Coupled Electromagnetic-Thermal Analysis and Evaluation of Ester Oil under Power Frequency Conditions

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

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in
Power Systems

Submitted by

Anjali Uppal
801742003

Under the Guidance of
Dr.C.S Narasimhan
Head, R &D Savita Oil Technology, Ltd., Mumbai

Dr. Jeyabalan Velandy
Manager, CG Power & Industrial Solutions, Mumbai

Ms. Manbir Kaur
Associate Professor, EIED, TIET

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OF ENGINEERING & TECHNOLOGY
(Deemed to be University)

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

DECLARATION CERTIFICATE

I hereby certify that the work which is presented in dissertation entitled, **"Coupled Electromagnetic – Thermal Analysis and Evaluation of Ester Oil under Power Frequency Conditions"**, in partial fulfilment of the requirements for the award of the degree of Master of Engineering in Power Systems, submitted to Electrical & Instrumentation Engineering Department of Thapar Institute of Engineering & Technology University, Patiala is as authentic record of my own work carried under the supervision of **Ms. Manbir Kaur**, Associate Professor, EIED , **Dr. C.S. Narasimhan**, Head R&D Department, Savita Oil Technologies Limited, Mumbai, **Dr.Jeyabalan Velandy**. Manager, CG Power and Industrial Solutions, 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.

Place: Patiala
Date: 11-7-2019

Anjali Uppal
(Anjali Uppal)
Roll No.: 801742003

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

Date: 11.7.2019

Manbir Kaur 11.7.2019
(Ms. Manbir Kaur)
Associate Professor
Electrical & Instrumentation Engineering Department
Thapar Institute of Engineering & Technology
Patiala

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

Dr. Jeyabalan Velandy
Manager
R&D Department
CG Power & Industrial Solutions
Mumbai

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ANJALI UPPAL

(801742003)

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NOMENCLATURE

CRGO	Cold Rolled Grain Oriented
FEM	Field Element Method
LV	Low Voltage
HV	High Voltage
MS	Mild Steel
MO	Mineral Oil
NE	Natural Ester
E_{max}	Maximum value of Electric Stress

ABSTRACT

With rapid increase in the demand of electrical energy, it becomes indispensable to transmit large quantity of power from major generating stations to load centers with minimum losses. This has necessitated the development of higher rating power transformers. The losses in power transformer need to be estimated accurately as even 3-5kW reduction in losses give a competitive advantage. Stray load loss contributes significantly 20%- 30% of the total load losses. This loss primarily depends upon the leakage flux. Hence it is quite evident to study the electromagnetic behavior of each component of transformer to accurately estimate stray loss. Finite element method (FEM) is a highly efficient numerical method to analyze and compute the electromagnetic field and power losses in conducting parts. Stray losses occur in windings and structural parts of transformer. The other important aspect is to enhance the continuous overloading level of transformer. In oil filled transformer, mineral oil plays a role of coolant and insulator as well. Owing to the good environmental performance in terms of higher flash and fire point as compared to mineral oil, esters liquids are considered as an alternative for higher breakdown strength and more safety and reliability in operation.

The study in this project is aimed to estimate the stray losses for optimal operation of power transformer. Further it is aimed to investigate the ac withstand level of natural ester oil, synthetic ester oil and the effect of polar contamination in transformer oil by considering pure mineral oil as a benchmark. Rising voltage method is used to measure AC breakdown voltage in all cases.Sphere-Needle electrode configuration is considered to create non-uniform field in order to evaluate the winding insulation under actual operating conditions. Weibull distribution is used to model the non-uniform field with 1% breakdown probability. Finally, FEM technique is used to estimate the maximum stress and the degree of uniformity in the consideredliquidunder observation.

It is concluded that the stray losses in the power transformer can be reduced by splitting winding base and use of tank shields.On the other hand the breakdown strength of the transformer insulating liquid having different grades of mineral oil is affected by adding the polar contamination and aromatics content.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The transformer is the building block of power system, which is connecting the network at different stages i.e. from generating stations to the user premises. There are lot of improvements and evolution that have taken place in transformer designing, analyzing, manufacturing strategies and condition monitoring technologies in last ten years. In the forthcoming years, the technological leap will be continuing. It is the responsibility of transformer manufacturing industry to deliver good, cost effective transformers for the phenomenal growth of the power systems. The ratings of generator transformers as well as autotransformers are increasing day by day because the demand of the power is increasing continuously. There is an increase in the voltage rating of transformer on account of continuing trend of the usage of high voltage system for transmission of power due to technical and economical reasons. Although the transformer is the most energy efficient equipment in the power system, but with an increase in the rating of the transformer there is an incremental change in the losses.The Indian power system records nearly 21.42-40% of transmission and distribution losses [1] which is significantly high.

Special design and manufacturing considerations are needed for increasing the ratings of voltage and current. The quality of transformer model and manufacturing procedure should be insured by using advanced computational techniques supported by experimental verifications. There are some essential design challenges such as controlling of stray losses, meticulous prediction of hot spots in winding, withstands under short circuit conditions and reliable design of insulation.With increase in the MVA rating of transformer, there is increment in weight and the size which exceeds the cost of transportation and manufacturing capability. There are number of continuous efforts to optimize material content due to rapidly increase in competition in the global market place.The main objective of the study in this dissertation work, is to estimate stray losses, finding ways to reduce it and to optimize material content for competitive advantage.

Now a day's various transmission and distribution transformers would be coupled by national electricity transmission and distribution network. Most of the power transformers are filled with oil having laminated iron core with paper insulated conductors in an oil filled tank.

The transformer oil has various main functions as it acts as an insulation, coolant and information conveyor. Apart from this there are some secondary properties also which are expected from transformer oil i.e. compatibility of liquid with cellulose solid insulation, fire safety consideration and environmental requirements, etc. Till now, the dominant oil considered for insulation of power transformer is mineral oil because it has been used widely and successfully in practice over a century.

Currently, the ester liquids including both the natural as well as synthetic esters can be considered as an alternatives to the mineral oil due to effective performance related to enviornment and high fire and flash point [2].These liquids are widely used in traction and distribution transformer,but to use them in power transformers, it is crucial to minimize chances of failure in factory tests. To mitigate these factors researchers are gaining more knowledge of the material characteristics and the properties of ester oils whether physical or chemical. The most attractive feature of esters includes high biodegradability, non toxic and high fire and flash point in nature which put no risk to the surrounding environment. The ester oils have a high saturation level of moisture, which helps in the absorption of water from cellulose materials and protects the insulation paper from ageing and deterioration [2]. Since esters are having different physical and chemical properties w.r.t mineral oil, thus it is required to understand the dielectric behavior of liquid and its impact on transformer design.

For using the transformer for high voltage rating it is aimed to control stray losses and to investigate the performance of mineral oil, natural ester oil and synthetic ester oil for transformer applications this dissertation is divided into two parts;

Part I: - Coupled electromagnetic and thermal analysis of power transformer.

Part II: - Powerfrequency withstands level of liquid insulation for transformer applications and effect of polar contamination in mineral oil filled transformer.

1.2 RESEARCH OBJECTIVES

The main objective of this dissertation work is depicted below:-

- Estimation of stray losses in power transformers and to optimize the same for decreasing the capitalized cost in the global market for improving the life expectancy of power transformer
- To evaluate the electrical behavior of ester liquids and mixture of ester liquid in various grades of mineral oil under ac voltage for application in power transformer.
- To determine the value of electrical stress experienced by the insulating liquids in highly non-uniform field at 1% failure probability voltage using the software package ELECNET so as to overcome the chances of failure of the transformer.

1.3 SIGNIFICANCE OF THE PROJECT

- Failure reductions at manufacturing place and at site.
- Optimization and lowering of stray losses for saving the transformer cost.
- To avoid hot spot area under operating conditions of transformer at site.

1.4 OUTLINE OF DISSERTATION

A brief introduction for contents of each chapter is depicted as follows:-

Chapter 1 Introduction

This chapter discusses about research contexts, the main objective for research and the outline of this dissertation.

Chapter 2 Literature Review

This chapter splits into two sections. The first one provides information about different losses in transformer, measures to control stray losses and various techniques utilized to predict the stray losses in transformer. The second part gives a general literature review on the breakdown mechanism of oil under AC voltage. It covers various breakdown theories. The literature review in the respective areas under study is concluded to project research gaps.

Chapter 3 Coupled electromagnetic and thermal analysis of power transformer

This chapter deals with estimation of stray losses, temperature of structural parts of transformer using FEM numerical technique and then its optimization through coupled electromagnetic-thermal analysis of different models aiming at reducing losses and temperature to make it cost effective.

Chapter 4 Power frequency withstand level of liquid insulation for transformer applications

This chapter investigates the difference between the breakdown phenomenon in mineral oil and esters. This chapter also compares the performance of two ester oils with others under power frequency conditions in highly ac divergent fields with 1% failure probability calculations for design purpose of transformer.

Chapter 5 Effect of dielectric strength of mineral oil on mixing with natural ester oil as polar contamination

In this chapter, the AC breakdown performance and comparison of different grades of mineral oil having paraffins and napthenes on adding 10% polar contamination of ester oils under AC conditions is discussed. The study in this chapteralso explores the effect of aromatic content with polar contamination in horizontal field configuration.

Chapter 6 Prediction of dielectric stress analysis due to horizontal cell configuration at power frequency voltage conditions

This chapter discusses about the variation of maximum dielectric stress values at different voltage levels for various types of oils under consideration, at different gaps between the electrodes ranging from 1mm to 20mm.

Chapter 7 Conclusion and future work

This chapter summarizes conclusion and it discusses the further scope of this work.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The designing of basic structure and manufacturing technology of power and transformer has not changed over the decades, so there is not much research and analysis which is required for understanding the various parameters which are related to the transformer.

To model the transformer cost effective and beneficialat high voltage ratingby controlling stray losses and to investigate the breakdown performance of mineral oil, natural ester oil and synthetic ester oil for transformer applications this thesis is divided into two parts

Part I: Coupled electromagnetic and thermal analysis of power transformer.

Part II: Powerfrequency withstands level of liquid insulation for transformer applications and effect of polar contamination in mineral oil.

Part 1:- Literature review for coupled electromagnetic and thermal analysis

2.2 ORGANIZATION OF LITERATURE REVIEW

This chapter consists firstly all the books and research papers i.e. pioneering basic literature review, which deals with the stray losses. It is important for researcher to read the reviews which includes all the papers and books related to eddy current and the stray losses. A subsequent part of the chapter contains the review of paper which is related to eddy currents, stray loss components. Stray loss components are tank, flitch plates, frame, winding base, base supports and other core clamping components. There are some papers which are related to 2-D and 3-D methods of calculating the stray losses are also reviewed.

2.3 BASIC LITERATURE

Karsai [3] deals with the calculation and control of stray losses. It has been well explained that with increase in losses in transformer in structural parts and rise in the temperature as well. This book deals with the analytical 2-D method for computation of eddy losses. For estimation of stray losses in tank, for finding hotspot areas various 3-D analytical methods has been discussed.

Book by Turowski [4],is also very important which deals with the electromagnetic field in transformers and other electrical machines. This book covers the basic fundamental equations which are related to electromagnetic fields. This book consists of many useful formulae, thumb-rules and various curves which are very helpful for the designer for understanding and to estimate the stray losses.

The remarkable book by Savini and Silvester [5] deals with the FEM technique and it is very good book for beginner to understand the basic concepts of FEM, formulation of mesh, how to represent the magnetic material.

Kulkarni and Khaparde [6] in their remarkable book on transformer design, technology deals with the theory and computation of electromagnetic fields in the transformer. This book also discussed about the vector algebra and calculus which proved to be very helpful in understanding the behavior and electric field distributions inside the transformer.

2.4 LOSSES IN TRANSFORMER

2.4.1 WINDING EDDY LOSSES

The eddy losses in transformer due to the presence of radial and axial component can be estimated with basic formulae and various analytical and numerical methods. But it is dubious to calculate eddy losses due to radial component with the help of conventional formulae because it will not give accurate results. For computation of eddy losses due to both axial as well as radial component 2-D FEM technique can be used. The winding is divided into many sections and ampere turn density is defined for each particular section. After this by adding the losses of whole winding sections, the eddy current losses are then calculated. The knowledge of flux density distribution is also fruitful for choosing the dimensions of the conductor. In large power transformers, it is advisable to design low voltage winding with CTC having lower dimensions of strip axially and radially for reducing eddy losses [8].

On dealing with small transformers, the modeling of every turn of LV winding should be done in FEM because sometimes the flat conductor having more thickness as compare to skin depth of material copper and sometimes it is comparable.

2.4.2 CIRCULATING CURRENT LOSS IN WINDINGS

Circulating currents produced when unequal emf induced due to unequal leakage flux field in low voltage winding which is made up of parallel conductors. With the help of continuous transposition these losses can be reduced to a very small value which is almost negligible [8], [9]. The circulating current losses are also calculated more accurately by 3-D simulations.

2.4.3 STRAY LOSSES IN FRAMES [7],[9]

Frames are also known as yoke beams and it is used for providing support to winding and for clamping the yokes. The hotspots seldom develop in them because of their large surface area. FDM(Finite Difference Method) and analytical techniques are used for calculating stray losses. Frame is generally made up of material named mild steel, aluminum and non magnetic steel and the corresponding losses in them are compared.It is not recommended to use non magnetic steel as a material for frames. Its cost is very high and losses are less only when thickness is small.

2.4.4 STRAY LOSSES IN FLITCH PLATES

The flux which departs radially from the interior surface of the winding is called stray flux. It strikes with flitch plates which are seated on the core. The magnetic flux density may be more on the outside part of flitch plate as compared to tank surface. However, the losses which appears in a flitch plate are not forming an important part of the total load loss of transformer, but the rising temperature in transformer can be more higher and hazardous due to large value of flux incident on it and poor cooling system.Flitch plates have different designs for different ratings of transformers. For small rating of transformers flitch plates are generally made up of material named mild steel having no slots to lower the incident field which results in producing the hot spots. For large transformers where incident field is more, flitch plates are provided with slots at both top as well as bottom ends respectively. Wholly slotted plates are also superior, but they are not mechanically strong and have complicated manufacturing process on comparison to other designs. Laminated flitch plates would be the best option when the incident leakage is more than large generator transformer [5-7]. Table 1 depicts the losses in mild steel (MS) flitch plate.

Table 2.1:- Calculation of Losses in MS Flitch Plate

Type of MS Flitch Plate	**Losses (W)**
No slot	120
1 slot at bottom	90
2 slots at top and bottom	50
3 slots through the length	43
7 slots	30
Laminated flitch plate	25

2.4.5 STRAY LOSSES IN TANK

The stray losses in tank structure forming a large portion of total losses in large power transformers. Magnetic flux which departs radially from the outer periphery contributes a major portion of the total stray loss in windings and causes the increment of losses due to eddy currents in transformer tank walls [9].The losses in tank structure may be more due to its more area, although the stray flux density is low. Since the oil is carrying the heat away from the which results in the formation of hotspots which may or may not develop on the tank walls. If the tank material has good thermal conductivity, then it aids to diminish the hot spots. The stray losses in tank walls can be controlled by magnetic or eddy current shields.[8],[9] Earlier analytical methods were used nut now for getting accurate results 3-D FEM technique is to be used.

2.5 OVERVIEW OF SOME TECHNIQUES FOR STRAY LOSS EVALUATION

There is not a direct measurement method of stray losses. It is important to understand the methods used for the computation of stray lossesanalytically. Finite element method based 2-D and 3-D models are evolved to estimate stray losses analytically.

2.5.1 TWO-DIMENSIONAL (2-D) METHOD

This method is practiced for guesstimate of leakage flux in which the distribution of current density can be firmly determined into space harmonics with the help of double Fourier series. This method is utilized to calculate the estimated value of losses because the distributions of leakage field in the core window can be achieved with this 2-D approach. The two dimensional FEM technique is basically consider to attain static magnetic field and various analytical methods are used for finding losses in the tank walls [7]. These 2-D methods are particularly used for computation of eddy losses in the windings.

2.5.2 THREE- ANALYTICAL FORMULATIONS

In the world full of three dimensional calculations, 2-D methods are only preferable for the daily estimations of stray losse. The 3-D formulation uses the method of images to obtain the radial flux distribution. This method simply ignores the outcome of eddy currents which induced in the tank due to the incident field. The Maxwell's equations can be used for calculation of flux density and the magnetic field intensity. Then by assuming the step magnetizing characteristics, the power loss per unit area can be easily calculated with this resultant peak. By integrating the losses over entire area the total losses can be calculated. These analytical methods are not applicable for complicated structure of tank and for accurately detecting the effects of the tank shield [7-10].

The Maxwell's equations are valid for the static, time harmonic dependent fields and for the free space. The Maxwell's equations in differential form are given below:-

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{2.1}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{2.2}$$

$$\nabla . B = 0 \tag{2.3}$$

$$\nabla . D = 0 \quad (2.4)$$

H= magnetic field strength

E= electric filed strength

B= flux density

J= current density

D= electric flux density

ρ= volume charge density

2.5.3 3-D NUMERICAL METHODS

These methods holds good for estimation of 3-D fields in interior of the transformers and accurate calculation of stray losses. It is quite difficult to decide the boundary condition to structural parts and for non magnetic steel because these are open boundary condition and that's why the boundary element method is most preferable. Some researchers also use FEM for open boundary conditions. For generation and making the mesh easier FEM with Surface Impedance is proposed [12].However FEM technique is versatile method used for handling the non linearity. It is used to solve complex field problems by simulation using commercial software. There are different types of formulations of FEM

1. Static Formulations
2. Time Harmonic formulations
3. Transient formulations

Time Harmonic Formulation: - These are basically falls under the category to analyze the eddy current losses and stray loss in structural components of transformer. It is assumed that the materials used in transformer are magnetic in nature, such all the voltages, current and fields are sinusoidal in nature for given sinusoidal voltage and current excitation which allows them to be treated as time harmonic (phasor) quantities.

Transient formulations:-Transient formulations are useful for the computation of magnetic fields that varies over time; these fields are basically caused by surges occurs due to voltage and current.However, this method takes more simulation time to achieve accuracy of certain standard level. Both linear and nonlinear analysis can be possible.Using transient formulations inrush currents and dynamic short circuit forces can be calculated using the partial differential equation for two dimensional in linear medium can be expressed in equation (2.5) as:-

$$\frac{1}{\mu}\frac{d^2 A(t)}{dx^2} + \frac{1}{\mu}\frac{d^2 A(t)}{dy^2} = -J(t) + \sigma \frac{\partial A(t)}{\partial t} \quad (2.5)$$

μ= permeability

A= magnetic vector potential

J= current density

σ= conductivity

Axisymmetric problems: - This is basically used for analysis of leakage field and forces which are related to transformer winding. The cylindrical coordinates are basically used to solve the Poisson's equation for finding the flux lines. The corresponding partial differential equation is expressed as:

$$\frac{\partial}{\partial r}\left(\frac{1}{r\mu}\frac{\partial(rA_\phi)}{\partial r}\right)+\frac{\partial}{\partial z}\left(\frac{1}{\mu}\frac{\partial(rA_\phi)}{\partial z}\right)=-J_\phi \tag{2.6}$$

Non Linear problems: - Nonlinear problems are basically used for those materials whose property varies as a function of filed variables. The non linearity is dependent on the material permeability. The permeability curve for a nonlinear material can be presented by the equation (2.7) as:

$$H=(a_1e^{a_2B^2}+a_3).B \tag{2.7}$$

Where, H= magnetic field strength

B= flux density

Where a_1, a_2 and a_3 are termed as constants to determine the shape of the B-H curve.

The reluctivity of particular material is shown in equation (2.8)

$$v=a_1e^{a_2B^2}+a_3 \tag{2.8}$$

The Newton-Raphson method is basically used because of its quadratic convergence characteristics. In this method the initial solution is attained by considering that the reluctivity has the constant value in various nonlinear regions. Value is updating iteratively as expressed in equation (2.9), in finite elements by using a multiplying factor (η) which is called as relaxation factor.

$$v_{new} = v_{old} + \eta(v_{new} - v_{old}) \tag{2.9}$$

Part II: - Power frequency withstand level of liquid insulation for transformer applications

In this section the breakdown theories in insulating liquids are reviewed first and then followed by the explanation of breakdown process in both non divergent and divergent fields. By considering the most useful experimental results from extensive literature, it is believed to provide complete background and research achievement of breakdown mechanisms in transformer insulating liquids over the last 100 years.

Most of the previous studies mainly investigate the usage of mineral oil or saturated hydrocarbon liquids. In the past few years, it became successful to use esters liquids in distribution transformer, but still much research effort is required to prepare for the application of ester in high voltage rating power apparatus. Therefore it is very important to understand the dielectric performance of esters.

2.6 THEORIES OF BREAKDOWN

It is not simple to explain the breakdown theory since the mechanism responsible for the breakdown is still a controversial topic. Many breakdown theories came into picture which can be categorized as follows:-

- Ionization theory explains that at high voltage the electrons quicken to ionization energy and the collision of electrons and accumulative ionization process in insulation liquids is responsible for breakdown [2].
- Weakest- link theory believes that the dielectric strength of liquid depends on either the inhomogeneities in the bulk liquid or by the impurities, chemical additives, dissolved water, geometry, gap between the electrodes, irregularities on electrode surface [16],[17].
- Streamer Theory postulates that the breakdown in insulating liquids occurs due to initiation and propagation of gaseous channel which is known as streamer. Streamer theory is widely accepted that breakdown occurs when streamer channel bridges both the electrodes.

