ELECTRICAL STRESS DISTRIBUTION OF ESTER OIL TRANSFORMERS UNDER LIGHTNING IMPULSE CONDITIONS

A Dissertation submitted in fulfillment of the requirements for the Degree

of

MASTER OF ENGINEERING

in

Power Systems

Submitted by

Ritika Agarwal
(Registration no.: 801742029)

Under the guidance of

Dr. Ashish Paramane
Lecturer, EIED
Thapar Institute of Engineering & Technology, Patiala

Dr. C.S. Narasimhan
Head, R&D
Savita Oil Technologies Limited, Mumbai

2019

Electrical and Instrumentation Engineering Department
Thapar Institute of Engineering & Technology, Patiala
(Declared as Deemed-to-be-University u/s 3 of the UGC Act., 1956)
Post Bag No. 32, Patiala – 147004
Punjab (India)

DECLARATION CERTIFICATE

I hereby certify that the work which is presented in dissertation entitled, **"Electrical stress distribution of ester oil transformers under lightning impulse conditions"**, in partial fulfilment of the requirements for the award of the degree of Master of Engineering in Power Systems, submitted to Electrical & Instrumentation Engineering Department of Thapar Institute of Engineering & Technology University, Patiala is as authentic record of my own work carried under the supervision of **Dr. Ashish Paramane**, Lecturer, EIED and **Dr. C.S. Narasimhan**, Head R&D Department, Savita Oil Technology Limited. It refers to other researcher works which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part or in full to any other degree to any other university or institute except as reported in text and references.

Place: Patiala
Date: 15/July/2019

Ritika
(Ritika Agarwal)
Roll No.: 801742029

It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

(Dr. Ashish Paramane)
Lecturer
Electrical & Instrumentation Engineering Department
Thapar Institute of Engineering & Technology
Patiala

(Dr. C.S. Narasimhan)
Head
R&D Department
Savita Oil Technology Limited
Mumbai

ACKNOWLEDGEMENT

It would be my pleasure to extend thanks firstly to Thapar Institute of Engineering and Technology, Patiala and Savita Oil Technology Limited, Mumbai for giving me this great opportunity to work in an industry in collaboration with TIET for M.E. Dissertation.

I would like to extend profound gratitude to my both mentors, **Dr. Ashish Paramane** (TIET Mentor) and **Dr. C. S. Narasimhan** (Industry Mentor) for their guidance during my project work. Without their help and guidance, it would never have been possible to gain a lot of experience and knowledge.

I would like to thank Senior Professor **Dr. R.S. Kaler** (Head, EIED, TIET) and **Dr. Nitin Narang** (PG Coordinator, EIED, TIET) for providing a healthy learning environment to explore as much as we can.

I would like express my most profound feeling of appreciation towards **Dr. V. Jeyabalan,** Manager, CG Power and Industrial Solutions Ltd., R&D Mumbai who has been a steady wellspring of motivation for me all through this project

It would be unfair to forget the great efforts being done by all the TIET staff members for cooperating with me at every moment, Savita Oil Technologies Ltd R&D members and CG Power and Industrial Solutions Ltd R&D and Staff members for teaching me the basic technicalities about the project by giving me their precious time from their busy schedule.

Finally, I would like to thank my family and friends who have always been a motivation and support for me during the project.

Ritika Agarwal

(Registration no.: 801742029)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Mineral oil	MO
Natural ester oil	NE
Maximum electric stress	E_{max}
Average electric stress	E_{mean}
Utilisation factor	ξ
High voltage winding	HV
Low voltage winding	LV
Surface end ring	SER
Design insulation level	DIL
Continuous double disc	CDD

ABSTRACT

Ester oils are becoming potential substitutes for mineral oil, due to their better biodegradability and high flash and high fire point compared to conventionally used transformer oil. The high affinity of ester fluids for moisture helps in enhancing the life of the paper insulation and hence that of the transformer. Due to higher permittivity of both natural ester and synthetic ester than mineral oil it is advantage for the electrical field distribution in the power transformer. With the increase in its popularity, it becomes important to understand complete insulating properties of natural esters and synthetic ester and also their impact on transformer insulation design.

Compared to sphere- sphere configuration, point sphere configuration is more dangerous in transformers. Most of the failures that happen in transformers are due to non-uniformity in the field experienced by insulation which leads to failure of insulation system inside the transformers. Due to this reason, performance of two natural esters and a mineral oil is examined under lightning impulse using the point-sphere using vertical electrode configuration. The impact of both positive and negative polarities is explored. The obtained data is further analyzed by Weibull distribution (3-parameter Weibull) to predict the 1% failure probability breakdown voltage for each type of oil and by using FEM technique electrical stress analysis is performed resulting in calculation of utilization factor. Further, from time to breakdown, velocity of streamer is calculated under both positive and negative polarity.

Above all analysis is performed for small oil electrode gaps. For long oil gaps stress analysis using ElecNet is performed. In this dielectric strength of the insulation structure between HV lead connection to tap winding of 36MVA, 220/6.9kV power transformer is evaluated. To reduce the complexity of the full model, quarter model of winding, tank and core assembly is considered. Only single phase winding is considered for analysis. HV winding is modeled as discs with paper covering and applied with AC switching impulse test voltages. The complete tap and LV windings are assumed as single cylinder windings.

Further for impulse voltage distribution testing, laboratory scale single phase transformer model is fabricated in which continuous double disc winding is incorporated. Due to change in permittivity of oil experiments are performed for both mineral oil and natural ester oil.

CHAPTER 1
INTRODUCTION

1.1 OVERVIEW

A power transformer is critical and essential part of electrical power systems. A failure of transformer is a major concern as it could cause a number of economic losses to the industry in the form of penalty payment to government authorities, capital loss, or even compensation to fatal injuries [1, 2]. So, it is extremely important to ensure safe operation of transformers throughout their working lives.

Post failure analysis of transformers showed that the major culprit behind the transformer failures is insulation failures [2]. From the years, Oil and paper are the choices for providing insulation to the transformers. To raise the dielectric strength of power transformer insulation, insulating oil is filled in the tank so that it can impregnate voids of solid (paper) insulation and fill up the distance between the components of main transformer tank [3]. Transformer oil not only behaves as the insulating oil for the transformers but also transfers the heat generated inside the transformer as a result of winding and core loss. Furthermore, it acts as the carrier for examine the condition of transformer during operation.

Traditionally used mineral oil has a number of desirable properties for transformers. With its wide availability and low cost, it has been used for both distribution and power transformers (oil filled) since the beginning of transformer industry. However its poor biodegradability, low flash and fire points and high toxicity which can cause serious contamination to the environment are responsible for increasing the need of substitutes of mineral oil [3]. Therefore, technology of using natural and synthetic esters as insulating liquids in distribution & power transformers is increasing day by day. Main reason behind this is environmental benefit in comparison to the conventionally used mineral oil. Major attractive features of esters which have been already evaluated are: good biodegradability, non-toxicity, high moisture absorption ability and high flash and fire a point (usually above 300°C) which lowers the risks for humans as well as environment [4]. Due to high moisture saturation levels of esters it protects the paper insulation by absorbing the water from cellulosic materials.

The major technical challenge that usage of esters are facing in recent years is to extend its use from low voltage distribution transformers to transmission power transformers having high voltage [5, 6]. Since the insulating properties of mineral oil are different from esters, it might affect the design and manufacturing of transformers. Therefore, it becomes important to understand complete insulating behaviour of esters liquids and their impact on power transformer insulation manufacturing design.

Previous studies showed a differentiation between the dielectric strength of natural ester oil and mineral liquid under uniform and divergent fields at lightning impulse [5]. But limited information is available on standard impulse breakdown voltage of esters with different polarities over a wide range of electrode gap distances with horizontal electrode geometry. Therefore, it is essential to study the breakdown behaviours as well as electrical performance of esters under various fields with standard impulse conditions.

1.2 RESEARCH OBJECTIVES OF THESIS

The objectives of the project are summarized below for dielectric design guidelines of ester oil for transformer application under impulse condition:

- To evaluate dielectric behaviour of ester oil for power transformer application under impulse condition.
- To determine the dielectric strength of natural ester oil under positive and negative standard full wave impulse condition in non-uniform field.
- To determine electrical stress experienced by natural ester at 1% failure probability breakdown voltage using ElecNet Software
- To evaluate the dielectric strength of the insulation between HV lead to tap winding of 36MVA, 220/6.9kV power transformer using ElecNet Software.
- To determine impulse voltage distribution of mineral oil and natural ester transformer under standard impulse wave shape.

1.3 SIGNIFICANCES OF PROJECT

As transformer insulation mainly consists of insulating oil and paper, moreover oil has lower permittivity as compared to paper insulation so probability of oil insulation failure is more under impulse condition. Therefore prediction of failure probability voltage plays a important role in transformer manufacturing process. Major significances of the project are summarized below:-

- Designing the guidelines of ester oil transformer under impulse conditions.
- Prediction of streamer propagation with the help of time to breakdown and streamer velocity.
- Design optimization is done with respect to mineral oil.

- Reducing the failure and fault probability in transformers.
- Reducing the possibilities of faults by manpower at factory floor conditions

1.4 OUTLINE OF THESIS

Brief descriptions of all the chapters in thesis are given below:-

Chapter 1 – Introduction

This section discuss about the background, research objective, significance of project and overview of the thesis.

Chapter 2 – Literature Survey

This section represents general literature review about insulating liquid and their properties, benefit of ester oil over mineral oil, design of electrodes, high voltage testing techniques and effect of method on measured breakdown voltage.

Chapter 3 – Effect of vertical electrode configuration on breakdown mechanism of ester oil

In this chapter vertical electrode test cell is designed and the measurement of standard impulse withstand & impulse breakdown voltage level of ester oil taking reference of mineral oil under non-uniform fields with both the polarities (positive & negative) for various gaps and with Solid Works model electric stress analysis is performed.

Chapter 4 – Stress analysis for long oil gaps in ester oil transformers

This section discusses about the design of insulation system in transformer, FEM analysis, and maximum stress point and stress analysis for long oils gaps

Chapter 5 – Impulse voltage distribution of mineral oil and natural ester oil transformer under standard impulse wave shape

This section gives details about the type of winding used in transformer with their lumped parameter model and experimental description of impulse voltage produced through a surge generator by comparing for different impulse wave shapes

Chapter 6 – Conclusions and Future work

This section summarizes major conclusions of the thesis and suggests future work on study of dielectric strength of insulating oil in transformers

CHAPTER 2
LITERATURE SURVEY

2.1 OVERVIEW

Conventional transformer fluid has been utilized for the purpose of insulation and cooling in transformers. Mineral oil is a mixture of different hydrocarbon molecules. Major parts of its segments are paraffinic, naphthenic and aromatic segments [10]. Currently use of new liquids like vegetable oils, is finding use globally as a replacement to mineral oils to impart better fire safety and loading characteristics to a transformer.

Looking toward applications in huge power transformers, any selected liquids ought to fulfill basic insulation level of transformer design. Standard lightning impulse withstands quality for the transformer oils are critical for protection of expensive high voltage power transformers. Therefore, impulse test is part of any transformer acceptance test for transformers above 72.5kV class so it is very critical to study the behavior of new ester oils under lightning impulse voltages. With the end goal to consider the dielectric suitability of the selected ester oils, one need to surely know pre-breakdown and breakdown phenomenon in transformer liquids. In transformer oil, a breakdown occasion is commonly the result of the inception and propagation of conductive low thickness channels called 'streamer' [11]. These streamers are started from high neighborhood electric fields connected to the transformer oils. These streamers could cause totally connect two conductors inside the transformer and cause insulation failures. It has been perceived by industry and researchers that particles adversely affect the dielectric quality of insulating.

2.2 TRANSFORMER OILS USED IN THIS PROJECT

2.2.1 MINERAL OIL (TRANSOL)

Mineral oil (Transol produced by Savita Oil Technologies Limited) is category of inhibited insulating oil (with high anti-oxidation additives). It mainly constitutes saturated hydrocarbon molecules, such as paraffin, naphthenic and aromatics and small amount of oxygen and sulphur, as shown in figure 2.1. It is synthetically stable and has low oxidation ability due to the saturated molecular structures [6]. Its insulating strength is higher, more than 70 kV/ 2.5mm (according to IEC60156 with a 2.5 mm gap of electrodes) with sample is treated, but considerably decreased when it is tarnished with foreign particles as well as water [7]. Mineral oil has many drawbacks mainly with environmental unfriendliness & fire hazards. The major issue with mineral oil is its low flash and fire point and non-biodegradable behaviour which affect their application for power transformers. Also, the water saturation limit for mineral oil is low, 55 parts per million (ppm) at ambient temperature. Table 2.1 describe the key properties of Transol.

Figure 2.1: Basic hydrocarbon structures of Mineral oil

Table 2.1: Key properties of Transol

	Unit	Test method	Typical data
1. Physical			
Density, 20ºC	kg/dm³	ISO 12185	0.882
Viscosity, 40ºC	mm²/s	ISO 3104	8.7
Flash point	ºC	ISO 2719	144
Pour point	ºC	ISO 3016	-60
Interfacial tension	mN/m	ISO 6295	50
2. Chemical			
Acid number	mg KOH/g	IEC 61125	0.08
Aromatic components	%	IEC 60590	10
Moisture level	mg/kg(ppm)	IEC 60814	<20
3. Electrical			
Dissipation Factor, 90ºC	-	IEC 60247	<0.001
Breakdown Voltage	kV	IEC 60156	
-before treatment			40-60
-after treatment			>70

2.2.2 NATURAL ESTER

Vegetable Oil (ester oil) has been developed as a potential substitute to the mineral oil which is used as coolant for the distribution (small scale) and power transformers. They have rapid and complete biodegradation properties as compared to mineral oil [14]. They are categorized as low flammable liquids means high flash and fire points. In this project, two natural esters are used.

They are BioTransol which is defined as natural ester (NE(A)) and another one natural ester (NE(B)). BioTransol HF is manufactured by Savita Polymers in Mahad while the other natural ester (NE(B)) is procured from market

BioTransol (NE(A))

BioTransol is basically a natural ester based dielectric liquid which is made from the renewable vegetable oils. This liquid is biodegradable, environment friendly and non-toxic to the aquatic life as per the US EPA OECD 301B. Table 2.2 describes the key properties of BioTransol (NE(A)).

Table 2.2: Key properties of BioTransol (NE(A))

	Unit	**Test method**	**Typical data**
1. Physical			
Density, 20ºC	kg/dm^3	ASTM D1298	0.92
Viscosity, 40ºC	mm^2/s	ASTM D445	32 – 35
Flash point	ºC	ASTMD92	>260
Fire point	ºC	ASTMD92	360
Pour point	ºC	ASTMD97	-15 - -18
Interfacial tension,25 ºC	mN/m	ASTM D971	24
2. Chemical			
Acid number(TAN)	mg KOH/g	ASTM D974	0.03
Water content	mg/kg(ppm)	ASTM D153	<50
3. Electrical			
Dissipation Factor, 100ºC	-	ASTM D924	0.03
Breakdown Voltage	kV	ASTM D1816	70 (2.5mm)

NATURAL ESTER (NE(B))

Natural ester (NE(B)) is also a natural ester procured from the market. The structure of natural esters shown in figure 2.2 consists of triglycerides containing carbon double bonds or even carbon triple bonds.

The structure of the natural ester makes them easily biodegradable. Natural esters have good dielectric strength of over 56 kV/2mm (estimated by ASTM D1816 utilizing a 2 mm gaps separate). Natural esters (NE(A) and NE(B)) described above are used in power transformers as insulation fluids. Table 2.3 describes the key properties of natural ester (NE(B)).

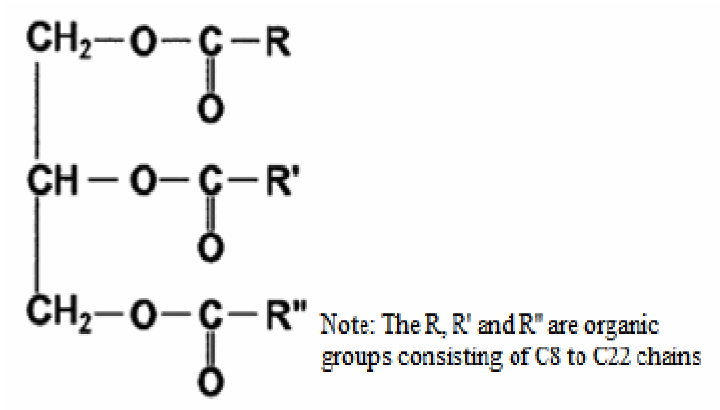


Figure 2.2: Molecular Structure of Natural Ester (NE(B))

Table 2.3: Key properties of Natural Ester (NE(B))

	Unit	Test method	Typical data
1. Physical			
Density, 20ºC	kg/dm^3	ASTM D1298	0.92
Viscosity, 40ºC	mm^2/s	ASTM D445	32
Flash point	ºC	ASTMD92	330
Pour point	ºC	ASTMD97	-20
Interfacial tension,25 ºC	mN/m	ASTM D971	24
2. Chemical			
Acid Number (TAN)	mg KOH/g	ASTM D974	0.02
Water content	mg/kg(ppm)	ASTM D153	30
3.Electrical			
Dissipation Factor, 100ºC	-	ASTM D924	0.03
Breakdown Voltage	kV	ASTM D1816	56 (2mm)

2.3 BENEFIT OF ESTER OIL OVER MINERAL OIL

The most important features of ester insulating oils in comparison with mineral insulating liquid are discussed below:

- Ester liquids are readily biodegradable as compared to mineral oil which is beneficial for environment as well as for people.
- Ester oils have higher fire point and flash point than mineral oil which indicates high reluctance to ignition, in turn reduces the chances of fire hazard in electrical power equipment.
- Ester liquids are non-toxic; therefore they are safe for health consideration.

- Moisture is a major factor which accelerates ageing of cellulose in transformers. Due to hygroscopic nature of esters liquids than mineral oils they can absorb more water from cellulose material which slows down ageing process of cellulose insulation [19].
- Permittivity of ester liquids is near to that of transformer solid insulation which causes even stress distribution between liquid and solid materials as compared to mineral oil [18]. It also reduces the local stress in oil wedges which helps in typically setting off a discharge.
- In comparison with mineral oil ester liquids have more viscosity, and it may reduce the flow of oil, further affect (or worsen) the effect of heat transfer property of a transformer considering ON (Oil Natural) mode. On the other hand, with respect to thermal conductivity ester oils are having more as compared to mineral liquid, and this could provide some compensation for heat dissipation [18].
- Ester liquids are more polar in nature as compared to mineral oils which may bring space charge issues. Moreover volume resistivity is lower for ester liquids which reduce their insulation resistance.

2.4 DESIGN OF ELECTRODES

Electrode geometry is very vital parameter for the breakdown voltage of impulse at a particular gap distance. In real transformers, the dielectric materials are stressed under distinctive electrical fields. To consider the different field setups present in transformers, the terminal designs with exceedingly uniform to non-uniform electric fields have been examined [8].The terminals considered are plane-plane, cone-cone, plane-needle and plane-cone. To study these for the small gaps in air and oil, the following electrode measurements are considered and are shown in the figures 2.3 to 2.6. All the dimensions of electrode configurations are taken in mm.

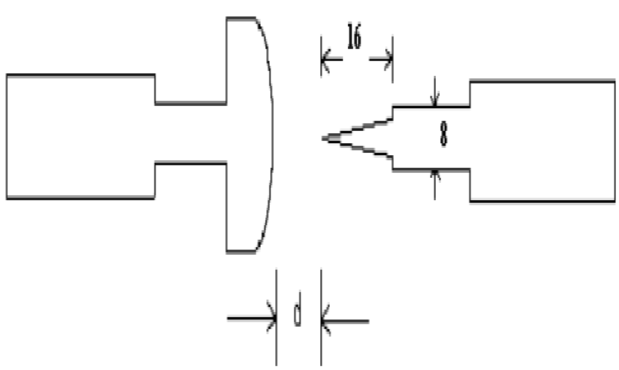


Figure 2.3: Plane- needle electrode configuration

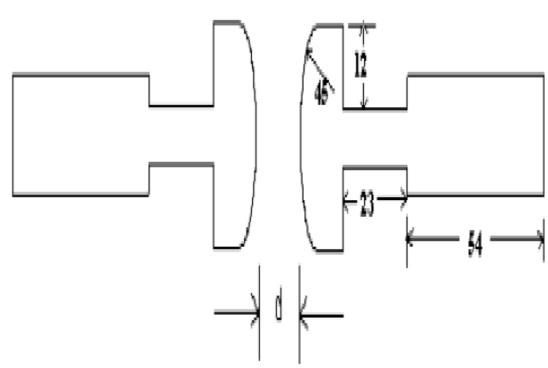


Figure 2.4: Plane-plane electrode configuration

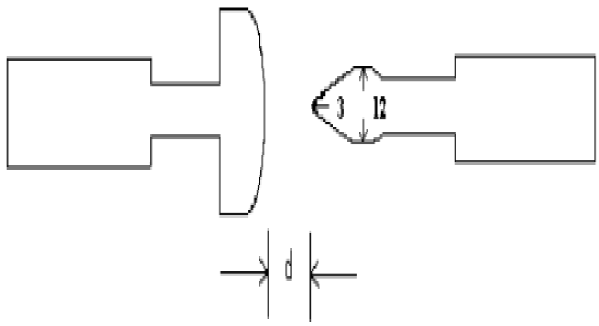


Figure 2.5: Plane-cone electrode configuration

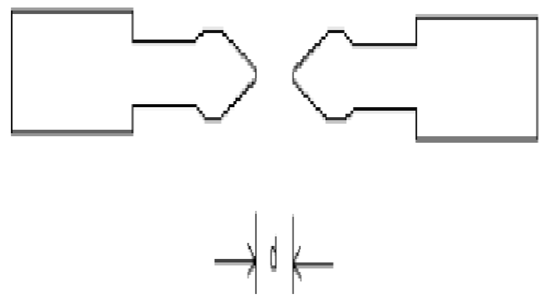


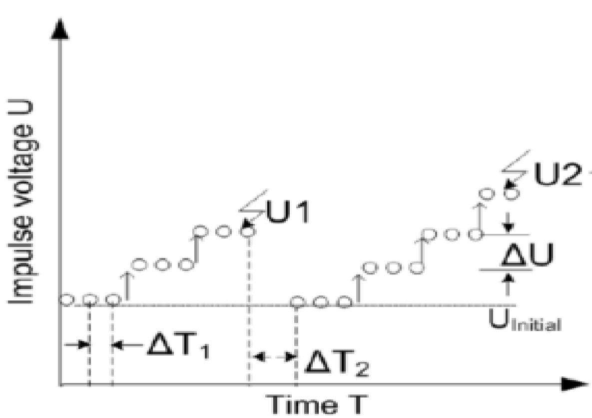
Figure 2.6: Cone-cone electrode configuration

It can be concluded that the more will be the uniform field more will be utilisation factor and in non-uniform field, the utilisation factor is less. Plane-plane configuration is considered as highly uniform field whereas plane-needle and plane-cone is consider as non- uniform field.

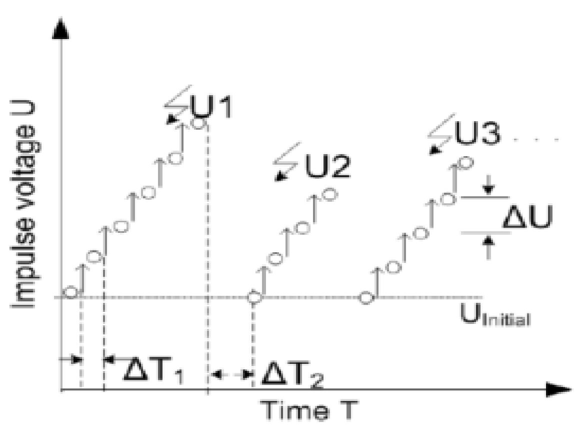
2.5 HIGH VOLTAGE TESTING TECHNIQUES

2.5.1 RISING VOLTAGE METHOD

This method is mostly used for both AC as well as impulse [16]. In this type of test, the voltage is increased at a certain rate till the breakdown happens. To repeat test, similar procedure is followed and number of breakdown voltages can be recorded. Mainly for AC testing this method is used to have an easy control on the voltage whereas for impulse testing voltage increasing in shots and voltage level is more preferred [16]. ASTM D 3300 and IEC 60897 [17, 18], standards for lightning impulse breakdown tests of dielectric liquid, follows the same method. The major difference in them is 3 shots per voltage for ASTM standard while 1 shot per voltage for IEC standard as described in figure 2.7. ΔT1 represents the time duration between two shots; ΔT2 represents the time duration between two tests and ΔU is step increment voltage.



