

DIELECTRIC AND THERMAL DESIGN GUIDELINES FOR ESTER OIL TRANSFORMERS

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Submitted by

Apurti Jain

Regd. No.801742006

Under the Guidance of

Dr. Ashish Paramane

Lecturer

Electrical and Instrumentation Engineering Department,

&

Dr. Jeyabalan Velandy

Manager,

CG Power and Industrial Solutions Ltd., Mumbai



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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

DECLARATION


I hereby certify that the work which is presented in dissertation entitled, "DIELECTRIC AND THERMAL DESIGN GUIDELINES FOR ESTER OIL TRANSFORMERS", in fulfillment of the requirements for the award of the degree of Master of Engineering in Power Systems, submitted to Electrical & Instrumentation Engineering Department of Thapar Institute of Engineering & Technology (Deemed to be University) is an authentic record of my own work carried under the supervision of Dr. Ashish Paramane, Lecturer, Electrical and Instrumentation Engineering department, TIET and Dr. Jeyabalan Velandy, CG Power and Industrial Solutions Ltd., Mumbai. It refers others researcher's work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

Place: **TIET, Patiala**
Date: **1/7/19**


(APURVI JAIN)
Roll No.: 801742006

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


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


(Dr. Jeyabalan Velandy)
Manager
CG Power and Industrial Solutions Ltd.
Mumbai

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Apurti Jain

(Registration no.: 801742006)

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NOMENCLATURE

Main symbols and notations used in this study are listed below. Sometimes a symbol may have alternate meaning but in such a case; the context is sufficient to avoid confusion.

PD	Partial discharge
FEM	Finite element method
SOV	Stressed oil volume
LVI	Low voltage impulse
SFRA	Sweep frequency response analysis
CC	Correlation coefficient
SD	Standard deviation
ASLE	Absolute sum of logarithmic error
MSE	Maximum square error
MM	Min- max ratio
DIL	Design insulation level
SER	Static end ring

ABSTRACT

The mineral or synthetic oil is mostly being used in conjunction with paper as the dielectric medium in most of the high voltage equipment. However, impact on environment, lack of petroleum oil reserves and disposal problems with used oils, have prompted researchers to direct their focus on to biodegradable and renewable insulating materials. The new insulating liquid materials development is guided by multiple factors such as electrical and thermal performance aspects, environmental requirements, safety and economic considerations. As cautious approach is necessary for any step change in technology, transformer manufacturers have to face new specifications related to these new requirements. This work reviews the current status of vegetable oils use as transformer oil, including their production, processing, and characterization.

Since transformer's reliability depends on strength of insulation involved in it, hence characterisation of insulations based on standards are important for designing of power transformers. This project utilises the concept of testing with standard impulse wave shape as per IEC 60243 for defining dielectric/insulation guidelines for 132 kV ester oil transformers along with investigation of electrical performances and electrostatic stress analysis including influence of axial and radial fields on insulation. Additionally, thermal performance evaluation of ester liquids according to IS-2026 and frequency response analysis as per IEC 60076-18 is done.

The results indicate that impulse strength of ester liquids for breakdown in a quasi-uniform field is 10-15% lower as compared to mineral oil. Because of higher permittivity than mineral oil, lower electric stress in insulating oils in case of esters and slight deviations from mineral oil response are observed in frequency response analysis . Additionally because of hydrophilic nature of ester molecules, though having higher viscosity than mineral oil hence higher hotspot temperature , ester oils do not require additional increase in cooling capacity of transformers or to diminish transformer power rating. Ester oils enable life extension of transformers. In result increases the total reliability of power system .

Keywords: Ester oil, BIL, dielectric design guidelines, SFRA, Thermal performance, breakdown probability, electric stress, dielectric constant, insulation design.

CHAPTER 1

INTRODUCTION

1.1. PROJECT BACKGROUND

Mineral oil, together with cellulose, has been the insulation of choice for large power transformers over the past century because of performance, inexpensiveness and easy accessibility. Unfortunately mineral oil is harmful to the environment if spilt and is not readily biodegradable. In recent years there has been interest in non-toxic and readily biodegradable transformer oils such as those based on esters. Using esters as transformer dielectrics is by no means a recent innovation. Natural esters were among first oils which are used in form of dielectrics [1-3]. A team led by George Westinghouse used castor and linseed oils as dielectric liquids and insulator impregnates from the late 1880s. One disadvantage, however, was that esters would quickly oxidise in the presence of air and subsequently gel. Therefore esters were replaced by more chemically stable oils, such as mineral oil, which Thompson patented for use in transformers in 1892 [4,5].

Even though esters are already being used as the dielectric in the aforementioned power transformers, comprehensive studies are required to understand the impact of using esters as power transformer is main component of power system and its reliability depends on insulation involved. Reliability of insulation used depends upon its dielectric, thermal, chemical and physical properties[6]

Insulation in transformer is broadly divided as major, minor and end insulation. Oil and paper are commonly used major insulation materials used in and around windings and these are stressed under various electrostatic field configurations ranging from uniform to quasi-uniform and non-uniform [7]. Because of electric fields inside transformers, it requires fluid with good withstand strength. Hence, for failure free functioning of high voltage transformers, reliability of insulation used in it should be good. Withstand strength of insulating oil (= volts/m) depends on gap between conductors and decreases as the gap increases. This is called 'long gap' effect. Smaller gaps of order of tens of mm are found in sections of windings. While large gaps of order of tens of cm are found between leads and wall of tank which is earthed. Fig 1.1 represents internal arrangement of transformer.



Fig.1.1 Internal Arrangement of transformer

Solid insulation barriers are placed between windings of different phases since they carry greater insulation strength as compared to oil. This characteristic of solid insulation is significant when pre-breakdown phenomena and propagation of streamers are dealt with [7]. If gap between different windings are insulated only with oil then it will result in lesser strength to withstand over voltages. As a result larger gaps need to be provided for getting better insulation characteristics. This, ultimately affects overall cost and size [8]. Therefore, for designing transformer optimally and for extensive adoption of ester oil as insulation, basic understanding of behavior of ester is essential.

Apart from dielectric properties of liquid insulation, it is also considered as coolant. Three main properties decided its usefulness: its thermal conductivity, specific heat and viscosity. The viscosity of oil affects the rating of the pump required to circulate the oil within the transformer [10] to distribute temperature rise in transformers evenly. High viscosity of insulating liquid leads to slower rate of flow and hence results in lower heat transferring efficiency. Hence, transformers employing lesser combusive fluid requires improved cooling facilities[11] otherwise working at lower rating. The thermal cooling capability of an oil is helps to build thermal model of transformers to ensure that they do not fail prematurely.

1.2.PROBLEM STATEMENT

To analyze main causes of failure of power transformers, mode of failures has been divided into three parts:

1. Electrical
2. Thermal

3. Mechanical

These faults are further classified into external and internal components failure which usually occur in main tank , bushings, tap changers, dielectrics, windings and core.

Referring to the statistical survey in past as shown in Fig.1.2, maximum percentage of overall factors which lead to transformers failure are due to dielectric, electric issues followed by thermal .Major portion of failures occur in windings.

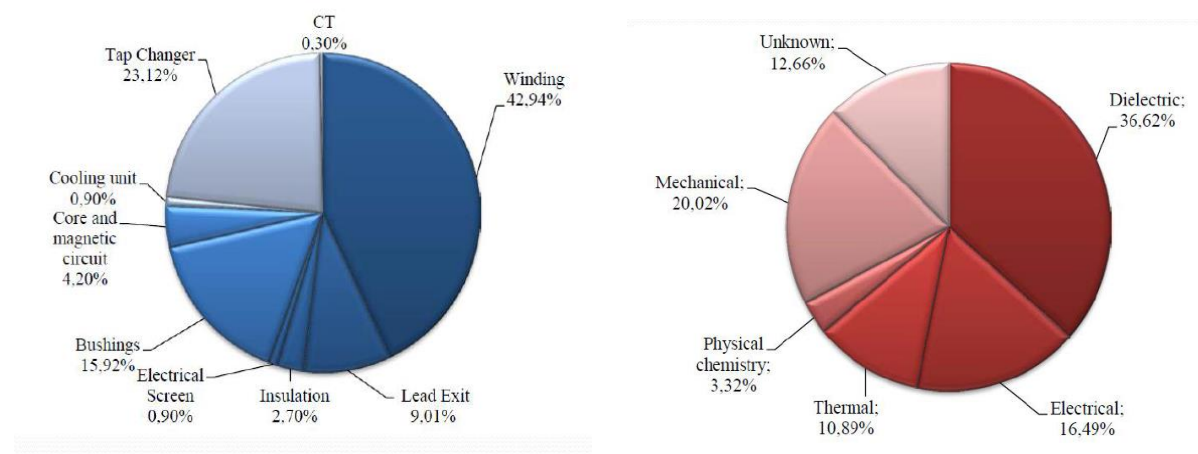


Fig 1.2 Factors contributing to power transformer failure

At inceptive stages, faults in windings have insignificant effects on performance of transformers , hence such faults remain unidentified often. Over time, these faults manifest into severe winding faults and as a result, damaging the noticeable portion of the transformer windings and core. Thermal performance is also affected by incorrect modelling of transformers or due to changes in insulation properties over the time. In past time, several strategies have been evolved for detection and study of winding faults (inter-turn and inter-disc) and thermal modelling of transformers but executing these strategies practically involves few challenges e.g. expensiveness, lesser reliableness and accuracy and requirement of additional apparatus inside transformer. Moreover, none among existing technology are appropriate to monitor transformer condition online or in real time condition. Hence, due to lack of any established methodology, this dissertation works focuses on dielectric, electrical and thermal studies of ester oil in terms of insulation characteristics , impulse testing of inter-turn and inter-disc insulation strength, temperature rise studies and frequency response analysis of symmetry of various components of transformers. These studies contribute in further technology development and failure reduction in case of ester oil applications in

power transformers. All the results of ester oil are compared with mineral oil characteristics and hence changes to be made in design of transformers are considered.

1.3. ORGANIZATION OF DISSERTATION WORK

Chapter 1 –Introduction

This chapter discusses about application of solid and liquid insulations in transformers along with their dielectric and thermal properties. Evolution and need of ester liquids are also discussed due to shortcomings of mineral oils. Later section of this chapter elaborates motivation for this dissertation work.

Chapter 2 –Literature Survey

This chapter contains a literature review . Properties of various insulating oils are discussed. Ester oil technology as transformer insulation is a new concept and very less work has been done. So, to study behaviour of insulating liquids such as breakdown mechanism, electrostatic stress distribution in insulation components, thermal performance and frequency response of winding in mineral and ester oils are discussed. On basis of former outcomes, insulation design of transformers is explained.

Further, gaps in previous research are considered as objective of this work.

Chapter 3 – Standard impulse testing of interdisc insulation of transformer winding

This chapter quantitatively analyze impulse withstand strength of interdisc insulation of windings. Pre-requisites and basics of test model are mentioned along with material requirements as per IEC standard. Being tested with standard impulse voltage and statistically analyzed with weibull distribution for 1% failure probability, electrostatic stress analysis discusses stress distribution in solid and liquid insulation.

Chapter 4- Thermal performance if transformer insulation liquids

This chapter analyses heat dissipation quality of liquid insulation commonly used in transformers. Temperature rise test has been discussed and on basis of results hence obtained, hotspot temperature is discusses. Further, higher hotspot temperature limits of etser liquids as discussed as per transformer applications.

Chapter 5-Evaluation of difference in permittivity of insulating liquids through frequency response

This chapter discusses effect of higher permittivity of ester liquids on impedance of transformer through frequency response analysis. Principle of SFRA is discussed along with case studies to evaluate effect of permittivity in detail. Further, for frequency response

interpretation graphical method and numerical parameters are compared. Hence, better way of interpretation is analyzed.

Chapter 6- Insulation design of transformers

This chapter discusses designing of insulation of power transformers with basics of FEM model. Minimization of stress with enhancement in safety margin is evaluated through various configuration of solid and liquid insulation used.

Chapter 7- Conclusion and future scope

This chapter summaries the major findings and conclusion of this work and provide the suggestions for future work which is required to further understand the behavior of ester liquids.

CHAPTER 2

LITERATURE SURVEY

Insulating oil such as mineral oil is basically being employed in high voltage fields in combination with paper in order to form dielectric media. Nonetheless, affect on environment, depletion of petroleum reserves and issues regarding disposal, have caused researchers to impart their attention on biodegradable insulation. Developing substitute insulating medium is accompanied by multiple factors such as environmental needs, safety and economic studies. Hence transformers manufacturer have to undergo latest enumeration related to respective design changes.

Looking for applications in power transformers, any alternate should satisfy basic insulation level of design of transformer [8]. Main criteria for design of insulation in power transformers is standard impulse withstand strength of transformer oil. Also, standard impulse test is a part of validation tests done on transformers having rating higher than 72.5 kV[11]. Standard impulse withstand i.e. electrical performance is closely related to chemical properties of an insulating oil[8,9]. In addition to satisfying basic insulation level, it is required to understand dielectric performance of liquid. Breakdown, in general, is related to initiation and propagation of conductive path 'streamers' [12]. Initiation is controlled by many aspects like physical and chemical properties, dissolved content, electrode geometry, impurities, ability of insulation to allow electric field through them i.e. permittivity etc. Permittivity changes also affect the quality of insulation thereby plays role in process of breakdown. Hence, breakdown of insulation is a stochastic event which can be demonstrated through statistical analysis. Along with dielectric properties, thermal performance of insulation also affects its application in power transformers. Quantity of heat dissipated is subjected to thermal properties of liquid which consequently affects life of insulation of transformer. Thereby influencing reliability of design of transformers.

Hence this chapter presents an overview of transformer liquids and industrial application of alternative liquids around the world. Mechanisms of dielectric failure in liquids are discussed along with study on propagation of streamers and electric stress analysis in liquid, solid and at their interfaces. Since breakdown is a statistical distributed phenomena as it depends on the complex physics and chemistry of the oil and impurities involved [1, 2, 12-14]. 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 [13, 14]. Hence, statistical distribution which is followed by breakdown process is discussed.

Additionally, failures are not developed by large electric stress, analogous chemical, mechanical and thermal aspects also have remarkable effect over breakdown procedure. Further literature survey followed by study of thermal performance of liquid along with temperature distribution in transformers. Decay and seasoning of mechanical and electric property make the process of prediction their performance more difficult, hence frequency response analysis is discussed to find effect of various factors over electrical parameters. At the end, discussion is done related to insulation design of transformers, electric stress distribution and factors affecting insulation design.

Lastly, it summaries the gaps in research in present literature survey providing objectives which are required to further understand the behavior of ester liquids.

2.1 PREFACE TO OILS USED IN EXPERIMENTS

Basically three types of oils are used. This sections elaborates detailed properties of insulating oils used for in this work.

- Transol-Mineral oil
- Biotransol- Natural ester oil
- Transol synth 100- synthetic ester oil

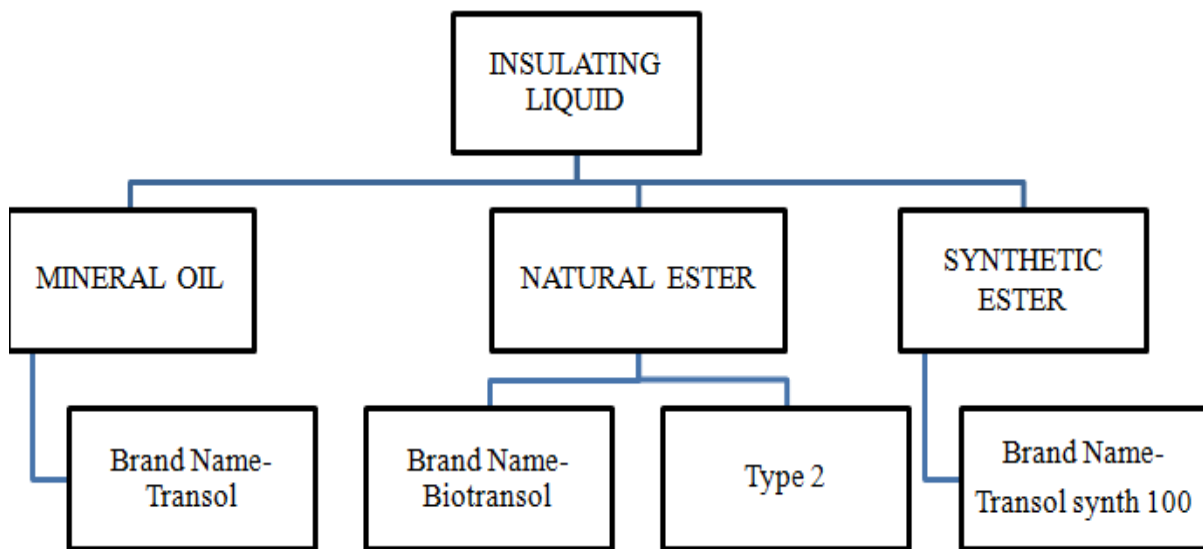


Fig 2.1 Classification of insulating oils

2.1.1 Mineral oil

Transol oil produced by Savita Oil Technologies Limited is utilized in this work. Mineral oil is most widely used insulating liquid for transformers derives from crude petroleum. It mainly constitute hydrocarbon compounds like naphthenic, aromatics and paraffinics as shown in Fig.2.1 [13]. Generally, naphthenics are better than paraffins since it is having

rational low temperature performance and less chances of forming waxes. Standard impulse insulation properties of mineral oils are improved due to aromatics but these are unstable to oxidation and leads to formation of sludges.

On the basis of anti-oxidants added in mineral oils, it can be classified as uninhibited, trace inhibited and inhibited. Advantages of mineral oil can be counted as easy availability, cheap and good in-service performance. Whereas due to poor biodegradability (20%-30% degradation after 21 days of biodegradability tests), less fire/flash points (approx. 170/150 °C) and corrosive sulphur, shortage in coming time, transformer industries are forced for looking its alternatives.[14].

2.1.1 Natural Ester Liquid:

Biotransol as natural ester liquid manufactured by Savita polymers limited, Mahad. It is derived from soybean seeds. Type 2 ester oil is also derived from vegetable oils and is purchased from market. Its structure is shown in fig2.2. Both liquids are readily biodegradable as per US EPA OECD 301B, environmental friendly and non-toxic. Because of superior properties as compared to mineral oil. Both are classified under K class based on its high flash and fire point. Additionally both liquids shows superior moisture handling capability.

2.1.2 Synthetic Ester Liquid:

Transol Synth 100 manufactured by Savita Polymers Limited, Mahad is utilised in this work. This liquid belongs to K class and follows the specifications of IEC 61099/IS 16080. This comprises of pentaerythritol ester as shown in Fig. Owing to presence of oxygen in molecule, it displays greater polar nature in comparison to natural ester. Trans Synth 100 displays high moisture tolerability hence enhancing insulation life of cellulose preventing deterioration.

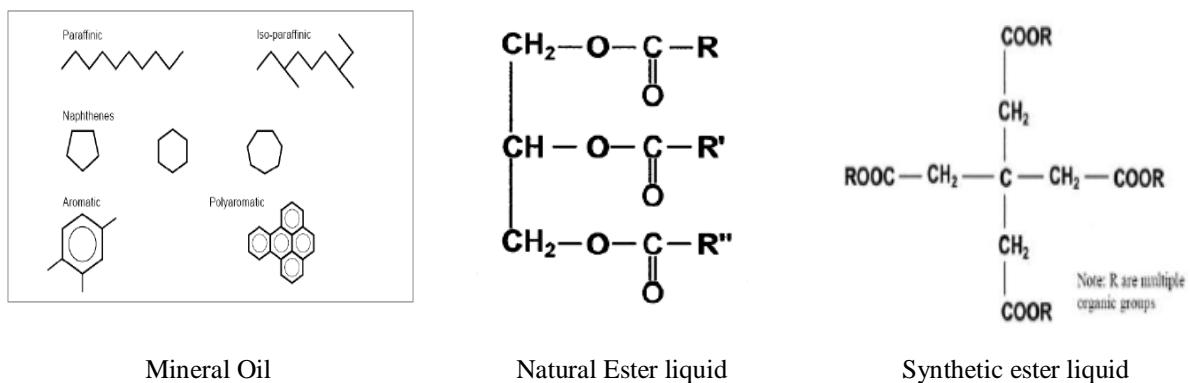


Fig. 2.2 Molecular structure of transformer insulating liquids

Table 2.1 Specifications of Mineral oil

Properties	Value	Unit	Standard
Electrical			
Loss factor (90°C)	< 0.001		IEC 60247
Breakdown voltage (2.5 mm gap)	>70	kV	IEC 60156
Physical			
Density (20 °C)	0.88	Kg/dm ³	ISO 12185
Viscosity (40°C)	8.5	Mm ² /sec	ISO 3104
Flash point	140	°C	ISO 2719
Pour point	-65	°C	ISO 3016
Chemical			
Acid content	0.08	Mg KOH/g	IEC 61125
Moisture	<25	ppm	IEC 60814

Table 2.2 Specifications of Natural ester oil

Properties	Value	Unit	Standard
Electrical			
Loss factor (90°C)	0.01-0.04		IEC 60247
Breakdown voltage(2.5 mm gap)	65-70	kV	IEC 60156
Physical			
Density (20 °C)	0.92	Kg/dm ³	ISO 3675
Viscosity (40°C)	35	Mm ² /sec	ISO 3104
Flash point	>265	°C	ISO 2719
Pour point	-20	°C	ISO 3016
Chemical			
Acid content	0.04	Mg KOH/g	IEC 62021-3
Moisture	<50	ppm	IEC 60814

Table 2.3 Specifications of synthetic ester oil

Properties	Value	Unit	Standard
Electrical			
Loss factor (90°C)	0.02		IEC 60247
Breakdown voltage(2.5 mm gap)	>70	kV	IEC 60156
Physical			
Density (20 °C)	0.94-0.96	Kg/dm ³	ISO 3675
Viscosity (40°C)	30.33	Mm ² /sec	ISO 3104
Flash point	264	°C	ISO 2719
Pour point	-58	°C	ISO 3016
Chemical			
Acid content	<0.02	Mg KOH/g	-
Moisture	<50	ppm	IEC 60814

On comparison of physical , chemical and electrical properties of esters, this can be concluded that esters displays adequate values to be recognized as insulating liquid for high voltage applications [16]. However, high viscosity of natural ester represents their limitation.

2.2 DIELECTRIC FAILURE OF TRANSFORMER OIL:

The mechanism of breakdown of liquids is still ambiguous. Since, results from experiment depends largely upon set-up and stipulation, it is difficult to generate a single theory which can explain every or just majority of results. Hence they are normally interpreted by one or some speculations.

Totally two dominant theories contend with each other[17]

2.2.1 Electron breakdown theory

On the basis of studies done in past, it is observed that breakdown in gaseous insulations happens because of collision and ionization continuously which results in electron avalanches. Breakdown phenomena in liquids is explained through analogous notion with modifications i.e. the electronic ionization theory [18]. Presence of electronic process is influenced by electron scavenging and low ionization potential additives on the streamer propagation. For instance, Devins suggested two-stage theory for negative streamers i.e. firstly negative ions is concentrated which traps electrons present in liquid. In second stage,

electric field is built up from ionic space charges which results in ionization after reaching critical value. Since, plasma channel tracks down and hence electrons are readily added in process[19].

2.2.2 Bubble theory

Due to vaporisation of liquid or impurity in it, streamer originates from localized bubble [20].As the charge is injected at tip of electrode, intense and localized thermal energy is injected. This charge injection at the filament tip results in production of intense and localized thermal energy. At this stage, liquid is converted into supercritical form radiating shockwave with development of instant vapour phase and its expansion later with decrease in temperature and pressure. As a result, filament tip acts as moving source of heat forming channel by expansion of vapour [21].

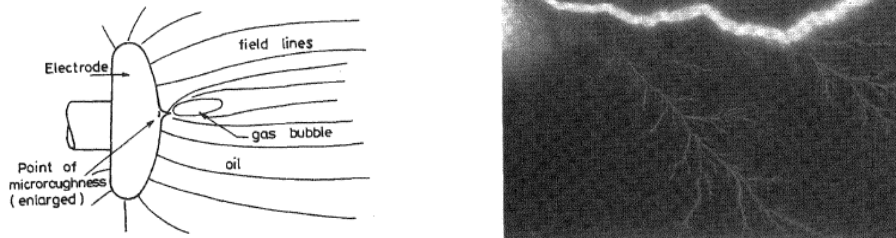


Fig 2.3 Discharge leading to breakdown

Since,transformer comprises of composite insulation as solid and liquid insulation. Hence, solid insulation also affects initiation and propagation of streamers, therefore contributes in breakdown process. Next section explains the effect of solid interface on propagation of streamers and breakdown phenomena.

