

**EVALUATION OF DIELECTRIC WITHSTAND
LEVELS OF ESTER OILS (NATURAL & SYNTHETIC)
AND OIL IMPREGNATED PRESSBOARD UNDER
IMPULSE STRESS CONDITIONS FOR
TRANSFORMER APPLICATION**

A Dissertation submitted in fulfillment of the requirements for the Degree
of

MASTER OF ENGINEERING
in
Power Systems

Submitted by

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DECLARATION CERTIFICATE

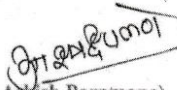
I hereby certify that the work which is presented in dissertation entitled, "Evaluation of Dielectric Withstand Levels of Ester Oils (Natural & Synthetic) and Oil Impregnated Pressboard under Impulse Stress Conditions for Transformer Application", in partial fulfillment of the requirements for the award 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 Technologies Limited, Mumbai. 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.


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NOMENCLATURE

Main symbols and notations used in this study are listed below.

Mineral oil	MO
Natural ester oil	NE
Synthetic ester oil	SE
Maximum electric stress	E_{\max}
Average electric stress	E_{avg}
Utilisation factor	η / ξ

ABSTRACT

Ester oil is becoming increasingly popular as a potential alternative to mineral oil. Main reason behind this is environmental benefit and high continuous over loading capability in comparison to the conventionally used mineral oil. Major attractive features of esters which has been already evaluated are: good biodegradability, non-toxicity, high moisture absorption ability and high flash and fire points (usually above 300°C) which lowers the risks for humans as well as environment. 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 is facing in recent years is to extend its use from distribution transformers (low voltage) to power transformers (high voltage). The high interest on ester oil has led to several studies aimed to understand complete dielectric behaviour of esters and their impact on transformer design for manufacturing. Therefore, this work focuses on evaluation of their dielectric breakdown performance for transformer application. Main objective is to evaluate impulse withstand voltage of ester oils and their impregnated pressboard under standard positive and negative impulse for uniform (non-divergent) and non-uniform (divergent) electrode configurations. Sphere-sphere and Sphere-needle electrode configurations are considered to create a uniform and non-uniform field respectively. The study compares different ester oils with conventional mineral oil, which serves as point of reference. Electrodes and test procedures followed are according to standard ASTM–D3300. The best estimate of 3-parameter Weibull distribution is calculated for 1% breakdown probability voltage. From experimental investigations, conclusions have been made considering geometry effect and polarity effect. Furthermore, electric stress experienced by all insulating liquids at 1% failure probability voltage is determined with the help of ElecNet software. Similarly, for impregnated pressboards, electric stress is determined at average breakdown voltage.

Last but not the least, an effort has been made to study effect of aromatic content and polar contaminant on dielectric breakdown performance of mineral oil. This section discusses the effect of aromatic content by comparing paraffinic inhibited and naphthenic inhibited mineral oil. Further to analyse effect of polar contamination in mineral oil, natural ester insulating oil (polar contaminant) is mixed to mineral oil, which is highly non-polar in nature. The results indicated that these effects are prominent under negative polarity of impulse.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

As transformer is critical and most 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]. Historically, oil and paper are the choices for providing insulation to the transformers. To increase the dielectric breakdown strength of transformer insulation, insulating oil is filled in the tank so that it can impregnate voids of solid insulation and fills the gap between the elements of main transformer insulating liquid 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 [3, 4]. Furthermore, it also performs function as the information carrier to examine the condition of transformer during operation.

Traditionally used mineral oil has a number of desirable properties for transformers. With the 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 for mineral oil [4]. Therefore, the importance of technology of using natural and synthetic esters oils as insulating fluids 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 points (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 is facing in recent years is to extend its use from low voltage distribution transformers to power transformers of high kV class [3, 4]. Since the insulating properties of mineral oil are different from esters, it might affect the

design and manufacturing of transformer [5]. Therefore, it becomes imperative to understand complete insulating properties of esters liquids and their impact on transformer insulation design. In the past decades, a significant amount of experience has been gained on breakdown phenomena of mineral oil in different electric field configurations under lightning impulse voltage conditions [6-12]. Similar information is very important for ester oil due to its increasing use in transformers. In the recent times, many researches have been reported from different laboratories to compare chemical, physical and electrical features of ester oil with mineral oil [3, 4, 13-19].

The evaluation of impulse dielectric breakdown of ester oils is one of the important criteria to utilize the ester oil for transformer application. The impulse breakdown behaviour is closely related to intrinsic and chemical properties (nature) of the oil [16, 19]. There is no well-established theory in physics to explain the breakdown phenomena of oils [18]. Therefore, selection criteria of ester oil for transformers should be based on experimental results of the breakdown data that will help in insulation design.

In this study, in order to simulate the actual conditions that exist in a transformer winding insulation, sphere-sphere and sphere-needle electrode configurations are considered with both polarities of impulse. It has to be noted that evaluation of 50% breakdown voltage is of less importance compared to voltage range for low breakdown probability (i.e. higher withstand voltage). This is because only a sufficiently low breakdown risk is acceptable for technical dimensioning of transformer design rule [20-22]. Hence, 1% failure probability is estimated using 3-parameter Weibull distribution. Dielectric withstand voltage of insulating test liquids is evaluated with various oil gaps. In case of impregnated pressboard experiments, high density 1.5 mm thickness pressboard is considered for evaluation of average breakdown voltage.

It is usually observed that negative lightning impulse breakdown strength of mineral oil reduces with increase in aromatic content [10]. It gives an idea, that chemical composition of any insulating oil is a key factor in deciding the impulse breakdown voltage of that insulating oil. Therefore, it becomes necessary to investigate ester oil in detail under impulse stress for power transformer application.

1.2 INSULATING LIQUIDS USED IN PROJECT

This project investigates the properties of ester liquids to substitute traditional mineral liquid for high voltage transformers. Majorly three types of insulating liquids are used in this

work, they are mentioned below and Figure 1.1 shows the detailed description of all the insulating oils.

- Transol as Mineral liquid
- Biotransol as Natural ester liquid
- Transol Synth 100 as Synthetic ester liquid

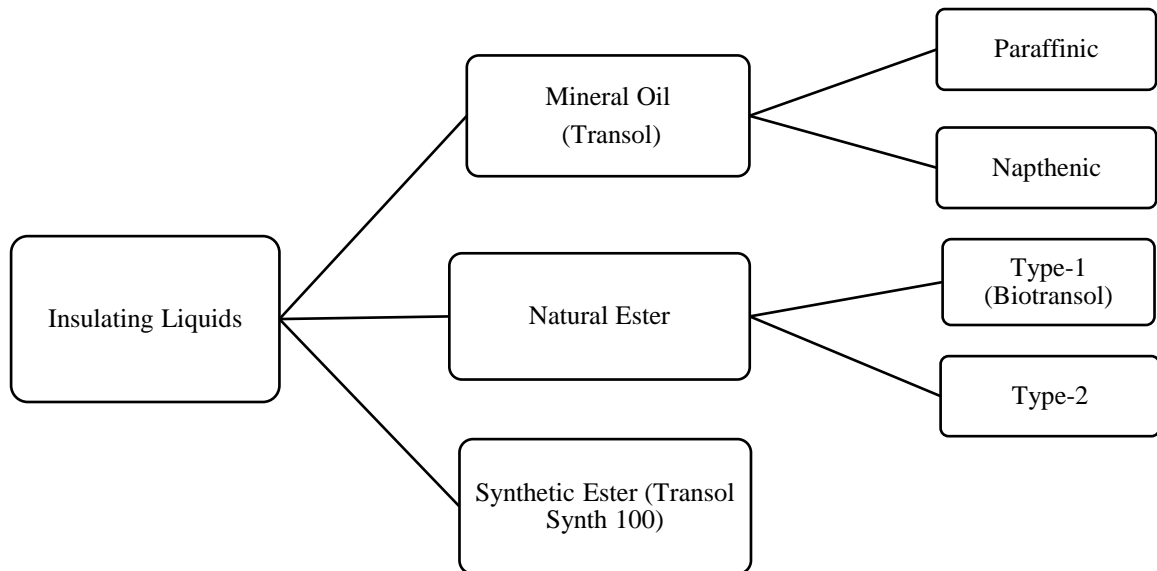


Figure 1.1 Types of insulating liquids

1.2.1 MINERAL OIL

Mineral oil (Transol produced by Savita Oil Technologies Limited) is a type of inhibited insulating oil (with 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 1.2. It is chemically stable and has low oxidation ability due to the saturated molecular structures. Its insulating strength is higher, more than 70 kV/ 2.5mm (according to IEC60156 with a 2.5 mm gap of electrodes) with the sample is treated, but considerably decreased when it is tarnished with foreign particles as well as water [23]. 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.

1.2.2 NATURAL ESTER LIQUID (TYPE-1 &TYPE-2)

Natural ester NE1 is Biotransol produced by Savita Polymers Limited located in Mahad near Mumbai. It is a dielectric liquid derived from renewable vegetable oil. NE2 is a natural ester procured from the market and it is also based on vegetable seed oils. Both are highly

biodegradable as per US EPA OCED 301B, non-toxic and environment friendly [24]. They consist of ester linkage. They have dielectric strength is around 70kV/ 2.5mm (according to IEC 60156) and are classified under K class on the basis of its high flash as well as high fire point [24]. At present, these oils are used for both distribution and power transformers of KV class 232 and above. They have higher water saturation limit i.e., 1100 ppm as compared to mineral oil.

1.2.3 SYNTHETIC ESTER LIQUID

Transol Synth 100 is a type of synthetic ester produced by Savita Polymers Limited located in Mahad near Mumbai. It is a K- class fluid and meets the specifications of IEC 61099/IS 16080 [25]. It consists of pentaerythritol ester which is shown in Figure 1.4. In its structure there are total four ester groups represented as ‘-COOR’ where R indicates the multiple alkyl groups. Because of high electronegativity of oxygen present in four ester groups, synthetic ester becomes more polar as compared to natural ester which has only three ester groups. Transol Synth 100 has very high moisture tolerance which enhances cellulose insulation life and prevents its deterioration.

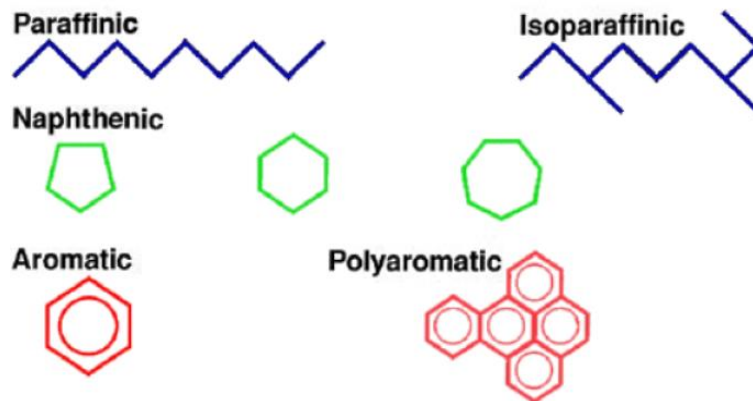


Figure 1.2 Basic hydrocarbon structures of Mineral oil

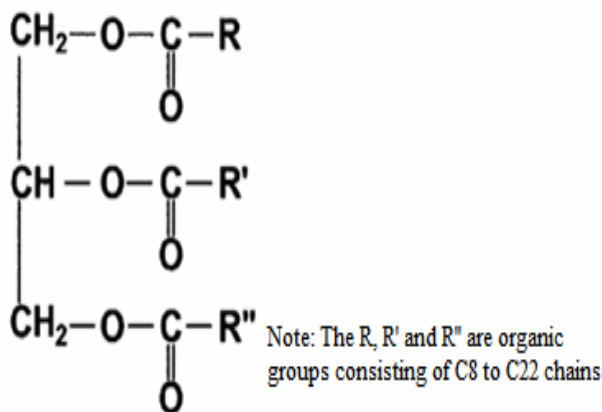


Figure 1.3 Chemical structure of Natural ester [24]

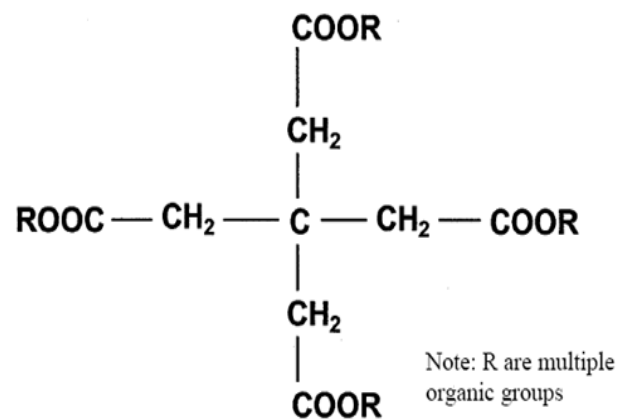


Figure 1.4 Chemical structure of Synthetic ester [25]

Major properties of ester and mineral liquids are shown in Table 1.1

Table 1.1 Comparison between Mineral oil and Ester liquids [23-25]

Parameters	Mineral oil	Natural ester	Synthetic ester	Significance of parameters
Dielectric strength as per IEC 60156	70 kV	>70kV	>70kV	Tells the presence of moisture and particles in the oil. If moisture increases, dielectric strength decreases
Relative permittivity as per IEC 60247	2.2	3.3	3.2	Signifies the quality and performance of insulators
Dissipation factor	<0.001	<0.05 (0.02-0.03)	0.01	It signifies the power loss and presence of acidity in oil. Tan δ increases, power loss increases.

1.3 RESEARCH OBJECTIVES OF THESIS

The objective of this thesis is to evaluate dielectric breakdown strength of ester oils and their impregnated pressboard under impulse stress condition for transformer application. The objectives of the project are summarized below:

- To evaluate the dielectric withstand strength of natural and synthetic ester liquids under positive & negative standard full wave impulse condition in uniform and non-uniform field configurations for various gaps.
- To evaluate the dielectric breakdown strength of natural and synthetic ester liquid impregnated pressboard under positive & negative standard full wave impulse condition in uniform and non-uniform field configurations.
- To determine electrical stress experienced by all the insulating oils as well as impregnated pressboard at 99% withstand voltage using ElecNet software.
- To determine electrical stress experienced by all the insulating oil impregnated pressboards at average breakdown voltage using ElecNet software.
- To examine the effect of aromatic content and polar contaminant on the dielectric breakdown strength and time to breakdown of mineral oil under positive & negative impulse condition in non-uniform field configuration for various gaps.

1.4 SIGNIFICANCE OF PROJECT

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

- Provide design guidelines of ester oil transformer under impulse condition.

- Prediction of streamer propagation with the help of time to breakdown and velocity of streamer.
- Eliminating the probability of faults as well as failure of transformer.
- Propagation of streamer and breakdown event of both the esters that are natural and synthetic under impulse lightning voltage stress condition.
- Minimizing the possibility of faults by manpower at factory floor conditions.

1.5 OUTLINE OF THESIS

Brief descriptions of chapters of thesis are as follows: -

Chapter 1 – Introduction

This chapter in short discusses the research objectives, background of research and scope of the work.

Chapter 2 – Literature Survey

This chapter presents general literature review about breakdown mechanism of insulating liquid in uniform as well as non-uniform field. Furthermore, provides information about the relevant research findings related to esters.

Chapter 3 – Experiment Description

This chapter discusses about the insulating liquids under the test with comparison of their properties. A detailed description is provided for sample preparation of both liquid and solid insulation under test. Also, presents information of test setup and testing methodology for both uniform (non-divergent) and non-uniform (divergent) field configurations.

Chapter 4 – Evaluation of Dielectric Impulse Withstand Voltage of Insulating Oils

This chapter discusses about the measurement of standard impulse withstand & impulse breakdown voltage level of ester oil taking reference of mineral oil. Two types of field configurations are chosen that are uniform and non-uniform field configuration. Electrode gaps are varied between 1mm to 20mm. Majorly three types of insulating oils are considered that are mineral, natural ester and synthetic ester.

Chapter 5 – Evaluation of Dielectric Impulse Breakdown Voltage of Insulating Oil Impregnated Pressboards

In this chapter experiments are performed to evaluate dielectric withstand voltage of different insulating oil impregnated pressboards under positive and negative impulse. High density pressboard of thickness 1.5 mm is used for experiments. They are studied in extreme field configurations that are uniform and non-uniform.

Chapter 6 – Effect of Aromatics and Polar Contaminant on Impulse Dielectric Strength and Time to Breakdown of Mineral Oil

This chapter focuses on study of change in dielectric characteristics of mineral oil due to presence of aromatics and polar contaminant. A part of this chapter deals with real time factory condition. In order to understand the effect of aromatic content paraffinic inhibited and naphthenic inhibited mineral oil are compared under both impulse polarities in non-uniform field and various electrode gaps. Further to analyse effect of polar contamination in mineral oil, natural ester liquid (polar contaminant) is mixed to mineral oil, which is non-polar in nature. As non-uniform field is more critical as compared to uniform field, needle-sphere configuration is used for experiments considering short oil gaps ranging between 1mm to 10mm.

Chapter 7 – Conclusions & Future work

This summarizes the major findings and conclusions of the thesis and suggests some future research work to study dielectric performance of esters for transformer applications.

CHAPTER 2

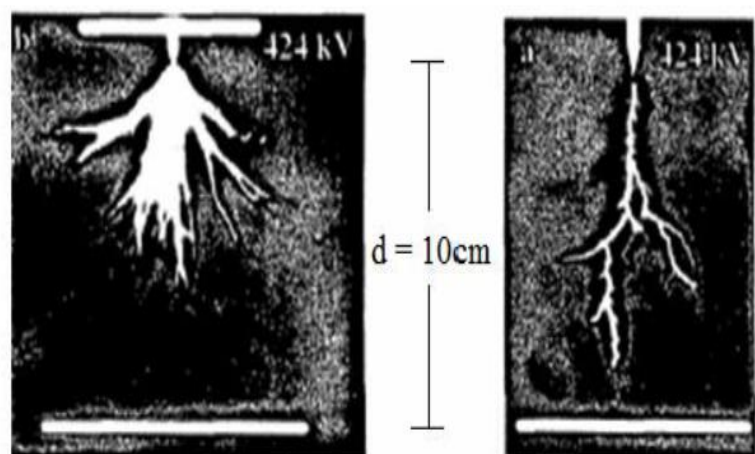
LITERATURE SURVEY

2.1 INTRODUCTION

Firstly, this chapter discusses about the breakdown mechanism of insulating liquid and impregnated pressboard in uniform as well as non-uniform field with brief description of cellulose and its properties. Secondly, it presents an overview of research findings relevant to ester oil under impulse stress condition. Thirdly, a brief description of effect of electrode geometry, variation of maximum electric stress and utilization factor with gap distance. Lastly, a brief introduction of impulse generator, high voltage testing techniques and statistical distribution is presented. It also discusses about locations of field distribution in transformers.

2.2 BREAKDOWN IN LIQUIDS UNDER UNIFORM & NON-UNIFORM FIELD

In order to study the electrical behaviour of transformer liquids it is necessary to have knowledge of the pre-breakdown phenomena of insulating fluids which are evaluated by streamer initiation and propagation [3, 4]. Generally, breakdown phenomena is linked with electric field created by electrode geometry. However, the breakdown mechanism of insulating liquid is still unclear and there is no well-established theory closely related to breakdown mechanism of insulating oils, although some literature studies have reported many breakdown theories like bubble theory, ionization theory, weakest-link theory etc. [26]. As breakdown mechanism is dependent on electrode field configuration, comparison of breakdown mechanism in uniform and non-uniform field is shown in Table 2.1. Also, the streamer formation is shown in Figure 2.1.



(i) Under uniform field

(ii) Under non-uniform field

Figure 2.1 Streamer structure in (i) Under uniform field (ii) Under non-uniform field [26]

Table 2.1 Comparison study of breakdown phenomena in uniform field and non-uniform field [26]

Breakdown in Uniform field	Breakdown in Non-uniform field
Breakdown is mainly due to the occurrence of a streamer, and final breakdown will happen when the streamer fully spans the liquid electrode gap	Breakdown is mainly due to the occurrence of a streamer, and final breakdown will happen when the streamer fully spans the liquid electrode gap
Each streamer will lead to breakdown because of high average electric field	Every streamer will lead to partial breakdown or complete breakdown.
As streamer is initiated by (particle, gas, and water content) it is mainly affected by extraneous factors.	Mainly affected by intrinsic properties (example: Electron affinity).
The breakdown of liquid in uniform field is determined by streamer initiation.	Breakdown is dependent on streamer propagation
Inception voltage of streamer is equal to breakdown voltage.	Streamer inception voltage is much lower than liquid breakdown voltage.

2.3 INSULATING OIL IMPREGNATED CELLULOSE

Transformer insulation is a combination of solid and liquid insulation. The durability of the insulation system in a transformer is principally decided by the data obtained on withstand voltages at different oil gaps [18]. Since the solid insulation has higher dielectric strength than oil, pressboard is used to subdivide the long oil gaps into smaller oil gaps of 6-8mm [22]. This solid insulation is formed from cellulose and it is a polymer of glucose. It is made up of anhydro β -D-glucopyranose units linked with each other through glucosidic bond (1-4) as shown in Figure 2.2 [27]. Degree of polymerization (DP) is a number associated with the quality and age of a cellulose. It is equal to number of anhydro β -D-glucopyranose units present in a cellulose molecule. Usually, viscometric method is used to measure DP of any paper and pressboard insulation [28, 29]. New cellulose transformer insulation has DP around 1200 and when it goes below or equal to 200 it signifies that the cellulose has reached to end of its life.

Cellulosic fibers present in cellulose insulation are porous with voids therefore they are impregnated by insulating oil and are referred as impregnated cellulose based materials [27]. This impregnation helps in eliminating voids and improve dielectric properties of cellulosic material.

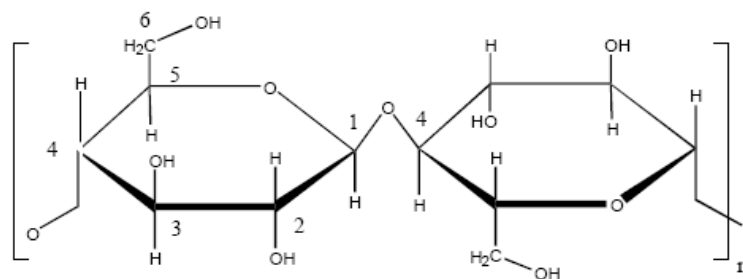


Figure 2.2 Chemical structure of the anhydro β -D-glucopyranose unit [27]

2.4 RESEARCH FINDINGS RELATED TO ESTER OIL

With increase in interest of esters as a substitute for transformer applications, lot of research has been done by researchers worldwide to compare properties of esters and mineral oil. This section majorly includes research findings on ester oils and their electrical performance under impulse voltage.

Some areas of a transformer insulation experiences stress due to different electric field configurations [30, 31]. Mostly, transformer insulation system is stressed under quasi uniform field as compared to divergent field. Therefore, research has been carried out mainly under quasi uniform field.

Considering, quasi uniform field, as per literature, esters are comparable to mineral oil. In non-uniform field configuration study, it is noted that esters have less breakdown voltage as compared to mineral liquid [17, 18]. For this configuration generally point plane electrodes are used. But these studies do not consider any polarity effect under both the field configurations. In addition, as results revealed that esters have less breakdown voltage as compared to mineral oil so it signifies that a detailed investigation is required to understand the breakdown mechanism and behaviour of ester oils under positive and negative impulse condition. A cross comparison of natural ester and synthetic ester oils and their impregnated pressboards with mineral oil is worthy of detailed research.

2.5 DESIGN OF ELECTRODE GEOMETRY

Considering actual transformer, different insulation arrangement in a transformer experiences stress under different electrical fields. So, to take into account the different field configurations present in actual transformer, electrodes producing highly uniform and highly divergent field have been studied. Mainly the electrodes geometry considered are plane-plane, plane-needle, cone-cone and plane-cone as shown in Figures 2.3-2.6.