(a) 3shots/step, ASTM- D3300



(b) 1shot/step, IEC 6089

Figure 2.7: Sketch of rising voltage method [17, 18]

2.5.2 UP-AND-DOWN METHOD

This method was given by Dixon and Mood, allows a prediction of 50% dielectric breakdown voltage, when their normal distribution of breakdown voltage [19]. This is mostly used in impulse lightening tests to minimize the time duration of testing. Test Procedure of up-and-down method is explained in figure 2.8: (i) The test voltage is increased from an initial voltage, at that point having no chances of breakdown will occur, in voltage steps of a single voltage ΔU, till the first breakdown occurs; (ii) The voltage is decreased by the similar voltage step ΔU until dielectric breakdown does not occur; (iii) The voltage is now increased again till one more breakdown happens, and so on so forth. The mean value of the applied voltages of which the minimum voltage is take into account having minimum two shots, is considered as 50% breakdown voltage [19].

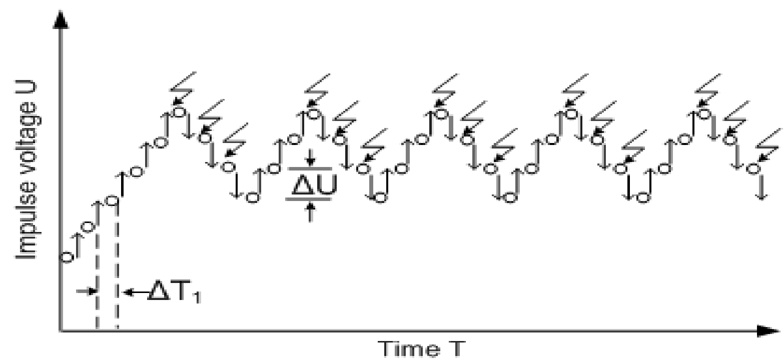


Figure 2.8: Sketch of up-and-down method [19]

2.5.3 MULTIPLE-LEVEL METHOD

It is also named as constant-voltage method, describes the conventional method for evaluating probability of breakdown [19], as shown in figure 2.9. The test procedure involves applying a no. of fixed impulse shots at various voltage steps and noting the no. of breakdowns at every voltage step.

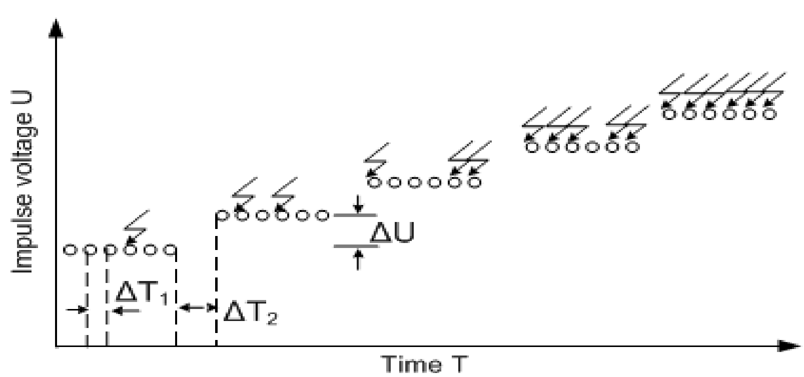


Figure 2.9: Sketch of multiple-level method [19]

2.6 EFFECT OF METHOD ON MESEAURED BREAKDOWN VOLATGE

50% impulse lightning breakdown voltages of natural ester and mineral oil performed with different testing procedures are summed up as shown in figure 2.10. From this, it can be concluded that various testing techniques have remarkable effect on the experimental breakdown voltage [18]. For method of rising-voltage, results following 1 shot per voltage step method are greater as compared to 3 shot at voltage step method. For method using multiple- level & method using rising-voltage with 1 shot at step rate of increase gives similar outputs, which are usually greater than as compared to other two testing methods. It is notable that the technique which affects the results of breakdown voltages does not change the trend of the results of both mineral oil and esters [18, 19]. As shown in Figure, ester liquids are always showing less breakdown voltage as compared to mineral oil without depending on method used for testing purpose.

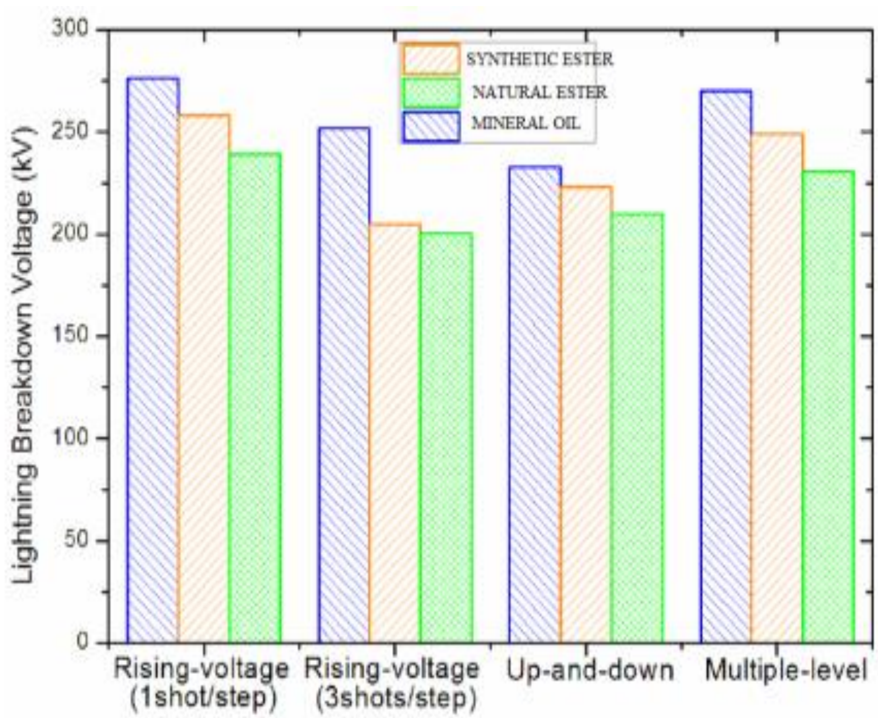


Figure 2.10: Comparative study of impulse breakdown of ester liquids and mineral liquid by diverse testing techniques; d=3.8 mm. [19]

2.7 DESIGN OF INSULATION SYSTEM IN TRANFORMER

In oil filled transformers, while designing the insulation structure of a transformer for a given design the insulation system designer must consider whole system into consideration. For a specific design the insulation system should adequate sufficient dielectric strength for operating and test voltage stresses. The insulation structure which is considered must provide sufficient cooling channels so that it can allow liquids to dissipate the heat which is generated in the windings and it should provide adequate mechanical support for the windings under both normal and abnormal service conditions such as in case of faults the force is generated [20]. For any insulation design there are main three critical areas which exist in the transformer:

- Solid (paper) Insulation
- Fluids
- Interface between solid (paper) and liquid(insulating oil)

Figure 2.11 and 2.12 show the barrier based design in transformer for uniform as well as non-uniform field. Function of barriers in transformers plays an important role in both the fields. In uniform field it increases the dielectric strength and reduces the overall insulation volume by dividing the long oil gaps into shorter gaps for example in the main insulation between the windings. In non-uniform field it matches the dielectric strength and gap width to the local field for example in lead exit system.

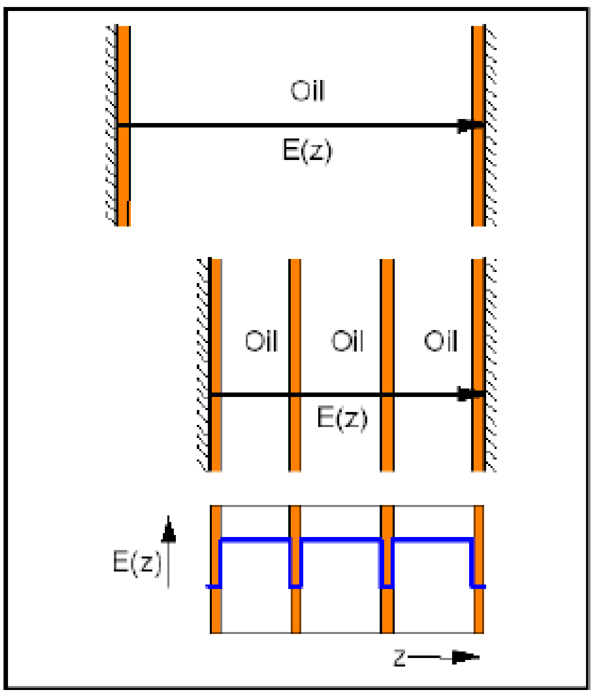


Figure 2.11: Barrier based design for uniform field in transformer

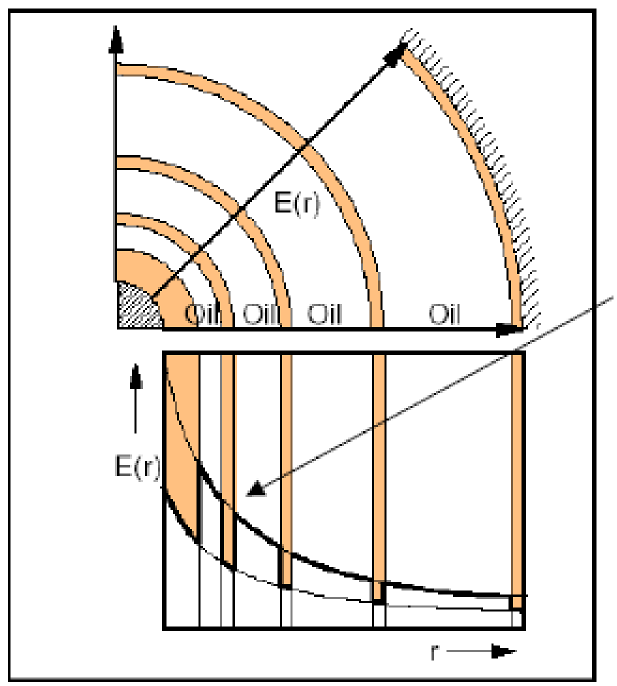


Figure 2.12: Barrier based design for non-uniform in transformer

2.8 SURGE PHENONMENA IN TRANSFORMERS

Voltage distribution within windings needs to be evaluated for designing the insulation system to withstand overvoltage stress. For this reason the calculation are done for voltage stress within the transformer windings for test voltages. For AC stress values at power frequency test can be calculated when the distribution of voltage is linear with respect to its number of turns. For impulse voltage stress or distribution of voltage in the winding can be calculated by considered equivalent circuit of winding having lumped parameters (R, L & C) [22]. When there is effect of step voltage on the windings of the transformer, than the initial distributed voltage in the winding depends upon following parameters:

- Capacitances between turns of the windings
- Capacitance between windings and ground

There is no effect of winding inductances in the initial distributed voltage of winding as magnetic field needs less amount of time to increase as the current passes through an inductor cannot be established immediately. Hence, due to this drawback practically inductance does not carry any current and all the factors related to distribution of voltage in winding depend upon the capacitance.

CHAPTER 3
EFFECT OF VERTICAL ELECTRODE CONFIGURATION ON BREAKDOWN MECHANISM OF ESTER OIL

3.1 INTRODUCTION

Generally the important insulating material in a power transformer is the dielectric oil. Insulating oil has many functions such as providing electrical protection, cooling and acting as common carrier for condition monitoring purposes. The common insulating oil used in all type transformers is mineral oil. With its wide availability and low cost, it has been in use for both distribution and power transformers (oil filled) since the beginning of transformer industry. However its poor biodegradability, low flash and fire points and high toxicity to environment are the primary causes for actively looking for substitutes for mineral oil [3]. Therefore, technology of using esters as insulating liquids in distribution & power transformer is becoming common. The major drivers for using esters as alternative fluids are: good biodegradability, non-toxicity, high moisture absorption ability and high flash and fire points (usually above 300°C) which considerably improve their fire-safety [4]. The high affinity of ester fluids for moisture helps in enhancing the life of the paper insulation and hence that of the transformer. Both natural ester and synthetic ester have greater permittivity than mineral oil which is a merit for the electrical field distribution in the power transformer.

Standard lightning impulse breakdown voltage is a crucial parameter that characterizes properties of the insulating oils. This parameter shows the behavior of insulating liquid in the presence of lightning impulse voltage stress. It can be measured by standards ASTM D 3300-12 or IEC 60897 In this standard the comparison of lightning performance for different insulating oil is based on the procedure presented in the ASTM D 3300-12.The standard recommends a procedure of making 5 measurements and by calculating the mean value of standard lightning impulse breakdown voltage and its standard deviation. This approach is extended to additional 10 measurements and it provides 10 breakdown values. Time to breakdown is also measured with the help of the voltage waveform displayed in DPO (Digital Phosphorous Oscilloscope). It is the time between beginnings of the voltage waveform to the moment of sudden collapse.

Compared to sphere- sphere configuration, point sphere configuration is more dangerous in transformers. Most of the failures that happen in transformers are due to non-uniformity in the field experienced by insulation which leads to failure of insulation system inside the transformers. Due to this reason, performance of two natural esters and a mineral oil is examined under lightning impulse using the point-sphere electrode configuration. The impact of both positive and negative polarities is explored. The obtained data is further analyzed by Weibull distribution (3-parameter Weibull) to predict the 1% failure probability breakdown voltage for each type of oil. Further, from time to breakdown, velocity of streamer is calculated under both positive and negative polarity.

3.2 GENERATION OF IMPULSE WAVE SHAPE

Generally, transformer insulation experiences various electrical stresses at different locations during its operation. Transformer insulation is a combination of oil and paper. The dielectric strength of the transformer insulation system is predominately determined by oil insulation. The present study focuses on behavior of the selected oils under impulse conditions. A 2-stage impulse generator having the nominal rated voltage of 280 kV and energy 1.96 kJ is utilized to generate the standard lightning impulse of both polarities is used for the study. Digital phosphorous oscilloscope (DPO) is used to record the waveforms with sampling rate. The waveforms are also registered by a digital phosphorous oscilloscope at sampling rate up to 1Gs/S. The Marx impulse generator circuit is shown in figure 3.1.

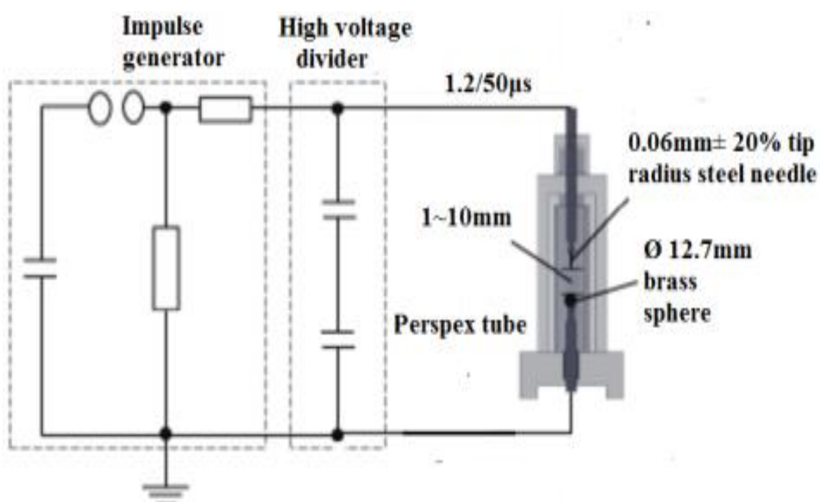


Figure 3.1: Schematic diagram for impulse test with needle-sphere configuration

A 2-stage impulse generator of peak voltage 280 kV and having energy 1.96kJ is used to generate the standard impulse 1.2(±30%)/50(±20%) μsec as shown in figure 3.2. Waveform of impulse is recorded by a high-voltage capacitive divider. In the complete divergent field tests, both positive and negative impulse is used for testing to examine polarity effect. Table 3.1 shows the specifications of the impulse generator.

Figure 3.2: Impulse generator test setup

Table 3.1: Impulse setup specification

Name of Components	No. of Components	Rating
HV Test Transformer	01	200V/100Kv
Charging Resistor	02	2.5Mohm
Charging Capacitor	02	100000pF ± 10%, 140kV peak
Sphere gap	02	100mm diameter, maximum gap setting 90mm, Rated impulse voltage 140Kv
Wave Front Resistors	02	350ohm
Wave Tail Resistor	02	677ohm
Efficiency of generator	-	92%

3.3 EXPERIMENTAL DESCRIPTIONS

3.3.1 LIQUIDS UNDER TEST

Insulating oil in transformer plays a vital role in maintaining the efficient as well as reliable functioning of the power transformer. Dielectric strength of insulating oil is determined by its physical and molecular structure. The chemical nature of insulating oil depends on the polar and non-polar component in the oil. There are basic differences in the chemical structures of the mineral oils and natural esters. The conventional mineral oils used in transformers predominantly consist of paraffinic, naphthenic and aromatic structures. Natural ester oils obtained from natural vegetable seeds (such as soybean, rapeseed etc.) consist of triglyceride fatty acid esters. A highly refined mineral oil (Transol), produced by Savita Oil Technologies Limited, and is used as the benchmark. The natural ester fluids used in the study are BioTransol manufactured by Savita Polymers Limited which is referred as natural ester (NE(A)) and the second natural ester(NE(B)) obtained from the market. Both natural ester (NE(A) and NE(B)) are refined forms of soybean seed oil. Figure 3.3 shows colour appearance of oils. Table 3.2 shows the comparison of Analysis properties

Figure 3.3: Colour appearance of liquid samples

Table 3.2: Comparative analysis of oil properties

Property	**Test method**	**Mineral oil (TRANSOL)**	**Natural Ester (BIOTRANSOL)**	**Natural Ester NE(B)**
Viscosity at 40°C (mm²/s)	ISO 3104	3.5-12	32-35	32-34
Pour point	ISO 3016	-40	-15 to -18	-18 to -23
Water /moisture level (mg/kg)	IEC 60814	<30	50	50
Acidity (mg KOH/g)	IEC 62021-1 or IEC 62021-2	0.01	0.03	0.03-0.042
Dielectric strength (kV)	IEC 60156	>70	70to 80	70-80
Relative permittivity@25° C	IEC 60247	2.2	3.2	3.2

Dissipation factor (Tan δ)	IEC 60247 or IEC 61620	<0.001	<0.05(0.02-0.03)	0.023

3.3.2 TEST CELL

A cylindrical (vertical) test cell made up of transparent perspex made as per the standard ASTM D3300 is used and is shown in figure 3.4. The oil holding capacity of the cell is 500ml. Material used in the cell has high dielectric strength and has the following dimensions: height 430mm, inner diameter 50mm and outer diameter 100mm. The dimensions are chosen to ensure that the breakdown is only restricted to the electrode gap. The sphere electrode is fixed and the point electrode is mounted on the top side. The gap distance can be varied in steps of 0.5mm using screw gauze provided as an attachment.

Figure 3.4: Vertical electrode cell

3.3.3 ELECTRODE CONFIGURATION

Electrode configuration is an important parameter which decides the electric field as well as breakdown voltage of any insulating liquid. To generate the strong non-homogeneous field, point-sphere electrode configuration is used in this test setup (figure 3.5). The point electrode is made up of steel material which can be ordinary phonograph needle with radius of curvature of 0.06mm±20% and the sphere ground electrode is made up of brass material of diameter 12.7mm [15]. The needle was changed after 5 breakdowns as drawn tip needle is not recommended in the standard ASTM D3300.

Figure 3.5: Needle-sphere electrode configuration

3.3.4 ADJUSTMENTS AND CARE OF ELECTRODES AND TEST CELL

ELECTRODE SPACING

For the electrode spacing, reduce the electrode gap to zero spacing. Spacing was done very carefully to avoid damaging the needle tip [15]. Measuring of gap distance between the electrodes was done with the help of Vernier caliper.

CLEANING

Degreasing was done for the cell and electrodes by washing them with reagent grade petroleum ether, washing with cleanser and heated water, rinsing altogether in the hot tap water, and then rinsing them with water. Drying the cell and the electrodes in an oven for 2 h at around 105 to 110°C and then it was remove and store in the desiccator until required [15].

DAILY USE

Every day before testing the sphere electrode was cleaned and polished and the needle electrode was changed after each breakdown to maintain the maximum stress at the tip of needle electrodes [15].

3.3.5 SAMPLE PREPARATION

The quality of insulating liquids plays a vital role in the studies carried out. Therefore, moisture and particle content are carefully controlled and are comparatively low in fresh insulating oil. But due to slow ageing and contamination from environment these qualities may deteriorate during transportation process or long term storage of oil. To avoid this degradation, the oil is transported and stored in a non- transparent barrel sealed under nitrogen to create inert atmosphere.

The entire liquid samples were pre-processed by:

1. Filtration

2. Dehydration
3. Cooling
4. Testing

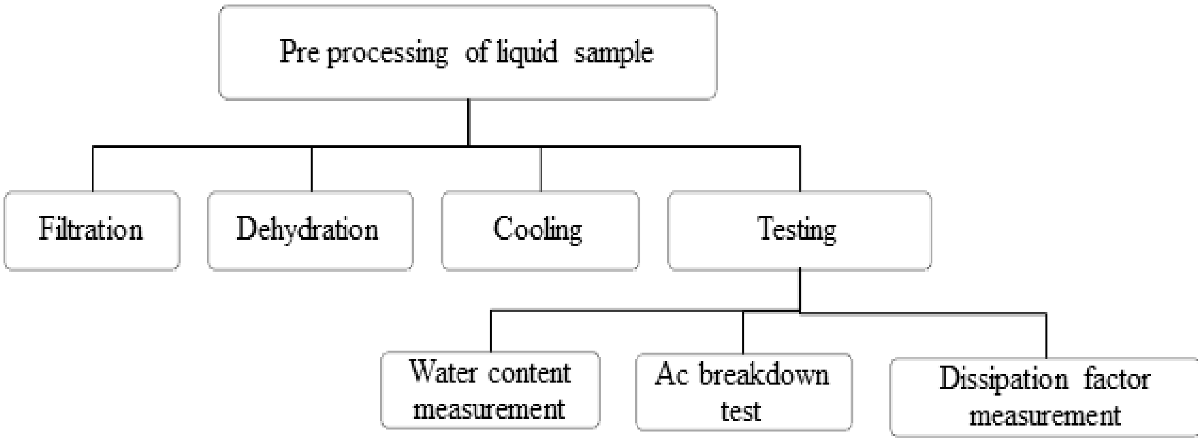


Figure 3.6: Pre-Processing of liquid Sample

FILTRATION

The received liquids from drum were filtered by nylon membrane filter (filtration assembly) having filter paper of the pore size of 0.4 μm. A particle counter having provision for the automatic bottle sampler was utilised to detect the particle number of liquid sample. It can measure up to a diameter of ranges 1, 1, 2, 5, 15, 25, 50, 100 and 200 μm.

DEHYDRATION

The filtered samples received were then degassed and dehydrated in vacuum oven under at 85^{o}C temperature for 2 hours.

COOLING

After dehydrating the entire liquid sample is kept for 24 hour to cool down at room temperature under vacuum conditions before doing the impulse testing.

MEASUREMENT OF AC BREAKDOWN VOLTAGE (kV)

To verify the good condition of processed oil its breakdown is checked. Figure 3.7(d) shows the setup to measure AC breakdown test according to IEC 156.