2.3 INFLUENCE OF SOLID INTERFACE ON STREAMER PROPAGATION AND BREAKDOWN PHENOMENA

Although, interface of solid and liquid insulation demonstrate to be weak link because of permittivity differences, high amount of free charge particles because of weaker physical bonds at interfaces and also unevenness of surface of pressboard leads to enhancement in local fields hence causing lowering of overall dielectric strength.. Streamers are discharges which initiate breakdown in liquids. Generally, two arrangements of solid interface are used to analyse its effect [20].

2.3.1 SOLID INTERFACE IN PARALLEL DIRECTION OF ELECTRIC FIELD

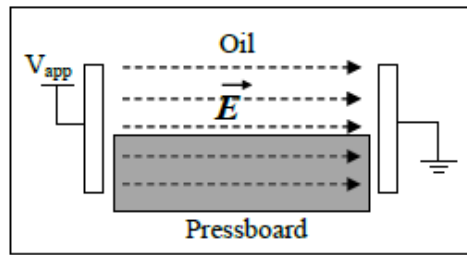


Fig. 2.4 Electric field parallel to oil-pressboard interface

In fig.2.4, first arrangement exhibits solid interface is in parallel to electric field.

Introduction of pressboard do not affect breakdown voltage according to results shown in Figure 2-5. It is also observed streamers always propagates along the solid-liquid interface in case of parallel arrangement.

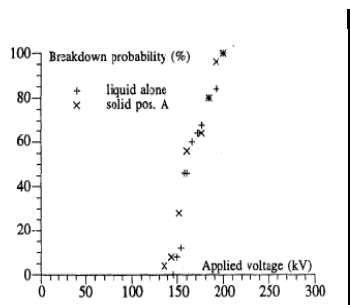


Fig 2.5 Influence of pressboard (parallel) on BDV

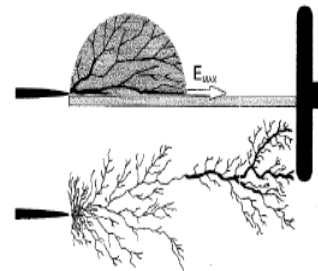


Fig 2.6 Illustration of streamer propagation on pressboard interface

2.3.2 SOLID INTERFACE PERPENDICULAR TO DIRECTION OF ELECTRIC FIELD

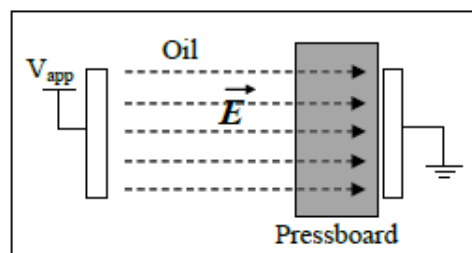


Fig .2.7 Electric field perpendicular to oil-pressboard interface

Position of pressboard perpendicular direction to the electric field is called barrier effect as in shown in fig 2.7 .Presence of pressboard barrier results in increasing the breakdown voltage significantly as shown in fig 2.8

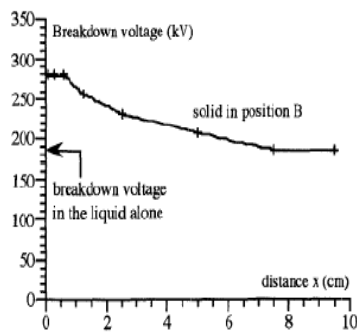


Fig 2.8 Influence of pressboard disk (perpendicular) on voltage

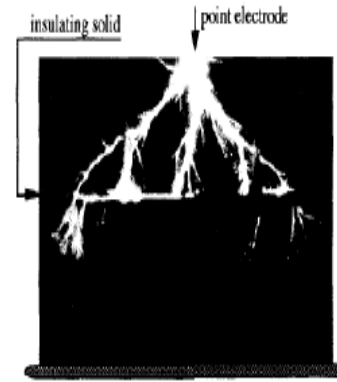


Fig 2.9 Streamer propagation getting breakdown around pressboard barrier

Increase in breakdown strength can be explained because of increase in discharge path between high-voltage and ground electrode.

Since breakdown is a stochastic phenomena which can be more complicated by different types insulation, impurity, external factor and operation of transformers. Hence, in view of such uncertainties statistical evaluation needs to be conducted to understand nature of process. Later section administers the characteristics of probability distribution which are followed by breakdown process.

2.4 STATISTICAL ANALYSIS

Because of random phenomena of breakdown, breakdown voltages are statistically distributed quantities. In various researches, breakdown voltage of samples are considered as mean of breakdown voltages and dispersion of breakdown voltages are not considered. This way of analyzing breakdown voltages is unacceptable in case of assessment of compatibility and reliability of insulation. To consider natural ester as a substitute of mineral oil, statistical analysis is to be done to establish reliability [22-24].

For statistical analysis of breakdown process, it should consistently follow any of the distributions [25]. Various distribution methods like Exponential, Gumbel, Lognormal, Gaussian, weibull etc. are utilized to analyze rate of failure at distinct probabilities [20-27]. For making certain the goodness of fit in a specific distribution, it is important to follow hypothesis testing like Anderson Darling Test, Chi Squared test, Kolmogorov Smirnov (K-S) test and Shapiro Wilk test [28]. From past work, it is concluded that breakdown voltages follow gaussian distribution [23]. While to develop and predict failure rate, hazard rate and survival rate of any medium, weibull distribution is used majorly [26,27]. Reason can be

attributed to flexibility of weibull distribution to model variety of data sets along with potential of presuming attributes of different distributions.

2.5 THERMAL PERFORMANCE OF TRANSFORMER LIQUIDS

Apart from acting as insulation, insulating oils also acts as a coolant, removing heat from within the transformer. The viscosity of oil affects its cooling capability. In previous literature investigations has been done on consequences of viscosity of oil on thermal model of transformer[29]. As stated in ASTM standard D341 [30], variation in viscosity of oil with respect to temperature can be given by Eq. (1),

$$\text{Log log}(v + 0.7) = A - (B \times \log T) \quad \text{.....(1)}$$

Where,

v is viscosity in centistokes

T is temperature in Kelvin ,

and A and B are constants for a given oil.

Variation of viscosity of mineral and ester oil is plotted in Fig. 2.10. From Fig.2.10, it can be concluded that rate of change in viscosity falls as temperature is increased. Hence, it can be concluded that change in thermal performance of transformer because of viscosity of oil will have less extent as temperature increases.

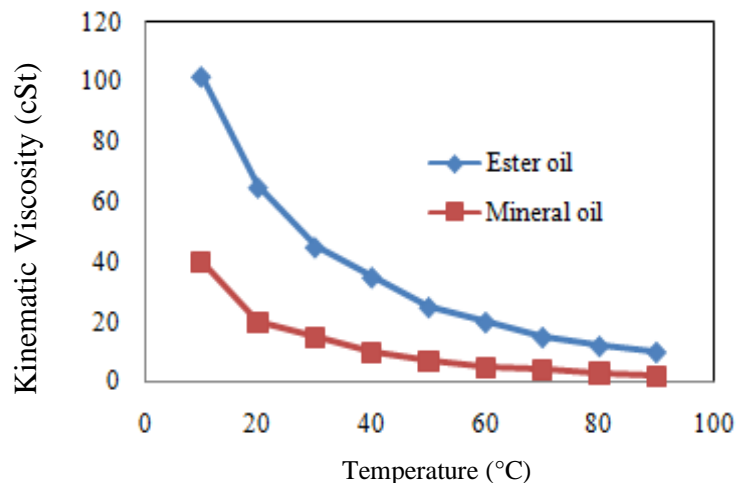


Fig.2.10 Kinematic viscosity of Ester and Mineral oil

Rate of heat loss by an oil is influenced by design of winding and oil duct in transformer, flow of oil flows in ducts and height of heat exchanger. Evaluating thermal performance of insulating liquid helps to certain transformers do not fail prematurely due to temperature rise. The most severe consequence of increased thermal stress is accelerated aging of the solid

insulation. The process of aging is a chemical reaction, where heat works as a catalyst. Hence, an elevated temperature accelerates the chemical reaction, i.e., the aging of the transformer. Following this reasoning, it becomes intuitively clear that the hottest part of the solid insulation undergoes the most rapid aging. That part of the solid insulation is referred to as the hotspot. Its corresponding temperature is referred to as the hotspot temperature. Additionally hot spot temperature is major factor which limits loading on transformer. Since, viscosity of natural ester is three times higher than mineral oil. Hence, temperature of winding with natural ester will be higher as compared to that with mineral oil if modification is not done in loading or designing of transformer.

As stated by IEC 60076-7, operating lifetime of non-thermally upgraded paper insulation becomes half for every 6°C increase in temperature. Proper thermal evaluation of insulation in transformer assist in ensuring that cellulose is properly cooled and increase of temperature at hotspots is not immoderate. As per previous researches, there is approx 30 deg Celsius difference between hotspot temperature of winding as compared with mineral oil transformers[31]

Various studies have been done on evaluation of distribution of inside transformer. A Methodology for calculating hot spot temperature has been proposed international standards [32]. FEM and FVM technique has been used to calculate distribution of temperature in transformer [33-36]. Conventional thermocouple sensors undergoes electromagnetic interference hence cannot be utilized inside transformers. Evaluation through calculation of international standard and software analysis lags precision and accuracy due to various assumptions which are incorrect i.e. temperature of oil in cooling duct is assumed to be same as top oil temperature, variation in viscosity of oil with temperature is neglected[33]. Hence, substitute of existing equations need to be developed taking into account latest improvements and factors affecting performance of insulation.

Temperature rise test is real time experiment which takes care of all above factors. Hence is proved to be more efficient method understanding temperature distribution in transformers and difference in thermal performance of ester and mineral oils. It is routine testing which is required to be done on one unit of specific design.

2.6 SWEEP FREQUENCY RESPONSE ANALYSIS

Transformers exhibit very essential role in the efficient transmission of power. Any failure in transformer or its associated peripherals will result in loss of power transmission adding up to huge losses. Hence the emerging technology of condition Monitoring or diagnostics testing of

transformers and other major equipment has come to the fore and is increasingly being considered to predict condition of equipment before it forces outages and/or major breakdowns. Traditional condition monitoring techniques such as : DGA, winding resistance measurement, capacitance and loss factor measurement etc. But none of these tests conclusively detect changes in working of Power Transformers , which vary impedance network. Issue related to this change is the abnormality occurring on the working Transformer i.e. short circuit etc, which produces enough axial and radial stresses which may lead to disturb the mechanical integrity of the Transformers. Additionally, working of transformers are affected by its accessories i.e. bushing, tap connections [37] and due to its degradation of insulation characteristics for eg.ageing,moisture content. [38]. So to pre identifies changes in working condition of power transformer, it is advisable to observe condition of transformer regularly during service to issue an early warning of failure. For this purpose SFRA is globally accepted as a reliable graphical tool to SFRA elaborate electrical property of transformer. This method has become one of common test since introduction of IEC 60076-18. SFRA testing is accomplished at end of acceptance testing for establishing transformer's genuine fingerprint, after transportation and during commissioning. Frequency-based methods are not only highly sensitive in detection of minute change in transformers, but can also be help in estimating its location This localization feature, although still in its infancy, makes this tool unique and worthy of further scrutiny.

2.6.1 OBJECTIVE AND BACKGROUND

Transformers are complex network of resistance, inductance and capacitance. Response of transformer to frequency analysis is dependent on inductive and capacitive elements which are essentially related to physical construction of transformer.

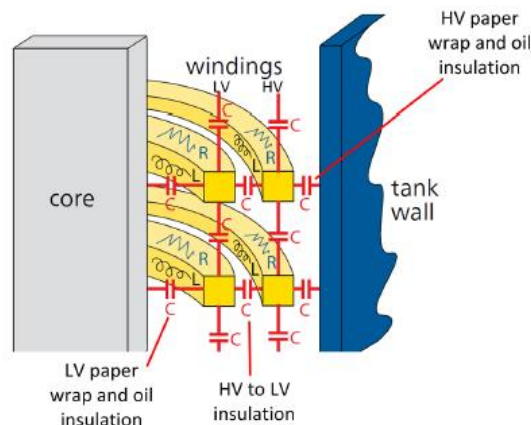


Fig 2.11 Cutview of transformer winding

Primary aim of SFRA is determining behaviour of impedance of test specimen (i.e. winding in case of Transformers) over a specified range of applied frequencies. Sinusoidal excitation voltage with continuously increasing frequency is injected into one end of the transformer winding and the response signal returning from the other end is measured. The result is a transfer function representation of the RLC network in the frequency domain as given by equation (2),

$$H(j\omega) = \frac{V_{output}(j\omega)}{V_{input}(j\omega)} \quad \dots\dots (2)$$

Magnitude and phase of transfer function can be used to plot bode plot over a large span varying frequency from 20 Hz to 1MHz..Hence equation (3) & (4) specifies the attributes required for bode plot.

$$A(dB) = 20 \log_{10}(H(j\omega)) \quad \dots\dots (3)$$

$$A(\theta) = \tan^{-1}(H(j\omega)) \quad \dots\dots (4)$$

Figure 2.12 below shows simplified equivalent circuit with lumped RLC components. Windings have complex distributions of resistance, inductance and capacitance. Each winding turn is inductively linked to others to a greater or lesser extent, whether in the same disc, layer or winding. Each turn is also capacitive linked to its immediate neighbors, with a hierarchy of capacitances, e.g., turn-turn, disc-disc, winding and earth. The stray capacitance values in the transformer winding depend upon the surface areas presented between turns, windings, core and tank, various combinations of the dielectric properties of the insulating oil, craft paper insulation and pressboard insulation. The dielectric properties of these materials themselves depend on various factors such as moisture, contamination, temperature and frequency of thermal load cycling of the transformer. Winding inductance depends on air core inductance between turn-to-turn and also on clamping pressure.

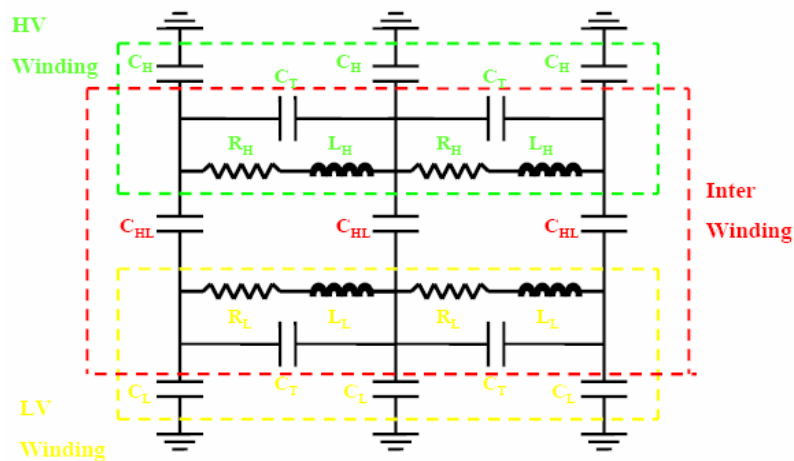


Fig.2.12 Equivalent circuit of winding with lumped R-L-C parameters

Owing to parameter and their interaction in transformers, typical frequency response can be Divided into four regions:

1. At lower frequencies (<2 kHz), response is purely inductive and first resonant frequencies correspond to iron core effects and parallel capacitance of winding. This frequency domain is sensitive to short circuit faults. This resonance happens because of interaction of magnetizing inductance with shunt capacitance of windings. If there occurs two flux paths in the core of different lengths, then there will be a double resonance. The first resonant frequencies can vary with the state of residual magnetization.
2. 2 kHz-100 kHz: At medium frequency there occurs group of resonances, because of interaction of air-cored inductance of the windings with shunt capacitance.
3. Above 100 kHz to 1 MHz- interaction between air inductance of winding and series or/and parallel capacitances of winding parts.
4. Above 1MHz-generally not taken into account-influence of leads and connection to ground may be very important.

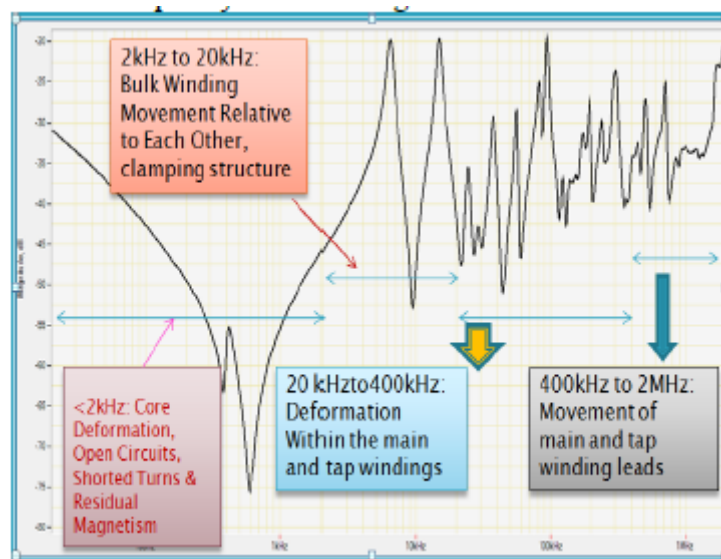


Fig2.13 Regions of typical frequency response

2.6.2 INTERPRETATION OF SFRA:

2.6.2.1 GRAPHICAL ANALYSIS

Graphical analysis comprises of comparing graphs of amplitude vs. frequency for reference and measured responses. Experienced personnel inspect curves for significant differences [39]. Differences can be usually understood as:

- Changes in shape of graph
- Creation of new resonant frequencies or elimination of existing resonant frequencies

- Large shifts in existing resonant frequencies.

Main difficulty in this method lies in expert's opinion that may lack both subjectivity and transparency. The conclusion relies on experience of person. Sometime minute deviations in graphs are not readily recognizable. Risks of incorrect estimation are more in slightly deformed winding. Solution to address such problems is to observe resonant frequencies. This provides objectivity and transparent information on account of resonances that have been created, eliminated or shifted. Although, this can extract information from the results at the resonances. As noise can be confused with resonant frequencies, hence this method tends to be difficult for application through computers.

To avoid such mistakes and thereby making SFRA easier to understand numerical parameters need to be employed.

2.6.2.2 NUMERICAL INTERPRETATION TECHNIQUES

In latest studies, various numerical parameters [38,40] have been employed to interpret frequency response. Zhijian et al. [38] utilised standard deviation (SD) and correlation coefficient (CC) for judging winding state. Wang et al. [41] suggested statistical methods on basis of difference in admittance amplitude, and area to detect distortion or faults in winding. Conclusion was drawn that it requires more investigations for determination of best method of evaluation. De Nigris et al. [40] employed signature difference method (SDM) and concluded that difference larger than 5dB in waveshapes within a particular frequency range can indicate critical defects in transformers. However, peaks and valleys may affect this method. Kim et al. [39] referred numerical methods i.e. sum-squared ratio error, max-min ratio error and absolute sum of logarithmic error (ASLE) and concluded that ASLE method appears to be most absolute criterion. Statistical indicators are particularly useful as they add objectivity and transparency making SFRA observation simple and easy to understand.

Though graphical representation explain mathematical relationships and looks visually appealing, however there are high chances inaccurate interpretations, treating irrelevant data important and complexity to deal with data.

2.7 INSULATION DESIGN OF TRANSFORMERS:

Acknowledging dielectric, thermal and electrical performance of insulation of transformers, design is among most dominant feature in engineering of transformer. Rational design procedure involves employing suitable insulation, constrained manufacturing procedure and righteous management, hence ensuring standard and secure functioning of transformers. To improve reliability of insulation components, comprehensive verification of difference

between withstanding degree and operating stress is required. To obtain operating stress, precise estimation of level of stress through explanatory electrode arrangement inside transformer via different test voltage and different test connections are done. Latest evaluation techniques such as FEM are utilized. Not only lowering of maximum electrical stress in dielectric is required so that safety margin is increased; additional factors i.e. waveforms of voltages applied voltages, voltage -time nature of dielectric, condition of surface and shape of electrodes, inception features of PD in dielectric, water content, decreament in non uniform field, impurities, removal of voids and local stress, processing and impregnation of insulation affects withstanding strength. Hence, it should also be considered while designing transformers.

2.7.1 Stress computation in various configurations:

As transformer consists of composite insulation. Hence, distribution of electric stress between various insulation materials is controlled by permittivity (dielectric constant) of insulating material as shown in fig.2.14 [42]

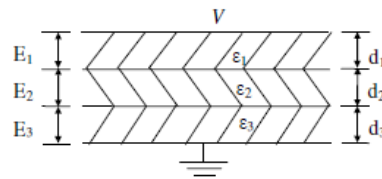


Fig 2.14 Sharing of the electric field across a composite insulator

$$E = \frac{V}{\epsilon_i \left(\frac{d_1}{\epsilon_1} + \frac{d_2}{\epsilon_2} + \frac{d_3}{\epsilon_3} \right)} \quad \text{where } i= 1,2,3,\dots \quad \dots(5)$$

As permittivity of solid insulation changes due to dissimilarity of permittivity among mineral and ester oils,hence, permittivity of oil impregnated cellulose can be calculated as [43]

$$\epsilon_{impregnated\ insulation} = \epsilon_{Fibre} \cdot \left[1 - K^2 \left(1 - \frac{1}{1+K \left(\frac{\epsilon_{Fibre}}{\epsilon_{Oil}} - 1 \right)} \right) \right] \quad \dots(6)$$

$$\text{where, } K = \sqrt[3]{\frac{V_{oil}}{V_{insuation}}}$$

Using FEM technique, to compute stress in ester and mineral oil, it is found that stress in oil is more in case of mineral oil than esters as it can be referred from fig.2.15 [43].Reason can

be attributed to higher permittivity of esters which results in equal distribution of electric stress between solid and liquid insulation.

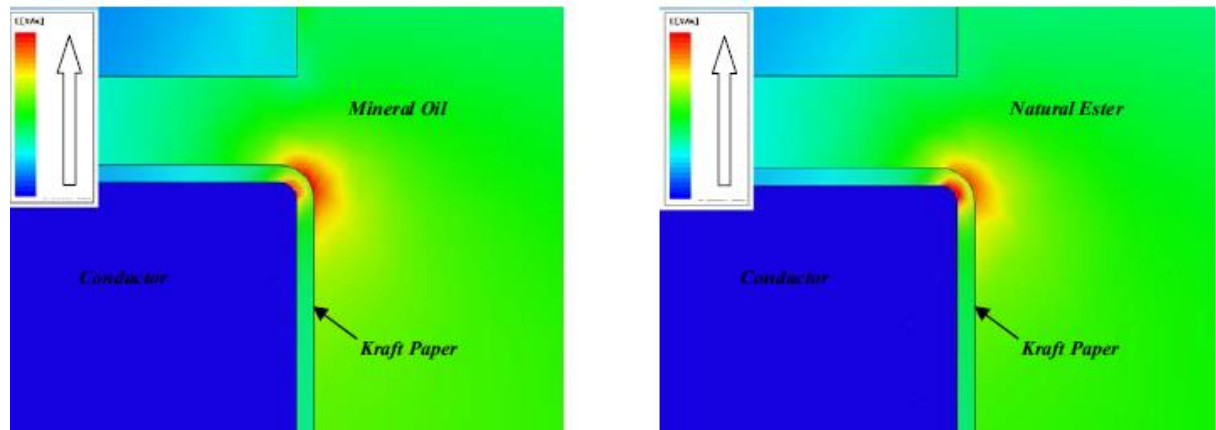


Fig. 2.15 Electric stress in transformer design for mineral and Natural ester oil

However, stress is more at the interface of solid-liquid insulation in case of esters. This interface can be modelled as wedge shaped regions which are filled with oil around conductors as shown in Fig 2.16. Hence wedge shaped regions are risk areas in transformers because electric field surrounding curved surfaces are higher than that on flat surfaces.

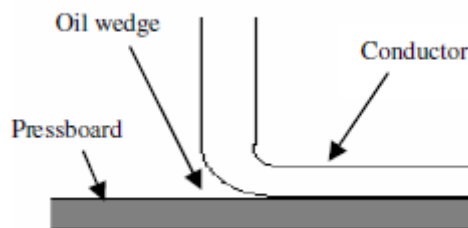


Fig 2.16 Location of oil wedge in transformer design

Usually, two types of failure takes place at solid-oil composite insulation in transformers. First involves whole loss of dielectric strength in between two electrodes. This can be in found in form of jump or bulk-oil breakdown, creepage breakdown through solid-liquid interface or in combines state of both. Second type comprises of local failure (for e.g. partial discharges) that may not instantaneously lead to failure. If breakdown does not happens completely, oil local regions may get ionize. These ions bombard cellulose and create conductive tracking on cellulose surface resulting into insulation failure. Partial discharges which are sustained guide towards diminishing of insulating property hence consequently leading to breakdown.