2.6.1. BREAKDOWN OF INSULATING LIQUIDS IN UNIFORM FIELDS

The features of breakdown in insulating liquids reported in the research [13], [14] is concluded as:

- The streamer is responsible for the breakdown and the final breakdown occurs when streamer fully spans the electrode gap.
- The average electric field is high for each streamer leads to the final breakdown.
- In highly uniform fields the breakdown is determined by the streamer initiation.
- The streamer is initiated by the presence of particles, gas and water content.
- In uniform fields the streamer inception voltage is equal to the breakdown voltage.
- The breakdown is mainly dependent on negative streamers because negative streamers are produced at lower voltage than positive streamers

2.6.2 CONDITIONING EFFECT

It is observed that initially insulating liquid shows the lower breakdown voltage while using new electrodes. The value of breakdown voltage increases noticeably after few breakdowns and gets stabilized acting as conditioning. This phenomenon is observable in both impulse as well as A.C conditions. It can be minimized by polishing the electrodes or by de-gassing the liquid in vacuum.

2.6.3 BREAKDOWN OF LIQUID UNDER DIVERGENT FIELDS

The breakdown in liquids subjected to divergent fields as reported in paper [13] has been concluded as:

- Streamer will lead to partial or complete breakdown.
- Mainly affected by intrinsic properties such as electron affinity.
- When streamer occurs the value of average field is low, the breakdown is determined by streamer propagation
- The streamer inception voltage is less than the breakdown voltage.
- In divergent fields the positive streamers can easily propagate than negative streamers. The positive streamers are responsible for the breakdown in insulating oils

2.7 STREAMER INITIATION IN INSULATING LIQUIDS

The streamer initiation in liquids is basically influenced by the tip radius and the field geometry also.

2.7.1 INFLUENCE OF TIP RADIUS OF CURVATURE AND FIELD GEOMATRY

- Local electric field is an important factor for initiation of streamer.
- In non uniform needle – sphere arrangement, the maximum electric field is dependent on the tip radius of curvature as compared to gap distance.
- It has been observed that plane- plane and sphere –sphere arrangement has more value of streamer inception voltage for both positive and negative streamer rather than needle–sphere arrangement due to electrostatic influence of plane electrode behind the triggering tip. The streamer inception voltage increases with an increase in the tip radius [2],[12],[13],[14].
- Although with the increase in tip radius, the reduction in the inception field with an increase in inception voltage has been reported. The inception field has been calculated on the basis of inception voltage and electrode geometry, explained by area effect.
- Area Effect: - As the surface area of electrode is increasing, the increase in the chances of defects on the electrodes and in locally stressed liquids has been reported.

2.8 STREAMER PROPAGATION [21]

- The propagation of streamer takes place when applied voltage exceeds the inception voltage.
- The propagation of positive streamer for enhancement of field is very high at tip to ionize the surrounding molecules of liquids. The streamer tips absorb all the electrons produced by ionization process.It leaves behind all the positive ions which are responsible for extension of streamer channel
- The negative streamers are near to HV electrode, they only start their propagation when threshold voltage is lower than applied voltage. The propagation of negative streamers results in the expansion of the gaseous streamer channel due to high temperature and pressure inside the channels by the currents.

2.9 BREAKDOWN PHENOMENON IN OIL AT AC CONDITIONS

The breakdown phenomenon of insulating liquids is generally affected by the dissolved water, metallic impurities, geometry, and material, gap between the electrodes, temperature conditions, amount of dissolved gasses, and the wave shape of applied voltage. Therefore breakdown is a statistical phenomenon, if test conditions changes, might be there is change in the breakdown values. The above mentioned factors are dominating in non-divergent field. In non divergent fields, due to high average field every streamer will propagate to breakdown and the streamer inception voltage is almost same as breakdown voltage. For highly divergent field (sphere-needle) configuration streamers propagation plays a major role. In divergent field due to enhanced electric field streamer initiation is easy. The breakdown is determined by streamer propagation as low value of average field. When the applied voltage is high enough or more than the streamer inception voltage, then streamer start propagates and reaching towards opposite electrode for final breakdown. Thus the breakdown voltage is more than the streamer inception voltage. The space charge effect also playing an effective role in the propagation of streamers under AC voltages [2]. The duration of voltage application under AC is in a few milliseconds as compared to impulse in few nanoseconds, more space charges need to be injected by HV electrode in the liquid surrounding the electrode, and thus the space charge effect has been significant in AC. The streamer inception voltage is increased by homo-charge and reduced by the hetro-charge as reported.

CHAPTER 3

COUPLED ELECTROMAGNETIC AND THERMAL ANALYSIS OF POWER TRANSFORMER

3.1 INTRODUCTION

The transformer is connecting the network at different stages from generating stations to the user premises. It consists of magnetic circuit which is known as a heart of the transformer. The magnetic circuit is in the form of laminated core structure, which transferring the electrical energy from one circuit to another. As this is well known that transformers operate 24*7 during which it undergoes various losses as shown in Figure 3.1. These losses can be categorized in two types.

1. No load losses
2. Load Losses

No load losses consist of eddy losses and hysteresis losses which occurs in laminations of the core, whereasload losses are those which occurs in windings due to ohmic resistance and some additional losses. Moreover, the additional losses which occurs because of the leakage flux of windings and due to high current carrying leads are known as stray losses. The stray losses increases with the increment in the rating of transformer, inters increase in the normal temperature which degrades the life of a transformer.

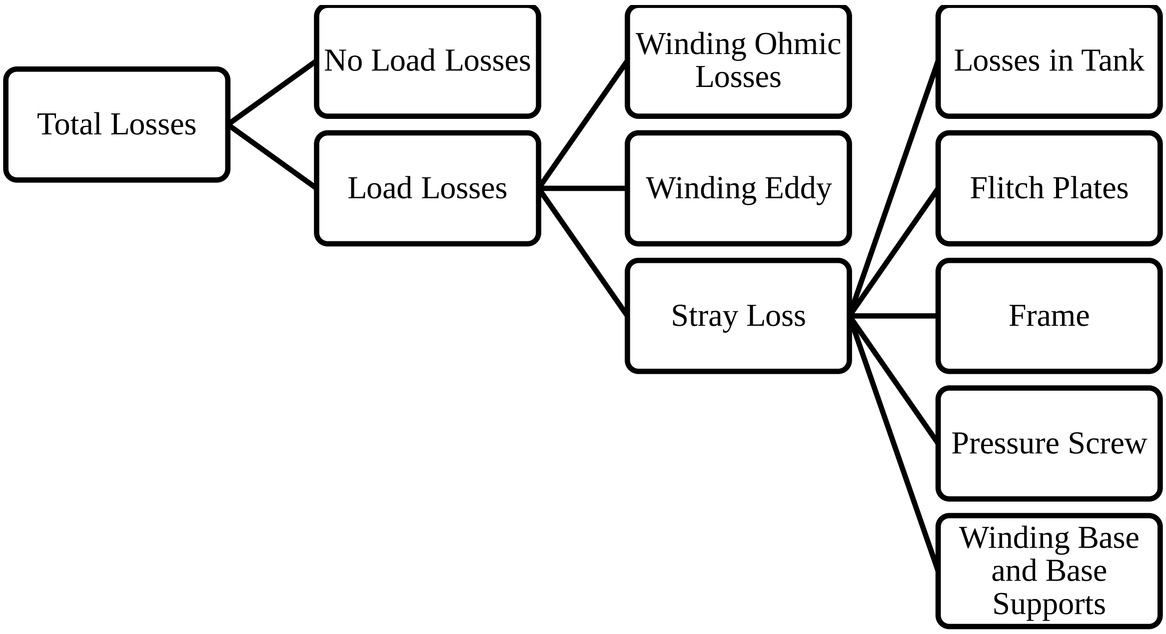


Fig. 3.1:- Classification of Different Types of Transformer Losses

Winding ohmic losses cannot be reduced to much extent because it depends on the property of the material whereas winding eddy losses depends on the particular formula. Eddy current losses vary in the form of frequency class i.e. with the square of frequency. Winding eddy losses can be reduced by using laminated core and by using superimposed conductor. It is difficult to compute stray losses of transformer because it is asymmetrical and having 3-D structure.

Hence various analytical and numerical techniques are utilized to estimate the stray losses in transformer.

In structural part, the stray losses mostly occur in tank and in all supporting structures. Supporting structures mainly includes flitch plates, clamps and frame etc. Because of the large size of tank, major portion of losses occurs in it only. Stray field coming out of the winding basically hits the tank in radial direction [7]. The tank is usually made of Mild steel, which is the property of a magnetic steel and ferromagnetism. The tank can also be made of stainless steel, which is non-magnetic steel that has the property of paramagnetic. Thus the factors affecting stay losses are called thickness, frequency, material, source, load, resistivity etc. Stray losses are low clamping elements having smaller area (e.g.) flitch plate, but the field incident on them is high enough to cause unacceptable rise in local temperature and then affects the transformer life.

Increasing the performance of a particular transformer will positively reflect on the quality of its network. The power transformer is one of the highest efficiency power machine of the order of 99%. However, manufacturers also want to accomplish high efficiency and want to be more competing in the electricity transformer market. It is much important for calculating the performance of power transformer at this level, and that it is not only the result of the assessment i.e. the loss of a similar transformer. Here correct calculation of performance is required, for example, a stray loss of a power transformer on the basis of numerical modeling brings improvement in the transformer model and increases the overall efficiency in case of less losses.

3.2 STRUCTURAL COMPONENTS OF TRANSFORMER

Core of transformer: - The part of core which is between the winding is called limb while the other part which is not covered by winding is known as yoke. The yoke is essential for completion of the path of magnetic flux. Core leg carries all the LV, HV and tap windings. The low voltage windings are provided with insulation from core as they are placed next to core. The high voltage windings are laid over low voltage winding with proper insulation between the two. The core of transformer can be built using stack laminations having thickness in the range of 0.23mm to 0.35mm. The main purpose of core is to provide a path having low reluctance to magnetic flux which is produced by excited winding. As most of the flux is present in the core helps to reduce stray losses in structural components of transformer.

Frame: -Frame of transformer is also known as yoke beams. It serves to provide clamping to yokes and supports the winding also.

Flitch plates: - Flitch plates are assembled on the core. These are used to strengthen the core laminations together in vertical direction.

Top Stay and Base foot: -The both structural component of transformer is used for mechanical locking. They are used to hold core and frame. Top stay is used to support top where base foot is used to support bottom.

End tie rods: -Tie rod is a long rod having bolts or tie bolts at both the end. This rod tightens the two adjacent frames.

Pressure Screw: - Pressure screw is used to tighten the core and frame. It gives force to compress the winding.

Winding base: -The main function of winding base is to hold and support the entire structure of windings.

Winding base supports: -The winding base supports provide mechanical strength to winding base by joining it with frame.

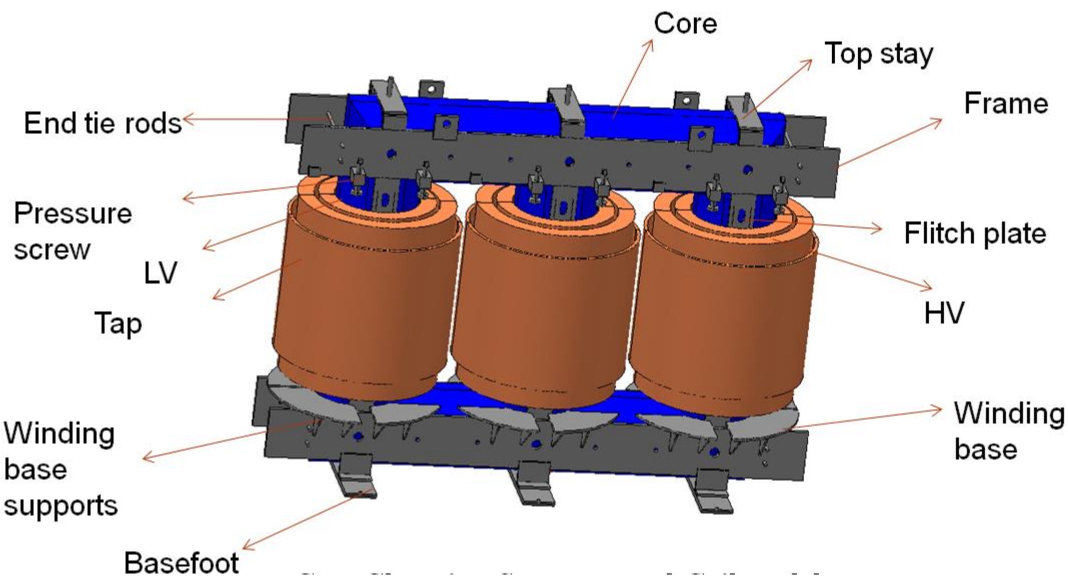


Fig. 3.2:- Basic Structure of Transformer

3.3 ESTIMATION OF STRAY LOSSES

The main objective of this work is to predict and estimate the stray losses which happen due to presence of leakage field in transformer winding and in magnetic structures and the temperature distributions within the transformers. This work is mainly focused on the reducing the stray losses in transformer and optimize the cost of material which helps in to reducing the overall size of transformer and improving the energy efficiency by reducing the failures in terms of electrical and thermal. Stray losses may contribute about 20% - 30% of total load losses in transformer if not evaluated and controlled properly [1],[7]. An accurate estimation of these stray losses is required which gives correct value of capitalized cost and also helps to avoid financial penalties.

In this 25/31.5MVA,66/11KV power transformer is used for estimation and minimization of stray losses in structural components of transformer. Losses at different components like Tank, Flitch plate, and Frames has been estimated using the simulation tool MagNet. The losses then reduced to a considerable amount by providing transformer tank shunt or shielding and slots in the flitch plate and by providing slots in winding base.

3.3.1 SOLUTION METHODOLOGY

For designing of transformer the major necessary parameters are:-

- Power Rating
- Voltage Level
- Current
- Core Area
- Number of turns

ASSUMPTIONS:- For supply frequency of 50Hz, the basic need is magnetic flux and turns per volt. For designing a transformer the magnetic flux is averagely taken as 1.72 Tesla according to IS2026. It is a practical transformer so it is necessary to consider the core calculated using Equation (10) as:

- Core diameter ,cm= $4*\sqrt[4]{KVA}$ (3.1)

  $=4*\sqrt[4]{31500}$

  =53.2cm

  Where, 4 is the value of numerical constant at 50 hertz frequency. For diameter 53.2cm, the area is taken as 2314 cm^2

- Calculate V/T based on 1 and 2

  V/T $=\sqrt{2}*\pi*f*B*A$ (3.2)

  = 4.44*50*1.727*2314

  = 119 V/T

  Where, f= frequency

  B= magnetic flux density

  A= area of core

- Calculate turns of lowest voltage winding

LV turns= $\frac{LV\ phase\ voltage}{\frac{V}{T}}$ (3.3)

= 92 turns

Similarly, the number of HV turns can be calculated.

3.3.2 Maxwell FEM analysis – MAGNET

1. **Problem definition: -** To estimate the stray losses in the power transformer and then optimize the actual model by reducing the losses.
2. **Field Domain:** - The domain is encircled in one boundary which is termed as air box. The space which is outside this boundary is not considered in the field problem domain.
3. **Dimension:** - Three dimensional problems specified in XYZ plane.
4. **Medium:** - The dielectric medium is different for different components of transformer. The core structure has anisotropic property, but for structural parts, the dielectric medium is isotropic (i.e. it has the same behaviour w.r.t. field at a negligent of the direction of that particular field). Both mild steel and stainless steel can be used for structural components. Mild steel is nonlinear in nature, whereas stainless steel is linear. The value of relative permittivity is also different for both.
5. **Type of problem:** - The problem considered here is 3D linear Time Harmonic analysis. It is assumed that the materials used in transformer are magnetic in nature, so that all voltages, currents and fields are sinusoidal in the problem domain for given sinusoidal voltage and current excitation which allows them to be treated as time harmonic (phasor) quantities.
6. **Governing equation:-**The Maxwell's equations holds good for static, time harmonic dependent fields and free space. The Maxwell's equation in differential form is given as in Equation (3.4):

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (3.4)$$

Where E= electric field strength

B= flux density

7. **Governing Method: -**The Newton- Raphson iteration method is used because of its quadratic convergence characteristics.

8. **Boundary Condition: -** The surface Impedance boundary method [18] assumes that the current density is uniformly distributed which allows the use of large element sizes.

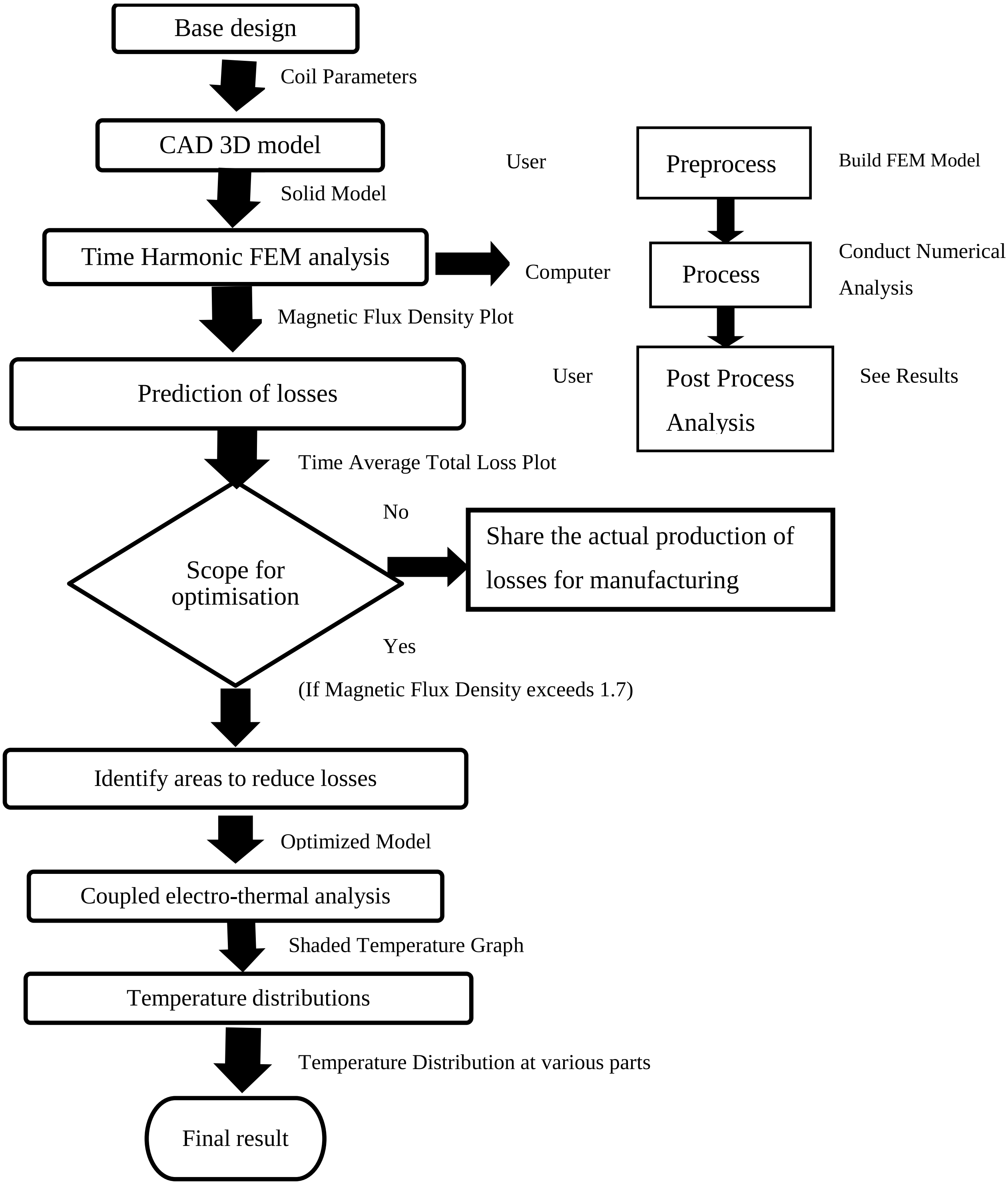


Fig. 3.3:- Flowchart for Electromagnetic Analysis

Base design represents the design sheet of the transformer. The design sheet specifies the MVA, Type(Auto/Non Auto),rated voltage ratio, frequency, impedance, connections of the transformer.

1. **Importing the 3-D model**: - Firstly import the solid model as shown in Figure 3.4which is designed in solid works in the software package named MagNet.

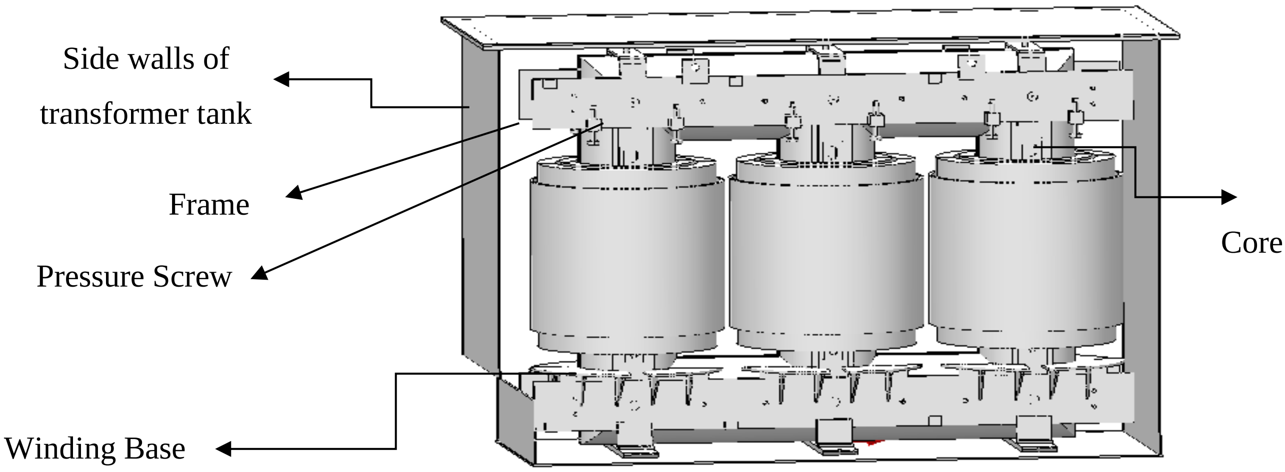


Fig. 3.4:- Front View of Solid Model of Three Phase Transformer

2. **Material**:- Assign the material to each and every component of the transformer by considering the dielectric medium
   - MS non linear: - Tank and other structural parts of transformer.
   - CR10:- For core structure.
   - Copper 5.77e7 Siemens/m: - LV, HV and tap windings for all three phases

The variation in losses with the plate thickness is presented in Figure 3.5.