MEASUREMENT OF MOISTURE CONTENT (IN PPM)

To fulfill the passing criteria (<50ppm) of processed sample moisture is measured by Karl-Fischer method. Figure 3.7(e) shows the setup to measure moisture content of sample.

(a) (b) (c)

(d) (e)

Figure 3.7: Preprocessing procedure of liquid
(a) Filtering (b) Dehydration (c) Cooling (d) AC breakdown test setup
(e) Moisture content measurement

3.3.6 TESTING PROCEDURE

Generally, different testing methods, rising-voltage, up-and-down and multiple-level were used for impulse breakdown tests over the past years [14, 16]. Selection of the method does not influence the comparison of trends between oil types under impulse breakdown voltage conditions. So in this study, multiple level methods are adopted in order to create stress on the oil. Multiple level method is used is as per the ASTM D3300 standard procedure. Total 10 breakdown voltages test are performed for each oil sample. The experimental procedure is as follows:

Setting the desired distance between the electrode with the help of screw gauge.

↓

Rinsing the cell with the portion of the sample to be used for testing. Slowly filling the cell with the test liquid.

↓

Connecting the ground electrode to the ground terminal and the HV electrode to the high voltage terminal of generator.

↓

Applying the impulse wave of specified polarity starting 60% of expected withstand voltage.

↓

Applying 2 shots at each voltage step level.

↓

Increasing voltage in 2kV steps till the breakdown occurs.

↓

10 breakdown experiments are performed on same sample.

Figure 3.8: Flow chart for test procedure of insulating oils

3.4 EXPERIMENTAL RESULTS

3.4.1 STATISTICAL ANALYSIS

Statistical techniques like parametric and non-parametric are mostly used to analysis the behaviour of breakdown voltage distribution of insulating oil in transformer. Distributions which are commonly studied are normal distribution, minimum Gumbel distribution (Double Exponential distribution), and Weibull distribution, and their respective functions are given in Equations 3.1 to 3.3 [15]. Both Gumbel distribution and Weibull distribution considered asymmetry with high and low rate of failures as both are extreme-value distributions.

$$P_N(E;\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \int_{-\infty}^{E} e^{\frac{-(t-\mu)^2}{2\sigma^2}} \, dt \qquad (3.1)\ \text{(Normal)}$$

$$P_G(E;\mu,\beta) = 1 - e^{-e^{\frac{(E-\mu)}{\beta}}} \qquad (3.2)\ \text{(Gumbel)}$$

$$P_W(E;k,\lambda) = 1 - e^{-(\frac{E}{\lambda})^k} \qquad (3.3)\ \text{(Weibull)}$$

It is generally recognized that Weibull distribution is best function describes the behavior at low probabilities for breakdown data [18]. It estimates the combination of statistical parameters, which fit the breakdown data with different failure probability values. In this context, the application of 3- parameter Weibull distribution gives a better choice for the engineers to indicate at which level of low probability (1% or less) the designed insulation structure will breakdown. Therefore in this report, three parameter Weibull distribution plots of the dielectric strength results are establish on the fitted curve with specific shape, scale and threshold are obtained according to least square method under various gaps and polarities [17, 18, and 19]. Figure 3.9 show three parameter weibull distribution plots of breakdown voltage data of Transol, BioTransol (NE(A)) and Natural ester (NE(B)) for the gap of 10mm under negative polarity of the impulse wave shapes.

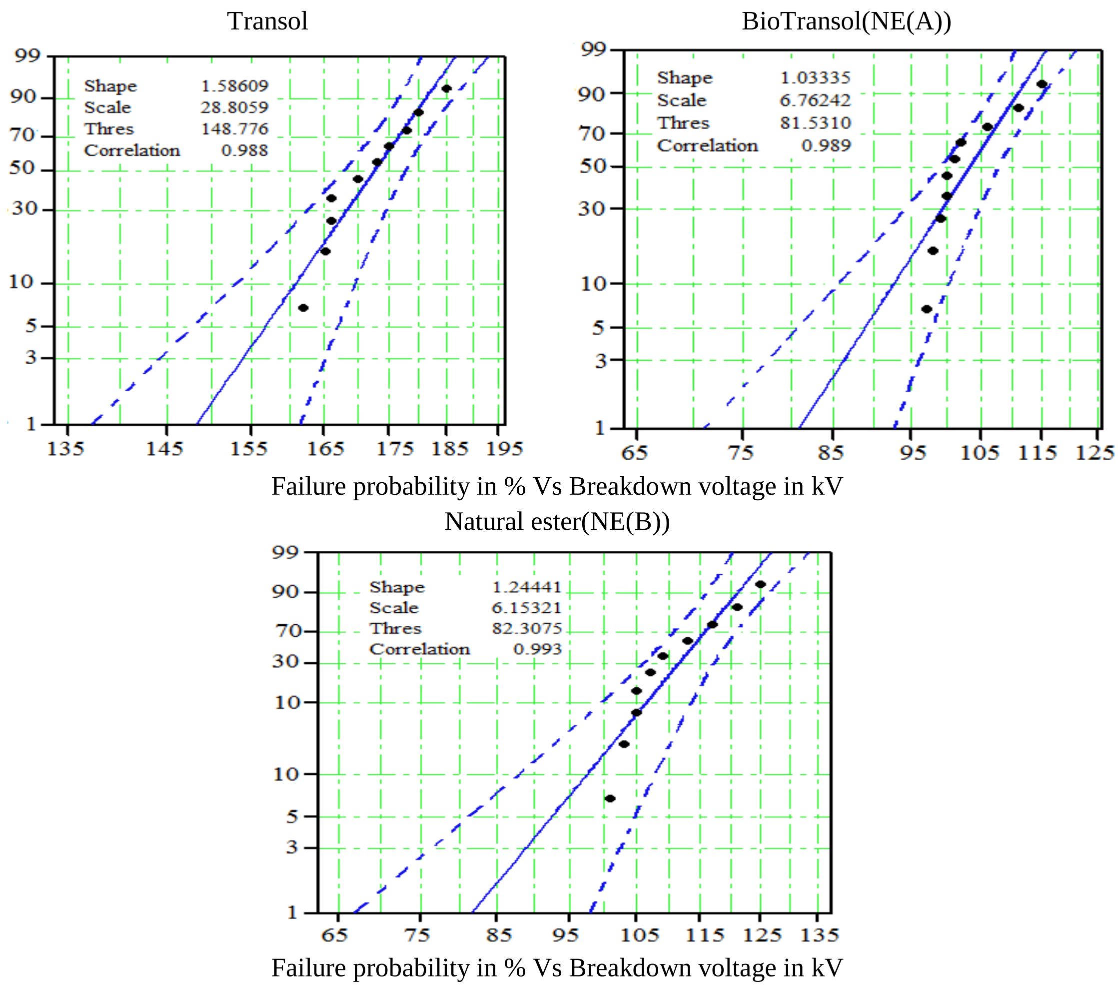


Figure 3.9: Three parameter weibull distribution plots of breakdown voltage data of Transol, BioTransol (NE(A)) and Natural ester (NE(B)) for the gap of 10mm under negative polarity of the impulse wave shapes.

In figure 3.9, the 99% withstand voltage of mineral oil under negative polarity is 150.36 kV. As the predicted results always have unavoidable uncertainty, so it can be obtained by considering the 95% confidence interval. In this fig it can be seen that actual values of withstand of mineral oil that is predicated by 95% confidence interval might not be same for positive as well as negative polarity but it will be somewhat around of their respective values. With 95% confidence interval, it is 95% probability that the actual withstand value of negative polarity it will be between 148.77 kV to 153.43 kV. Similar predication can be made for natural ester. It is observed that withstand voltage mineral oil is higher in negative polarity as compare to natural ester whereas in positive polarity both are comparable. For the insulation designing it is more reliable to use lower limit of confidence interval rather than using the predicated withstand voltage

Table 3.3: Evaluation of withstand voltages using Weibull distribution of negative polarity with 10mm oil gap

	Transol (kV)	**BioTransol (NE(A)) (kV)**	**Natural Ester (NE(B)) (kV)**
U1% (kV)	150.36	81.60	82.46
95% Confidence interval	148.77- 153.43	78.53- 82.82	79.30- 83.64

3.4.2 BREAKDOWN OR WITHSTAND VOLTAGE

At the time of designing the insulation of the transformer the withstand voltage of insulating oil should be provided with necessary limits to ensure safety margin. Therefore, designer will design the insulation on the basis of 1% probability breakdown voltage or 99% withstand voltage [19]. The insulating oil of in-service transformer experiences gradual decrease of withstands voltage due to ageing process. Therefore, insulating oil with higher withstand voltage ensures better and safe operation of transformer. Results under negative and positive polarity impulse test for electrode gaps 1mm, 5mm and 10 mm are presented in table 3.4 and 3.5 respectively that includes average breakdown voltage, standard deviation and median of the experimental breakdown data.

Table 3.4: Mean breakdown voltage, standard deviation and median of different insulating oil under negative polarity

Type of liquid	**Electrode gap (mm)**	**Average value (kV)**	**Standard deviation (kV)**	**Median (kV)**
Transol	1	36.8	2.5	36.5
	5	97.7	4.4	97
	10	173.6	5.9	169.9
BioTransol (NE(A))	1	35.2	2.3	36
	5	63.2	4.6	63.5
	10	82.3	5.7	83.5

Natural ester (NE(B))	1	34.7	2.6	35.7
	5	62.6	4.7	61.9
	10	81.9	5.6	82.5

Table 3.5: Mean breakdown voltage, standard deviation and median of different insulating oil under positive polarity

Type of liquid	**Electrode gap (mm)**	**Average value (kV)**	**Standard deviation (kV)**	**Median (kV)**
Transol	1	35.3	3.8	36
	5	65.8	4.7	65.5
	10	81.7	6.8	81
BioTransol (NE(A))	1	42.8	2.2	42.4
	5	72.7	3.2	73
	10	89.1	5.0	90
Natural ester (NE(B))	1	43.3	2.1	43
	5	73.5	3.4	73.6
	10	88.3	5.2	89.7

From table 3.4 and 3.5 followings points are observed under negative polarity, mean breakdown voltage of Transol is higher as compared to natural ester (NE(A) and NE(B)). This difference is gradually increased with respect to electrode gap.

- Under positive polarity, mean breakdown voltage of Transol is lower as compared to natural ester (NE(A) and NE(B)).
- In case of negative polarity, standard deviation for Transol, natural ester (NE(A) and NE(B)) are comparable. However, under positive polarity, the standard deviation of mineral oil is higher than that of natural ester (NE(A) and NE(B)). Also, with increase in gaps, standard deviation is increased for every insulating oil under both the polarities.
- The mean breakdown voltage and standard deviations of natural ester (NE(A) and NE(B)) are almost similar. The differences in breakdown voltage between for both the natural esters are around 1 to 2kV, which can be ignored.
- In Transol, positive polarity breakdown voltage is much lower as compared to negative polarity breakdown voltage.
- In natural ester (NE(A)) , positive polarity breakdown voltage is slightly higher as compared to negative polarity breakdown voltage. The same trend is also observed for natural ester (NE(B)). High electron affinity of ester molecules is the main reason of

lower breakdown voltage in negative polarity. Due to this property, esters facilitate easier propagation of negative streamers and hence show lower withstand voltage

The graphs of 1% breakdown voltage with distance between the electrodes for different insulating oil under both polarities are shown in figure 3.10 and 3.11.

From the figures 3.10 and 3.11, the following points are observed due to impulse application:

- Under negative polarity, as shown in figure 3.10, the 1% breakdown voltage of mineral oil is higher as compared to natural esters. It is also observed, that with increase in gap, percentage difference between mineral oil and natural ester is drastically increased like for 10mm mineral oil is almost 50% higher than that of natural ester. This may be due to high electron affinity of ester molecules that makes them weaker in the presence of negative polarity.
- Under positive polarity, as shown in figure 3.11, natural esters are superior as they are having higher 1% breakdown voltage as that of mineral oil. In fact, mineral oil is around 4-5% lower in terms of breakdown voltage as compared to natural esters.

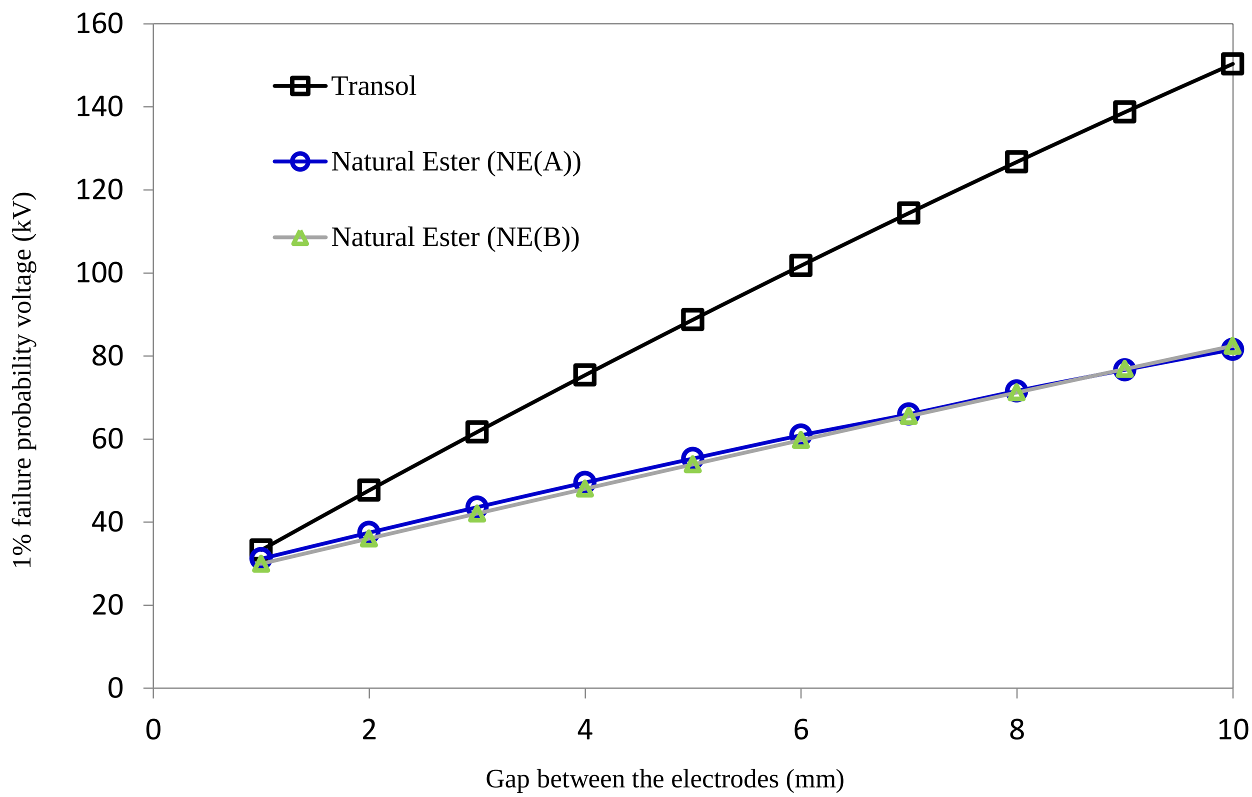


Figure 3.10: Comparison of 1% failure probability voltage of different insulating oil under negative polarity

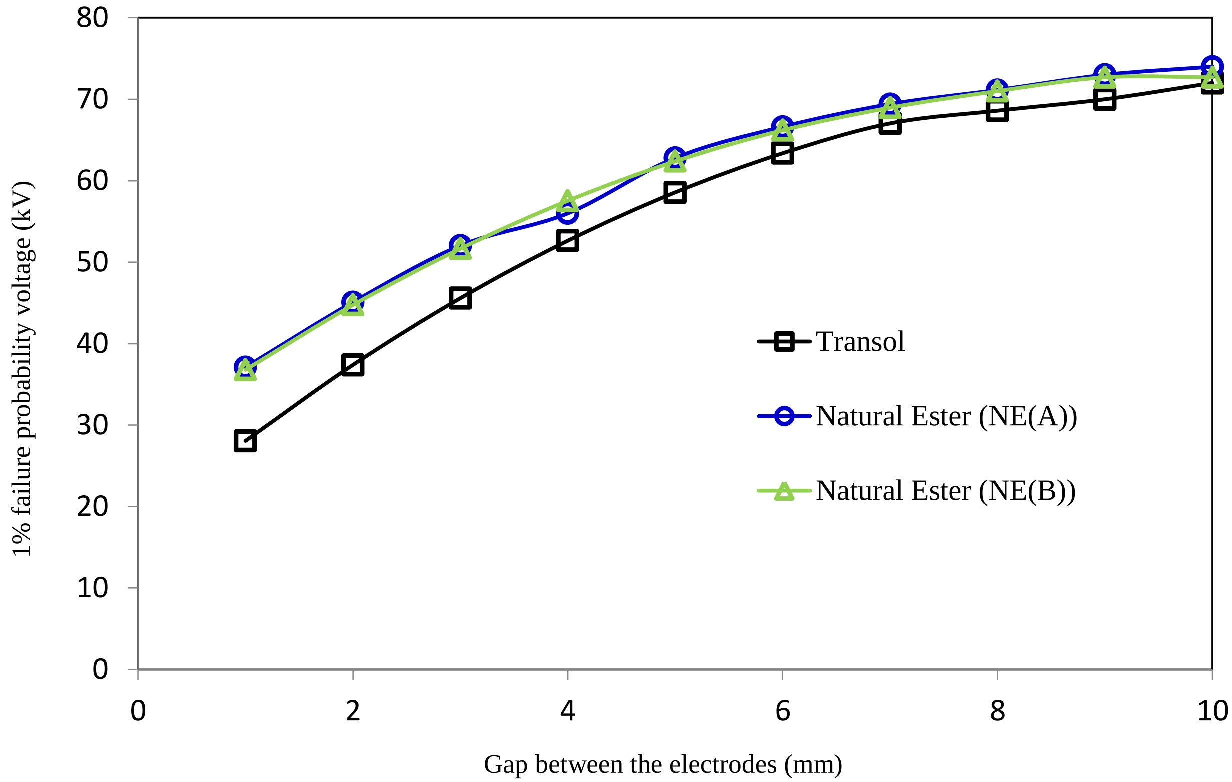


Figure 3.11: Comparison of 1% failure probability voltage of different insulating oil under positive polarity

Another observation is that, both the natural esters (NE(A) and NE(B)) are having almost same values of 1% breakdown voltage under both the polarities. A difference between both is of 1-2% which can be ignored such small differences may be attributed to small differences to oil handling.

3.4.3 STREAMER VELOCITY

Usually, streamer velocity is statistically distributed parameter which is a function of streamer stopping length and propagating time [11-14]. Stopping length is the straight-line distance from the farthest tip point of a stopped streamer to the point electrode. It is important parameter for characterize the streamer initiation and propagation. Once breakdown occurs it is dependent on gap distance and time to breakdown [18]. In this study, velocity of streamer is calculated by ratio of gap distance and time to breakdown. It is assumed that streamer stopping length is equal to gap distance between electrodes and time to breakdown is equivalent to streamer propagating time. Figure 3.12 and 3.13 shows the graph between velocity of streamers and gap distance between the electrodes for negative and positive polarity respectively considering all the three testing liquids.

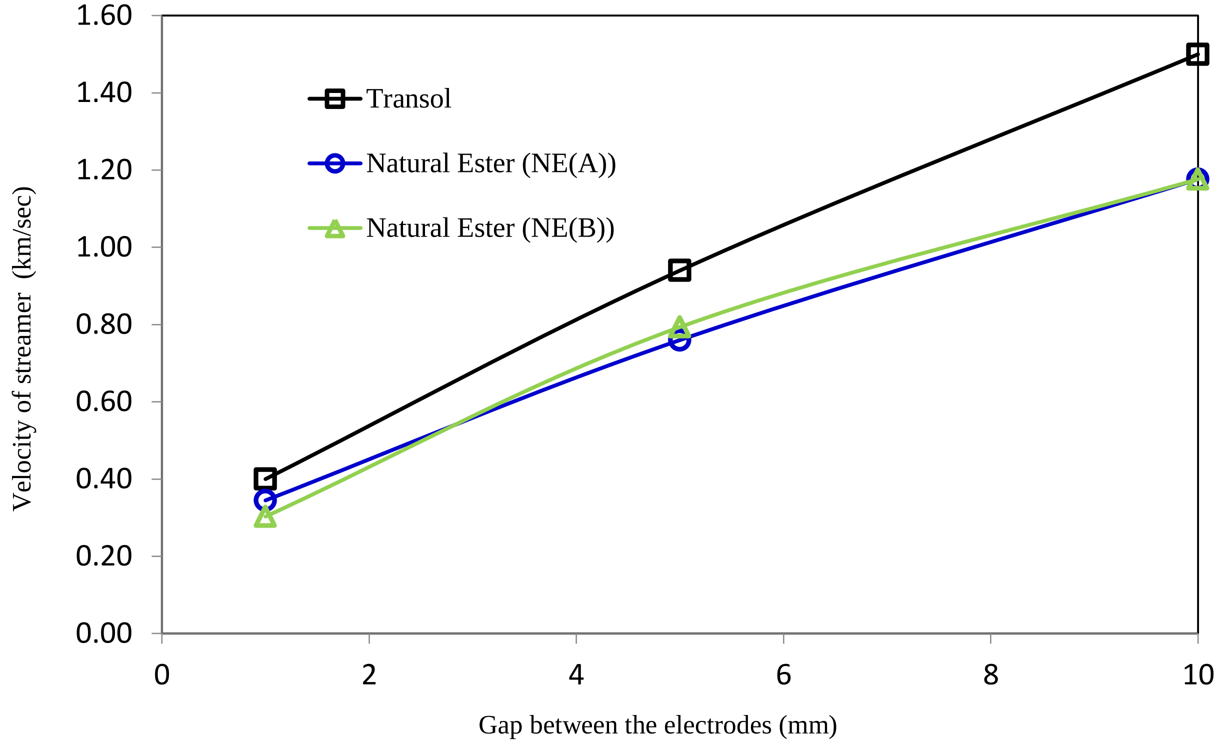


Figure 3.12: Velocity of streamer in different insulating oil under negative polarity.

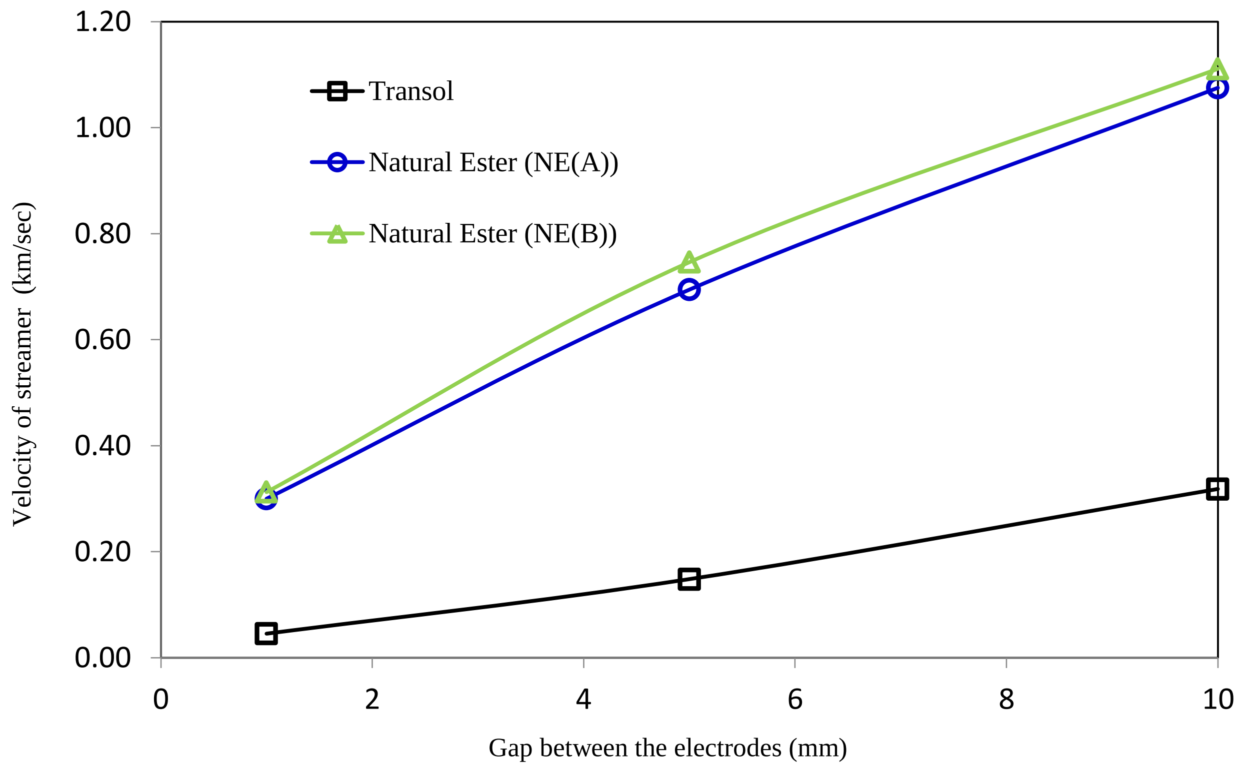


Figure 3.13: Velocity of streamer in different insulating oil under positive polarity.