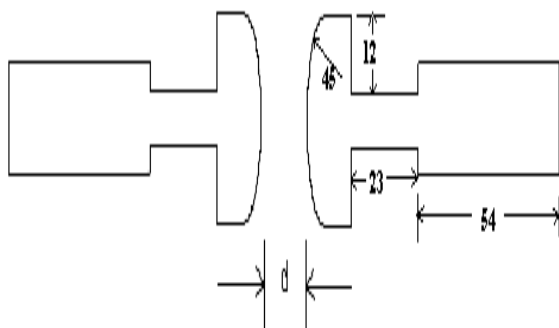


Figure 2.3 Plane – plane configuration [32]

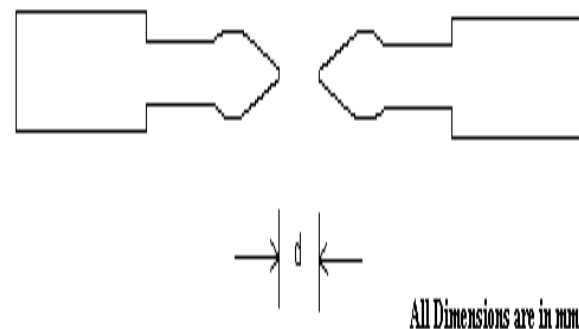


Figure 2.4 Cone – cone configuration [32]

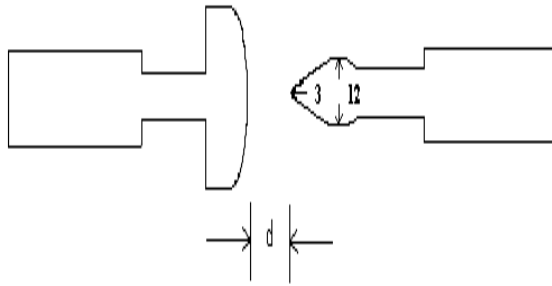


Figure 2.5 Plane – cone configuration [32]

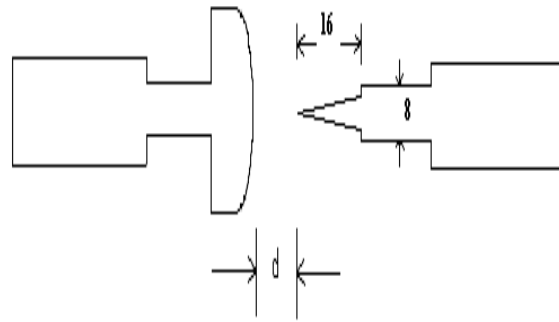


Figure 2.6 Plane – needle configuration [32]

2.6 DEGREE OF UNIFORMITY OF ELECTRIC FIELD CONFIGURATIONS OR UTILISATION FACTOR

Basically, utilization factor signifies the uniformity of the electric field. Therefore, the more the utilisation factor (η), the more the uniform electric field and vice-versa. The relationship between utilization factor and maximum stress (E_{\max}) is defined below in Equation 2.1. Also, the variation of E_{\max} and utilization factor (η) with electrode gap (mm) is expressed in Figures 2.7 & 2.8 respectively. From these Figures it can be concluded that: -

- As non-uniformity of field increases, utilisation factor decreases.
- With increase in distance, dielectric strength increase, so E_{\max} decreases.
- For complete uniform field, η is nearly constant with increase in distance.
- For quasi uniform and non-uniform fields, η decreases with increase in distance.

$$\eta = \frac{E_{\text{mean}}}{E_{\text{max}}} = \frac{U}{d} * \frac{1}{E_{\text{max}}} \quad (2.1)$$

E_{mean} – Average electric stress on dielectric

d – Distance between the electrodes

E_{max} – Maximum electric stress on dielectric

U – Peak value of voltage between electrodes

2.7 GENERATION OF IMPULSE VOLTAGE

Impulse is an aperiodic transient voltage, which increases rapidly to a peak value and then decays more slowly to zero [33]. It is needed to simulate practical impulse condition for testing of any power equipment. Impulse breakdown result of any equipment is one of the major factors in designing of its insulation. The Figure 2.9 shows the standard positive impulse waveform where T_1 is the front time and T_2 is wave tail time.

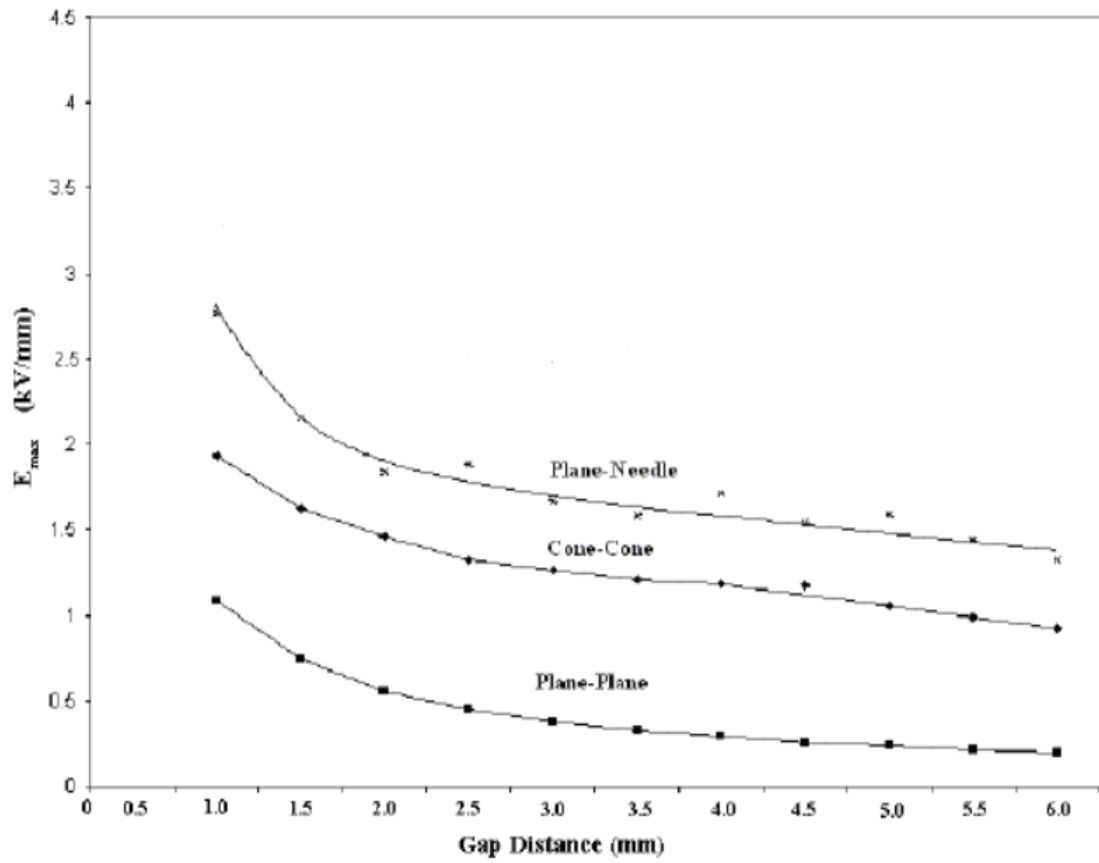


Figure 2.7 E_{max} as function of gap distance for different electrode configuration

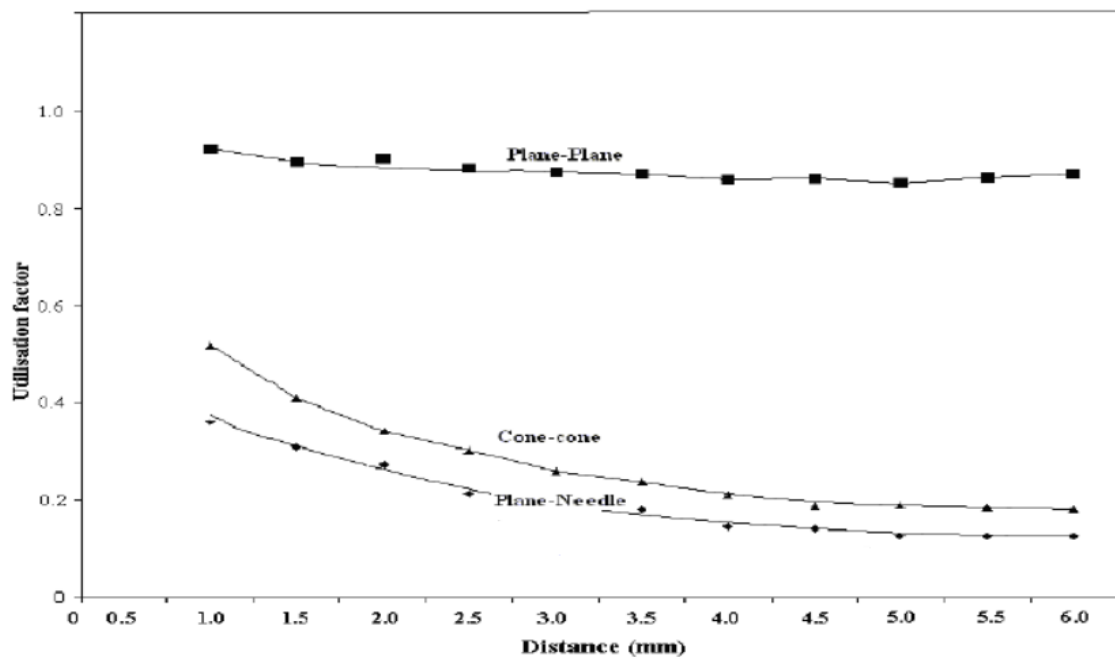


Figure 2.8 Utilisation factor as function of gap distance for different electrode configuration

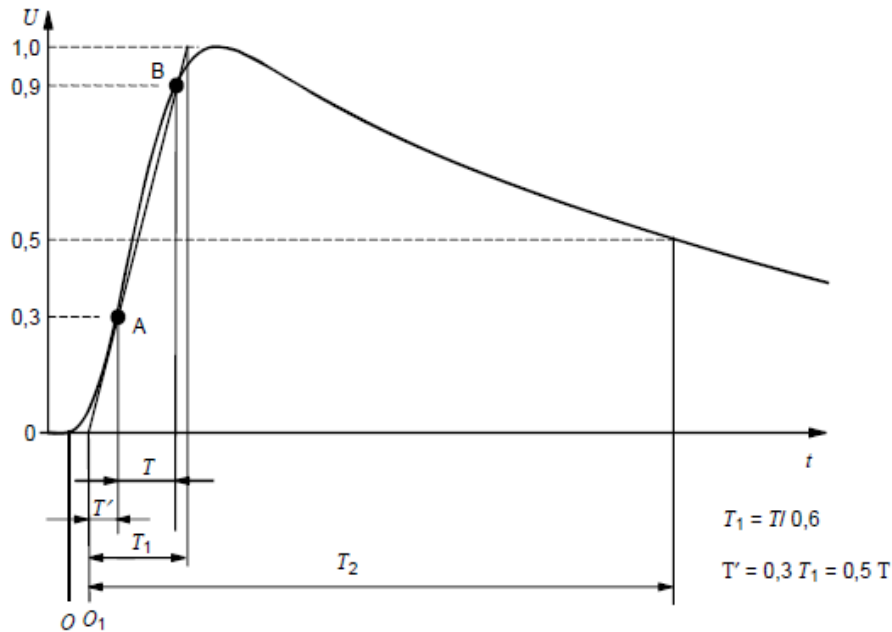


Figure 2.9 Standard impulse waveform [33]

2.7.1 COMPONENTS OF IMPULSE GENERATOR

It mainly includes step up transformer, rectifier (AC to DC), charging resistor, charging capacitor, sphere gap, tail resistance (to control tail time of impulse), front resistance (to maintain front time of resistance) and potential divider.

2.7.2 WORKING OF IMPULSE GENERATOR

Step up transformer steps up the voltage and rectifier convert AC to DC. The charging capacitor (C_s) is charged till the breakdown across the sphere(S) takes place and then it gets discharges upon voltage divider (C_{D1} & C_{D2}), over tail resistor (R_2), front resistor (R_1) [33]. Front wave shape resistor and tail wave shape resistor controls the wave shape of impulse wave. With the help of voltage divider impulse propagates to the test object. Figure 2.10 shows the circuit diagram of impulse voltage generator.

2.8 HIGH VOLTAGE TESTING TECHNIQUES

The main objectives of high voltage testing and different test methods used are as follows: -

- To design guidelines of any power equipment.
- To predict response of equipment to various stresses.
- To ensure withstand voltage of equipment.
- For acceptance of product by customer.

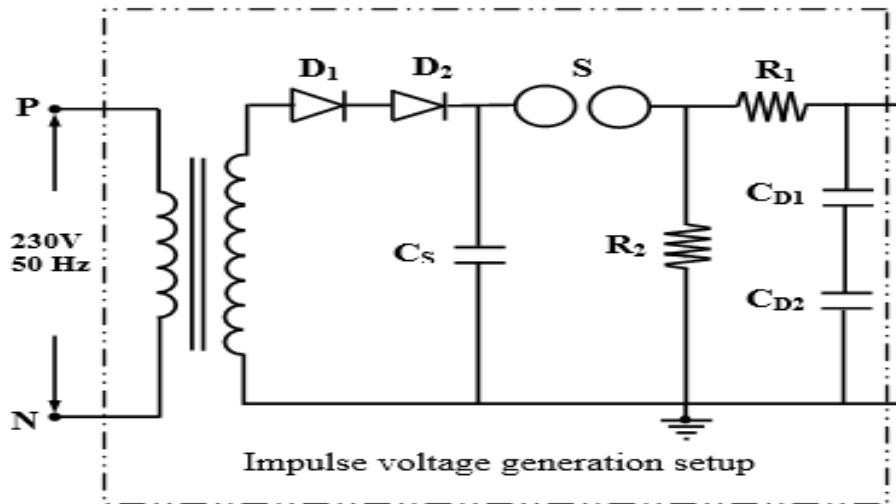
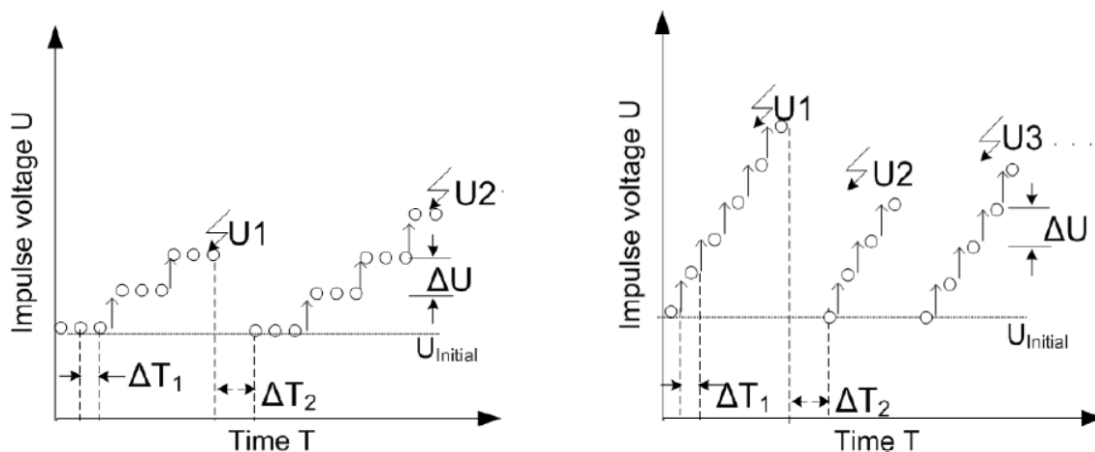


Figure 2.10 Impulse generator circuit diagram [33]

2.8.1 RISING VOLTAGE METHOD

This method can be used for both AC as well as impulse [4]. In this type of test, the voltage is increased at a one rate till the breakdown occurs. To repeat test, similar procedure is followed by taking certain duration and no. 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 [4]. ASTM D 3300 and IEC 60897 [34, 35], standards for lightning impulse breakdown tests of dielectric oil, 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 2.11. ΔT_1 represents the time duration between two impulse shots; ΔT_2 represents the time duration between two tests and ΔU is step increment voltage.



(a) 3shots/step, ASTM- D3300

(b) 1shot/step, IEC 6089

Figure 2.11 Sketch of rising voltage method [34, 35]

2.8.2 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 [4]. This is mostly used in impulse lightning tests to minimize the time duration of testing. Test Procedure of up-and-down method is explained in Figure 2.12: (i) The test voltage is increased from starting voltage, (at point there is no chances of breakdown occurring), in voltage steps of a single voltage ΔU , till the first breakdown happens; (ii) The voltage is decreased by the similar voltage step ΔU until dielectric breakdown does not happen; (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 taken into account having minimum two shots, is considered as 50% breakdown voltage [4].

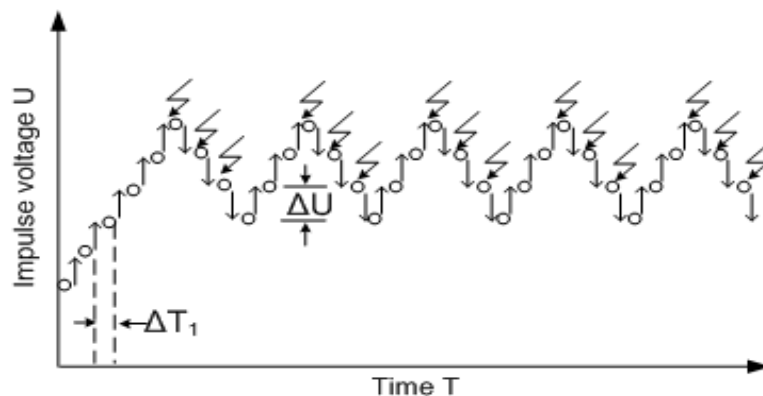


Figure 2.12 Sketch of up-and-down method [4]

2.8.3 MULTIPLE-LEVEL METHOD

It is also called as constant-voltage method. It describes the conventional method for evaluating probability of breakdown [4], as shown in Figure 2.13. The test procedure involves applying a number of fixed impulse shots at various voltage steps and noting the number of breakdowns at every voltage step. The cumulative frequency distribution is also obtained on the basis of results.

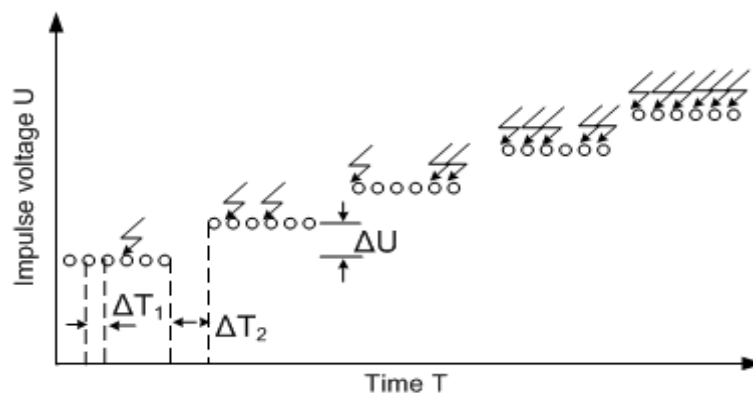


Figure 2.13 Sketch of multiple-level method [4]

2.8.4 EFFECT OF METHOD ON MEASURED BREAKDOWN VOLTAGE

50% impulse lightning breakdown strength of mineral and ester oil performed with different testing procedures are summed up as shown in Figure 2.14. By this, it can be concluded that various testing techniques have remarkable effect on the experimental breakdown voltage [4, 17]. For method of rising-voltage, results following one impulse shot per voltage step are higher as compared to three shot at voltage step method. Multiple-level method using rising-voltage with one impulse shot gives similar outputs, which is usually greater than as compared to other two testing methods. It is notable that the technique which affects the results of breakdown voltages do not change the trend of the results of both mineral and ester oils [4]. As shown in Figure 2.14, ester liquids are always showing less breakdown voltage as compared to mineral oil without depending on method used for testing purpose.

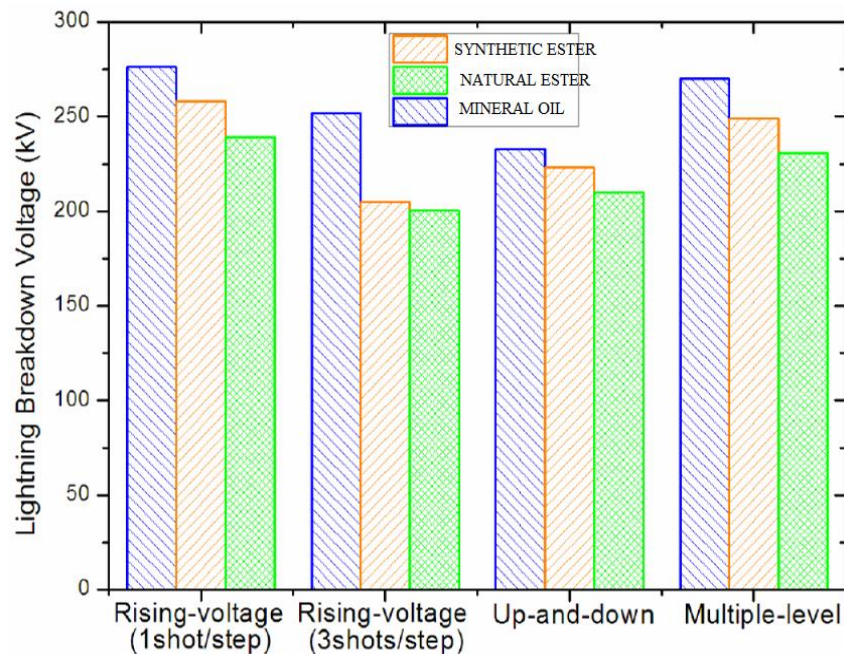


Figure 2.14 Comparative study of impulse breakdown of ester liquids and mineral liquid by diverse testing techniques; $d=3.8$ mm under negative polarity. [4]

2.9 IMPACT OF CURRENT LIMITING RESISTOR

During the study it is concluded in the Manchester thesis that there is no impact of current limiting resistor on the breakdown strength results [4]. Both ATP simulation and experimental measurement indicated that the actual voltage waveform applied on the test cell in the test circuit with R_L was slightly distorted i.e. the front time was slowed down to $2\mu\text{s}$ without any change in tail time and reduction in peak voltage was less than 5%. Further verification tests with and without the current-limit resistor were performed with three types of liquid under lightning impulse voltage. Five breakdowns were done at each case. Figure

2.15 shows the results of breakdown strengths of both the ester oils and mineral liquid performed with limiting resistor (LI with R_L) and without limiting resistor (LI without R_L).

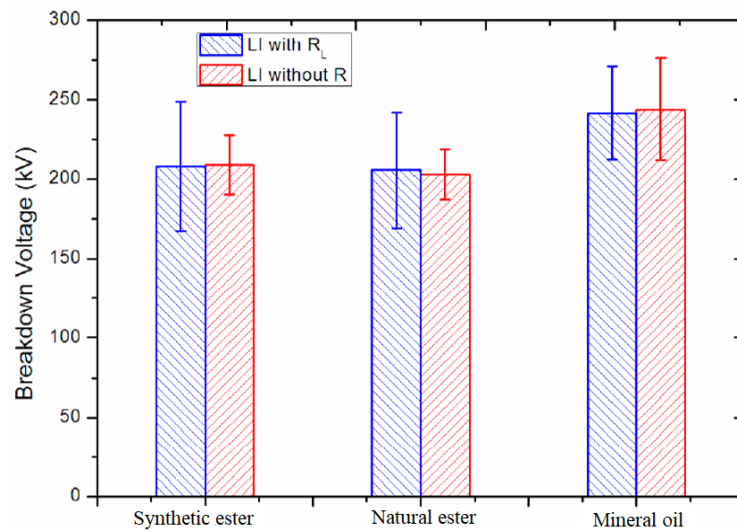


Figure 2.15 Influence of current-limit resistor R_L on impulse breakdown voltage [4]

2.10 UNIFORM AND NON-UNIFORM ELECTRIC FIELD IN TRANSFORMERS

During operation of transformer, various electric field distribution is experienced by transformer insulation. This variation in electric field distribution is due to change in design of transformers at every location [30]. For example, uniform field is experienced by inter turn, inter disc and insulation between two phases with small oil gaps between 1mm to 8mm. Whereas, paper insulation of high voltage lead connected to bushings experiences non-uniform field or quasi uniform field with long oil gaps between 15 to 40mm depending on the rating of transformer. Figure 2.16 depicts the transformer core coil assembly insulation model showing the various electric field distribution and Figure 2.17 shows inter disc insulation.