Since transformer oil can be changed according to its status over the time but cellulose cannot be replaced easily. Hence attention should be given that derivatives of oils should not damage solid insulation[42].

2.7.2 Factors influencing insulation strength:

Breakdown of dielectrics is a stochastic process which varies as a function of chemical and physical properties. Not only electrical stress participates in occurring of failure, interrelated chemical, thermal and mechanical characteristics also influence. These factors reciprocate because of ageing or diminishing of mechanical and electrical strength hence prediction of failure becomes more difficult. Therefore this section deals with behaviour of factors affecting insulation strength.

2.7.2.1 Effect of moisture and impurities:

Moisture decays both mechanical and electrical strength of insulation. Increase in moisture content in oil reduces strength drastically up to a saturation point beyond which no significant decay is observed in strength. Hence, saturation act as decision factor in affecting insulation strength of dielectrics [17,18]. Presence of solid impurities more significantly affect even though oil contains lesser moisture. makes the effect more significant even with low moisture content in the oil. Solid insulation displays more affinity for moisture in comparison to oil. Various chemical reactions leading to ageing of solid insulation takes place because of moisture absorption hence leading in diminishing its withstanding strength [19].

Origin of moisture in transformers can be stated as

- (a) residue moisture (typically 0.5% or less after factory processing),
- (b) Moisture absorbed during repairing, installation, poor sealing or because of pressure difference in respect of atmosphere.
- (c) aging of solid insulation

2.7.2.2 Effect of temperature

Temperature variations in transformers under normal operating conditions are the main reason of transferring of moisture content between solid insulation and oil. With temperature increment, moisture is transferred from solid insulation to oil while lowering of temperature results in return of moisture again to solid insulation but at slower rate. Also distribution of moisture in solid insulation layers is not uniform. Because of slower rate of transfer in solid insulation, free water appears in oil hence reducing its dielectric strength[25]. Moreover, increase in temperature leads to higher mobility of charge carriers hence results in increase of dielectric loss. Insulation resistance of insulation have negative temperature

coefficient which further enhances flow of current through it. Ultimately it leads to breakdown.

2.7.2.3 Effect of thickness

Dielectric strength of insulation does not increase proportionally with increase in thickness of insulation. Relation can be established [40] by equation (7),

$$E = (\text{thickness})^n$$

Constant n varies from 0.5 to 1 as it is dependent on processing of insulation and degree of uniformity of field. An untreated insulation exhibits lower n in comparison to treated insulation. For good shape of electrodes n displays higher value.

2.7.2.4 Stressed volume effects

Increase in stressed volume of oil leads to decrease strength of oil [41]. Strength calculations on basis of stressed volumes are commonly used in industries. Experimentally relationship between stressed oil volume and breakdown strength for a plain oil gap [12] can be obtained as given by equation (8),

$$E = 17.9 (SOV)^{-0.137} \text{ kVrms/mm} \quad \dots(8)$$

where the stressed oil volume (SOV) is in cm^3

Breakdown of gap is generally initiated at weakest spot under a high stress. However, if in other gap have greater volume of oil being subjected to equal level of stress, it is probable in resulting in breaking down at lower voltage since impurities and protrusions on electrodes are important consideration in volume or area effects. If in some other gap a greater volume of oil is subjected to the same level of stress, it is quite probable that a still weaker spot is present, resulting in the breakdown at a lower voltage. The amount of impurities and electrode protrusions become important considerations for the area/volume effects. Calculated stress value in design should be less than E by some experience-based margin.

2.7.2.5 Effect of oil velocity

Breakdown voltage aims to be higher if velocity of oil flow is greater than the force with which impurities are drawn in higher stress area as observed in stationary oil. When it increases beyond a limit, decrement in breakdown voltage may be related to stressed oil volume effect where probability of impurities passing through high stress area increases. This can be related to weak link theory; weak links in oil i.e. impurities or particles may start discharge as stressed volume of oil passes through high stress [18]. On contrary to this concept, higher velocity reduces the time for which impurity resides in stresses area. Contrary and breakdown voltage should display increment behaviour according to volt-time

characteristics. Hence, breakdown voltage at higher velocity depends on two effects namely volt-time effect or the oil volume effect, is the determining factor.

2.8 GAPS IN RESEARCH

Concluding literature review with research done in past, following are less explored areas in the field of application of ester oils in transformers.

- I. Study of breakdown phenomena and factors affecting with electrode configurations instead of actual working condition of liquid-solid insulation interfaces.
- II. Consideration of area effect in actual transformer winding
- III. Study of axial and radial stress i.e. combined electric stress
- IV. Thermal performance and overloading capability of ester oil transformer
- V. SFRA studies and effect of different permittivity of oils.

2.9 OBJECTIVES OF DISSERTATION WORK

Objective of this dissertation work lies filling the gap which is found in research done till date.

- I. Considering actual solid-liquid interface medium i.e. wedge shaped models for studying breakdown phenomena.
- II. Consideration of area effect in transformer windings and combined electric stress analysis.
- III. Evaluation of thermal performance of ester oil transformer
- IV. SFRA study of ester oil transformer.
- V. Insulation design of ester oil transformers
- VI. Minimization of failure at factory as well as at site.

2.10 CONCLUSION

To reduce major cause of transformer failure i.e. faults in windings (inter-turn and interdisc), it is required to understand breakdown phenomena through requisite approach. Also, thermal properties, permittivity differences with respect to mineral oil and insulation design of ester oil transformers have not been given necessary attention for applications in high voltage transformers in past literature. Hence, above objectives are fulfilled through the methodologies proposed in subsequent chapters.

CHAPTER 3

STANDARD IMPULSE TESTING OF INTERDISC INSULATION OF TRANSFORMER WINDING

3.1 INTRODUCTION

Inner insulation design of transformer is complex, as there are various components with different potentials in transformer, and oil-solid composite insulation is usually utilized for withstanding stresses. Nonetheless, major electric field in transformer for e.g. between turn to turn and disk to disk, are quasi-uniform fields. Hence, this chapter discusses experiments performed for developing dielectric design guidelines and understanding the behavior of composite solid-liquid interdisc insulation in mineral oil and ester oils under impulse voltage application. Section 3.2 describes two model of windings are proposed to utilize concept of axial stress and combination of axial and radial stress respectively over breakdown of insulation. Breakdown voltages computed from impulse testing are fitted in weibull distribution to compute voltages corresponding to 1% failure probability in section 3.3. As besides 50% breakdown voltages, withstand voltage corresponding to lower breakdown probability i.e. 1% are even better for insulation designing. Electric stress analysis is performed in section 3.4 utilizing voltages corresponding to 1% breakdown probability. At last, analysis is done in section 3.5 involving effect of permittivity difference in ester and mineral oil over stress distribution in oil and winding. Additionally, breakdown locations owing to electric stress are also discussed.

3.2 EXPERIMENTAL DESCRIPTION

3.2.1 TEST MODEL

High voltage windings in transformers are manufactured in various types of configurations like discs with and without spacers in between them. Inter-disc and inter-turn insulation in transformer windings filled with oil are usually of oil-impregnated paper (OIP). Breakdown of composite dielectric like OIP is a mixed phenomenon depending on many physical factors e.g. gap between two discs or turns and electrical factors e.g. electric stress and quasi-uniform state of field in interdisc and interturn space. In place of testing with conventional electrode configurations like needle-sphere, sphere-sphere or needle plane to evaluate dielectric strength of oil, typical inter-disc winding insulation [26] as shown in Fig.3.1 is utilized in this project to accurately estimate composite solid-liquid insulation withstand

strength. As inter-disc spacing is decided by impulse stresses, hence impulse testing as per IEC 60243-3 is opted for dielectric strength estimation.

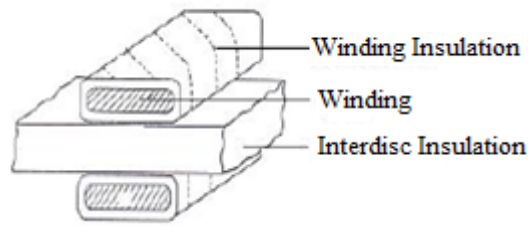


Fig 3.1 Typical inter-disc winding insulation

Electric field in between discs is majorly axial in case of standard lightning impulse testing and is affected by geometry of winding and voltage distribution across them. HV winding is generally located around LV winding in transformers. Radial distance between HV and LV windings is called main gap. Electric field in the main gap majorly demonstrate radial geometry and is also affected by geometry and voltage distribution in winding. Usually axial stresses between discs and radial stress between windings is considered in separate fashion - as two mutually independent factors, which transformer should be capable of withstanding both. Therefore, this work considers two models, Model A and Model B to emulate axial and combination of axial and radial fields respectively.

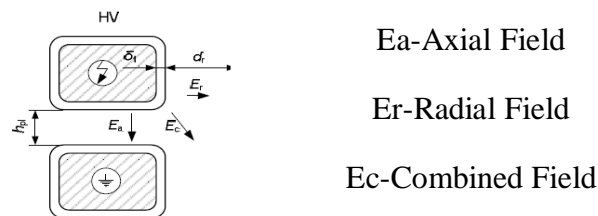
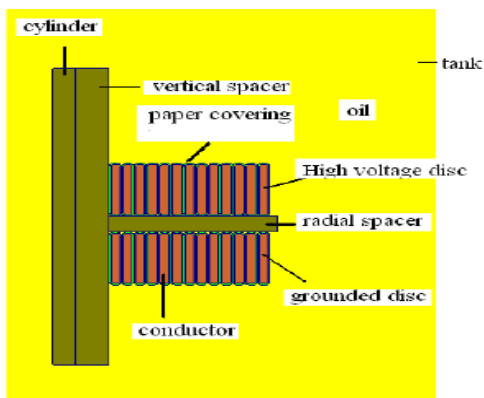


Fig .3.2 Components of electric field in winding

3.2.2 TEST OBJECT SPECIFICATION

Model A and B windings to study axial and combined field stress are shown in Fig.3.3 (a) and (b). Model B is designed with additional grounded copper foil to emulate combined field effect as shown in Fig.3.4.

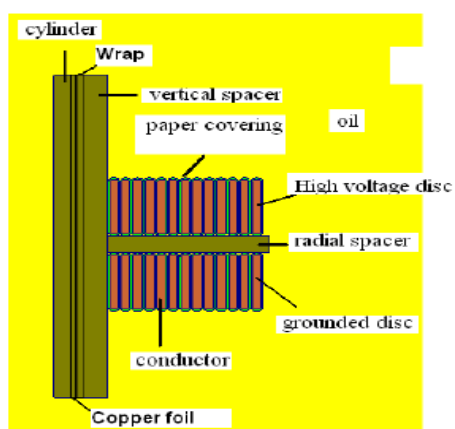


Solid Model



Real time Object

(a) Model A winding



Solid Model



Real time Object

(b) Model B winding

Fig 3.3 Test Objects for impulse testing

Twenty four test models to be tested with positive and negative impulse voltages are manufactured with different combinations of paper covering and keyspacers as shown in Table 3.1.

Table 3.1 Combination of paper covering and keyspacers

	PAPER COVERING(mm)	0.5	0.8	1.1			
MODEL	KEYSPACER(mm)				TOTAL	POLARITY	WAVESHAPE
A	3	2	2	2	6	+ & -	1.2/50 μ s
	4.5	2	2	2	6	+ & -	1.2/50 μ s
B	3	2	2	2	6	+ & -	1.2/50 μ s
	4.5	2	2	2	6	+ & -	1.2/50 μ s

3.2.3 MANUFACTURING OF WINDINGS

Winding process is succession of several stages requiring for each one a high skill level from the personnel involved. To start with manufacturing the model required in this study, formerly components are selected as per IEC standards as given in Table 3.2.

Table 3.2 Components description according to IEC standards

S.No.	COMPONENT	STANDARD
1.	Cylinder	IEC 60641-2
2.	Axial sticks	
3.	Key spacers	
4.	Wrap	
5.	FRP clamping	IEC 60803
6.	Ester oil	IEC 60296
7.	Mineral oil	IEC 60156
8.	Copper with kraft paper covered	IEC 60137-27

To start with winding conductors ,first a properly made anchorage of pressboard cylinder maintaining inner diameter of coil 420 mm is arranged over former. To support conductor and for providing channel for oil flow, axial sticks are pasted over cylinder. For Model B ,copper foil is wrapped over cylinder with help of resin tape to emulate effect of core. Winding procedure is then followed according to design requirement and associated process description of type of winding. The operator is required to follow instruction of designer in respect of type and location of conductors. For both models A & B, winding the conductors is started from left to right direction following the required flow path of flux with 60 mm gap from top. Conductors of dimensions 12.5 x 1.6 with 0.5 mm edge radius are used and wound into 10 identical disc pairs maintaining an outer diameter of 480 mm respectively. Each disc pair is separated with 30 mm key spacer. Leads of 10 disc pairs are taken out at right angles and are placed in different bays. Later disc of each pair is brazed to vertical rod to ground them consequently while applying voltage at former disc of disc pair. Fig.3.4 shows the real time test object.

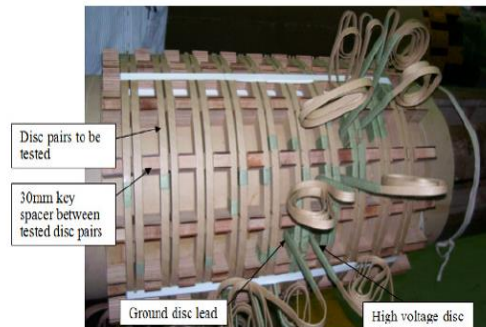


Fig.3.4 Real time test object

3.2.4 ASSEMBLY, PROCESSING AND TESTING OF WINDING

Insulation of winding mainly consist of cellulose components whose moisture content while testing is critical in terms of electrical behaviour .Additionally, winding dimensions changes with moisture level which may result in movement of conductor/insulation in winding hence resulting in failures due to short circuit forces. Hence, considering symmetry of parts of winding, sizing and stabilization of windings are done after manufacturing. Fig. 3.5 further refers to the procedure followed.

- **Assembly of winding:**

To stabilize winding from axial forces, two FRP plates are clamped on top and bottom of coil with force of 60 kN. High voltage leads taken out at 90°. From disc assembly are covered with extra paper insulation to avoid breakdown at undesirable location and maximising the chances of breakdown of insulation in interdisc gap. Hence, testing breakdown strength of composite insulation of interdisc gap. For setting clearances of 70mm from testing tank, high voltage leads are guided to their respective bushing for testing with help of supporting structure made of wood.

- **Processing:**

As moisture is not only critical in terms of dielectric behaviour of insulation, it also impacts magnitude of short circuit forces and also ability of winding to withstand those forces. Hence, drying procedure enumerate to necessary before testing. The number of required drying processes and drying technology to be used depends on environmental conditions within factory and amount and type of insulation material with windings. In this study, for drying whole winding along with structure, is kept in oven at temperature of 100 °C for 24 hours until the moisture is decreased to less than 0.5 %.After 24 hours, winding is taken out and repacked. Repacking of winding refers to process of retightening after final drying process is completed. because of loosening of structure due to moisture loss.

- **Oil filling and Impregnation:**

After repacking, winding is mounted within testing tank. As quickly as possible, tank is closed and vacuum pump is switched on to ensure insulation absorbs minimum moisture possible.

Vacuum is applied until reaching a tank pressure of less than 0.5 mbar and filling with oil. Before filling tank with insulating oil, oil have to be degassed, filtered and heated up to a temperature of around 60 deg Celsius. These measures guarantee following oil parameters according to IEC 60296

Table 3.3 Specification of oils under impulse testing

Parameters of oil	Mineral oil	Natural ester oil
	Transol	BioTransol
Breakdown voltage in kV for 2.5mm gap	65-70	60-65
Water content in ppm	<50 ppm	< 50 ppm
Loss factor at 90°C	<0.5%	<0.5%

To avoid electrostatic charging and reducing risk of creation of air pockets, oil filling rate is limited to 1200 litres per hour.

After oil filling, soaking period is provided so that insulation get fully impregnated with oil. Impregnation time is allotted for twenty four hours for mineral oil and forty eight hours for ester oils due to their high viscosity under vacuum of 0.5 torr.

- **Testing:**

Testing of interdisc insulation is carried out according to step-by-step method as per IEC 60243-3. First disc of a disc pair is tested with positive and negative polarity standard impulse applying five shots in steps until breakdown happens. Subsequently settling time of one hour is provided after breakdown of insulation of one disc pair. Consequently same procedure is adopted for remaining disc pairs. At last, windings are dismantled to locate breakdown position.

Ten breakdown voltages are obtained from ten disc pairs of winding which are fitted in weibull curve to find voltage corresponding to 1% breakdown probability for electrostatic field analysis.



Fig.3.5 Testing Procedure

3.3 WEIBULL DISTRIBUTION FOR DEDUCTION OF BREAKDOWN PROBABILITY

According to IEC 62539, selection of proper distribution demonstrates a major role in analysis of breakdown data. All samples which are tested should be analysed with statistical distribution to acknowledge their behaviour. Aim of utilizing weibull distribution is to plot data in order to have useful interpretation of behaviour of oils. The plot are additionally utilized for prediction of failures so that preventive measurements can be taken.

The major advantage of weibull analysis lies in its high applicability for systems which fail following the failure of weakest links [44]. Also, weibull distribution is advantageous over gumbell and normal distribution [53] as weibull distribution is versatile to model various data sets along with capability of assuming characteristics of different kinds of distributions unlike gumbell and normal distributions. Weibull analysis also provide essential information for both engineers and managers by offering easy, manageable and comprehensive graphical plots. These plots comprise features related to physics of failure, characteristics of breakdown voltages and breakdown strength of samples.

In this work for computing voltage corresponding to 1% breakdown probability, three parameter weibull distribution is used. Analysis is done using MINITAB 16.2

Three parameter weibull is given as

$$F(v) = 1 - e^{-\frac{(v-\gamma)^\beta}{\alpha}}$$

Where, v = Measured parameter defined as breakdown voltage;

$F(v)$ = Probability of failure at voltage less than or equal to v ;

α = scale parameter;

β = shape parameter;

γ = location parameter or threshold value

In this analysis, least square method is used for estimation and correlation coefficient is chosen for evaluating goodness of fit of breakdown voltages obtained from impulse testing into three parameter weibull function.

Fig.3.6 demonstrates example of goodness of fit of data along with three parameters describing the properties of distribution of data.

Parameter Estimates				
Parameter	Estimate	Standard Error	95.0% Normal CI	
			Lower	Upper
Shape	35.0478	16.0355	14.2958	85.9239
Scale	171.635	37.4809	111.872	263.322
Threshold	-89.0731	37.4810	-162.534	-15.6118

Goodness-of-Fit	
Correlation Coefficient	= 0.967

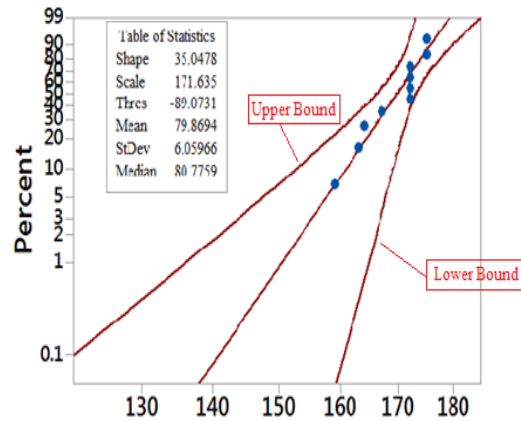
Fig.3.6 Parameters of weibull distribution

Shape, scale and threshold value characterises breakdown data. Depending on values of parameters, weibull distribution can be utilised for modelling various life behaviours. The shape parameter β is also known as slope which is measure of all ranges of breakdown voltages. If range of breakdown voltages is small, higher value of β is obtained. Additionally, shape parameter demonstrates class of failure. Scale parameter demonstrates the spread of data on abscissa scale. The location parameter γ is interpreted as threshold voltage at which failure probability is zero. Importance of this parameter lies in exhibiting breakdown strength of sample. Fig. 3.7 (a) and (b) represents probability of failure along with lower and upper bounds corresponding to that probability and pictorial representation of fit of data in weibull distribution. Upper and lower bounds of data

physically signifies the spread of data. More closer the upper bound and lower bounds are, lesser is the spread of data.

Percent	Percentile	Standard Error	95.04 Normal CI	
			Lower	Upper
1	61.4496	7.34600	47.0517	75.8475
2	64.4783	6.43745	51.8611	77.0955
3	66.2877	5.88780	54.7478	77.8276
4	67.5912	5.48944	56.8321	78.3503
5	68.6152	5.17554	58.4713	78.7591
6	69.4613	4.91582	59.8265	79.0962
7	70.1842	4.69393	60.9843	79.3841
8	70.8165	4.49999	61.9966	79.6363
9	71.3793	4.32761	62.8974	79.8613
10	71.8874	4.17235	63.7097	80.0650
20	75.3709	3.12843	69.2393	81.5025
30	77.5863	2.51040	72.6660	82.5066
40	79.3032	2.09082	75.2052	83.4011
50	80.7759	1.80908	77.2302	84.3216
60	82.1338	1.65238	78.8952	85.3724
70	83.4729	1.62800	80.2821	86.6637
80	84.9078	1.75498	81.4681	88.3475
90	86.6948	2.09342	82.5918	90.7978
91	86.9193	2.14652	82.7122	91.1264
92	87.1593	2.20536	82.8369	91.4817
93	87.4185	2.27116	82.9671	91.8699
94	87.7025	2.34571	83.1050	92.3000
95	88.0195	2.43171	83.2534	92.7856
96	88.3829	2.53359	83.4172	93.3486
97	88.8169	2.65937	83.6046	94.0291
98	89.3731	2.82635	83.8336	94.9127
99	90.2056	3.08647	84.1562	96.2550

(a)Table of percentile



(b)Weibull distribution

Fig 3.7 Pictorial representation of weibull distribution with confidence limits

3.4 ELECTROSTATIC STRESS ANALYSIS OF WINDINGS

Design of insulation requires analysis of electric field distribution. Fig. 3.3 represents two dimensional solid model of coils to be analyzed through Infolytica ElecNet utilizing concept of FEM and newton raphson method for electric fields distribution. Basic concept in finite element analysis is to estimate solution of complex problem by substituting with simple one. Approximate solution is obtained instead of exact solution as present tools are not sufficient to demonstrate exact answer for most of practical problems. Therefore, in absence of any other suitable method for finding approximate solution of problem, finite element method is preferred. In addition to, it also possible to enhance approximate solution through more computational efforts.

Problem definition in this study can be defined as to find to out electric stress for each solid model of coil having 24 combinations of paper covering and keyspacers. Dielectric medium chosen in study is isotropic i.e. have same behaviour with respect to field regardless of direction of field. Here, field domain which is enclosed in a boundary whose

condition is governed by Dirichlet boundary condition. Space outside this boundary is excluded from field domain. Thus is an interior problem by neglecting effect of fringing. Two dimensional electrostatic field analysis is done in RZ plane. As electrostatic field analysis is chosen, governing equation is given by Poisson equation as

$$\nabla^2 V = \rho / \epsilon_0$$

As, electric fields depends on permittivity of insulation along with gap between with them. Table 3.3 shows the specifications of various insulation materials used in solid model.

Table 3.4 Specifications of materials used in solid model

Insulation		Permittivity
A. Liquid Insulation		
	Mineral oil	2.2
	Ester oil	3.3
B. Solid insulation		
i. Impregnated with mineral oil	Paper covering	3.5
	Pressboard	4.4
ii. Impregnated with natural ester	Paper covering	4.1
	Pressboard	4.8

Electric stress analysis of coils are done at voltages corresponding to 1% breakdown probability, as 1% breakdown probabilities are even better for insulation designing. To understand the effect of permittivity, ester and mineral oil electric stress distribution is analysed. Elaboration of outcomes of variations of insulation gaps are done through variation of interdisc gap and paper thickness..

3.5 RESULT AND DISCUSSION

This section discusses results obtained from methodology adopted in section 3.2 and 3.4.

3.5.1 EFFECT OF POLARITY ON BREAKDOWN VOLTAGE

With reference to Fig 3.8, following points can be inferred

- There is not very significant difference in breakdown voltage on polarity basis. At lower thickness of insulation, negative polarity is having slightly higher breakdown in comparison to positive polarity.
- Reason can be quoted as positive polarity causes surface flashover which leads to breakdown at lower voltage. While both polarities are giving similar response at higher insulation thickness. Hence, it can be inferred that there is not much effect

of polarity visible in quasi-uniform field (i.e. inter-turn and inter-disc) in windings.

