serious at higher frequencies.

1.2.5 ELECTROCHEMICAL BREAKDOWN

When cavities are formed inside solid dielectrics, dielectric strength in solid specimen decreases. When the gas in the cavity breaks down, the surface of the specimen provides instantaneous anode and cathode. Some electrons dashing against the anode with enough energy shall break the chemical bonds of the insulating surface. Same way positive ions bombarding against the cathode increase the surface temperature and produce thermal stability. Chemical degradation may also occur from active discharge products e.g. O_3, NO_2 etc. formed in air. The overall effect of all these processes is a steady erosion of the material and a consequent reduction in the thickness of the specimen. Generally it is desired that with ageing the dielectric strength comes down with time of voltage application or even without voltage application and in most cases; the decrease in dielectric strength (E_b) with time follows the following empirical relation

$$t E_b^n = \text{constant} \tag{1.4}$$

where the exponent n depends upon the dielectric material, the ambient temperature humidity and the quality of manufacture. This is the vital reason why a.c. voltage testing is not recommended.

1.2.6 BREAKDOWN DUE TO INTERNAL DISCHARGES

Partial discharge is a localized discharge process in which the distance between two electrodes is partially bridged *i.e.*, the insulation between the electrodes is partly punctured. Partial discharges may start directly at one of the electrodes or occur in a cavity in the dielectric.The Partial

Discharge study has been a topic in the field of solid insulations over the past few decades, which is very much evident from the large number of literatures associated with it [7-16]. It is well known that voids within the solid insulating materials are the main sources of Partial Discharge c as Artificial Neural Network (ANN), Fuzzy Logic (FL), approximate reasoning, derivative-free optimization methods, such as, Genetic Algorithms (GA) and Simulated Annealing (SA). The seamless integration of all these paradigms forms the core of SC, aimed at solving real-world decision-making, modeling problems. These problems are usually imprecisely defined and require human intervention. Thus, the SC with their ability to incorporate human knowledge and adapt their knowledge base via optimization techniques plays an important role in the design of intelligent systems.

1.3 MOTIVATION

The SC model is an important and a flexible model in predicting the breakdown voltage due to PD in voids. To overcome the modern energy demand, it’s required highly complex and reliable power system from transmission to distribution unit, for that it’s very much essential to develop the better quality insulating material. One of the main reasons of degradation of insulating material is PD within the cavities. The breakdown voltage due to PD in cavities is a nonlinear phenomenon. The magnitude of this voltage is critical for judging the quality of the insulation for industrial purpose. However, it is extremely difficult to predict this voltage. Hence, it is necessary to resort to the process of modeling in order to predict the magnitude of this breakdown as a function of different variables. The use of this model in order to tackle this PD issue needs further exploration as the prediction of this breakdown voltage is so important industrially.

1.4 OBJECTIVES

The main objective of the research predicting the breakdown voltage using Least Square Support Vector Machine (LS-SVM) and ANN structures, namely the Multilayer Feedforward Neural Network (MFNN).

1.5 THESIS OUTLINE

This thesis primarily attempts at modelling of PD initiated breakdown voltage of solid insulations by different SC techniques. The requisite experimental breakdown voltage data under AC conditions are generated in the laboratory with artificially created void and insulation dimensions using Cylinder-Plane Electrode System. This thesis contains five chapters; out of which Chapter 3 and Chapter 4 are the contributory Chapters.

Chapter 1 has reviewed the existing literatures on the breakdown voltage of the solid insulating materials in general while giving more emphasis on the breakdown due to PD in cavities. The advantage of using SC models over the Conventional models in solving the prediction of breakdown due to PD in cavities have been discussed thoroughly in this Chapter.

Chapter 2 has discussed the experimental set up for the Cylinder-Plane Electrode System used for obtaining the breakdown voltage data under AC conditions.

Chapter 3 has described a brief theory of the Multiforward Neural Network. This structure is then used to propose three breakdown voltage models using the experimental data obtained from the Cylinder-Plane Electrode System.

Finally, **Chapter 4** summarises the main findings, draws certain conclusions arising out of the thesis work and compares of the MAE of the test data E_{ts} obtained from the various models of Chapter 3 and 4 using similar data to show the effectiveness of the SC techniques used here. At the end, it outlines the scope for the future research.

CHAPTER 2

EXPERIMENTAL SET UP

2.1 INTRODUCTION

As mentioned in Chapter 1, the primary objective of this thesis work is to develop different soft computing models, which will be able to predict the breakdown voltage of solid insulating materials due to PD in cavities. For modelling purpose, breakdown voltage data are generated experimentally on application of AC power frequency voltages. The chapter 2 covers total experimental procedure for predicting the experimental breakdown voltage of five insulating materials namely, White Minilex, Leatheroid Paper, Glass Cloth, Manila Paper and Lather Minilex

2.2 EXPERIMENTAL PROCEDURE

The procedure adopted for the generation of experimental value of the breakdown voltage is as follows:

2.2.1 SAMPLE PREPARATION

The samples are prepared from three commercially available insulation sheets, namely White Minilex, Leatheroid Paper, Glass Cloth, Manila Paper and Lather Minilex of different thicknesses. The variation of thicknesses is as follows:

White Minilex Paper	0.26, 0.18 and 0.125 mm
Leatheroid Paper	0.235, 0.175 and 0.13 mm
Lather Minilex	0.245, 0.185 and 0.12 mm
Glass Cloth	0.195 and 0.155 mm
Manila Paper	0.06 and 0.035 mm