Figure 2.16 Transformer core coil assembly model



Figure 2.17 Inter disc insulation

2.11 STATISTICAL DISTRIBUTION

Weibull distribution is best function to explain the behaviour of breakdown (statistical) data at low probabilities than Normal and Gumbel statistical distribution [20, 26]. It estimates the combination of statistical parameters based on the fitted curve with specific shape, scale and threshold, which fit the breakdown data with different failure probability values. 3-parameter Weibull Distribution with 95% confidence limit is known as the best fit for statistical distribution method of data [26]. It helps to predict 1% failure probability voltage or 99% withstand voltage. 3 parameter Weibull probability density function is given by equation 2.2.

$$f(t) = \frac{\beta}{\alpha} \left(\frac{t-\gamma}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}} \quad (2.2)$$

where,

$$f(t) \geq 0, t \geq \gamma ;$$

$$\beta > 0;$$

$$\alpha > 0;$$

$$-\infty < \gamma < +\infty$$

and,

α represents scale parameter,

β defines shape parameter (slope),

γ signifies location parameter

CHAPTER 3

EXPERIMENT DESCRIPTION

This chapter discusses about the insulating liquids under the test with comparison of their properties. A detailed description is provided for sample preparation of both liquid and solid insulation under test. Also, presents information of test setup and testing methodology for both uniform (non-divergent) and non-uniform (divergent) field configurations.

3.1 INSULATING LIQUIDS UNDER TEST

This research work investigates the insulating properties of esters to substitute traditional mineral liquid for high voltage transformers. Four types of insulating oils are used in this work and are given below. Also, Figure 3.1 shows their colour appearance.

- 1) Transol as Mineral oil (MO)
- 2) Biotransol as Natural ester liquid 1 (NE1)
- 3) Natural ester liquid 2 (NE2)
- 4) Transol Synth 100 as Synthetic ester liquid (SE)

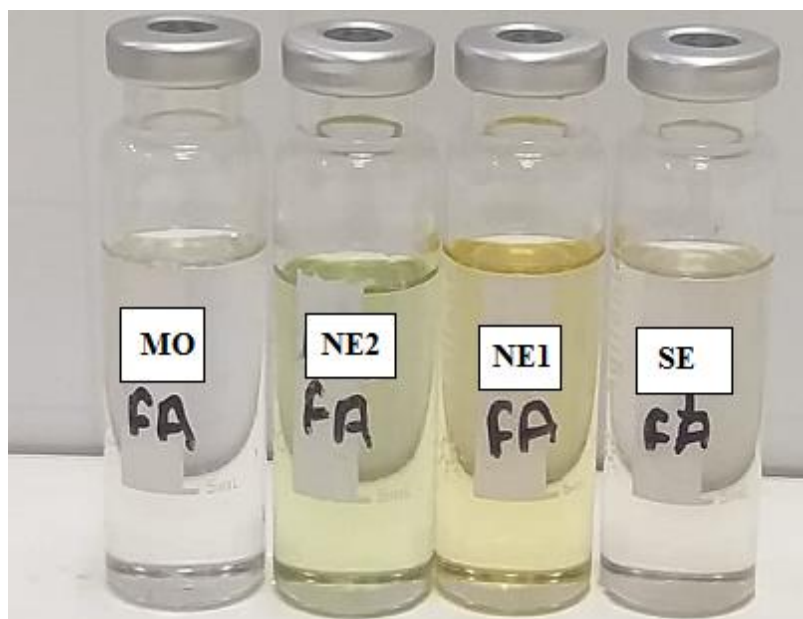


Figure 3.1 Representation of Mineral oil (MO), Natural ester (NE2), Natural ester (NE1) and Synthetic ester (SE) (from left to right)

3.1.1 PROPERTIES OF MINERAL AND ESTER LIQUIDS

The major features of mineral and ester oils are totally different from each other. These properties are governed by the IEC and ISO standards. Table 3.1, Table 3.2 and Table 3.3 shows the basic key properties of mineral oil (Transol), natural ester oil (Biotransol) and synthetic ester oil (Transol Synth 100) respectively.

Table 3.1 Key properties of Mineral liquid (Transol) [23]

	Unit	Standard Used	Data
1.Physical			
Density, 20°C	Kg/dm ³	ISO 12185	0.882
Viscosity, 40°C	mm ² /sec	ISO 3104	8.7
Flash Point	°C	ISO 2719	144
Pour Point	°C	ISO 3016	-60
2.Chemical			
Acidity	Mg KOH/g	IEC 61125	0.08
Water Content	Mg/kg(ppm)	IEC 60814	<20
3. Electrical			
Dissipation Factor, 90°C	-	IEC 60247	<0.001
Breakdown Voltage	kV	IEC 60156	
- before treatment			40-60
- after treatment			>70

Table 3.2 Key properties of Natural ester liquid (Biotransol) [24]

	Unit	Standard Used	Data
1.Physical			
Density, 20°C	g/cm ³	ISO 3675	0.92
Viscosity, 40°C	mm ² /sec	ISO 3104	32
Flash Point	°C	ISO 2719	>260
Pour Point	°C	ISO 3016	-18
2.Chemical			
Acidity	mg KOH/g	IEC 62021-3	0.03
Water Content	mg/kg(ppm)	IEC 60814	<50
3. Electrical			
Dissipation Factor, 90°C	-	IEC 60247	0.02-0.03
Breakdown Voltage	kV	IEC 60156(2.5mm gap)	70

Table 3.3 Key properties of Synthetic ester liquid (Transol Synth 100) [25]

	Unit	Standard Used	Data
1.Physical			
Density, 20°C	kg/dm ³	ISO 3675	0.95-0.96
Viscosity, 40°C	mm ² /sec	ISO 3104	32-33
Flash Point	°C	ISO 2719	265
Pour Point	°C	ISO 3016	-57
2.Chemical			
Acidity	mg KOH/g	-	<0.02
Water Content	mg/kg(ppm)	IEC 60814	<50
3. Electrical			
Dissipation Factor, 90°C	-	IEC 60247	0.01
Breakdown Voltage	kV	IEC 60156(2.5mm gap)	>70

3.1.2 COMPARISON BETWEEN ESTER LIQUIDS AND MINERAL OIL

The 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 liquids are non-toxic; therefore, they are safe for aquatic and marine life.
- 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 [3, 4].
- Moisture is a major factor which accelerates ageing of cellulose in transformers. Due to hygroscopic nature of esters liquids compared to mineral oils they can absorb more water from cellulose material which slows down ageing process of cellulose insulation [26].
- Permittivity of ester liquids is close to that of transformers solid insulation which causes even stress distribution between liquid and solid materials as compared to mineral oil [26]. It also reduces the local stress in oil wedges which help 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, ester oils have higher thermal conductivity and higher specific heat compared to mineral liquid, and this could provide some compensation for heat dissipation [17].
- 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 [18].

3.2 SAMPLE PREPARATION

3.2.1 PRE-PROCESSING OF LIQUID INSULATION

Before taking oil for impulse test, it undergoes some processes to reduce the impact of impurity on the results. These processes are shown through flow chart given in Figure 3.2.

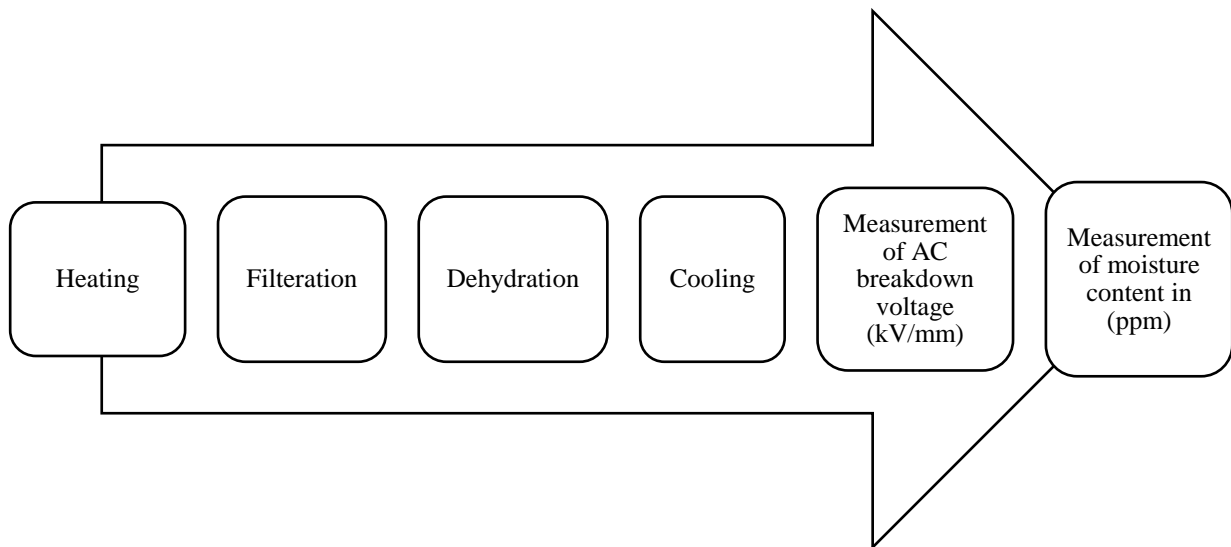


Figure 3.2 Flow chart for sample preparation of insulating oil

- **Heating** – Firstly, after taking samples from sealed barrels test sample is heated in a beaker as shown in Figure 3.3 to reduce its viscosity and to make easier flow of samples through filtration unit. For mineral oil, sample is heated up to 50-60°C and for ester liquids, this temperature lies between 100-120°C because it has higher viscosity than mineral oil.
- **Purification or Filtration** – Secondly, this heated sample is filtered using nylon filter membrane of MF 75Nalgene, of size 0.2micrometer under vacuum. Figure 3.4 shows the filtration process.
- **Degassed and Dehydration** – The filtered oil is again heated at 60°C for mineral oil and 110°C for ester oils in a heating mantle under vacuum of 760mmHg to remove moisture content and dissolved gases from the filtered sample. Figure 3.5 shows the dehydration process.
- **Cooling** – The sample after above processes is cooled for 4- 5 hours.
- **Measurement of AC breakdown voltage (kV)** – To verify the good condition of processed oil its breakdown is checked. Figure 3.6 shows the setup to measure AC breakdown test according to IEC 600156 [36].
- **Measurement of moisture content (in ppm)** – To fulfil the passing criteria (<50ppm) of processed sample moisture is measured by Karl-Fischer method. Figure 3.7 depicts the setup to measure moisture content of sample.



Figure 3.3 Heating



Figure 3.4 Filtration process



Figure 3.5 Dehydration



Figure 3.6 AC breakdown test setup



Figure 3.7 Moisture content measurement

The breakdown strength of insulating fluid is dependent on quality of insulating fluid [9]. 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 the quality 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 [12]. The mineral and ester oil samples are taken from same sealed barrels in order to maintain consistency of oil quality for all experiments.

The properties like AC breakdown voltage, and water content have major effect on impulse breakdown voltage as if moisture in insulating oil sample is increased, the breakdown voltage is drastically reduced [37]. Therefore, to maintain these properties according to their standards these oil samples undergoes the pre-processing analysis as discussed above. The initial properties of the oil like AC breakdown voltage, water (moisture) content and relative saturation are evaluated prior to the test and presented in Table 3.4.

Table 3.4 Properties of processed oil sample used for impulse breakdown experiments

Properties	Mineral oil (Transol)	Natural ester oil		Synthetic ester oil (Transol Synth 100)
		Biotransol (NE1)	(NE2)	
Breakdown voltage in kV for 2.5mm gap	65-70	70-80	70-80	70-80
Water contents in PPM	4-5	55-70	65-70	55-70
Relative saturation in %	10	7	7	7

3.2.2 IMPREGNATED PRESSBOARD SAMPLES (SOLID INSULATION)

High density pressboard of 1.2g/m^3 are cut into dimensions $100*100\text{mm}$. The thickness of pressboard sample is 1.5mm . Before taking pressboard samples for impulse test, they undergo some processes to eliminate moisture and gaseous impurities from the porous voids. These processes are shown through a flow chart in Figure 3.8.

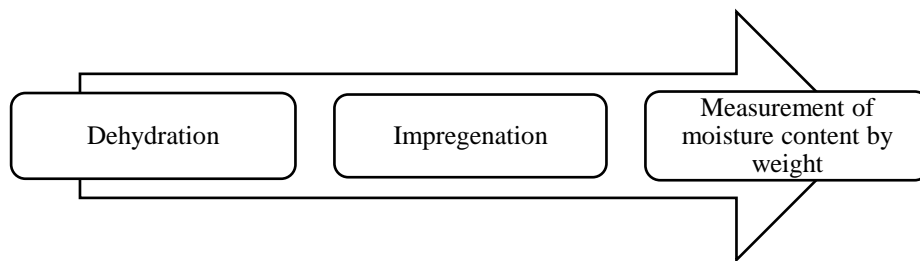


Figure 3.8 Flow chart of sample preparation of impregnated pressboard sample

The fresh pressboard sample of $100*100\text{mm}$ is shown in Figure 3.9. Now firstly, pressboards are kept in an oven (air circulating) at 120°C for 12 hours to remove absorbed moisture from the samples as shown in Figure 3.10. Secondly, immediately these samples are impregnated by insulating oil in a nitrogen purged closed container as shown in Figure 3.11. Now, they are kept still for 36 hours to ensure proper impregnation of samples. Lastly, after 36 hours moisture of pressboard is measured which is maintained less than 0.5% by weight. Now, pressboard samples are ready for impulse test. They are placed immediately inside the cell as shown in Figure 3.12 and impulse testing is carried out.

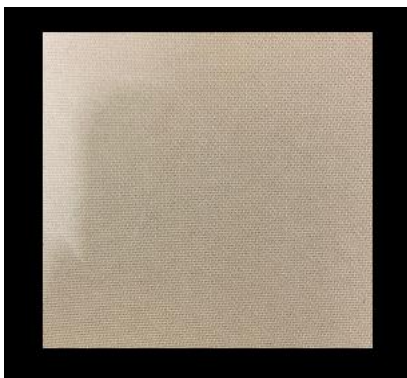


Figure 3.9 High density pressboard sample of $100*100\text{mm}$ dimension



Figure 3.10 Pressboard sample in the oven for dehydration



Figure 3.11 Pressboard impregnation

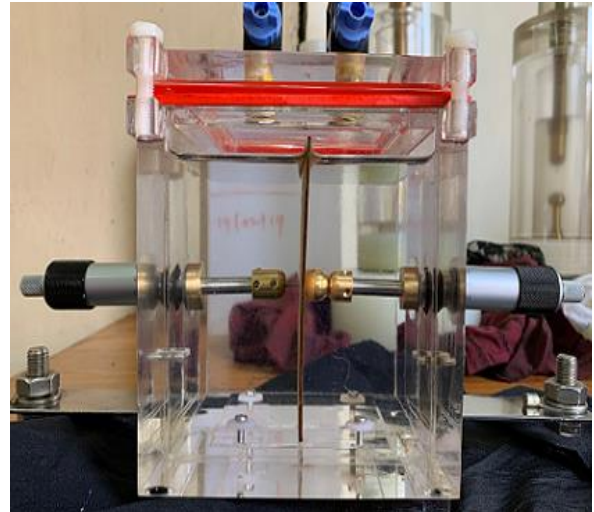


Figure 3.12 Pressboard sample in impulse test cell

3.3 IMPULSE GENERATOR SPECIFICATIONS

A 2-stage impulse generator of peak voltage 280 kV and having energy 1.96kJ is taken into account to generate the standard impulse $1.2(\pm 30\%)/50(\pm 20\%) \mu\text{sec}$ and it is shown in Figure 3.13. The standard lightning impulse waveform with different polarity is applied across sphere-sphere and sphere-needle electrodes with oil gap between 1mm to 20mm. Waveform of impulse is measured by a capacitive divider (high voltage). The applied impulse voltage and time to breakdown are measured by using a digital phosphor oscilloscope (Tektronix make DPO 2014) at a sampling rate of up to 1G Sample/s. Table 3.5 shows the specifications of the impulse generator.



Figure 3.13 Impulse generator test setup

Table 3.5 Impulse test setup specification

Name of Components	No. of Components	Rating
HV Test Transformer	01	200V/100kV
Charging Resistor	02	2.5Mohm
Charging Capacitor	02	100000pF \pm 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%

3.4 ELECTRODE SPECIFICATIONS

For completely non-uniform field, needle – sphere electrode configuration is used which are designed according to ASTM-D3300 [35] as shown in Figure 3.14. Ground electrode is made up of polished steel or brass sphere of 0.5 inch (12.7 mm) in diameter. High voltage electrode is steel phonograph needle with a specification of 0.06 mm \pm 20 % radius of curvature.

For uniform field configuration, sphere – sphere electrode configuration is used which are also designed according to ASTM-D3300 as shown in Figure 3.15. Both ground and high voltage electrode are made up of steel or brass sphere of 0.5 inch (12.7 mm) in diameter.

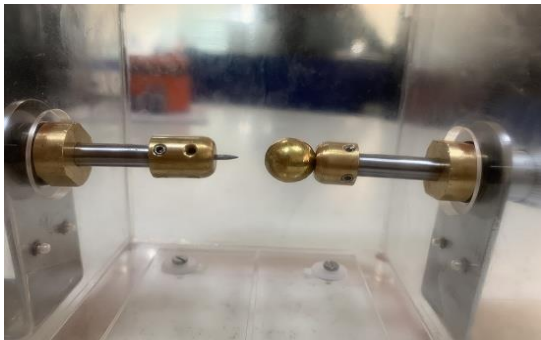


Figure 3.14 Needle – Sphere electrode configuration Figure 3.15 Sphere – Sphere electrode configuration

3.5 IMPULSE TEST CELL

Cuboidal test cell is fabricated in order to establish experimentally confirmed and statistically supported value of breakdown voltage of oil due to various gaps with different polarities. This test cell, made up of high dielectric strength material (i.e. Acrylic), has an oil capacity of 1L. All the sides of the impulse test cell walls are made of transparent acrylic in order to observe the breakdown phenomena. The distance between HV and low voltage

electrodes in the test cell can be set in steps of 0.5 mm with the help of screw gauges on either side of the electrode terminals.

Horizontal electrode configuration impulse test cell is used for both the polarities as shown in Figure 3.16 and design of cell is shown in Figure 3.17. The dimensions of test cell are given below:

Specifications –

- Size of Test cell – 101mm x 103mm x 111mm
- Volume of cell – 900 mL
- Maximum gap between the electrodes – 45mm

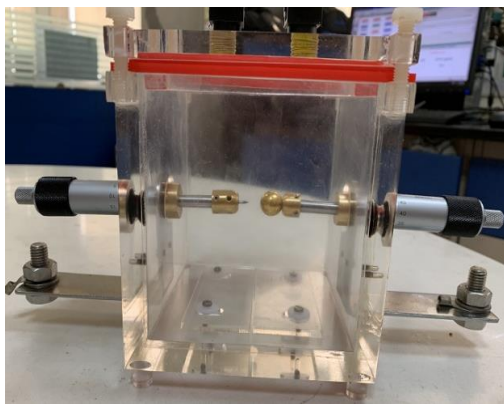


Figure 3.16 Horizontal electrode geometry test cell

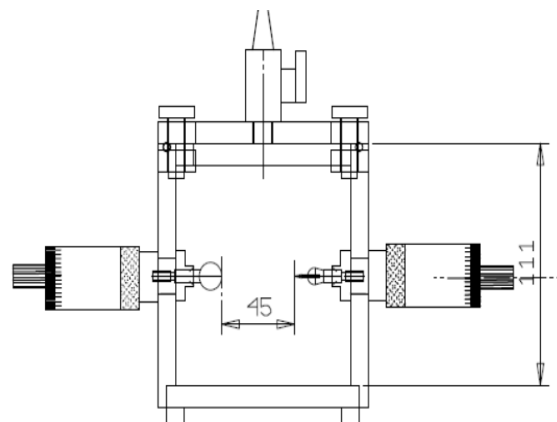


Figure 3.17 Design of horizontal cell

CHAPTER 4

EVALUATION OF DIELECTRIC IMPULSE WITHSTAND VOLTAGE OF INSULATING OILS

4.1 INTRODUCTION

Petroleum based mineral oil is being used for well over hundred years in both distribution and power transformers [3]. Recently, with the increased environmental concern, ester oil is becoming popular as an option in place of mineral oil for a wide range of voltage levels in transformers. In the past decades, a significant amount of experience has been gained on breakdown phenomena of mineral oil in different electric field configurations under lightning impulse voltage conditions [6-12]. Similar information is very important for natural ester oil due to its increasing use in transformers. In the recent times, many researches have been reported from different laboratories to compare chemical, physical and electrical features of ester oil with mineral oil [13-19]. The prediction of dielectric breakdown of ester oil is one of the important criteria to utilize the ester oil for transformer application under lightning impulse excitations since impulse test is one of the important factory tests to ensure capability of the insulation system of transformers. Lightning impulse strength as basic insulation level (BIL) is important for the design insulation of transformer [22].

The transformer insulation arrangement is a complex structure [31]. Generally, the transformer winding insulation undergoes different types of electrical stresses from the high voltage lead to the end of the winding, depending on the location of its use [30]. This is the reason, extreme uniform (non-divergent) and non-uniform (divergent) field configuration is chosen. The dielectric capability of the insulation system in a transformer is significantly decided by the data obtained on withstand voltages at different oil gaps [37]. Also, it is well known that breakdown strength of insulating liquid majorly depends on oil gap distance.

This chapter discusses about the evaluation and comparison of impulse withstand & breakdown voltage level of ester oil taking reference of mineral oil in uniform (non-divergent) and non-uniform (divergent) field configuration under positive and negative polarity. Oil gaps between 1mm to 20mm are studied. Electrodes dimensions and test methodology is adopted from ASTM D 3300 “Dielectric Breakdown Voltage of Insulating Oils of Petroleum Origin under Impulse Conditions” [35]. For transformer higher than 170kV impulse test is compulsory and hence a detailed comparative impulse study is undertaken. The experimentally obtained breakdown voltage values are statistically fitted using 3-

parameter Weibull distribution using Minitab software to estimate 1% breakdown probability voltage. Further, these 1% failure probability voltage values are used to determine the maximum electric stress experienced by the insulating oil, using FEM ElecNet software. In this study, the parameters used for comparison of oils are 1% breakdown probability voltage, average breakdown voltage, standard deviation of breakdown voltage and time to breakdown (breakdown time). Breakdown time is measured from the breakdown voltage waveform recorded by the oscilloscope in microseconds.

4.2 TESTING METHODOLOGY

Standard impulse testing procedure according to standard ASTM D 3300 is followed for both the field configurations. The voltage rising method used for impulse testing is a multiple-level method already discussed in chapter 2. For impulse testing it is mostly preferred. Also, this method causes maximum amount of stress on dielectric under test. The test procedure for both polarities (positive & negative) is explained below through a flow chart in Figure 4.1. Also, wait time between two consecutive breakdowns is maintained to 2.5 to 3 minutes and between two experiments is 4.5 to 5 minutes for mineral oil. But, for ester oil this wait time is increased to 4-5 minutes (between two consecutive breakdowns) and 6-7 minutes (between two experiments).