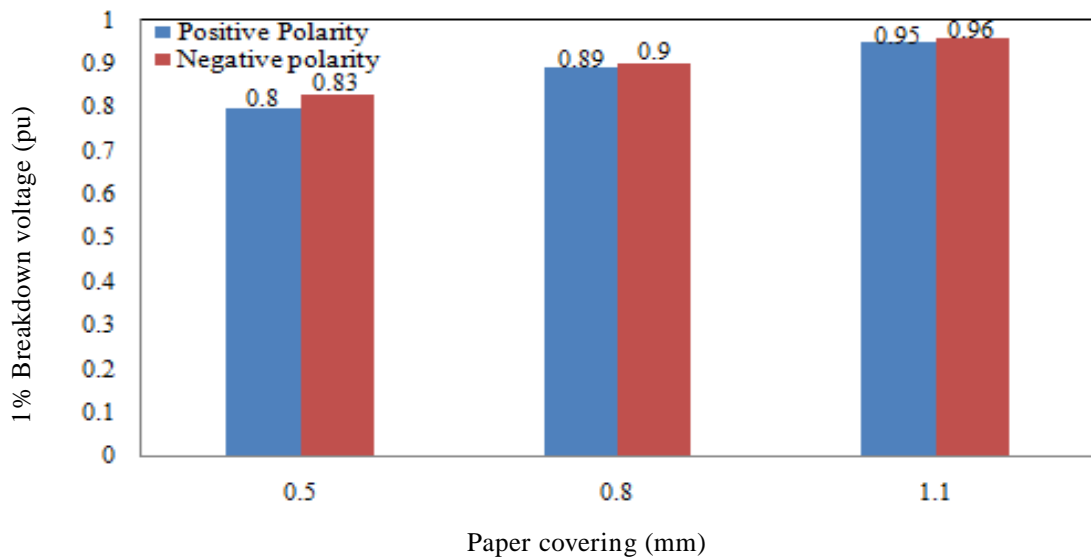
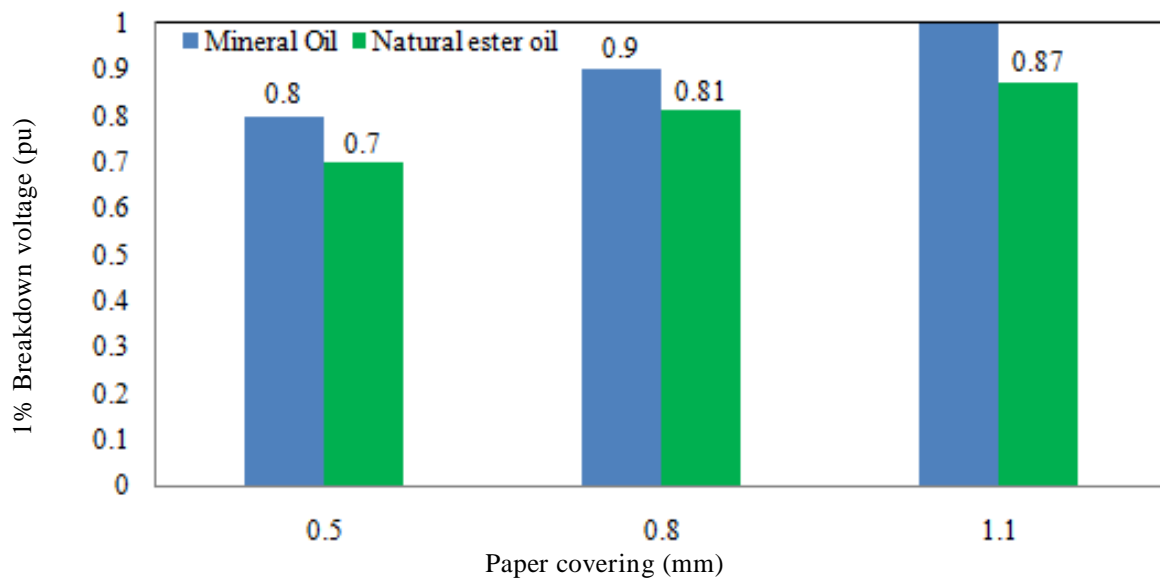


Fig. 3.8 Comparison of breakdown voltage for positive and negative polarity

3.5.2 EVALUATION OF BREAKDOWN VOLTAGE OF INSULATING LIQUIDS IN DIFFERENT FIELD GEOMETRY

Comparing breakdown voltages of ester and mineral oils with consideration of axial stress (Model A) and combination of axial and radial stress (Model B) from fig 3.9

- Esters oils exhibit 0.1-0.15 pu lesser breakdown voltage in comparison to mineral oil as shown in Fig.3.9



(a)Model A

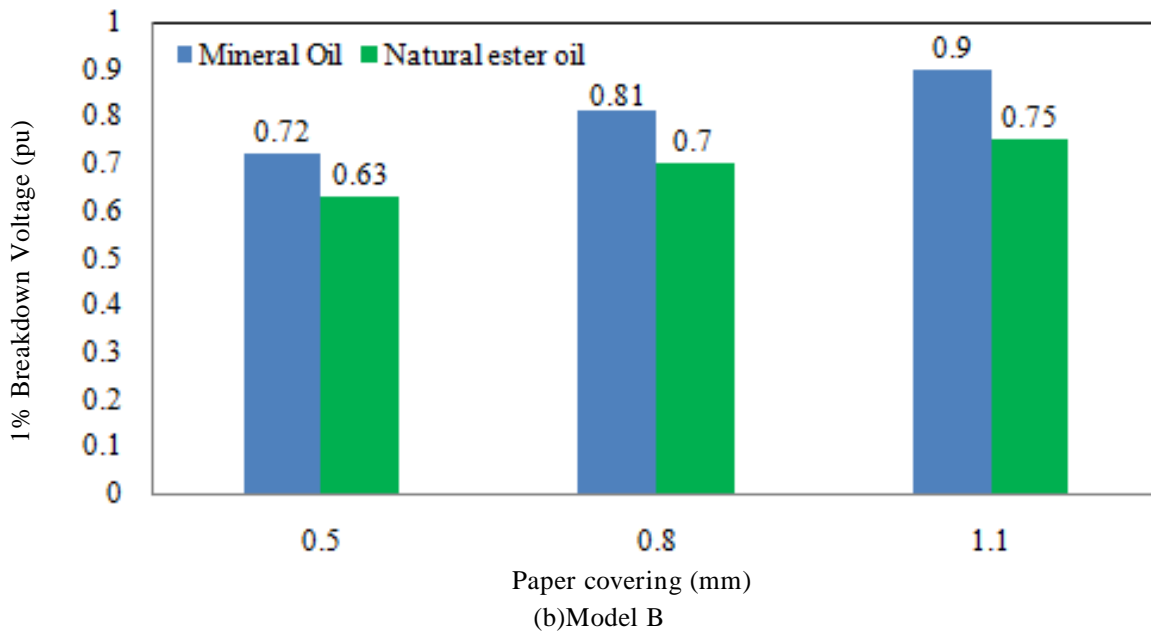
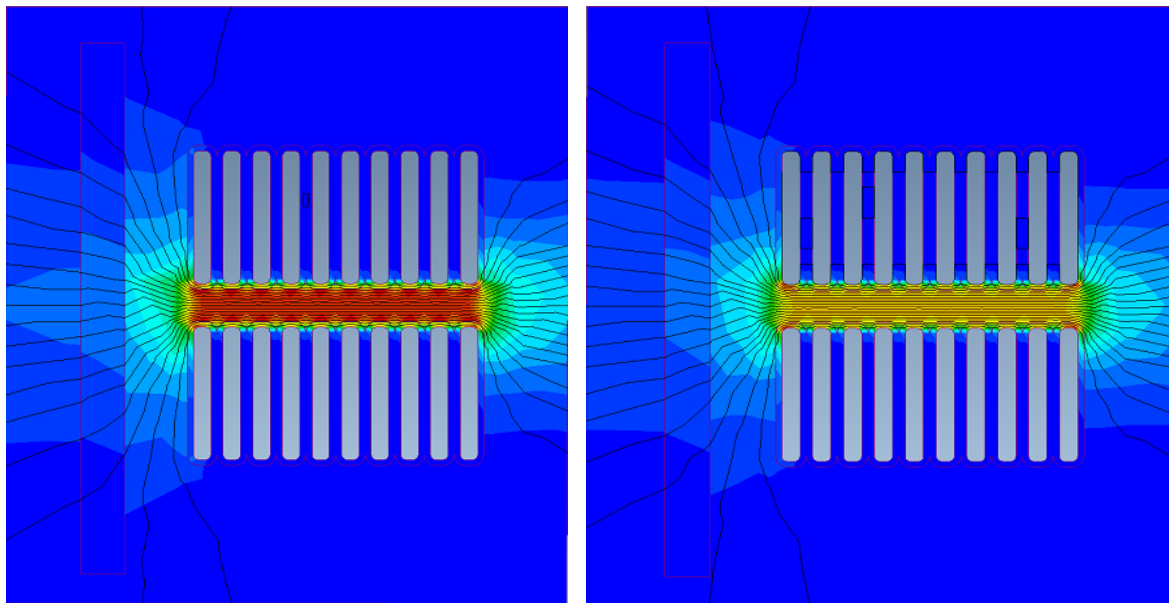


Fig. 3.9 Comparison of breakdown voltage between Mineral and Ester oil

- Since breakdown in liquids usually include two procedure i.e. initiation and propagation of the streamer. Breakdown mechanism is related to electric field of the utilized electrode configuration. Since, in non-uniform fields having low homogeneity factor such as long point-plane gap, breakdown is majorly caused by streamer propagation and in uniform or quasi-uniform fields (inter-turn and inter-disc) having high homogeneity factor such short sphere-sphere gap, breakdown is majorly caused by streamer initiation [50]. Although, streamer inception voltages of the ester liquids are comparable with mineral oil. However, streamers propagate faster in ester liquids than in mineral oil at equal level of voltage. It is because in mineral oil, the breakdown is mainly induced only by positive streamers while the breakdown voltage of natural ester oil is induced by both positive and negative streamers [50,51]. However, the negative streamers can easily propagate in ester oil due to their high electro negativity. Hence, ester corresponds to lower breakdown voltage as compared to mineral oil.
- Comparing Fig.3.9 (a) & (b), Model B exhibits lesser breakdown voltage as compared to Model A. As model B comprises combination of axial and radial stress, hence lesser breakdown voltage is observed.

3.5.3 ELECTROSTATIC STRESS ANALYSIS THROUGH FEM

➤ FOR MODEL A (AXIAL STRESS)



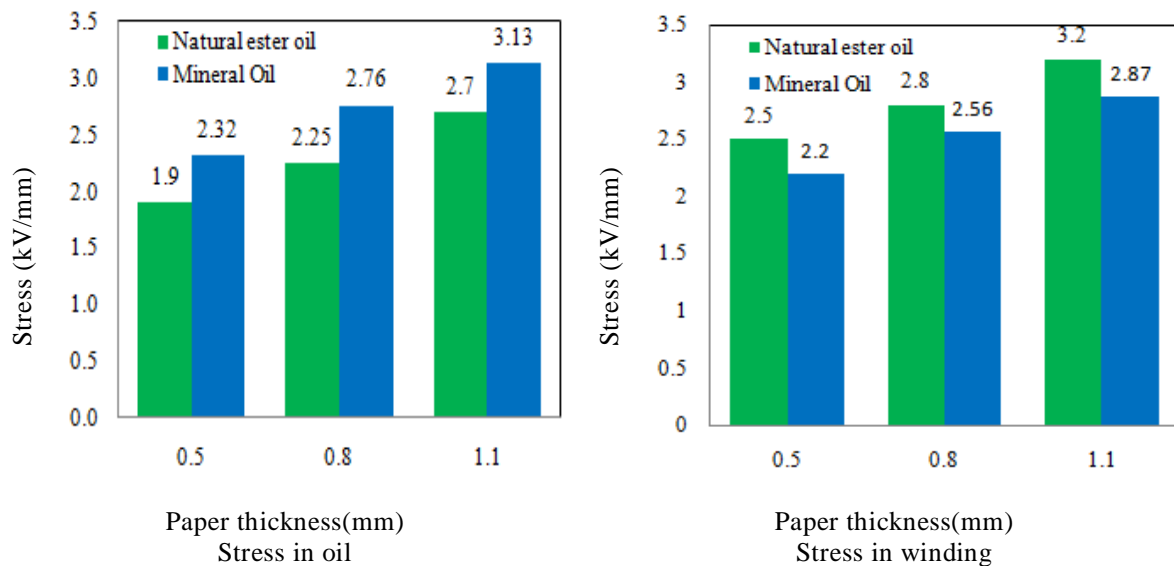
Mineral Oil

Ester oil

Fig 3.10 Pictorial representation of electric stress in mineral and natural ester in Model A

Stress in oil and point stress in winding for different combinations of insulation

Referring to Fig 3.10 and Fig.3.11, Stress in mineral oil is large as compared to ester oil for all combination of paper insulation and keyspacer. Reason can be attributed to lower permittivity of mineral oil, which leads to higher stress value.



(a) Keyspacer-3.0 mm

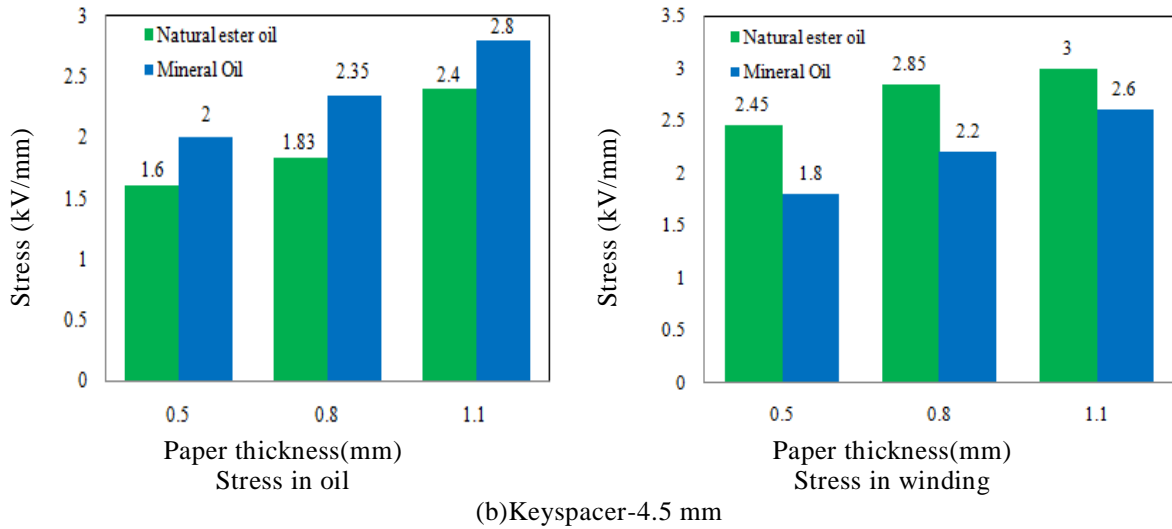


Fig.3.11 Stress Analysis for mineral and ester oil in Model A

- Referring to Fig.3.11, stress in winding edges is more for ester oil than mineral oils for all combination of paper insulation and keyspacer.
- However, lesser stress in oil and windings are observed for 4.5 mm keyspacer configuration as compared to 3mm keyspacers. Since interdisc gap is increased due to increase in keyspacer thickness, hence less stress is accounted.
- Dividing interdisc gap into three regions, as shown in Fig.3.12 as left (L), middle (M) and right(R), where on top conductor voltage is applied and bottom conductor is grounded, maximum number of breakdown locations are found on edges of conductor i.e. on left and right region. Numerals signify number of breakdowns on respective edges. Reason can be attributed to axial direction of electric field in model A.

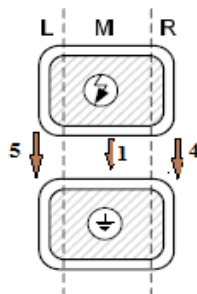


Fig.3.12 Breakdown locations in Model A

➤ **FOR MODEL B (AXIAL AND RADIAL STRESS)**

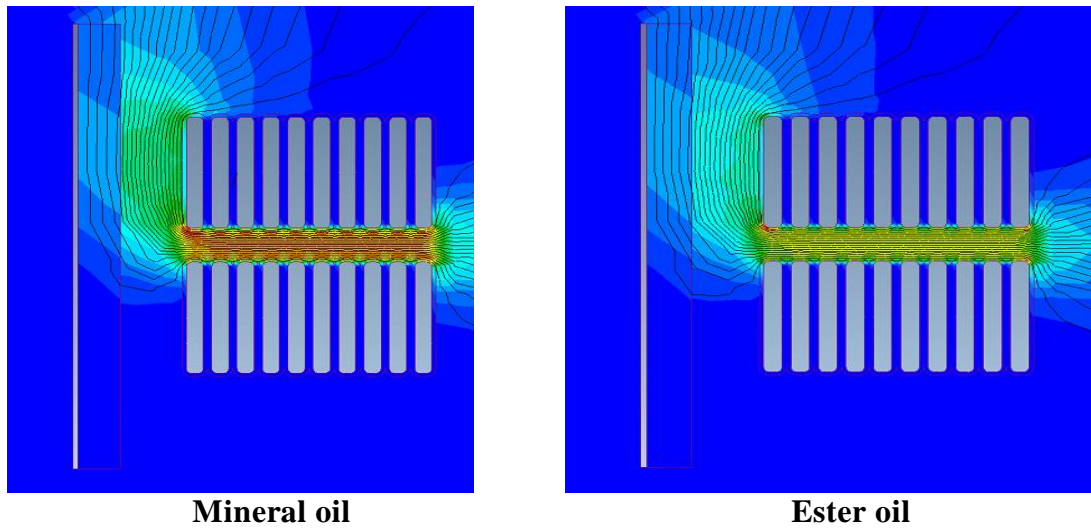
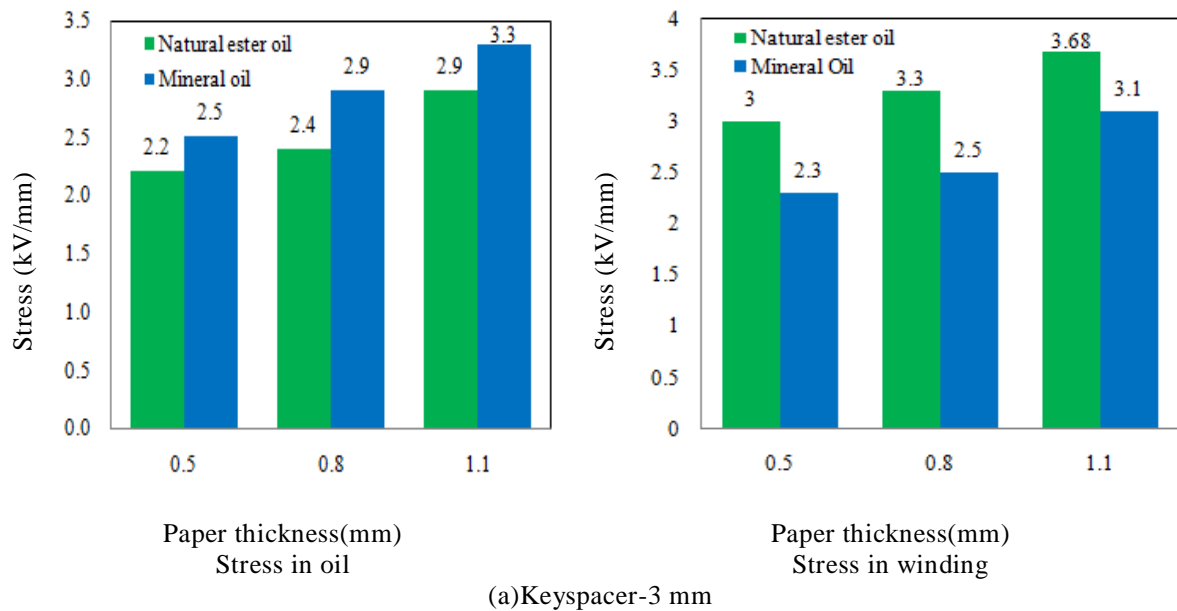
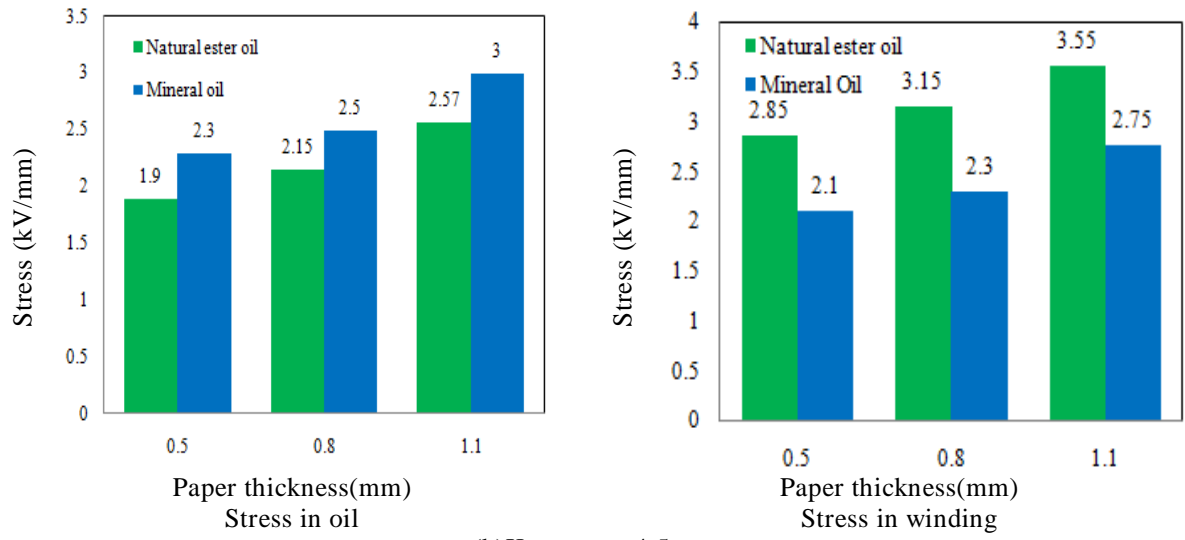


Fig. 3.13 Pictorial representation of electric stress in mineral and natural ester in Model B.

Stress in oil and point stress in winding for different combinations of insulation:

Referring Fig.3.13 & Fig 3.14, Stress in oil and winding are following the same pattern as in Model A, i.e. more stress is appearing in mineral oil while more stress in winding in ester oils accounting to permittivity difference.





(b)Keyspacer-4.5 mm
 Fig.3.14 Stress Analysis for mineral and ester oil in Model B.

- Similar as in model A, lesser stress in oil and windings are observed for 4.5 mm keyspacer configuration as compared to 3mm keyspacers. Since interdisc gap is increased due to increase in keyspacer thickness, hence less stress is accounted.
- However, comparing Fig.3.11 & 3.14,in Model B, more stress is observed in inner edges of conductor i.e. which are nearer to core.
- Dividing interdisc gap into three regions, as shown in Fig.3.15 as left (L), middle (M) and right(R),where on top conductor voltage is applied and bottom conductor is grounded, maximum number of breakdown locations are found on edges of conductor i.e. on left and right region. Numerals signify number of breakdowns observed on respective edges. Reason can be attributed to addition of axial and radial electric field in model B.

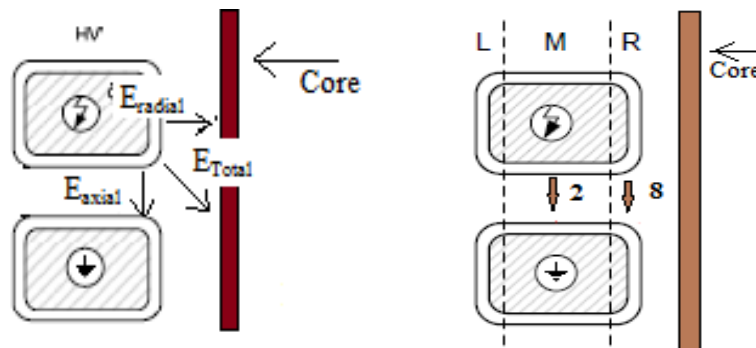


Fig.3.15 Breakdown locations in Model B

3.6 CONCLUSION

On the basis of methodology proposed, ester are found out to be having 0.15-0.2 pu lesser breakdown voltage as compared to mineral oils. Reason can be attributed to breakdown induced by both negative and positive streamers in esters. Additionally, negative streamers propagate faster in esters due to their electro-negativity. Axial stress and combined stress i.e. combination of axial and radial stress are studied along with their effect on different combination of solid insulation. Breakdown location affected by stress is also experimentally and logically verified.