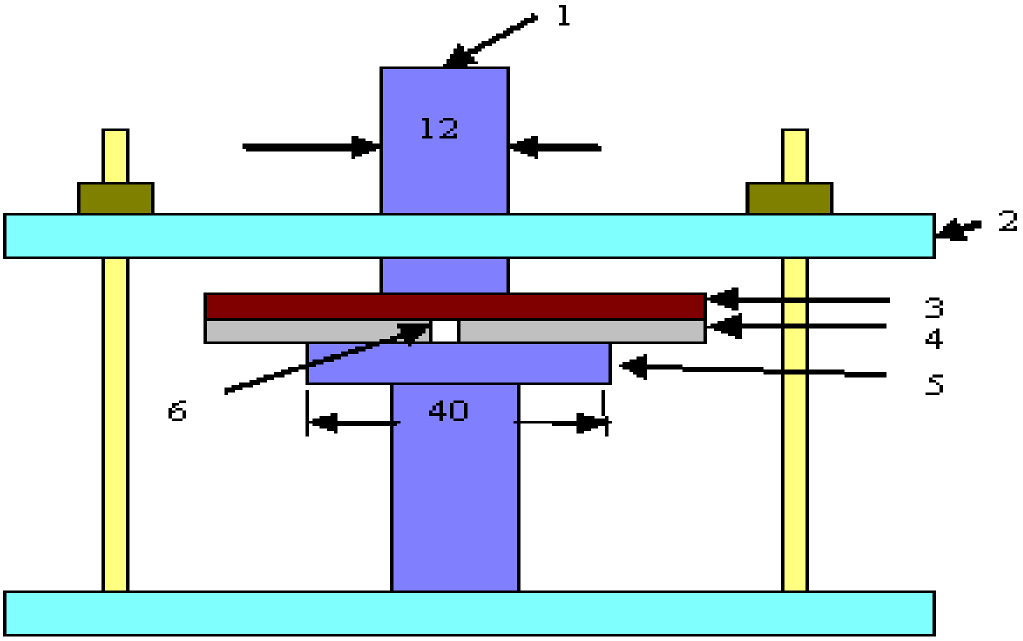
Thus, the thickness range is varying from 0.035 mm to 0.26 mm. Before testing, the conditioning procedure was adopted to the test specimen in accordance with that laid in ASTM Handbook [27]. This ensured that the surfaces of the insulating sample were cleaned, since the contamination on the insulating specimen or absorption of moisture may affect the breakdown voltage.

2.2.2 CREATION OF VOID

The voids of different sizes are artificially created by means of a spacer made up of Kapton film, with a circular punched hole at the centre. The diameter of the voids is 1.5 mm, 2 mm, 3 mm, 4 mm and 5 mm. The thicknesses of the Kapton spacer used are of 0.025 mm and 0.125 mm. Thus, the sizes of the void, that is, the volume of air space, depends on a typical diameter of the punched hole and thickness of the spacer. Utmost care has been taken to maintain the surface smoothness of the punched holes.

2.2.3 ELECTRODE GEOMETRY

The electrode system used in this work for breakdown voltage measurements is shown in Figure 2.1. To get a high reproducibility of the tests and low data scatter, the cell sample was built following a standard assembling methodology. It consists of a cylinder-plane electrode configuration, including a cavity in the middle. The depth of the void was fixed by the Kapton film as explained before. The electrodes, both high voltage and low voltage, were made of brass. They were polished, buffed and cleaned with ethanol before the start of the experiment. Again, the electrodes contact surfaces are cleaned by ethanol between two consecutive applications of voltage to avoid contaminations that may arise due to application of voltage. Sufficient care had been taken to keep the electrode surfaces untouched and free from scratches, dust and other impurities. The insulation sample is sandwiched between the electrodes with the help of insulating supports as shown. The main characteristic of the employed electrode system is that discharges occur in a concentrated area and continue corroding the insulation until breakdown takes place. The breakdown was considered as due to a real puncture of the sample



1. High Voltage Electrode 2. Insulating supports with nuts & bolts 3. Insulation sample under test 4. Spacer 5. Ground Electrode 6. Cavity (Dimensions are in mm)

FIGURE 2.1 CYLINDER-PLANE ELECTRODE SYSTEM USED FOR BREAKDOWN VOLTAGE MEASUREMENT

2.2.4 MEASUREMENT OF AC BREAKDOWN VOLTAGE

The 50 Hz AC voltage applied to the insulating samples was obtained from a 40 kV AC/DC Series Hipot Tester (MODEL HD 100) that is manufactured by Hipotronics, USA. The voltage is raised with steps of 200 V held constant for period of 30s each and every level until the breakdown occurs. The total time from application of voltage to the instant of breakdown was observed. Five data points were obtained for a particular type of sample and void condition and the mean value of the voltage is taken for modeling. At room temperature and atmospheric pressure all the five tests were carried out in air. The obtained breakdown data are then corrected for atmospheric condition before being used for modeling.

2.2.5 MEASUREMENT OF RELATIVE PERMITTIVITY OF SOLID INSULATING MATERIALS

The insulating samples of 12mm diameter were silver coated at the identical zone on the both sides to measure the relative permittivity. The silver coated samples were then pressed between the two brass sample holder electrodes of the dielectric interface of an impedance gain/phase analyser (Solartron, UK). The samples from the impedance gain/phase analyzer are applied from an AC voltage of 0.1 V (rms) at 50 Hz and relative permittivity values of the insulating materials are recorded. Table 2.1 shows the measured values of the relative permittivity of materials at 50 Hz frequency.

TABLE 2.1 RELATIVE PERMITTIVITY AGAINST MATERIALS

Insulating Materials	ε_r
White Minilex	4.4
Leatheroid paper	4.21
Glass Cloth	4.97
Manila Paper	4.68
Lather Minilex	5.74

From Table 2.2 to Table 2.6 are the data of White Minilex, Leatheroid Paper, Glass Cloth, Manila Paper and Lather Minilex of experimental breakdown voltage in kV with their thickness t, depth of void t_1, diameter of void d, and relative permittivity ε_r .

TABLE 2.2: EXPERIMENTAL BREAKDOWN VOLTAGES FOR WHITE MINILEX INSULATING SAMPLES UNDER AC TEST CONDITION

Serial no.	Insulating Material	Thickness of Insulator, t in mm	Void Depth, t_1 in mm	Void Diameter, d in mm	Relative Permittivity, ε_r	Breakdown Voltage, kV (experimental)
1	White Minilex	0.26	0.025	1.5	4.4	2.2000
2		0.26	0.025	2	4.4	2.2000
3		0.26	0.025	3	4.4	2.2000
4		0.26	0.025	4	4.4	2.2000
5		0.26	0.025	5	4.4	2.2000
6		0.26	0.125	1.5	4.4	2.2000
7		0.26	0.125	2	4.4	2.2000
8		0.26	0.125	3	4.4	2.2000
9		0.26	0.125	4	4.4	2.2000
10		0.26	0.125	5	4.4	2.2000
11		0.125	0.025	1.5	4.4	2.3000
12		0.125	0.025	2	4.4	2.3000
13		0.125	0.025	3	4.4	2.3000
14		0.125	0.025	4	4.4	2.3000
15		0.125	0.025	5	4.4	2.3000
16		0.125	0.125	1.5	4.4	2.3000
17		0.125	0.125	2	4.4	2.3000
18		0.125	0.125	3	4.4	2.3000
19		0.125	0.125	4	4.4	2.3000
20		0.125	0.125	5	4.4	2.3000
21		0.18	0.025	1.5	4.4	2.2000
22		0.18	0.025	2	4.4	2.2000
23		0.18	0.025	3	4.4	2.2000
24		0.18	0.025	4	4.4	2.2000
25		0.18	0.025	5	4.4	2.2000
26		0.18	0.125	1.5	4.4	2.2000
27		0.18	0.125	2	4.4	2.2000
28		0.18	0.125	3	4.4	2.2000
29		0.18	0.125	4	4.4	2.2000
30		0.18	0.125	5	4.4	2.2000