From figures following observations are made:

- Under negative polarity, shown in figure 3.12, the streamer velocity in Transol is very low that is ranging between 0.05-0.32 km/sec as that of both the natural esters. In NE(A) this range is around 0.3-1.08 km/sec whereas in NE(B) it is 0.31-1.11km/sec, which denotes both NE(A) and NE(B) having comparable streamer velocity.
- Under positive polarity, shown in figure 3.13, the streamer velocity in both the natural esters is low. For NE(A) its range is between 0.34-1.18 km/sec and for NE(B) is 0.3-1.18km/sec whereas for Transol it is approximately 0.4-1.5 km/sec.

3.5 SIMULATION RESULTS

3.5.1 MAXIMUM ELECTRIC STRESS

Electric stress experienced by the insulation arrangement at different location under impulse stress condition is an important parameter for an insulation design of transformer. After post failure analysis of transformer many researchers have reported that insulation failure is one of major reasons behind failure of transformer. To avoid these types of failures, maximum electric stress experienced by different insulating oils at 1% failure probability voltage is evaluated using ElecNet FEM software. The electrical field distribution across the insulation between different electrodes is computed using FEM. Two-dimensional Newton rapson equation in electrostatic field is solved using ELECNET FEM software.

Figure 3.14: Test cell model of vertical electrode

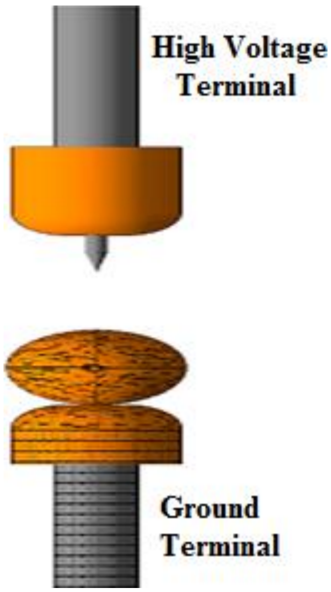


Figure 3.15: Electrode model for non-uniform field

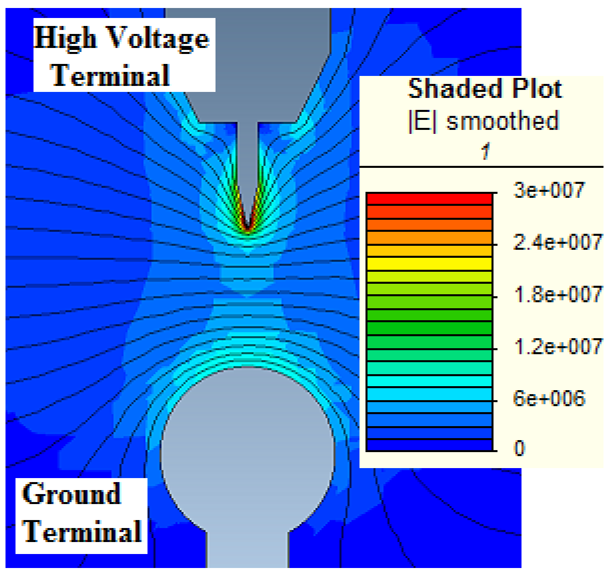


Figure 3.16: Electrical stress analysis for 10mm gap for BioTransol (NE(A))

Figure 3.14 and 3.15 represents the models made in solid works for performing electric stress analysis. All the models are made considering the actual dimensions of test cell and electrodes to avoid any errors. Figure 3.16 shows electrical stress analysis performed for BioTransol (NE(A)) with 10mm gap. Similarly electrical stress value for Transol, Natural ester (NE(A) and NE(B)) for gaps between 1mm to 10mm are evaluated.

3.5.2 DEGREE OF UNIFORMITY

For optimal designing of insulation that could provide long performance of the transformer, it is important to understand the electrical field due to breakdown voltage. The performance of the dielectric strongly depends upon the field configurations and magnitude. There is no physical theory of the breakdown of insulating oil. Generally, the distribution of electrical stress between the insulating materials during impulse test depends upon the permittivity of the materials. The higher value of permittivity for natural ester oil is close to solid insulation and it does improve the electric field distribution along the transformer insulating materials. Breakdown mechanism of oil is closely related to the uniformity of electric field in the geometry of electrode. The utilisation factor, ξ (homogeneity factor or uniform field factor) is commonly describing the degree of uniformity of the field configuration. The higher the utilization factor, the higher the degree of uniformity a field configuration has. The relationship between utilization factor (ξ) and maximum stress (E_{max}) is defined below in equation 3.4.

$$\xi = \frac{E_{mean}}{E_{max}} \qquad (3.4)$$

Where,

E_{mean} & E_{max} represents average electric stress and maximum stress experienced by the oil respectively.

The variation of utilization factor (ξ) with respect to gaps between the electrodes under negative and positive polarity is expressed in figures 3.17 and 3.18.

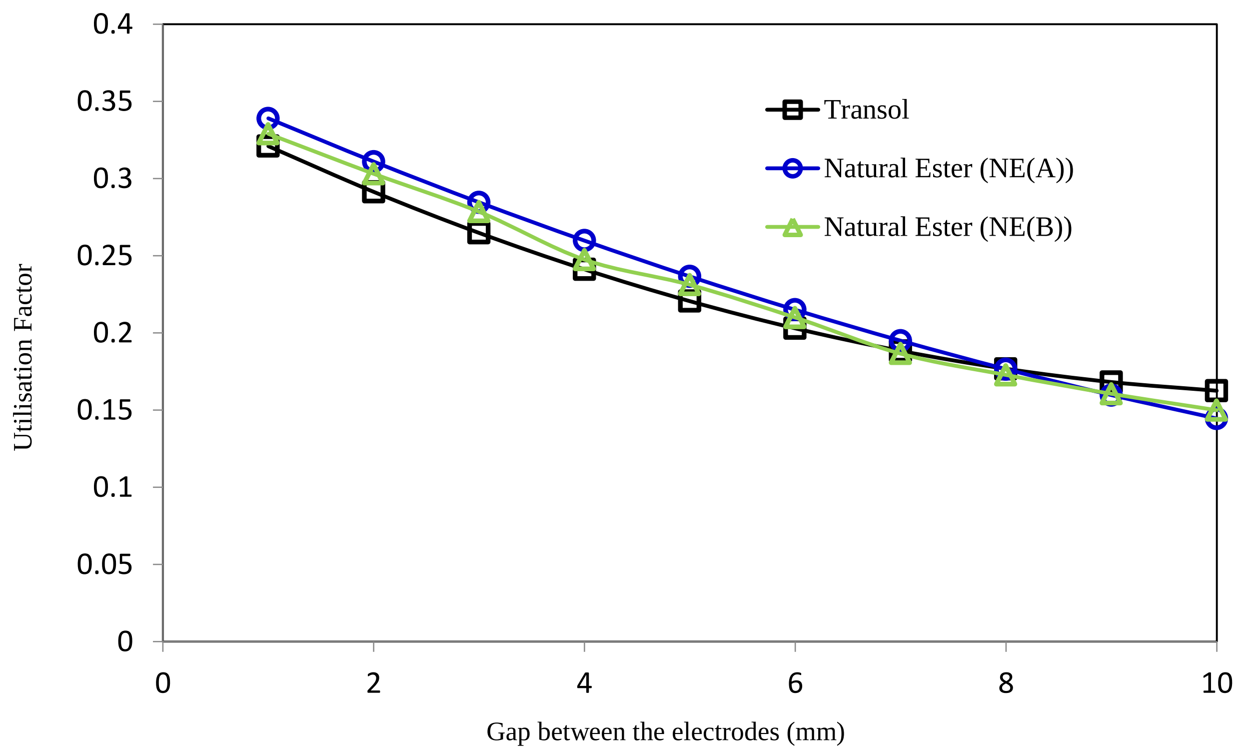


Figure 3.17: Comparison of utilisation factor of different insulating oil under negative polarity

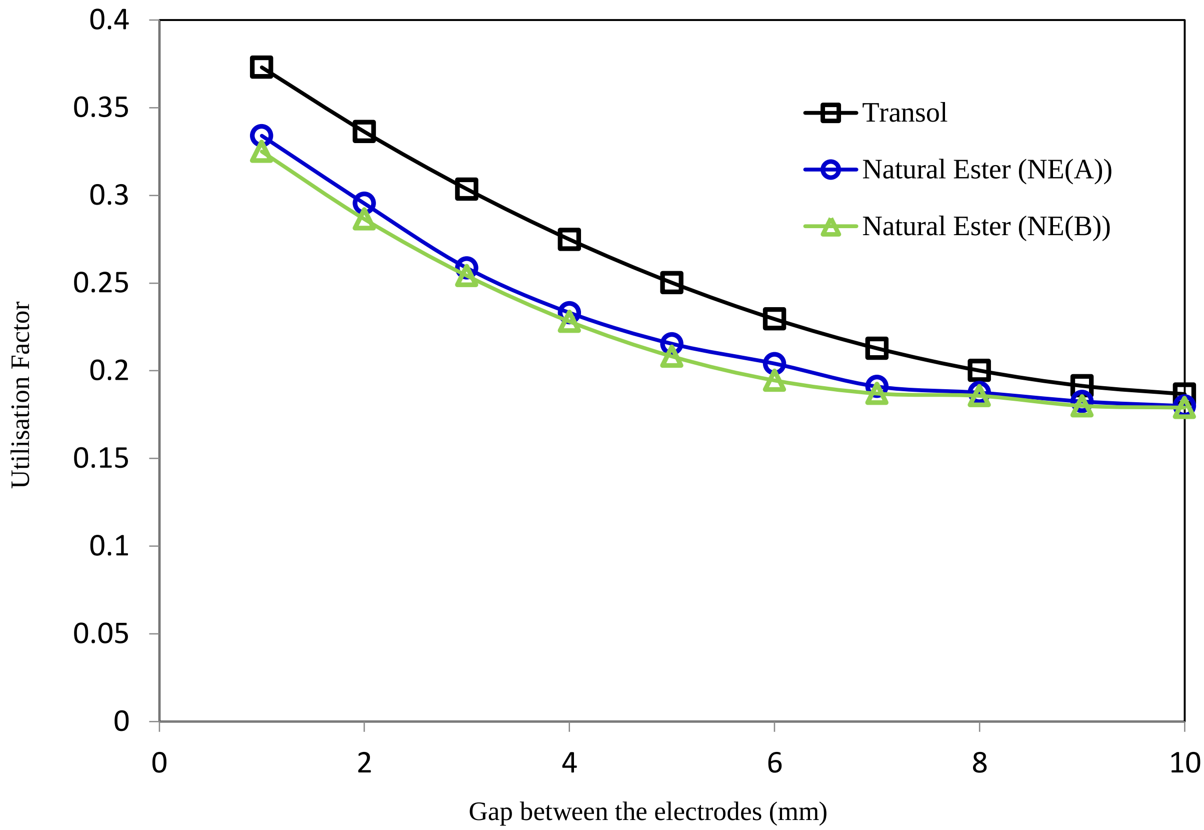


Figure 3.18: Comparison of utilisation factor of different insulating oil under positive polarity

From figures 3.17 and 3.18, it can be concluded that

- For a non-uniform field configuration, with the increase in gap distance, both E_{mean} and E_{max} increases (due to increase in breakdown voltage). However, the increase in E_{max} would be more significant than the increase in E_{mean}. Therefore, the utilisation factor decreases. This effect is seen in both the polarities for all the insulating oils.
- Under negative polarity, utilisation factor is in the range of 0.13- 0.33 for all the insulating oils. Moreover, Transol has lower utilisation factor as compared to natural ester (NE(A) and NE(B)), which signifies it is withstanding higher electric stress at 1% failure probability breakdown voltage.
- Under positive polarity, utilisation factor is in range of 0.17-0.37 for all the insulating oils. Moreover, natural ester (NE(A) and NE(B)) have lower utilisation factor as compared to Transol , which signifies it is withstanding higher electric stress at 1% failure probability breakdown voltage.

3.6 SUMMARY

With growing interests in utilisation of natural ester oil as substitute to mineral oil for transformer application, an experimental analysis is performed on natural ester oil in comparison with conventional mineral oil [19]. The objective is to evaluate the breakdown strengths of mineral oil and natural ester oil and compare their breakdown voltages at a low failure rate (i.e. high withstand probability) under varying oil gaps.

It is found that, under negative polarity of impulse, withstand voltage of ester oils is much lower as compared to mineral oil. This behavior is result of high electronegativity of ester molecules which makes them electrically unstable under negative polarity. However, under positive polarity the withstand voltage of ester molecules is slightly higher as compared to mineral oil. It is also found that streamer velocity of mineral oil is much higher than natural esters under negative polarity. Further, under positive polarity natural esters has more streamer velocity. In both the polarities utilization factor decreases for all insulating oils as with the increase in gap distance, both E_{mean} and E_{max} increases (due to increase in breakdown voltage).

CHAPTER- 4
STRESS ANALYSIS FOR LONG OIL GAPS IN ESTER OIL TRANSFORMERS

4.1 INTRODUCTION

Key components in a reliable electrical grid are the healthy power transformers. Enormous financial losses can occur by unplanned interruptions which can disturb the large supply area or production in industry. There is an increase in pressure to keep older units into operation for economic growth. A situation occurs where population of transformers are getting older along with running at higher load due to increase in demand. In the process of power transform from primary to secondary a transformer of high voltage is required. Under such circumstances adequate insulation is necessary [20]. Maximum attention is required while constructing an insulation system fir transformer. Oil paper and pressboard are the basic requirements for insulating material in the past years usage of insulation system as a solid surrounded with insulating fluid for power and distribution. Various tests have been performed under this insulation system to satisfy the dielectric performance criteria defined in transformers standards various design practises are performed usage of natural ester is new among all solid has higher dielectric strength than fluid in accordance to order of magnitude. Thus fluid has weak structure than solid in insulation. So by bringing both solid and liquid's permittivity together we can easily reduce the stress by distributing it equally in solid [21]. It further sets the design clearance. Function of the width of the gap is the dielectric strength of oil gap to divide oil gaps into smaller ones in order to allow higher average stress while preventing partial discharges the solid insulation is used by insulation designer. Dielectric strength of the insulation structure between HV lead connection point H1 main winding terminal to tap winding of 36MVA, 220/6.9kV, Dyn1 power transformers is evaluated by FEM analysis with AC voltage for switching impulse Discs voltages.

4.2 NEED OF INSULATION DESIGN IN TRANSFORMERS

Design of insulation system in transformer is important for the following reason:

- As voltage rating increases, insulation design becomes the most necessary aspect of designing the transformers.
- Comprehensive design verification is essential for reliability and optimization
- Insulation optimization can be a tricky and complicated problem.

- It also reduce the edges between withstand levels and working stress levels
- It is important to accurately estimate stress levels for different electrode geometry inside the transformer

4.3 OPTIMIZATION OF INSULATION SYSTEM IN TRANSFORMERS

Some general rules which need to be follows for optimization of the transformer insulation system:

- In paper- oil insulation system, oil is weaker as compare to paper. With the length of stressed oil gaps, the relative strength of oil decreases. Due to large scattering the dielectric strength of oil is affected.
- In paper-oil insulation system, distribution of electric field has to be carefully calculated to ensure the dielectric stress of all, short and longer, oil gaps with respect to the applied voltages.
- Quality of solid insulation parts has to be controlled and the crucial factor is the uniform, reproducible strength of every manufactured piece in a series.

4.4 THE WEIDMANN REFERENCE CURVE

Weidmann has developed insulating systems composed of properly positioned barriers subdividing the highly stressed oil volume into a number of smaller oils gaps which can be stressed to a higher level. The basic design tool determining the appropriate distance between the barriers is the “oil design curve” [20], also referred as “Weidmann reference curve-WRC”, since than it has been used by many transformer manufacturers.

The WRC expresses the maximum admissible stress as low probability (approx. 1%) inception stress of partial discharges (PD’s). The WRC is given by: $E_{cum}=\frac{22}{d^{0.37}}$ [kV/mm] for well degassed oil, and the E_{cum} denotes the tolerated cumulative electric field integrated along a chosen line, starting from the highest field value. When plotted against the oil gap length, in logarithmic coordinates, the WRC yields a straight line. With reference to well degassed oil, the WRC ordinate is decreased by 15% for an oil saturated with gas, and takes 30% lower values for the creep-stress along an oil-transformer board interface [20].

The system is stressed with design insulation level (DIL) voltage, which usually corresponds to (one minute) induced voltage test. The cumulative field E_{cum} calculated along a chosen line is superimposed on the WRC graph, and the safety margin is determined by the WRC to E_{cum}ratio, and expressed in percentage, at the point where these two curves come close. In other words, at the DIL voltage, the PD inception probability attains 1% where these two curves meet [20]. Figure 4.1 show the curve for determination of DIL.

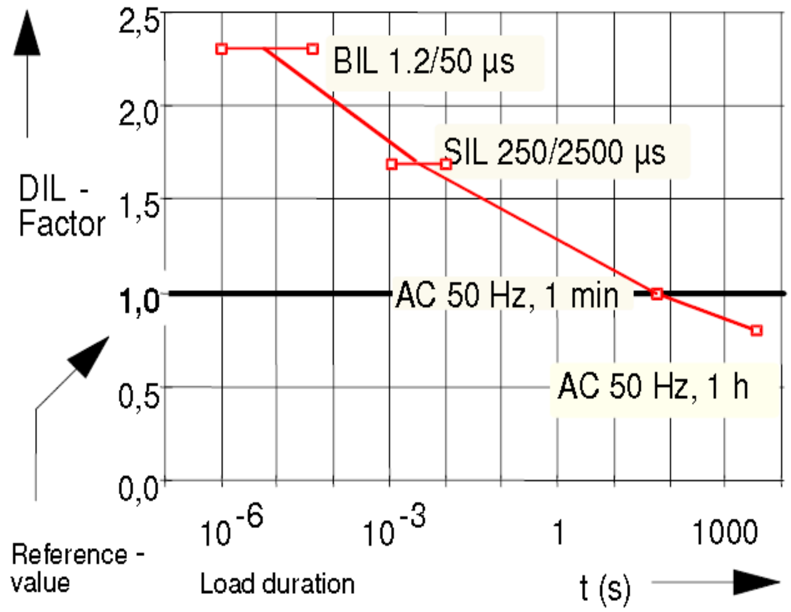


Figure 4.1: Determination of the design insulation level (DIL)

4.5 FINITE ELEMENT METHOD ANALYSIS

Replacing the complicated problem with simpler ones is the basic technique used in finite element method. An approximated solution is found rather than an exact one, as the actual problem is replaced by simpler one. In most of the practical problems, the existing mathematical tools are not sufficient to find the exact solution. So, finite element method is preferable in the absence of any other convenient method to even find the approximated solution. By spending more computational effort, it is possible to refine or improve the approximated solution [23]. Following features makes this method more efficient and popular

- Handling geometric complexities
- Its applicability in real life makes transformers easy due to availability of several commercial software.
- Can handle nonlinear, non-uniform and anisotropic media
- Coupling of electromagnetic fields with circuits and other physical field activities can be easily solved

Main steps involved in this analysis are given below:

4.5.1 CREATION OF GEOMETRY:

In 2-D or 3-D complex case of cemeteries' number of commercial FEM programs are built that allow import of the figures drawn in the drafting packages, which makes it simpler and time to create geometries is less. The problem domain has a boundary in which it is always bounded (example, abcda in Fig. 4.2), 2-D problems can easily be solved either in Cylindrical or Cartesian coordinates [22].

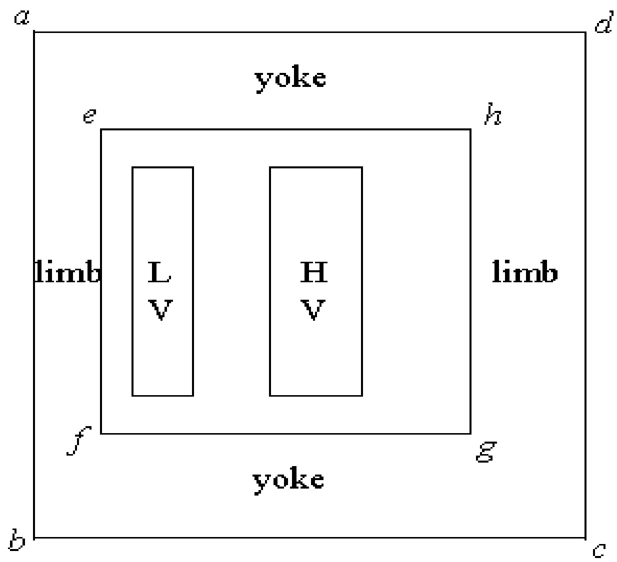


Figure 4.2: Geometry for FEM analysis

4.5.2 SYSTEMS OF COORDINATES:

A reference coordinates system is required to calculate the value for a field variable at a point in the space. Most of the time orthogonal systems are used it is simple and convenience. From all the known 3-D orthogonal systems, the commonly used are cartesian (x, y, z), cylindrical and spherical systems. Cartesian system is very simple to contemplate and it is a general system that can be utilised for any 3-D arbitrary problems where there is are no symmetry. In case of transformers, analysis which included all three phase would need the use of a cartesian system. With the completion of 2-D approximation of the systems (i.e., evaluation in the x-y plane), the configuration of infinite extent in z direction is assumed and the quantities of field and the figures of performance are executed in z direction at per unit length. This kind of approximation is required for the windings of age diameters [22].

4.5.3 PROPERTIES OF MATERIAL

Relative permeability is describes as few tens of thousands in a core and it does not affect much if it is explain as 10000 and 5000 as all the energy which is stored in the nonmagnetic regions are outside the core area [22]. Here dielectric medium is Isotropic (i.e., it has the same behavior with respect to a field at a point regardless of the direction of that field), uniform with relative permittivity. The problem considered here is Electrostatic problem.

4.5.4 GOVERNING EQUATION

Since it is electrostatic problem governing equation will be Poisson's equation. This equation is derived from coulomb's law and gauss's theorem. Gauss's law equation:

$$\nabla . D = \rho_f \quad (4.1)$$

Where $\nabla.$ is divergence operator, D is electric displacement field and ρ_f is the free charge of volume density. From constitutive equation:

$$D=\varepsilon E \qquad (4.2)$$

Where ε is the permittivity of the medium and E is the electric field. Substituting equation 4.2 in equation 4.1

$$\nabla . E = \frac{\rho}{\varepsilon} \qquad (4.3)$$

From Helmholtz decomposition: E$= -\nabla\varphi$ where φ is scalar electric field potential, substitute this value of E in equation 4.3

$$\nabla^2 \varphi = -\frac{\rho}{\varepsilon} \quad (4.4)$$

Equation 4.4 gives the poison's equation for electrostatics.