CHAPTER 4

THERMAL PERFORMANCE OF TRANSFORMER INSULATION LIQUIDS

4.1 INTRODUCTION

In the course of continuous efforts for making power system efficient, monitoring condition of transformers is important in field of transformer engineering. The maximum temperature in transformer interior is major factor guiding a transformer working life. Although, immediate effect of temperature rise is not there but it triggers undesirable effect such as excess deterioration of insulation which reduce life of transformer and hence affects power system economy. Therefore, for evaluating operating conditions and to estimate remaining life of transformer, it is important to estimate maximum possible temperature rise for a certain type of loading. Even with all advances in the design techniques as well as material engineering, transformer insulation liquid thermal performance decides designing of transformer and loading on it. Hence this chapter elaborates temperature rise test for measuring temperature of oil and winding in section 4.2. Section 4.3 deals with estimation of temperature for 2MVA, 33/0.433 kV transformer formerly filled with ester oil and later with mineral oil.

Discussion of results obtained from section 4.3 are done in section 4.4 to conclude and compare thermal performance of ester oils with respect to mineral oils.

4.2 EXPERIMENTAL DESCRIPTION

4.2.1 Temperature Rise Tests

Usually temperature rise tests are conducted for evaluating whether transformer satisfies limit of temperature rise of top oil and average winding in normal state. Researches done in past have examined effect of viscosity of oil only on temperature of top oil. But, CIGRE brochure on thermal performance of the transformer [45] suggested considering mean winding, oil and hot-spot temperatures while estimating effectiveness of oil as coolant. Hence, this concept is also utilized in following approach.

During temperature rise test, transformer is operated at rated loading and power equal to addition of no load and load loss is fed to transformer. High voltage winding is excited while low voltage being short circuited at its terminals. For measuring ambient temperature, three thermometers are kept at different places around transformers at half way up the cooling area

and at a distance of one or two meters from radiators. Ambient temperature is taken as average of readings of three thermometers. Thermometers placed in oil filled pocket measures top oil temperature. It is expected insulation of transformer will reach highest temperature as specified by IEC 60076-2 during temperature rise test. According to IEC recommendation for ensuring temperature distribution in transformer under steady state is to wait until rate of increment in top oil temperature rise falls below 1 °C per hour and remains as such for three hours [45]. Hence, at this point, evaluation of thermal performance is done.

4.2.2 Temperature rise of windings

When temperature rise of top oil becomes constant in duration of test, current corresponding to rated value is circulated at rated frequency. This current is made constant for an hour. Windings temperature are then determined by resistance method.

Measurement of winding resistance

After supply is switched off, measurement of winding resistance is made immediately. However, sufficient time is allowed for inductive effect to disappear. For each winding, ten readings of resistance is noted and winding resistance at switching off supply is then obtained by extrapolation method.

4.2.3 Calculation of hotspot temperature

For determining hotspot temperature, following formulae are used:

- Temperature rise= Top oil temperature - Ambient temperature
- Average oil temperature rise at shut down= oil temperature rise at shut down- $\frac{1}{2}$ *(Top oil temperature in cooler - bottom oil temp. in coolers at shut down)
- Winding gradient= (Winding temperature at shut down)– (Average oil temperature at shutdown)
- Winding temperature rise=winding gradient + average oil temperature at steady state
- Average oil temperature rise at steady state=Oil temp. rise at steady state - $\frac{1}{2}$ *(Top oil temperature in cooler - bottom oil temperature in coolers at steady state)
- Hot spot temperature rise = Oil temperature rise +(hotspot factor*winding gradient)
- Hotspot factor=1.1
- Hotspot temperature at ambient temperature= hotspot rise + ambient temperature

4.3 EVALUATION OF TEMPERATURE RISE TEST

Table 4.1 represents the specifications of transformer tested firstly with ester oil and later with mineral oil.

Table 4.1 Specification of transformer for temperature rise test

	Specification
Rated voltage	33/0.433 kV
Rated capacity	2 MVA ,50 Hz

4.3.1 ESTIMATION OF WINDING RESISTANCE AT RATED LOAD

Table 4.2 Winding resistance value after shutdown

TIME (sec.)	Natural Ester Oil (KNAN)		Synthetic ester oil (KNAN)		Mineral oil (ONAN)	
	HV resistance (Ω)	LV resistance (Ω)	HV resistance (Ω)	LV resistance (Ω)	HV resistance (Ω)	LV resistance (Ω)
80	2.437	0.4636	2.285	0.437	2.2844	0.4344
100	2.436	0.4632	2.283	0.436	2.2824	0.4314
120	2.434	0.4629	2.281	0.435	2.2804	0.4308
140	2.433	0.4628	2.279	0.434	2.2786	0.4302
160	2.431	0.4627	2.277	0.433	2.2750	0.4296
180	2.430	0.4625	2.276	0.432	2.2734	0.4290
200	2.428	0.4624	2.274	0.431	2.2718	0.4284
220	2.427	0.4623	2.273	0.430	2.2702	0.4280
240	2.426	0.4621	2.271	0.429	2.2686	0.4276
260	2.425	0.4619	2.270	0.4327	2.2670	0.4270

HV and LV resistance by extrapolation method

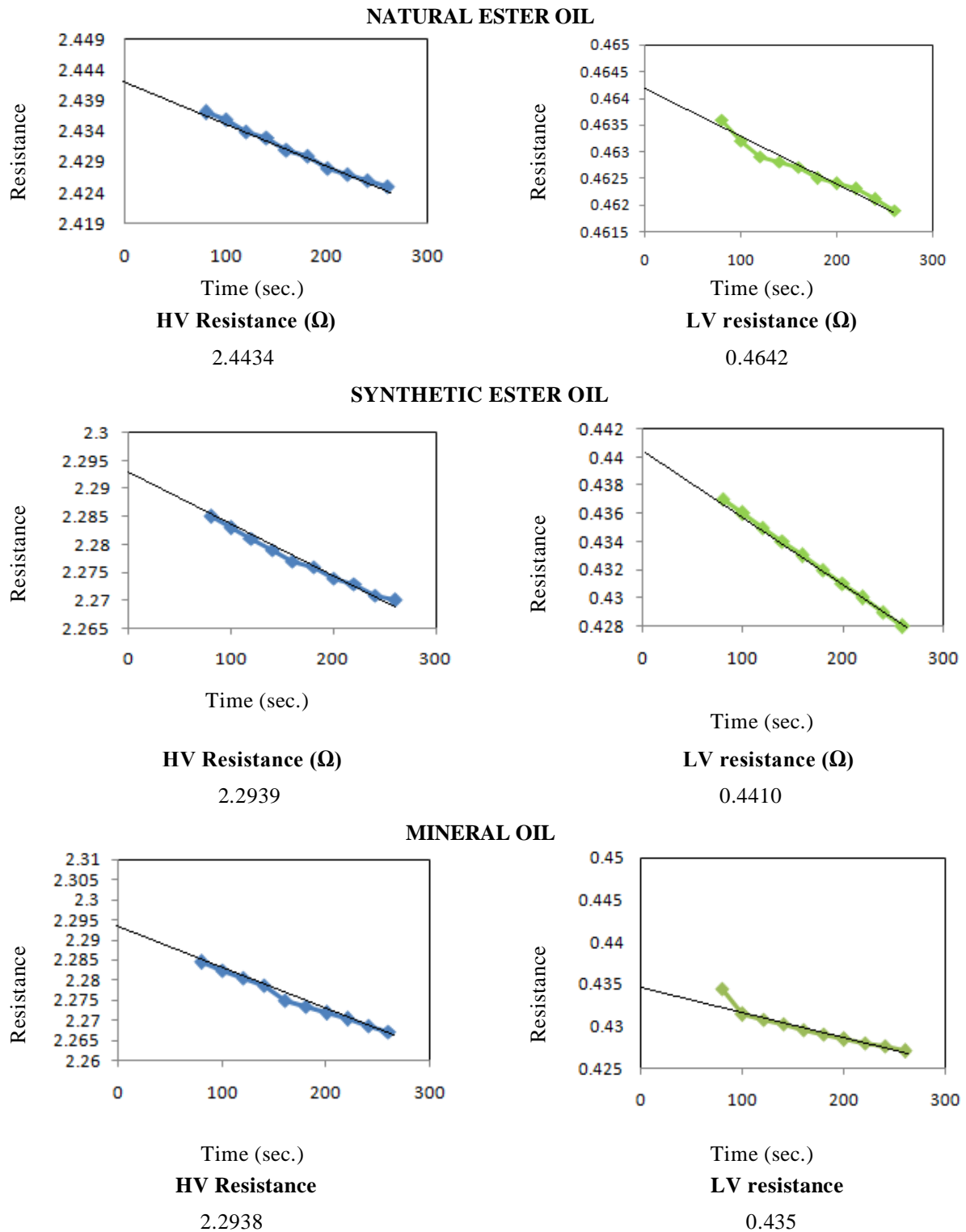


Fig 4.1 Estimation of HV and LV winding resistance by extrapolation method

4.3.2 TEMPERATURE RISE AT RATED LOAD:

Table 4.3 Observations for temperature rise test

	Natural Ester Oil		Synthetic Ester Oil		Mineral Oil	
MVA	2		2		2	
Ambient Temperature (°C)	32		33		32	
Oil temperature rise (°C)	33.33		37.43		28	
Top liquid temperature(°C)	74.7		75.5		68	
Cooler top temperature(°C)	68.7		70		62	
Cooler bottom temperature(°C)	52.8		54		31.02	
Winding name	HV	LV	HV	LV	HV	LV
Hot resistance (Ω)- shutdown	2.44	0.46	2.29	0.44	2.29	0.439
Cold resistance (Ω)	2.14	0.40	2.14	0.40	2.14	0.40
Cold temperature (°C)	38	38	38	38	38	38
Winding temp. (°C) at shutdown	75.34	77.52	76.74	78.56	60	62.51
Average oil temp (°C) at shut down	66.75	66.75	67.85	67.85	52.51	52.51
Avg temp. rise (°C) at shutdown	25.42	25.42	26.53	26.53	12.8	12.8
Winding gradient	8.59	10.77	8.92	11.5	7.49	10
Avg oil temp rise(°C) at steady state	24.83	24.83	25.96	25.96	12.25	12.25
Winding temp. rise (°C)	33.42	35.6	34.88	37.46	19.25	24.16
Hotspot temperature rise (°C)	42.78	45.18	47.242	50.08	36.239	39
Hot spot temperature(°C)	74.78	77.18	79.242	82.08	68.2	73.1

4.4 RESULTS AND DISCUSSION

This section elaborates results obtained from temperature rise test done for ester and mineral oil.

4.4.1 EVALUATION OF HOTSPOT TEMPERATURE FOR INSULATING LIQUIDS

- Referring to Fig.4.3, at rated load, esters are having 5-10 °C high hotspot temperature as compared to mineral oil.

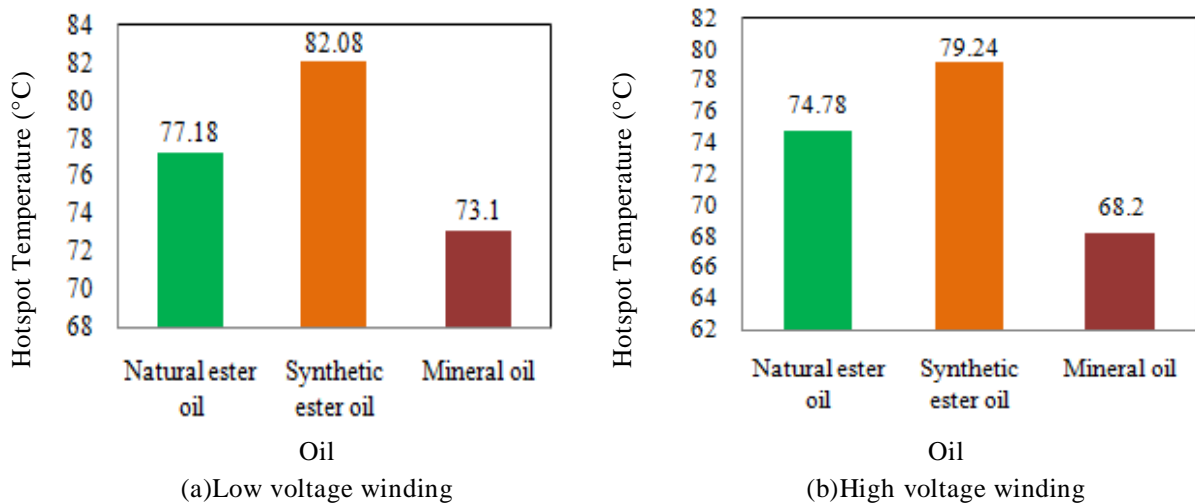


Fig. 4.2 Hotspot temperature of ester oils and mineral oil at rated load

4.4.2 EVALUATION OF TOP LIQUID TEMPERATURE FOR INSULATING LIQUIDS

- From Fig.4.4, it can be observed that there is 5-10 °C increase in top liquid temperature in esters as compared to mineral oil.

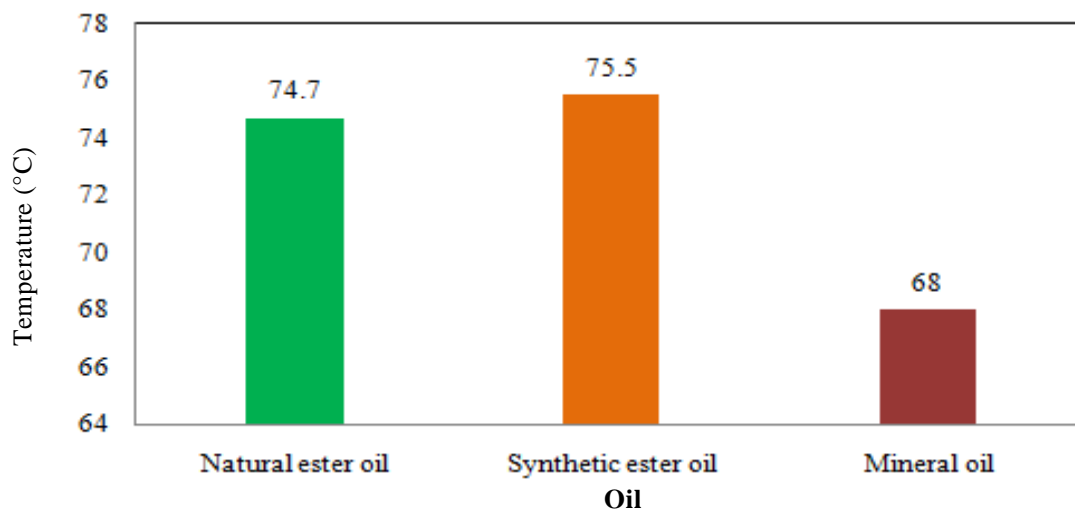


Fig. 4.3 Top Liquid temperature of ester oil and mineral oil at rated load

4.4.3 TRANSFORMER APPLICATION OF HIGHER TEMPERATURE LIMITS OF ESTER LIQUIDS

- Increase in temperature limits of hotspot, while implementing ester oils as insulation in transformers, may accelerate the ageing of insulation paper around windings and hence shortens the life of transformers.
- Quantity of oxygen and water in paper and in locality affects ageing of cellulose [42]. Pressboards and papers are majorly made up of polymeric chain of cellulose which are formed by d-glucose monomers. Because of water, oxygen and temperature, cellulose polymers splits and mechanical strength reduces..
- As hydrophilic property is displayed by natural esters i.e. they are water loving substances and constitute water saturation limit of five to eight times higher than mineral oil at normal working conditions . Therefore lesser moisture is held into solid insulation. This results in reduction of degradation rate upto four times as compared to solid insulation impregnated with mineral oil [52].
- Life performance of cellulose which are aged in natural esters is enhanced because of trans esterification and chemical reaction of water generated during ageing with natural esters (hydrolysis), which produces free fatty acids resulting in change of cellulose structure.
- This leads to either increase in life of insulation at normal operating conditions or to ability of transformer to operate at 20 °C higher hotspot temperature maintaining same life expectancy in comparison to mineral oil as demonstrated in Fig.4.4

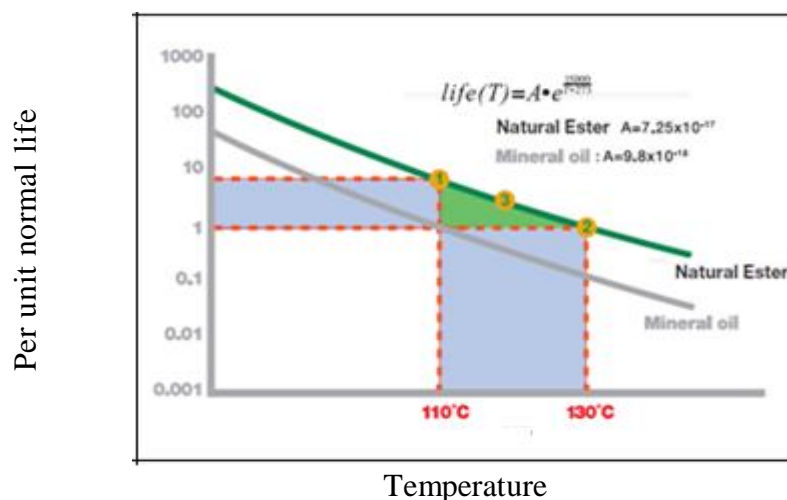


Fig 4.4 Per unit life comparison of ester and mineral oil

- This survey allows higher temperature and rise limits with natural ester oil.
- Hence, when designing new transformer, such increment in temperature limits can be converted in either increase of power rating or in more compact transformer. Thereby, not requiring additional cooling capacity or under loading ester transformers

4.5 CONCLUSION

Even though ester displays higher hotspot temperature as compared to mineral oil, ageing of solid insulation is lesser because of hydrophilic nature of ester oils. Resulting ageing of cellulose impregnated with ester is reduced by four times than impregnation with mineral oil. Hence, ester provides benefit by enhancing life of transformers.

CHAPTER 5

EVALUATION OF DIFFERENCE IN PERMITTIVITY OF INSULATING LIQUIDS THROUGH FREQUENCY RESPONSE

5.1 INTRODUCTION

Transformers exhibit very essential role in the efficient transmission of power. Any failure in transformer or its associated peripherals will result in loss of power transmission adding up to huge losses. Hence the emerging technology of condition Monitoring or diagnostics testing of transformers and other major equipment has come to the fore and is increasingly being considered to predict condition of equipment before it forces outages and/or major breakdowns. Traditional condition monitoring techniques such as : DGA, winding resistance measurement, capacitance and loss factor measurement etc. But none of these tests conclusively detect changes in working of Power Transformers, which vary impedance network. Physical changes in transformer can be measured through frequency changes through SFRA. This leads to identifying the cause of respective changes. Hence this chapter elaborates changes in insulation characteristics through frequency response analysis. Sections 5.2 elaborates basics of SFRA measurement with section 5.3 describing implementation of SFRA to detect changes due to permittivity changes i.e. change in insulating oil. Section 5.4 interpret results obtained through experiments in section 5.3. by graphical and numerical analysis .Various advantages of interpretation by numerical methods are also mentioned.

5.2 PRINCIPLE AND MEASUREMENT

The changes in impedance can be accounted through FRA.FRA can be carried out by using sweep frequency voltage source [40] or by low voltage impulse (LVI) source [46]. Transfer function is derived through the response of LVI method.. Briefly, major benefit of LVI method over SFRA is lesser time required for measurement . But it is limited to range 10 kHz to 1 MHz . Such restricted ranges result in problems related to interpretation of changes in electric properties. The main advantages of sweep frequency method over impulse response methods are given as [39]:

- Good signal to noise ratio
- Accurate and precise across whole measurement range
- Greater range of frequency
- Lesser requirement of measuring equipment

Fig 5.1 below shows the procedure for SFRA Measurement.

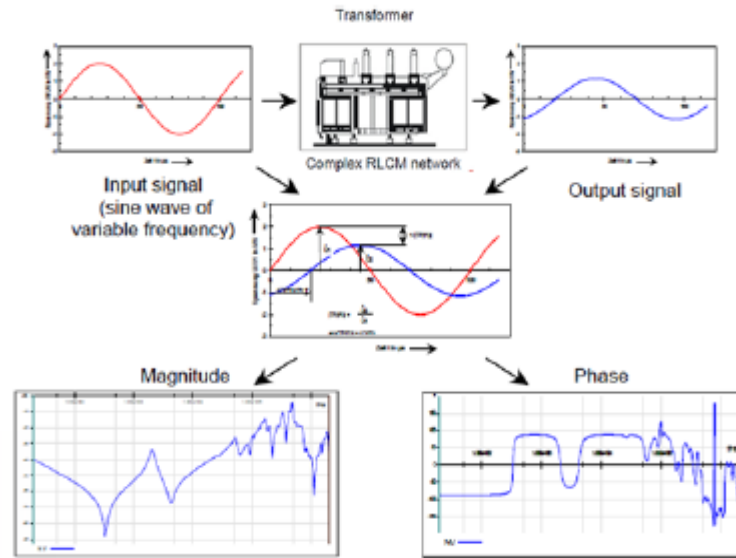


Fig.5.1 SFRA Measurement

Impedance of transformer is integrated value of winding components i.e. resistances, reactance and capacitance and the excitation components i.e. conductance, and susceptance [47]. Capacitive (C) and Inductive (L) elements are accounted for resonance and transients.

Resonant frequency f_r is generally given as (1)

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad \dots(1)$$

5.3 EXPERIMENTAL DESCRIPTION

5.3.1. TRANSFORMER WINDINGS AND TEST OBJECT

Transformer windings can be broadly classified into two main categories i.e. Disc and layer [27]. Classifications are done on basis on voltage rating. Layer windings can be used upto 66kV and disc windings are used for 66kV and above. Layer winding can further be classified into spiral and helical. This classification is done on basis of fashion of winding the conductors [47]. Disc windings can also be classified as continuous and interleaved disc windings. Differentiation are done on basis of winding conductor which consequently result in higher ground capacitance and smaller series capacitance for uniform distribution of voltage[27]. Because of this property, disc windings are used for power transformers.

Test object in this study comprises of Continuous double discs .To be precise, LV and HV windings are continuous disc type winding with top entry. LV winding is placed adjacent to

core, and then HV winding is set between low voltage winding and tank. Fig. 1 elaborates symbolic representation of winding.

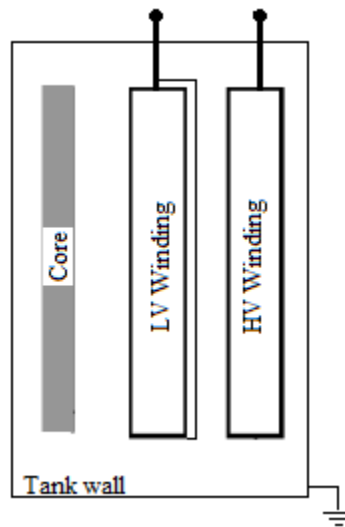


Fig.5.2 Representation of test object

Further, Table I elaborates the specifications of winding geometry

Table 5.1 Specifications of winding geometry

Winding Geometry	Low voltage winding	High voltage winding
Winding Type	Continuous disc	Continuous disc
Starting point	Top entry	Top entry
Disc numbers	32	32
Turn number	10 turns/disc	10 turns/disc
Disc width	16.8 mm	16.8mm
Disc height	3.22 mm	3.22 mm
Interdisc distance	6 mm	6 mm
Paper insulation	1.42 mm	1.42 mm
Radial distance between windings	13.2 mm	
Radial distance between winding and core/tank	6.5 mm	5.2 mm

Copper foil is used to emulate core. Main inter-winding insulation consists of pressboards between core & LV of thickness 1 mm and between LV & HV of thickness 1.5mm. Winding insulation consists of paper covering on conductors and key spacers between discs. Paper and key spacers are used as winding intersection insulations [48]

5.3.2. TEST OBJECT PREPARATION

As insulation of winding structure is made of cellulosic material whose moisture content adversely affects electrical properties [48] hence, proper drying procedure needs to be followed. Drying procedure and technology depends on environmental conditions within factory and amount and type of insulation material used. Hence, considering symmetry of parts of winding, sizing and stabilization of windings is to be done after manufacturing.