TABLE 2.3: EXPERIMENTAL BREAKDOWN VOLTAGES FOR LEATHEROID PAPER INSULATING SAMPLES UNDER AC TEST CONDITION

Serial no.	Insulating Material	Thickness of Insulator, t in mm	Void Depth, t_1 in mm	Void Diameter, d in mm	Relative Permittivity, ε_r	Breakdown Voltage, kV (experimental)
31	Leatheroid Paper	0.13	0.025	1.5	4.21	1.2000
32		0.13	0.025	2	4.21	1.2000
33		0.13	0.025	3	4.21	1.2000
34		0.13	0.025	4	4.21	1.2000
35		0.13	0.025	5	4.21	1.2000
36		0.13	0.125	1.5	4.21	1.2000
37		0.13	0.125	2	4.21	1.2000
38		0.13	0.125	3	4.21	1.2000
39		0.13	0.125	4	4.21	1.2000
40		0.13	0.125	5	4.21	1.2000
41		0.175	0.025	1.5	4.21	1.8000
42		0.175	0.025	2	4.21	1.8000
43		0.175	0.025	3	4.21	1.8000
44		0.175	0.025	4	4.21	1.8000
45		0.175	0.025	5	4.21	1.8000
46		0.175	0.125	1.5	4.21	1.8000
47		0.175	0.125	2	4.21	1.8000
48		0.175	0.125	3	4.21	1.8000
49		0.175	0.125	4	4.21	1.8000
50		0.175	0.125	5	4.21	1.8000
51		0.235	0.025	1.5	4.21	2.2000
52		0.235	0.025	2	4.21	2.2000
53		0.235	0.025	3	4.21	2.2000
54		0.235	0.025	4	4.21	2.2000
55		0.235	0.025	5	4.21	2.2000
56		0.235	0.125	1.5	4.21	2.2000
57		0.235	0.125	2	4.21	2.2000
58		0.235	0.125	3	4.21	2.2000
59		0.235	0.125	4	4.21	2.2000
60		0.235	0.125	5	4.21	2.2000

TABLE 2.4: EXPERIMENTAL BREAKDOWN VOLTAGES FOR GLASS CLOTH INSULATING SAMPLES UNDER AC TEST CONDITION

Serial no.	**Insulating Material**	**Thickness of Insulator, t in mm**	**Void Depth, t_1 in mm**	**Void Diameter, d in mm**	**Relative Permittivity, ε_r**	**Breakdown Voltage, kV (experimental)**
61	Glass Cloth	0.195	0.025	1.5	4.97	2.2000
62		0.195	0.025	2	4.97	2.2000
63		0.195	0.025	3	4.97	2.2000
64		0.195	0.025	4	4.97	2.2000
65		0.195	0.025	5	4.97	2.2000
66		0.195	0.125	1.5	4.97	2.2000
67		0.195	0.125	2	4.97	2.2000
68		0.195	0.125	3	4.97	2.2000
69		0.195	0.125	4	4.97	2.2000
70		0.195	0.125	5	4.97	2.2000
71		0.155	0.025	1.5	4.97	2.3000
72		0.155	0.025	2	4.97	2.3000
73		0.155	0.025	3	4.97	2.3000
74		0.155	0.025	4	4.97	2.3000
75		0.155	0.025	5	4.97	2.3000
76		0.155	0.125	1.5	4.97	2.3000
77		0.155	0.125	2	4.97	2.3000
78		0.155	0.125	3	4.97	2.3000
79		0.155	0.125	4	4.97	2.3000
80		0.155	0.125	5	4.97	2.3000

TABLE 2.5: EXPERIMENTAL BREAKDOWN VOLTAGES FOR MANILA PAPER INSULATING SAMPLES UNDER AC TEST CONDITION

Serial no.	**Insulating Material**	**Thickness of Insulator, t in mm**	**Void Depth, t_1 in mm**	**Void Diameter, d in mm**	**Relative Permittivity, ε_r**	**Breakdown Voltage, kV (experimental)**
81	Manila Paper	0.035	0.025	1.5	4.68	0.8000
82		0.035	0.025	2	4.68	0.8000
83		0.035	0.025	3	4.68	0.8000
84		0.035	0.025	4	4.68	0.8000
85		0.035	0.025	5	4.68	0.8000
86		0.035	0.125	1.5	4.68	0.8000
87		0.035	0.125	2	4.68	0.8000
88		0.035	0.125	3	4.68	0.8000
89		0.035	0.125	4	4.68	0.8000
90		0.035	0.125	5	4.68	0.8000
91		0.06	0.025	1.5	4.68	0.9000
92		0.06	0.025	2	4.68	0.9000
93		0.06	0.025	3	4.68	0.9000
94		0.06	0.025	4	4.68	0.9000
95		0.06	0.025	5	4.68	0.9000
96		0.06	0.125	1.5	4.68	0.9000
97		0.06	0.125	2	4.68	0.9000
98		0.06	0.125	3	4.68	0.9000
99		0.06	0.125	4	4.68	0.9000
100		0.06	0.125	5	4.68	0.9000