The value of losses in various mild steel, aluminum and stainless steel plates for 1.0mm thickness of plate are 12.2kW, 1.5kW respectively [7].

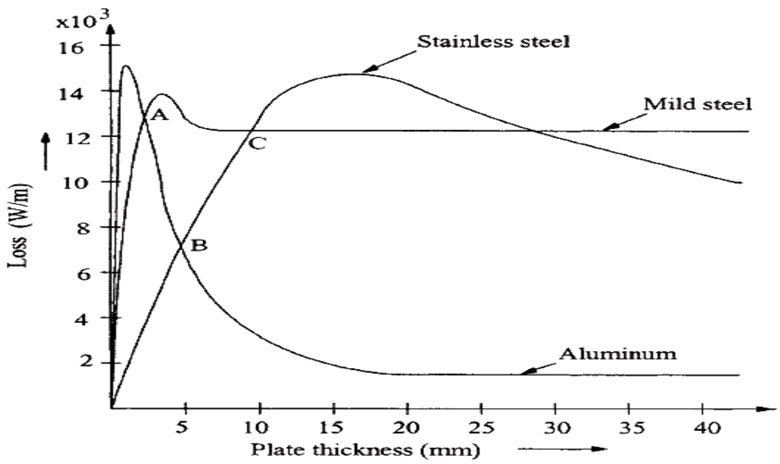


Fig 3.5:- Thickness Versus Loss Graph for Different Materials

Thus the losses are very less in aluminum. But the losses reach its minimum value only when thickness is more than 20mm. For thickness less than 6.6, the losses are more and it may cause overheating in the plate. While using aluminum and copper for shielding purpose it should be kept in mind that must have sufficient thickness to reduce overheating and minimizing the stray losses [19],[20].

Moreover the stray losses in stainless steel are lower only when thickness has lesser value than 10mm.On other hand skin depth is small for mild steel so we cannot control eddy currents by reducing its thickness. So, magnetic shunts are used to minimise the stray losses.

Coil Properties: - For designing of specific rating of transformer, a certain number of turns are required. For calculating number of turns for both LV and HV and Tap mmf has to be balanced.

For HV tap transformer :

mmf balance equation:- $N_{LV}I_{LV}=N_{HV}I_{HV}+N_{Tap}I_{Tap}$ (3.5)

HV current = tap current (since tap is connected with HV)

- Direction of flow of current for HV winding is opposite to that from LV winding [6].
- For reduction of eddy currents graded conductors are used [6].

N_{LV}, N_{HV}, N_{Tap} are the number of turns for low voltage, high voltage and tap winding of transformer (ampere

Table 3.1:- Coil parameters and excitations

Coil parameters	**LV**	**HV**	**Tap**
No. of Turns	92	812	144
Strand Area (mm^2)	729	75.11	56.52
Current RMS (Amps)	1312	126.26	126.26

The screenshot of the s/w slide showing LV properties is shown in Figure 3.6 and various parameters are assigned as:

Coil attributes

- Type of coil: Whether it is LV, HV or Tap
- Area: The area for LV, HV and Tap coil is shown in Table 3.1

Waveform

- Current: The value of current is taken from design sheet is shown in Table 3.1
- Phase angle or Phase difference= 0,120,240 respectively for R,Y and B phase

Assign the current direction

- Dot for current is flowing outside the coil
- Cross for current flowing inside the coil

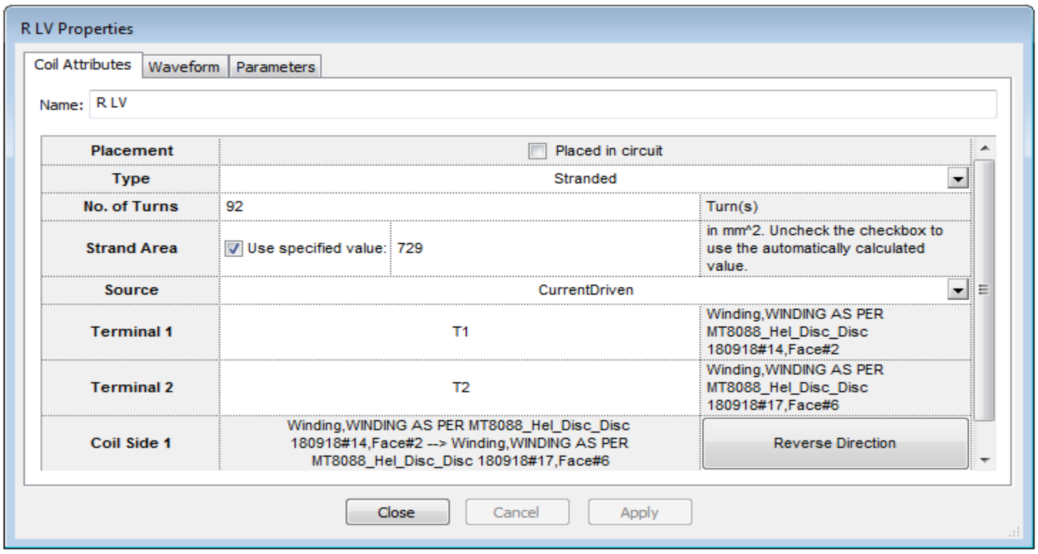


Fig.3.6:- Assigning Various Coil Parameters

3. **Source and Boundary Conditions:-**The numerical technique (FEM) is utilized for estimation of eddy and stray losses it is important that the size of element should be small than the skin dept of particular element. When overall dimensions are in meters, it would be difficult to have small element size.

The surface Impedance boundary method [18] assumes that the current density is uniformly distributed which allows the use of large element sizes. The 3-D transformer model having surface impedance boundary condition is shown in Figure 3.7

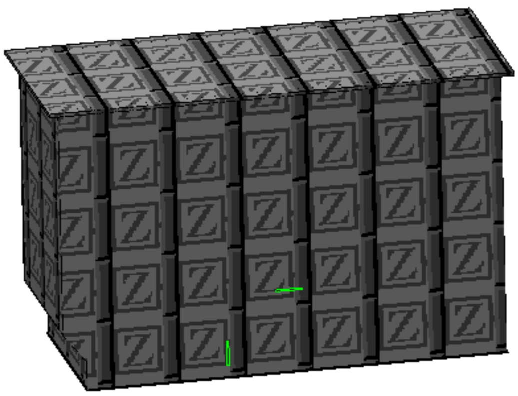


Fig.3.7:- Surface Impedance Boundary Condition

Here, H_s is magnetic field which is above the surface and the is real part of surface impedance Z_s is given in equation 3.6

$$Z_s = \frac{E_s}{H_s} = \frac{j\omega\mu}{j\omega\mu\sigma} = \sqrt{\frac{j\omega\mu}{\sigma}} \tag{3.6}$$

Where, σ= conductivity

μ= permeability

Surface impedance loss is

$$P_{sl} = \frac{1}{2}\oiint R_e \left|(Z_s)H_s\right|^2 dA \quad (3.7)$$

And skin depth is given by

$$\delta = \frac{1}{\sqrt{(\pi f \mu \sigma)}} \quad (3.8)$$

4. Analysis Type: - 3D linear Time Harmonic Analysis

Time harmonic formulations are mostly used to analyze the eddy current losses in winding and other structural components of transformer. The loss distribution in the all LV, HV and tap windings, tank and all structures in transformer are three dimensional so 3D analyses to be done.

The FEM analysis involves the following steps:

- Discretization of the problem solution into finite number of small domains.
- Derivation of all governing equations to approximate the solution.
- Assemble all the elements in the system.
- Final solution by solving some equations.

Step 1:-Discretization means splitting the problem domain into finite number of small elements. Selection of particular elements depends on its shape whether it is triangular or tetrahedral [6],[35] as shown in Figure 3.8

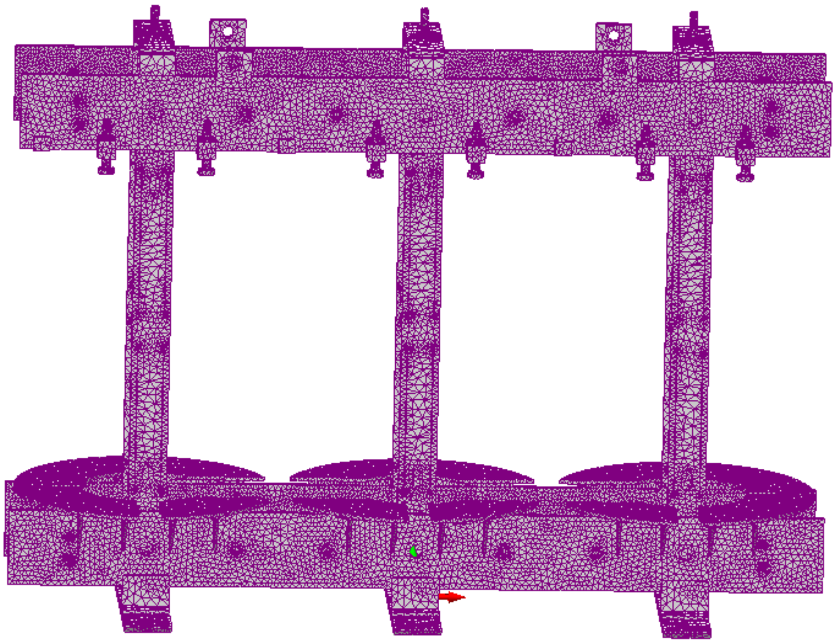


Fig.3.8 Dividing the problem domain into small components

Step 2:- Solution of Laplace equation

The field distribution can be calculated by following equation:-

$$\frac{1}{\mu}\nabla^2 A = J = 0 \qquad (3.9)$$

$$\frac{1}{\mu}\{\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2}\} = 0 \qquad (3.10)$$

Where, A=magnetic vector potential also known as momentum per charge.

μ= permeability

It is considered that magnetic material is homogenous in nature and has behaves isotopically. To find the magnetic vector potential region is dividing into finite elements. It seek an estimation for magnetic vector potential A_e within an element e, interrelating the distribution in different elements so that the vector potential should be continuous across all the boundaries [35]. The approximated and estimated solution is given by equation (3.11)

$$A(x,y) \cong \sum_{e=1}^{N} A_e(x,y) \qquad (3.11)$$

N=Number of triangular elements which divides the problem solution domain.

For the approximation of A_e, the approximation by polynomial is very common. A linear polynomial is considered in equation 3.12

$$A_e(x,y) = a_1 + b_1 x + c_1 y \qquad (3.12)$$

The value of A_e is non zero within element e whereas outside the value is zero. In this analysis all the elements considered are triangular elements because these elements are easily conformed to curved boundary.

Consider a triangular element have A_{e1}, A_{e2} and A_{e3} at nodes 1, 2, 3 respectively

$$\begin{bmatrix} A_{e1} \\ A_{e2} \\ A_{e3} \end{bmatrix} = \begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{bmatrix} \begin{bmatrix} a_1 \\ b_1 \\ c_1 \end{bmatrix}$$

The coefficients for a_1, b_1, c_1 are

$$\begin{bmatrix} a_1 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{bmatrix}^{-1} \begin{bmatrix} A_{e1} \\ A_{e2} \\ A_{e3} \end{bmatrix}$$

Substituting the coefficients of a_1, b_1 and c_1 in equation 3.12

$$A_e = \begin{bmatrix}1 & x & y\end{bmatrix}\frac{1}{2A}\begin{bmatrix} x_2y_3 - x_3y_2 & x_3y_1 - x_1y_3 & x_1y_2 - x_2y_1 \\ y_2 - y_3 & y_3 - y_1 & y_1 - y_2 \\ x_3 - x_2 & x_1 - x_3 & x_2 - x_1 \end{bmatrix}\begin{bmatrix} A_{e1} \\ A_{e2} \\ A_{e3} \end{bmatrix}$$

Or , it can be written as

$$A_e = \sum_{i=1}^{3} N_i(x, y) A_{ei} \tag{3.13}$$

$$N_1 = \frac{1}{2A}\left[(x_2y_3 - x_3y_2) + (y_2 - y_3)x + (x_3 - x_2)y\right] \tag{3.14}$$

$$N_2 = \frac{1}{2A}\left[(x_3y_1 - x_1y_3) + (y_3 - y_1)x + (x_1 - x_3)y\right] \tag{3.15}$$

$$N_3 = \frac{1}{2A}\left[(x_1y_2 - x_2y_1) + (y_1 - y_2)x + (x_2 - x_1)y\right] \tag{3.16}$$

A= area of triangular element

N_m = element shape function. It has the following properties

$$N_m = \begin{Bmatrix} 1, m = n \\ 0, m \neq n \end{Bmatrix} \tag{3.17}$$

$$\sum_{m=1}^{3} N_m(x, y) = 1 \tag{3.18}$$

The functional energy corresponds to Laplace equation $\frac{1}{\mu}\nabla^2 A = J = 0$ is given by

$$W_M = \frac{1}{2\mu}\int_s |\nabla A|^2 ds \tag{3.19}$$

$$W_M = \frac{1}{2\mu}\int_s \nabla \sum_{m=1}^{3} \left[N^e A^e\right]^2 ds \tag{3.20}$$

$$W_M = \frac{1}{2\mu}\int (\nabla N_1 A_1 + \nabla N_2 A_2 + \nabla N_3 A_3).(\nabla N_1 A_1 + \nabla N_2 A_2 + \nabla N_3 A_3).ds$$

$$W_M = \frac{1}{2\mu}\sum_{m=1}^{3}\sum_{n=1}^{3}\int_s A_i \nabla N_m . \nabla N_n A_n ds$$

$$W_M = \sum_{m=1}^{3} \sum_{n=1}^{3} [A_m][A_n] \int_s \nabla N_m . \nabla N_n ds$$

$$W_M = \frac{1}{2\mu}\sum_{m=1}^{3}\sum_{n=1}^{3} A_m \left[\int_s \frac{\partial N_m}{\partial x}\frac{\partial N_n}{\partial x} + \frac{\partial N_m}{\partial y}\frac{\partial N_n}{\partial y}\right] A_n$$

$$C_{mn} = \frac{1}{\mu}\int \frac{\partial N_m}{\partial x}\frac{\partial N_n}{\partial x} + \frac{\partial N_m}{\partial y}\frac{\partial N_n}{\partial y} \tag{3.21}$$

$$C_{mn} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \tag{3.22}$$

Step 3 :- Assembly of all the elements.

$$W_M = \frac{1}{2}[A_e]^T[C^e][A_e] \tag{3.23}$$

Step 4:- Solving the equations

The Laplace equation can be satisfied when the total energy consumed in the solution region is minimum. Thus the partial derivative of W, w.r.t to each nodal value potential is zero.

$$\frac{\partial W}{\partial A_1} = \frac{\partial W}{\partial A_2} = \dots\dots\dots.\frac{\partial W}{\partial A_n} = 0$$

$$\frac{\partial W}{\partial A_k} = 0 \quad k=1,2,3\dots..n \tag{3.24}$$

From equation 33,

$$0 = \frac{\partial W}{\partial A_1} = 2A_1C_{11} + A_2C_{12} + A_3C_{13} + A_4C_{14} + A_5C_{15} + A_2C_{21} + A_3C_{31} + A_4C_{41} + A_5C_{51}$$

So, $\frac{\partial W}{\partial A_k} = 0$ leads to

$$0 = \sum_{m=1}^{n} A_m C_{mk} \tag{3.25}$$

Where n= number of nodes

Iteration Method:-The Newton Raphson iteration methodology is the updated version of Newton method adopted to matrix system of equations. It works on basis of Taylor series.It is used to predict the stray losses of transformer.

The algorithm for iteration method is as follows:

- Approximate the value of magnetic vector potential A close to the final solution.
- Using the approximated value for A, calculate magnetic field intensity i.e. H from B-H curve and then obtain μ and $\frac{\partial \mu}{\partial H^2}$.
- Calculates the element matrix term having S (3,3) using μ.

- With S (3,3), $\frac{\partial\mu}{\partial H^2}$ and A of previous iteration, calculate the Jacobian terms and residuals.

$$J(n,k) = S(n,k) + \frac{4}{\mu^2}\left[\frac{\partial\mu}{\partial H^2}\right]\left[\sum_{e=1}^{3} S(n,e)A_e\right]\left[\sum_{e=1}^{3} s(k,e)A_e\right] \tag{3.26}$$

  The term S (3,3) is needed for calculation of Jacobian Matrix, which is calculated using the values of A_e in triangle. The assembly of all these terms which are presented in equation 35 provides the global Jacobian, called here SJ. The matrix system to be solved is:

  SKΔA =P

  P= Residual Vector which originates from previous iteration which should be zero.

- With the values of ΔA , calculate the new values of A.

The solution is obtained Newton-Raphson iteration methods for convergence, having relative error of 0.01, is shown in article number 3.6.1

- Repeat all the steps until and unless the convergence criterion is not satisfied.

After this simulation results are obtained. In shaded plot, if the value of B is more than 1.6Tesla then it is advisable to optimize the transformer by reducing the losses.

3.3 COUPLED ELECTROMAGNETIC AND THERMAL ANALYSIS

It is basic necessity to avoid over-heating in transformer structures because heating is very familiar phenomenon on electromagnetic devices In electromagnetics there are various sources for heating some of them are joule effect due to eddy currents, hysteresis and mechanical friction.

Coupled electromagnetic and thermal analysis is solved on ThermNet software package. It calculates the temperature in windings and all other structural components of the transformer. Because of the current harmonics, eddy losses in windings and stray losses in other structural components of transformer increases temperature to a higher value as depicted in Figure 3.9. The losses which are calculated in electromagnetic analysis are useful in calculating the steady state temperature increment in other structural parts with the help of Thermal FEM analysis. The coupled electromagnetic-thermal analysis uses both frequency and time domain. The time constant of thermal field is higher than the time constant of electromagnetic field so both are weakly coupled. Moreover, there is negligible difference in the electrical properties of material due to overheating and it is not high enough to bring the change in the electromagnetic field. So electromagnetic analysis is to be done by time harmonic analysis and thermal analysis is solved as transient 3-D

In thermal model meshing is given to geometry only. Meshing means splitting the whole geometry into small elements and the boundary condition given is of convection type in which air is taken into consideration and it uses convection coefficient at boundaries.

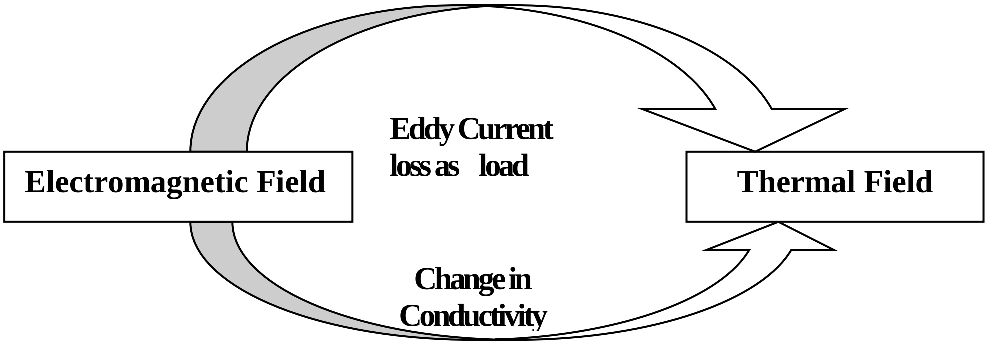


Fig 3.9:- Weakly Coupled Magnetic-Thermal model

3.5 OPTIMIZATION OF BASE MODEL

The stray flux which departs radially and axially from the interior of transformer winding strikes the winding base which supports the winding. The stray flux density might be more higher at winding base portion than other structural components of transformer. Although the losses occurring in it may not contribute much value in total losses of transformer, still it increases the local temperature rise. The local temperature enhancement can be high because of poor cooling conditions and large value of incident flux density. Higher temperature causes the deterioration of insulation and affecting the life of transformer.

The reduction in losses is done by various methods and techniques

- The base model is the original transformer design model without any optimizations.

1) Base model+ 45mm down winding base slotted

The winding base is bringing 45 mm down from winding and core to reduce the circulating currents in winding base. The winding base is shown in Figure 3.11.The circulating currents are produced by the net induced emfs formed in the loops by the parallel connection of winding conductors. These circulating currents are flowing in the parallel conductors and it is not allowed to flow outside the transformer winding thus adds up the value of circulating current in stray loss component. These losses can be avoided by choosing the proper location of stray loss component so that leakage flux will be less.

2) Base model+ 45mm down winding base + cutting fingers

The cutting fingers are dividing the winding base into small slots as shown in Figure 3.12 It is used to reduce the eddy loss. The incident flux changes its direction after the deep penetration in the mild steel plate due to its small skin depth. The introduction of fingers distorts the pattern of eddy currents at small thickness. When cutting fingers are used then losses can be reduced by factor (n+1). The additional loss value can also be reduced due to reduced area available for induced eddy current.

3) Base model + 45mm down winding base+ cutting fingers+ 15mm shunt

The magnetic shields or shunts are basically used to control stray loss and it offers fewer path for reluctance to the leakage magnetic field. The structural model of magnetic shunts is shown in Figure 3.13. The ideal magnetic shunt has infinite permeability and magnetic voltage drop is negligible across its length. They are used to provide shielding to the structural components from stray and leakage field. Silicon Steel is used as magnetic shunt. There are different grades available for magnetic shunts such as M3, M4, M5, MOH etc. Each of them are silicon steel material with various percentage of carbon in silicon-carbide BCC (Body Centered Cubic) structure. 15mm represents the thickness of the shunt material.