4.5.5 BOUNDARY CONDITION

Dirichlet and Neumann are the two main types of boundary conditions. Dirichlet boundary condition is present when a potential value is described on a boundary. In abcda where flux lines are parallel to this boundary, dirichlet condition is present with the value of magnetic vector potential as zero. Here it is noted that contour which is passing through equivalent values of magnetic vector is a flux line [22].

4.6 LEAD EXIT SYSTEM

Non-uniform field configuration mostly exists between the HV winding terminal and lower connection of bushing. At the surface of the conductor high field strength decreases rapidly with radius. In order to decreases the electric stress at outer insulating surface the conductor is wrapped with the insulating paper and rest all the oil gap is exposed to non-uniform field there is no protection for against particles in highly stress areas [20]. Due to large scattering in breakdown voltage results in lower dielectric strength. This is considered as main reason for the "anomalous breakdown" in extra high voltage lead exits and due to this drawback this type of design now a day are rarely used.

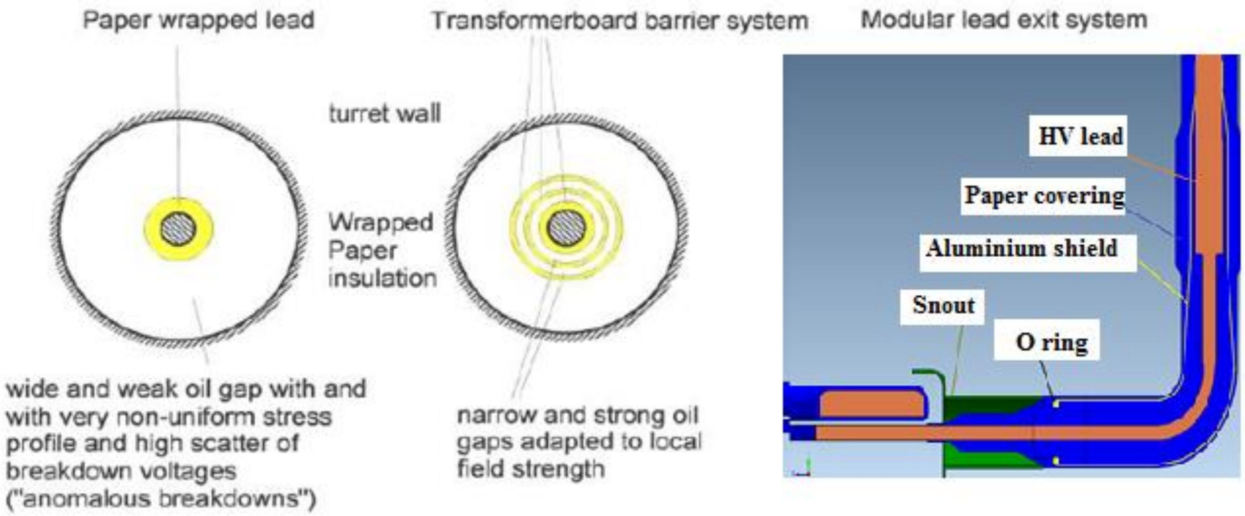


Figure 4.3:Lead exit with paper insulated conductor and single wide oil gap (left) and improved lead exit system with transformer board barriers and subdivided oil gaps schematic view (middle) , 3D model of modular lead exit (right)

In modular lead exit system transformer barriers system are provided due to which the oil gaps are subdivided in small gaps. Gaps width and dielectric strength are change to different local electric field. Due to subdividing of gaps, the conductor surface and highly stress area are protected from the deposition and alignment of fibers and particles. Conductor surface is coated with molded layer of transformer barrier board. These barriers are widened at bushings end and at the termination of winding in order to surround the protecting electrodes and it will increase the strength of the highly stressed area across its termination [21].

4.7 DIELECTRIC STRESS ANALYSIS FOR LONG OIL GAPS

a) Relative permittivity of the materials consider for analysis

Materials	Dielectric Constant
Mineral oil	2.2
Bio Transol	3.2
Paper	3.5
Pressboard	4.4

b) Geometric model and boundary conditions

Following assumptions have been made in the analyses:

- To reduce the complexity of the full model, quarter model of Winding, tank and core assembly is considered for analysis as shown in the figure 4.3.
- Conductor and paper covering of 0.68mm and 1.05mm radius (0.65mm & 1.055mm) and considered.
- Whole model is divided into 8 planes to check the dielectric stress in different plane areas as shown in figure.
- Only single phase winding is considered for analysis.
- HV winding is modelled as discs with paper covering and applied with the AC-Switching impulse test voltages.
- The complete tap and LV windings are assumed as a single winding cylinder.

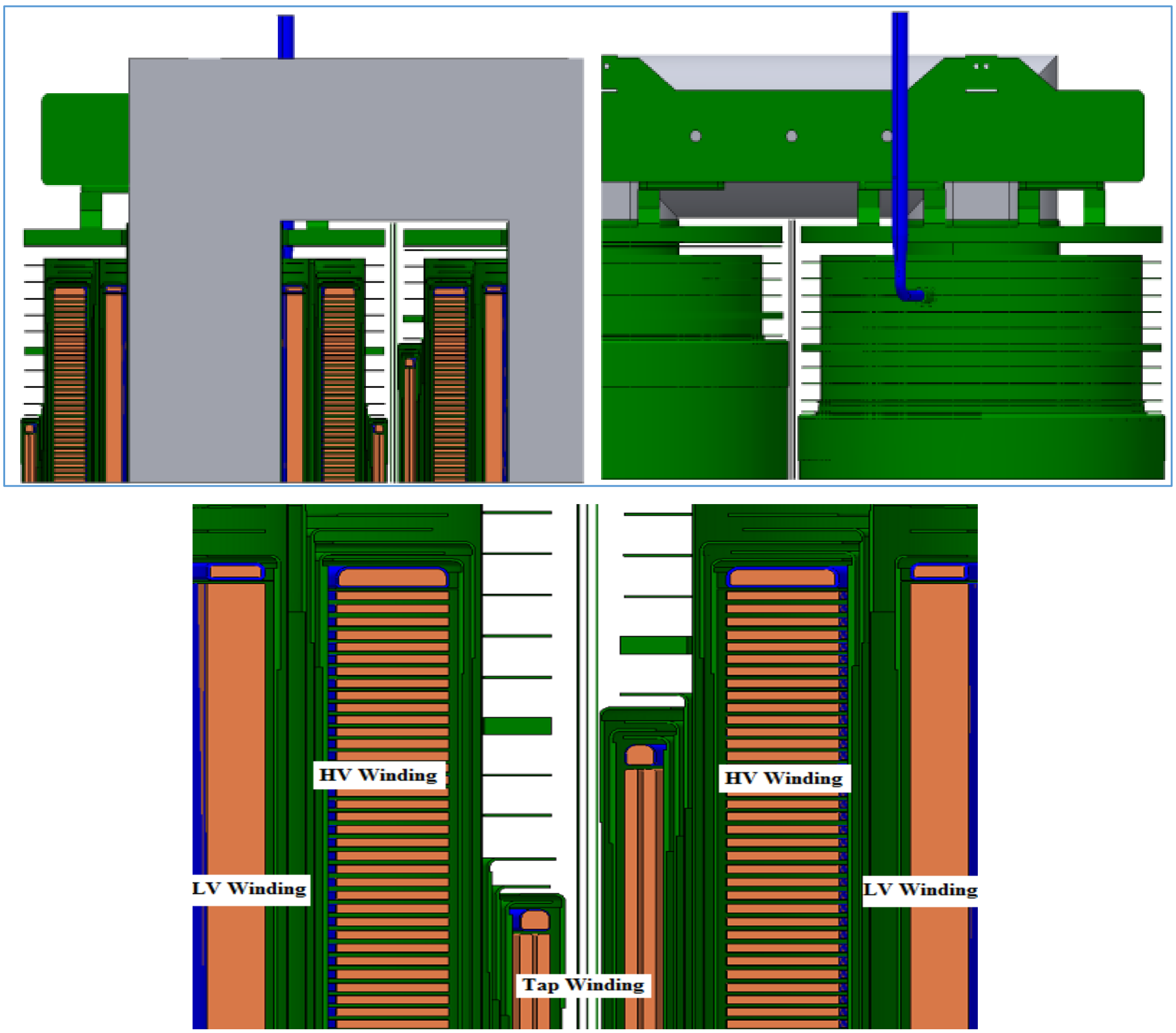


Figure 4.4: 3D model of transformer

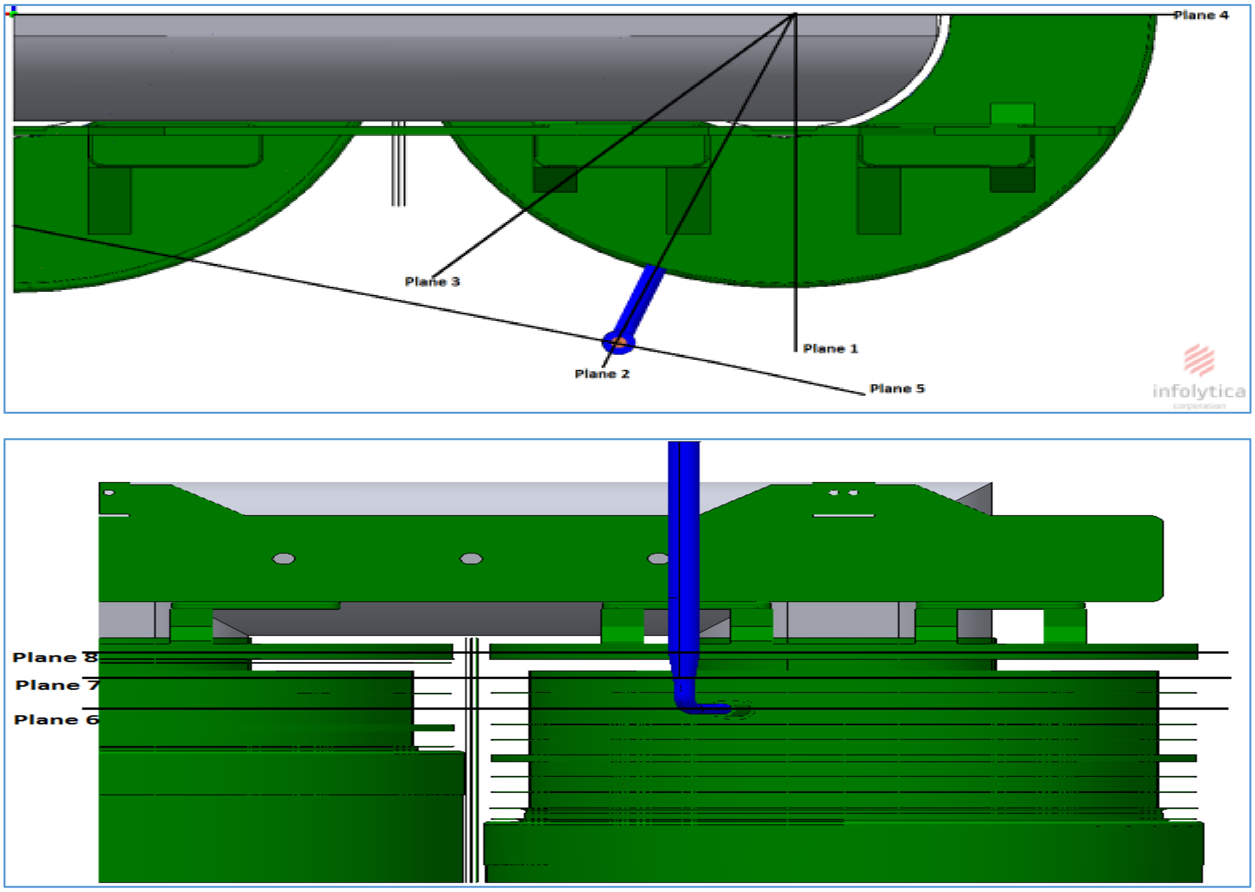
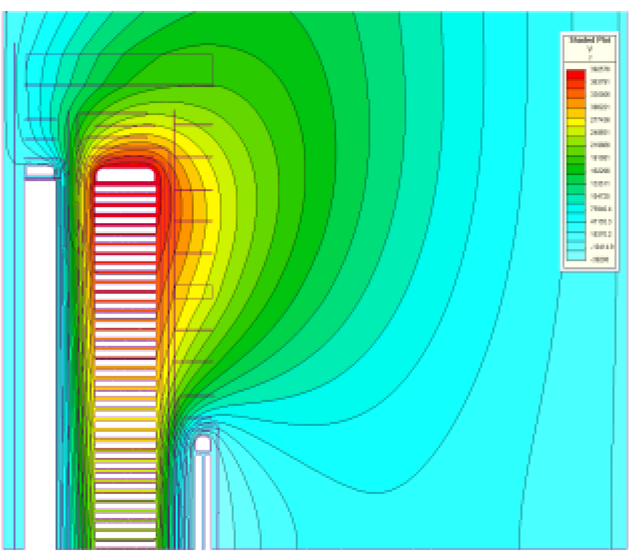


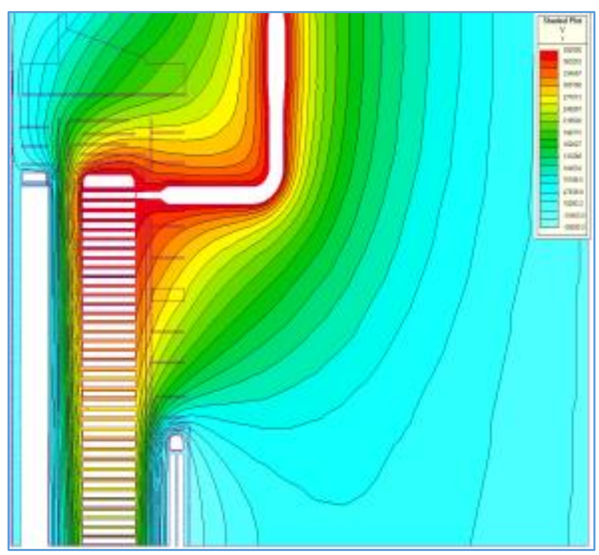
Figure 4.5: Plane views of 3D model

c) Voltage distribution plots

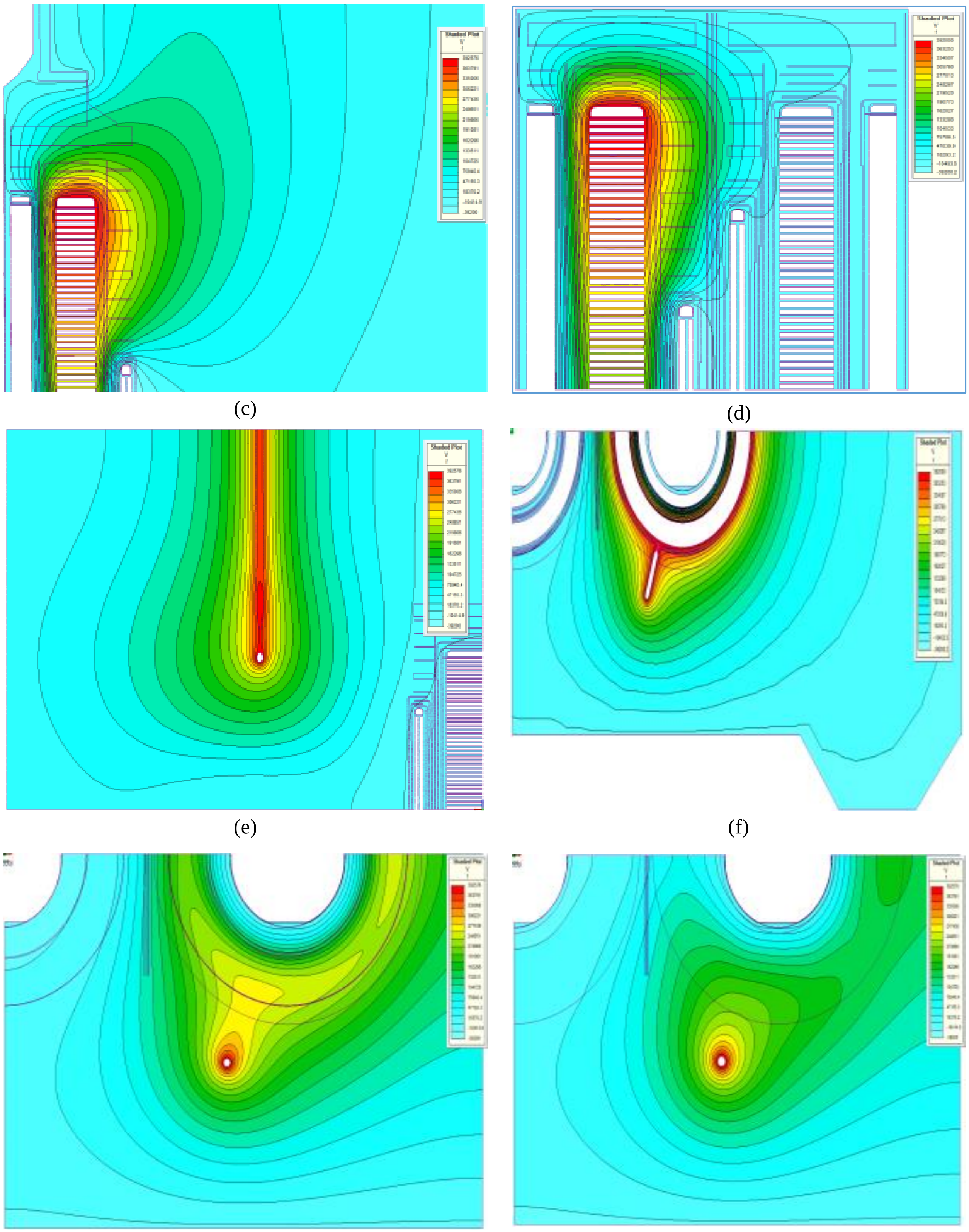
Voltage distribution plot for all the 8 plane with mineral oil are shown in figure:



(a)



(b)

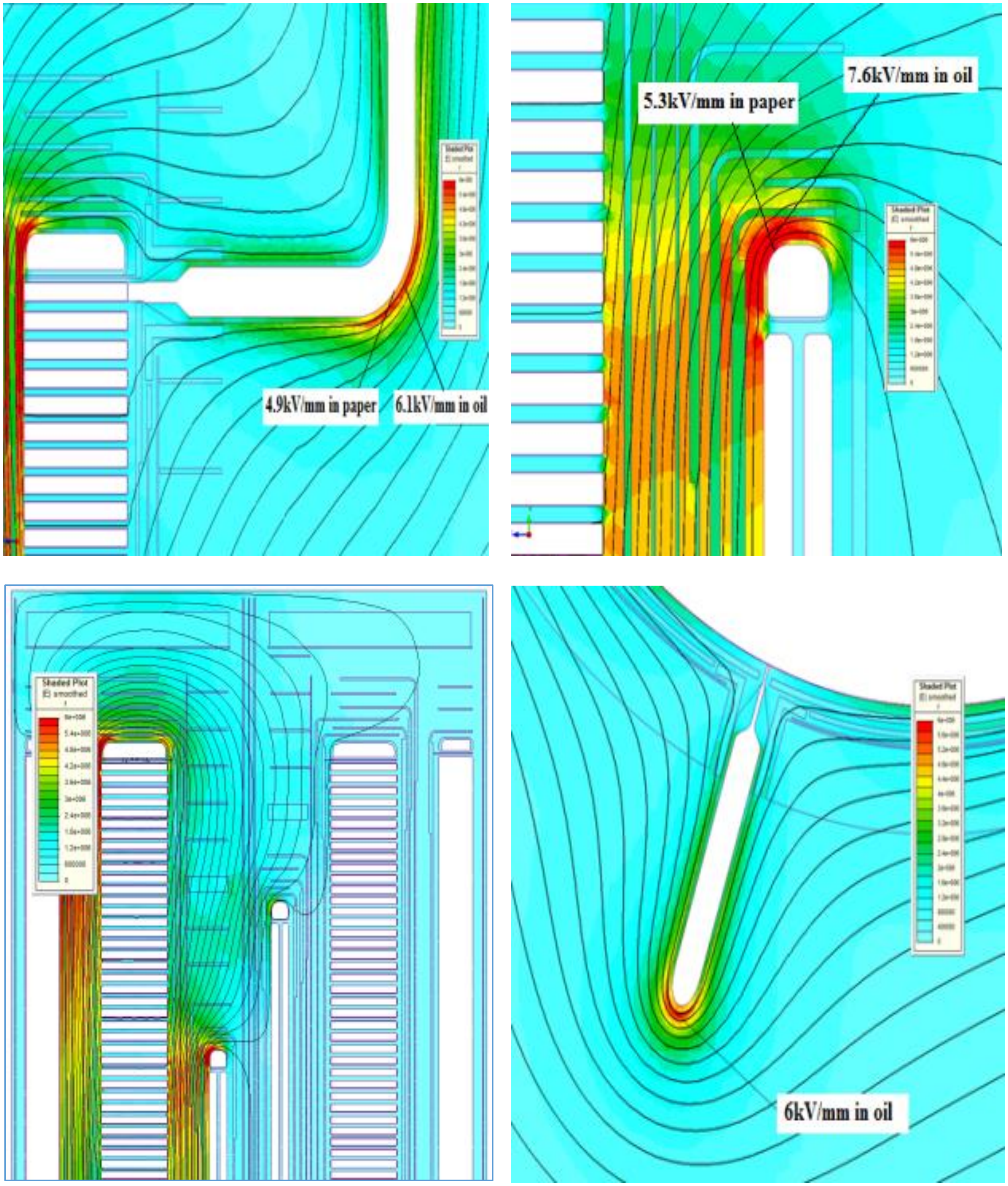


(c) (d) (e) (f) (g) (h)

Figure 4.6: Shaded plot of electric potential V: (a) Plane 1 (b) Plane 2 (c) Plane 3(d) Plane 4 (e) Plane 5 (f) Plane 6 (g) Plane 7 (h) Plane 8

d) Electric stress distribution plots

Electric stress distribution plot for mineral oil is shown in figure:



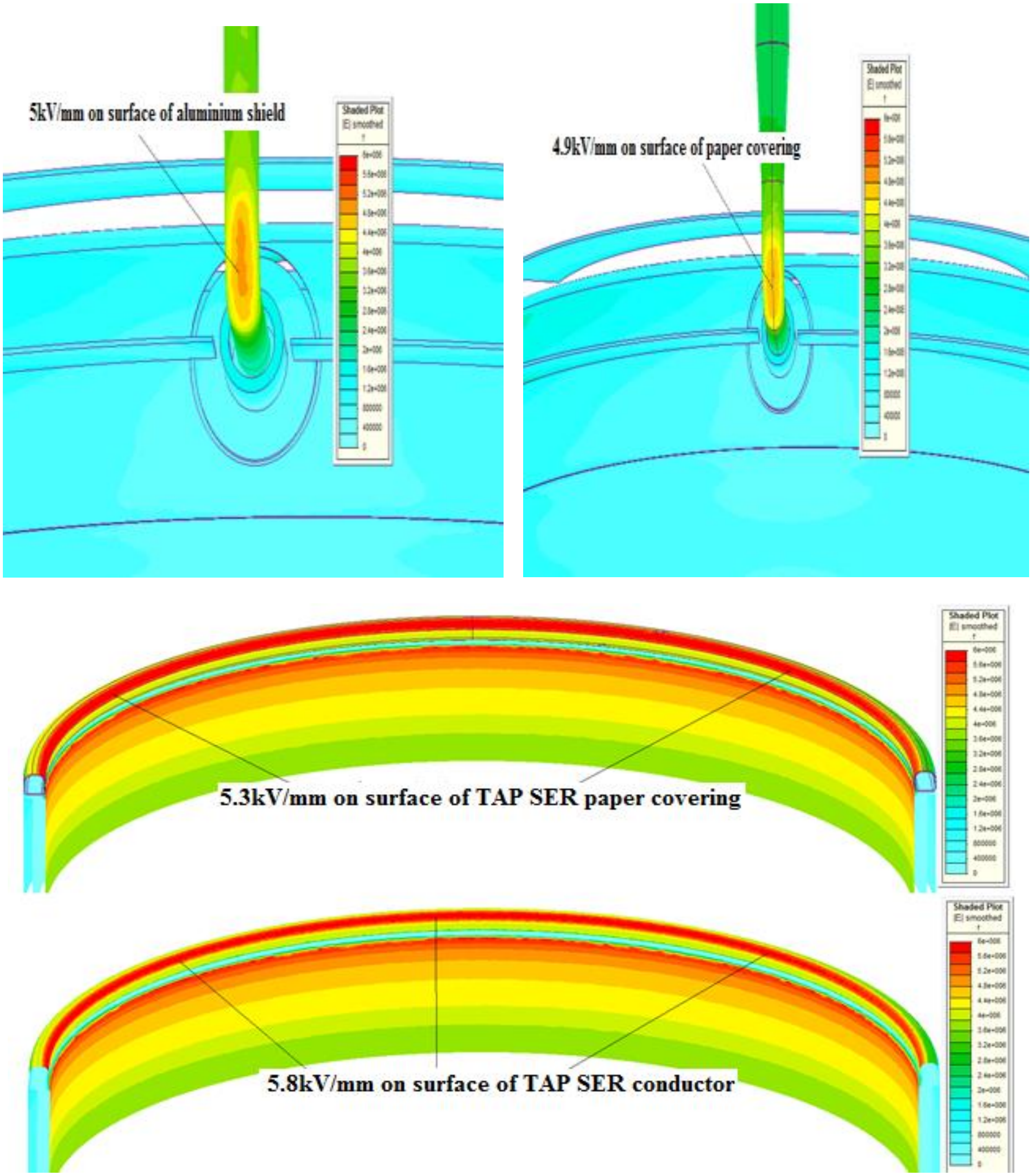


Figure 4.7: Shaded plots of electric stress

4.7 ANALYSIS RESULTS

A continuous effort has been made to reduce insulation content in the transformers as of the ever increasing competition in global market [22]. For accuracy in calculations of electrical stress level at different electrode configurations inside a transformer with various test voltages, greater efforts from scholars and designers are required. Finite element method are utilised for the accurate values of the point stress inside the insulation of transformers. Table 4.1 show the maximum stress points for mineral oil and natural ester.