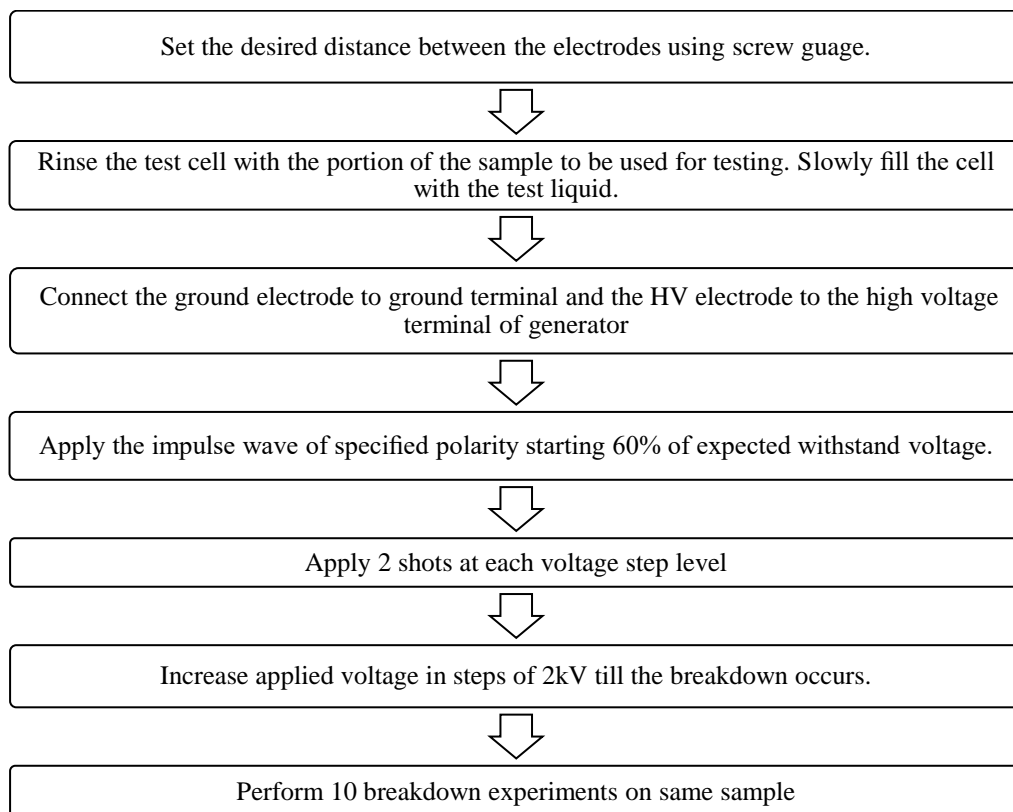


Figure 4.1 Flow chart of impulse test procedure of insulating oil

4.3 EXPERIMENTAL RESULTS

4.3.1 EVALUATION OF AVERAGE AND STANDARD DEVIATIONS OF BREAKDOWN VOLTAGE

The breakdown strength of oil is a statistically distributed parameter. It is mainly dependent on the physics, chemistry and impurities present in the oil [38]. The breakdown strength of oil provides useful information on the design criteria of transformer insulation systems and it would always obey some probability distribution functions [17, 18]. Hence, the best estimates of the statistical parameters, probability distribution with least square method of curve fittings are evaluated [20]. In this context, to measure the dispersion of a dataset relative to its mean value of breakdown voltage, standard deviation of breakdown voltages and average breakdown voltage of different oils (MO, NE1, NE2, SE) under positive and negative polarities in uniform non-uniform field configurations are evaluated and presented in Table 4.1 and 4.2.

Table 4.1 Statistical results of Mineral, Natural ester and Synthetic ester oil under positive polarity

Electrode combinations	Statistical values	Gap in mm	Positive polarity of impulse wave shapes			
			Mineral oil (MO)	Natural ester oil (NE)		Synthetic ester oil (SE)
				NE1	NE2	
Uniform field configuration	Average value in kV	1	56	58	57	75
		5	92	93	94	105
		10	136	139	140	139
		15	140	143	142	143
		20	145.7	146	146	147
	Standard deviation	1	1.5	3.4	1.9	2.9
		5	1.6	2.4	2	2.4
		10	1.6	2.3	2.4	2.8
		15	1.9	2.7	2.5	2.5
		20	2.2	2.6	2.2	2.6
Non-uniform field configuration	Average value in kV	1	34	38	40	46
		5	57	65	63	87
		10	75	82	81	129.5
		15	105	108	107.9	133
		20	129	130	131	137
	Standard deviation	1	2.1	2.8	3.1	2.3
		5	2.8	3	2.9	2.4
		10	5.8	2.2	3	2.2
		15	4.5	2.7	2.7	2.5
		20	3.5	2.6	2.9	2.6

From Tables 4.1 and 4.2, the following points are observed:

- The polarity effect in mineral oil and ester oil is quite evident under uniform and non-uniform field.

- Under positive polarity, standard deviation of ester oil is more than mineral liquid in uniform field configurations whereas in non-uniform field the two oils are comparable up to 5mm after that mineral oil is having higher standard deviation.
- Under negative polarity, standard deviations are comparable for both mineral and ester oil in uniform field. However, in non-uniform field mineral oil is having higher standard deviation than esters.

The difference in the absolute values of breakdown voltages between (Biotransol) NE1 and NE2 under both polarities is small in both field configurations and it can be ignored. Therefore, further in the thesis the results of mineral oil will be compared with synthetic ester and one natural ester, Biotransol (NE1).

From the Table 4.1 and 4.2, the ester oil with lesser standard deviation provides a good reproducibility in the impulse withstand voltage for design guidelines evaluations.

Table 4.2 Statistical results of Mineral, Natural ester and Synthetic ester oil under negative polarity

Electrode combinations	Statistical values	Gap in mm	Negative polarity of impulse wave shapes			
			Mineral oil (MO)	Natural ester oil (NE)		Synthetic ester oil (SE)
				NE1	NE2	
Uniform field configuration	Average value in kV	1	56	58	56	57.5
		5	98	94	93	93
		10	140	127	126	132
		15	144	131	132	137
		20	148	136	135.7	143
	Standard deviation	1	2.7	2.3	2.7	2.4
		5	2	2	2.4	2.6
		10	3.5	2.9	2.1	2.7
		15	3.6	2.2	2.4	2.0
		20	3.4	2.5	2.5	2.7
Non-uniform field configuration	Average value in kV	1	46	36	37	43
		5	103	62	64	85
		10	146	90	89.3	129
		15	149	98	97.5	133
		20	151	112.7	111.6	139
	Standard deviation	1	3.8	2.3	3.4	2.5
		5	3.4	2	3.7	2.9
		10	5.5	3.7	3.1	2.3
		15	5.7	3.4	3.5	2.5
		20	5.6	3.8	3.9	2.7

4.3.2 ESTIMATION OF 1% FAILURE PROBABILITY VOLTAGE

It is generally recognized that Weibull distribution is the best function to describe the behaviour at low probabilities for breakdown data as compared to Normal distribution and Gumbell distribution [17, 20]. 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. Hence 3-parameter Weibull distribution plots of the breakdown results dependent on the fitted curve with particular shape, scale and threshold are obtained according to least square method under various gaps and polarities [17, 18].

Figures 4.1 and 4.2 shows 3-parameter Weibull distribution plots of breakdown voltage data of mineral oil (Transol), natural ester (Biotransol) and synthetic ester (Transol Synth100) for both field configurations with the gap of 10mm under positive and negative impulse voltage respectively. In Figures 4.2 and 4.3, solid line shows the results of 3-parameter Weibull distribution based on ten impulse breakdown voltage values obtained from experiments. The dashed line shows upper and lower confidence level at 95%. Generally, the withstand voltage is considered as the breakdown voltage at 1% failure probability. The 99% withstand voltage of oil is predicted by the cross-section of the Weibull distribution curve fitting and the 1% failure probability rate [3].

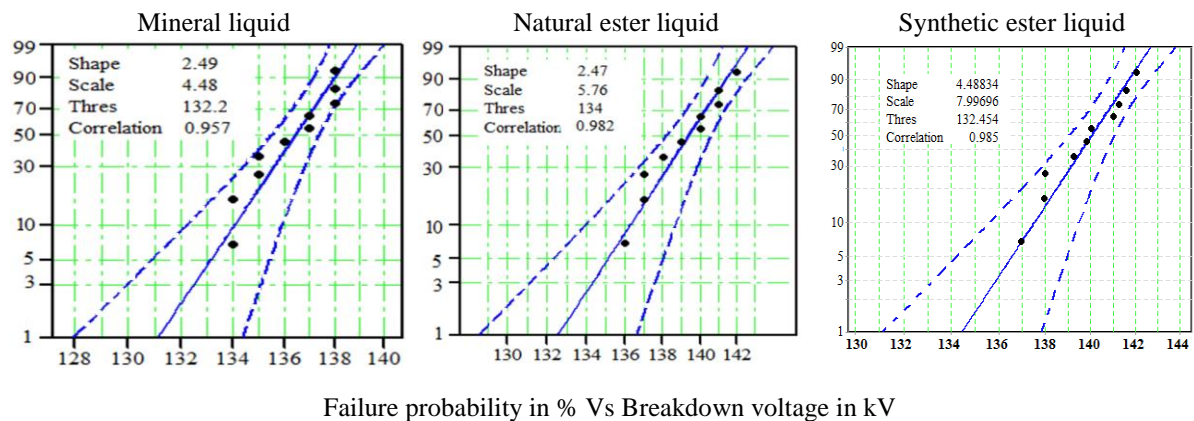


Figure 4.2(a) Weibull distribution of sphere-sphere configurations breakdown data under positive polarity for 10mm gap.

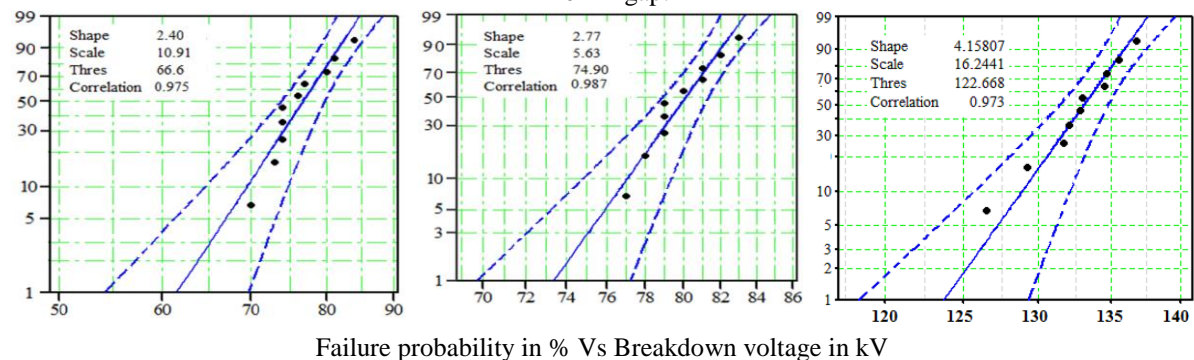


Figure 4.2(b) Weibull distribution of sphere-needle configurations breakdown data under positive polarity for 10mm gap.

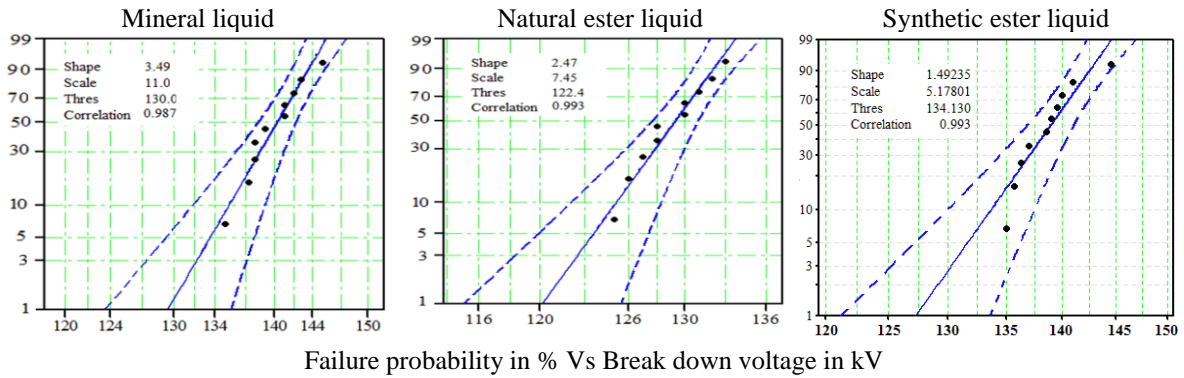


Figure 4.3(a) Weibull distribution of sphere-sphere configurations breakdown data under negative polarity for 10mm gap.

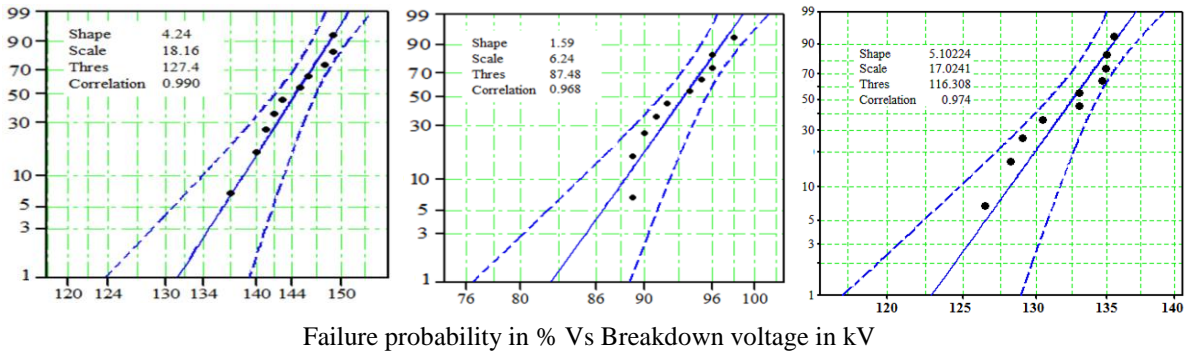


Figure 4.3(b) Weibull distribution of sphere-needle configurations breakdown data under negative polarity for 10mm gap.

From the Figure 4.2(a), It is found that the withstand voltage of mineral oil is 131 kV for 10mm gap for uniform electrical field configuration under positive polarity of impulse wave shape. However, the predicted result from Weibull distribution analysis provides an inevitable uncertainty [18, 20]. Therefore, mineral oil impulse withstand voltage might not be exactly 131 kV and it will be near the withstand voltage value of 131 kV. Hence, the actual impulse withstand voltage lies between 128 kV to 134.2 kV based on 95% confidence interval. Therefore, it is understood from Figure 1a, the withstand voltage of Transol is 131kV and 95 % confidence interval of impulse withstand voltage level lies between 128kV to 134.2 kV.

4.3.3 EFFECT OF ELECTRODE GEOMETRY ON WITHSTAND VOLTAGE

If the transformer designer needs to consider the confidence interval for insulation design criteria then it is reliable to utilize the lower level in the confidence limits than predicted withstand voltage. From the predicted results of Weibull distribution, 99% withstand voltage (1% failure probability) of mineral, natural ester and synthetic ester oil are extracted from Weibull distribution analysis, and it is shown in Figures 4.4 and 4.5. Figures 4.4(a) and 4.4(b) shows the 1% failure probability voltage (99% withstand voltage) of mineral oil (Transol), natural ester (Biotransol) and synthetic ester (Transol Synth 100) under positive polarity and

negative polarity impulse respectively in uniform and non-uniform field configurations to compare field effect in different polarities.

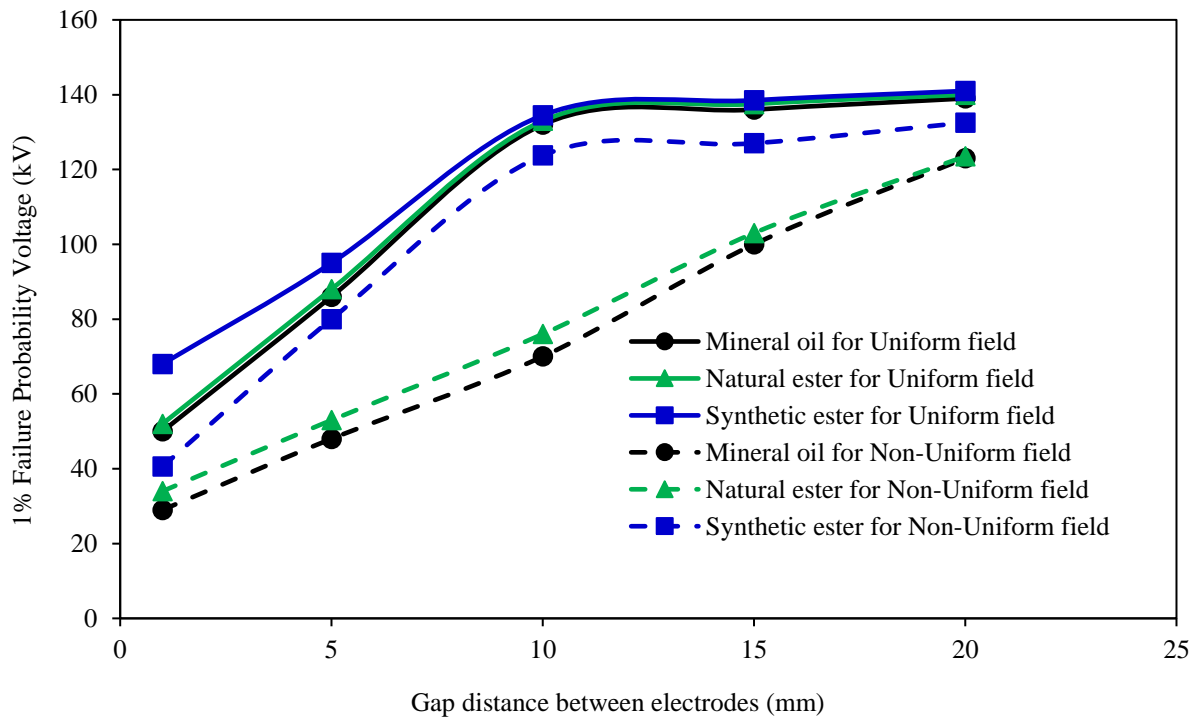


Figure 4.4(a) 1% failure probability voltage of Mineral, Natural ester and Synthetic ester oil in uniform and non-uniform field configuration under positive polarity of impulse

From Figure 4.4(a) following points are observed due to application of positive polarity of impulse:

- In uniform field, impulse withstand voltage of synthetic ester is slightly higher than that of mineral oil and natural ester oil up to gap distance of 10mm. After 10mm, impulse withstand voltage of all the three oils is comparable. Moreover, the impulse withstand voltage gets saturated after 10mm gap distance for both mineral oil and ester liquids.
- In non-uniform field configuration, synthetic ester is leading for all the gap distances as compared to mineral oil and natural ester. Among natural ester and mineral oil, impulse withstand voltage of natural ester is slightly higher than mineral oil.
- In mineral oil, natural ester and synthetic ester oil, electrode geometry effect is quite evident as impulse withstand voltage in uniform field is higher as compared to in non-uniform field. However, the effect is more prominent for mineral oil and natural ester oil as compared to synthetic ester oil. That means, synthetic ester is least affected by geometry and field configuration under positive polarity.

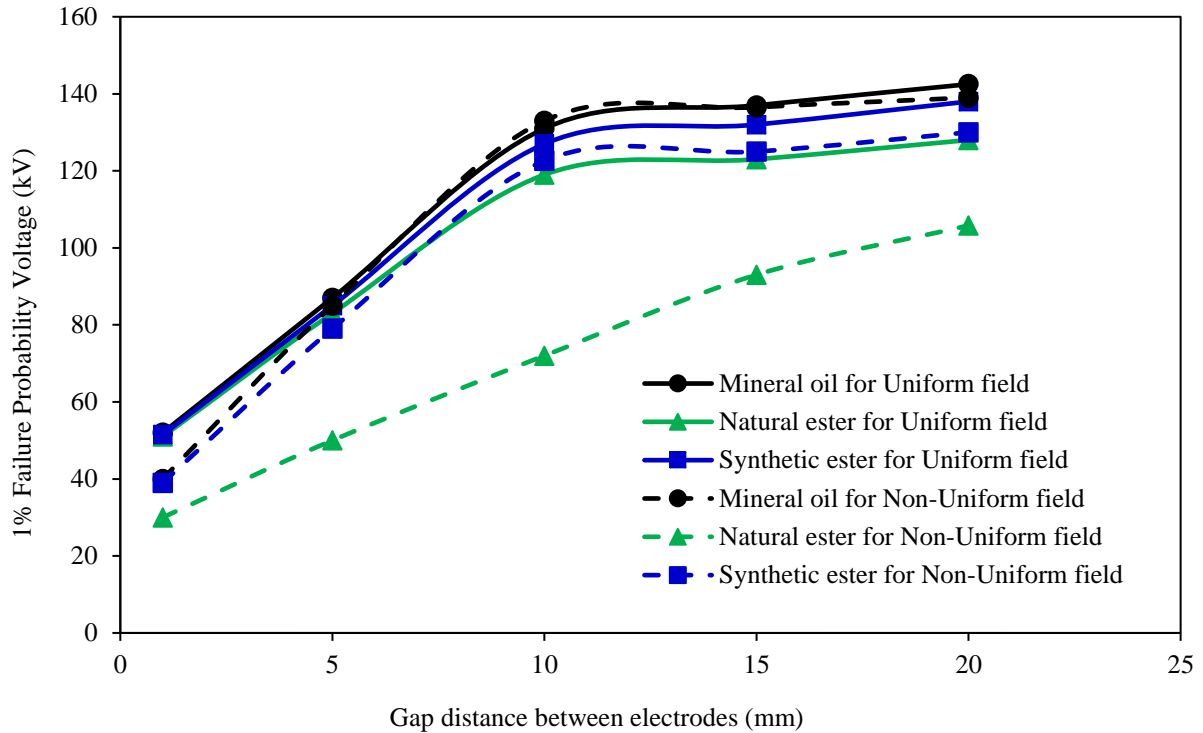


Figure 4.4(b) 1% failure probability voltage of Mineral, Natural ester and Synthetic ester oil in uniform and non-uniform field configuration under negative polarity of impulse

From Figure 4.4(b) following points are observed due to application of negative polarity of impulse:

- In uniform field, impulse withstand voltage of mineral liquid is slightly more than ester oils and impulse withstand voltage of natural ester oil is lower than synthetic ester oil. Moreover, the impulse withstand voltage gets saturated after 10mm gap distance for both mineral and ester oils.
- In non-uniform field configuration, mineral oil is superior for all the gap distances than both the ester fluids. Also, the trend of mineral oil and synthetic ester is same that their impulse withstand voltage is getting saturated after 10mm but this particular trend is not observed for natural ester oil.
- In mineral oil, there is no electrode geometry effect as impulse withstand voltage in uniform field is equal to that in non-uniform field. Moreover, the effect is significant for ester oils. In this case that is under negative polarity, mineral oil is least affected by geometry and field configuration.

From Figures 4.4(a) and 4.4(b) it can be concluded that, irrespective of impulse polarity, natural ester oil is most affected by electrode geometry.

4.3.4 EFFECT OF IMPULSE POLARITY ON WITHSTAND VOLTAGE

Figures 4.5(a) and 4.5(b) shows the 1% failure probability voltage (99% withstand voltage) of mineral oil (Transol), natural ester (Biotransol) and synthetic ester (Transol Synth 100) in uniform and non-uniform field configurations respectively under positive impulse and negative impulse polarity impulse to compare impulse polarity effect in different geometries.

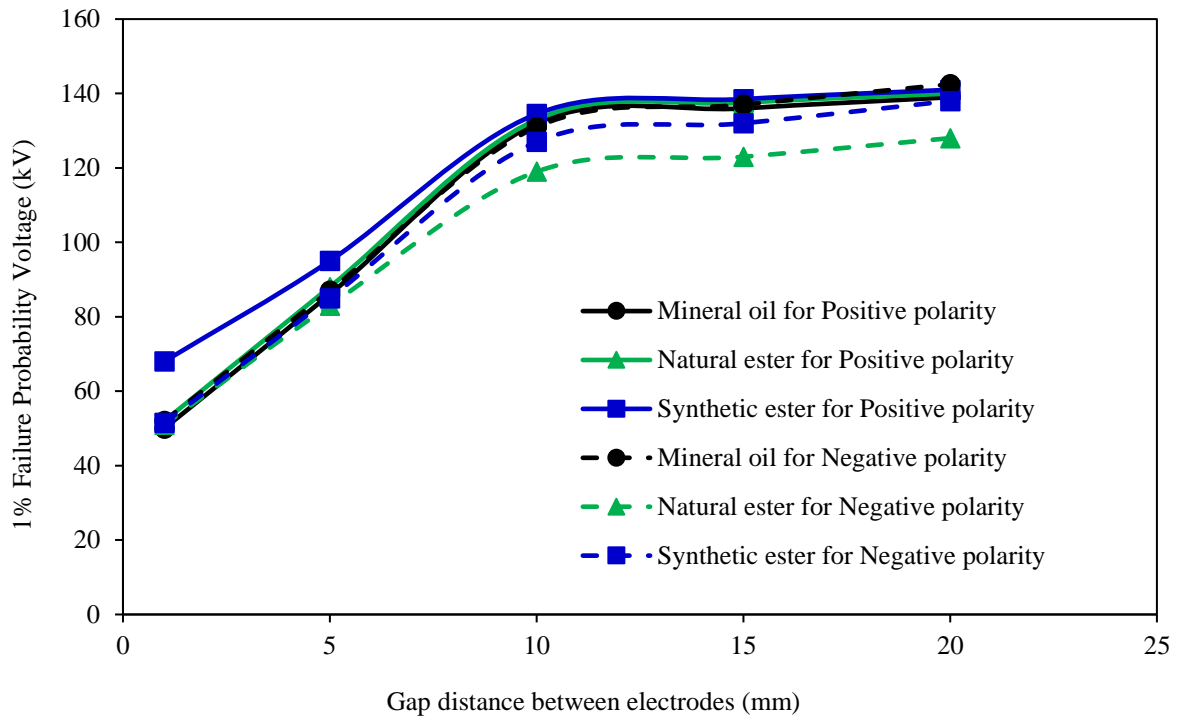


Figure 4.5(a) 1% failure probability voltage of Mineral, Natural ester and Synthetic ester oil under positive and negative polarity of impulse in uniform field configuration

From Figure 4.5(a) following points are observed due to application of uniform field configuration:

- Under positive impulse, impulse withstand voltage of synthetic ester is higher than mineral oil and natural ester up to 10mm gap distance. After 10mm, impulse withstand voltage of all the three insulating oils are comparable.
- Under negative impulse, impulse withstand voltage of mineral oil is slightly higher as compared to ester liquids. Among ester oils, synthetic ester has higher withstand voltage than natural ester oil.
- In mineral oil, there is no polarity effect as the impulse withstand voltage in positive polarity is equal to that in negative polarity. However, polarity effect is observed in both the ester liquids.