4) Base model+ 45mm down winding base+ cutting fingers+ 10mm shunt

In this optimization technique the CRGO material used for shunt is having thickness of 10mm. The thickness of shunt material plays a vital role in reduction of the transformer losses. The losses are less in the material having less thickness.

$$P = \frac{\omega^2 B^2 t^2}{24\rho} \tag{3.27}$$

P= total Losses

t= thickness

ρ= volume charge density

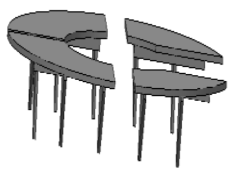


Fig.3.10:- Base design of Transformer

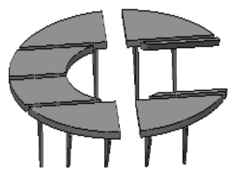


Fig.3.11:-Base design + 45mm downbase

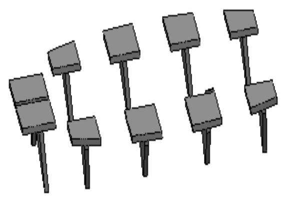


Fig.3.12:-Base design+ 45mm down base+cutting fingers

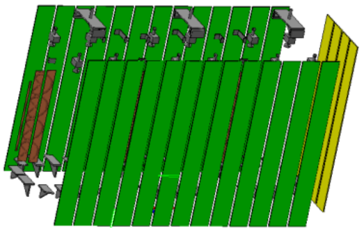


Fig.3.13:- Base model+45 mm down base +cutting fingers

3.5.1 TANK SHIELDS OR MAGNETIC SHIELDING

Magnetic shunts are much effectual as compare to non magnetic shields. They are used to shielding the structural components from leakage field but not from high currents [5],[18]. Magnetic shunts are pack of cut laminations of silicon steel material and are made up of CRGO. Magnetic shunts can be arranged in different fashions such as edge wise and flat wise. Flat wise shunts are used to be placed on tank such that there should be small width which makes it possible to lower the losses which enter from top and bottom positions. It is necessary to keep the gap as small as possible between two shunts for providing effective shielding. The magnetic shunts should have more height than height of the winding approximately 1meter. The winding height can also be judged on the basis of leakage field pattern in FEM.

3.5.2 MODELING OF MAGNETIC SHUNTS

The value of magnetic flux density can be considered as 1.7 Tesla for CRGO material and it is 1.4 Tesla for CRNGO material. When there is condition of any overloading, the shunts reach to saturation state and are not much effective. So the need of the hour is to lower the flux density which also helps to improve the overloading conditions.

When the stack of laminations are subjected to the magnetic field, stacking factor representing anisotropic properties of the material is considered. For using the cut laminations, anisotropic means B-H curves are different in all three directions i.e. stacking, rolling and transverse.

The relative permeability of the magnetic shunt is augmented by stacking factor as

$$\mu_{bx}^{eff} = \mu_{by}^{eff} \frac{1}{1-s} \tag{3.28}$$

μ_{bx} and μ_{by} are relative permeability in both the direction i.e. x and y, the values provided by the material supplier.

s= stacking factor

The permeability of CRGO material is very high as a result of which leakage flux lines will pass to the shunt material because it provides low reluctance path before passing to the tank. The shunt will be more effective if the material used in shunt is same as that used in core. Otherwise the permeability of the core becomes less than that of the shunt. Here the core material is M.O.H, so an M.O.H shunt is considered as good material for shunts. The material property is defined by B- H curve in each rolling, transverse and stacking direction. The material used and its dimension and properties is given in the Table 3.2.

The B-H curve i.e. loss curve can be fitted by equation 38 in Steinmetz coefficients K_e, K_h, α and β as shown in Figure 3.13

$$P = K_h f^{\alpha} B^{\beta} + K_e (sfB)^2 \quad (3.29)$$

Where, P= power loss per unit volume

B= maximum magnetic flux density

α,β = steinmetz coefficients

K_e = steinmetz coefficient for eddy loss

K_h= steinmetz coefficient for hysteresis loss

s= stacking factor

3-D FEM uses electric and magnetic non linear anisotropy property under consideration. According to the directions i.e. rolling and stacking the material is assigned to the magnetic shunt as z= stacking direction and y= rolling direction

Tank shield material is taken as **M4-non LINEAR_ANIS-Yrd-zsd**

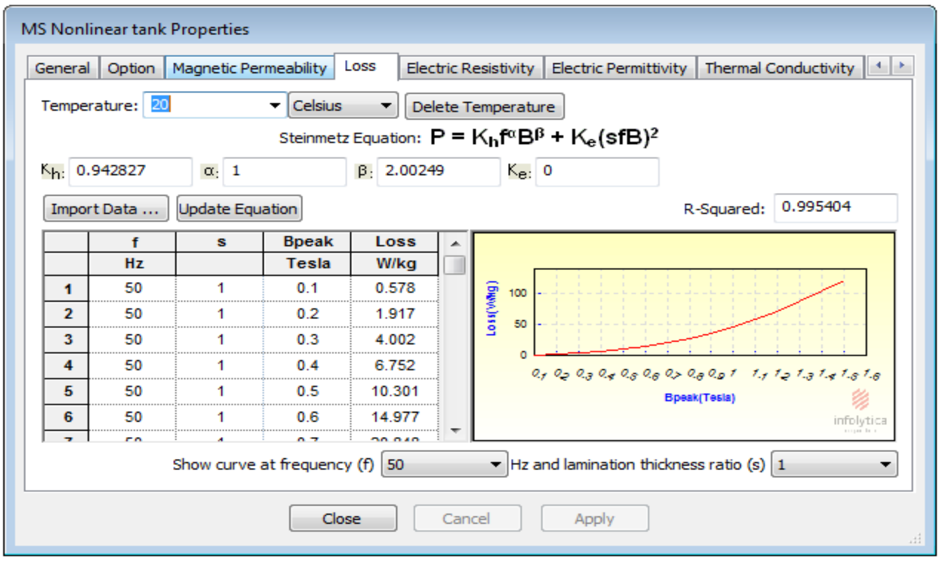
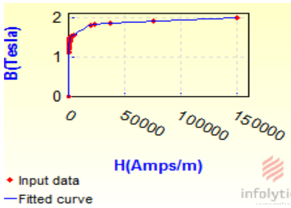
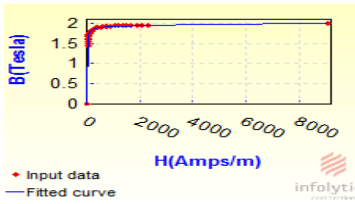
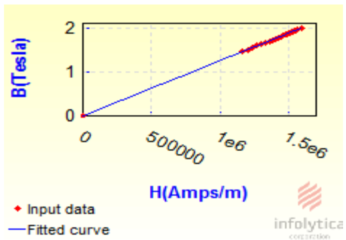


Fig.3.14:- Loss Curve and Loss Equation

Table 3.2:- Shunt Material Details

Shielding/ Shunt material	Thickness (mm)	Width (mm)	Height (mm)	Permeability (μr)	Conductivity (S/m)
M.O.H	10	200	1600	Anisotropic	2.08e6
Copper	6	200	1600	1	6.41e7

Table3.3 :- Properties of Shunt Material

M4 grade	With respect to grain direction	B-H Curve	Resistivity (ohms.m)
Anisotropic	Transverse		4.8e-007
	Rolling		4.8e-007
	Stacking		0.001

It is reported in literature that use of tank shields reduce the losses. When cutting fingers is used for winding base then the use of material named MS non linear is used less, circulating currents are also very less .As a result of which the losses decrease and it also saves the cost of the transformer.

3.6 RESULTS

Results of the Base Design

Ohmic losses I^2R losses through FEM are almost equal to the losses calculated by performing experiment. Eddy losses are to be calculated by software named as ITRACS (Integrated Transformer Calculation Systems). In MagNet we can predict stray losses.

Total losses = I^2R + Eddy +Stray losses

Table3.4:- Total Losses in Base Design

I^2R Losses in percentage		Eddy In %	Stray %	Total %
Design Tested	FEM			
68.35	67.8	6.1	26	100

Table 3.5:-Loss Split Up Values of All Structural Components

Tank	Frame	Pressure screw	Flitch plates	Winding base	Winding base supports	Total Stray Loss in percentage
51	16	2	6	17	6	100

After calculating the loss split up values for each component responsible for generation of stray loss. Total losses can be estimated.

3.6.1 Shaded Plots After Simulation

It is necessary to see the shaded plots because shaded plots represent amount of losses in core corresponding to flux density value in rms, such that if the particular area has more red color it represents losses are more in that particular area.

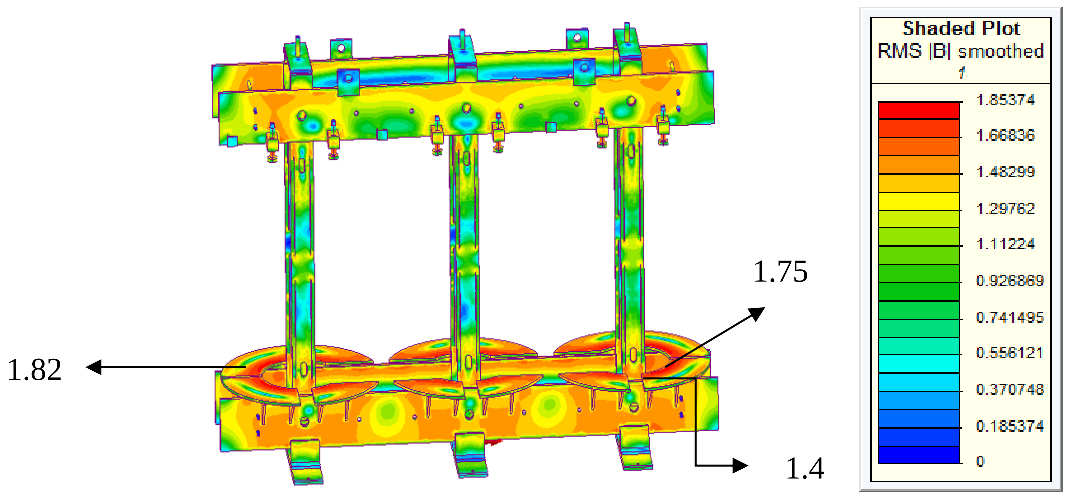
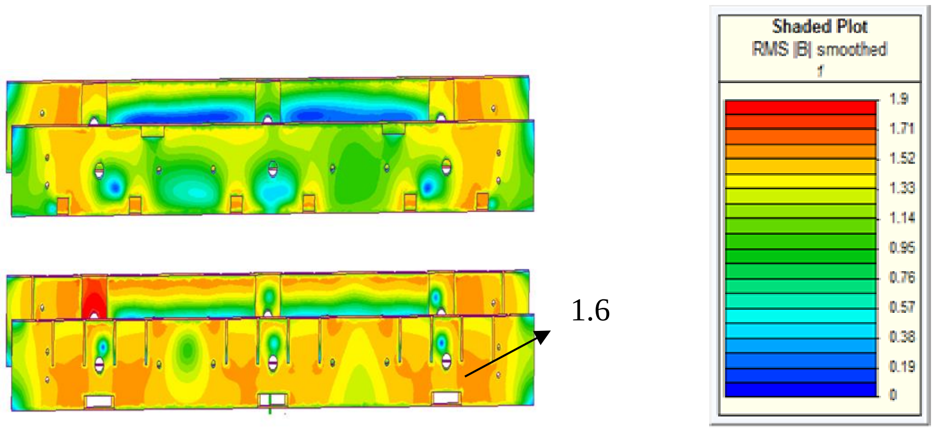
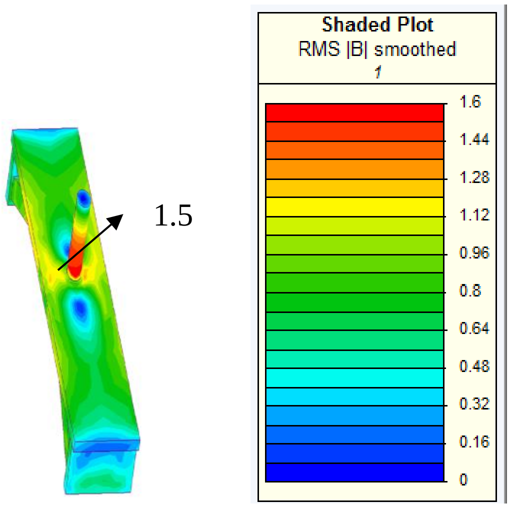


Fig.3.15:- Magnetic Flux Density in TESLA for Base Design of Transformer

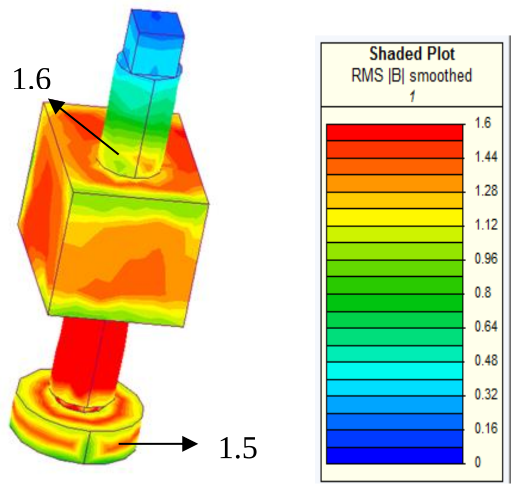
The value of magnetic flux density for all the structural components of transformer is shown in pallet form on right side.



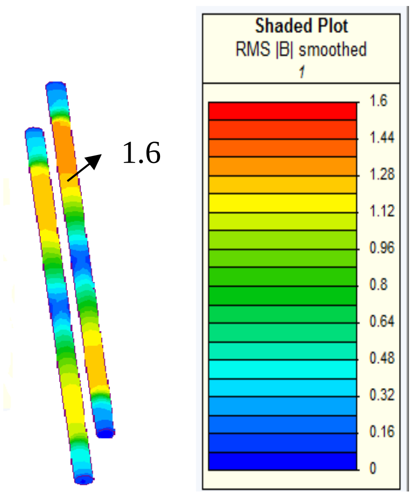
(a) Frame



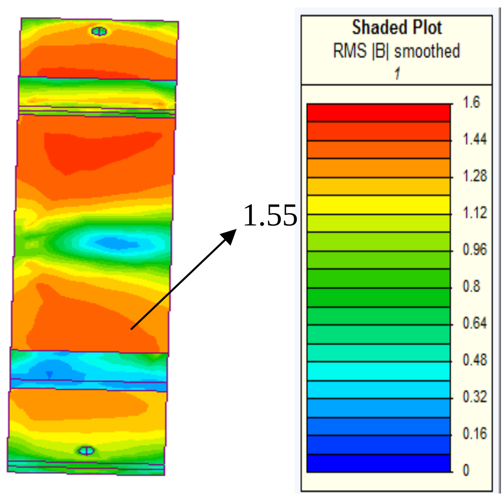
(b) Top Stay



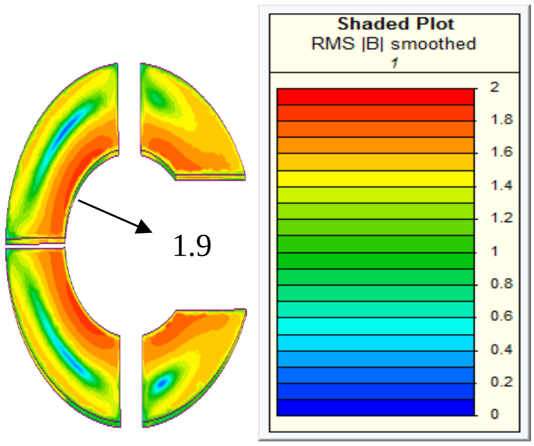
(c) Pressure Screw



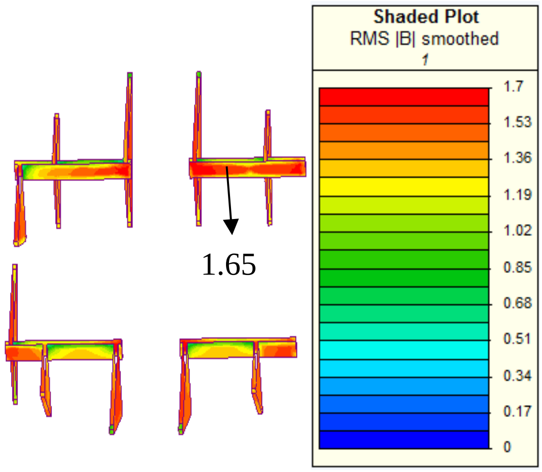
(d)End Tie Rods



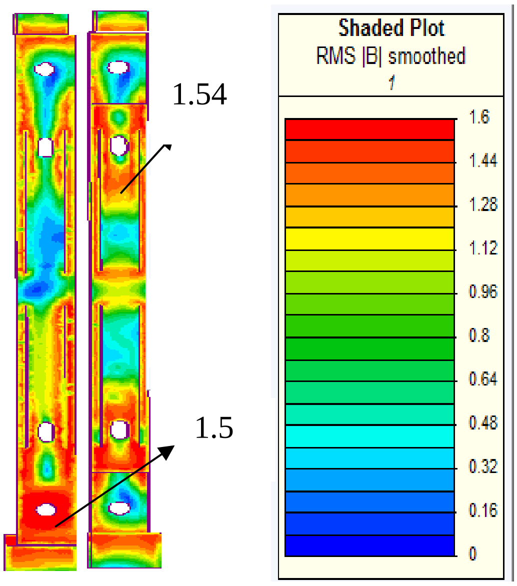
(e) Basefoot



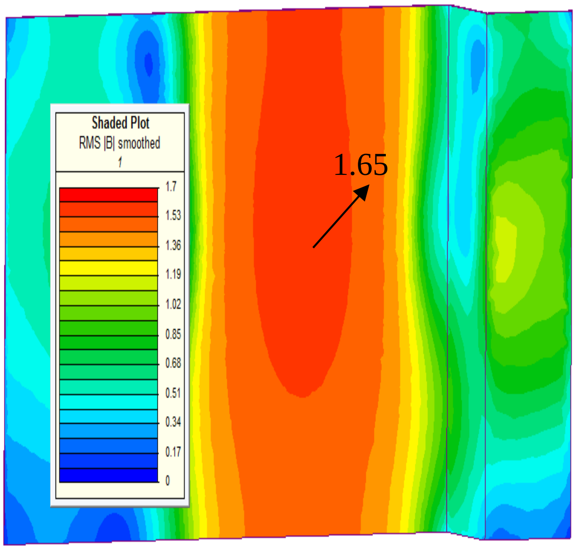
(f) Winding Base



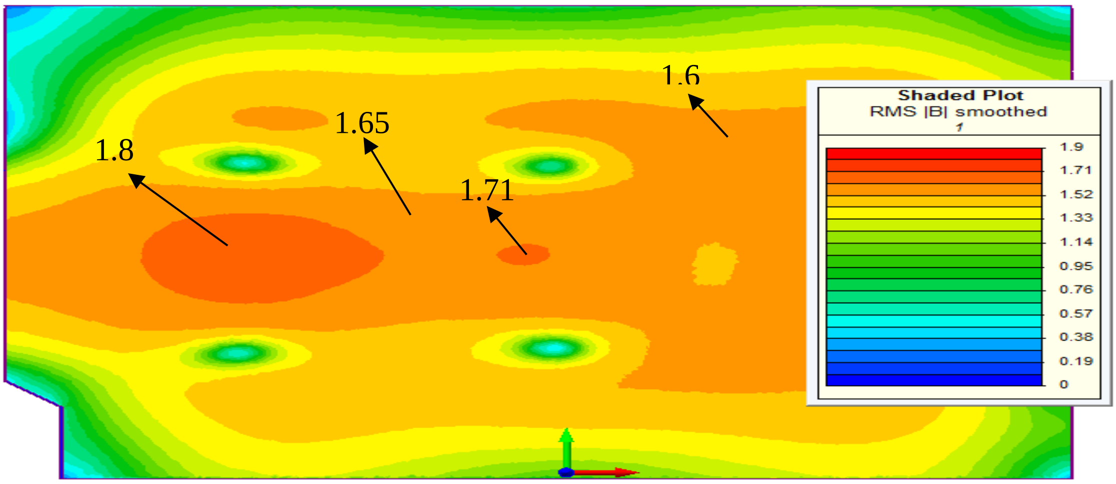
(g) Winding Base Supports



(h) Flitch Plates



(i) Tank Side Walls



(j) Tank

Fig. 3.16:-Magnetic Flux Density Plot for Structural Components of Base Model of Transformer

Here it is seen that value of flux density is more than 1.6 [6] on the various parts of transformer visible in red colour. It is seen from the above figures that the value of magnetic flux density is more (of the order of 1.8T) at winding base in comparison with other components of transformer.

Core losses are calculated using Equation (3.29). For low losses, the magnetic flux density should be less.