Following sections refers to the preparation of continuous double disc before SFRA testing:

- **Vapour phase drying**

For vapour phase drying, winding is placed in autoclave which is evacuated to below 50 mbar absolute pressure which removes moist air as well as surface moisture. Heating is then initiated using conventional radiant heating. During heating process, pressure is reduced in stages. When temperature reaches a pre-set level, spirit vapour is admitted into autoclave. Solvent carrying extracted water is evacuated from autoclave and is passed through a separator where water is removed. Spirit is returned to system for recirculation. Reaching final drying temperature of 100 °C and 120 °C, spirit supply is terminated and temperature is maintained by conventional drying system of oven. At this final temperature, autoclave is evacuated to less than 20 mbar. A fine vacuum phase is then followed, with special vacuum pump and pressure is maintained at 0.1 to 0.5 mbar absolute pressure.

Vapour phase drying is advantageous as compared to conventional drying as solvent used in producing vapour has ‘dry-cleaning’ action, which removes oil and debris present in insulation. As continuous double disc is priorly tested for mineral oil and later with ester oil, hence even minute portion of mineral oil needs to be evacuated from insulation to properly to address characteristics of ester oil through SFRA. Additionally, uniform rate of drying of all components is accounted and aging of cellulose is greatly reduces because of lesser temperature in pressure drop state. This helps in estimating sole effect of permittivity difference apart from effects of moisture or ageing of cellulose on SFRA responses.

- **Oil filling and impregnation process**

As removal of moisture leads to loosening of winding parts, hence winding is re-clamped with force of 60 kN. After re-clamping, winding is mounted in testing tank. As quickly as possible, tank is closed and vacuum pump is switched on to ensure insulation absorbs minimum moisture possible.

Vacuum is applied until reaching a tank pressure of less than 0.5 mbar and filling with oil. Before filling tank with insulating oil, oil have to be degassed, filtered and heated up to a temperature of around 60 deg Celsius. These measures guarantee following oil parameters according to IEC 60296.

Table 5.2 Specification of oils under testing

Parameters of oil	Mineral oil	Natural ester oil
	Transol	BioTransol
Breakdown voltage in kV for 2.5mm gap	65-70	60-65
Water content in ppm	4-5	55-70
Loss factor at 90°C	<0.5%	<0.5%
Relative permittivity	2.2	3.3
Viscosity at 40°C mm ² /sec	8.83	32

To avoid electrostatic charging and reducing risk of creation of air pockets, oil filling rate is limited to 1200 litres per hour.

After oil filling, soaking period is provided so that insulation get fully impregnated with oil. Impregnation time is allotted for twenty four hours for mineral oil and forty eight hours for ester oils due to their high viscosity of esters [38] under vacuum of 0.5 torr.

5.3.3. TESTING POSTULATES

Experimental set-up is established to experimentally observe changes in electrical properties of transformers windings due to different test connections and variation in insulation.

Variation in insulation can be in terms of temperature and moisture content amount [26]. In this study, all these factors are kept constant by following strict test object and oil preparation. Several different FRA measurement connections can be made on a particular set of transformer windings. However, for this study, with voltage application on high voltage winding, mainly three ways of measurement connections are employed which are as followed

- i. Core ungrounded with low voltage winding ungrounded and left open circuited
- ii. Core grounded with low voltage winding left open circuited.
- iii. Core grounded with low voltage winding short circuited and grounded.

5.4 RESULTS AND DISCUSSION

5.4.1 SFRA INTERPRETATION FOR DIFFERENCE IN PERMITTIVITY

FRA is completely comparative technique, where measured response is compared reference. However, FRA is a sound diagnostics method, still there are no guidelines for interpretations. Few industries utilize their own process of evaluation. Organizations like CIGRE and IEEE are making efforts for developing standard recommendations and tests for FRA measurement on transformers.

Conventional FRA evaluation relies on graphical analysis for diagnosis. Graphical analysis accounts for changes in shape, creation of new resonant frequency, elimination of existing frequencies, any shifts in resonant frequencies or changes in peak values. As, graphical evaluation needs experts for correct interpretation of test results recognizing failures and their tendencies in transformer. Inferences solely depend on experience of personnel. In Budapest Colloquium of CIGRE SC-12, it has been reported few interpretations of FRA were not understandable and criteria of failure was uncertain.

Trials are being carried out for developing an evaluation technique that can be applied by inexperienced personnel using numerical parameters. A remarkable amount of indices are introduced in past without a concluding comparison of indices. Each study has introduced some new indices and compared with a few others [37-41]. Hence, if it is required to utilize an index, it has not been discussed which one to prefer.

This section is an attempt which first discusses characteristics of numerical indices such as correlation coefficients (CC), standard deviation (SD), absolute sum of logarithmic error (ASLE), Maximum square error (MSE) and Max-min ratio (MM) to provide a deeper understanding of their role in interpreting frequency response graphs in terms of resonant frequencies and changes in peak. Frequency response behaviours of mineral and natural ester oil is later studied through three case studies which adopts testing postulates as described in previous section, graphically and later examine responses graphically and on basis of numerical indices also.

A. Properties of numerical parameters

- Correlation Coefficient (CC)

It is a statistical estimator which defines strength of relationship between two data sets. CC changes its value from 1 to 0 while 1 indicating strong relation between two data sets, and

0 indicating no linear relationship . CC value between 0 and 1 displays more or less relationship between two sets depending on extent of deviation.

$$CC = \frac{\sum_{i=1}^N X(i)Y(i)}{\sqrt{\sum_{i=1}^N [X(i)]^2 \sum_{i=1}^N [Y(i)]^2}}$$

- Standard deviation (SD)

SD measures quantity of dispersion in between two data sets. With SD value as 0 indicates perfect match between two data sets, value greater than 0 concludes data points spread over a wider range.

$$SD = \sqrt{\frac{\sum (Y(i)-X(i))^2}{N-1}}$$

- Absolute sum of logarithmic error (ASLE)

ASLE is designed to realize fully logarithmic scale comparison. As ASLE compares on logarithmic scale, hence minimizes the smaller deviations between data sets. ASLE value as 0 represents perfect match of two data, while ASLE greater than 0 indicates dispersion of data wider range of values.

$$ASLE = \frac{\sum_{i=1}^N |20 \log_{10} Y(i) - 20 \log_{10} X(i)|}{N}$$

- Mean square error (MSE)

MSE repress smaller deviations and enlarge large deviations. MSE value of 0 indicates two perfectly matching sets. While other than 0 indicates deviation.

$$MSE = \frac{\sum_{i=1}^N [Y(i)-X(i)]^2}{N}$$

- Max-Min ratio (MM)

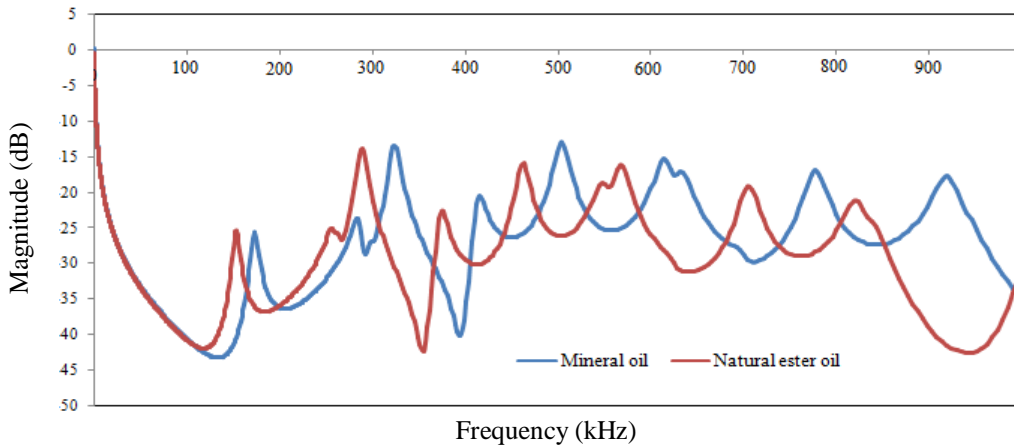
MM is sensitive regarding peak changes in magnitude. Ideal value for MM is 1.

$$MM = \frac{\sum_{i=1}^N \text{Min}[Y(i),X(i)]}{\sum_{i=1}^N \text{Max}[Y(i),X(i)]}$$

B. Case studies

Fig. 5.4 refers to three case studies experimentally performed with different testing postulates in order to evaluate efficiency of graphical analysis and precision, accuracy, sensitivity of numerical parameters.

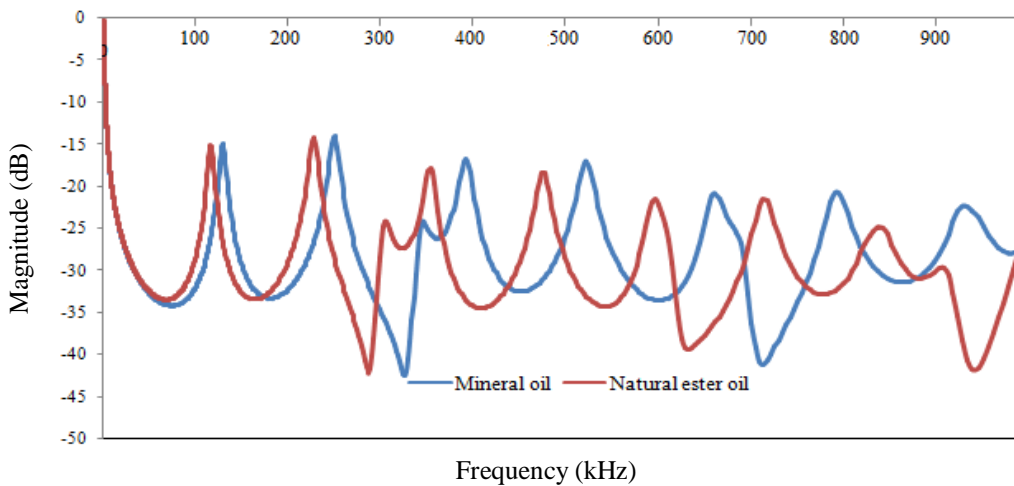
Case study 1- Core and Low voltage winding not connected to ground



Shift in frequency peaks	
Δf_1	17 Hz
Δf_2	24 Hz
Δf_3	30 Hz
Δf_4	40 Hz

Numerical parameter values	
CC	0.9752
SD	5.9917
ASLE	0.0884
MSE	35.8648
MM	1.1465

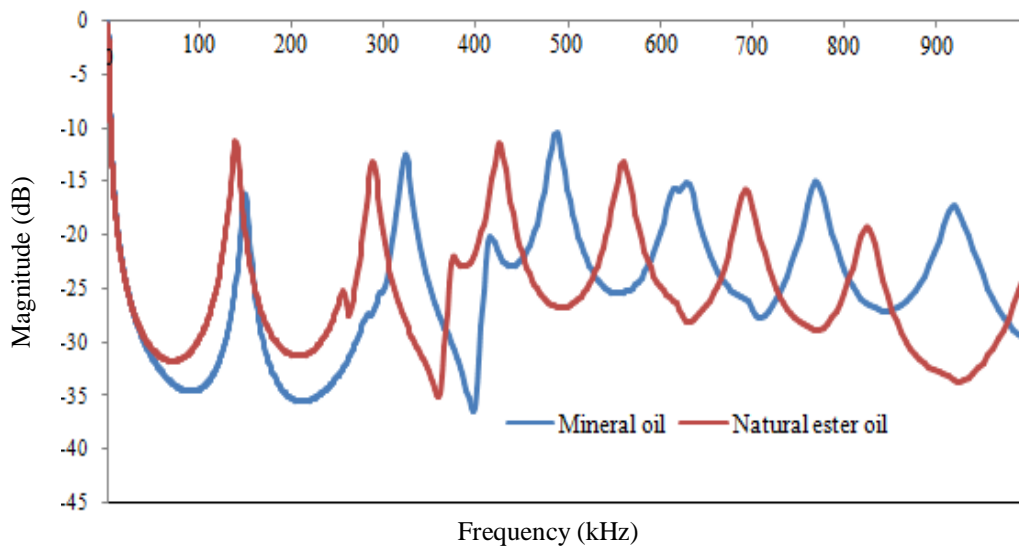
Case study 2- Core grounded and LV winding not grounded



Shift in frequency peaks	
Δf_1	10 Hz
Δf_2	15 Hz
Δf_3	20 Hz
Δf_4	25 Hz

Numerical parameter values	
CC	0.9700
SD	6.3371
ASLE	0.1265
MSE	40.1188
MM	1.166

Case study 3- Core and LV winding grounded



Shift in frequency peaks		Numerical parameter values	
Δf_1	12 Hz	CC	0.9656
Δf_2	14 Hz	SD	6.4216
Δf_3	22 Hz	ASLE	0.1059
Δf_4	26 Hz	MSE	41.1962
		MM	1.2013

Fig 5.4 Observations from case studies

5.4.2 GRAPHICAL ANALYSIS

From, aforementioned three case studies following common conclusions can be studied-

- In low frequency region (< 100 kHz), responses corresponding to ester and mineral oil exhibit same nature in all case studies. Hence, it can be inferred that permittivity do not affect inductance property which is solely a magnetic quantity and permittivity reflecting its properties related to electric quantities.
- In high frequency region (> 100 kHz), significant deviation in terms of shift in resonant frequencies is observed. Response of natural ester oil is shifted to lower frequencies. Tables in Fig.5.4 displays difference in frequency of resonant peaks. As, major changes are observed in winding region i.e. high frequency (>100 kHz) which is dominated by capacitance of windings. Since permittivity has shown significant impact in higher frequency region, hence it can be concluded to have direct effect on capacitance which comprises inter-winding capacitance as well as interturn & interdisc capacitance of winding itself.

Taking example of case study 3, Let f_{r1} be the ratio of frequency of natural ester and mineral oil, f_{r2} be the ratio of frequency in intersection utilizing permittivity paper covering

impregnation with natural ester and mineral oil respectively, f_{r3} be the ratio of frequency in interwinding utilizing permittivity of pressboards impregnated with natural ester and mineral oil. Using equation (1), following ratios can be estimated,

$$f_{r1} = \sqrt{\frac{3.3}{2.2}} = 1.22$$

$$f_{r2} = \sqrt{\frac{4.1}{3.5}} = 1.08$$

$$f_{r3} = \sqrt{\frac{4.8}{4.4}} = 1.04$$

Referring the graph f_{r4}, f_{r5}, f_{r6} and f_{r7} corresponds to first and subsequent resonant frequencies

$$f_{r4} = \frac{150}{140} = 1.07$$

$$f_{r5} = \frac{310}{300} = 1.03$$

$$f_{r6} = \frac{400}{390} = 1.02$$

$$f_{r7} = \frac{480}{460} = 1.04$$

From above estimation, it can be concluded that first resonant frequency demonstrate features of intersection of winding as ratio of frequencies f_{r2} and f_{r4} are equal where as second to fourth resonant frequencies displays features that include influences of interwinding since f_{r3}, f_{r5}, f_{r6} and f_{r7} are equal.

- Magnitude values are not clearly differentiable at first and second frequencies. However, this can be observed that slight change in magnitude is there at third resonance frequency and for further frequencies.
- Though, graphical analysis is not precise enough to tell deviations significantly, hence to account for precise computation of frequency shift and magnitude differences, Table VI displays values of numerical parameters obtained from comparison of natural ester and mineral oil response.

5.4.3 ANALYSIS THROUGH NUMERICAL PARAMETERS

- From the tables referring values of numerical parameters related to three case studies, CC deviates maximum to 0.9656 from its ideal value of 1. Characteristics of displays that CC relies on shape of two responses and do not considers the magnitude difference between them. Hence, less deviation from ideal value of “1” is obvious.
- Similarly, in case of ASLE, maximum deviation in its value displays to be 0.1265 from ideal value of 0. As, ASLE neglects smaller variation because of logarithmic computation. This proves ASLE to be less accurate and sensitive since in case variation in insulation characteristics, lesser deviation also need to be pointed.
 - Values of SD, MSE and MM, they show significant deviation of 6.42, 41.19 and 1.2 respectively from their ideal value of 0,0 and 1 respectively.

Referring to characteristics of SD, MSE and MM, SD measures the amount of variation in two responses along with MSE signifying the larger deviations. Also, MM is sensitive towards the changes in magnitude of two responses. As, these characteristics of SD, MSE and MM are also proven experimentally to acknowledge frequency shifts and magnitude changes. Hence, SD, MSE and MM accounts to be correct numerical parameters to study permittivity effects of two different oils on frequency response analysis.

- From detailed study of numerical parameters, it proves that graphical analysis is more time consuming and cumbersome process and precision and accuracy of interpretation depends on experience of personnel.

5.5 CONCLUSION

As mineral oil is being replaced by ester oils in transformer applications with investigation of dielectric, chemical and thermal properties of ester oils. Further, electrical properties of ester oils also need to be evaluated. Apart from affecting electrostatic field distribution in solid and liquid insulation, higher permittivity of ester oils also affect electrical properties of transformers. Hence, this work concentrates on experimental analysis to investigate the effect of permittivity changes on FRA signature. During experiment, moisture content in insulation along with temperature is maintained constant to demonstrate effect of permittivity solely. In low frequency region, results illustrated no effect of permittivity while shift in resonant frequencies is observed in higher frequencies regions. Hence, low frequency region can also be utilized to discriminate between deformation in winding and insulation changes as shunt capacitance is affected by geometry or deformation of windings hence affecting shape of

response at lower frequency. Higher permittivity of ester oils, leads to higher capacitance and hence occurrence of resonance at lower frequencies as compared to mineral oil.

Additionally, graphical analysis didn't discuss much features about deviation in responses of natural ester oil with respect to mineral oil. Only shift in resonant frequencies is clearly visible. Also, graphical analysis requires expertise of a person to detect changes in FRA, hence numerical techniques have been proposed to find deviations in patterns. Based on the characteristics of the parameters used changes in frequency or peak can be noted down. therefore, most sensitive parameter is taken as most precise to illustrate smallest deviation in response. On account of this, SD and MSE as designated to be most precise parameters. Numerical parameters provides less cumbersome process, more efficient and accurate prediction of response which may get affected by several factors such as insulation and temperature changes, ageing of insulation and mechanical deformation.

CHAPTER 6

INSULATION DESIGN OF TRANSFORMERS

6.1 INTRODUCTION

Concluding dielectric, thermal and electrical performance of insulation of transformers, one of dominant feature of transformer engineering is its design. Proper design involves utilizing suitable insulation, administered manufacturing and appropriate housekeeping, hence ensuring standard and security of transformers. Reliable insulation depends on proper and safe designing. Hence, broad knowledge is required for appearing voltage stresses and their admissible limits. Tests and statistical evaluations are done to find technical limits of voltage stresses and dielectric stresses are computed through numerical field calculations (FEM technique). Consequently, post processors compare the calculated stresses with their limits and decision is taken for design. Hence, new and improved insulation designs are made which are more safe and economical as much as possible. This chapter is divided into five sections, while second section deals with specification of solid model of 125MVA.132/11 kV transformer to be analysed through FEM technique to understand electric field distribution for insulation designing. Third section elaborated measures to be taken for designing insulation with the determination design insulation level (DIL) and electric stress. Fourth section illustrates results hence obtained from adopting proposed methodology concentrating on determination of safety margin and judging point for design of transformer insulation. Last section highlights placement of insulation material according to electric field distribution and advantage of solid insulation in oil gaps.

6.2 BASICS OF SOLID MODEL OF TRANSFORMER

. Table 6.1 shows specification of transformer for insulation designing.

Table 6.1 Transformer specifications

KVA		12500/16000
TYPE OF OIL		NATURAL ESTER
COOLING		KNAN/KNAF
VOLTAGE	HV	132000
	LV	11000
AMPERES	HV	54.67/69.98
	LV	656.07/839.78
PHASES	HV	3

	LV	3			
BIL (kV)	HV	LI	650	AC	275
	LV	LI	75	AC	28

Figure 6.1 shows basic transformer models for FEM Analysis with windings and insulations symmetry. Transformer comprises of disc winding with paper insulation of 0.6 mm and interdisc spaces of 4.5 mm. Solid insulation arrangement of pressboard of 1 mm thickness is used to break the oil gaps between windings. Size of structure plays role in deciding field at breakdown and breakdown voltage as well. Size can be interpreted as area or volume effect [49] which is a controlling factor. Though, studies on insulation application in industries has favoured volume approach from point of view of physical characteristics, hence large volume of insulation increases probability of failure or event which initiates breakdown at high stress area. If dielectric design is studied in this way, then placing solid barriers in large volume of oil is effective and hence raising the withstand voltages. Table 6.2 shows the material assigned along with their properties in solid model for transformer for electric stress calculation.

Table 6.2 Material specifications

Material		Specification	
		Permittivity	Thickness(mm)
Insulating oil	Ester Oil	3.5	
Solid Insulation	Paper covering	4.4	0.6
	Pressboard	4.8	1
	Interdisc spacer		4.5
	Permawood		
Winding conductor	Copper		

6.3 PROPOSED METHODOLOGY FOR INSULATION DESIGN

Course of insulation design relies on the distribution of electrostatic fields in transformer.

Following procedure is undergone to study electric fields in proposed transformer model:

- Determination of design insulation level (DIL)
- Collection of stresses in all essential zones
- Design limits for transformer oil.

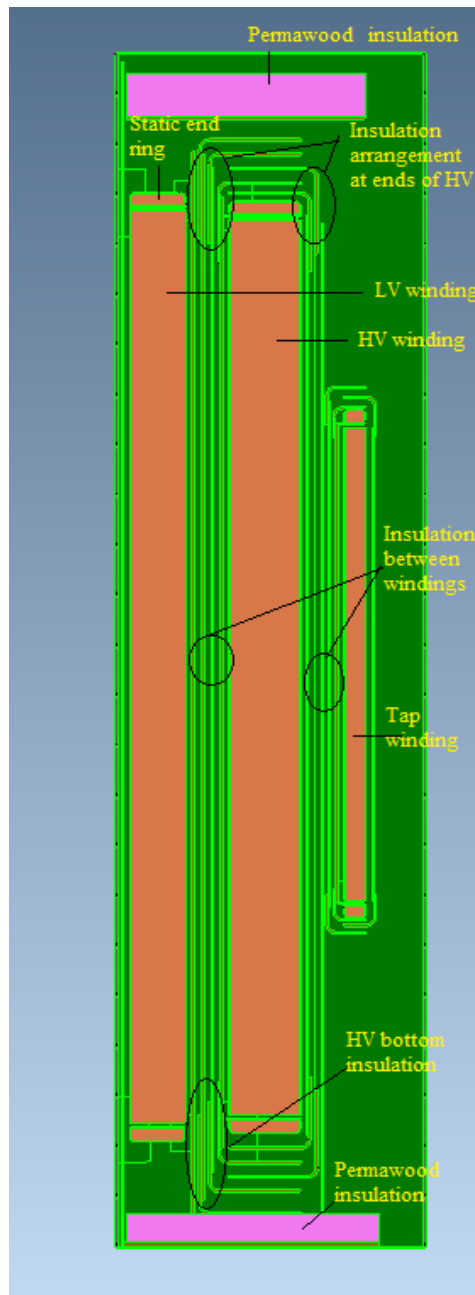


Fig.6.1 Transformer model for FEM analysis

6.3.1 TEST VOLTAGES AND DESIGN INSULATION LEVEL (DIL)

In working condition, insulation in transformer is subjected to operating stress and stress due to overvoltages. Working stress on insulation is decided by operating voltages. However, over voltages can be broadly classified as lightning , switching and temporary overvoltages Basically four types of tests are performed for various classes of voltage to check insulation condition i.e. lightning and switching impulse, short and long duration power frequency with PD measurement. First three tests evaluate insulation capability to withstand

overvoltage, long duration testing is done for evaluating behaviour of insulation under normal operating stress.

DESIGN INSULATION LEVEL: Surges appearing on transformer insulation under all test conditions i.e. AC and impulse are converted to one equivalent voltage, which is generally one-minute short duration power frequency voltage and maximum of all voltage levels during four different test conditions. Equivalent voltage is known as design insulation level (DIL), expressed in kVrms.

According to different voltage class of transformers, different impulse ratios as represented in Table 6.3 are utilized as insulation to be designed vary according to voltages appearing on transformers and hence on BIL and power frequency test level. Other voltage levels are also converted into DIL using conversion factors as shown in Table 6.4

Table 6.3 Impulse ratio for different voltage levels

Voltage Category(kV)	BIL (kVp)	Power frequency test level (kV rms)	Impulse ratio(kVp/kVrms)
132	550	230	2.39
220	950	395	2.4
400	1300	570	2.28

Table 6.4 Conversion ratio for equivalent voltage

Test	Factor
Lightning impulse full wave (BIL)	2.39
Switching impulse (SIL)	1.7
Applied voltage (1 minute)	1

To calculate one equivalent voltage from the test voltage in present transformer model as specified in Table 6.5, following procedure is carried out.