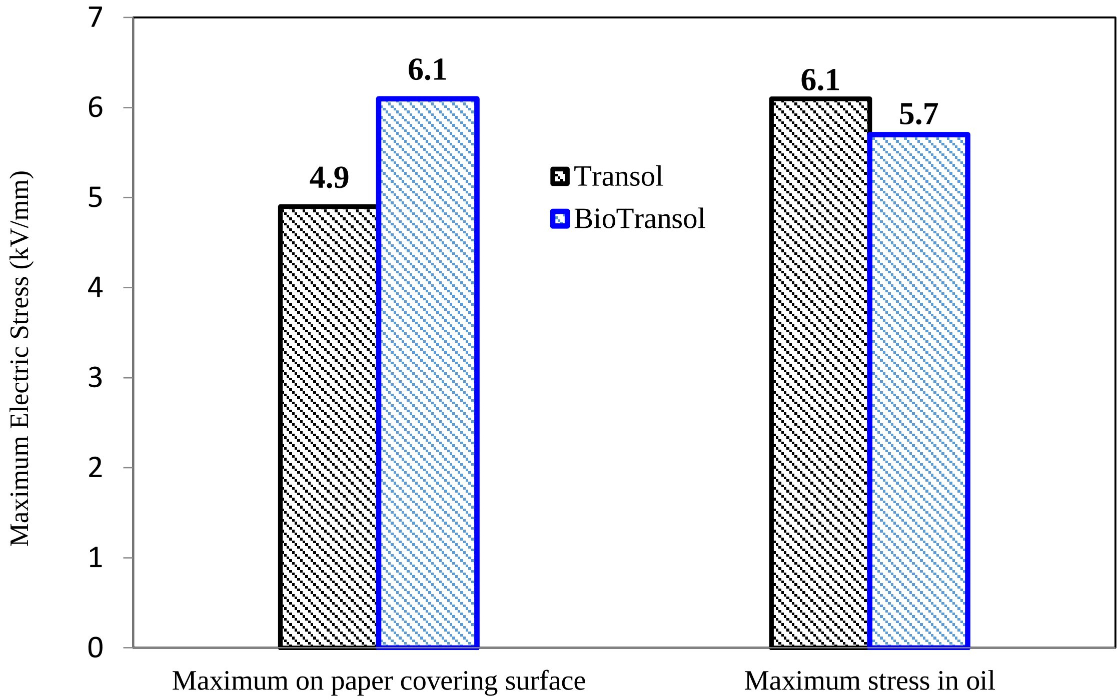


Figure 4.8: Maximum electric stress on HV lead paper covering surface and oil for Transol and BioTransol

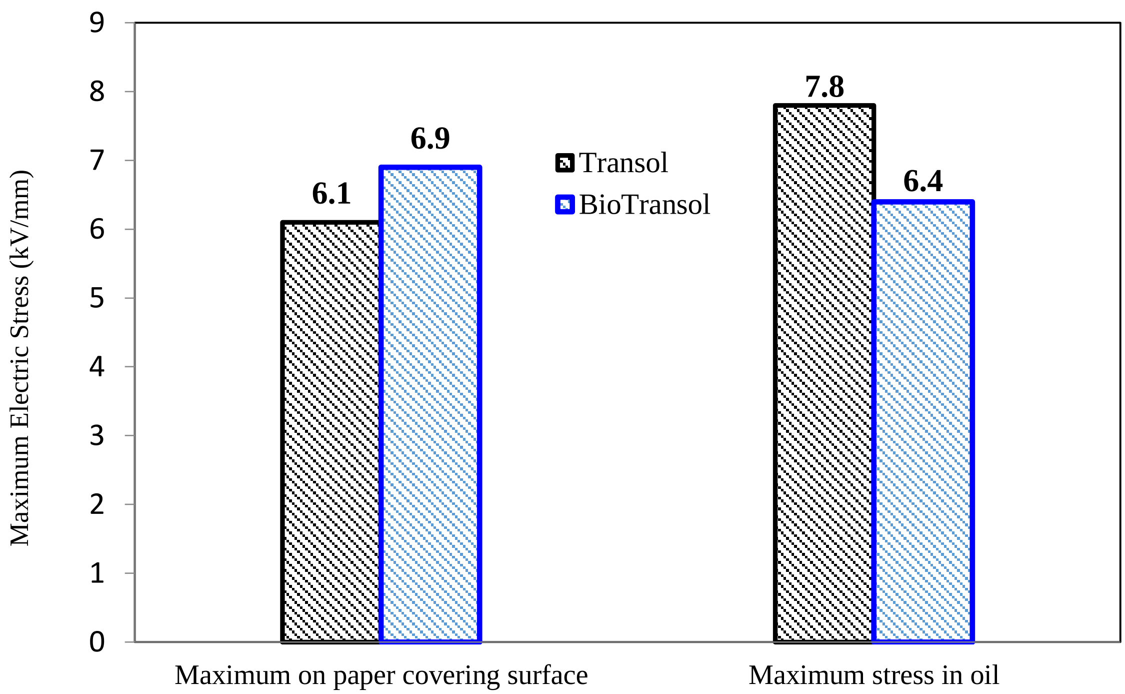


Figure 4.9: Maximum electric stress on paper covering surface and oil near HV SER for Transol and BioTransol

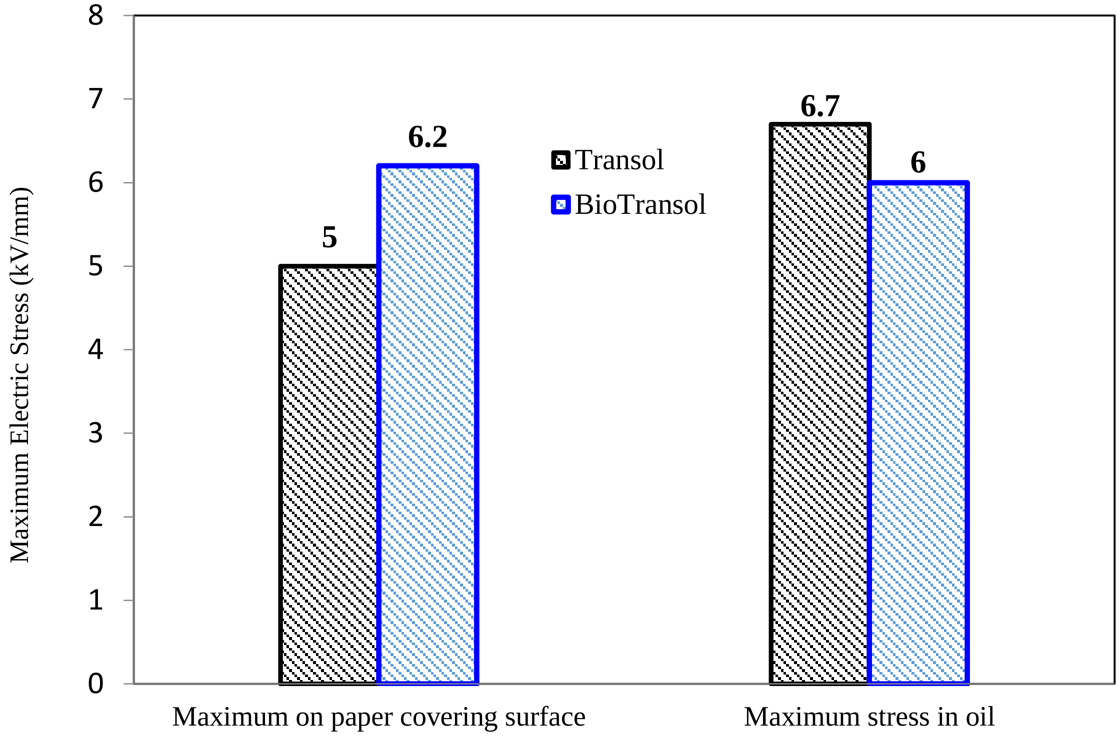


Figure 4.10: Maximum electric stress on paper covering surface and oil near LV SER for Transol and BioTransol

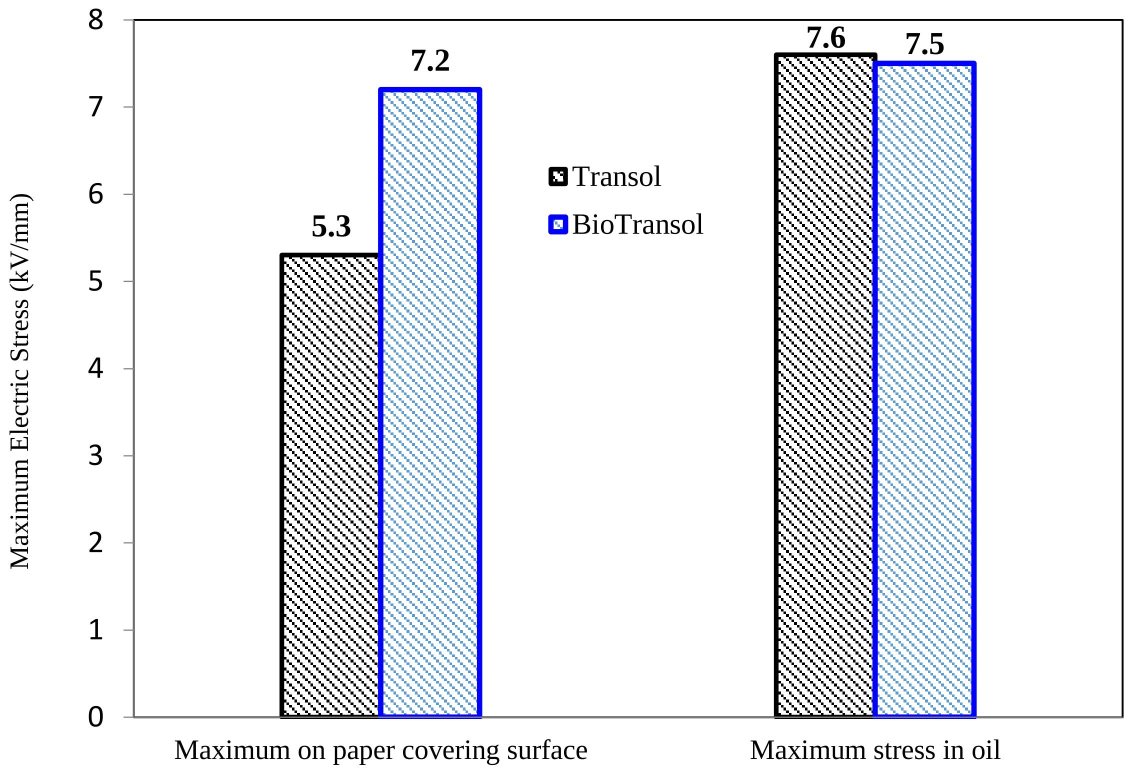


Figure 4.11: Maximum electric stress on paper covering surface and oil near TAP SER for Transol and BioTransol

Table 4.1: Maximum stress points for mineral oil and natural ester

S.no.	Maximum stress points (E_{max})	Mineral oil	Natural ester
1	Electric stress on HV lead paper covering surface	4.9kV/mm	6.1kV/mm
2	Electric stress in oil near HV lead	6.1kV/mm	5.7kV/mm
3	Electric stress on HV SER paper covering surface	6.1kV/mm	6.9kV/mm
4	Electric stress in oil near HV winding SER	7.8 kV/mm	6.4kV/mm
5	Electric stress on LV SER paper covering surface.	5 kV/mm	6.2kV/mm
6	Electric stress in oil near LV winding SER	6.7 kV/mm	6kV/mm
7	Electric stress on Tap SER paper covering surface	5.3 kV/mm	7.2 kV/mm
8	Electric stress in oil near Tap winding SER	7.6kV/mm	7.5kV/mm

4.8 Summary

The life of large power transformer depends on its insulation design. In high voltage transformer at design stage more focus is given on the designing of the insulation system. The transformers are subjected to different voltages during their testing and different electrical stresses are produced across each insulation parts. To maintain the required stress values FEM analysis is done in which winding are provided with different voltages which are obtained from testing [23].

Electric Stress values are calculated and if more stress is there in insulation part it is reduced by providing the more solid insulation. Stress values are maintained as due to highly competitive market, manufacturer has to reduce the losses in winding and other part of transformer. It can be achieved only by optimizing the insulation design with high technology and reducing stress especially across the non- symmetrical geometry in the transformer. Non-symmetrical geometry needs 3D calculation and therefore, 3D investigation. If solved just with 2D, the interpretation of results needs a lot of knowledge and experience of the design engineer, and accuracy is still moderate only.

CHAPTER- 5
IMPULSE VOLTAGE DISTRIBUTION FOR MINERAL OIL AND NATURAL ESTER TRANSFORMER UNDER STANDARD IMPULSE WAVESHAPE

5.1 INTRODUCTION

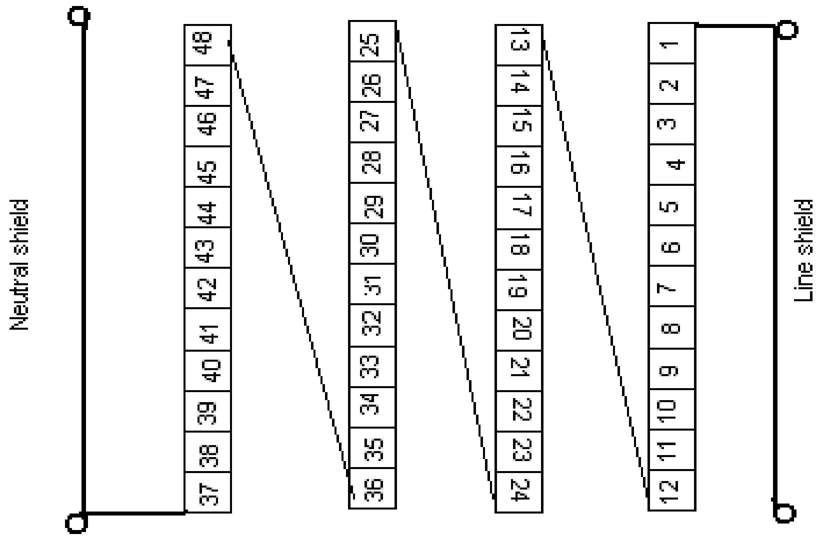
Through circuit switching high frequency electromagnetic transients are produced in transformers by lightning stroke. At various positions, sharp impulsive voltages of abnormal amplitudes appear along with the winding causing insulation breakdown to the ground. This is non-uniform distribution due to transient over voltage in transformer. Observation shows that 60% of these voltages show up crosswise over initial 10% length of winding. This leads to destruction in insulation of transformer [24]. Observations shows that 1.2/50 us impulse voltage distribution along inter leaved winding is uniform than continuous disc winding. Capacitance between coil in inter leaved windings is much larger than continuous ones which gives more improved voltage distribution. However, equivalents frequency gets higher rather than making the voltage distribution less uniform. Range of resonance frequency generally lies within 100 Hz to 1000 kHz depending upon the circuit parameters of the transformer windings

5.2 TYPES OF TRANSFORMER WINDINGS

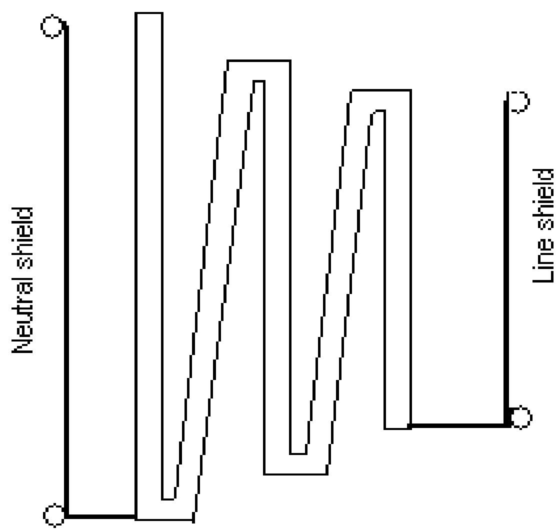
The transformer is most important components of a power system. The investing cost of the transformer and the economic consideration is extremely high. Winding is one of the main components in the transformers [25]. Different types of transformer windings are used in the industries. These are layer, continuous disc and interleaved windings. This chapter brief explanation about internal connections, voltage distribution, distribution constant and application of the transformer windings.

5.2.1 LAYER WINDING

Generally used for transformers which are star connected and having graded high insulation and for voltages higher than 132kV class. In these windings coils are arranged in the number of concentric spirals. Layers are graded in lengths from the longest at the neutral end (innermost layer) to the shortest at the line end (outmost layer). The layers are arranged between two concentric cylindrical shields, connected one to each end of the winding [25]. If number of turn of layer coil is more it can be single, double and multiple layer. All these layers are connected in series, wherein two schemes are possible, viz. parallel type-layer winding (Figure 5.1(a)) and tapered type-layer winding (Figure 5.1(b)).



(a)



(b)

Figure 5.1: Layer winding (a) Parallel type layer winding (b) Tapered type layer winding

The layer in coil is separated by the oil ducts and paper cylinders. During manufacturing of winding, the latter are arranged to extend well beyond the turns of the layer and afterwards these extensions are pealed and bent over at right angles to form insulating flanges between succeeding layers [25]. These flanges provide an insulation system to ground, which increases progressively from the neutral-end to a maximum for the line-end coil.

Equivalent capacitances in series are formed by dimensioned of series capacitor which is formed by winding layers and its shielding. This ensures a relatively uniform distribution of surge voltages throughout the winding.

When the winding current and the density of the leakage flux are not very high, the winding can be wound with conductors of rectangular cross-section. For large currents and higher density of leakage flux, transposed conductors are used.

5.2.2 CONTINUOUS DISC WINDINGS

In continuous disc windings, as the name sounds they might occur as numbers of strips in parallel or number of discs wounded in single wire. There are turns wounded one over the other and the conductor passing uninterrupted from disc to disc in each disc. Whenever possible the conductor is used in such drum lengths as will be sufficient for a complete winding, or section of a winding between tapings, but such joints as are necessary in manufacture should be made at the outside of the winding and be electrically welded or brazed [25].

The conductor may be either a single rectangular strip or a number of rectangular strips in parallel, wound on the flat. This reduces considerably the risk of the strip twisting slightly in winding and thereby making an unsatisfactory disc.

Good axial forces and mechanically strong are the features of each disc. Each section has either internal or fractional no of turns and this is the basic advantage of these coils. Medium current ratings and voltage between 33kV to 132 kV is used in these coils. The figure 5.2 shows the internal connections of continuous disc winding.

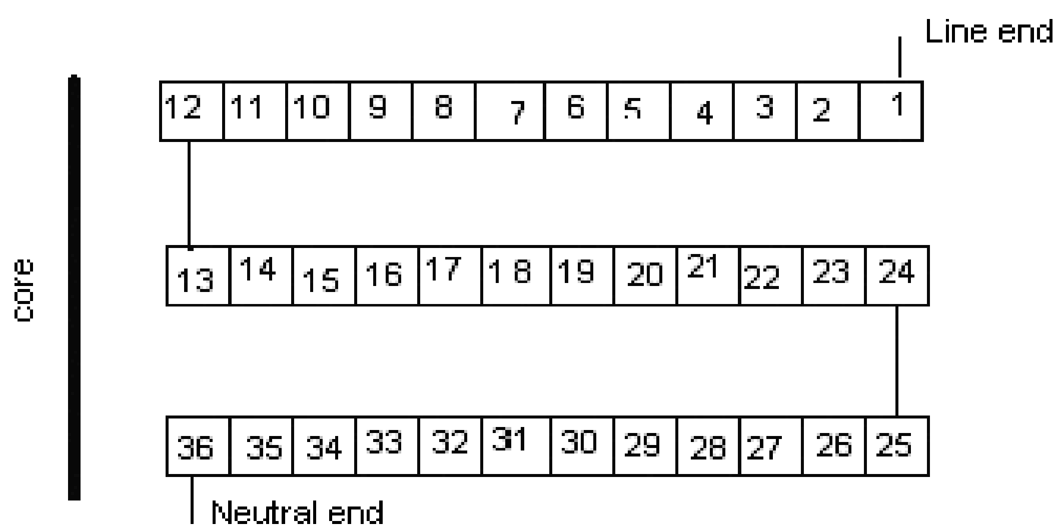


Figure 5.2: Continuous disc winding

Important terms of Continuous disc winding

- The series capacitance of winding consists of turn to turn capacitance of all series turns and disk-to-disc capacitance of all discs in the winding.
- As turn to turn capacitances are in series, so it results into smaller capacitance for the whole winding.
- Degree of non-linearity is high.
- Due to lesser value of ground and higher value of series capacitances, disc winding is used in impulse distribution as compared to layer windings.
- Distribution constant (α) is low compared to layer winding.

5.2.3 INTERLEAVED WINDINGS

Strength against the impulsive voltages is not adequate for voltages above 145k volt and this is the major demerits with continuous disc. If turns are interleaved in such a manner that an adjacent conductor belongs to different turns, the impulse voltages withstand behavior of disc coils can be increased [25]. Interleaving has been done in each pair of disc and is this winding is shown in figure 5.3. '2n' conductors are necessary in hand for winding when the no of conductors are in parallel.