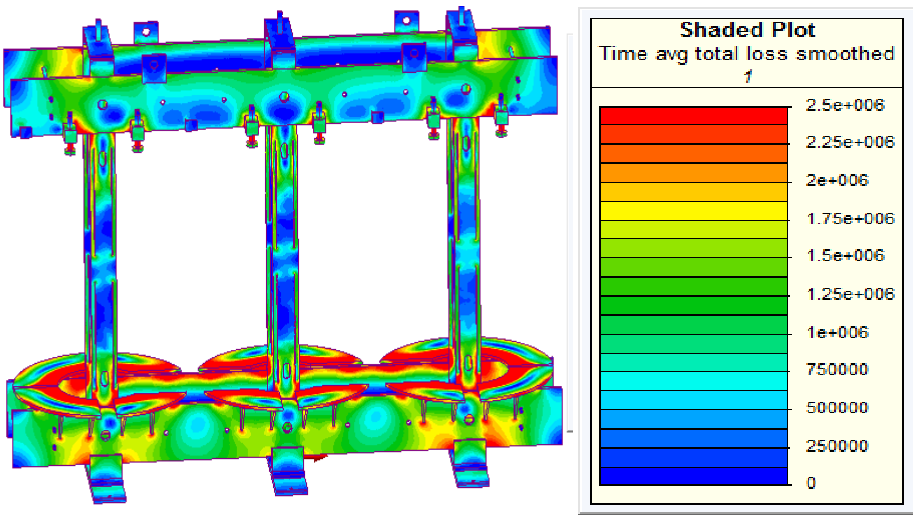


Fig 3.17:- Total Loss Smoothed (watts/m^3)

3.6.2 Shaded Plot of Temperature

To minimize the total losses in transformer by decreasing the value of B and to reduce the temperature inside the transformer for the increment of life expectancy it is necessary to optimize the actual model of transformer by various optimization techniques mentioned in article no. 3.5

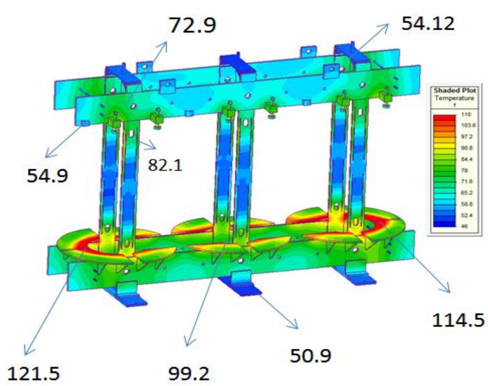


Fig.3.18:- Temperature Plot for Structural Part of Base Model Transformer

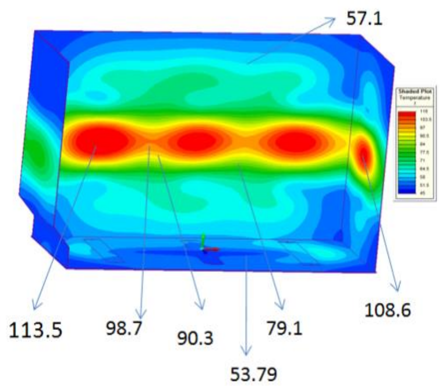


Fig.3.19:-Temperature Plot for Tank Side Walls of Base Model

The results obtained after applying various optimization techniques to base model is represented below

3.6.3 RESULTS OF THE UPDATED BASE MODEL

The updated base model considers 45mm down winding base with cutting fingers having 10mm shunt thickness**.**

Table 3.6:-Total Losses of Updated Model

I2R Losses in %		**Eddy %**	**Stray %**	**Total %**
Design	FEM			
68	68	6	10.7	84

Table 3.7:-Loss Split Up Values for Structural Components of Updated Model

Tank	**Frame**	**Pressure screw**	**Flitch plates**	**Winding base**	**Winding base supports**	**Shunts**	**Total In %**
3.9	3.1	0.54	0.65	0.62	0.36	0.85	10

3.6.4 SHADED PLOTS OF UPDATED MODEL

The shaded plots of magnetic flux density for different structural components after updating the base design i.e. actual model of transformer is providing with tank shunts and by dividing the winding base into small parts is shown in Figure 3.21 .

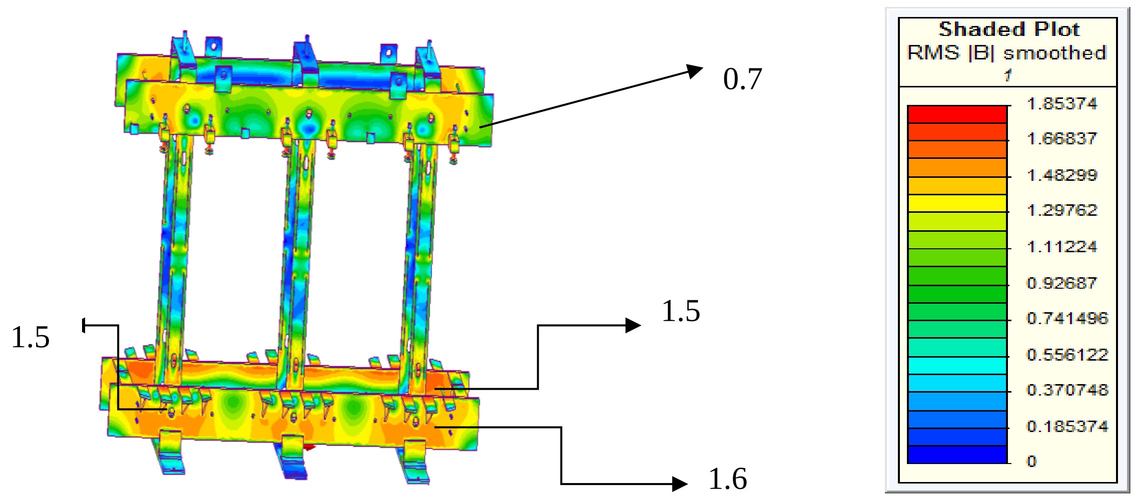
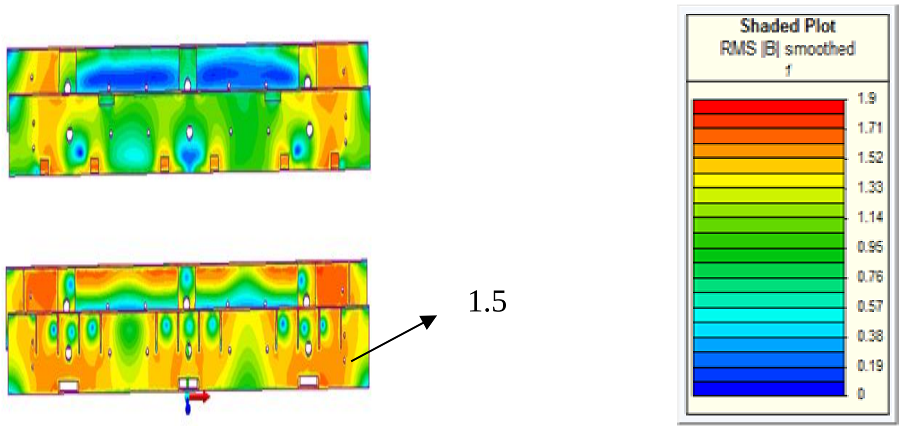
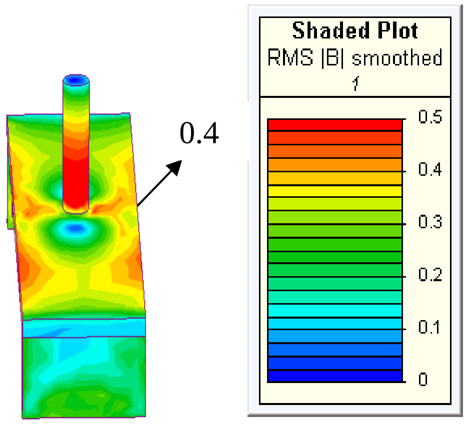


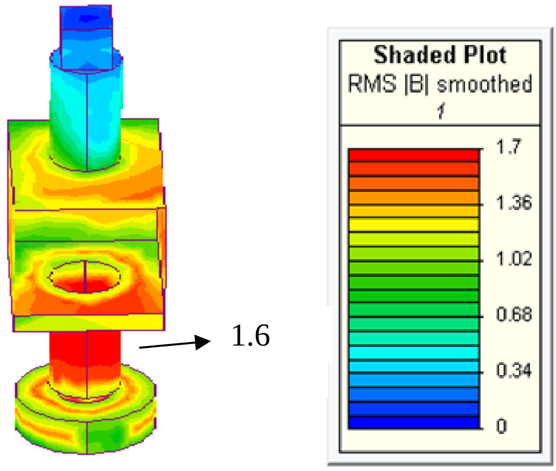
Fig. 3.20:- Magnetic Flux Density in TESLA for Updated model



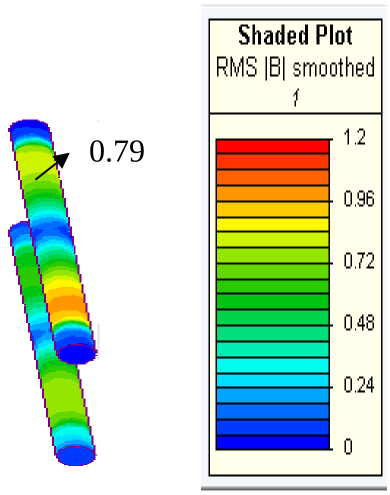
(a) Frame



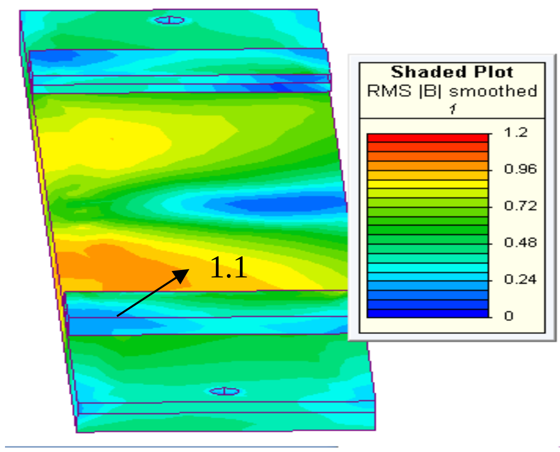
(b) Top Stay



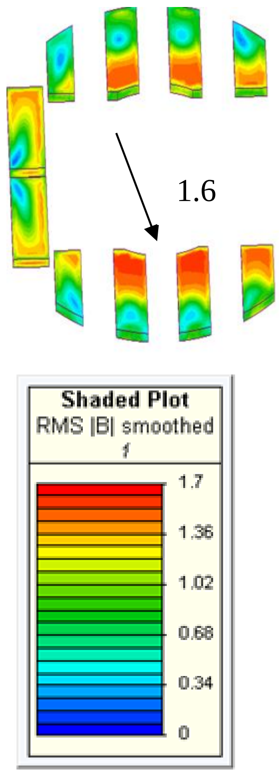
(c) Pressure Screw



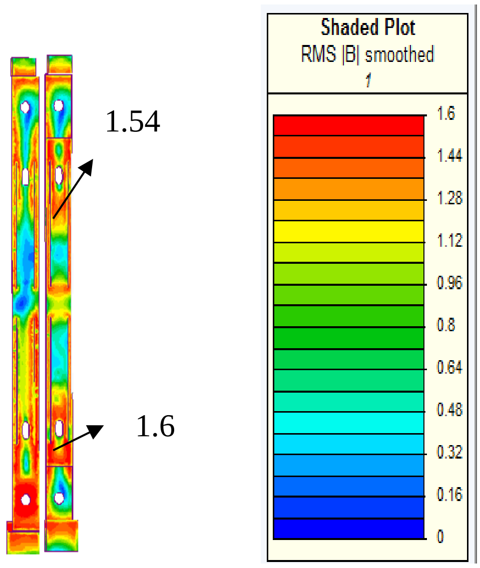
(d) End Tie Rods



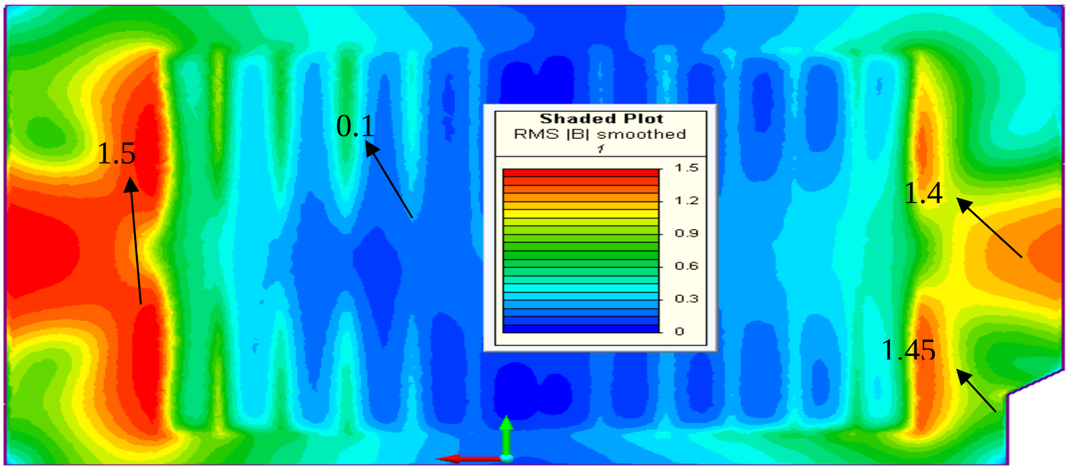
(e) Basefoot



(f) Winding Base



(g) Flitch Plates



(h) Tank

Fig.3.21:-Magnetic Flux Density Plot for Structural components of Updated Model of Transformer

The shaded plot for total losses is shown in Figure 3.22 depicts that total losses in winding base are reduced to some extent

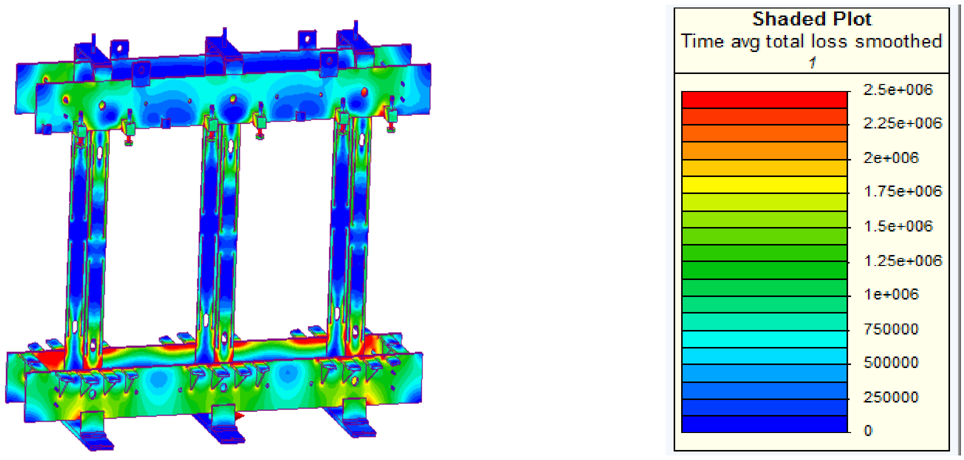


Fig.3. 22:- Time Average Total Loss (Watts/m3) of Updated Model

3.6.5 SHADED PLOT OF TEMPERATURE OF UPDATED BASE MODEL

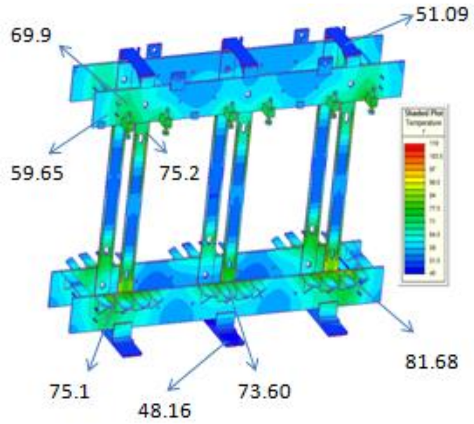


Fig.3.23:-Temperature Plot for Structural Part of Updated Base Model of Transformer

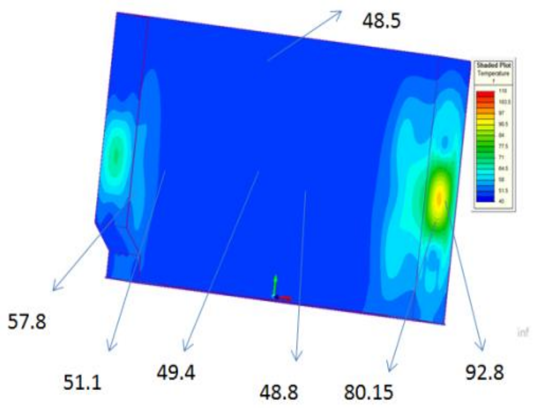


Fig.3.24:-Temperature Plot for Tank Side Walls Part of Updated Base Model Transformer

3.7 COMPARISON OF TOTAL LOSSES IN TRANSFORMER

Table3.8:- Comparison of Losses in Different Models of Transformer

Model	I^2R losses in %		Eddy in %	Stray losses in %	Total losses in %
	Design tested	FEM			
Base model	68.35	67.8	5.9	26.0	99.8
Base model + 45mm down				23.7	97.5
Base model+ 45mm down + cutting fingers				23.3	97.1
Base model + 45mm down + 10 mm shunt				11.2	84.9
Base model + 45mm down + 15 mm shunt				10.6	84 .5
Base model+ 45mm down + cutting fingers+10mm shunt				10.7	84.5

It is concluded that total losses were 97.8% with base model. The losses are reduced to 84.5% amounting to 15% reduction in total losses, with use of the following modifications

- Configurations
- Optimization tool to minimize losses
- Different design of winding base
- Tank shield.

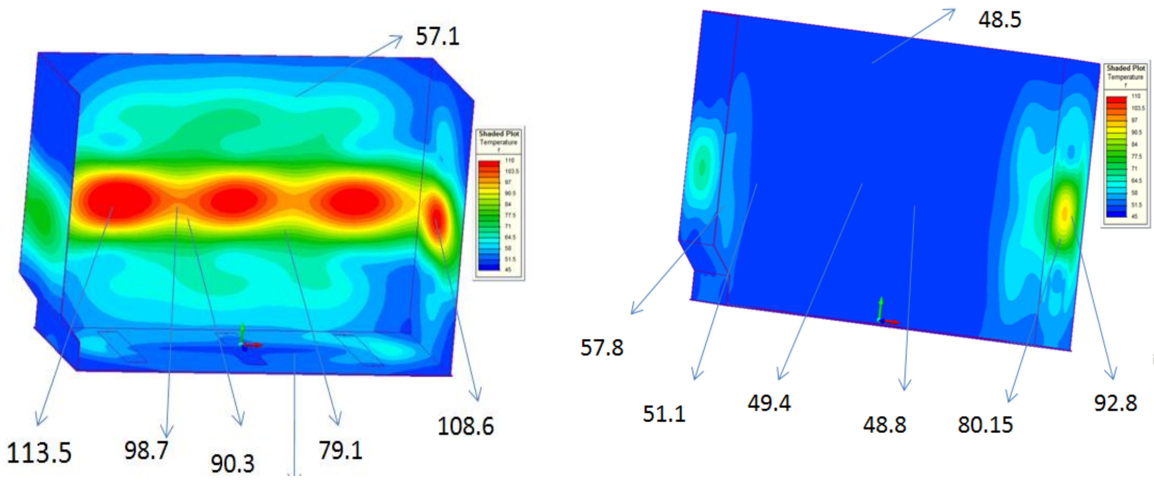
Further, with the base model, the stray losses are estimated as 26%, that gets reduced to 10.7% with the optimized model.

Table 3.9:- Loss Split up Values for structural components of different Models

Model	**Percentage Losses in**							
	Tank	**Frame**	**Pressure Screw**	**Flitch plates**	**Winding base**	**Winding base supports**	**Shunts**	**Total**
Base model	13.4	4.26	0.4	1.5	4.3	1.5		25.4
Base model + 45mm down	13.7	4.23	0.70	1.6	2.00	0.81		23.2
Base model+ 45mm down + cutting fingers	14.1	4.75	0.7	1.51	0.95	0.52		22.7
Base model + 45mm down + 10 mm shunt	3.7	2.70	0.55	1.2	1.45	0.57	0.82	11
Base model+ 45mm down + cutting fingers +10mm shunt	3.9	3.10	0.54	0.65	0.62	0.36	0.85	10

It is concluded that with flatwise magnetic shields, amounts of losses in the tank is reduced as shields provide low reluctance path to the leakage field.

With the reduction of losses in tank and other structural part temperature is also reduced in tank The comparison of tempertaure rise in base model and the optimised model of the transformer tank can be visualised from figure 3.25 (a) and (b) respectively.



(b)

Fig.3.25: Comaprion of Temperature on Tank Walls

(a) Temperature Plot for Base Model (b) Temperature Plot for Updated Base Model

The simulated image of the base model shows more area in red indicating high temperature area, whereas in the optimized model,the red colour area is very small. Overall, there is 60% reduction in tank temperature with optimized model due to reduction in stray losses to the extent of 58.8 %. This leads to the reduction in hot spot temperature.

3.8 CONCLUSIONS

Stray losses are in various structural components of transformer are estimated. It is clearly noticed that the regions accounts for more losses where magnetic flux density value is high. Tank shields are provided to control losses in the tank. The provision of laminations and slots help to reduce losses in the flitch plates. In winding base, it is advisable to reduce area of material by splitting the base into small parts which is known as cutting fingers. End tie rods can be used to reduce losses in frame. Further stray losses in transformer can be decreased by splitting the winding base into small components which is known as cutting fingers. By using shunts and bringing the winding base 45mm down and cutting fingers the losses in structural parts can be reduced to 58.8% which contributes about 15% reduction in total losses of transformer. This reduction in losses is helpful to reduce the overall capitalized cost of transformer.

CHAPTER 4

POWER FREQUENCY WITHSTAND LEVEL OF LIQUID INSULATION FOR TRANSFORMER APPLICATIONS

4.1 INTRODUCTION

The crude oil based mineral oil is used as an insulating fluid in oil-filled distribution and power transformers ever since late 19th century due to its extensive availability, good physical and electrical performances, reliability and low cost [2]. However, because of the low biodegradability (below 30%) and low flash and fire point esters liquids are considered as an alternative to the crude based mineral oil. Esters reduces the risk of fire hazard in electrical power apparatus by providing high resistance to ignition due to their far high flash and fire point as compare to mineral oil. Moreover, esters are more biodegradable and non-toxic in nature which fulfills the requirements of environmental-friendliness [23]. The major technical challenge that ester is facing today is to extend its range from low voltage distribution transformer to high voltage power transformers. The chemical compositions and molecular structure of ester liquids is different from mineral oil as esters are having polar structure than mineral oil [2],[24],[25]. The AC dielectric strength falls under the category of routine test. This test is generally used for checking the quality and to accept the transformer liquid before filling into a new transformer. Breakdown strength of oil is a statistical phenomenon influenced by various factors i.e. electrode (material, scale, area, gap distance, geometry), water content, particle content and type of voltage applied (AC, DC and impulse). While studying the breakdown mechanisms of esters the intrinsic (more polar components, electron affinities) and physical properties (higher viscosities) should be taken into consideration while changing the insulating liquids from mineral to esters [26-28]. The selection criteria of natural ester oil for transformer application should be done on the basis of experimental results that taking into account the some factors mentioned above.