TABLE 2.6: EXPERIMENTAL BREAKDOWN VOLTAGES FOR LATHER MINILEX INSULATING SAMPLES UNDER AC TEST CONDITION

Serial no.	Insulating Material	Thickness of Insulator, t in mm	Void Depth, t_1 in mm	Void Diameter, d in mm	Relative Permittivity, ε_r	Breakdown Voltage, kV (experimental)
101	Lather Minilex	0.245	0.025	1.5	5.74	2.4000
102		0.245	0.025	2	5.74	2.4000
103		0.245	0.025	3	5.74	2.4000
104		0.245	0.025	4	5.74	2.4000
105		0.245	0.025	5	5.74	2.4000
106		0.245	0.125	1.5	5.74	2.4000
107		0.245	0.125	2	5.74	2.4000
108		0.245	0.125	3	5.74	2.4000
109		0.245	0.125	4	5.74	2.4000
110		0.245	0.125	5	5.74	2.4000
111		0.185	0.025	1.5	5.74	2.2000
112		0.185	0.025	2	5.74	2.2000
113		0.185	0.025	3	5.74	2.2000
114		0.185	0.025	4	5.74	2.2000
115		0.185	0.025	5	5.74	2.2000
116		0.185	0.125	1.5	5.74	2.2000
117		0.185	0.125	2	5.74	2.2000
118		0.185	0.125	3	5.74	2.2000
119		0.185	0.125	4	5.74	2.2000
120		0.185	0.125	5	5.74	2.2000
121		0.125	0.025	1.5	5.74	2.4000
122		0.125	0.025	2	5.74	2.4000
123		0.125	0.025	3	5.74	2.4000
124		0.125	0.025	4	5.74	2.4000
125		0.125	0.025	5	5.74	2.4000
126		0.125	0.125	1.5	5.74	2.4000
127		0.125	0.125	2	5.74	2.4000
128		0.125	0.125	3	5.74	2.4000
129		0.125	0.125	4	5.74	2.4000
130		0.125	0.125	5	5.74	2.4000

2.3 SUMMARY

This Chapter has provided the groundwork for prediction of the breakdown voltage of five insulating materials namely White Minilex, Leatheroid Paper, Glass Cloth, Manila Paper and Lather Minilex due to PD in cavities by carrying out experimental data generation with the help of cylinder-plane electrode system.

CHAPTER 3

MULTILAYER FEEDFORWARD NEURAL NETWORK

3.1 INTRODUCTION

Artificial Neural Networks (ANNs) have become the subject of widespread interest, largely because of their wide range of applicability and the ease with which they handle complex and non-linear problems. They are massively parallel-interconnected networks of simple elements intended to interact with the real world in the same way as the biological nervous system. They offer an unusual scheme based programming standpoint and exhibit higher computing speeds compared to other conventional methods [28]. ANNs are characterized by their topology, that is, the number of interconnections, the node characteristics that are classified by the type of nonlinear elements used and the kind of learning rules employed. The ANN is composed of an organized topology of Processing Elements (PEs) called neurons. In Multilayer Feedforward Neural Network (MFNN) the PEs are arranged in layers and only PEs in adjacent layers are connected.

3.2 THEORY OF MFNN

The MFNN used here consists of three layers namely input layer, hidden layer and output layer as represented in figure no 3.1. The Input layer of MFNN consists of different number of inputs variables according to the modeling of MFNN. The input variables are thickness of the material, void diameter, void depth and permittivity of the insulating material. The number of output neuron is decided by the number of estimated parameters; therefore in this model only one output neuron is taken corresponding to breakdown voltage V_b.

The Back Propagation Algorithm (BPA) is used to train the network. The sigmoid function represented by equation (3.1) is used as the activation function for all the neurons except for those in the input layer.

$$S(x) = 1 / (1+e^{-x}) \tag{3.1}$$

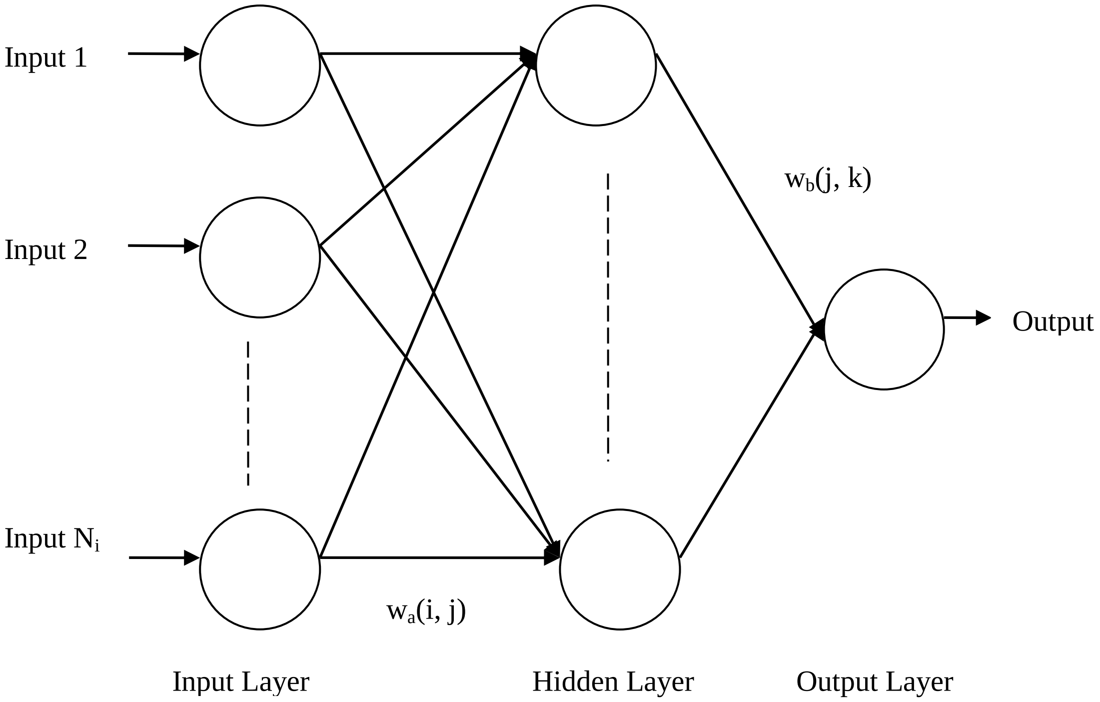


FIG.3.1 MULTILAYER FEEDFORWARD NEURAL NETWORK

3.2.1 CHOICE OF HIDDEN NEURONS

The optimal choice of number of hidden neurons, N_h is one of the most interesting and demanding aspect in designing MFNN. There are lots of schools on thought in determining the value of N_h. Simon Haykin [29] has mentioned that N_h should lie between 2 and ∞. Hecht-Nielsen [30] makes use of ANN interpretation of Kolmogorov's theorem to reach at the upper bound on N_h for a mono hidden layer network as $2(N_i+1)$, where Ni is the number of input neurons. But, this value should be decided very intelligently depending on the requirement of problem. Large value of N_h reduces the training error associated with MFNN, but at the expense of increasing computational complexity and time. For instance, if one gets a tolerably small value of training error with certain specific value of N_h, there is no gain in further increasing the value to enhance the performance of MFNN. The input and the output data are standardized before processing in the network as follows:

In this way of normalization, the maximum values of input and output vector components:

$$n_{i,\max} = \max\left(n_i\left(p\right)\right) p=1 \ldots N_p, i= 1,\ldots\ldots N_i \tag{3.2}$$

Where N_p is the number of patterns in the training set and N_i is the number of neurons in the input layer. Again,

$$O_{k,\max} = \max\left(o_k\left(p\right)\right) p =1,\ldots\ldots N_p, k=1,\ldots\ldots N_k \tag{3.3}$$

Where, $N_k$is the number of neurons in the output layer.

Normalized by these maximum values, the input and output variables are given asfollows.

$$n_{i,nor}\left(p\right) = \frac{n_i\left(p\right)}{n_{i,\max}}, p = 1,\ldots\ldots N_p,\ \ i = 1,\ldots\ldots N_i \tag{3.4}$$

and

$$o_{k,nor}\left(p\right) = \frac{o_k\left(p\right)}{o_{k,\max}}, p = 1,\ldots\ldots N \tag{3.5}$$

After normalization, the input and output variable lay [31] in the range of 0to 1.

3.2.2 CHOICE OF ANN PARAMETERS

The learning rate, η and the momentum factor, α have a very important effect on the learning rate of the BPA. BPA provides an approximation to the path in the weight space computed using the method of steepest descent [29]. If the value of ηis very small, this results in very slow rate of learning, whereas if the value of η is too huge in order to accelerate the rate of learning, the MFNN may become unstable (oscillatory). A simple method of improving the rate of learning without making MFNN unstable is by addition of the momentum factor α [32]. The values of η and α should lie between 0 and 1 [29].

The weights between the hidden layer and the output layer are updated based upon the equation

3.2.3 WEIGHT UPDATE EQUATIONS

as follows:

$$w_b(j,k,m+1) = w_b(j,k,m) + \eta_1 \times \delta_k(m) \times S_b(j) + \alpha \times \left(w_b(j,k,m) - w_b(j,k,m-1)\right) \qquad (3.6)$$

$_p$, $i = 1,\ldots\ldots N_k$

Where m is the number of iterations, j varies from 1 to N_h and k varies from 1 to N_k. $\delta_k(m)$ is the error for the kth output at the mth iteration. $S_b(j)$ is the output from the hidden layer.

Similarly, the weights between the hidden layer and the input layer are updated as follows:

$$w_a(i,j,m+1) = w_a(i,j,m) + \eta_1 \times \delta_j(m) \times S_a(i) + \alpha \times \left(w_a(i,j,m) - w_a(i,j,m-1)\right) \qquad (3.7)$$

Where i varies from 1 to N_i as there are N_i inputs to the network, $\delta_j(m)$ is the error for the jth output after the mth iteration and $S_a(i)$ is the output from the first layer. The $\delta_k(m)$ in equation (3.6) and $\delta_j(m)$ in equation (3.7) are related as

$$\delta_j(m) = \sum_{k=1}^{K} \delta_k(m) \times w_b(j,k,m) \qquad (3.8)$$

3.2.4 EVALUATION CRITERIA

The Mean Square Error E_{tr} for the training patterns after the mth iteration is defined as:

$$E_{tr} = \left(\sum_{p=1}^{P} \left(V_{b1p} - V_{b2p}(m)\right)^2 \right) \times \left(\frac{1}{P} \right) \qquad (3.9)$$

Where V_{1p} is the experimental value of breakdown voltage, *P* is the number of training patterns and V_{2p} (m) is the estimated value of the breakdown voltage after mth iteration. The training is stopped when the least value of E_{tr} has been obtained and this value does not change much with the number of iterations.

3.2.5 MEAN ABSOLUTE ERROR

The Mean Absolute Error E_{ts} is a good performance measure for judging the accuracy of the MFNN System. The E_{tr} tells how well the network has adopted to fit the training data only, even if the data are contaminated. On the other hand, the E_{ts} indicates how well a trained network behaves on a new data set not included in the training set. The value of E_{ts} is calculated based on the least value of E_{tr}. The E_{ts} for the test data expressed in percentage is given by

$$E_{ts} = \left(\frac{1}{S}\right) \times \left(\sum_{s=1}^{S} \left| \left(V_{b4s} - V_{b3s} \right) \right| / V_{b3s} \right) \times 100 \qquad (3.10)$$

Where V_{3s} is the experimental value of the breakdown voltage taken for testing purpose, V_{4s} is the estimated value of the breakdown voltage after the testing input data is passed through the trained network and S is the number of testing patterns.

3.3 RESULTS AND DISCUSSION

The equations of MFNN model have been used to predict the breakdown voltage of White Minilex, Leatheroid paper, Glass cloth, Lather minilex and Manila paper under AC condition in the presence of voids. Figure 3.2 has been derived from Figure 3.1 by substituting $N_i=4$. The inputs are the thickness of the insulating material, void depth, void diameter and relative permittivity of the insulating materials while the output is the breakdown voltage.