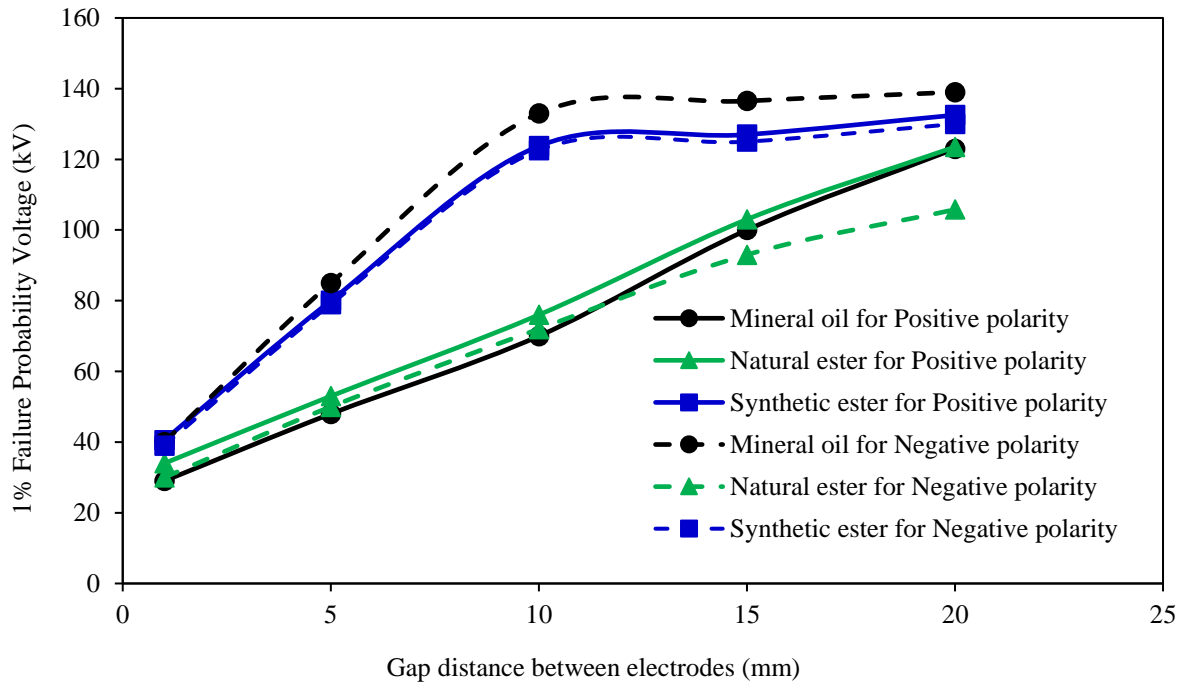


Figure 4.5(b) 1% failure probability voltage of Mineral, Natural ester and Synthetic ester oil under positive and negative polarity of impulse in non-uniform field configuration

From Figure 4.5(b) following points are observed due to application of non-uniform field configuration:

- Under positive impulse, impulse withstand voltage of synthetic ester is much higher than that of mineral oil and natural ester oil. Whereas, impulse withstand voltage of mineral oil and natural ester are comparable.
- Under negative impulse, impulse withstand voltage of mineral oil is significantly higher compared to ester liquids. Among ester oils, synthetic ester has higher withstand voltage than natural ester oil.
- In mineral oil, polarity effect is evident as the impulse withstand voltage in negative polarity is much higher than that in positive polarity. However, slight polarity effect is observed in natural ester oil and no polarity effect is observed in synthetic ester oil in non-uniform field configuration.

From Figures 4.5(a) and 4.5(b), it can be concluded that, slight polarity effect is present in natural ester liquids despite of field any configuration.

4.3.5 EVALUATION OF TIME TO BREAKDOWN

Time to breakdown is defined as the time between the beginning of the voltage waveform to the moment of sudden collapse. Figures 4.6(a) and 4.6(b) shows the variation of time to

breakdown and gap distance between the electrodes of mineral oil, natural ester oil and synthetic ester oil under positive and negative impulse in uniform and non-uniform field configuration respectively.

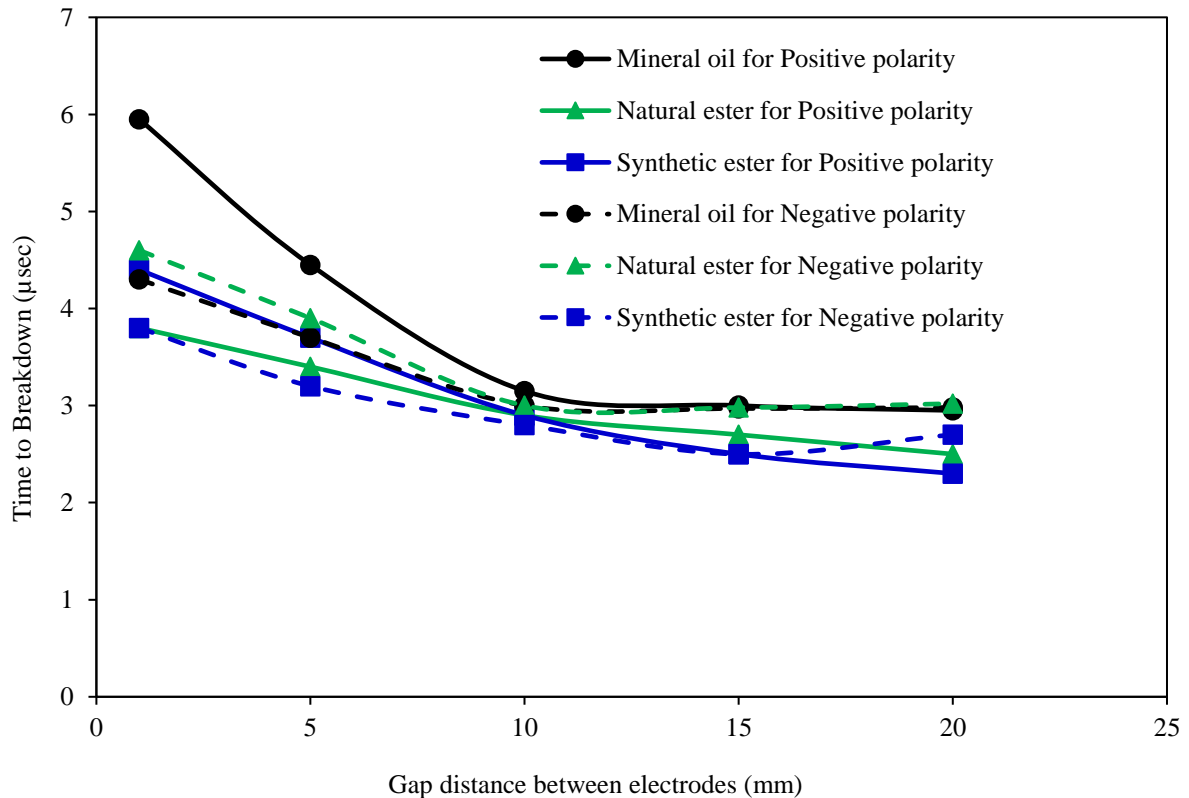


Figure 4.6(a) Time to breakdown of Mineral, Natural ester and Synthetic ester oil under positive and negative impulse in uniform field configuration

From Figure 4.6(a) following points are observed due to application of uniform field configuration:

- Under positive impulse, time to breakdown of mineral oil is higher than ester oils. Moreover, time to breakdown of synthetic ester is more than natural ester oil.
- Under negative impulse, time to breakdown of mineral and natural ester oil are comparable. Time to breakdown of synthetic ester oil is lower than both mineral oil and natural ester oil.

From Figure 4.6(b) following points are observed due to application of non-uniform field configuration:

- Under positive impulse, time to breakdown of natural ester oil is higher as compared to mineral oil and synthetic ester oil. Moreover, time to breakdowns of synthetic ester oil and mineral oil is comparable.

- Under negative impulse, time to breakdown of natural ester oil is higher as compared to synthetic ester oil. But, a totally different trend is observed for mineral oil under negative polarity and non-uniform configuration. This particular trend is observed for all the types of mineral oil like paraffinic and naphthenic mineral oil.

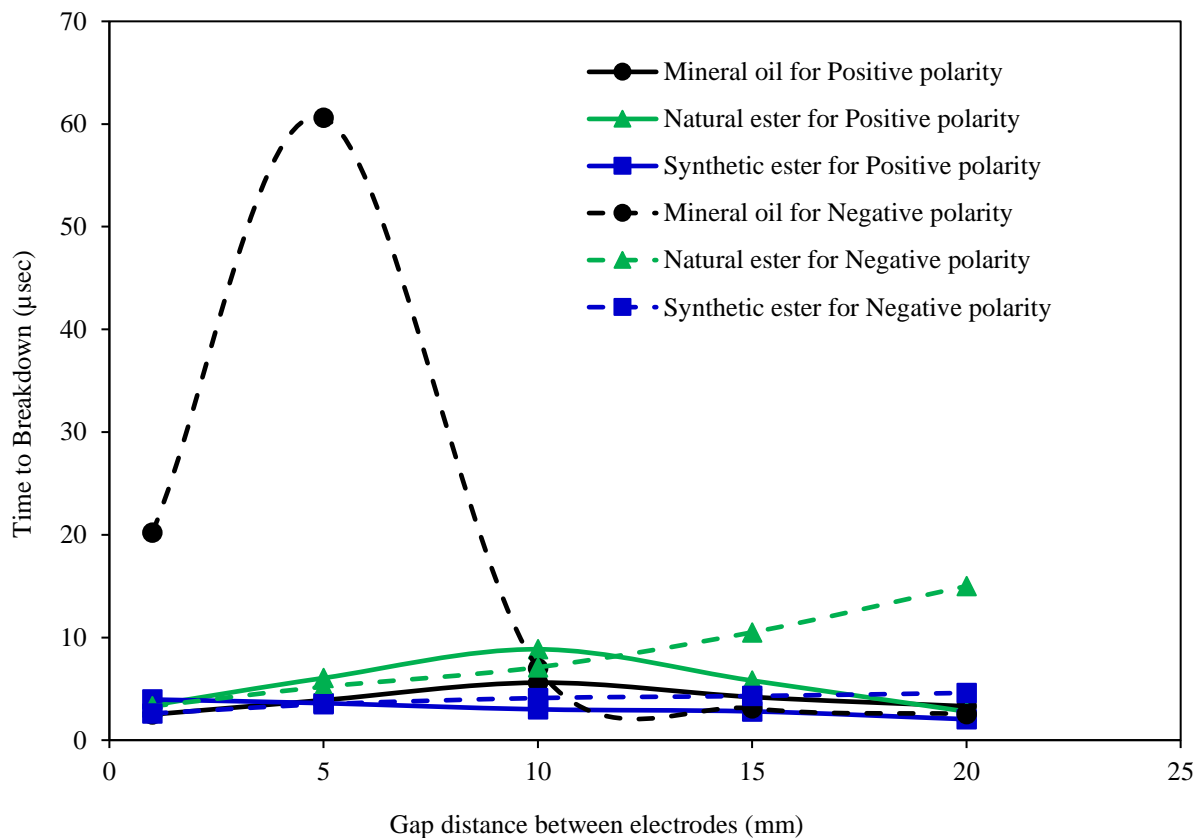


Figure 4.6(b) Time to breakdown of Mineral, Natural ester and Synthetic ester oil under positive and negative impulse in non-uniform field configuration

4.4 SIMULATION RESULTS

Electric stress experienced by the insulation arrangement at different location under impulse stress condition is an important parameter for an insulation design of transformer [31]. After post failure analysis of transformer many researchers have reported that insulation failure is one of major reasons behind failure of transformer [22]. To avoid these type 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. From the field plots, Utilization factor (ξ) are calculated to analyse the electrode geometry effects on the breakdown characteristics of the given insulation. These maximum electric stress (E_{max}) values for different insulating oils provides maximum limit of stress value that

will be considered while insulation design of transformer. Further, maximum electric stress and average electric stress is determined which leads to determination of utilization factor for particular field configuration. Figure 4.7(a), 4.7(b), 4.7(c) 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. Also, Figure 4.8 and 4.9 shows the electric field lines and area where maximum electric field is present in non-uniform and uniform field respectively for natural ester (Biotransol) 10mm gap positive polarity.



Figure 4.7(a) Test Cell model

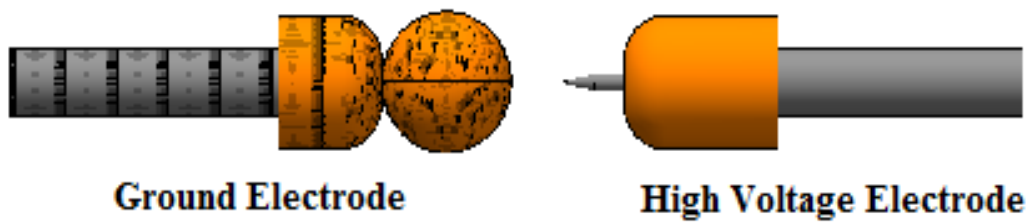


Figure 4.7(b) Electrode model for non-uniform field

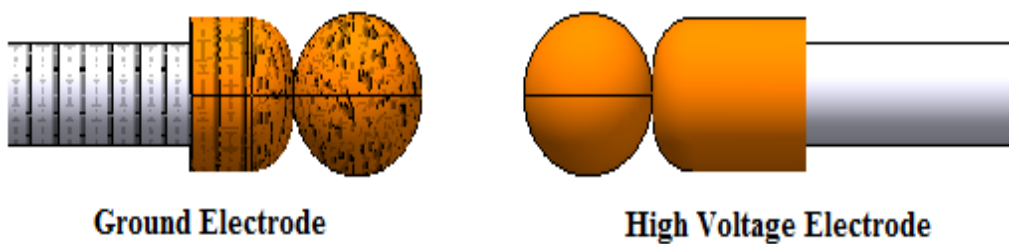


Figure 4.7(c) Electrode model for uniform field

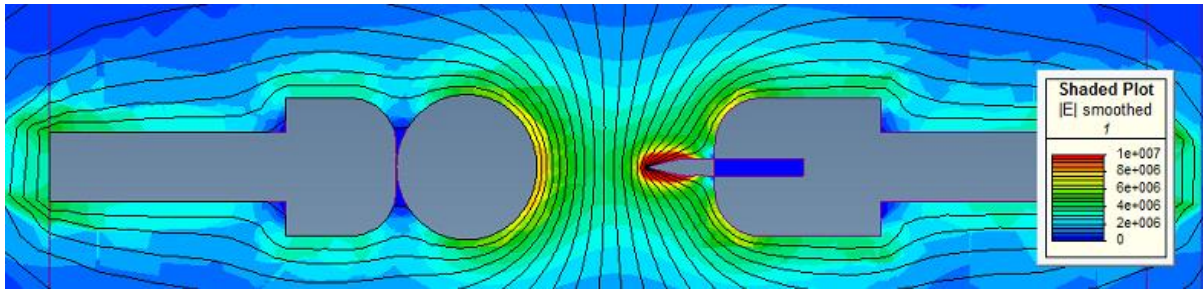


Figure 4.8 Electric field lines in non-uniform field with Natural ester (Biotransol) (10mm gap, positive polarity)

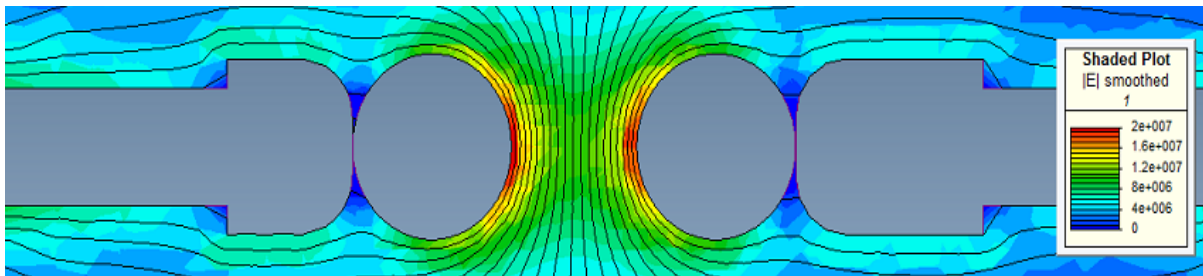


Figure 4.9 Electric field lines in uniform field with Natural ester (Biotransol) (10mm gap, positive polarity)

4.4.1 MAXIMUM ELECTRIC STRESS ON INSULATING LIQUIDS

The maximum electric stress on insulating oil can be defined as the maximum stress applied on oils by electrical field. Generally, the distribution of electrical stress between the insulating materials during impulse test depends on the permittivity of the materials and applied voltage magnitude. The higher value of permittivity for natural ester oil is close to solid insulation improving the electric field distribution along the transformer insulating materials and therefore stress experienced by the oil decreases. As applied voltage increases, stress value on oil also increases. In this study for design insulation of transformer maximum electric stress on oil is determined in mineral oil, natural ester and synthetic ester for all the cases at 1% failure probability voltage. Table 4.3 represents the maximum stress value under positive and negative polarity with uniform and non-uniform field in mineral oil, natural ester and synthetic ester.

4.4.2 UTILISATION FACTOR

Breakdown mechanism is firmly associated to the uniformity of electric field by the electrode geometry [7]. The utilisation factor, ξ (homogeneity factor or uniform field factor) is usually used to explain the degree of uniformity of a field configuration. The relationship between utilisation factor (ξ) and maximum stress (E_{max}) is defined below in Equation 4.1. It ranges between 0 to 1 and also known as Schwainger factor. For extremely uniform field it is equal to 1 that signifies there is complete utilization of dielectric properties of any dielectric whereas for extremely non-uniform field it is less than 0.25.

$$\xi = \frac{E_{mean}}{E_{max}} \quad (4.1)$$

Where,

E_{mean} & E_{max} represents average electric stress and maximum stress experienced by the oil respectively. Figure 4.10 shows the variation of utilisation factor with gap distance for mineral, natural ester and synthetic ester oil in uniform and non-uniform configuration under negative polarity.

Table 4.3 Maximum electric stress in Mineral, Natural ester and Synthetic ester oil at 10mm gap distance

Electrode combination	Polarity of impulse wave	Mineral oil		Natural ester oil		Synthetic ester oil	
		99% Withstand Voltage (kV)	E_{max} (kV/mm)	99% Withstand Voltage (kV)	E_{max} (kV/mm)	99% Withstand Voltage (kV)	E_{max} (kV/mm)
Uniform Field Configuration	Positive Polarity	132	19.7	133	19.7	134.5	18.3
	Negative Polarity	131	19	121	18.3	127	17.2
Non uniform field configuration	Positive Polarity	70	269	76	280	123.75	460
	Negative Polarity	133	470	80	322	122.6	407

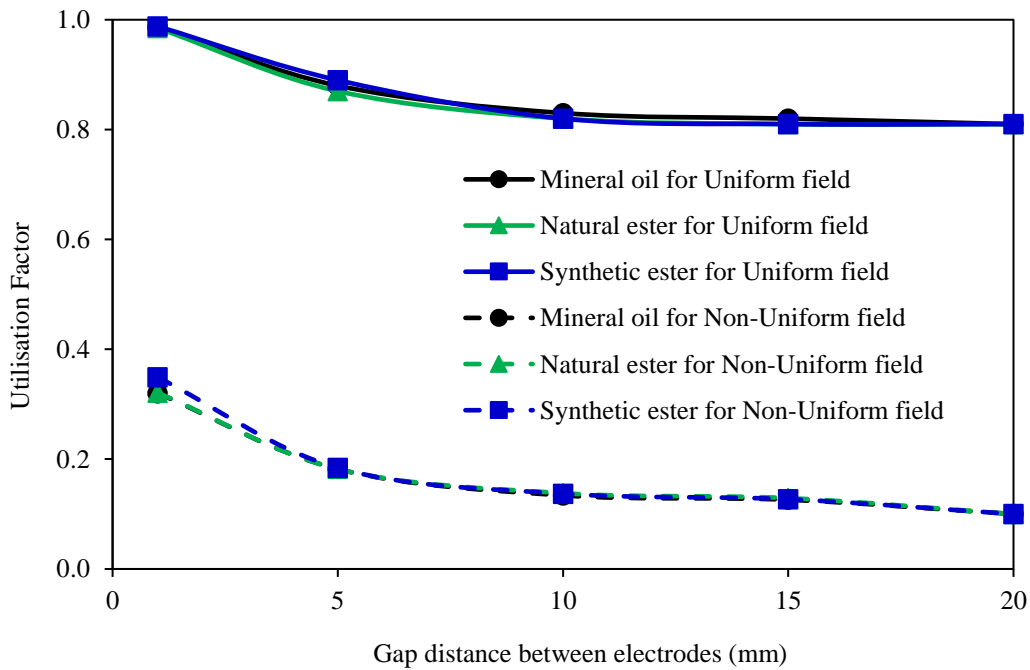


Figure 4.10 Variation of utilisation factor with gap distance for Mineral, Natural ester and Synthetic ester oil under negative polarity.

From Figure 4.10 following points can be concluded:

- For all the insulating oils, utilisation factor in uniform field is in range of 0.98 to 0.8 up to 20mm electrode gap. Whereas, in non-uniform field it is in range of 0.3 to 0.1.
- With increase in electrode gap, utilisation factor decreases as non-uniformity in electric field increases. However, after 10mm gap utilisation factor gets saturated up to 20mm especially in case of uniform field.

Similar trend is also observed under positive polarity with both electrode configurations.

CHAPTER 5

EVALUATION OF DIELECTRIC IMPULSE BREAKDOWN VOLTAGE OF INSULATING OIL IMPREGNATED PRESSBOARDS

5.1 INTRODUCTION

Generally, power transformers are filled with insulating oils. For these types of transformers, designed insulation arrangement is fusion of liquid and cellulose based insulation [39]. Cellulose insulation consists of paper, pressboard and blocks. They are used at various locations in the transformer according to their need. For instance, paper insulation is mostly used to wrap the copper conductors to avoid the direct contact of insulating liquid and conductors because copper will act as a catalyst for ageing of liquid insulation under high temperature.

Pressboard is used to subdivide the long oil gaps into smaller oil gaps of 6-8mm since solid insulation has higher dielectric strength than liquid insulation. Also, they are used to provide direction to cooling oil through windings to have efficient cooling of transformer [39, 40]. Further the pressboard spacers placed below the windings provide mechanical support for windings. Pressboards can be formed into any desired shape and form like plates, cylinder and angle rings.

Cellulosic fibers present in cellulose insulation are porous with voids [41]. Therefore, they are impregnated by insulating oil and are referred to as impregnated cellulose based materials. This impregnation helps in eliminating voids and improve dielectric properties of cellulosic material. Improper filling of the voids can be the sources of partial discharges due to trapped air bubbles [41, 42].

Insulation system of transformer can be divided into two categories: major insulation and minor insulation [22]. Major insulation arrangement comprises impregnated pressboard barriers, large volume of insulating liquids between the windings, between core and winding and tank and winding. Minor insulation mainly includes inter disc and inter turn insulation which have wrapped paper conductor, pressboard spacer for winding mechanical support and small insulating oil gaps.

It is well known that electric stress distribution along the transformer insulation depends on dielectric constant of the material [22, 30]. As permittivity of pressboard is different from insulating oil the stress distribution is unequally partitioned between both of them. For instance, insulating liquid is having half of the dielectric constant that of pressboard so the

electric stress subjected to insulating oil will be double as that of pressboard [41]. Even dielectric strength is also lower for insulating oil which makes it even worse. Because of these reasons, insulating liquid is more subjected to breakdowns and partial discharges. Thus, ester oils with higher dielectric constant or permittivity are better than mineral oil. Their dielectric constant is comparable with pressboard which reduces uneven distribution of electric stress on transformer insulation arrangement. Thus, the main key point for design of transformer insulation is to ensure that the insulating oil and impregnated pressboard can withstand the high electric stress during its operation.