It is significant important from the perspective of insulation design to evaluate the breakdown strength of ester oil applications in power and distribution transformers under AC stress.

4.2 INSULATING LIQUIDS

In this study, three ester liquids (two natural ester oils, synthetic ester oil) are investigated by considering mineral oil (Transol) as a benchmark. Transol is chemically stable due to saturated molecular structure and it has high oxidation stability.

Mineral Oil (Transol) is produced by Savita Oil Technologies through the process of distillation of paraffin, napthenes and aromatics. Mineral oil which contains predominantly normal paraffins is known as paraffinic base type and that which contains aromatics more cycloparaffins is known as naphthenic oil. The positive and negative streamer characteristics are influenced by aromatic components due to their minor ionization potential and more capability for trapping of electrons [26], [27]. The natural ester oil considered as NE1 is obtained from market whereas biotransol is also natural ester manufactured by Savita Polymers Limited considered as NE2. Both the natural esters are refined from soybean oil seed. The molecular structure of both ester oils contain triglycerides of fatty acids containing double and triple bonds of carbon-carbon atom. Because of this molecular structure natural ester oils are highly biodegradable and not stable to oxidation. The water saturation level is around 1100ppm which is more than transol at ambient temperature [24], [25], [31].

Trans Synth 100 is a type of synthetic ester produced by Savita Polymers Limited. It is derived from pentaerythritol having four fatty acids chains indicated by –'COOR' group. It is highly biodegradable as ester components are present in the molecular structure. Moreover the water saturation level is higher i.e. 2600ppm at ambient temperature which favors the absorption of water from cellulose material and protects the pressboard and paper insulation from deterioration. Samples of various types of transformer oils can be visualized in figure 4.1.

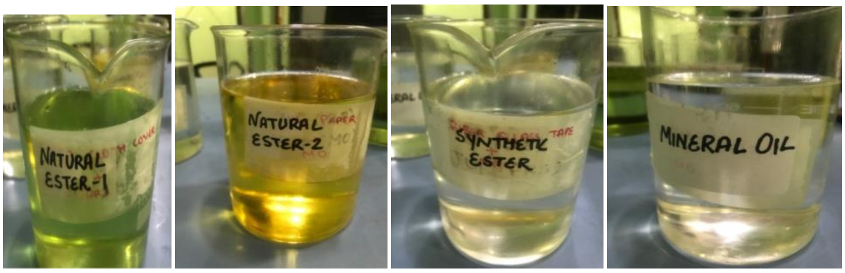


Fig. 4.1:- Various types of transformer oils for testing

4.3 SAMPLE PREPARATION

Pre-processing of liquid sample

The qualities of transformer liquids should be carefully controlled during the manufacturing process. Thus, the amount of moisture and particle content is very low in newly produced transformer liquids. However, due to transportation or during long term storage the qualities may deteriorate. Because of presence of moisture and atmospheric contaminations in the liquid, breakdown voltage will deteriorate. To avoid this, the liquid samples are filtered, dehydrates and degassed before any test. The liquid processing procedure is as follows

- **Filtration: -**The"as received" liquid is filtered by whatman filter paper having pore size 0.4µm to remove the particle content under vacuum.

- **Degassing and Dehydration: -** To remove the moisture content and dissolved gasses the filtered oil was heated at 50ºC for mineral oil and 100ºC for biotransol under vacuum oven under 500 Pascal pressure.
- **Cooling:-** The filtered sample after the above processes is allowed to cool at 3-4 hours.
- **Measurement of moisture content:** -The Karl Fischer titration method is used as per, IEC 60814 standards for calculating the water content in the transformer liquids. The equipment consists of three parts. The weight of the liquid sample is measured by Precisa XB120 having accuracy less than 0.1 mg. To vaporize all the water in liquid, the sample is heated in a 832 Thermoprep oven to 140ºC for at least 5 minutes. After this the vaporized water is brought into 684 Coulometer by dry air. The titration is carried out in coulometer having Hydranal liquid AG-H. A synchronous motor having constant speed of 300 rpm is used to drive electromagnetic stirrer during the titration process.

The coulometer reports the absolute weight of water content in micrograms. This value is converted into ppm by dividing weight of the liquid sample with microgram value. As it is known that esters are more hygroscopic in nature on comparison with mineral oil, so it is more advisable to compare the water content by the relative water content rather than absolute water content [2]. The relative water content is related to water saturation level when it is expressed in percentage. Due to the polar structure the saturation level in esters is more than mineral oil. The water content of processed liquid is measured shown by Figures 4.2, 4.3 and 4.4. The saturation level of water content is shown in the table 4.1 at ambient temperature of 25ºC.

Fig.4.2:-Filtration assembly

Fig.4.3:- Degassing of oil

Fig. 4.4:-PPM measurements

Table4.1:- Properties of processed oil

Properties	Mineral Oil	Natural Ester Oil-1	Natural Ester Oil -2	Synthetic Ester Oil
	TRANSOL	NE1	BIOTRANSOL (NE2)	TRANS-SYNTH 100
Breakdown voltage in kV for 2.5mm gap	70-75	70-80	70-80	90
Water contents in PPM	4-5	55-70	65-70	55-70
Water saturation level in PPM	55	1100	1100	2700
Relative saturation	2.5	3	3	3.5

Generally, the relative saturation of processed liquid should be kept low to 5% .The processed liquid samples is then be stored in sealed glass containers and are ready for use.

4.4 TEST CELL DISCRIPTIONS

The prediction of dielectric behavior of transformer insulating liquid is obtained experimentally when subjected to uniform i.e. non divergent and non-uniform i.e. highly divergent fields separately. The sphere–sphere and sphere- needle configurations are used to create uniform and non-uniform divergent electric field respectively.

For non-uniform divergent field, a cubical shaped test cell is used [32]. The test cell made up of acrylic according to ASTM D 3300, having needle-sphere electrode configuration has been used as shown in figure 4.5.

To facilitate the observation of breakdown the top lid and side walls of cell are made up of transparent acrylic. The needle is made up of steel phonograph as a point electrode having tip radius of curvature 0.06mm (± 20%), where the sphere electrode is made of brass having diameter 12.7mm. For experiment, the needle is connected to high voltage of the order of and sphere electrode to ground [29].The gap distance between the electrodes is adjustable from 1mm to 45mm by a set of thickness gauges with steps of 0.5mm.

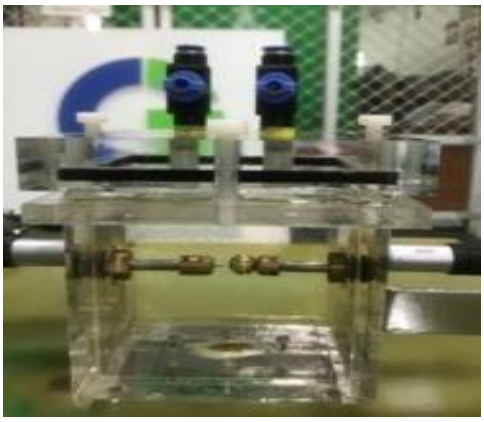


Fig 4.5:- Test Cell Having Needle- Sphere Arrangement

4.5 BREAKDOWN TESTING PROCEDURE

AC voltage is supplied by transformer of rating 150kKV, 50 Hz, 7.5KVA. The rising voltage method and step voltage method is used according to ASTM D1816 [36]. The step voltage method is also known as one minute power frequency method.

On comparison with mineral oil ester liquids are more viscous and have low interfacial tensions which results in slower expulsions of air bubbles out of sample. Therefore care should be taken to avoid air bubbles trapping in liquid samples while filling the test samples [29-31].

The air bubbles can be avoided by pouring the liquid sample along the wall of tilted container. It is recommended by to give settling time of at least 15 minutes[30].

The test procedure is as follows:-

- Set the gap between the two electrodes.
- Rinse the cell with the oil sample used for testing.
- Connect the sphere electrode with ground terminal.
- Set the initial voltage at HT electrode as 60% of expected breakdown voltage with the help of potential divider.
- Increase the voltage in a step of 2kV. The test voltage should be applied for duration of 1 minute.
- The oil sample should withstand minimum three voltages level before breakdown occurs.
- After breakdown there should be atleast 5 minutes time interval for ester liquid and 11 minutes for mineral oil.
- The oil is stirred after each breakdown and allowed to stand for a few minutes to avoid bubbles. Air bubbles are also responsible for lowering the breakdown voltage.
- According to standards the oil sample should be changed after each breakdown. It is observed that carbon particle formation is less in ester after breakdown compared to mineral oil. Oil samples are changed after three breakdowns for esters. However in case of mineral oil, the sample is to replace after every breakdown.

4.6 RESULTS

The insulation strength of a transformer is primarily determined by the strength of oil gap between the solid insulation. Since the solid insulation has more dielectric strength than oil, pressboard is used to divide the long oil gaps into smaller oil gaps [34]. Therefore, the present study focuses on evaluating withstand voltages of oil for gaps of 1-20mm. The evaluation method of natural ester oil with respect to mineral oil are compared by concerning the breakdown voltage, standard deviation, median value, maximum stress (η) for the gap between the two electrodes upto 20mm along the shortest field line in non-uniform field.

4.6.1 AVERAGE VALUE AND STANDARD DEVIATION OF BREAKDOWN VOLTAGE

Under power frequency voltage conditions i.e. ac , the breakdown phenomenon is affected by particles, gas bubbles and water content. Thus breakdown voltage of transformer insulating liquid is a statistical quantity. The average breakdown voltage and the standard deviation is used to express the breakdown voltage distribution by assuming that breakdown voltage of liquid follows the normal distribution. Mean breakdown voltages and standard deviations for various transformer liquids are presented in table 4.2.

Table 4.2:- Breakdown Voltages for Various Transformer Liquids

Statistical values	Gap between the electrodes (mm)	AC Breakdown Voltage (kV)			
		Mineral oil	Natural Ester		Synthetic Ester
			NE1	NE2	Trans Synth 100
Average value (kV)	1	17	15	15.4	16.6
	5	43.2	33	34	34.5
	10	57.7	44	44	50
	20	73.2	51	52	60.3
Standard deviations	1	1.1	1.5	0.9	0.9
	5	3.8	2.9	2	0.5
	10	6.8	3.3	2.3	1
	20	5.3	1.4	2.3	1.2

- Table 4.2, shows that the breakdown voltage of mineral oil is more as compared to esters. In mineral oil, the breakdown mainly occurs because of positive streamers. However the breakdown in both the esters (natural and synthetic) induced by both positive and negative streamers. Negative streamers can easily propagate in esters due to their high viscosity [29].
- The breakdown voltages are almost equal for the two natural ester oils, synthetic ester oil and mineral oil at 1.0 mm gap between the electrodes. At this small gap, breakdowns are mainly due to streamer initiation as the gap between the electrodes is less and the electric field in the liquid gap is semi-uniform [21],[22].
- When the gap is increased, breakdown in liquids is due to positive streamers and few breakdowns due to propagation of negative streamers.
- Both NE1 and NE2 have same average breakdowns but for NE1 the standard deviations are more as compared to NE2.

- Standard deviations are having less values in synthetic ester oils followed by natural ester 2 (NE2)

4.6.2 ESTIMATION OF 1% FAILURE PROBABILITY

It is assumed that the breakdown voltages of liquids follow the normal distribution as a result of which average breakdown voltage and standard deviation are used to exhibit the same. There are various parametric and non-parametric statistical techniques which are used to study the distribution of breakdown voltage of various transformer liquids. These distributions include normal distribution, double exponential method also known as minimum Gumbel distribution and Weibull distribution. Both Weibull and Gumbel distribution are considering the inequality between low and high failure rates. However, normal distribution gives the large prediction values than the measurement results of breakdown voltage at low failure rates (10%) and high failure rates (>90%), whereas Gumbel distribution gives smaller prediction than the measurement values of breakdown voltage. Thus the normal distribution overestimates and Gumbel distribution underestimates the value of breakdown voltage.

On the other hand, Weibull distribution gives the well overlapped results with the predicted values at whole failure rate limits [29], [30] and [33]. It estimates the combination of statistical parameters which represents the goodness of fit to the breakdown data with different failure probability value. The withstand voltage at breakdown probabilities of 1% can be easily deduced by knowing the shape and scale parameters of Weibull function [33].The three parameter Weibull probability density function is used to estimate the breakdown voltage is represented by the equation (4.1):

$$F(t) = \frac{\beta}{\alpha}\left(\frac{t-\gamma}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}} \tag{4.1}$$

α = scale parameter

β = shape

γ = location parameter

4.6.3 PROCEDURE FOR WEIBULL DISTRIBUTION ANALYSIS

Weibull distribution analysis on the test data is carried out using software MINITAB.

Step 1:- Import the data to MINITAB having the work sheet as shown in Figure 4.6.

Step 2:- For statistical analysis go to Stat ⟶ Reliability ⟶ Distribution Analysis

Step 3:- Plot 3- parameter Weibull distribution by selecting least square and 3-parameter Weibull distribution.

Step 4:- Note the value of 1% failure probability from result table as shown in figure 4.8.

Fig.4.6:- Importing Data to MINITAB

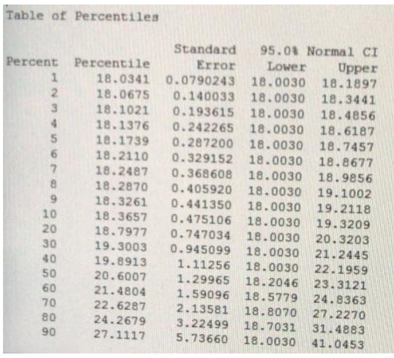


Table of Percentiles

Percent	Percentile	Standard Error	95.0% Normal CI Lower	Upper
1	18.0341	0.0790243	18.0030	18.1897
2	18.0675	0.140033	18.0030	18.3441
3	18.1021	0.193615	18.0030	18.4856
4	18.1376	0.242265	18.0030	18.6187
5	18.1739	0.287200	18.0030	18.7457
6	18.2110	0.329152	18.0030	18.8677
7	18.2487	0.368608	18.0030	18.9856
8	18.2870	0.405920	18.0030	19.1002
9	18.3261	0.441350	18.0030	19.2118
10	18.3657	0.475106	18.0030	19.3209
20	18.7977	0.747034	18.0030	20.3203
30	19.3003	0.945099	18.0030	21.2445
40	19.8913	1.11256	18.0030	22.1959
50	20.6007	1.29965	18.2046	23.3121
60	21.4804	1.59096	18.5779	24.8363
70	22.6287	2.13581	18.8070	27.2270
80	24.2679	3.22499	18.7031	31.4883
90	27.1117	5.73660	18.0030	41.0453

Fig4.7:- 1% failure Probability value

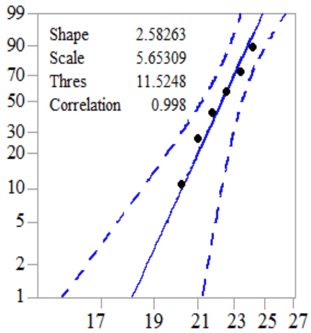


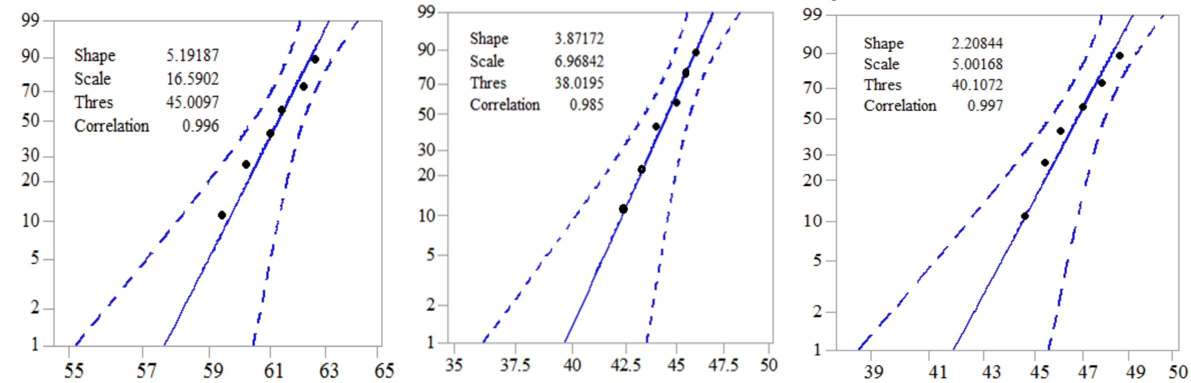
Fig.4.8:- Graph Plotting

4.6.4 WEIBULL DISTRIBUTION GRAPHS

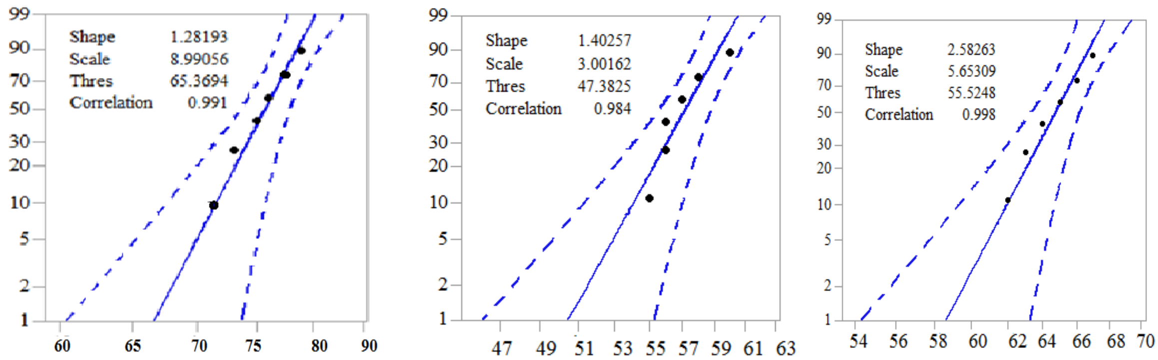
Figures 4.9 and 4.10 shows the graphical representation of 1% failure probability values of mineral oil, natural ester oil and synthetic ester.

The solid line in Fig 4.9 and 4.10 shows the 3-parameter Weibull distribution based on six set

Transol Natural ester Oil Synthetic Ester



Failure Probability in % V/s Breakdown Voltage in kV for 10mm gap
Figure 4.9:-Weibull Distribution of Sphere-Needle Configurations



Failure Probability in % V/s Breakdown Voltage in kV for 20mm gap
Fig 4.10:-Weibull Distribution of Sphere-Needle Configurations

of readings. The other two lines which are dotted show the 95% confidence level. From the Figure 4.9, it is found that the withstand voltage of Transol is 58 kV for 10mm gap for uniform electrical field configuration. However, the predicted result from Weibull distribution analysis provides an inevitable uncertainty [29]. Therefore, mineral oil withstand voltage might not be exactly 58 kV and it will be near the withstand voltage value of 58 kV. Hence, the actual withstand voltage lies between 55 kV to 61 kV based on 95% confidence interval.

Figure 4.11 is showing the variation of 1% failure probability of breakdown voltage with the electrodes gap distance for four different types of transformer liquids. It is summarized as:

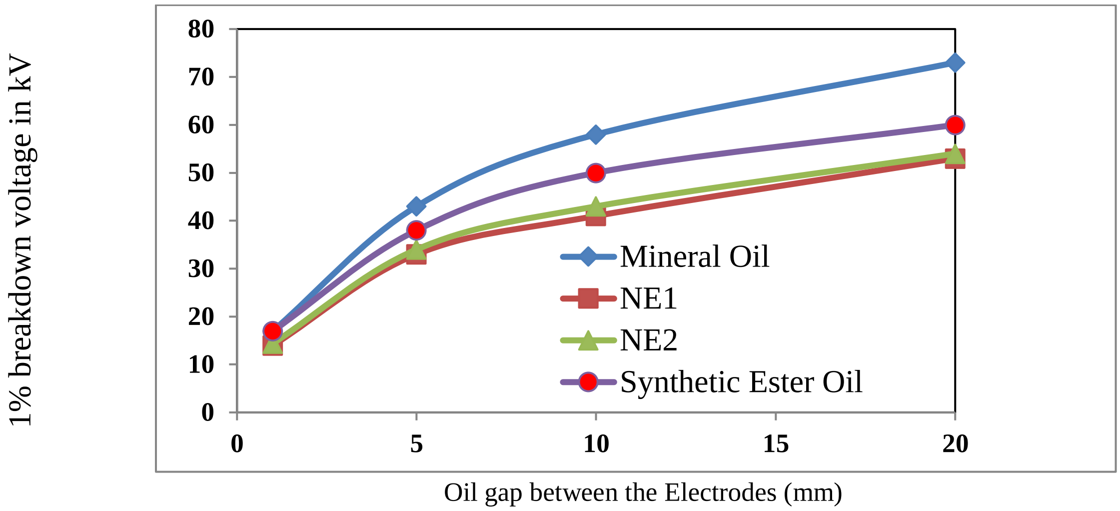


Figure 4.11. 1% Failure Probability of Breakdown Voltage for Different Insulating Liquids

- 1 % failure probability failure value for withstand voltage for both natural ester oils is almost same at gap distance of 1mm and 5mm.However, NE2 (biotransol) is having slightly higher withstand voltage value for 1% failure probability at 10mm gap between the electrodes.
- The mineral oil shows higher 1% failure probability values as compare to ester oil. At 5mm gap the mineral oil shows 33% higher value and at 10 mm it is around 48% higher value with respect to natural esters.
- However at 20 mm gap, the mineral oil is having 25.8% higher value w.r.t synthetic ester oil.