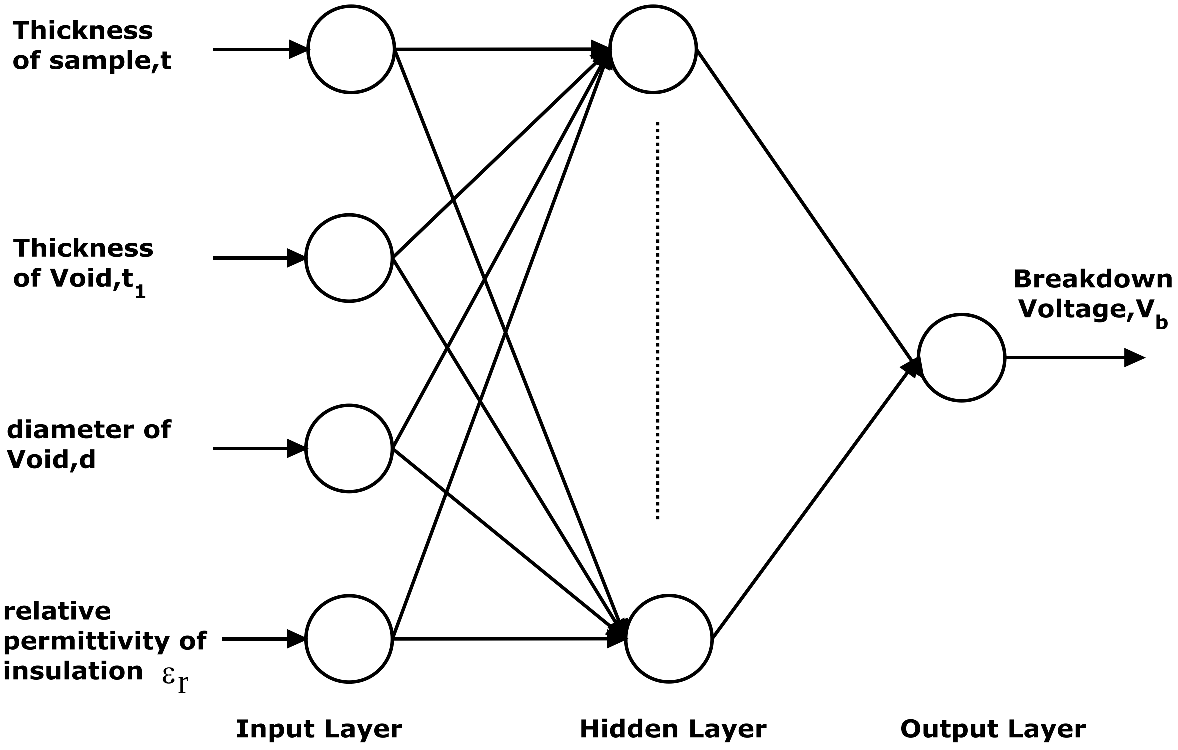


FIG.3.2 MFNN STRUCTURE

With the help of 130 sets of experimental input-output patterns, the proposed modeling are carried out; 115 sets of five insulating materials (27 sets of White Minilex, 27 sets of Leatheroid Paper, 17 sets of Glass Cloth, 17 sets of Manila Paper and 27 sets of Lather Minilex) are chosen input-output patterns used for training both networks and for testing purpose the remaining 15 sets of the five materials are used. The software programs developed are used for implementation using MATLAB version 9.1.

From Tables 3.1 to 3.3 and Fig. 3.2, it is quite obvious that when N_h = 10, α = 0.8 and η_1 = 0.99, the MSE for training data is the lowest at 2.3905×10^{-7}. The sequential mode of training has been adopted. It may be noted that the range of the values of η_1 and α should be between 0 and 1and value of N_h should not more than 10 as per the Hecht-Nielsen criteria. Hence we have stopped at N_h = 10 in Table 3.1 and in Table 3.2 we have stopped at η_1 = 0.99.

TABLE 3.1 VARIATION OF E_{tr} WITH N_h (η_1 = 0.1, α = 0.6, ITERATION = 400)

N_h	E_{tr}
2	0.0018
3	0.0012
4	3.7045×10^{-4}
5	2.7368×10^{-4}
6	2.7116×10^{-4}
7	1.4882×10^{-4}
8	1.4074×10^{-4}
9	1.2278×10^{-4}
10	1.1770×10^{-4}

TABLE 3.2 VARIATION OF E_{tr} WITH η_1 (ITERATION = 400, α = 0.6, N_h=10)

η_1	E_{tr}
0.1	1.1770×10^{-4}
0.2	2.0896×10^{-5}
0.5	2.8671×10^{-6}
0.6	2.2232×10^{-6}
0.7	1.8396×10^{-6}
0.8	1.5777×10^{-6}
0.9	1.3834×10^{-6}
0.99	1.2454×10^{-6}

TABLE 3.3 VARIATION OF E_{tr} WITH α (η_1 = 0.99, N_h = 10, ITERATION = 400)

α	E_{tr}
0.6	1.2456×10^{-6}
0.65	1.0191×10^{-6}
0.7	7.9460×10^{-7}
0.75	5.5291×10^{-7}

0.8	2.3905×10^{-7}
0.85	0.0012

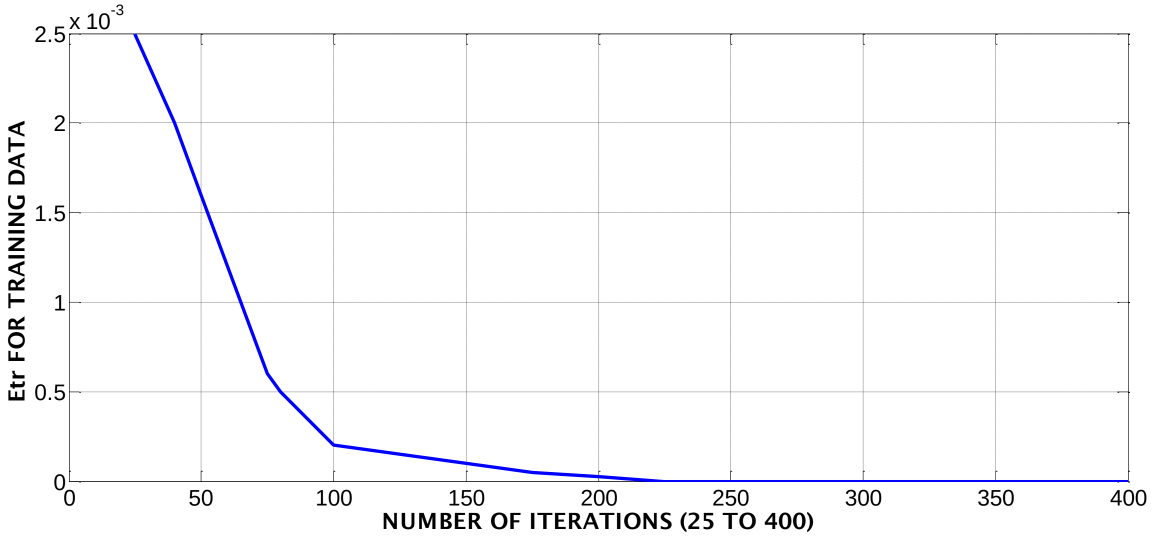


FIGURE 3.3 VARIATION OF E_{tr} WITH NUMBER OF ITERATIONS (η_1 = 0.99, α =0.8, N_H=10)

Finally, the function $V_b = f\left(t, t_1, d, \varepsilon_r\right)$ for the test data are calculated by simply passing the input data in the forward path of the network and using the updated weights of the network. Table 3.4 shows a comparison of the experimental and modeled data test data using MFNN model after 400 iterations.