Table 6.5 Estimation of design insulation level (DIL)

Voltages	Winding	Rating (kV)	Converted Voltages (kV)
Rated Voltage (50 Hz)	HV	132	
	LV	11	
Test voltage (50 Hz, 1 Minute)	HV	275	$275/1=275$
	LV	28	$28/1=28$
LI voltage	HV	650	$650/2.39 =272$
	LV	75	$75/2.39 = 27$

Since, maximum of the converted voltages are taken as equivalent voltage, equivalent voltage for stress estimation at high voltage winding and low voltage winding is taken as 275 kV and 28 kV respectively as calculated in Table 6.5.

6.3.2 ELECTRIC STRESS ESTIMATION

Determination of electric stress in insulation components accounts to be a major factor in insulation designing. Conventional design of insulation of transformer starts with modelling insulation system either in 2D or 3D. Complication of geometry and features needed for obtaining precise solution for dielectric stress decided to use 2D or 3D mode of analysis. Such models are constructed in CAD softwares and later transferred to FEM software for further evaluations.

FEM software selected in this study is ElecNet where problem definition is to calculate safety margin through cumulative stress calculation in oil gaps between solid insulation. Dielectric medium chosen in study is isotropic i.e. have same behaviour with respect to field regardless of direction of field. Here, field domain which is enclosed in a boundary whose condition is governed by Dirichlet boundary condition. Space outside this boundary is excluded from field domain. Thus is an interior problem by neglecting effect of fringing. Two dimensional electrostatic field analysis is done in RZ plane. As electrostatic field analysis is chosen, governing equation is given by Poisson equation as

$$\nabla^2 V = \rho / \epsilon_0 \quad \dots\dots(1)$$

Insulation failure is not only affected by electric stress. Hence, determining locations of high stresses in order to specify weakness in design is not sufficient. Mechanism included in initial stage of breakdown also include locality structures and region size which interacts with high stressed zones. Hence, this is logical to consider entire area which participates in loss of insulation characteristics. Consequently, essential zones are defined for calculating and assimilating design guidelines as follows,

- Between high and low voltage winding-considering puncture and flashover phenomena
- Between high voltage and tap winding
- From winding to tank body
- From winding to upper and bottom solid insulation

Volume of oil which is examined for evaluating volume effect is taken randomly as 90% of equi-gradient outline [49] as remote regions do not significantly influence the field. To

accumulate influence of all above defined notions along with factors affecting insulation design, cumulative stress in essential zones are calculated for defining and assimilate design guidelines.

6.3.3 CUMULATIVE STRESS AND DESIGN LIMITS

According to physics of design, magnitude and dispersion of electric field through a specific region (i.e. in bulk oil or along surface of insulation) should be taken into account. This purpose is served through calculating cumulative stress instead of actual value of field linked with respective point in selected region [26]. This methodology is utilized for assessing deign of oil gaps. Since, apart from size importance in evaluating breakdown, point of maximum stress also act as initiation site for failure. Hence, volume which is examined for stress distribution should be traced outwards from point of maximum stress.

Acknowledging various aspects which can affect impact curves which are selected for designing. Differentiation of influence of these factors and ideal strength of insulation [49] can done on basis of weidmann degas and saturated oil (reference) which are given by equations (2) & (3),

The withstand for degassed oil can be calculated by [51]

$$E = 21 d^{-0.37} kV/mm \quad \dots\dots(2)$$

And withstand for gas saturated oil is given by eq. (3)

$$E = 17.8 d^{-0.364} kV/mm \quad \dots\dots(3)$$

Where , d = oil gap between barriers and oil (mm)

The equation is rational for fine quality of insulation and degassed oil. Estimated extent of cumulative stress levels should be lesser than estimation done using Equation 2 and 3 as shown in Fig 6.3.

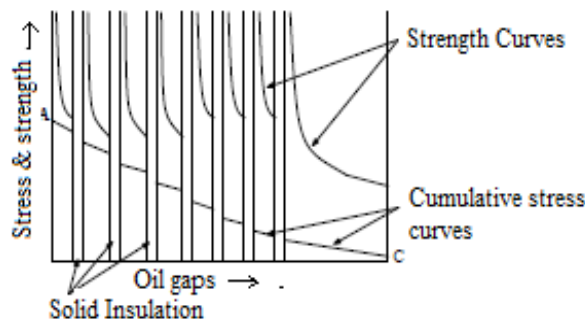


Fig. 6.2 Plot of cumulative stress

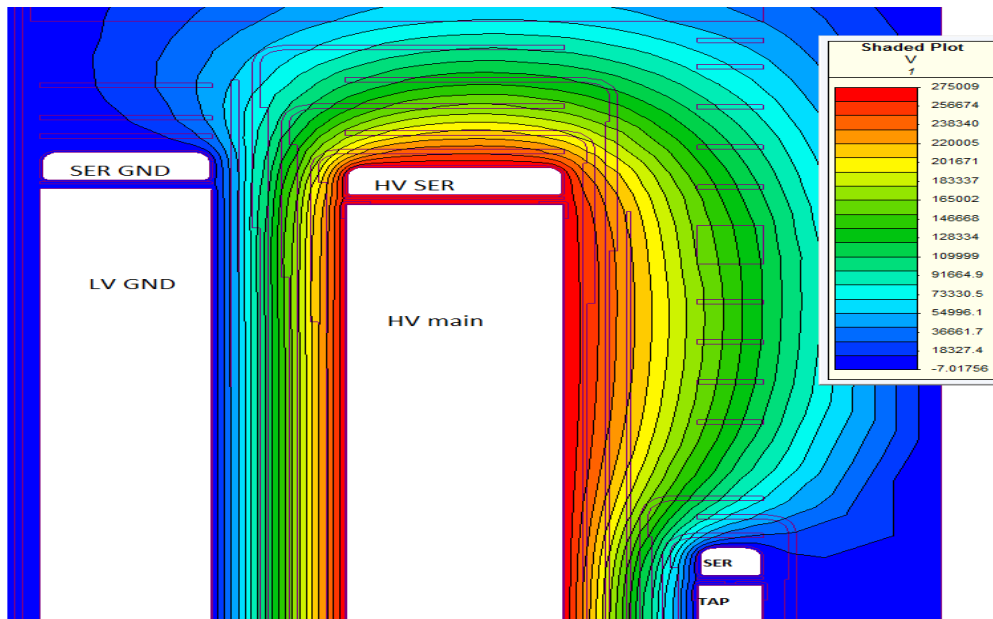
The value of cumulative stress differs reference value obtained from degassed and saturated oil equations by a margin known as safety margin. Safety margin depends on quality of components and manufacturing processes.

6.4 RESULTS AND DISCUSSION

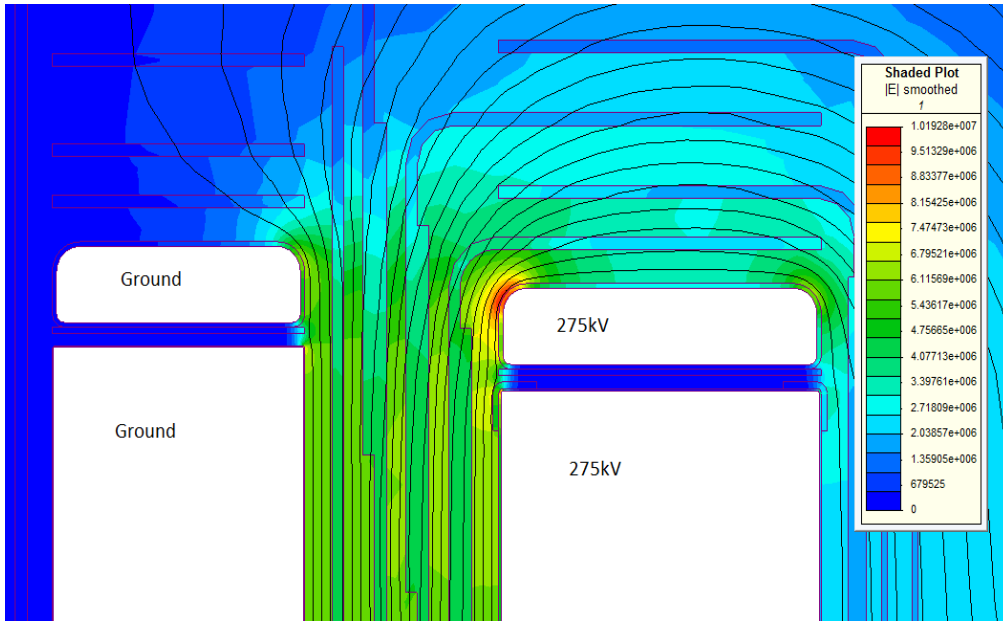
The objective of 2D dielectric field analysis is to evaluate the dielectric strength of the top, bottom, HILO insulation structure of 12.5/16MVA 132/11kV natural ester oil transformer. Following results display distribution of electric field and voltage for ester oil. However, for mineral oil, it has been found that there is reduction in stress by 10% percentage.

6.4.1 HIGH VOLTAGE WINDING INSULATION ARRANGEMENT & DESIGN

Estimation of voltage and stress distribution at high voltage winding is done with help of converted equivalent voltage applied to HV winding while LV winding and tap winding is grounded. Equivalent voltage for high voltage winding corresponds to 275 kV as estimated in Table 3.5 .Electrostatic filed distribution at high voltage winding of 132 kV transformer is shown in Fig.6.4

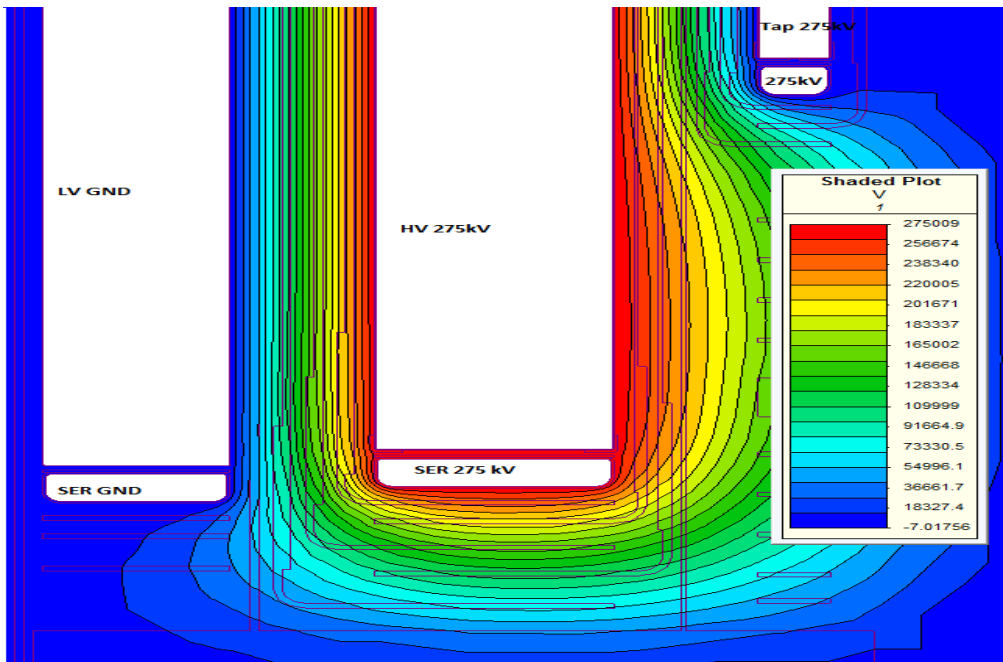


(a) Voltage distribution

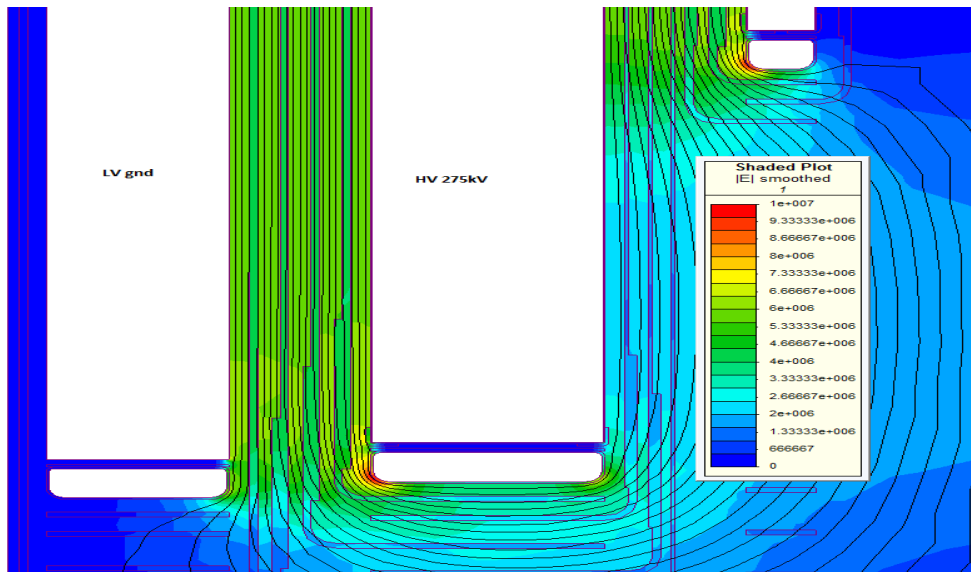


(b) Stress distribution

Fig.6.3 HV top insulation voltage and stress distribution



(a) Voltage distribution



(b) Stress distribution

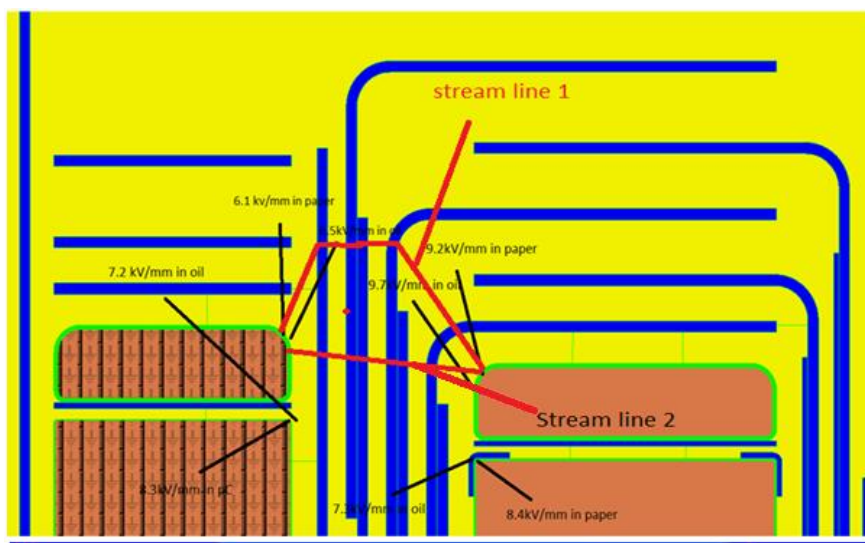
Fig.6.4 HV bottom insulation voltage and stress distribution

Essential measure that is utilized in completion and optimization of design of insulation comprises of

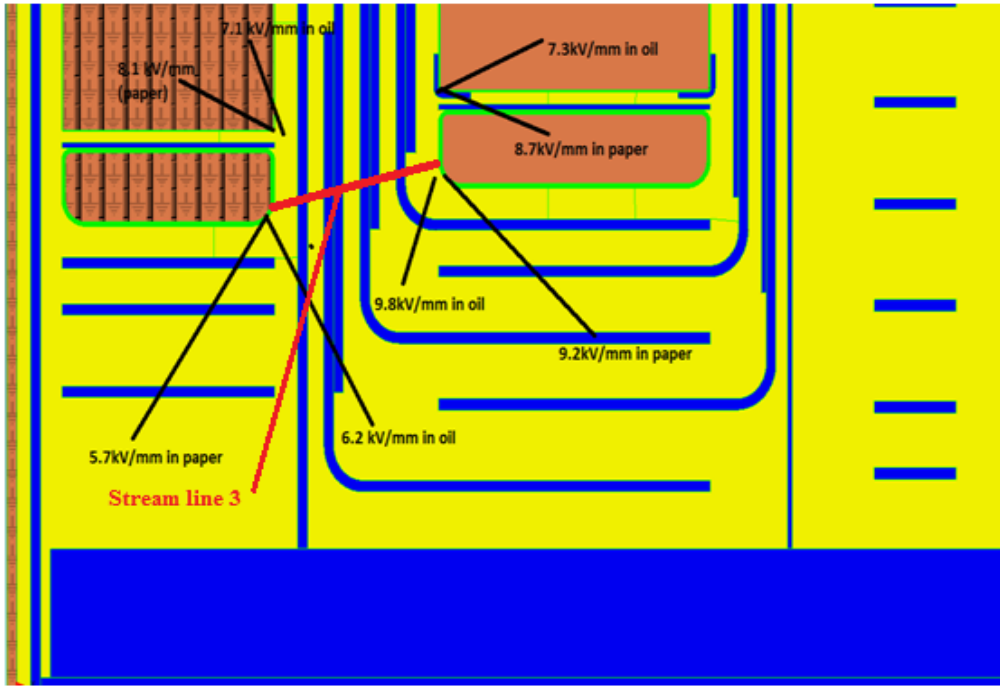
- maximum stresses at surface of winding i.e. point stress
- stress through oil gaps and flashover of oil gaps i.e. cumulative stress

A. STRESS ASSESSMENT AT HIGH VOLTAGE WINDING

Fig.6.6 represents points stress at winding edges in paper and oil with stream line 1 & 2 representing area for cumulative stress computation across the oil gaps between HV & LV winding.



(a) Top insulattion

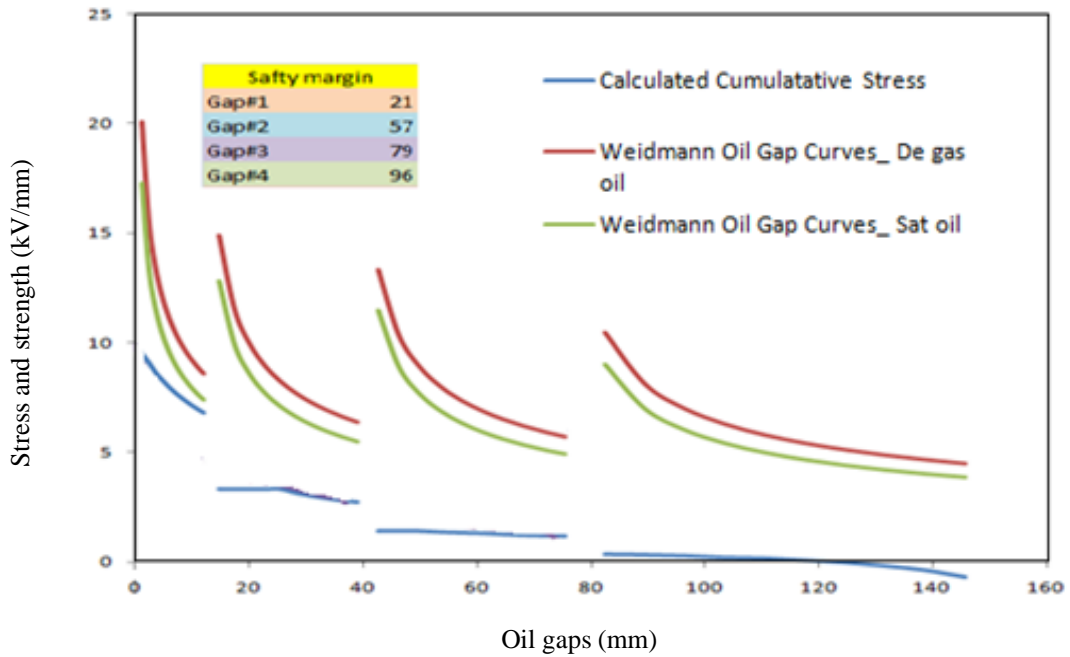


(b) Bottom insulation

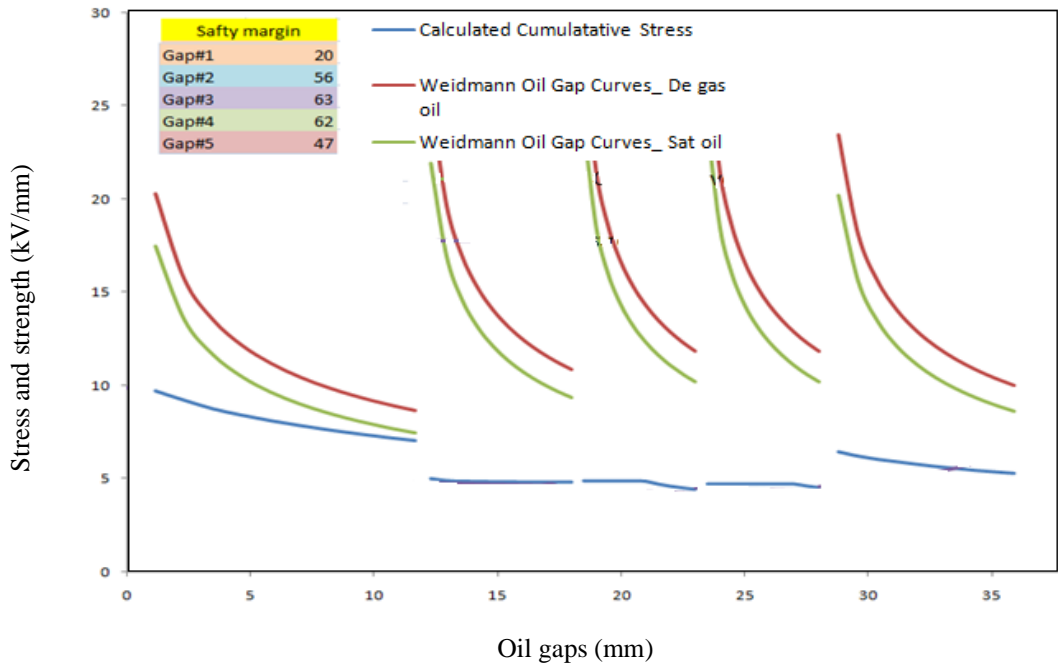
Fig.6.5 Point stress at high voltage winding

B.DETERMINATION OF SAFETY MARGIN

Safety margin for high voltage insulation is computed through cumulative stress computation at stream line 1,2 & 3 with reference to weidmann curves as shown in Fig. 6.7-6.9.