4.7 CONCLUSIONS

With growing interests in usage of natural ester oil as alternate to the mineral oil for transformer application, an experimental analysis is performed to predict the withstand voltage of natural ester oil in comparison with conventional mineral oil. Firstly the breakdown strengths of mineral oil and natural ester oils (NE2) are determined and then comparing their breakdown voltages at a low failure rate (i.e. high withstand probability).In order to get confidence in results obtained for natural ester oil, the another natural ester oil is evaluated which is obtained from market. The breakdown tests at gap distances from 1 mm to 20 mm are performed for sphere-needle electrodes.

This chapter concludes that both the natural ester oils are showing the same behavior under power frequency conditions. However the values of standard deviations of breakdown voltages are less for ester oil as compare to the mineral oil. Low value of standard deviations is beneficial for designing the insulation point of power transformer under ac conditions. The breakdown voltage of mineral oil is more than esters but having large standard deviations and large number of carbon particles which increases the chances of transformer failure. The breakdown voltage of natural ester oil is less with respect to mineral oil due to electronegative property in the natural ester oil. This happens because the negative streamers can easily propagate between the electrodes due to high electronegativity in natural ester oil. During the experimental studies it is found that the condition of mineral oil after breakdown is pretty bad in comparison to natural ester oil in all oil gaps because of formation of carbon particles.

CHAPTER -5

EFFECT ON DIELECTRIC STRENGTH OF MINERAL OIL ON MIXING NATURAL ESTER OIL AS POLAR CONTAMINATION

5.1 INTRODUCTION

The natural esters are considered as a new age dielectric coolant. It scores good point over mineral oil due to its biodegradability, high fire and flash point, more compatibility with high temperature insulation, less degradation of cellulose, less carbon particles.

Ester oils are easily soluble in water which makes it more insensitive to moisture than mineral oil. Due to these differences in physical and chemical properties, it is important to ensure that ester oils have adequate and acceptable dielectric strength in transformer applications [29].Generally; natural ester oils are completely miscible and appear like a transparent fluid when mixed with mineral oils. Therefore, there is a possibility that the two different oils may get mixed with each other accidentally either on the shop-floor while manufacturing the transformer or during service on site. However, in case of retro filling, small amount of ester liquid will not affect the performance of mineral oil, but the contamination with high proportion of natural ester oil(more than 7%) in mineral oil, the performance of the mineral oil may degrade asymptotically and it may change the electrical, chemical and thermal performance for transformer applications [23-28]. However, the fire point and biodegradability of the mixture oil (natural ester oil in mineral oil) will increases with respect to mineral oil [23], [24]. In this chapter the dielectric strength is analyzed on a mixture of 10% of natural ester oil in mineral oil for various oil gaps between 1 to 20mm in steps of 1 mm using sphere-needle electrodes under AC stress. The electric field distributions between sphere-needle electrodes are also calculated based on 1% failure probability of AC withstand voltage using Weibull distributions for various oil gaps.

5.2 EXPERIMENTAL DISCRIPTIONS

5.2.1 TRANSFORMER OIL AND TEST CELL

Mineral oil is a mixture of various hydrocarbon molecules having various structures such as paraffinic, naphthenic and aromatic [23[, [24]. Paraffinic based mineral oil consists of substantial quantities of naturally occurring paraffin than naphthenic oil. The oxidation of paraffin are producing a sludge which is insoluble in nature leads to higher viscosity and pour point. This results in reducing the capability of transfer of heat, overheating and it also reduces the servicing life of transformer under normal operating conditions at low temperature[22]. To mitigate these limitations of paraffinic based oil, the naphthenic has been came into picture.

Naphthenic oil has more polar features than paraffinic oil due to the presence of aromatic compounds which remain in the oil at low temperature [23], [24], [29], [30]. Naphthenic oil can easily oxidize than paraffinic oil. To improve the oxidation stability of oil, mineral oils may also contain inhibitors.

Natural ester oil is derived from natural plants (vegetable seeds). The main molecular component of natural esters is Glycerol esters. The ester linkage has three different C18 fatty acid chains which will contain one, two or even three double bonds [23], [24], [31]. Hence, natural ester oil has more polar structure than mineral oils due to the presence of ester linkages.

In this paper, transol grade of mineral oil, produced by Savita Oil Technologies Limited, and bioTransol grade of natural ester oil produced by Savita polymers limited are used to compare and predict the AC dielectric strength of pure liquids (mineral oil and natural ester oil) and a mixture containing 10% natural ester in mineral oil.

The test cell (1L volume) is fabricated according to ASTM D-3300 [32]. The cell is made from transparent acrylic in order to observe the breakdown phenomenon. The experimental set-up is used to establish the experimental confirmation and statistically supported value of the voltage of the oil at different intervals. Sphere-needle electrode configurations are chosen in this study to create non uniform local electric fields [29]. Steel phonograph needle is used as the point electrode having the tip radius of curvature 0.06mm (±20%) while the sphere electrode which is made up of brass having a diameter of 12.7mm.The gap distance between electrodes can be set insteps of 0.5 mm with the help of screw gauges on either side of the electrode terminals.

5.3 SAMPLE PREPARATION

The objective is to evaluate the breakdown voltage of mineral oil and natural ester oil and comparison of their breakdown voltages at a low failure rate (1% failure rate). Generally, the evaluation of 50% breakdown voltage is in fact of minor importance compared to the voltage range of low breakdown probability (1% failure probability), because only a sufficiently low breakdown risk is acceptable for technical dimensioning [33]. This objective demands high quality of oil preparation. Hence, the mineral oil and natural ester oil samples are precisely taken from sealed barrels in order to maintain same consistency of oil quality for all the experiments. The properties of the oil like breakdown voltage, water content and loss factor are evaluated prior to the test and are presented in Table 5.1.

A common procedure of sample preparation is used for both mineral oil and natural ester. The sample of the oil is filtered by using whatman filter paper, of size 0.45 μm. The filtered oil is heated at 100°C in vacuum oven at 720-740mm of Hg pressure to remove moisture content and dissolved gases from the filtered sample. As a general procedure, the heated oil is dehydrated and degassed in a vacuum oven before starting breakdown tests to minimize the influence of contamination in the test results [29],[30]. Therefore, after carefully filling with the oil sample, the test cell is kept still for about one hour before starting the breakdown tests, in order to remove any tiny air bubbles and stabilize oil samples.

The natural ester oil is mixed with mineral oil at ambient temperature with the help of a magnetic stirrer at a speed of about 1100 rpm for atleast 15min. To assure the miscibility of mineral oil with natural ester oil, mixtures are kept undisturbed for two days. After that, a homogeneous mixture can be observed without any phase separation.

Table 5.1:-Properties of Processed Sample Oil for Experimental Analysis

Parameters of Oil	Mineral oil	Natural ester oil	Mixture oil (90%Transol & 10% BioTransol)
	Transol	BioTransol	
Breakdown voltage in kV for 2.5mm gap	65-70	70-80	75-85
Water content in ppm	4-5	55-70	12-14
Loss factor at 90ºC	0.0022	0.2	0.0027
Relative permittivity	2.2	3.3	2.3
Viscosity at 40°C mm^2/sec	8.83	32	9.55

5.4 BREAKDOWN PROCEDURE

- Set the initial voltage level at 60% presumed breakdown voltage
- Voltage is increased with the steps of 2 kV and the test voltage is applied for the same length of time, usually 60 seconds.
- The oil sample must withstand a minimum of three voltage levels before breakdown occurs.
- After breakdown occurs, there is at least five minutes time interval before the next shot for natural esters and 11 minutes interval for mineral oil
- The oil is stirred after each breakdown and allowed to stand for a few minutes to avoid air bubbles.
- Oil sample is regularly changed after three breakdowns on average in order get consistent results.

5.5 EXPERIMENTAL RESULTS

The present study focuses on evaluating dielectric strength of oil for oil gaps of 1-20mm. The oils are compared in terms of breakdown voltage, standard deviation, gap between the two electrodes of 0<1<20mm.

5.5.1 EVALUATION OF AVERAGE VALUE AND STANDARD DEVIATION OF BREAKDOWN VOLTAGE FOR MIXTURE OF OIL

The breakdown phenomenon of oil is a statistically distributed quantity which is dependent on the complex physics and chemistry of the oil and impurities involved [2], [22[, [29]. The breakdown voltage of oil provides the useful information on the design criteria of transformer insulation systems and it would always obey probability distribution functions [2], [30]. Hence, best estimates of the statistical parameters of average breakdown voltage and standard deviations are calculated initially for comparative study of natural esters, mineral oil and its mixture oil are presented in Table 5.2, and 5.3.

Table 5.2:-Breakdown Voltages of Three Different Grades of Mineral Oil

Statistical values	Gap in mm	AC voltage of mineral oil (kV)			Natural ester oil
		Naphthenic inhibited	Paraffinic grades		
			Uninhibited	Inhibited	
Average breakdown value in kV	1	21.4	22.7	21	15.4
	5	43.2	43.7	44	35
	10	63.5	63	63.3	43
	20	72	71.3	72	50
Standard deviations	1	2.4	1.9	1.8	1
	5	2.6	1.4	1.4	1.7
	10	3	1.9	1.8	2.3
	20	3.1	1.8	1.7	2.3

From the Table 5.2 and 5.3, the following points are observed

- The breakdown voltages of three different grades of mineral oil are same. The small difference in the breakdown voltage of different grades of mineral oil may be due to oil handling.
- In addition, the breakdown voltage of natural ester oil is less in comparison to all grades of mineral oil.

- Above 5mm oil gap, the standard deviation of natural ester oil is higher than paraffinic grades. However, naphthenic inhibited oil shows higher standard deviation than natural ester oil and paraffinic grades of mineral oil

Table5.3:- Breakdown Voltage for Mixing of Three Different Grades of Mineral Oil with 10% Biotransol

Statistical values	Gap in mm	AC voltage under 10% natural ester oil mixture in to mineral oil (kV)		
		Naphthenic inhibited	Paraffinic grades	
			Uninhibited	Inhibited
Average breakdown value in kV	1	23	19	20
	5	49	38	41
	10	78	54	58
	20	88	64	66
Standard Deviation	1	1.7	1.6	1.5
	5	1.4	1.2	1.2
	10	1.7	1.6	1.4
	20	1.6	1.4	1.5

The natural ester oil and naphthenic inhibited oil with the highest standard deviation implies that breakdown can occur at a very distant voltage value (greater or smaller) than its mean value. In general the breakdown voltage of mineral oil is mainly induced only by positive streamers while the breakdown voltage of natural ester oil is induced by both positive and negative streamers [29, [30]. However, the negative streamers can easily propagate in ester oil due to their high electronegativity [21].

From Table III, if the natural ester oil is mixed with different grades of mineral oil, the following points are observed

- The breakdown voltage of naphthenic inhibited oil with 10% natural ester oil is increased with respect to pure naphthenic inhibited oil. It indicates that the presence of aromatics contents in the naphthenic oil is playing a major role with polar molecules of natural ester oil. The standard deviation of the naphthenic inhibited oil is lesser after 10% mixture of natural ester oil.
- The breakdown voltage of both paraffinic grades decreases when 10% of natural ester oil is mixed to it. However, the inhibited paraffinic oils show slightly higher breakdown

voltage compared to the uninhibited paraffinic oil. It indicates, the inhibitors are also playing a role in the breakdown voltage besides polar molecules. The standard deviation of both paraffinic grades oil is marginally decreased after 10% mixture of natural ester oil.

5.5.2 ESTIMATION OF 1% FAILURE PROBABILITY

As discussed previously that Weibull distribution is the best non parametric technique to estimate the failure probability. Here also, MINITAB software is used to estimate the lower and higher values of failure probability by considering 3- parameter Weibull distributions

From Table 5.4, it is found that the withstand voltage of mineral oil is 67 kV for 20mm gap. However, the predicted result from Weibull distribution analysis provides an inevitable uncertainty [33]. Therefore, mineral oil withstand voltage might not be exactly 67 kV and it will be near the withstand voltage value of 60 kV. Hence, the actual withstand voltage lies between 60kV to 75kV based on 95% confidence interval. Therefore, it is understood from Table 5.4 that the withstand voltage of mineral oil is 67kV and 95% confidence interval of withstand voltage level lies between 60kV to 67kV. Similarly, the values for other different grades of the oil are given in the Table IV. From the predicted results of Weibull distribution, 99% withstand voltage (1% failure probability) of mineral oil, natural ester oil and mixture oil are extracted from Weibull distribution analysis and it is shown in Figure 5.1. 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 instead of the predicted withstand voltage [30].

Table 5.4:-95% Confidence Interval of Withstand Voltage

Transformer oil		95% confidence interval in kV

		Gap (mm)	Lower boundary	1% failure probability	Upper Boundary
Mineral oil (all three grades)		1	12	18	20
		5	36	41	44
		10	46	54	57
		20	60	67	75
Natural ester oil		1	8	14	18
		5	24	28	32
		10	36	38	43
		20	39	48	49
Naphthenic oil & 10% Natural ester oil		1	12	17	18
		5	40	45	47
		10	70	76	78
		20	79	83	88
Paraffinic	Uninhibited & 10% Natural ester oil	1	14	17	20
		5	32	34	37
		10	45	49	52
		20	58	60	63
	Inhibited & 10% Natural ester oil	1	14	17	21
		5	34	35	37
		10	52	55	58
		20	55	61	63

From Table 5.4, it is found that the withstand voltage of mineral oil is 67 kV for 20mm gap. However, the predicted result from Weibull distribution analysis provides an inevitable uncertainty [33]. Therefore, mineral oil withstand voltage might not be exactly 67 kV and it will be near the withstand voltage value of 60 kV. Hence, the actual withstand voltage lies between 60kV to 75kV based on 95%confidence interval. Therefore, it is understood from Table 5.4 that the withstand voltage of mineral oil is 67kV and 95% confidence interval of withstand voltage level lies between 60kV to 67kV. Similarly, the values for other different grades of the oil are given in the Table 5.4. From the predicted results of Weibull distribution, 99% withstand voltage (1% failure probability) of mineral oil, natural ester oil and mixture oil are extracted from Weibull distribution analysis and it is shown in Figure 5.1. From Fig. 5.1, Mixture of naphthenic inhibited oil and 10% natural ester oil shows 1% failure probability ranges between 3-27% higher values than naphthenic pure oil.

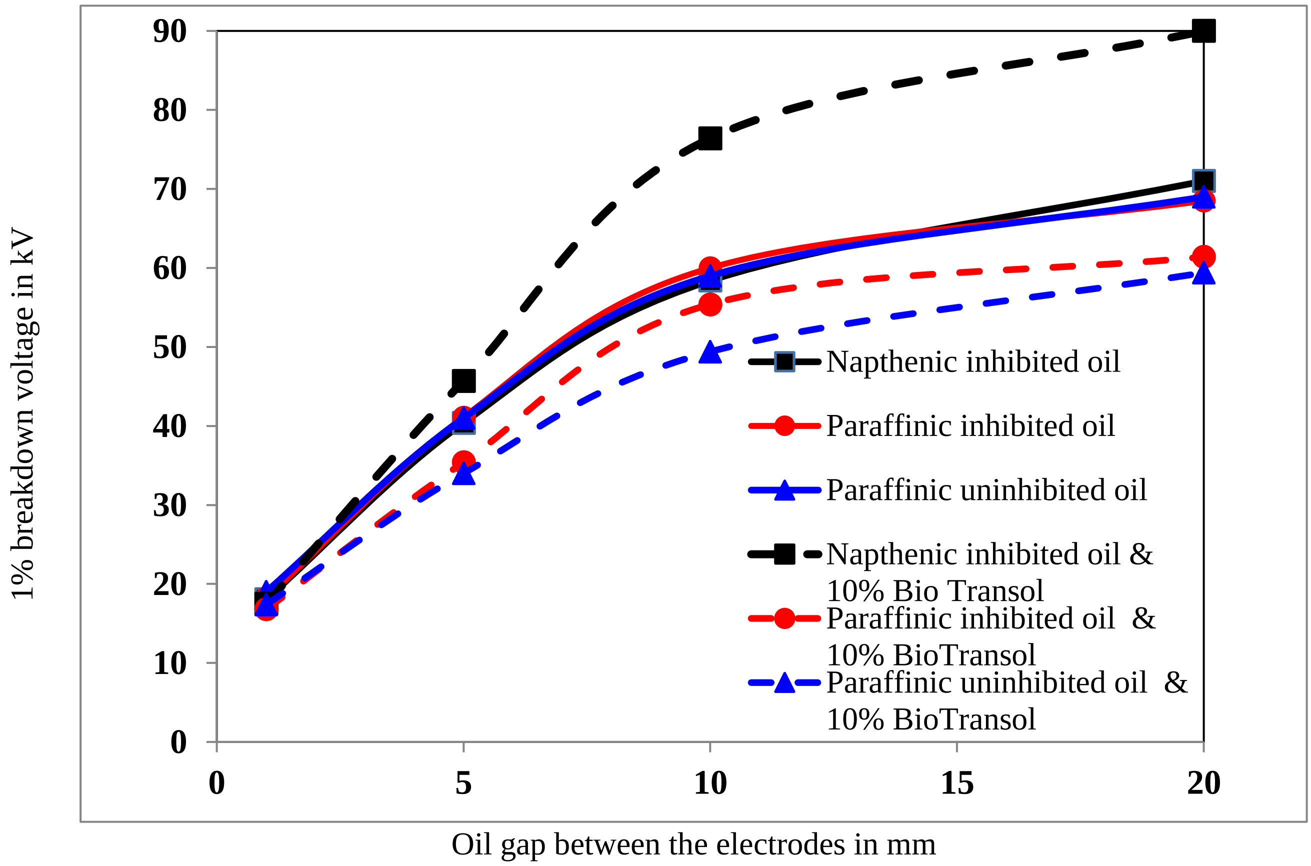


Fig.5.1:- 1% Failure Probability of Breakdown Voltage for Different Grades of Mineral Oil with 10% of Natural Ester Oil

- For paraffinic uninhibited oil, at 1mm gap value is 7 % lower, at 5mm gap 13.86%,at 10 mm 7.66% at 20 mm 10.36% lower than paraffinic uninhibited blank oil. In short it can be concluding that 1% failure probability of breakdown voltage is 7-14% lower with mixture of both paraffinic uninhibited oil and 10% natural ester oil.
- For paraffinic inhibited oil and 10% natural ester oil gives the value which is 8-17% lower with respect to pure paraffinic inhibited oil.

5.6 CONCLUSIONS

The mineral oil is very insensitive to the metal, polar and water impurities. Therefore an effort has been made to study the effect of polar contamination in the mineral oil having different grades under power frequency conditions. From the experimental results it is concluded that aromatics are also playing a role in breakdown voltage under power frequency conditions. The mixture of natural ester oil which is polar in nature in naphthenic based mineral oil having aromatics consists of cyclic and planer structure having resonance bonds increases the breakdown voltage. The increment value of breakdown voltage w.r.t to pure naphthenic oil is advantageous for transformer companies from insulation point of view. The paraffins based mineral oil leads to reduction in breakdown voltage w.r.t. pure paraffinic oil of the order of 7-14% only. This value indicated low safety margin. In case, ester oil is accidentally mixed with paraffinic oil, it increases the chances of failure of transformer whereas in naphthenic based it is advantageous. Thus a significant conclusion of this study is that from the perspective of dielectric strength, the mixtures of natural ester oil constitutes a good option for improvement of the dielectric behavior of naphthenic grade inhibited mineral oil and but not in the case of paraffinic grades of mineral oil.

CHAPTER 6

PREDICTION OF DIELECTRIC STRESS ANALYSIS DUE TO HORIZONTAL CELL CONFIGURATION AT POWER FREQUENCY VOLTAGE CONDITIONS

6.1 INTRODUCTION

The accuracy and safety of power transformer depends on the safe operation of transformer insulation. The insulation system of transformer is subjected to various operating voltages continuously and overvoltages occasionally. The operating voltages plays an important role in deciding the voltage stress on the transformer insulation. The overvoltages can be characterized into lightning overvoltage, switching overvoltages and short duration and long duration power frequency voltage [3-6]. The long duration power frequency voltage is mainly purposive for examining the insulation behavior under the voltage stress. The insulation between various electrodes is decided by overvoltages. The impulse stress decides the interdisk spacing in winding and the end insulation between windings is decided by the power frequency or ac test voltage [6]. For long term performance it necessiates to design the transformer with high quality manufacturing components and insulation system. Solid insulation is used to divide the highly stressed channels of oil into small oil gaps which increases the dielectric capability of oil gaps. The transformer with solid liquid composite insulation involves complete failure which occurs in the form of jump/ bulk oil breakdown and local failure between two electrodes which may not leads to breakdown immediately. Sustained partial discharges collapse the insulation system results in the final breakdown.

6.2 ELECTRIC FIELD DISTRIBUTIONS

The solid insulation can be used at many places in the inner side of the transformer i.e. between turns, layers, between winding and conductor. There are two types of failures occur in transformer: puncture and creepage. The solid insulation has lower creepage strength than puncture. The creepage failure occurs along the surface of insulation. The creepage flashover characteristics are mainly influenced by dissimilarity of permittivity between two insulation materials at their interface. Due to permittivity mismatch, the electric field in the oil which is adjacent to solid insulation is distorted. Thus it is required to match the permittivity of oil and the pressboard to avoid creepage failures. The permittivity of ester liquids is close to solid insulation which causes the even distribution of stress between solid and liquid materials. This also plays an important role to reduce the local stress in oil which typically sets of discharge.

6.3 DESIGN OF HIGH VOLTAGE AC INSULATION SYSTEM

The design of ac insulation system can be determined by the dielectric behavior and electric stress of the transformer oil which is based on the field analysis of stressed areas of insulation. Electrical stress is one of major factor which determines the insulation failure as well as the failure of transformer. For optimal design of insulation systems and to achieve good safety margin it is advisable to understand the electric field distributions in the oil due to breakdown voltage. Stress in oil usually depends on the permittivity, field configurations i.e. uniform field and non uniform field, and magnitude of breakdown voltage. During ac test, the distribution of electric stress between the insulating materials depends on the permittivity of the material. Due to changes in the permittivity of the ester oil having permittivity 3.3 with respect to mineral oil of permittivity 2.2, it is important to determine the electric stress distribution for dielectric design guidelines [2]. For this reason it is necessary to determine the points of highest stress for avoiding the insulation failure Hence, evaluation methods of different oil are extended further to predict the maximum stress.