Figure 5.1 shows the composite insulation arrangement of oil-pressboard around a winding in a transformer. Cylindrical shaped pressboards are taken into account to subdivide the long oil gaps into smaller gaps of high dielectric strength [39]. As it is already discussed in chapter 4 the dielectric breakdown capability of insulating oil mainly depends on the oil gap. Figure 5.2 and 5.3 depicts the electric stress variation curve for composite insulation arrangement in uniform and non-uniform electric field respectively.

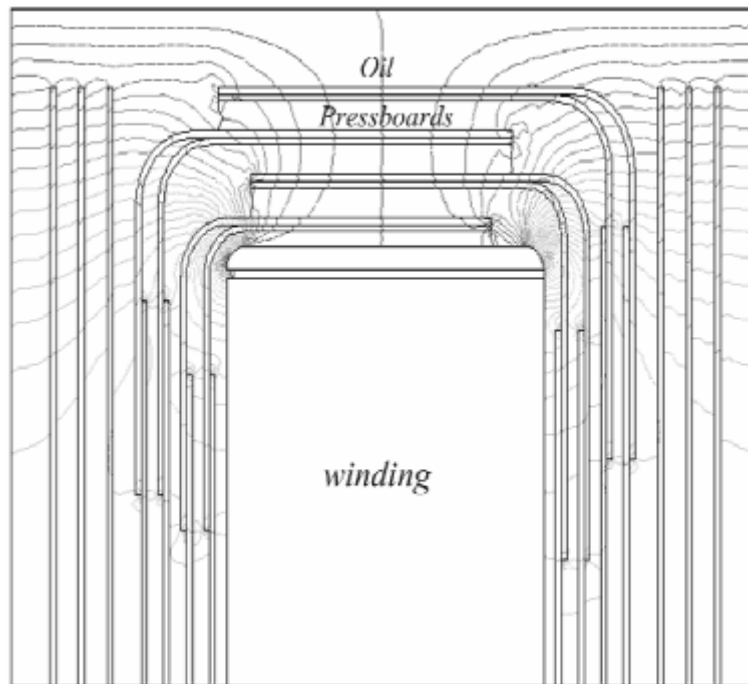


Figure 5.1 Composite insulation arrangement of oil-pressboard around a winding [39]

This chapter presents the experimental and simulation results of impulse testing of ester oil impregnated pressboards of 1.5mm thickness and 1.2g/m^3 density. Mineral oil (Transol), natural ester (Biotransol) and synthetic ester (Transol synth 100) are the insulating oils that are considered for impulse testing. Dielectric impulse breakdown strength of different insulating oil impregnated pressboards is evaluated and compared. Moreover, maximum

electric stress experienced by pressboard and oil near the pressboard is determined at impulse breakdown voltage using ElecNet FEM software.

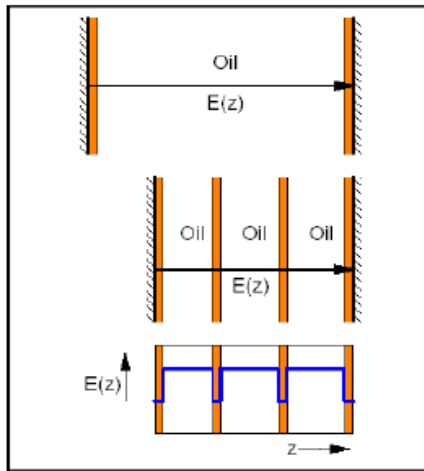


Figure 5.2 Electric stress curve of composite insulation arrangement (oil-pressboard) in uniform electric field.

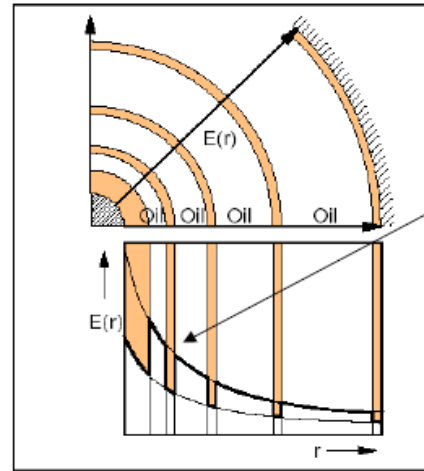


Figure 5.3 Electric stress curve of composite insulation arrangement (oil-pressboard) in non-uniform electric field.

5.2 TESTING METHODOLOGY

The voltage rising method used for impulse testing is multiple-level method as it is discussed in chapter 2. For impulse testing it is mostly preferred. Also, this method causes maximum amount of stress on dielectric under test. The test procedure for both polarities (positive & negative) is explained below through a flow chart in Figure 5.4.

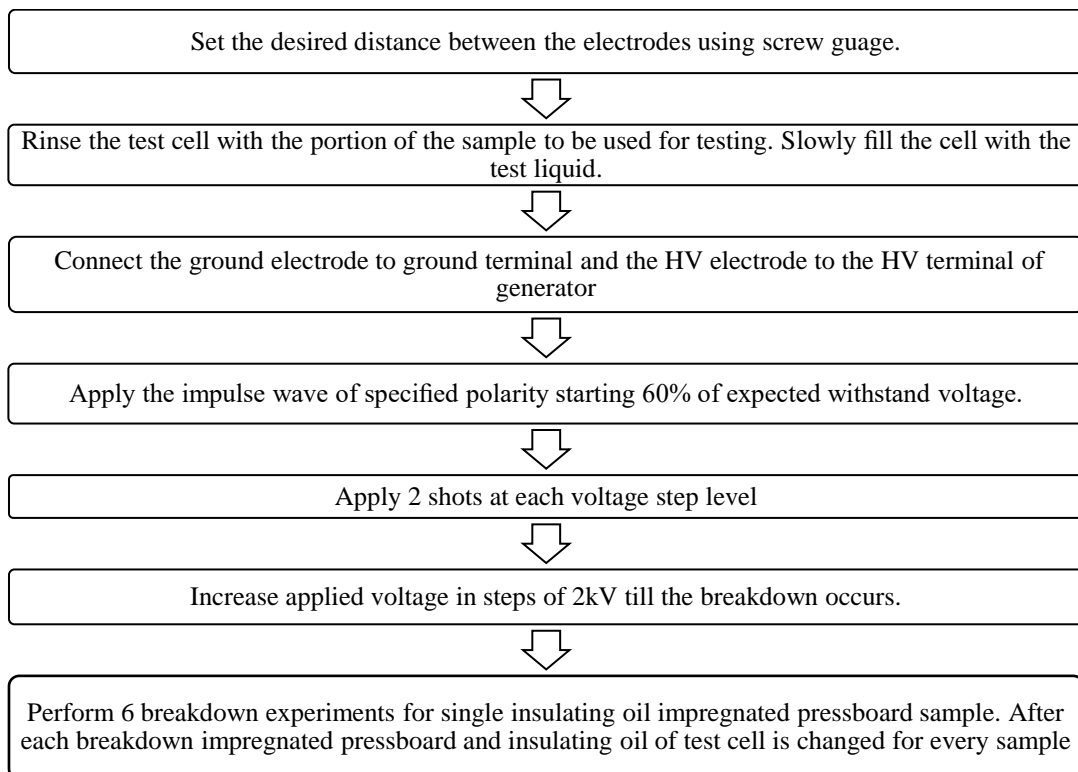


Figure 5.4 Impulse testing procedure of impregnated pressboards

5.3 EXPERIMENTAL RESULTS

For insulation design of a transformer, determination of breakdown strength of insulation (solid and liquid) becomes most important to avoid any type of insulation failure. Therefore, this study focuses on evaluation of dielectric impulse breakdown voltage of ester impregnated pressboards. Also, experiments are performed with mineral oil impregnated pressboards for comparison purpose. Electrode geometry and polarity of impulse wave shape are one of the major factors on which breakdown voltage of any dielectric insulation material depends. This is the reason the comparison of average breakdown voltage is studied in terms of effect of electrode geometry and effect of impulse polarity in the following sections.

5.3.1 EFFECT OF ELECTRODE GEOMETRY ON AVERAGE BREAKDOWN VOLTAGE

Figure 5.5 and 5.6 shows the bar graph representation of average breakdown voltage of mineral oil (Transol), natural ester (Biotransol) and synthetic ester (Transol Synth 100) impregnated pressboards in uniform and non-uniform field configuration under positive and negative polarity of impulse respectively.

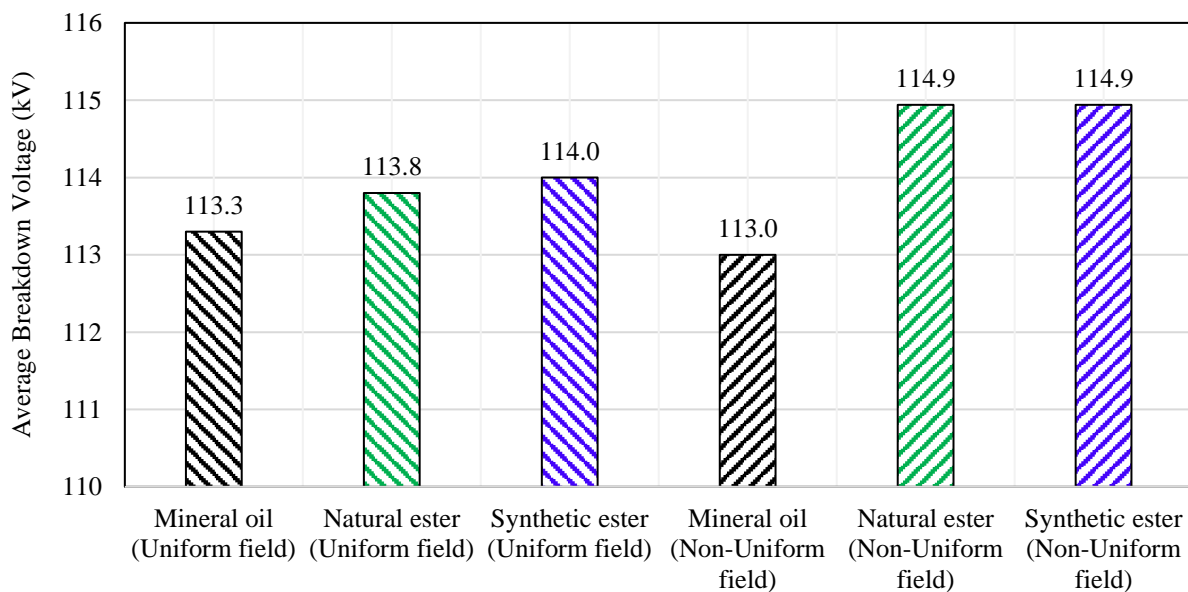


Figure 5.5 Average breakdown voltage of Mineral, Natural ester and Synthetic ester oil impregnated pressboards in uniform and non-uniform field configuration under positive impulse

From Figure 5.5 following points are observed due to application of positive polarity of impulse:

- In uniform field configuration, impulse breakdown voltage of mineral and natural ester impregnated pressboards is comparable and breakdown voltage of synthetic ester

impregnated pressboard is slightly higher as compared to both the insulating oil impregnated pressboards.

- In non-uniform field configuration, ester impregnated pressboards are superior to mineral oil impregnated pressboards in terms of breakdown voltage and both the ester impregnated pressboards are comparable.
- In mineral oil impregnated pressboards, it is observed that there is no electrode geometry effect as breakdown voltage in uniform field is comparable to non-uniform field.
- In ester impregnated pressboards, it is evident that there is a geometry effect and impulse breakdown voltage in non-uniform field is higher as compared to uniform field configuration.

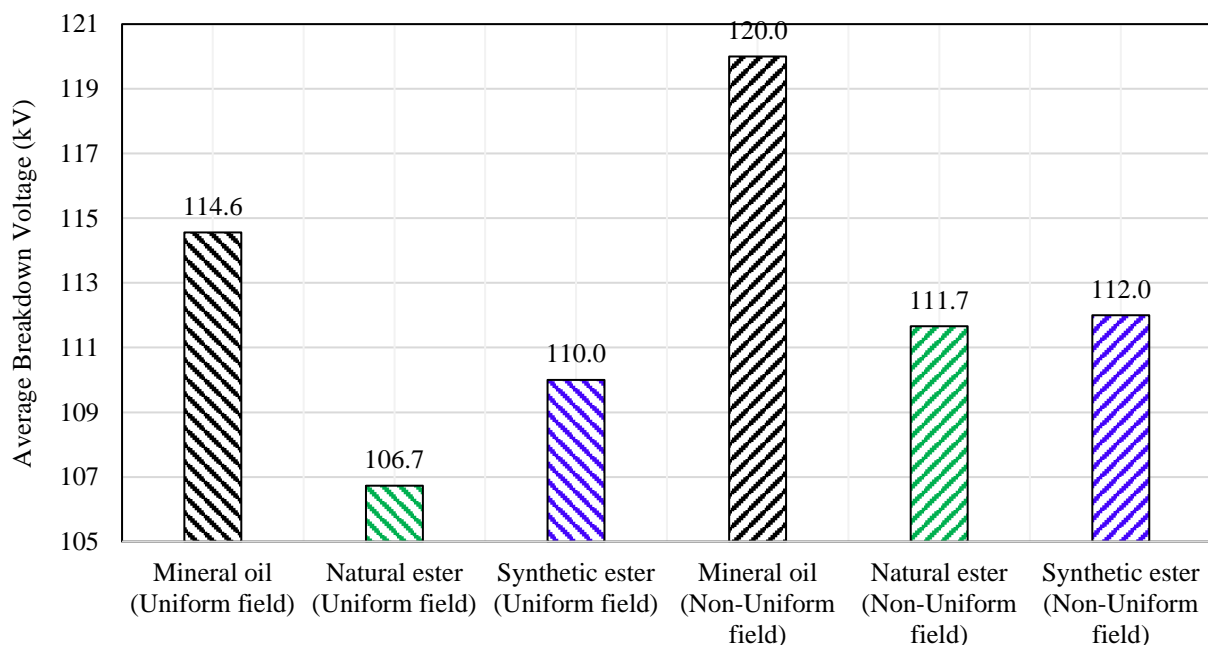


Figure 5.6 Average breakdown voltage of Mineral, Natural ester and Synthetic ester oil impregnated pressboards in uniform and non-uniform field configuration under negative impulse

From Figure 5.6 following points are observed due to application of negative polarity of impulse:

- In uniform field configuration, impulse breakdown voltage of mineral oil impregnated pressboard is higher than ester impregnated pressboards. Among ester impregnated pressboards natural ester impregnated pressboard is lower than synthetic ester impregnated pressboard because of its high electronegative nature.
- In non-uniform field configuration, similar trend is followed for impulse breakdown voltage of mineral oil impregnated pressboard which is much higher than ester

impregnated pressboards. However, both natural and synthetic ester impregnated pressboards are comparable.

- In mineral oil impregnated pressboards, there is an obvious electrode geometry effect as breakdown voltage in non-uniform field is much higher than that of in uniform field.
- In ester impregnated pressboards, it is evident that there is a geometry effect and impulse breakdown voltage in non-uniform field is higher as compared to uniform field configuration.

From Figures 5.5 and 5.6 it can be concluded that for most of the insulating oil impregnated pressboards, impulse breakdown strength is higher in non-uniform case as compared to uniform field case. On the contrary, for insulating oils, it is found that impulse breakdown strength in non-uniform case is lower as compared to uniform field case. It is mainly because in case of uniform field, complete surface area of oil impregnated pressboard experiences the high average electric field which leads to higher electric stress and lower breakdown voltage. Whereas, in case of non-uniform field, only a limited area of pressboard experiences the high electric stress.

Under positive polarity, average impulse breakdown strength of synthetic ester impregnated pressboard is higher as compared to natural ester and mineral oil impregnated pressboards irrespective of field configuration. In addition, under negative polarity, average impulse breakdown strength of mineral oil impregnated pressboard is higher as compared to ester oil impregnated pressboards in spite of field configuration.

5.3.2 EFFECT OF POLARITY ON AVERAGE BREAKDOWN VOLTAGE

Figure 5.7 and 5.8 discusses the bar graph representation of average breakdown voltage of mineral oil (Transol), natural ester (Biotransol) and synthetic ester (Transol Synth 100) impregnated pressboards under positive and negative polarity of impulse in uniform and non-uniform field configuration respectively.

From Figure 5.7 following points are observed due to application of uniform field configuration:

- Under positive polarity, impulse breakdown strength of mineral, natural ester and synthetic ester fluid impregnated pressboards are comparable.
- Under negative polarity, impulse breakdown strength of ester impregnated pressboards are lower than mineral oil impregnated pressboard and natural ester impregnated pressboard is lowest.

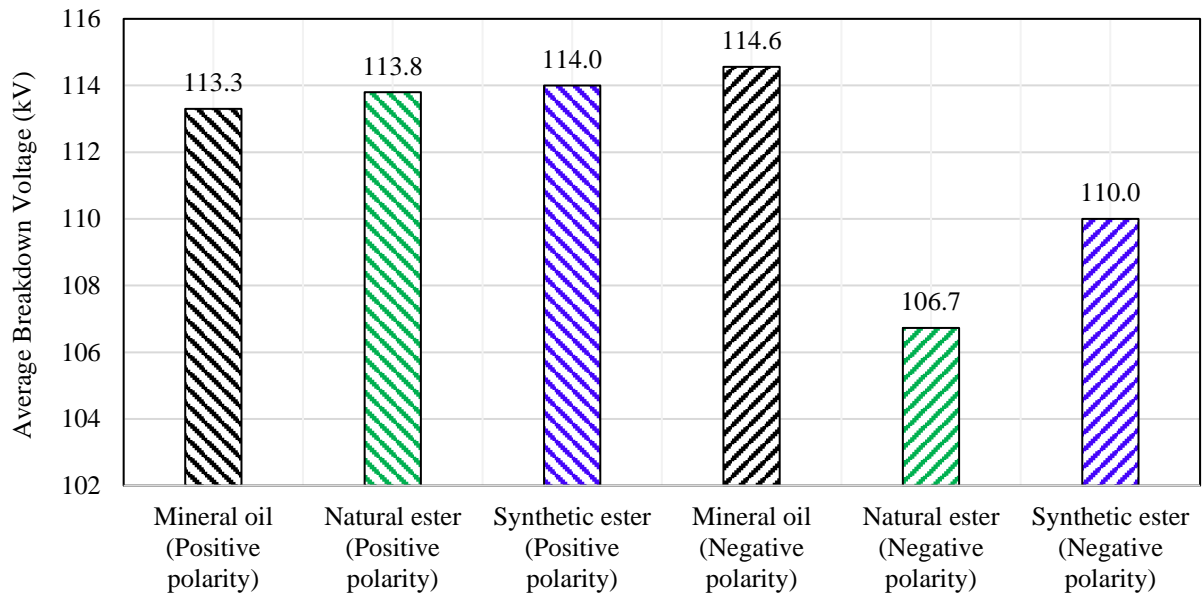


Figure 5.7 Average breakdown voltage of Mineral, Natural ester and Synthetic ester oil impregnated pressboards under positive and negative polarity of impulse in uniform field configuration

- In mineral oil impregnated pressboard, there is a slight polarity effect as impulse breakdown strength under negative polarity is more as compared to under positive polarity.
- In ester impregnated pressboards, polarity effect is prominent as impulse breakdown voltage under negative polarity is much lower as compared to under positive polarity. This is mainly because of electronegative nature of ester molecules which accelerates the negative streamer propagation and leads to faster breakdown.

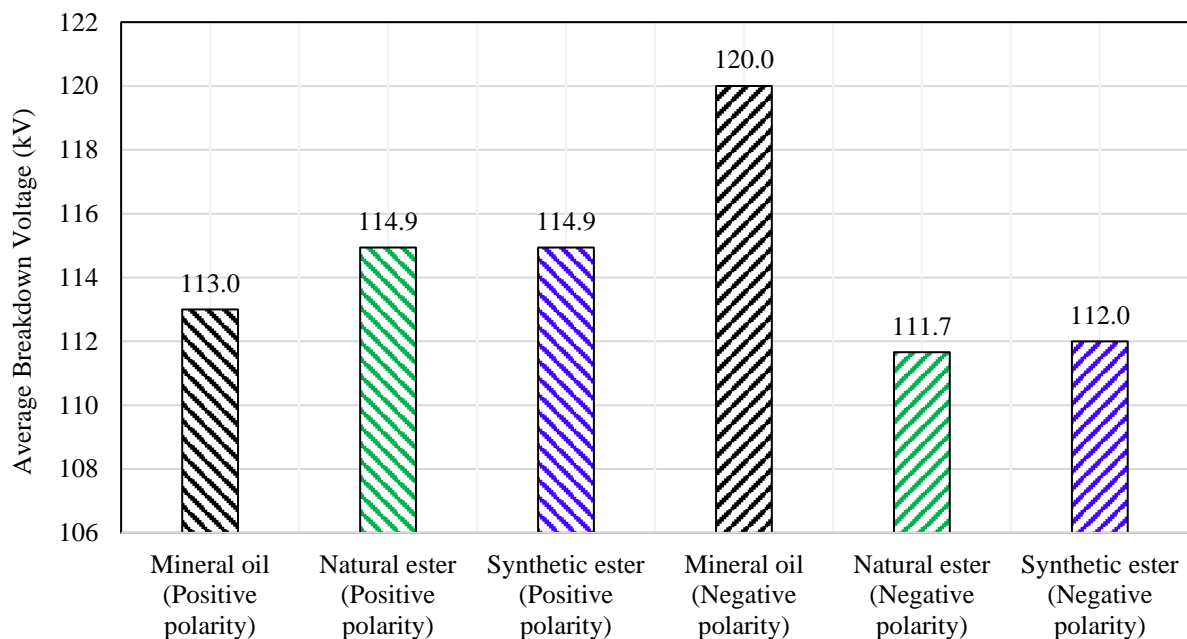


Figure 5.8 Average breakdown voltage of Mineral, Natural ester and Synthetic ester oil impregnated pressboards under positive and negative polarity of impulse in non-uniform field configuration

From Figure 5.8 following points are observed due to uniform field configuration:

- Under positive polarity, impulse breakdown strength of mineral oil impregnated pressboard is slightly lower as compared to ester impregnated pressboards. Whereas, natural ester and synthetic ester impregnated pressboards are comparable.
- Under negative polarity, impulse breakdown strength of ester impregnated pressboards is much lower than mineral oil impregnated pressboard. Also, natural and synthetic ester impregnated pressboards are comparable.
- In mineral fluid impregnated pressboard, there is a polarity effect as impulse breakdown voltage under negative polarity is higher as compared to under positive polarity.
- In ester impregnated pressboards, polarity effect is prominent as impulse breakdown strength under negative polarity is lower as compared to under positive polarity. This is mainly because of electronegative nature of ester molecules which accelerates the negative streamer propagation and leads to faster breakdown.

From Figures 5.7 and 5.8 it can be concluded for both the field configurations, polarity effect exists for both mineral oil and ester impregnated pressboards. Mineral oil impregnated pressboard have lower impulse breakdown strength under positive polarity despite of field configuration. Moreover, ester impregnated pressboards have lower breakdown strength under negative polarity regardless of field configuration.

5.4 SIMULATION RESULTS

Transformer insulation design engineer needs the limits of maximum electric stress for any insulating material under various conditions like AC, impulse, switching overvoltage etc. Simulation is carried out through software applications to determine the maximum electric stress that insulation can withstand. In this study, maximum electric stress experienced by the impregnated pressboard and insulating oil near the pressboard is determined at average breakdown voltage. This will give an idea to the designer that electric stress experienced by the insulation structure in a transformer should be less than the determined maximum electric stress for particular condition. Maximum electric stress is mainly dependent on electric field geometry and permittivity of insulating material [40]. Therefore, stresses are compared in the following sections in terms of effect of field geometry and effect of permittivity. Figure 5.9 and 5.10 shows the simulation model of oil impregnated pressboard in uniform and non-uniform field electrodes respectively. Also, Figure 5.11 depicts example of electric field (E) distribution arrow plot around the simulated model in non-uniform field under negative polarity for mineral oil.