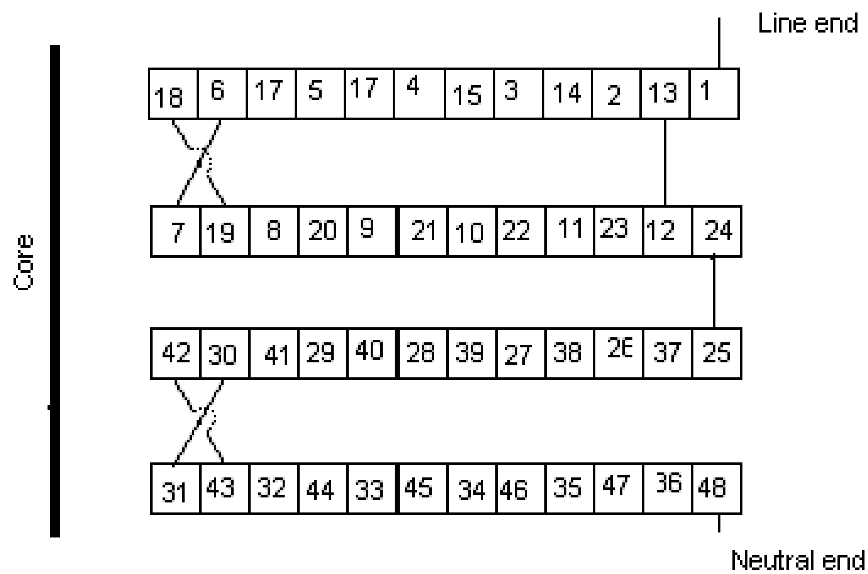


Figure 5.3: Interleaved winding (Number of disc E=2)

It is possible to have more no of discs in each interleaving apart from interleaving between every double disc as shown in figure 5.4. Although there are concomitant increased complexities, it gives improved behavior against impulsive voltage.

More labor and skill are required in interleaved windings than continuous disc windings. Sometimes a part of the winding is interleaved while the remaining part is plain disc, so as to combine the advantages of better impulse withstand at the high voltage end of the winding and reasonable labor cost for the winding as a whole. These are known as partially interleaved windings.

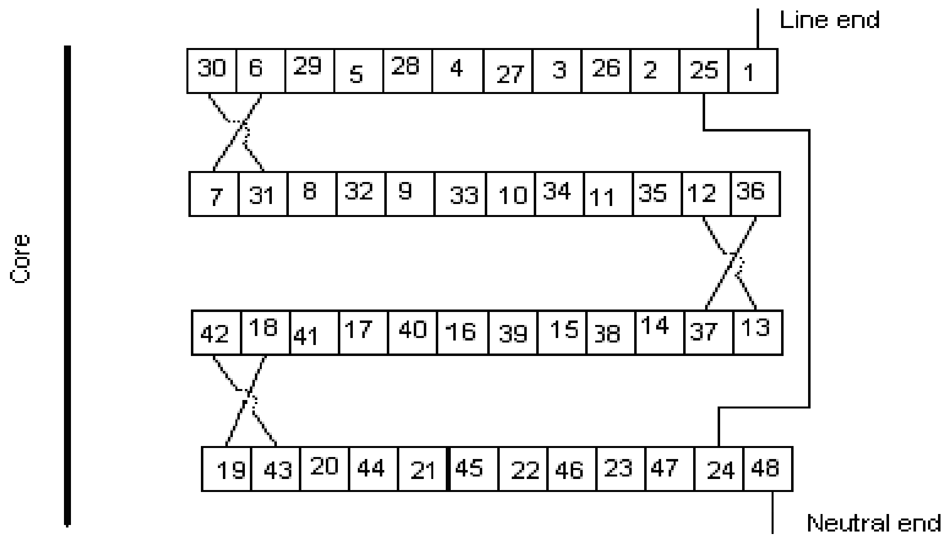


Figure 5.4: Interleaved winding (Number of disc E=4)

Important terms of interleaved winding

- The two consecutive electrical turns are separated physically by a turn, in interleaved winding which is farther along the winding.
- Advantage of winding is that they can be easily modified to increase the series capacitance.
- It increases the series capacitance but reduces the ground capacitance because of the improvement in space factor.
- Distribution constant (α) is low compared to continuous disc and layer windings.
- A greater merit of interleaved winding is their series capacitance can modified within limits, according to dielectric strength and economic considerations, without changing their number of turns and geometrical dimensions.
- The severity of voltage stresses is greatly reduced in interleaved winding.

5.3 EXPERIMENTAL DESCRIPATION

5.3.1 COIL UNDER TEST

A continuous disc winding with dimensions (90*665) mm consisting 32 discs each having 10 turns (total number of turns in the winding are 320) has been manufactured to perform various tests on the windings. The width of each turn is 3.22mm and the bare conductor is 1.68mm thick. Therefore, each conductor has paper covering 1.54mm (width of each conductor turn-thickness of bare conductor). In order to make the calculation easy, turns ratio have been taken as unity that mean both HV and LV windings are shown in figure 5.5 are separated by 1.5mm high density pressboard sandwiched between two axial spacers (5.2mm towards LV and 6.5mm towards HV). The main differences the two windings (HV and LV) is that taps from HV winding are taken out each connected to the individual bushing to perform testing. Continuous disc winding is shown in figure 5.6.

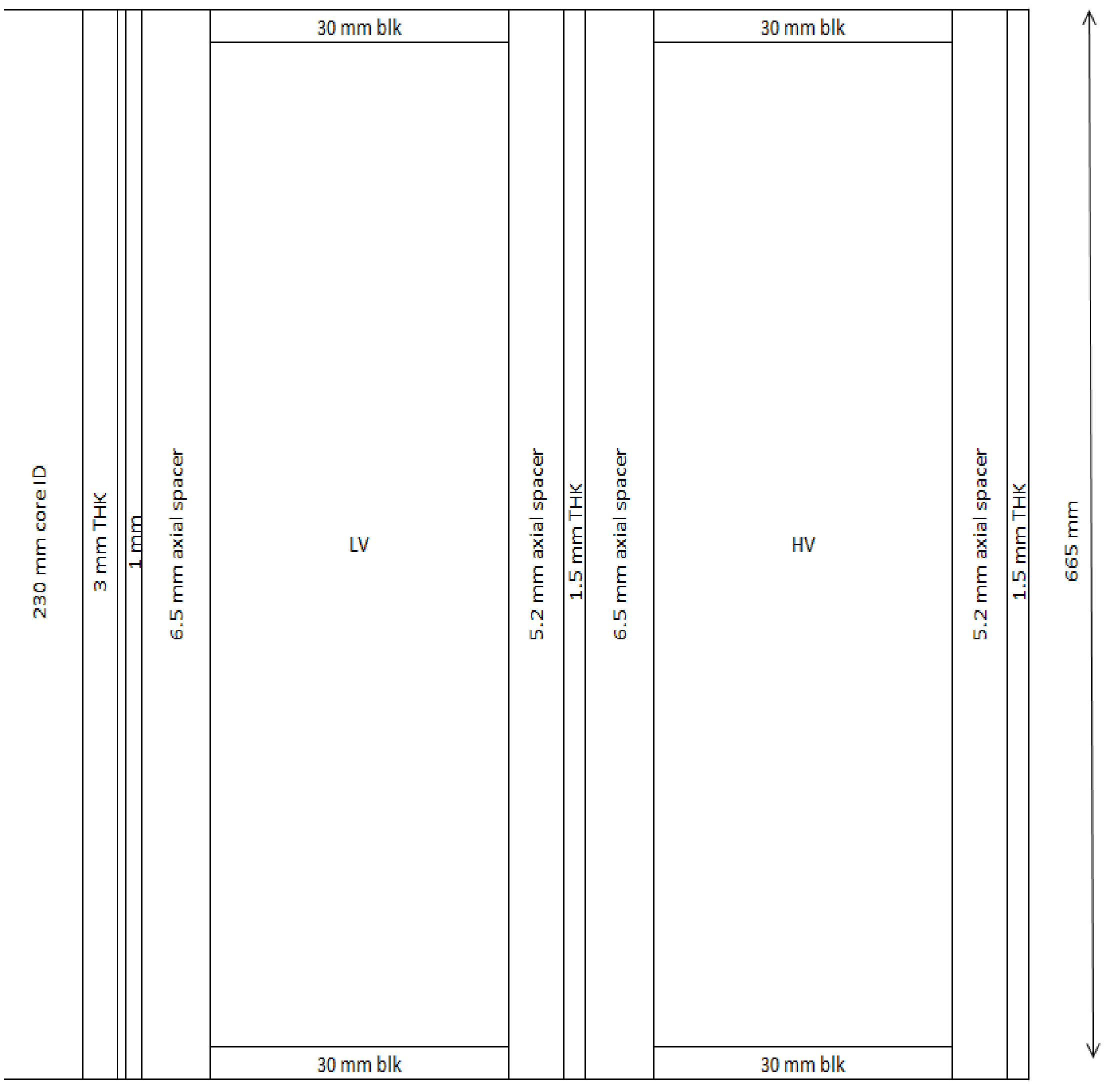


Figure 5.5: Insulation arrangement of coil

Figure 5.6: Continuous double disc winding

5.3.2 DRYING TECHNOLOGIES:

The technology for moisture removal has been the main area of concern over the years. The well-established processes for transformer drying which have eventually lead to vapor phase drying technology are hot air, hot air with rough vacuum, vacuum drying oven, oil circulation, oil spray & vacuum pressure impregnation.

HOT AIR

For heating up the active parts of transformer hot air with maximum temperature of 120ºC is used. Since the transformer tank is vacuum high, maximum insulation temperature of 150ºC is recommended. Through evacuation the drying process can be optimized. All active parts are non-uniformly heated [25].

HOT AIR WITH ROUGH VACUUM

The transformer is heated with hot air so to vaporize the moisture content in it. Then this hot air is extracted by themeans of rough vacuum to remove water so vaporized. This ensures that the water which has vaporized does get reabsorbed in the insulation materials. But this process also is time consuming as well not efficient [25].

VACUUM DRYING OVEN

In this process the transformer is kept in a vacuum oven where it is heated by means of electrical heaters. These results in water being evaporated which is present in the layers of insulation. Once the required temperature has been attained, vacuum is created in the oven with the help of vacuum pump so that the water vapor present in air around the transformer is extracted & maximum drying can be ensured [25].

OIL CIRCULATION

Oil purification equipment helps in circulating transformer oil. Particles are removed after filtering the oil which is heated to 80ºC in a vacuum degassing unit. It removes all residues and the moisture content is left less. Although it is not very efficient for removing moisture it is a necessary maintenance process but is indirect of the insulation which takes time Transformer oil is circulating through oil purification equipment.

VACUUM PRESSURE IMPREGNATION

In VPI the transformer coils are heated initially to remove the moisture from the layers of insulation. After the desired temperature has been attained, vacuum is created in the tank so as remove the air along with the water vapor. On reaching the desired level of vacuum, resin, which is atmospheric pressure, is allowed to impregnate the coils at a low pressure. As a result of the pressure difference, resin impregnates the innermost parts of the coils thereby providing effective insulation [25].

5.3.3 TESTING PROCEDURE OF COIL

The following procedure is used to test coil for impulse voltage distribution:

- Two FRP plates are tightened on top and bottom of coil.
- High voltage leads are crimped with aluminium lugs.
- Extra paper insulation is provided over leads taken to avoid failure at undesirable locations.
- Clearances of 70 mm are set and high voltage leads are guided to their respective bushings with help of supporting structure made of wood.
- Whole winding along with structure is kept in oven for drying at temperature of 110 degree Celsius for 24 hours until the moisture is decreased to less than 0.5 %.
- Wooden structure is there for winding support and winding is clamped with force of 70 kN.
- High voltage leads are connected to their respective bushings on tank cover and then tank is closed completely.
- Mineral oil (Transol) and Natural ester (BioTransol) is filled into tank one by one by maintaining its testing properties.

- Windings are left for impregnation for 24 hours under vacuum of 0.5 torr.
- Core and LV winding is grounded.
- Top and bottom terminal (1 and 9) of HV winding is provided with known surge voltage injected by recurrent surge generator and taken as reference for checking the wave shapes in remaining taps (2-8).
- One by one tap are connected and respective voltage drop is noted for standard impulse wave shape(1.2/50µs)

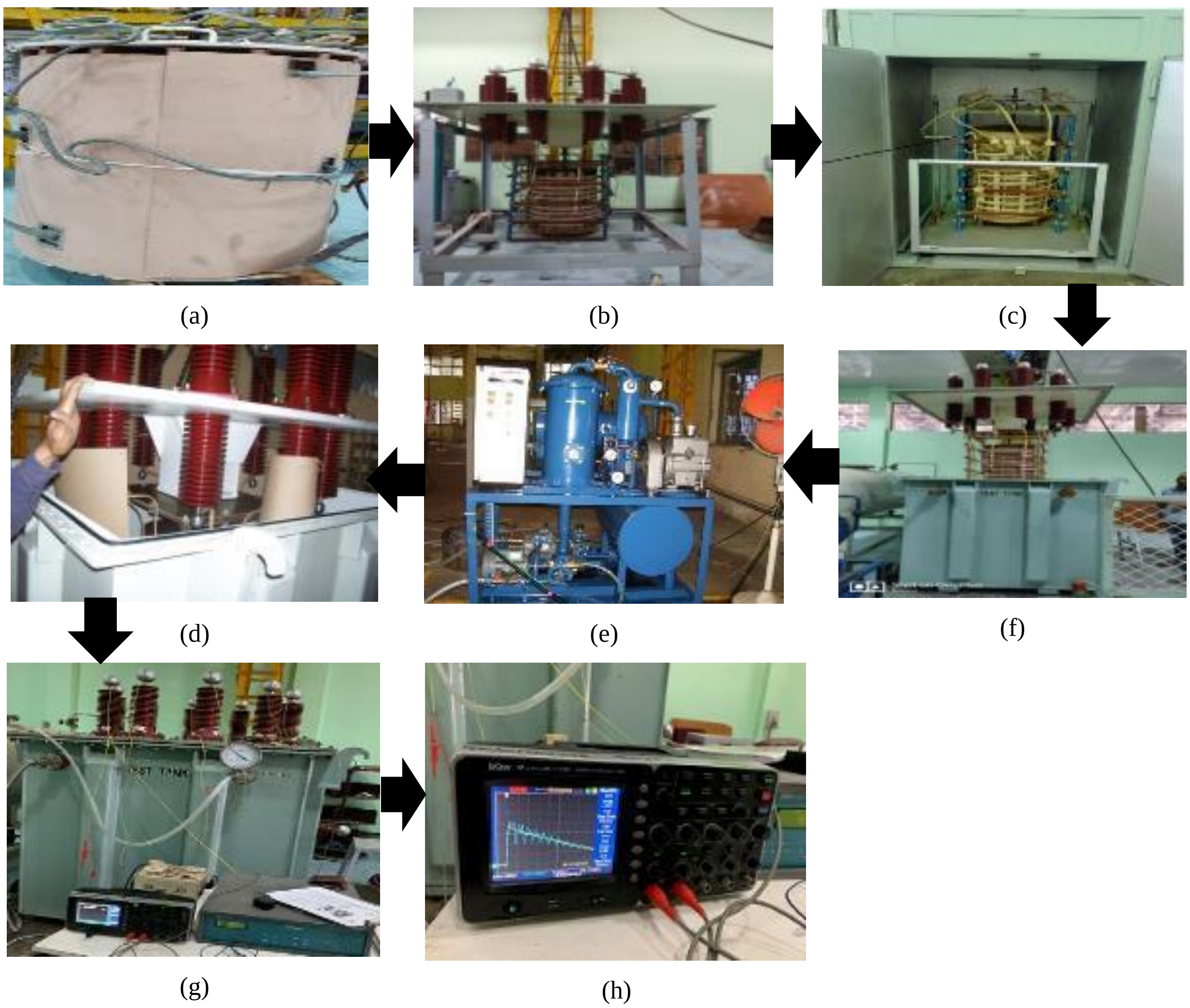
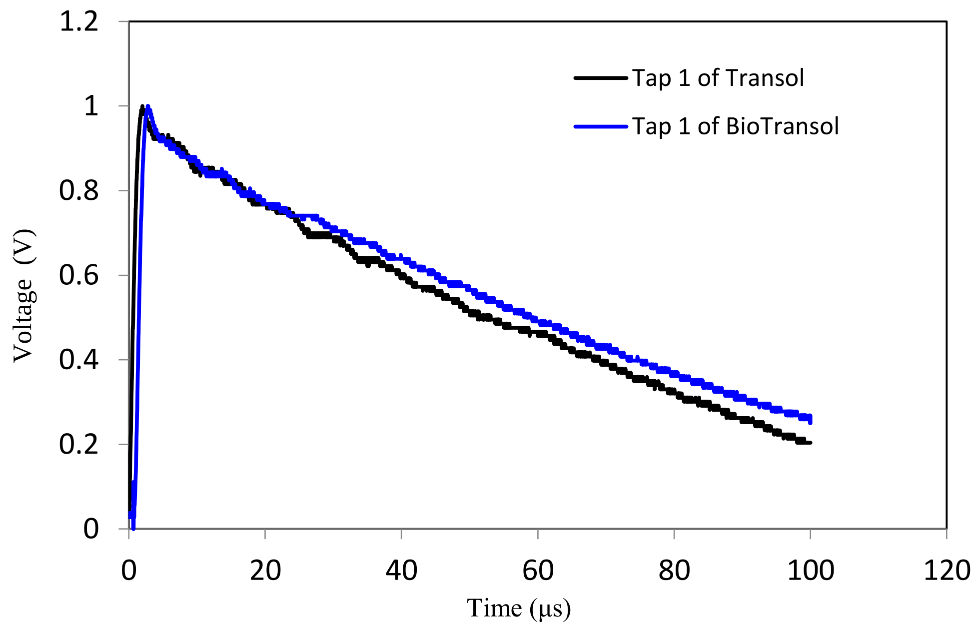


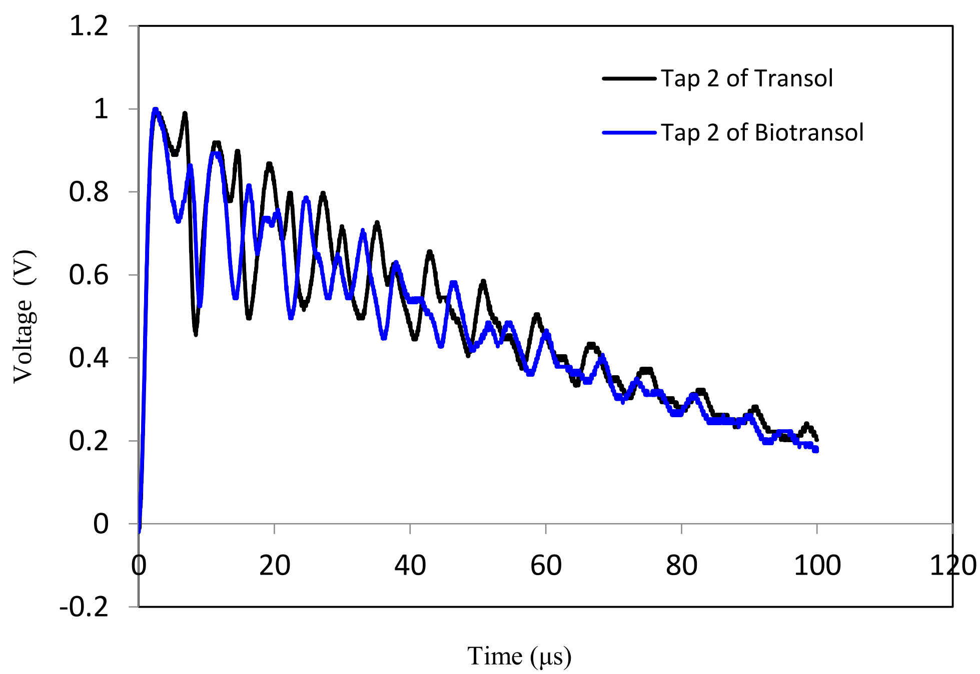
Figure 5.7: Testing procedure of coil (a) Continuous double disc coil (b) Clamping of coil (c) Drying of coil (d) Impregnation of coil (e) Filtration of oil (f) Tanking of transformer (g) Experimental setup (h) Impulse wave shape

5.3.4 EXPERIMENTAL RESULTS

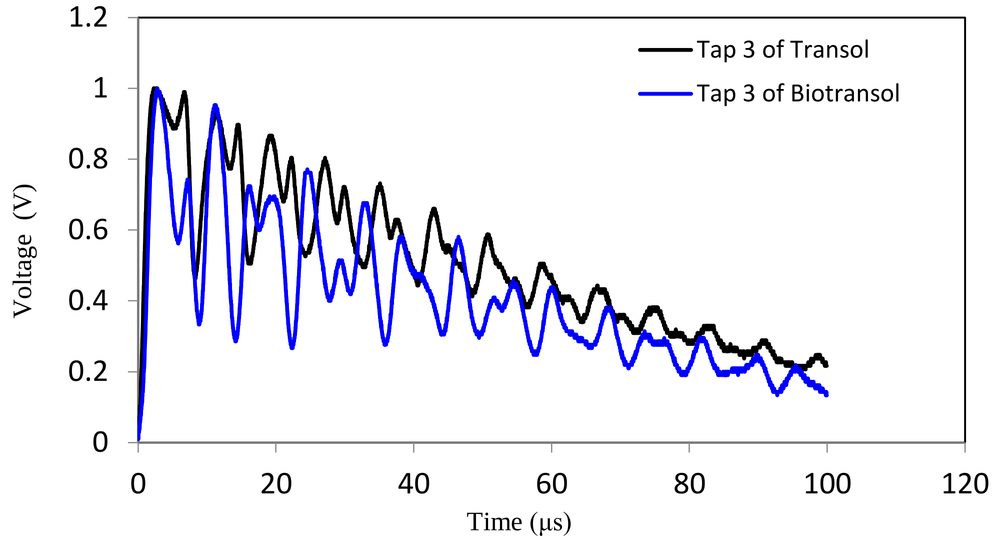
Design of transformer should be aware of impulse voltage stresses at all parts of windings. Accuracy at design state is important so that an efficient winding and insulation structure is selected [24]. Highly stressed regions in the first and last turn of discs are suggested in initial voltage distribution. The peak voltage at any node and highest duct voltage is observed in the middle region of the disc. For 1.2/50 impulse wave shape, tap of windings are compare for Transol and BioTransol in figure 5.8. The figure 5.9 shows the maximum voltage of impulse voltage distribution of continuous double disk. All the voltages are normalized voltage in both the figures.