6.3.1 FIELD ANALYSIS

It is necessary to determine critical field lines with high electric field strength for wide oil gaps. The transformer model may have critical field lines if the safety ratio between the dielectric strength of oil gap and field strength is small. Stress values are compared with the dielectric strength of oil gaps along the field lines. It is difficult to compute electric field distribution and the field lines by analytical methods. Hence various numerical techniques are used for calculations of field. The most powerful technique used from last four decades for electrostatic analysis is FEM. The polynomials of higher order can be used to estimate the potential distribution within the corresponding elements. The electric stress for all the elements are estimated by differentiating the approximated polynomial function. There is presence of different types of stresses on the transformer winding insulation due to the location. Stress varies from high voltage lead to end of the winding [4], [34]. Sphere–needle configuration which is highly non-uniform is considered to evaluate the transformer insulation under the worst case scenario. FEM technique is utilized for calculating electric field distributions between two electrodes by varying the gap up to 20mm. Field graph plots are used for calculation of maximum stress in the oil.

6.3.2 MAXWELL FEM ANALYSIS USING ELECNET

The FEM technique is used to find the solution of many complicated problems by replacing them into simpler one. Since the complicated problem is converted to simpler, one can be able to find the approximated solution rather actual solution. The FEM method refines the approximate solution by using more computational efforts. The problem definition of finite element method is shown below:

1. **Problem definition:-** To calculate the value of electric stress in transformer oil.
2. **Problem Domain**: - The field domain is encircled in the boundary which is known as oil box. All the space outside the boundary is excluded from the field domain problem
3. **Dimension: -**Three dimensional models is specified in XYZ plane.
4. **Type of problem: -**The problem considered here is electrostatic in nature.
5. **Governing Equation:-** The poisson's equation is the governing equation in electrostatic field distributions.

$$\nabla^2 V = \frac{-\rho}{\varepsilon} \tag{6.1}$$

ρ = surface charge density

V=electric scaler potential

ε= permittivity

6.3.3 PROCEDURE

Step 1:- Import 3-D solid model of test cell having needle sphere arrangement in ELECNET

Step 2:- Set all units in mm.

Step 3:- Assign material to each and every component according to ASTM D-3300

- Needle :- Stainless steel
- Sphere :- Brass
- Sphere and needle supports :- Brass
- Sphere and needle rods :- Stainless Steel
- Test Cell :- Acrylic
- Oil :- different oil for calculating stress having different value of permittivity

Step 4:- Mesh size depends on the size of the component. Needle is having tip radius of curvature 0.06mm, the appropriate mesh size is 0.001 or 0.0005 mm. It should be kept in mind that mesh should be smooth as shown in Figure 6.3

Step 5:- As needle electrode is connected to high voltage terminal and sphere electrode to ground. Assign the appropriate value of voltage at particular gap for particular oil to needle electrode.

Make the sphere electrode connected to ground by giving zero voltage or by giving ground boundary conditions according to Figure 6.1

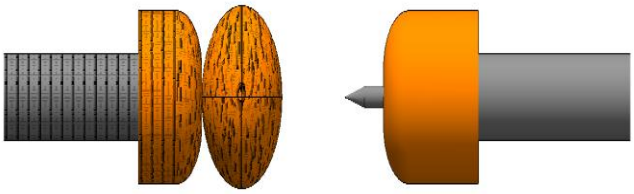


Fig 6.1:-Assigning Material and Boundary Condition

Step 6:- Run the model in static 3-D analysis.

Step 7:- After simulation results calculate the value of electric stress from the shaded plots by cutting the plot perpendicular to z direction as shown in Figure 6.2

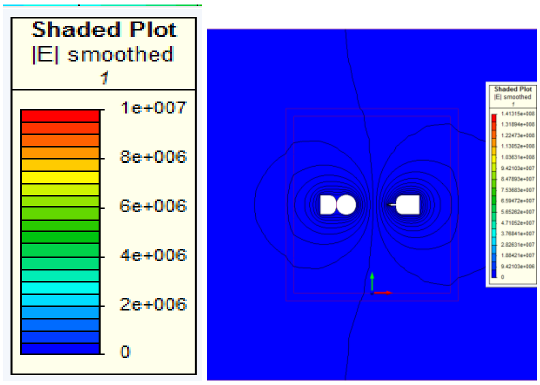


Fig.6.2:- Shaded Plot for Dielectric Stress

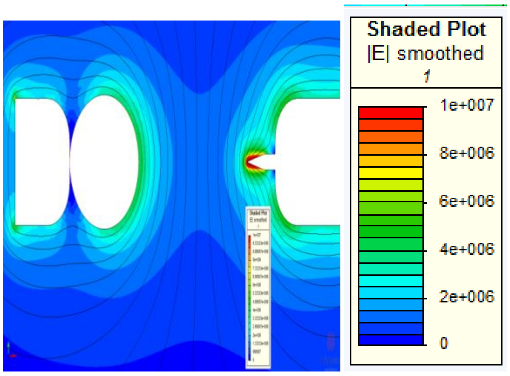


Fig.6.3:- Field Line Plots

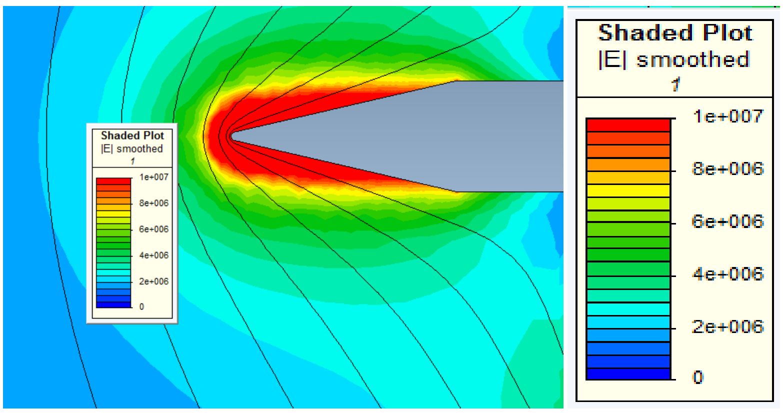


Fig 6.4:- Maximum Value of Stress Value at Tip Radius

6.4 RESULTS

The maximum value of dielectric electric stress is calculated from the shaded plot graph at various gap distances for different grades of oil.

- The breakdown voltages are more for mixture of naphthenic based mineral oil with natural ester oil leads to higher value of electric stress as compare to pure mineral oil
- Stress values are lower for natural ester oil and after 5mm gap the values are almost constant.

To compare the electrical gradient of natural ester oil with mineral oil due to 99% with stand voltage for electrical design limits predictions The effect of breakdown voltages of different oils is clearly reflected in maximum stress value and it shown in Fig. 6.5

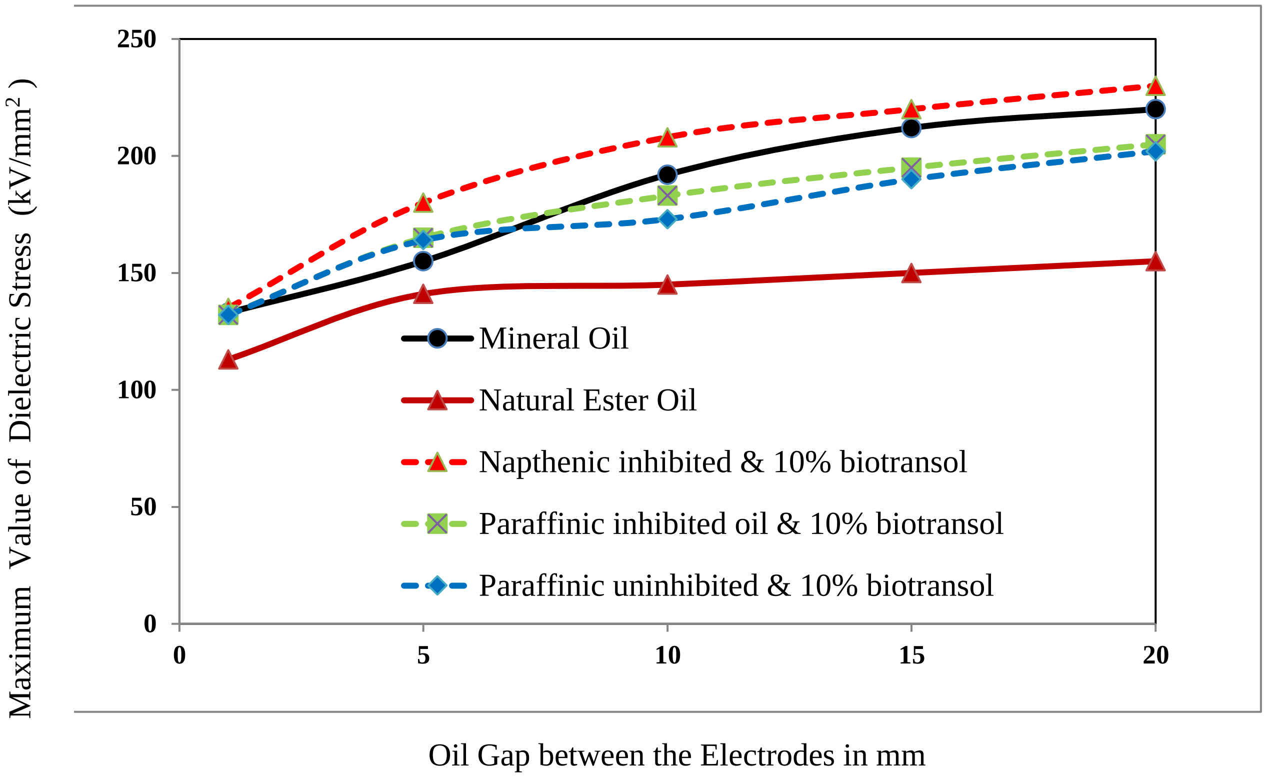


Fig.6.5:-Maximum Electric Stress in Different Transformer Oils versus Gap between the Electrodes

It can be seen from Figure 6.5, is that the stress value is lower for natural ester oil because the breakdown voltage is also less on comparison with other insulating liquids.

However pure mineral oil is showing higher stress value on comparing with mixture of paraffinic inhibited oil and biotransol and paraffinic uninhibited oil and biotransol.

The stress value is more for mixture of naphthenic inhibited oil and biotransol. The stress values follows the basic relation

$$E = -\nabla . V \qquad (6.2)$$

E= electric field intensity (Electric Stress)

V= electric scaler potential

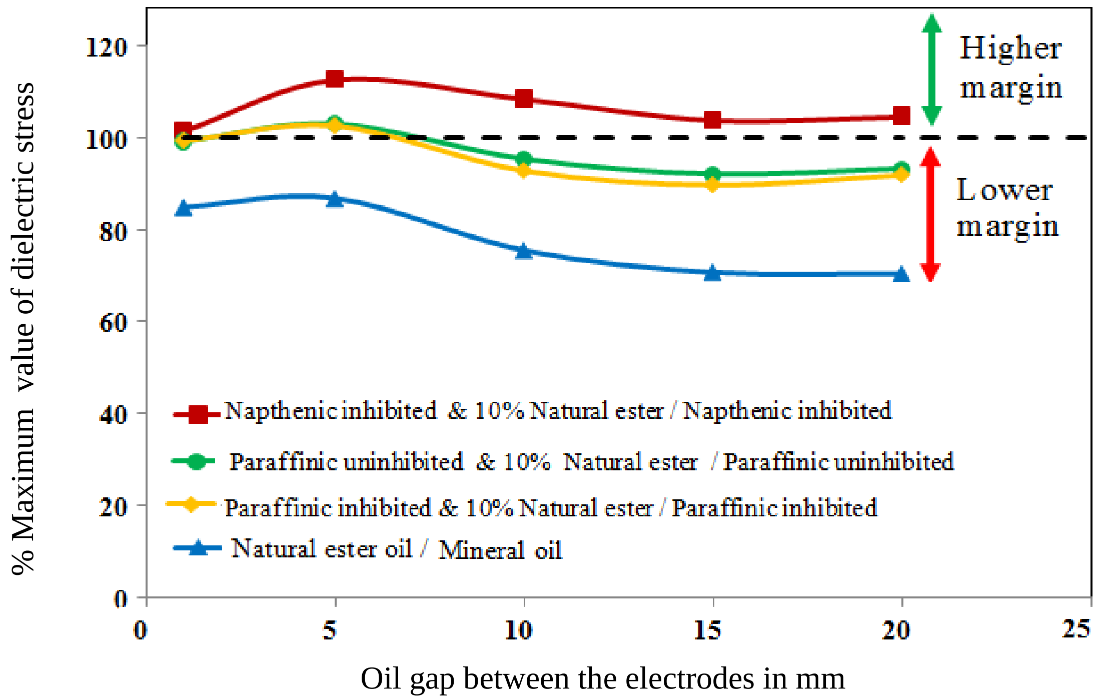


Fig.6.6:-Effect of Mixing of Natural Ester Oil in Mineral Oil interms of Maximum Stress.

Due to reduction of breakdown voltage of paraffinic grades of mineral oil after 10% of mixture of natural ester oil, the strength of dielectric stress is decreased and it leads to reduction of safety margin with respect to pure mineral oil. Although the breakdown voltage of both paraffinic grades of mineral oil with mixing of natural ester oil are slightly lower (about 90-95%) than those of base pure mineral oil. In case the natural ester oil is mixed with paraffinic grades of mineral oil accidently or intentionally during manufacturing or at service based on the percentage of the natural ester oil, mineral oil transformer may get fail at test bed or at site conditions depends on safety margin given in the pure mineral oil transformer guidelines.

6.5 CONCLUSIONS

The simulation result shows that the maximum value of electric stress varies with increase in the voltage. Therefore the transformer core coil assembly should be designed in such a way to reduce the chances of insulation failure. In case of mixture of naphthenic inhibited oil and biotransol although the breakdown voltage increases but at the same time dielectric stress also increases at that particular voltage.

CHAPTER 7

CONCLUSIONS & FUTURE SCOPE

This dissertation work is focused on the estimation and prediction of stray losses in transformer and to optimize the transformer and by applying various modifications in the design of transformer. The simulation results of electromagnetic-thermal analysis of power transformer are obtained using the software MAGNET. In the second phase of the work, electrical performance of various transformer liquids under power frequency conditions using needle-sphere field configuration is carried out. Through analytical and experimental studies, the objectives of the dissertation are achieved.

In this study, investigation of three objectives are covered as:

- Coupled – Electromagnetic and Thermal analysis of transformer
    - Estimation of stray losses in power transformer using the 3-D software package MAGNET.
    - Prediction of steady state temperature inside the transformer structural parts using the software THERMNET.
    - Optimization of transformer losses through modifications like, providing shunts of different widths, using various designs of winding base which holds the transformer winding.
- Power frequency withstand level of liquid insulation for transformer applications
    - Evaluation of average breakdown voltage for various insulating liquids and determination of 1% failure probability voltage.
    - Compares the performance of two ester oils with others under power frequency conditions in highly ac divergent fields.
- Effect on dielectric strength of mineral oil on mixing natural ester oil as polar contamination.
    - Effect of aromatics and polar contamination is studied in various grades of mineral oil having paraffinic and naphthenic base.
    - Effect of inhibitors in paraffins and napthenes based mineral oil is also studied under power frequency conditions.
- Prediction of dielectric stress analysis due to horizontal cell configuration at power frequency voltage conditions
    - To determine the maximum stress value in transformer insulating liquid.
    - Variation of maximum electric stress when pure mineral oil is changed to impure after adding 10% polar contamination.

7.1 SUMMARY OF MAIN FINDINGS

- The losses in transformer can be reduced after seeing the magnetic flux density plot. Higher the value of magnetic flux density, more the losses in the transformer. The losses in winding base can be controlled by bringing the winding base 45mm down from its original position and by splitting the same into small parts to increase the path for circulating current hitting from winding.
- The losses in transformer tank walls can be reduced by providing the tank shunts.
- The optimized model consists of tank shunts, 45mm down base and cutting fingers reduces the total losses about 20% and stray losses about 58.8% contributes the major reduction in transformer total losses.
- The breakdown voltage of natural ester oil is less with respect to all grades of mineral oil due to electronegative property in the natural ester oil. This is because the negative streamers can easily propagate between the electrodes due to high electronegativity in natural ester oil.
- The two natural ester oils studied- Biotransol HF and NE1 procured from market- behave more or less similarly in power frequency conditions only marginal differences.
- During the experimental studies it is found that the condition of mineral oil after breakdown is pretty bad in comparison to natural ester oil in all oil gaps because of formation of carbon particles.
- The breakdown voltages of three different grades of mineral oil are same for the entire oil gap between the sphere-needle electrodes.
- When natural ester oil is mixed with naphthenic inhibited mineral oil, breakdown voltage increases in comparison to pure naphthenic inhibited oil in non-uniform divergent fields which is an advantage for power industries from insulation point of view.
- The dielectric breakdown voltage of paraffinic grades is decreased after 10% of mixture of natural ester oil in comparison to pure paraffinic grades in non-uniform field configurations.

7.2 FUTURE SCOPE

This work mainly focuses on the electromagnetic analysis and power frequency testing of various insulating liquids of transformer. The dissertation represents a wide range of studies discussing about the dielectric behavior of transformer liquid under AC voltage. The esters have different molecular structure proved to influence the dielectric strength. This helps in designing the dielectric guidelines of power transformer having various insulating fluids as well as optimizing the cost by reducing the losses. However, some studies in this dissertation have scope for more investigations and research.

- For electromagnetic analysis , the future work could be carried out by considering these steps
  - In this dissertation, the losses are estimated by using Newton Raphson iterative technique. Further investigations successive approximation technique also to calculate the losses in magnetic structure of transformer.
  - The losses are reduced by splitting the winding base only. More investigations can be made on frame also by providing slots and laminated structure.
- For power frequency withstands level of transformer insulating liquids , the future work can be carried out, by following aspects
  - In this study, only 10% of natural ester oil is mixed with mineral oil. For better understanding of behavior of ester oil in mineral oil, the investigations can be carried out for mixing of 5% natural ester oil, 15% and 20% in mineral oil.
  - Moreover, in this dissertation, natural ester is mixed with mineral oil, studies can be carried out by mixing the small proportion of mineral oil in natural ester oil.

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APPENDIX-1 SOFTWARES UTILISED IN THESIS

The softwares utilized in this dissertation work are

- MAGNET
- THERMNET
- ELECNET
- MINITAB

MAGNET:- It is 2D/ 3D simulation software used by engineers and scientists for designing the motors, transformers, solenoids or any component with permanent magnets or coils.

It offers all the 2D and 3D simulations related to electromagnetic theory all within same user friendly interface:

- Magnetostatic Analysis
- Static, Transient and Time Varying for moving components,
- Predict various losses in device
- Based on FEM technique

ELECNET:- It is 2D/3D electric field simulation software tool. Designers can easily design and predict the behavior of complicated model. It works on the basis of FEM technique and solves for static, AC, transient electric field and current flow problems. It analyze and predict the performance of transformers, insulation systems, cables, busbars and many more.

THERMNET:- It simulates the steady state and transient temperature distribution of various heat sources. It has the capability to couple with MAGNET and ELECNET to provide accurate electro-thermal analysis for electric machines, transformers, surge arrestors.

- It simulates the temperature distributions caused by various heat sources in the presence of various thermally conducted devices.
- It couples with MAGNET for heating effect due to eddy current and hysteresis losses.

MINITAB:- It is powerful statistical software. It helps to spot trends, solve problems and discover valuable insights in data.

APPENDIX- II STANDARDS UTILISED

IS 2026-1 "Power Transformer Part-1"	Applicable to three phase and single phase transformer. Discusses about rating plates, different types of winding, various connections of transformer, variation of voltage with constant flux, measurement of losses in

	transformer.
ASTM-D 3300 “Standard Test Method for Dielectric Breakdown Voltage of Insulating Oils of Petroleum Origin Under Impulse Conditions”	This standard mainly focuses on the determination of dielectric breakdown voltage of transformer insulating liquids in non uniform field under impulse conditions. Discusses about the significance of the impulse testing, adjustments of electrodes and their diameters, testing procedure.
ASTM D-1816, “Standard test method for dielectric breakdown voltage of insulating oils of petroleum origin using VDE electrodes.”	This test is used for determination of dielectric breakdown voltage and testing of oil in power system equipments. Discusses about the significance of the ac testing of oil, apparatus required, test conditions, test cell and testing procedure.
IEC 60814 standard ‘Determination of water in liquid dielectrics by automatic Karl Fischer titration.	This standard describes how to determine the water content in insulating liquids and in oil- inpregenated cellulose insulation using Karl Fischer Iteration Method.

LIST OF PUBLICATIONS

[1] Paper entitled as A. Uppal, R. Agarwal, P.Sharma, C.S. Narasimhan, J. Velandy “ Effect of dielectric strength of mineral oil on mixing with natural ester oil as a polar contaminant under AC stress” has been communicated for acceptance to [IEEE Int. Conf. in CATCON 2019]

[2] Paper entitled as P.Sharma, R.Agarwal, A. Uppal, C.S. Narasimhan, G.Morde, 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.

[3] Paper entitled as P. Sharma, R. Agarwal, A.Uppal, C.S. Narasimhan, J. Velandy “Lightning Impulse Polarity Effects of Ester Oils and Mineral Oils for Transformer Applications” has been communicated for acceptance to [IEEE Int. Conf. in CATCON 2019]

[4] Paper entitled as R.Agarwal, P. Sharma, A. Uppal, C.S. Narasimhan, G.Morde, J. Velandy “ Behaviour of Natural Ester Oil under Negative and Positive Lightning Impulse Stress” has been communicated for acceptance to International Journal of Power and Energy Conversion.

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