From Table 3.4 it may be seen that the measured values and the modeled values are almost same and E_{ts} is found to be 0.0774%, thus shows the effectiveness of the proposed breakdown voltage modeling.

TABLE 3.4 COMPARISON OF THE EXPERIMENTAL AND MODELLED DATA USING MFNN MODEL

Insulating material	**t, mm**	**t$_1$, mm**	**d, mm**	**€$_r$**	**Breakdown voltage, kV (experimental)**	**Breakdown voltage, kV (modelled)**	**E$_{ts}$, %**
White Minilex	0.26	0.025	3	4.4	2.2	2.2000	0.0774
	0.125	00125	2	4.4	2.3	2.3000	
	0.18	0.025	1.5	4.4	2.2	2.2000	
Leatheroid Paper	0.13	0.125	5	4.21	1.2	1.2000	
	0.175	0.125	4	4.21	1.8	1.8000	
	0.235	0.025	2	4.21	2.2	2.2000	
Glass Cloth	0.195	0.025	5	4.97	2.2	2.2000	
	0.155	0.025	3	4.97	2.2	2.2000	
	0.155	0.125	1.5	4.97	2.3	2.3000	
Manila Paper	0.035	0.125	3	4.68	0.8	0.8000	
	0.06	0.025	2	4.68	0.9	0.9000	
	0.06	0.125	4	4.68	0.8	0.8000	
Lather Minilex	0.245	0.025	5	5.74	2.2	2.2000	
	0.185	0.125	1.5	5.74	2.4	2.3861	
	0.125	0.025	2	5.74	2.4	2.3861	

CHAPTER 4

CONCLUSION AND FUTURE WORK

4.1 INTRODUCTION

This thesis work deals with the modeling using ANN. Detailed discussions have been presented in Chapter 3 and conclusions have been made at the end of each chapter. Therefore, this concluding chapter is devoted to the summarization of the main contributions of the work and arriving at general conclusions.

4.2 SUMMARY

The major studies reported in this thesis pertain to:

1. The experimental procedure adopted in the laboratory in order to generate breakdown voltage data under AC conditions has described in Chapter 2. The experimental data are obtained with artificially created voids of various dimensions and with different insulation thicknesses of five common insulating materials, namely, White Minilex Paper, Leatherite Paper, Glass Cloth, Lather Minilex and Manila Paper using Cylinder-Plane Electrode System.

2. In Chapter 3, MFNN model is proposed for the prediction of the breakdown voltage of solid insulating materials due to PD in cavities as a function of four input parameters. The Mean Square Error E_{tr} for the training patterns and the Mean Absolute Error E_{ts} for the testing patterns has been calculated.

4.3 CONCLUSIONS

Before the thesis draws to a close, the general conclusions that emerge out from this work are highlighted. These conclusions are mainly arrived at based on the performance and the capabilities of the soft computing techniques presented here for breakdown voltage modeling. Based on such a critical appraisal, the current state of technology, its promises and pitfalls are charted. This finally leads to an outline of the future directions for research and development efforts in this subject area.

The main conclusions drawn are:

1. The combination of parameters for the best results in each of the models has been identified. A comparison of modeled and experimental results indicates that Soft Computing techniques can be very well employed for estimation of breakdown voltage as a function of insulation and void dimensions.
2. Tables 4.1 depict the the MSE for the training data E_{tr} obtained from the ANN model. **TABLE 4.1 E_{tr} OF ANN MODEL**

Model	$\mathbf{E_{tr}}$
MFNN	1.2454×10^{-6}

Thus, this work is successful in applying ANN for prediction of breakdown voltages under AC conditions as a function of insulation and void parameters.

As a future work a more generalization of the models to be developed, it would be interesting to include more parameters responsible for breakdown of insulating materials.

REFERENCES

[1] J. C. Fothergill, "Ageing, Space Charge and Nanodielectrics: Ten things we don't know about dielectrics", *IEEE 9th International Conference on Solid Dielectrics*, U.K.,Winchester, July 2007, pp. 1-10.

[2] C.L.Wadhwa, High Voltage Engineering, 2nd edition, Wiley Eastern Limited, 1994, pp.32-41.

[3] Jones J.P., Llewellyn J.P., Lewis T.J.: "The contribution of field-induced morphological change to electrical aging and breakdown of polyethylene", *IEEE Transaction. Dielectric and Electrical Insulation* 2005, 12, (5), pp. 951-956

[4] Fabiani D., Simoni L.: "Discussion on application of Weibull distribution to electrical breakdown of insulating materials", *IEEE Transaction. Dielectric and Electrical Insulation* 2005, 12, (1), pp. 11-16

[5] Basappa P., Jang S., Kim J.: "Electrical breakdown studies on electro-active paper", *IEEE Transaction. Dielectric and Electrical Insulation., 2007,14, (5), pp. 1125-1132*

[6] Garton C.G., Day A.G., Church H,F, : "Intrinsic related forms of breakdown in solids" , in Alston L.L. (ED.): "High voltage technology" (Oxford University Press, 1993, 3rd edition.), pp. 144-183

[7] C.A. Bailey, "A study of internal discharges in cable insulation", *IEEE Transactions on Electrical Insulation*, Vol. EI-2, No. 3, 1967, pp.155-159.

[8] F. J. Pohnan, "Voids and wax in solid high-voltage cables", *AIEE Transactions on Electrical Insulation*, Vol. 70, Issue 2, 1951, pp. 1372-1376.

[9] C. Laurent, C. Mayoux and A. Sergent, "Electrical breakdown due to discharges in different types of insulation", *IEEE Transactions on Electrical Insulation*, Vol. EI-16, No. 1, 1981, pp.52-58.

[10] A.W.W. Cameron, "Diagnoses of ac generator insulation condition by nondestructive tests", Power Apparatus and Systems, Part III, *Transactions of A.I.E.E.*, Vol. 71, 1952, pp. 263-274.