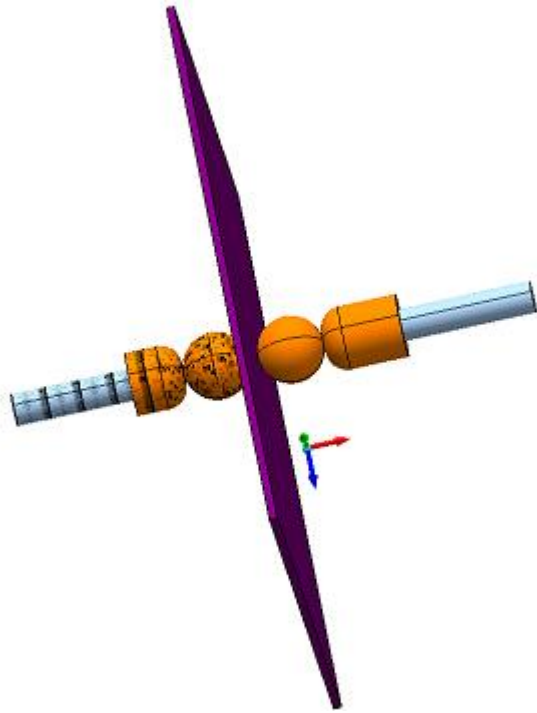


Figure 5.9 Simulation model of oil impregnated pressboard in uniform field

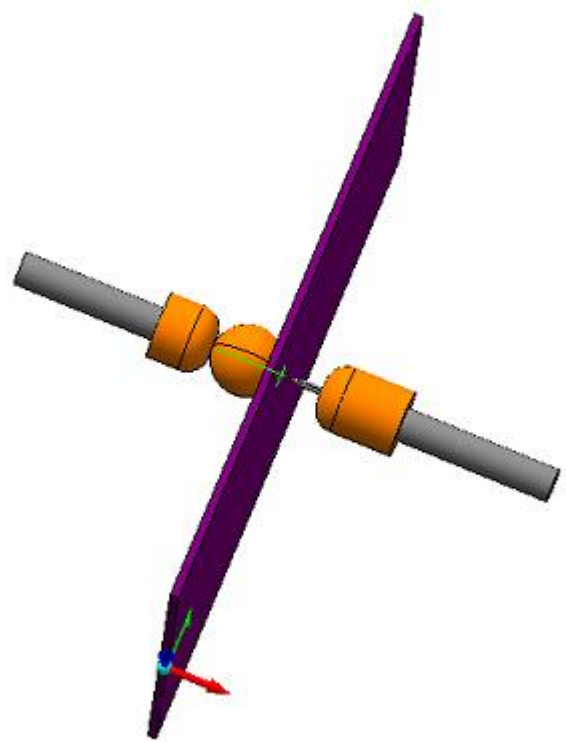


Figure 5.10 Simulation model of oil impregnated pressboard in non-uniform field

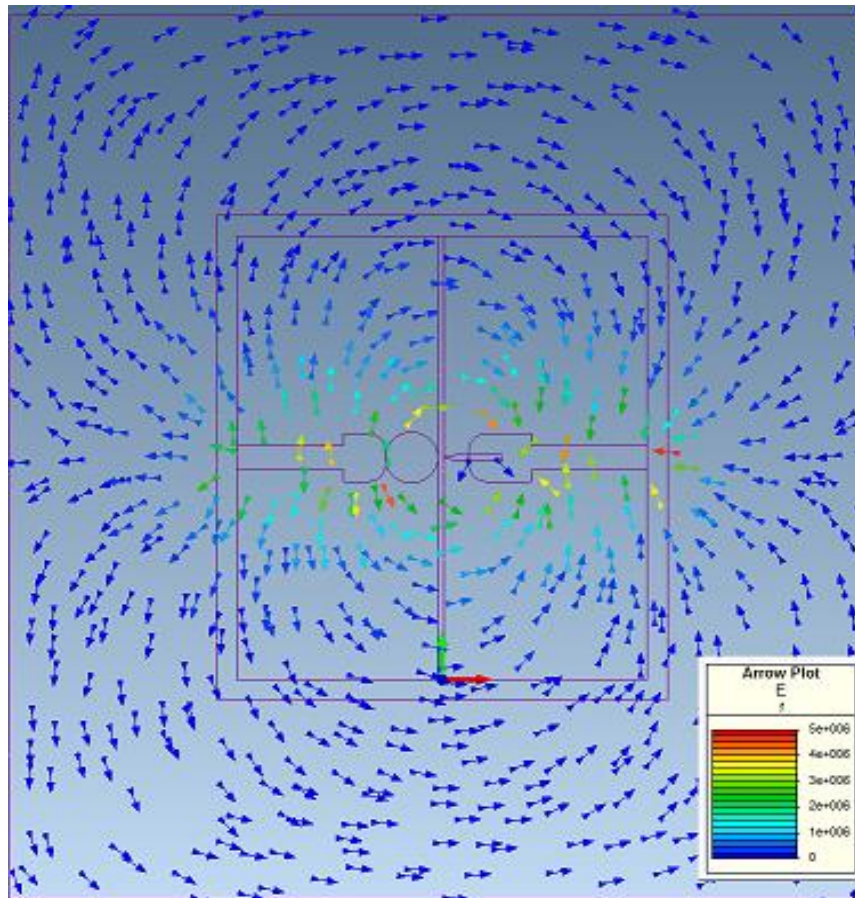


Figure 5.11 Electric field distribution arrow plot in non-uniform field

5.4.1 EFFECT OF ELECTRODE GEOMETRY ON MAXIMUM ELECTRIC STRESS

Figure 5.12, 5.13 and 5.14 shows the effect of electrode geometry on maximum electric stress under positive polarity on mineral oil (Transol), natural ester (Biotransol) and synthetic ester (Transol Synth 100) impregnated pressboards respectively.

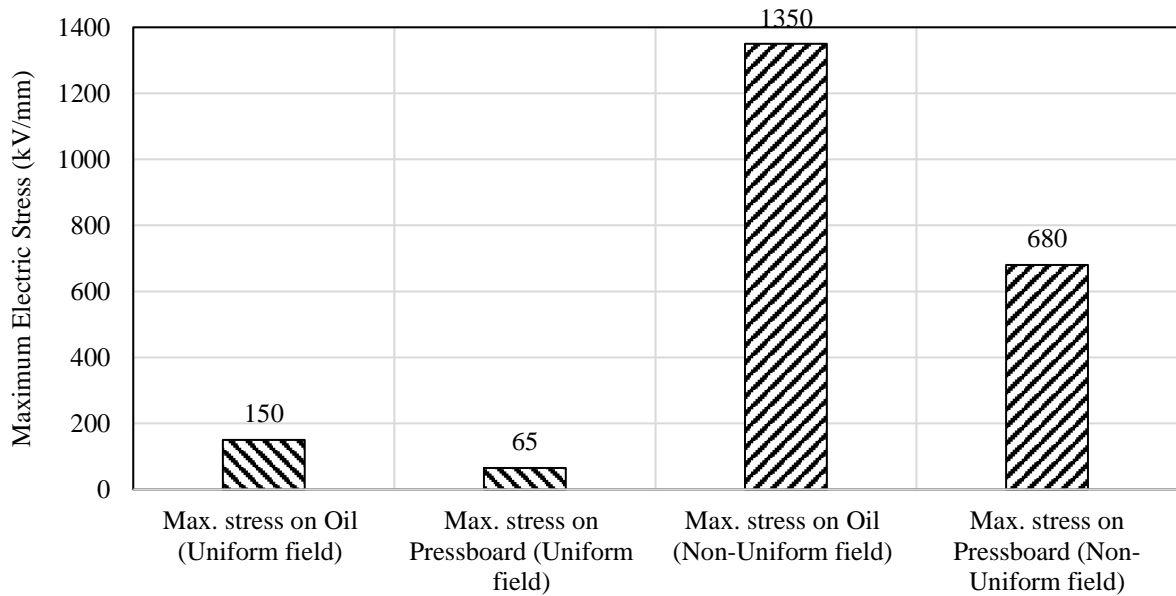


Figure 5.12 Maximum electric stress on Mineral oil impregnated pressboard under positive polarity of impulse in uniform and non-uniform field configuration

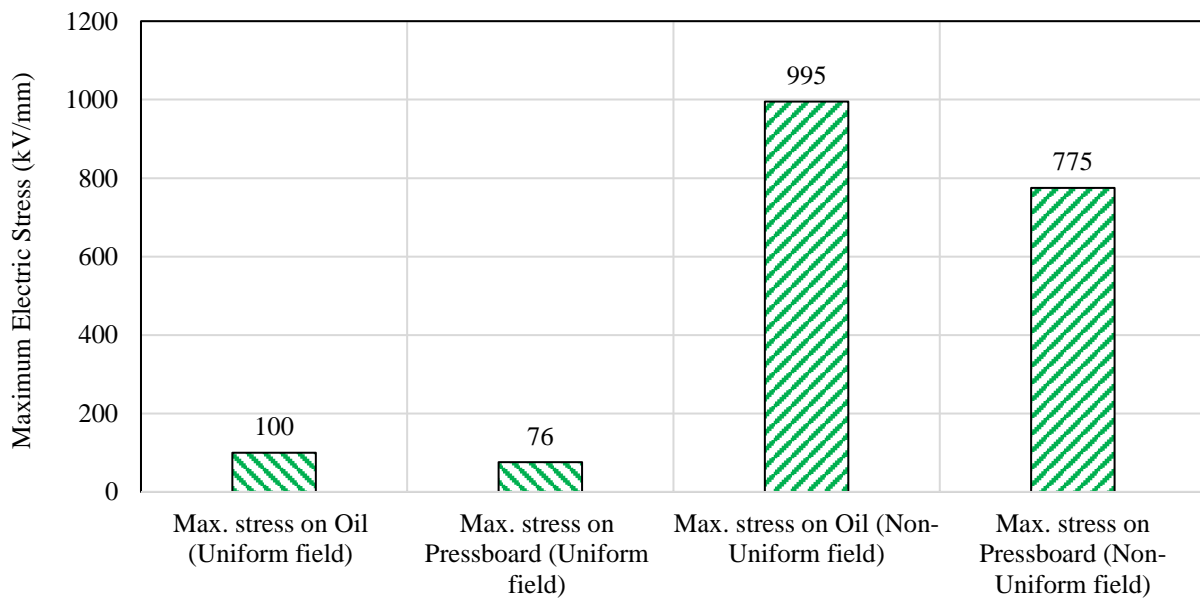


Figure 5.13 Maximum electric stress on Natural ester impregnated pressboard under positive polarity of impulse in uniform and non-uniform field configuration

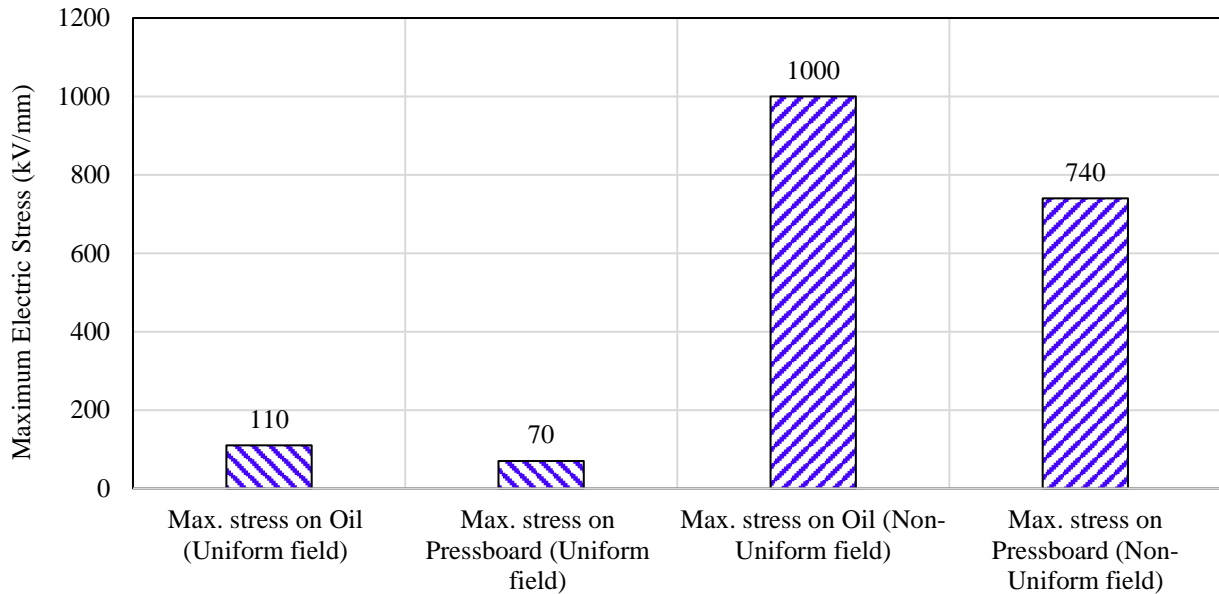


Figure 5.14 Maximum electric stress on Synthetic ester impregnated pressboard under positive polarity of impulse in uniform and non-uniform field configuration

It can be concluded from Figures 5.12, 5.13 and 5.14 that maximum electric stress experienced by the impregnated pressboard and insulating oil near the pressboard is higher for non-uniform configuration as compared to uniform field configuration irrespective of type of insulating oil. For instance, in natural ester impregnated pressboard, maximum electric stress on pressboard in non-uniform field is 775kV/mm at its average breakdown voltage (114.9kV) which is much higher than in uniform field which is 76kV/mm at 113.8kV. This means, impregnated pressboard is more susceptible to fail in uniform field. It signifies that while designing a transformer insulation electric stress limit on solid insulation should be maintained very low for all the insulating oils in uniform field under operating condition of transformer.

5.4.1 EFFECT OF PERMITTIVITY OF INSULATING LIQUID ON MAXIMUM ELECTRIC STRESS

Figure 5.15 and 5.16 shows the effect of permittivity of insulating liquid used for impregnation on maximum electric stress under positive polarity on mineral oil (Transol), natural ester (Biotransol) and synthetic ester (Transol Synth 100) impregnated pressboards in uniform and non-uniform configuration respectively.

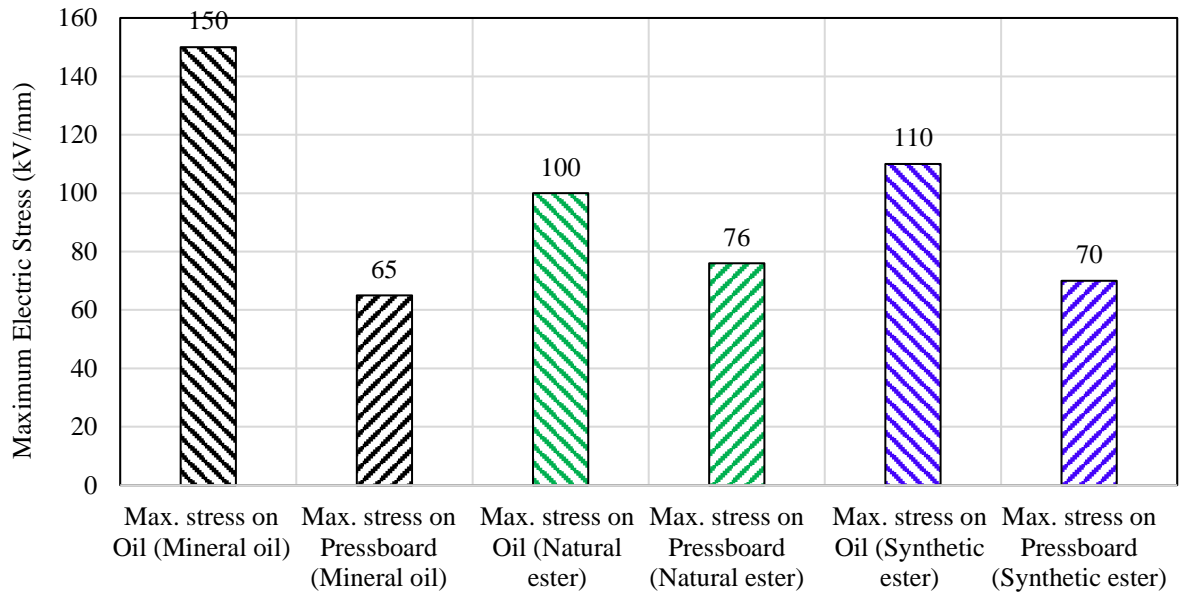


Figure 5.15 Maximum electric stress on Mineral and Ester oil impregnated pressboards under positive polarity of impulse in uniform field configuration

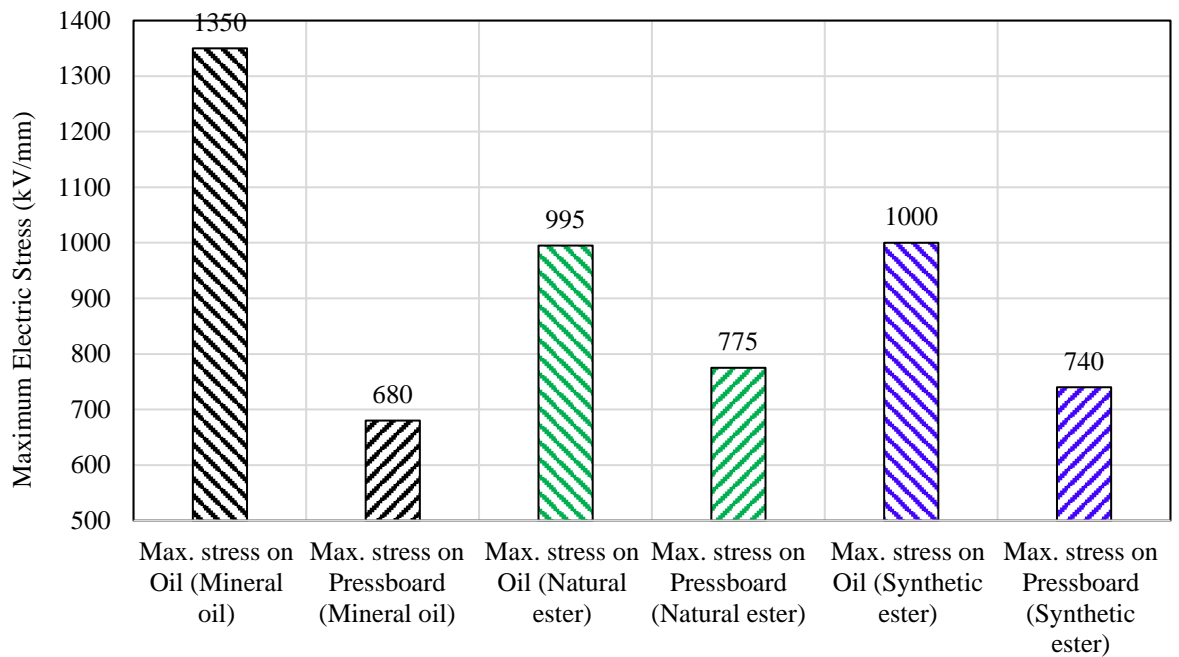


Figure 5.16 Maximum electric stress on Mineral and Ester oil impregnated pressboards under positive polarity of impulse in non-uniform field configuration

It is observed from the Figures 5.15 and 5.16 that with the increase of permittivity of insulating fluid the electric stress on oil is reduced and stress on pressboard is increased irrespective of field configuration. That means, stress distribution is becoming slightly uniform in case of esters as compared to mineral oil. For example, in uniform field configuration, maximum electric stress experienced by the mineral oil is 150kV/mm and its impregnated pressboard is 65kV/mm at impulse breakdown voltage of 113.3kV. The

difference between the electric stress of pressboard and oil is 85kV/mm whereas, in case of natural ester the electric stress on pressboard is increased to 76kV/mm and stress on oil is reduced to 100kV/mm at same impulse breakdown voltage of 113.8kV. So, the difference between the electric stress on natural ester impregnated pressboard and natural ester oil is 24 kV/mm which is very low as compared to the case of mineral liquid. As, the difference between the electric stress on impregnated pressboard and insulating oil is reduced, probability of insulation failure is also reduced.

CHAPTER 6

EFFECT OF AROMATICS AND POLAR CONTAMINANT ON IMPULSE DIELECTRIC STRENGTH AND TIME TO BREAKDOWN OF MINERAL OIL

6.1 INTRODUCTION

In the literature it is mentioned that mineral oil is extremely sensitive to any type of foreign impurities. Therefore, an effort has been made to study the effect of aromatics and polar contaminant on impulse withstand voltage and time to breakdown of mineral oil [8, 43]. Aromatics are the cyclic and planar structures having a ring of resonance bonds which gives better stability to the molecules (for example Benzene ring) [43]. Whereas, molecules containing polar bonds because of difference in electronegativity between the bonded atoms is called polar molecule like, natural ester.

In this research, to study effect of aromatics, two different types of mineral oils, paraffinic inhibited mineral oil (contains predominantly paraffinic chain structure) and naphthenic inhibited mineral oil (contains higher proportion of cyclic structures and aromatics compared to paraffinic oils). Further, to study the effect of polar contamination in mineral oil, natural ester oil (highly polar in nature) is mixed with mineral oil (paraffinic inhibited mineral oil) which is highly non-polar in nature. Experiments for both the cases are carried out under positive and negative polarity in non-uniform field considering electrode distances between 1mm to 10mm. From the results found in chapter 3, it is clear that most of the insulating oils are more susceptible to breakdown in non-uniform (divergent) field as compared to uniform field configuration. This encouraged to study these effects only in extreme non-uniform field.

6.2 EFFECT OF AROMATICS IN MINERAL OIL

Paraffinic mineral oil used in the experiment, contained no aromatics while the naphthenic oil contains cyclic carbon and aromatics rings [44, 45]. These aromatics rings have impact on impulse dielectric property as well as breakdown time of insulating fluid. In this study, these two types of mineral oils are compared to evaluate the effect of aromatics in mineral oil under positive and negative polarity in non-uniform configuration. Figure 6.1 and 6.2 shows the effect of aromatics on impulse dielectric voltage and time to breakdown of mineral oil respectively under positive and negative polarities.

6.2.1 EXPERIMENTAL RESULTS FOR IMPULSE BREAKDOWN VOLTAGE

Figure 6.1 shows the average breakdown strength of paraffinic inhibited mineral oil and naphthenic inhibited mineral oil in non-uniform configuration under positive and negative polarity of impulse.

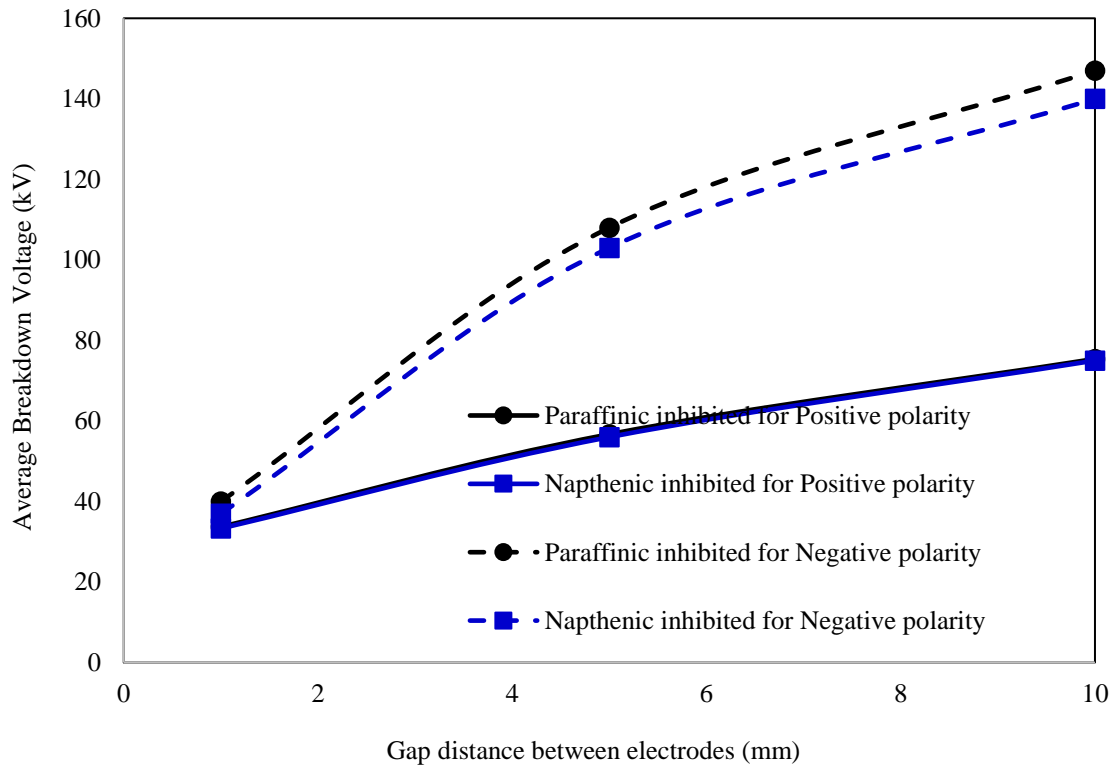


Figure 6.1 Average breakdown voltage of Paraffinic inhibited and Napthenic inhibited Mineral oil under positive and negative impulse in non-uniform field configuration

From the Figure 6.1, followings points are observed:

- Under positive polarity, impulse breakdown voltages of paraffinic inhibited and naphthenic inhibited mineral oil are comparable. It indicates that, there is no effect in impulse breakdown voltage due to aromatics present in mineral oil.
- Under negative polarity, dielectric voltage of naphthenic inhibited mineral oil is slightly lower as compared to paraffinic inhibited mineral oil. In other words, there is an effect of aromatics under negative polarity.