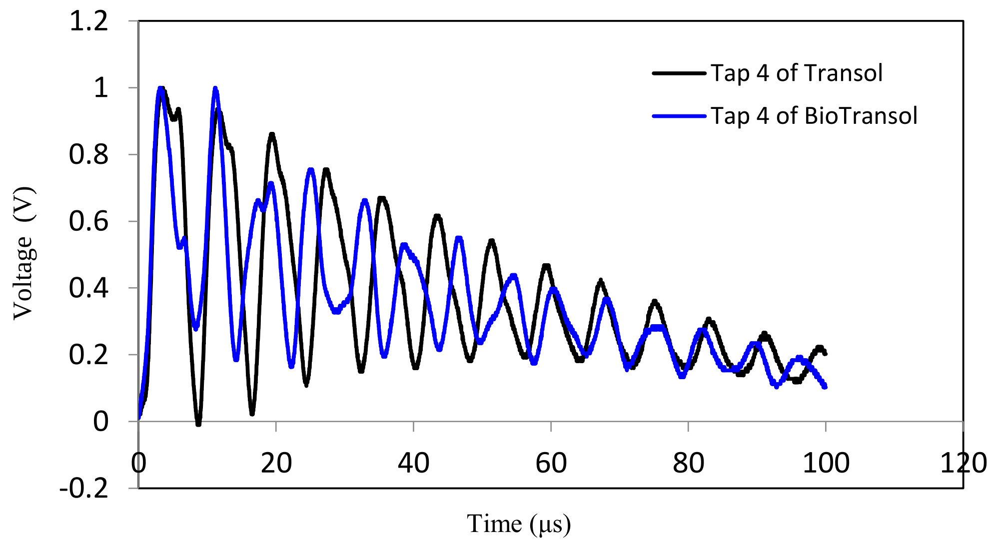


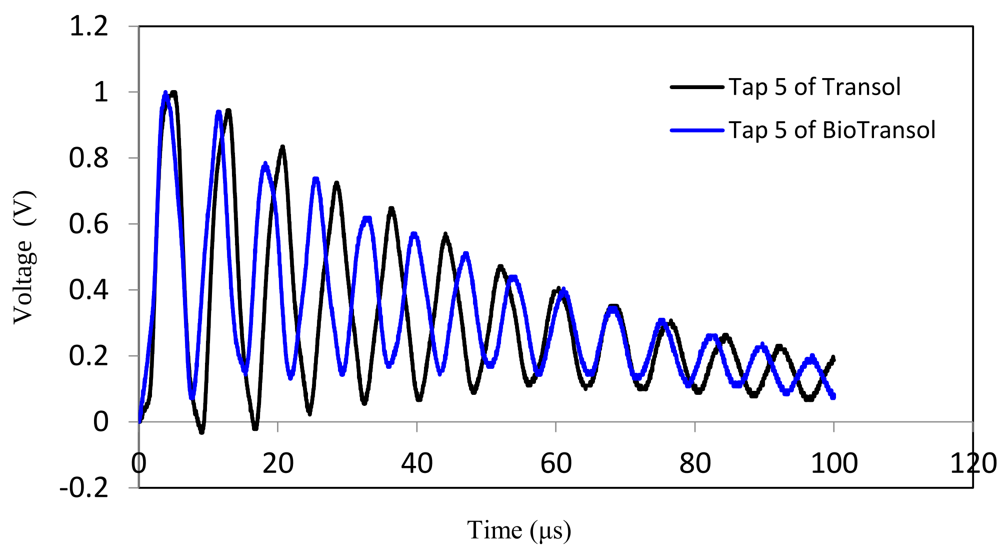
(a)

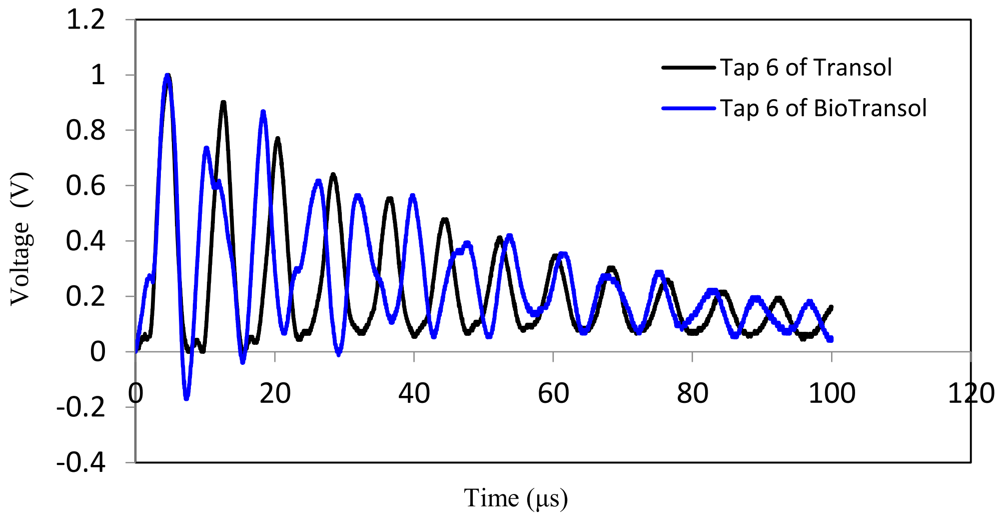


(b)

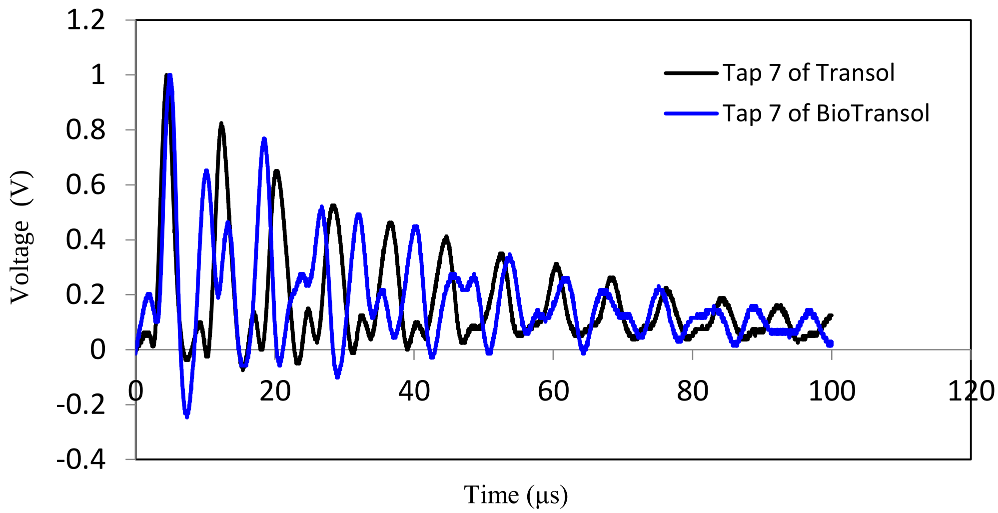

Tap 3 of Transol
Tap 3 of Biotransol
Voltage (V)
Time (µs)
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
(c)


Tap 4 of Transol
Tap 4 of BioTransol
Voltage (V)
Time (µs)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
20
40
60
80
100
120
(d)

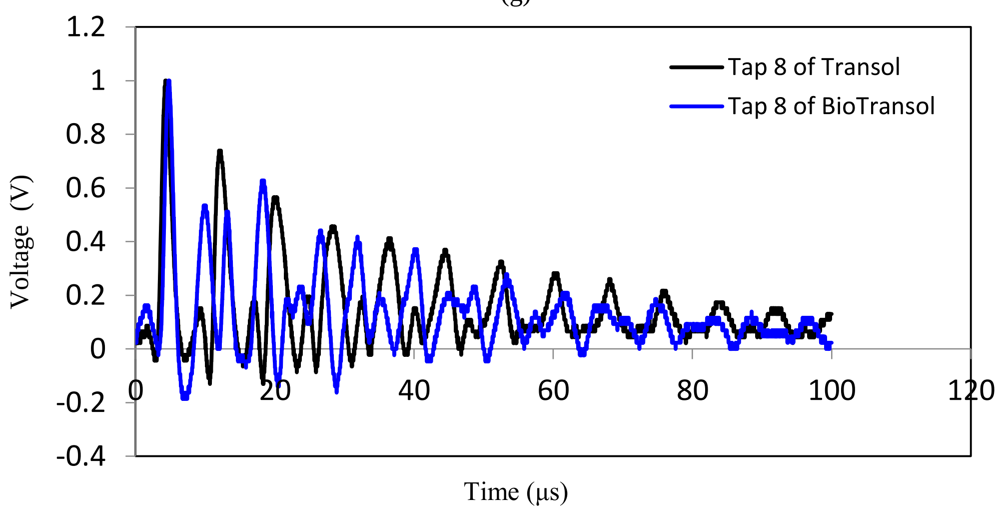

Tap 5 of Transol
Tap 5 of BioTransol
Voltage (V)
Time (µs)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
20
40
60
80
100
120
(e)



(f)



(g)



(h)

Figure 5.8: Comparison of different taps of winding for 1.2/50 wave shape for Transol and BioTransol:(a) Tap1 (b) Tap 2 (c) Tap 3 (d) Tap 4 (e) Tap 5 (f) Tap 6 (g) Tap 7 (h) Tap 8

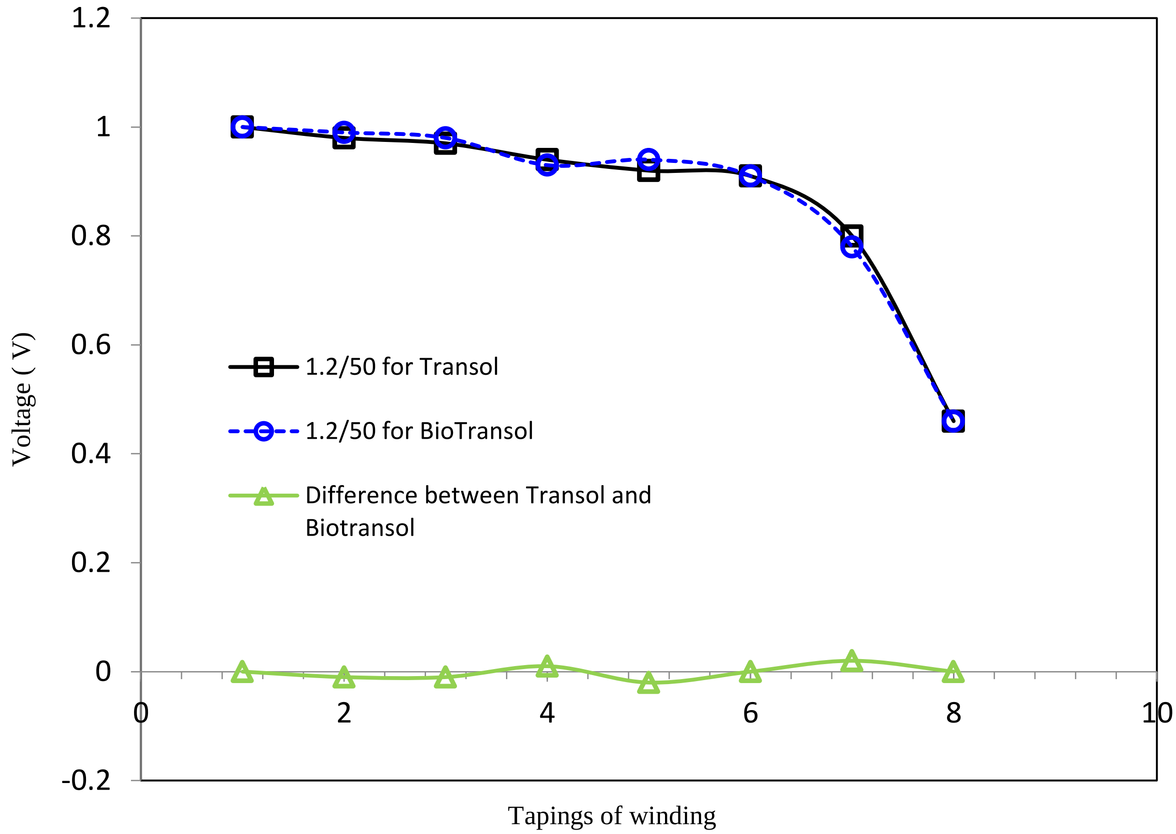


Figure 5.9: Maximum value of impulse distribution in coil discs for Transol and BioTransol under 1.2/50 impulse wave shape

From the above figure 5.8 and 5.9 it can be concluded that:

- As permittivity of oil changes it leads to change in internal capacitances of the winding.
- Theoretically, permittivity of BioTransol is more as compare to Transol so it should have more changes in voltage distribution as internal capacitances is more due to its high permittivity but practically it is seen in figures that in standard wave shape differences are very less in both the oil.
- As difference is very less, it can be said that there is no need to design different guidelines for natural ester in case of impulse voltage distributions in continuous disc windings.

5.4 SUMMARY

Impulse stress in winding is a result of strike at high voltage terminal of power. Main oscillating frequency range is in between 1 MHz to 50 MHz and very short rise time of 1usec or less in very fast transient over voltages. These windings have non-uniform distribution [24]. First 10 percent length of windings gets across 60 percent of these voltages. This can damage the transformer insulation. The subject focuses on the nature of internal voltage amplification and voltage stress at various transformer winding having impulse excitation [25].

As permittivity of oil changes it leads to change in internal capacitances of winding. Theoretically, permittivity of BioTransol is more as compare to Transol so it should have more changes in voltage distribution as internal capacitances is more due to its high permittivity but practically it is seen in figures that in standard wave shape differences are very less in both the oil. As difference is very less, it can be said that there is no need to design different guidelines for natural ester in case of impulse voltage distributions in continuous disc windings.

Chapter-6
CONCLUSIONS AND FUTURE WORK

6.1 CONCLUSIONS

6.1.1 GENERAL

Thesis focuses on dielectric design guidelines of ester oil under impulse voltage by taking into consideration the effects of field geometry, voltage polarity, gap distance, solid interface, stress analysis of transformer and impulse voltage distribution across the winding of power transformers. This thesis contains various experimental investigations and data analysis. Some useful findings are made and researcher's objectives are achieved.

Research topics covered in this thesis are:

- Breakdown voltage of Natural ester liquids in a non-uniform field
  - ➢ Standard lightning and switching tests
  - ➢ Influence of testing methods
  - ➢ Determination of withstand voltage
- Breakdown phenomena of ester liquids in a non-uniform configurations
  - ➢ Breakdown voltages at various gap distances
  - ➢ Evaluation of lightning breakdown strength at very large gaps
- Stress analysis for long oils gaps in transformer
  - ➢ Design of insulation system of power transformer
  - ➢ Electric stress analysis for long oil gaps
- Impulse voltage distribution of mineral oil and natural ester transformer under different impulse wave shape.
  - ➢ Manufacturing of different type of windings
  - ➢ Lumped parameter model of continuous disc winding
  - ➢ Impulse voltage distribution in impregnated winding

6.1.2 SUMMARY OF RESULTS

With growing interests in the utilization of ester oil as substitute to mineral oil for transformer application, an experimental analysis is performed on natural ester oil in comparison with conventional mineral oil. The objective is to evaluate the breakdown strengths of mineral oil and natural ester oil and compare their breakdown voltages at a low failure rate (i.e. high withstand probability) under varying oil gaps.

It is found that, under negative polarity of impulse, withstand voltage of ester oils is much lesser as compared to mineral oil. This behavior is result of high electronegativity of ester molecules which makes them electrically unstable under negative polarity. However, under positive polarity the withstand voltage of ester molecules is slightly higher as compared to mineral oil. It's found that streamer velocity of mineral oil is much higher than natural esters under negative polarity. Further, under positive polarity natural esters has more streamer velocity. In both the polarities utilization factor decreases for all insulating oils as with the increase in gap distance, both E_{mean} and E_{max} increases (due to increase in breakdown voltage).

Electric Stress values are calculated and if more stress is there in insulation part it is reduced by providing the more solid insulation. Stress values are maintained as due to highly competitive market, manufacturer has to reduce the losses in winding and other part of transformer. It can be achieved only by optimizing the insulation design with high technology and reducing stress especially across the non- symmetrical geometry in the transformer. Non-symmetrical geometry needs 3D calculation and therefore, 3D investigation. If solved just with 2D, the interpretation of results needs a lot of knowledge and experience of the design engineer, and accuracy is still moderate only.

As permittivity of oil changes it leads to change in internal capacitances of winding. Theoretically, permittivity of BioTransol is more as compare to Transol so it should have more changes in voltage distribution as internal capacitances is more due to its high permittivity but practically it is seen in figures that in standard wave shape differences are very less in both the oil. As difference is very less, it can be said that there is no need to design different guidelines for natural ester in case of impulse voltage distributions in continuous disc windings.

6.2 FUTURE WORK

With the advancement in technology, we are shifting gradually from conventional to renewable sources of energy. Now-a-days with the increasing awareness, clean and green sources are preferred. Transformer is considered to be the heart of the whole power system. Using ester oil as insulating oil in transformer, contributes to the green environment. In this report some valuable ends are made on dielectric design guidelines of ester oil for transformer application under impulse condition.

In the meantime there are new inquiries raised and more work should be possible for future study. For the non-uniform field (point sphere electrode configuration), as the DGA (Dissolve gas analysis) is strong technique to find the fault in the power transformer. So by doing DGA analysis of the impulse tested oil we can detect the fault and according to that more accurate results can be made. Ageing studies of in-service ester oils can be done as due to ageing the composition of oils can be changed and due to which more degradation occur and more number of polar compounds are generated.

In long oil gap analysis, the electric stress in end insulation can be determined with the help of software tool and then tries to reduce it and makes the transformer cost effective. As only two insulating oils electric stress are analyzed, in further work we can consider synthetic oil in comparison with conventionally transformer oil.

In impulse voltage distribution, similar models can be developed to characterize the switching impulse strength of windings. As only continuous disk winding is considered in further studies interleaved winding can be considered and comparison of voltage distribution in different windings can be analysed.

LIST OF PUBLICATIONS

[1]. Paper entitled as R. Agarwal, P. Sharma, A. Uppal, C.S Narasimhan, G. Morde and V. Jeyabalan, “Behaviour of Natural Ester Oil under Negative and Positive Lightning Impulse Stress” has been communicated for acceptance to Int. Journal of Power and Energy Conversion (IJPEC) Inderscience.

[2]. Paper entitled as P. Sharma, R. Agarwal, A. Uppal, C.S Narasimhan, G. Morde and J. Velandy, “Lightning Impulse Strength and Time to Breakdown of Natural Ester and its Effect in Mineral oil for Transformers” has been communicated for acceptance to IET High Voltage Journal.

[3]. Paper entitled as P. Sharma, R. Agarwal, A. Uppal, C.S Narasimhan and J. Velandy “Lightning Impulse Polarity Effect in Ester oils and Mineral oil for Transformer Application” has been communicated for acceptance to IEEE int. conf. on (CATCON 2019).

[4]. Paper entitled as A. Uppal, R. Agarwal, P. Sharma, J. Velandy and C.S Narasimhan, “Effect of Dielectric Strength of mineral oil on Mixing with a Natural Ester as a Polar Contaminant under AC Stress” has been communicated for acceptance to IEEE int. conf. on (CATCON 2019).

REFERENCES

[1]. E. O. Forster, 'Critical assessment of the electrical breakdown process in dielectric fluids', IEEE Transactions on Dielectrics and Electrical Insulation, 1985, 20(4), pp. 891–896.

[2]. J. K. Nelson, 'An assessment of the physical basis for the application of design criteria for dielectric structures', IEEE Transactions on Dielectrics and Electrical Insulation,24(5), pp. 835 – 847, Oct. 1989.

[3]. E. O. Forster, 'Progress in the field of electrical breakdown in dielectric fluids', IEEE Transactions on Dielectrics and Electrical Insulation, 1985, 20(6), pp. 905–912.

[4]. A. Beroual, and R. Tobazeon, 'Prebreakdown phenomena in liquid dielectrics', IEEE Transactions on Dielectrics and Electrical Insulation, 1986, 21(4), pp. 613–627.

[5]. D. Linhjell, L. E. Lundgaard, and G. Berg, 'Streamer propagation under impulse voltage in long point-plane oil gaps', IEEE Transactions on Dielectrics and Electrical Insulation,1994, 1(3), pp. 447–458.

[6]. Y. V. Torshin, 'Prediction of breakdown voltage of transformer oil from predischarge phenomena', IEEE Transactions on Dielectrics and Electrical Insulation, 2003, 10(6), pp. 933–941.

[7]. O. Lesaint, 'Prebreakdown phenomena in liquids and their relation with breakdown properties in high voltage applications', CIGRE conference, Belgium, 2007, pp. A2–D1.

[8]. V. Y. Ushakov, 'Impulse breakdown of liquids', Springer Berlin Heidelberg, New York, 2007.

[9]. D. Viet-Hung, A. Beroual, and C. Perrier, 'Comparative study of streamer phenomena in mineral, synthetic and natural ester oils under lightning impulse voltage', Int. Conf. on High Voltage Engineering and Application (ICHVE), 2010, pp. 560–563.

[10]. D. Vukovic, S. Tenbohlen, J. Harthun, C. Perrier, and H. Fink, 'Breakdown strength of vegetable-based oils under AC and lightning impulse voltages', IEEE Int. Conf. on Dielectric Liquids (ICDL), 2011, Paper No. 116.

[11]. T. B. Shanker, N. H. Narasimhaiah, D. Antony, and G. S. Punekar, 'Effects of Transformer-oil Temperature on Amplitude and Peak Frequency of Partial Discharge Acoustic Signals', IEEE Trans. Power Del. 2018, 14, pp. 1.

[12]. A. B. Eriksson, R. Liu, and C. Tornkvist, ‘Differences in streamer initiation and propagation in ester fluids and mineral oil’, IEEE Int. Conf. on Dielectric Liquids (ICDL), 2011, paper 40.

[13]. Ruijin Liao, ‘Thermal and electrical properties of a novel 3-element mixed insulation oil for power transformers’, IEEE Transactions on Dielectrics and Electrical Insulation, 2019, 26(2), pp. 610–61.

[14]. Q. Liu, ‘Electrical performance of ester liquids under impulse voltage for application in power transformers,’ PhD dissertation, School of Electrical and Electronic Eng., The University of Manchester, UK., 2011.

[15]. ASTM D 3300, ‘Dielectric breakdown voltage of insulating oils of petroleum origin under impulse conditions’, 1994.

[16]. Wu Lu, ‘Prebreakdown and breakdown phenomena of alternative transformer liquids under lightning impulse voltages,’ PhD dissertation, School of Electrical and Electronic Eng., The University of Manchester, UK., 2015.

[17]. Q. Liu, and Z. D. Wang, ‘Streamer characteristic and breakdown in synthetic and natural ester transformer liquids under standard lightning impulse voltage’, IEEE Transactions on Dielectrics and Electrical Insulation, 2011, 18(1), pp. 285–294.

[18]. Q. Liu, and Z. D. Wang, ‘Streamer characteristic and breakdown in synthetic and natural ester transformer liquids with pressboard interface under lightning impulse voltage’, IEEE Transactions on Dielectrics and Electrical Insulation, 2011, 18(6), pp. 1908–1917.

[19]. Q. Liu, and Z. D. Wang, ‘Breakdown and withstand strengths of ester transformer liquids in a quasi-uniform field under impulse voltages’, IEEE Transactions on Dielectrics and Electrical Insulation,2013, 20(2), pp. 571–579.

[20]. Derler, F., Kirch, H.J., Krause, Ch., Schiender, E., ‘Development of a design method for insulating structures exposed to electric stress in long oil gaps and along oil/transformer board interfaces’, 7th International Symposium on High Voltage Engineering, Dresden,1991.

[21]. Tschudi, D., Krause, Ch. Kirch, H.J., Franchek, M.,Malewski,R., ‘Strength of transformer paper-oil insulation expressed by the weidmann oil curves’, CIGRE, WG 33.03, 1994.

[22]. S.V. Kulkarni and S.A. Khaparde ‘Transformer Engineering Design, Technology, and Diagnostics’, 2nd edition, CRC Press Taylor & Francis Group, New york, 2013.

[23]. Zienkiewicz, O. C. Finite element method, McGraw-Hill, London, 1977.

[24]. Heller, B. and Veverka, A. ‘Surge phenomena in electrical machines’, IliffeBooks Ltd., London, 1968.

[25]. Chadwik, A. T., Ferguson, J. M., Ryder, D. H., and Stearn, G. F. ‘Design of power transformers to withstand surges due to lightning, with special reference to a new type of winding’, Proceedings IEE, Pt. II, Vol. 97, 1950, pp. 737–750.

PLAGIARISM REPORT

I hereby confirm that the plagiarism report of 9%. is generate by me through "Turnitin".

Ritika Thesis_1

ORIGINALITY REPORT

9%	2%	6%	5%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Liu, Q., and Z. D. Wang. "Breakdown and withstand strengths of ester transformer liquids in a quasi-uniform field under impulse voltages", IEEE Transactions on Dielectrics and Electrical Insulation, 2013. Publication	1%
2	Submitted to Universiti Pertahanan Nasional Malaysia Student Paper	1%
3	Submitted to Universiti Putra Malaysia Student Paper	1%
4	Khaparde, . "Impedance Characteristics", Transformer Engineering Design Technology and Diagnostics Second Edition, 2012. Publication	1%
5	Khaparde, . "Electromagnetic Fields in Transformers : Theory and Computations", Transformer Engineering Design Technology and Diagnostics Second Edition, 2012. Publication	1%