[11] G.L. Atkinson and W.R. Thomas, "An Epoxy-paper insulation system for high-voltage applications", *IEEE Transactions on Electrical Insulation*, Vol. EI-2, No. 1, 1967, pp. 18-24.

[12] D.A. Nattrass, "Partial discharge XVIII: The early history of partial discharge research", *IEEE Electrical Insulation Magazine*, Vol. 9, No. 4, 1993,pp. 27-31.

[13] F.H. Kreuger, M.G. Wezelenburg, A.G. Wiemer and W.A. Sonneveld, “Partial discharge part XVIII: errors in the location of partial discharges in high voltage cables”, *IEEE Electrical Insulation Magazine,* Vol. 9, No. 6, 1993, pp. 15-25.

[14] T. Tanaka, Y. Ohki, M. Ochi , M. Harada and T. Imai, “Enhanced partial discharge resistance of Epoxy/ Clay nano composite prepared by newly developed organic modification and solubilization methods” ,*IEEE Transactions on Dielectrics and Electrical Insulation* ,Vol. 15, No. 1, 2008, pp. 81-89.

[15] Y. Kikuchi, T. Murata, Y.Uozumi, N. Fukumoto, M. Nagata, “Effects of ambient humidity and temperature on partial discharge characteristics of conventional and nano composite enameled magnet wires” ,*IEEE Transactions on Dielectrics and Electrical Insulation* , Vol. 15, No. 6, 2008, pp. 1617-1625.

[16] P. H.F. Morshuis , “Degradation of solid dielectrics due to internal partial discharge: some thoughts on progress made and where to go now”, *IEEE Transactions on Dielectrics and Electrical Insulation* , Vol.12, No. 5, 2005, pp. 905-913.

[17] S. A. Boggs, “Partial discharge- Part III: Cavity-induced PD in solid dielectrics”, IEEE Electrical Insulation Magazine, Vol. 6, No. 6, 1990, pp. 11-18.

[18] J.C. Devins, “The physics of partial discharges in solid dielectrics”, IEEE Transactions on Electrical Insulation, Vol. EI-19, 1984, pp.475-495.

[19] J. H. Mason, “Effect of thickness and area on the electric strength of polymers”, IEEE Transactions on Electrical Insulation, Vol. 26, No. 2, April 1991, pp. 318-322

[20] S. Ghosh and N. K. Kishore, “Breakdown voltage behaviour of Leatheroid paper with or without a void,” Proceedings of *IEEE Conference,* ICET, India, Mumbai, 2006, pp. 2990-2992.

[21] P. Bjellheim and B. Helgee, “AC breakdown strength of aromatic polymers under partial discharge reducing conditions”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 1, No.1, Feb. 1994,pp. 89-96.

[22] N.P. Kolev and N. M. Chalashkanov, “Modeling of partial discharge inception and extinction voltages using adaptive neuro-fuzzy inference system (ANFIS)”, IEEE *9th International Conference on Solid Dielectrics,* U.K. Winchester, July 2007, pp. 605-608.

[23] S. Ghosh, “ Study of some aspects of artificial neural network modeling of partial discharge phenomenon”, Ph. D. Dissertation, IIT, Kharagpur, 1999.

[24] [24] GHOSH S., MOHANTY S.: ‘Modeling of breakdown voltage behavior of Leatheroid Paper in the presence of voids using artificial neural networks’. *Proc. IEEE Ninth Int. Conf on Solid Dielectrics,* Winchester, UK, July 2007, pp. 94–97.

[25] S. Ghosh and N.K. Kishore, "Modeling of partial discharge inception and extinction voltages of sheet samples of solid insulating materials using an artificial neural network", *IEE Proc- Sci. Meas. Technol,* Vol. 149, No. 2 , 2002, pp. 73-78 .

[26] J.S.R. Jang, C.T. Sun and E. Mizutani, "Neuro-Fuzzy and soft computing: A computational approach to learning and machine intelligence", (Prentice Hall International, Inc., (2nd Edition 1997), pp. 24-79.

[27] ASTM Designation: D202-97: 'Standard test methods for sampling and testing untreated paper used for electrical insulation', 2002.

[28] S. Mohanty, S. Ghosh: "Artificial neural networks modeling of breakdown voltage of solid insulating materials in the presence of void", *Institution of Engineering and Technology Science. Measurement and Technology,* 2010, Vol. 4, Iss. 5, pp 278-288.

[29] Simon Haykin.: 'Neural networks a comprehensive foundation' (Prentice Hall International Inc, New Jersey, USA, 1999), pp. 161–175, 270–300

[30] Hecht-Nielsen R.: (Addison-Wesley Publishing Company, Inc, 1990).

[31] S.Ghosh and N. K Kishore, "Modeling PD inception voltage of Epoxy Resin post insulators using an adaptive neural network", *IEEE Transaction. Dielectrics and Electrical Insulation,* Vol. 6, No. 1, 1999, pp. 131-134.

[32] Rumelhart D.E., Mcclelland J.L. (EDS.): 'Parallel distributed processing: explorations in the microstructure of cognition' (MIT Press, 1986, vol. 1).

[33] V.Vapnik, The Nature of Statistical Learning Theory, Springer, New York, 1995.

[34] V.Vapnik, Statistical Learning Theory, Wiley, New York, 1998.

[35] J.A.K Suykens, T Van Gestel, J De Brabanter, B De Moor, J Vandewalle, Least Square SVM. Singapore: World Scientific, 2002

[36] D Hanbay,. "An expert system based on least square support vector machines for diagnosis of the valvular heart disease", *Expert Systems with Application,* 36(4), part-1, 8368-8374.2009

[37] Z Sahli,, A.Mekhaldi, R.Boudissa, S.Boudrahem, "Prediction parameters of dimensioning of insulators under non-uniform contaminated condition by multiple regression analysis", *Electric Power System Research, Elsevier 2011* (*in press.)*

[38] B.Zegnini, A.H. Mahdjoubi and M.Belkheiri ," A Least Squares Support Vector Machines (LS-SVM) Approach for Predicting Critical Flashover Voltage of Polluted Insulators," *2011 IEEE Conference on Electrical Insulation and Dielectric Phenomena,* Mexico,pp.403-406, 16-19 0ct 2011.