6.2.2 EXPERIMENTAL RESULTS FOR TIME TO BREAKDOWN

Figure 6.2 shows the time to breakdown of paraffinic inhibited mineral oil and naphthenic inhibited mineral oil in non-uniform configuration under both polarity of impulse.

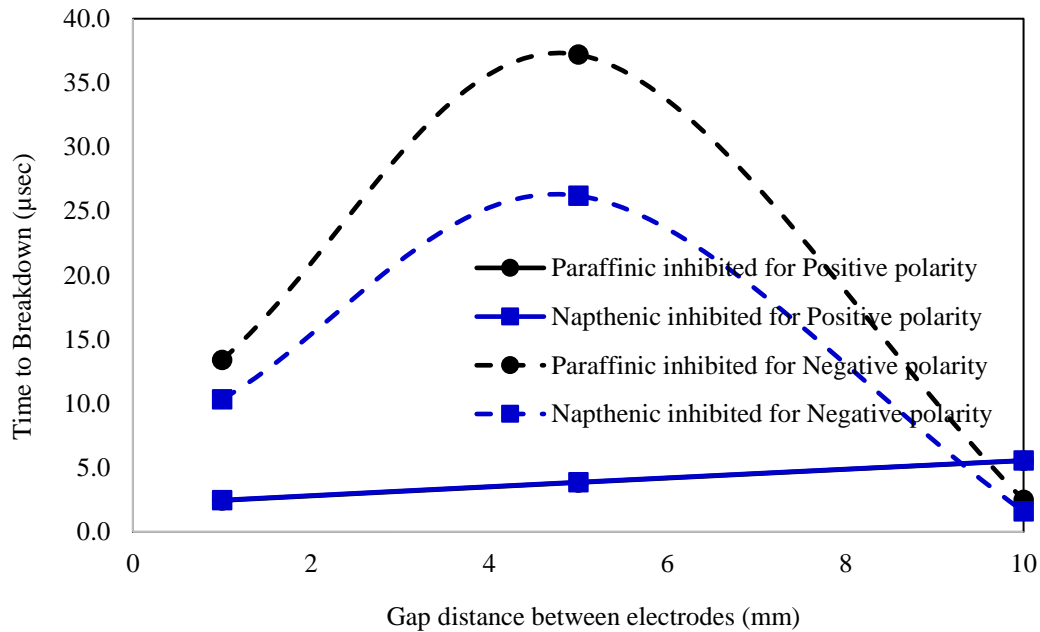


Figure 6.2 Time to breakdown of Paraffinic inhibited and Napthenic inhibited Mineral oil under positive and negative impulse in non-uniform field configuration

From the Figure 6.2, followings points are observed:

- Under positive polarity, time to breakdown of paraffinic inhibited and naphthenic inhibited mineral oil are comparable. It indicates that, there is no effect in time to breakdown of mineral oil due to aromatics.
- Under negative polarity, trend of time to breakdown in paraffinic inhibited mineral oil and naphthenic inhibited mineral oil is similar but the time to breakdown for naphthenic inhibited mineral oil is lesser as compared to that of for paraffinic inhibited mineral oil. Therefore, there is an aromatic effect under negative polarity.

6.3 EFFECT OF POLAR CONTAMINANT IN MINERAL OIL

In this work, natural ester oil (Biotransol) is used as polar contamination in mineral oil. Generally, natural ester oils are completely miscible with mineral oil in all proportions [46, 47]. Therefore, there is a possibility that the two oils may get contaminated with each other accidentally either at factory while manufacturing the transformer or during service maintenance activity at site. It will happen if the transformer maintenance engineer uses the same infrastructure such as oil filtration facility and transfer lines for both different oils. The mixing of two different oils can also take place while carrying out retro filling process without properly removing the residual oil. The retro filling process consists of intentional replacing of mineral oil in the old transformer by either natural or synthetic ester oil [48]. Such mixing can result in change in fire point, flash point and biodegradability of the

insulating oil. In addition, mixtures of two different oils may also exhibit a different dielectric behaviour.

This research work focuses on evaluation of dielectric impulse withstand voltage of mixture of insulating oils under positive and negative polarity in non-uniform field considering electrode distances between 1mm to 10mm. Oil mixture prepared for the study is made up of 90% of paraffinic inhibited mineral oil and 10% of natural ester (by weight). The resultant liquid is referred as Mixture.

The purpose of the studies on the mixture is aimed at understanding the dielectric behaviour when an accidental mix-up of oils takes place. Hence, the natural ester oil is mixed at 40°C with the aid of a magnetic stirrer for about 30 min. To ensure the miscibility (homogeneous mixture) of natural ester oil with mineral oil, mixtures are prepared and left to stand for 1day without disturbance. After the rest time, a homogeneous clear mixture is observed visually. Table 6.1 shows the basic dielectric characteristics of the mineral oil (Transol), natural ester (Biotransol), Mixture (10% natural ester oil in mineral oil).

Table 6.1 Properties of processed oil samples used for impulse experiments

Properties	Mineral oil (Transol)	Natural ester (Biotransol)	Mixture
Breakdown voltage in kV for 2.5mm gap	65-70	70-80	85-95
Water contents in PPM	4-5	55-70	5-6
Total Acid Number in mg of KOH/gm	Nil	0.03	0.0065
Loss Factor @ 90°C	0.0022	0.2	0.0027
Dielectric constant	2.2	3.3	2.31
Viscosity at 40°C in mm ² /sec	8.83	32	9.55

6.3.1 EXPERIMENTAL RESULTS FOR IMPULSE BREAKDOWN VOLTAGE

Figures 6.3(a) and 6.3(b) shows the average breakdown strength of mineral oil, natural ester and mixture in non-uniform configuration under positive and negative polarity of impulse respectively.

From the Figures 6.3(a), and 6.3(b), followings points are observed:

- Under positive polarity, impulse breakdown strengths of mixture and mineral oil are comparable. It indicates that, there is no effect on dielectric voltage due to 10% of natural ester oil in mineral oil.

- Under negative polarity, impulse dielectric voltage of mixture is significantly less as compared to mineral oil. In other words, the mixture is following the same trend as pure natural ester.

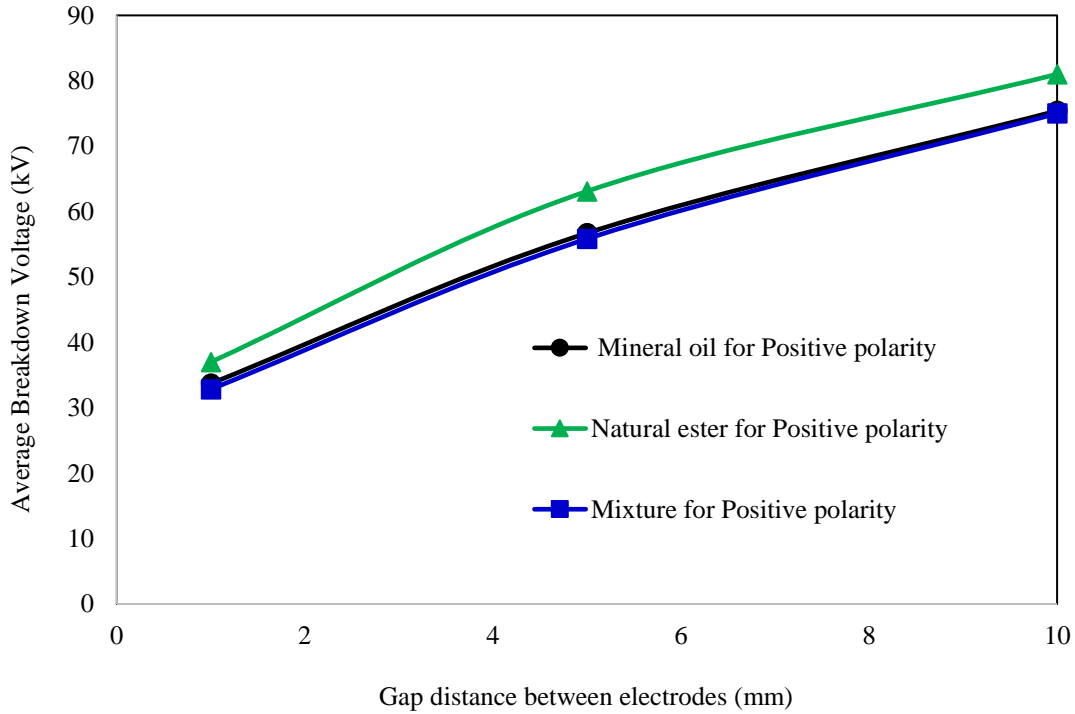


Figure 6.3(a) Average breakdown voltage of Mineral, Natural ester and Mixture oil under positive polarity of impulse in non-uniform field configuration

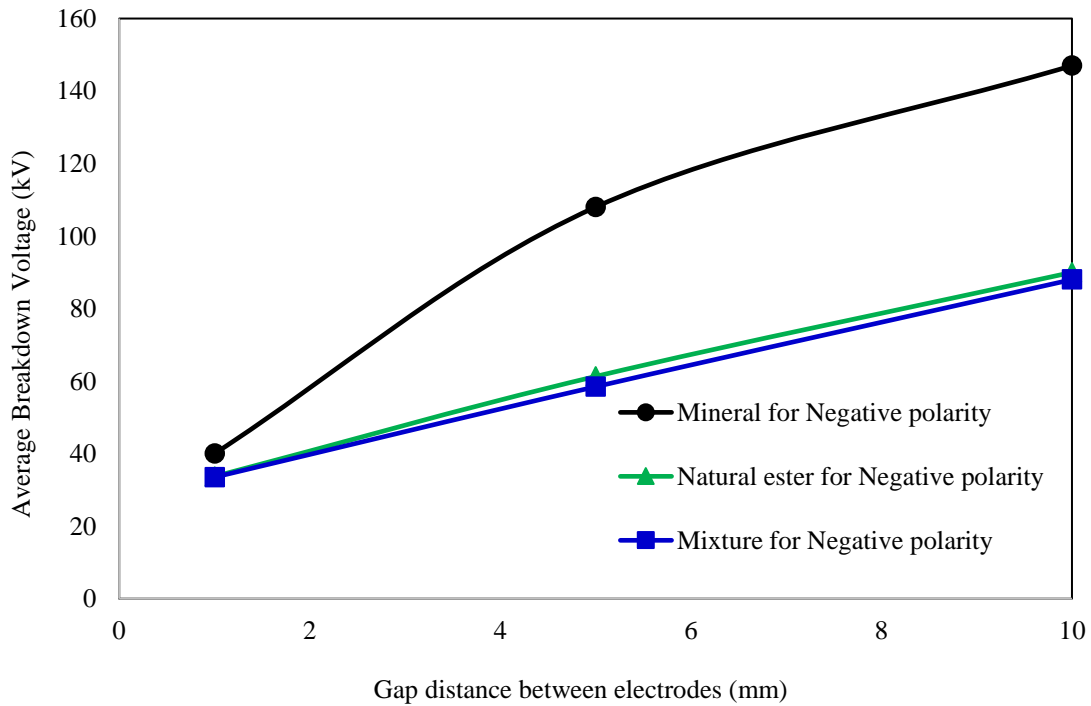


Figure 6.3(b) Average breakdown voltage of Mineral, Natural ester and Mixture oil under negative polarity of impulse in non-uniform field configuration

6.3.2 EXPERIMENTAL RESULTS FOR TIME TO BREAKDOWN

Figures 6.4(a) and 6.4(b) shows the time to breakdown of mineral oil, natural ester oil and mixture in non-uniform configuration under positive and negative polarity of impulse respectively.

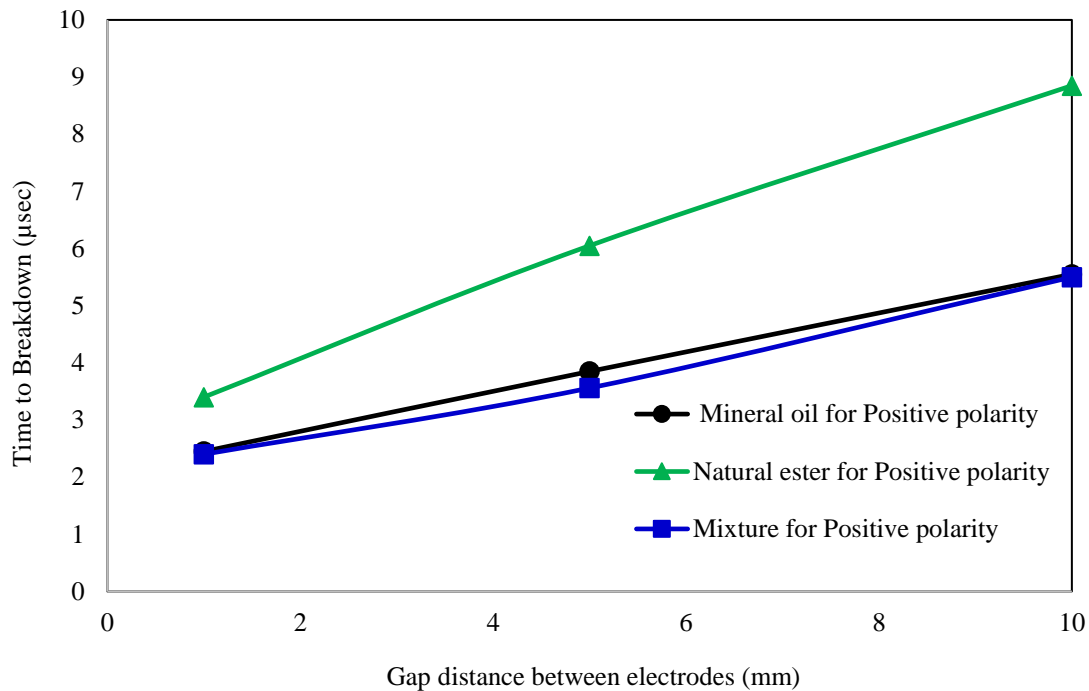


Figure 6.4(a) Time to breakdown of Mineral, Natural ester and Mixture oil under positive polarity of impulse in non-uniform field configuration

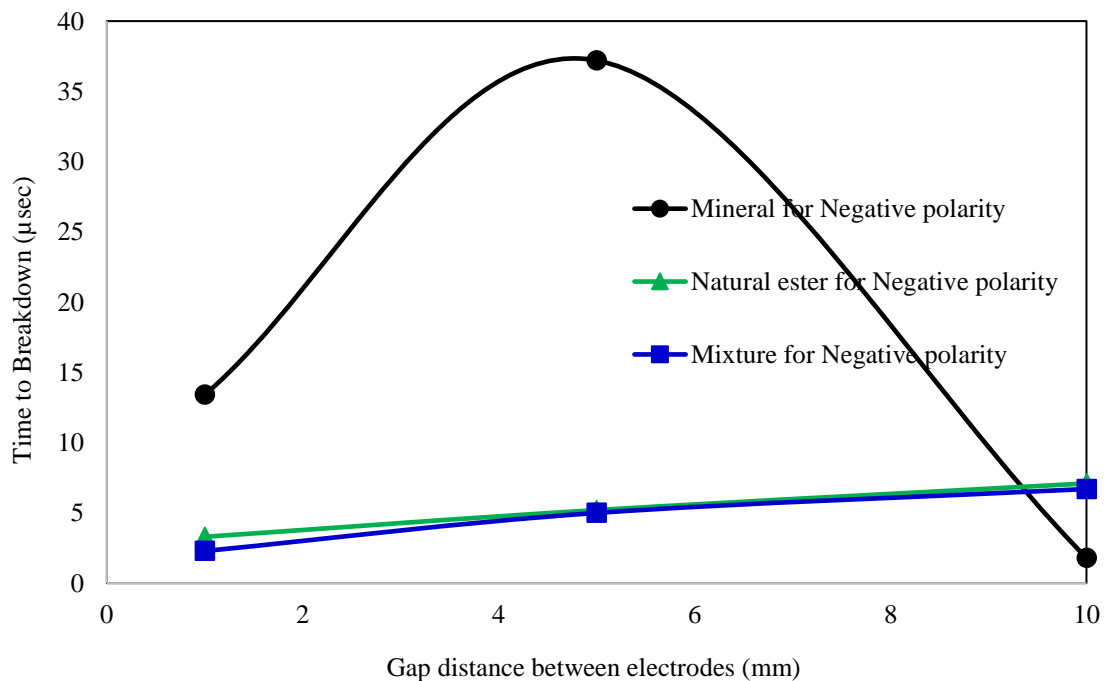


Figure 6.4(b) Time to breakdown of Mineral, Natural ester and Mixture oil under negative polarity of impulse in non-uniform field configuration

From the Figures 6.4(a), and 6.4(b), followings points are observed:

- Under positive polarity, time to breakdown of mixture and mineral oil is comparable. It indicates that, there is no effect in breakdown time due to 10% of natural ester oil in mineral oil.
- Under negative polarity, it is observed that mixture is not at following the basic trend of time to breakdown of mineral oil. Whereas, the trend of time to breakdown in mixture is similar to the trend of breakdown time in natural ester oil.

From the experimental results, it can be concluded that effect of aromatics and polar contaminant is significantly observed in mineral oil only under negative polarity of impulse and not in positive polarity impulse in non-uniform field configuration with respect to breakdown strength as well as time to breakdown.

CHAPTER 7

CONCLUSIONS & FUTURE SCOPE

This thesis work focuses on the dielectric behaviour of ester insulating liquids and its impregnated pressboards under impulse lightning voltage by considering the effects of electrode field geometry, polarity of voltage & electrode gap. Through experimental research work and analysis of data, the major research goals are achieved and thus some important findings are made.

The research areas covered in this thesis are as follows:

- **Evaluation of dielectric impulse withstand voltage of insulating oils**
 - Evaluation of average breakdown voltage and estimation of 1% failure probability voltage for transformer insulation design.
 - Effect of electrode configuration on withstand voltage of insulating fluids.
 - Effect of impulse voltage polarity on withstand voltage of insulating fluids.
 - Determination of maximum electric stress on insulating liquid at withstand voltage
 - Variation of utilisation factor with electrode gap in both field configuration.
- **Evaluation of impulse dielectric strength of insulating oil impregnated pressboards**
 - Effect of electrode geometry on average breakdown strength of insulating oil impregnated pressboard.
 - Effect of impulse voltage polarity on average breakdown strength of insulating oil impregnated pressboard.
 - Effect of electrode geometry on maximum electric stress experienced by insulating oil impregnated pressboard.
 - Effect of insulating oil permittivity on maximum electric stress experienced by insulating oil impregnated pressboard.
- **Effect of aromatics and polar contaminant on impulse dielectric strength and time to breakdown of mineral oil**
 - Effect of aromatics in mineral oil is studied by comparing paraffinic inhibited and naphthenic inhibited mineral oil in terms of impulse dielectric strength and time to breakdown.
 - Effect of polar contaminant (natural ester liquid) on impulse dielectric strength of mineral oil.

6.1 SUMMARY OF MAIN FINDINGS AND RESULTS

- **Summary of Conclusions on Pure Insulating Liquids**

- Especially in case of non-uniform field under both impulse polarities, ester liquids are having lower standard deviation of breakdown data as compared to mineral oil. Lesser standard deviation provides a good reproducibility in the impulse withstand strength for design guidelines of transformers.
- Electrode geometry effect is evident in ester fluids irrespective of polarity of impulse voltage. However, this effect is significant for mineral liquid under positive polarity but no effect is observed under negative polarity.
- Impulse polarity effect is significantly observed in natural ester oil regardless of field configuration. But trend for mineral and synthetic ester oil is different from natural ester oil. In mineral liquid, polarity effect is present under non-uniform field but not in uniform field. Moreover, in synthetic ester liquid it is prominent in uniform field but not in non-uniform field.
- In order to re-confirm the withstand voltages of natural ester liquid (Biotransol) another natural ester liquid of similar type NE2 is evaluated. It is found that there is only 3-4% difference between the withstand voltages of two natural ester oils.

- **Summary of Conclusions on Oil-Impregnated Pressboards**

- In ester impregnated pressboards, it is evident that there is a geometry effect under both the impulse polarities similar to pure ester liquids. Moreover, there is a geometry effect in mineral oil impregnated pressboard under negative polarity but not under positive polarity unlike the case of pure mineral insulating liquid. In case of most of the insulating oil impregnated pressboards, impulse breakdown strength is higher in non-uniform case as compared to uniform field case.
- Impulse polarity effect exists for both mineral oil and ester impregnated pressboards. Mineral oil impregnated pressboard has lower impulse breakdown strength under positive polarity irrespective of field configuration unlike the case of pure mineral insulating liquid. Moreover, ester impregnated pressboards have lower impulse breakdown strength under negative polarity regardless of field configuration.
- In ester impregnated pressboards, maximum electric stress on insulating oil decreases and increases on pressboards which leads to uniform distribution of electric stress on transformer insulation. This reduces the probability of faults in

transformer or insulation failure compared to a pressboard impregnated with pure mineral oil.

- **Summary of Conclusions on Effect of Aromatic Content and Polar Contaminant in Mineral Oil**

- Due to presence of aromatic content in mineral oil, impulse dielectric strength and breakdown time of mineral oil slightly decreases only under negative polarity. In addition, there is no effect under positive polarity.
- The mixture of oil (mineral oil with 10% natural ester oil) behaves like a typical natural ester oil in terms of breakdown strength and time to breakdown under negative polarity in non-uniform field configuration.

The experimental results indicate that, dielectric design guidelines of natural and synthetic ester oil transformer need to be investigated carefully. Moreover, it signifies that transformer insulation design guidelines of natural ester oil and synthetic ester oil should be different from each other. During dielectric designing of transformers, non-uniform field needs to be explored more for insulating oil and uniform field needs to be enquired more for oil impregnated pressboards.

The studies also indicate that in case a mineral oil filled transformer gets mixed with a natural ester oil during vacuum filtration or accidentally then the mineral oil filled transformer may fail in the negative impulse test which is an undesirable effect. Effect of aromatics and polar contaminant is significantly observed in mineral oil only under negative polarity of impulse and not in positive polarity impulse in non-uniform field configuration.

6.2 FUTURE SCOPE

This work majorly discusses about the dielectric performance of ester oils under impulse stresses. These results can help in designing of transformer insulation having ester oil as an insulating liquid and eliminate the probability of faults as well as failure of transformer. However, some research studies in this thesis have deeper scope to make more investigations and more exploratory research.

In this thesis, only 1.5mm pressboard is used for evaluation of impulse dielectric voltage of liquid impregnated pressboard. Study on ester impregnated pressboards with various thicknesses may be studied under impulse stress conditions. In order to understand the effect of polar contaminant on impulse breakdown voltage of mineral oil in more detail, studies can be carried out by varying the percentage of addition of natural ester oil in mineral oil. Also,

effect can be observed by addition of synthetic ester oil in mineral oil. Similar study may be carried out for the case of mineral oil as a contamination in ester fluids.

LIST OF PUBLICATIONS

- [1] Research 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 Oil and its Effect in Mineral Oil for Transformers," has been communicated for acceptance to *IET High Voltage Journal*.
- [2] Research 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 Applications," has been communicated for acceptance to *IEEE Int. conf. on (CATCON 2019)*.
- [3] Research 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 oil as a polar contaminant under AC stress," has been communicated for acceptance to *IEEE Int. conf. on (CATCON 2019)*.
- [4] Research paper entitled as R. Agarwal, P. Sharma, A. Uppal, C.S. Narasimhan, G. Morde and J. Velandy, "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*.

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