(a) Stream line 1



(b) Stream line 2

Fig 6.6 HV top insulation arrangement : safety margin

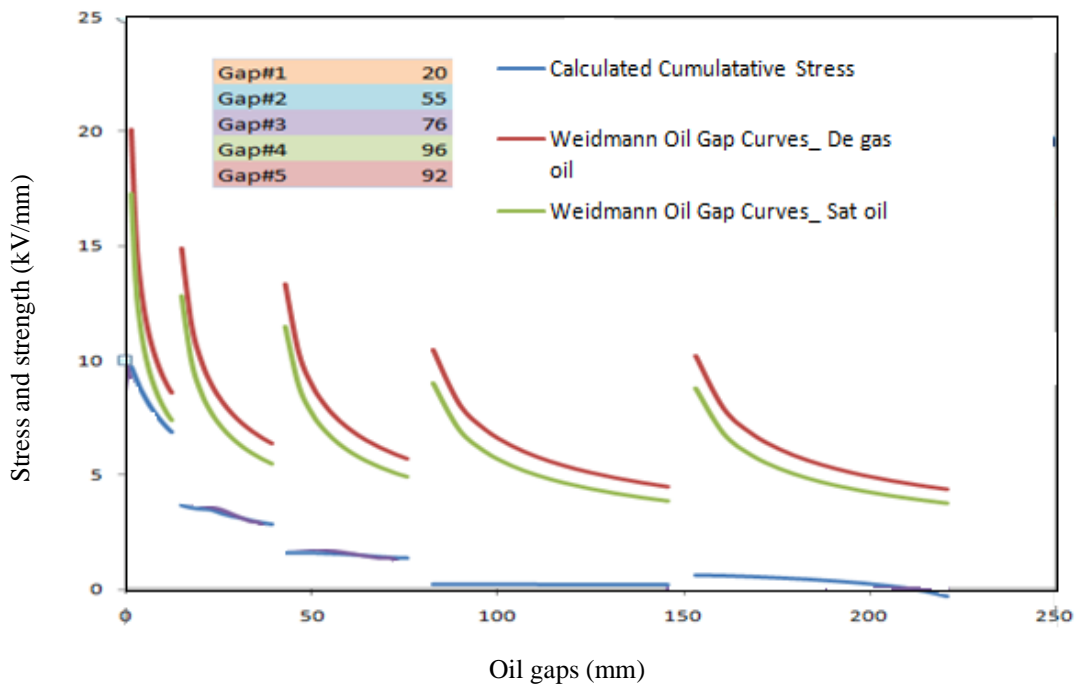
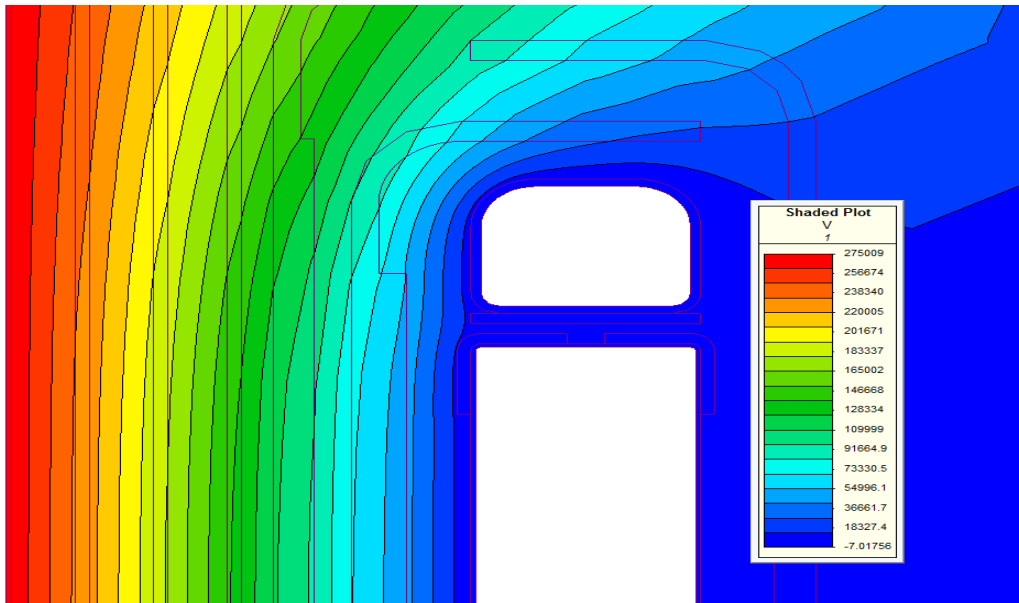


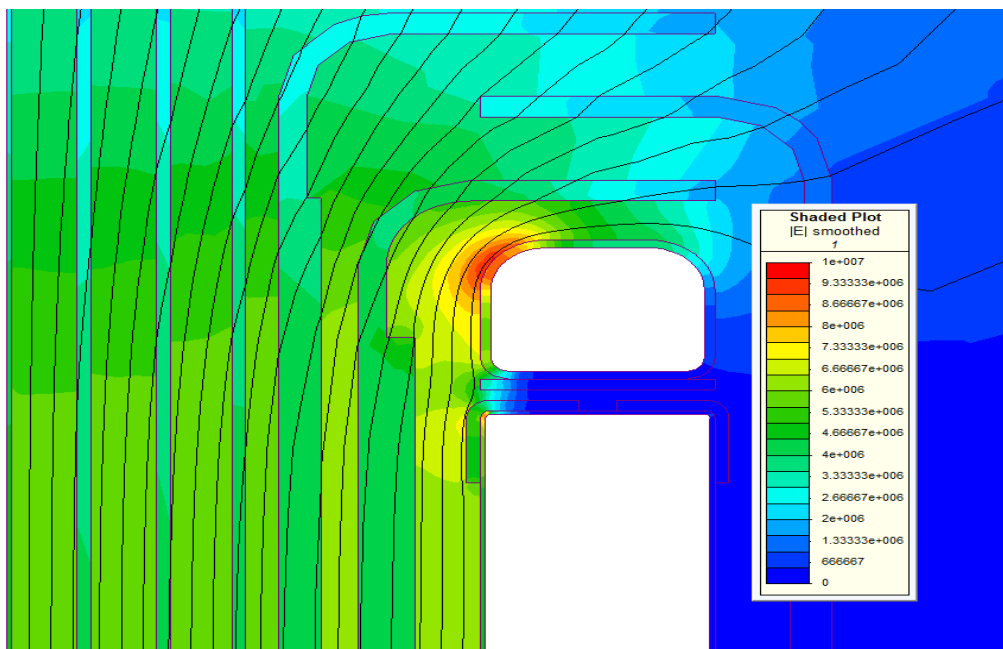
Fig. 6.7 HV bottom insulation arrangement : safety margin

6.4.2 TAP WINDING INSULATION ARRANGEMENT & DESIGN

Estimation of voltage and stress distribution at tap winding is done with help of converted equivalent voltage applied to HV winding while tap winding and LV winding are grounded. Equivalent voltage for HV winding corresponds to 275 kV as estimated in Table 3.5. Electrostatic field distribution at tap winding of 132 kV transformer is shown in Fig.

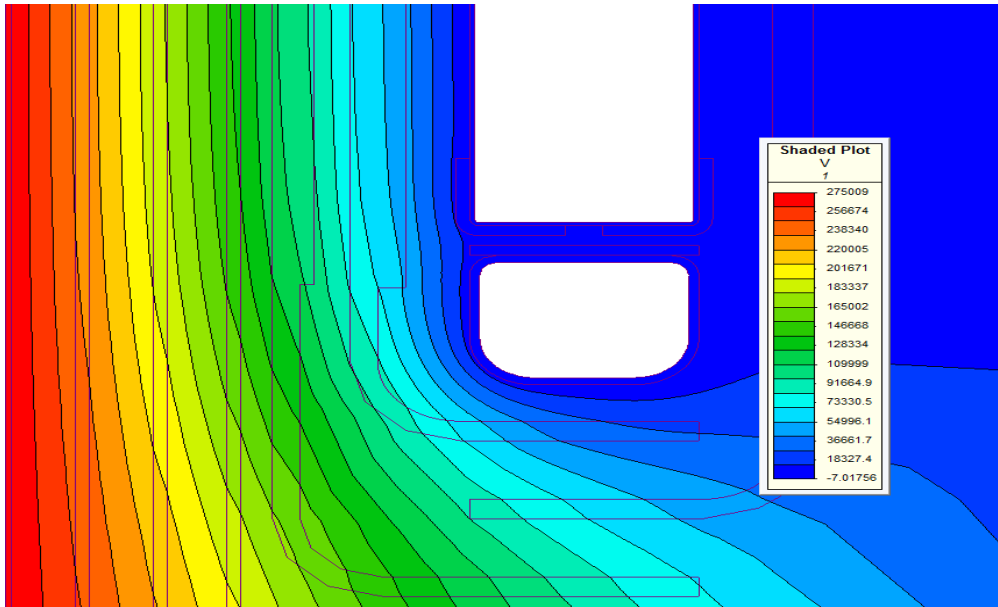


(a) Voltage distribution

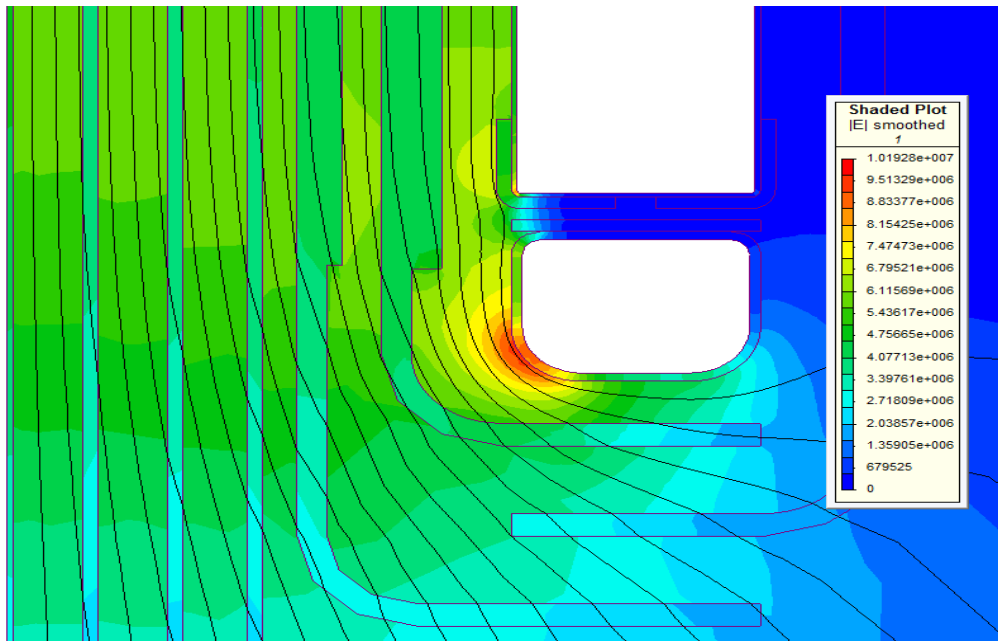


(b) Stress distribution

Fig.6.8 Tap top insulation voltage and stress distribution



(a) Voltage distribution



(b) Stress distribution

Fig.6.9 Tap bottom insulation voltage and stress distribution

A.STRESS ASSESSMENT AT TAP WINDING

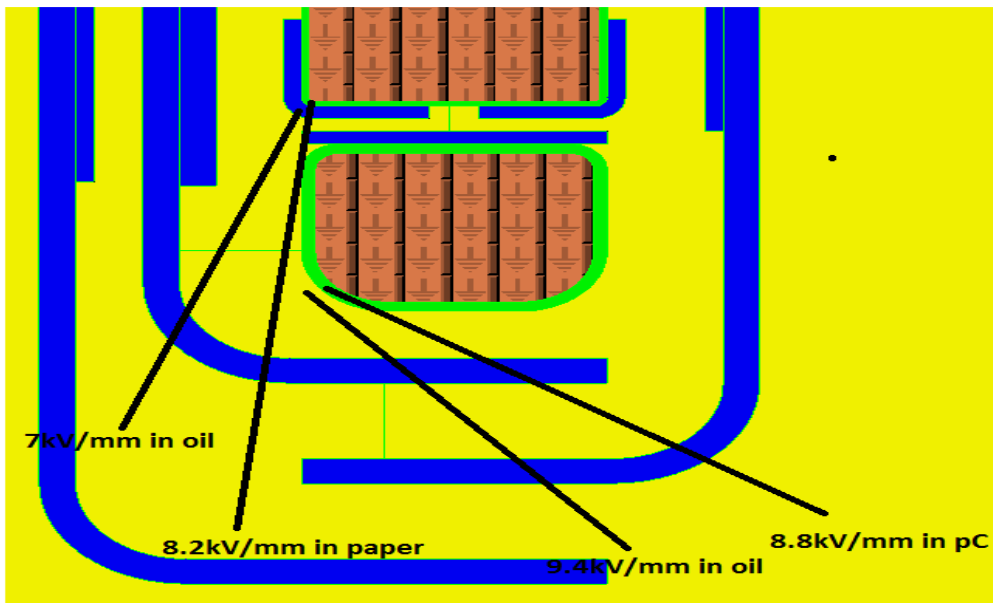


Fig.6.10 Point stress at Tap winding

B.DETERMINATION OF SAFETY MARGIN

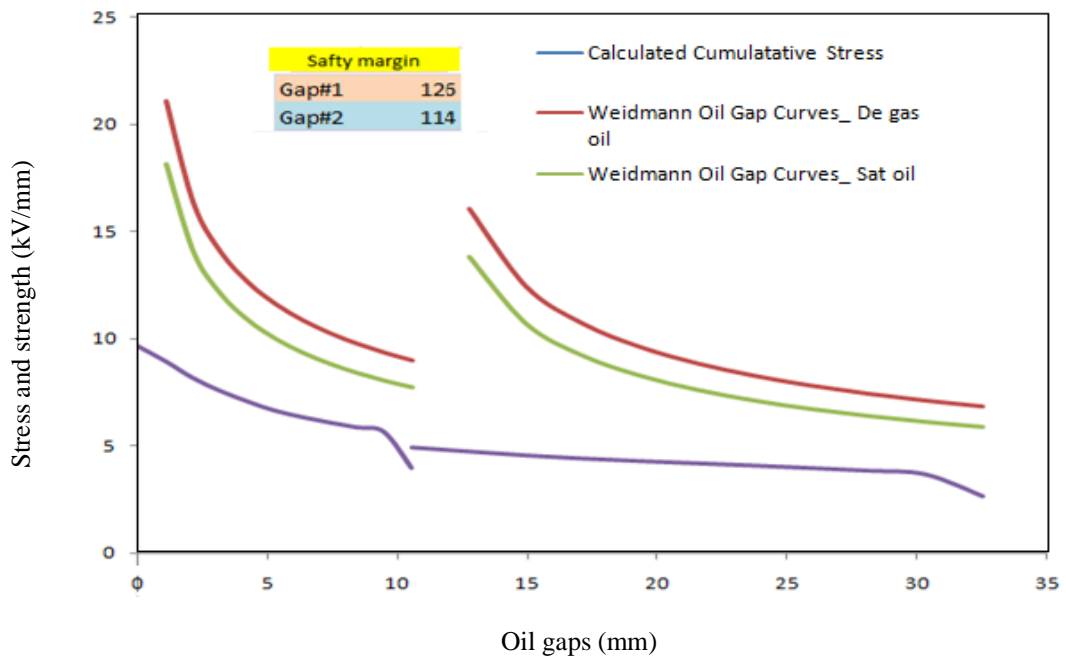
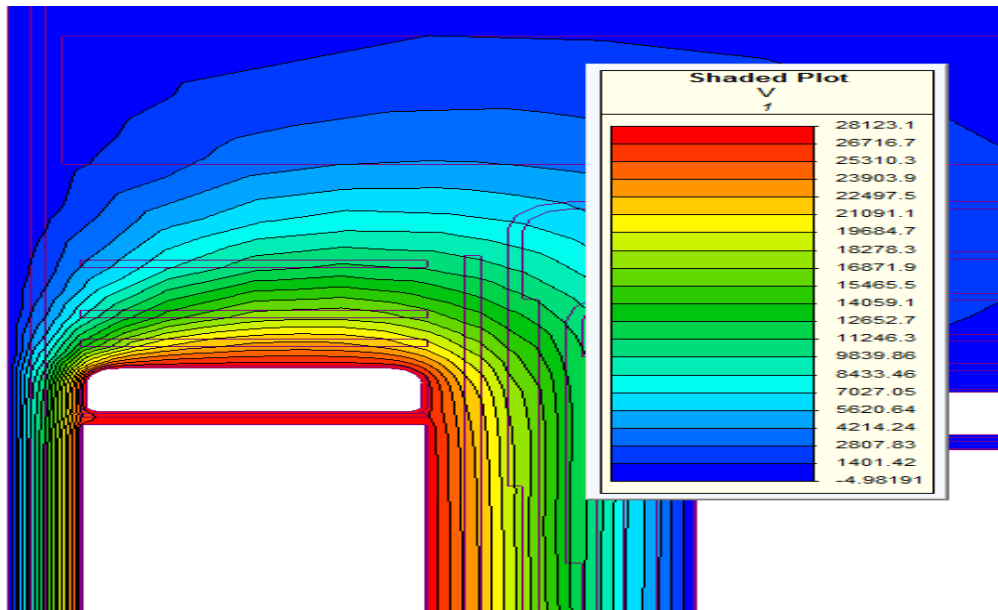


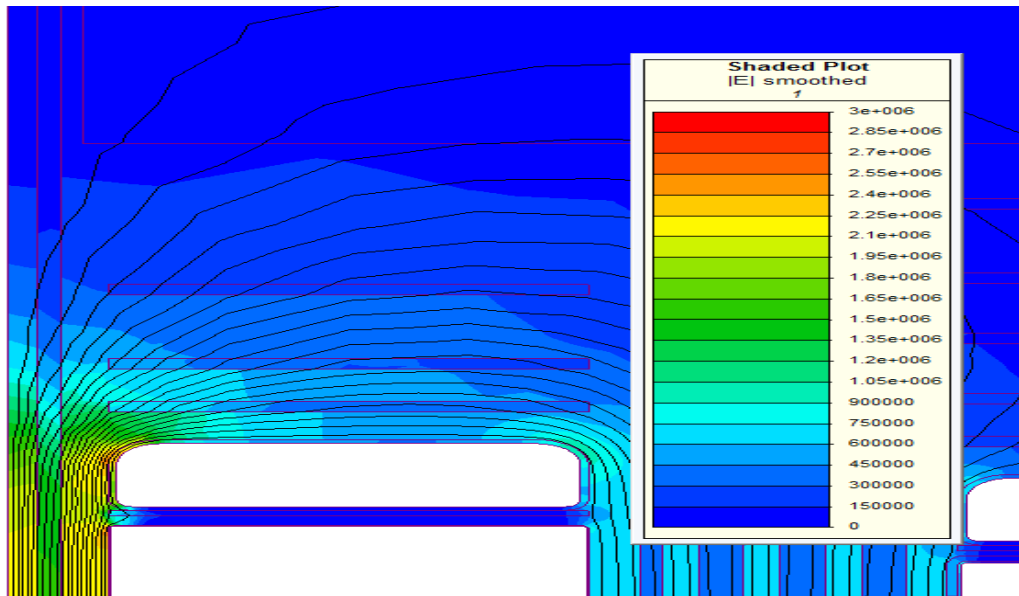
Fig. 6.11 Tap top insulation arrangement : safety margin

6.4.3 LOW VOLTAGE WINDING INSULATION ARRANGEMENT & DESIGN

Estimation of voltage and stress distribution at low voltage winding is done with help of converted equivalent voltage applied to LV winding while HV winding and tap winding are grounded. Equivalent voltage for low voltage winding corresponds to 28 kV as estimated in Table 3.5. Electrostatic field distribution at low voltage winding of 132 kV transformer is shown in Fig.

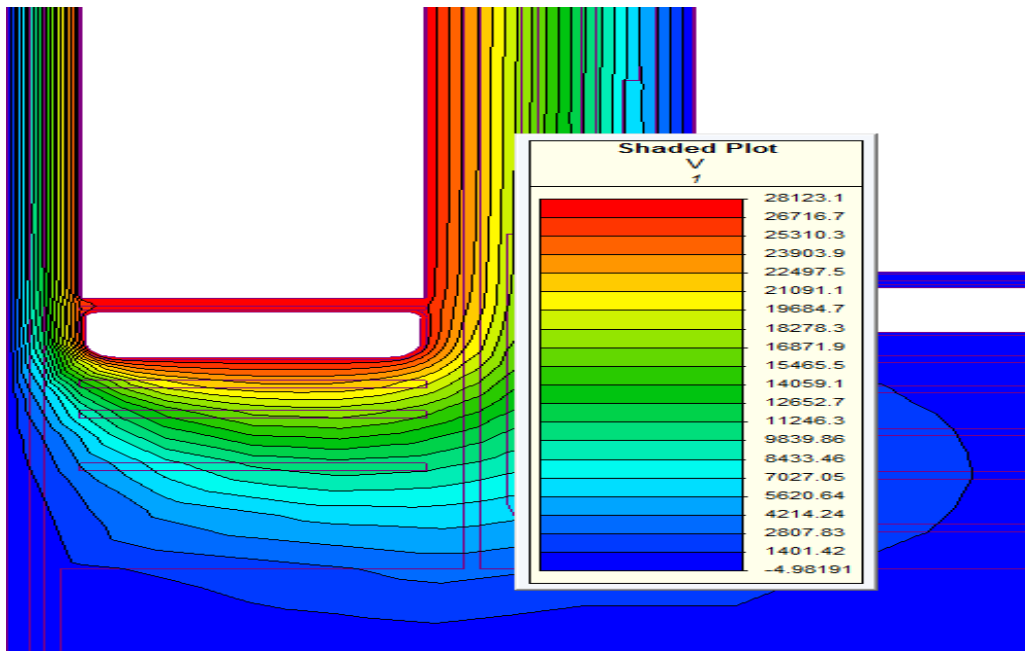


(a) Voltage distribution

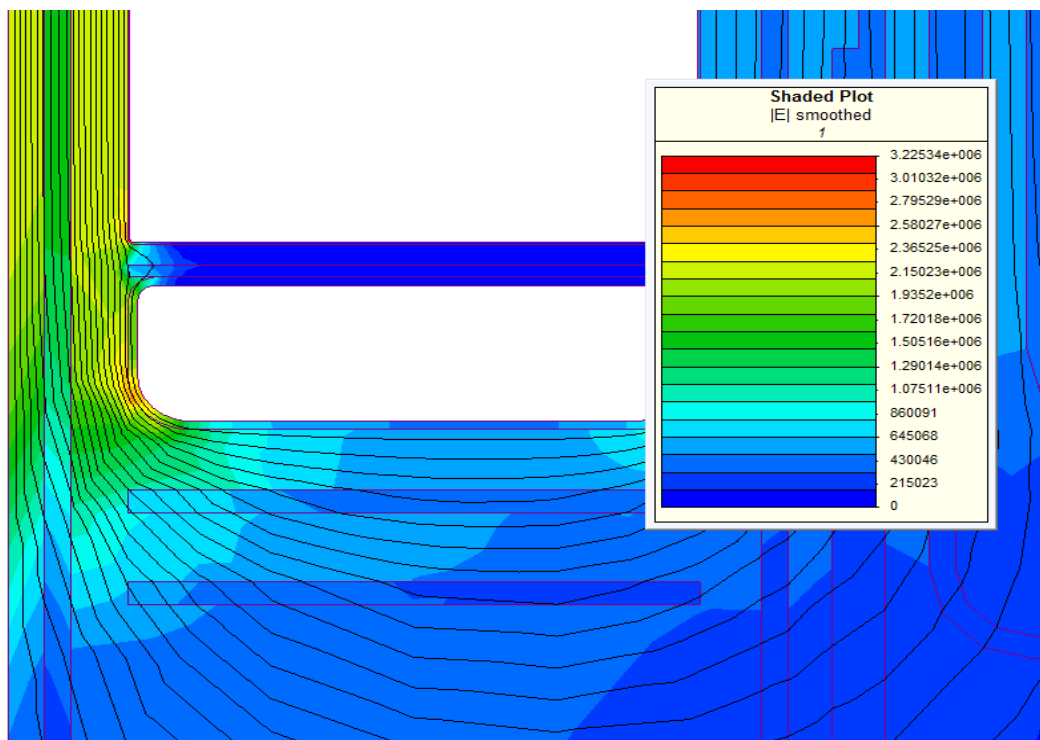


(b) Stress distribution

Fig. 6.12 LV top insulation voltage and stress distribution



(a) Voltage distribution



(b) Stress distribution

Fig. 6.13 LV top insulation voltage and stress distribution

A.STRESS ASSESSMENT AT LOW VOLTAGE WINDING

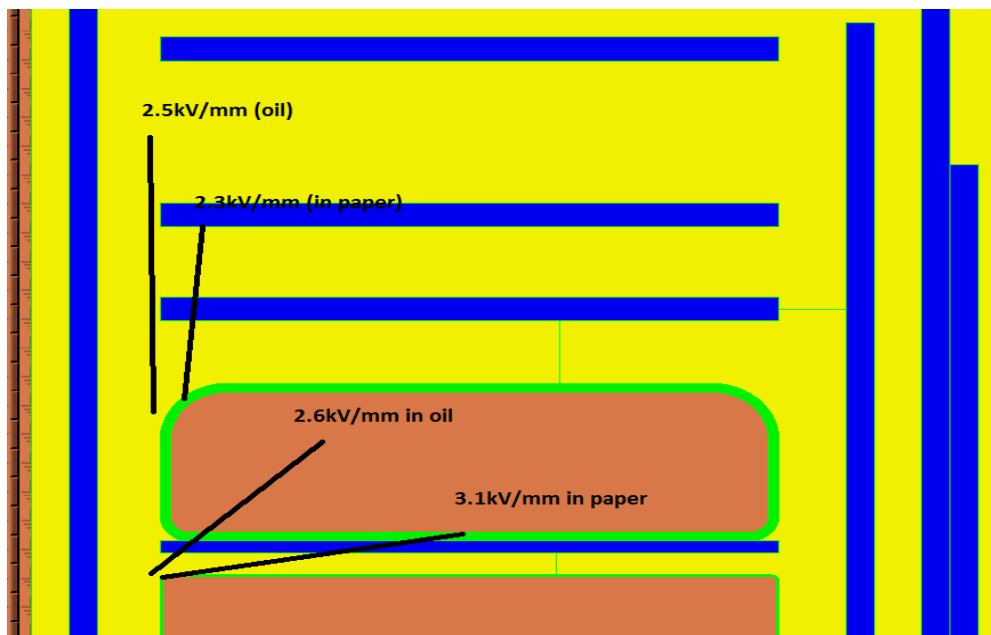


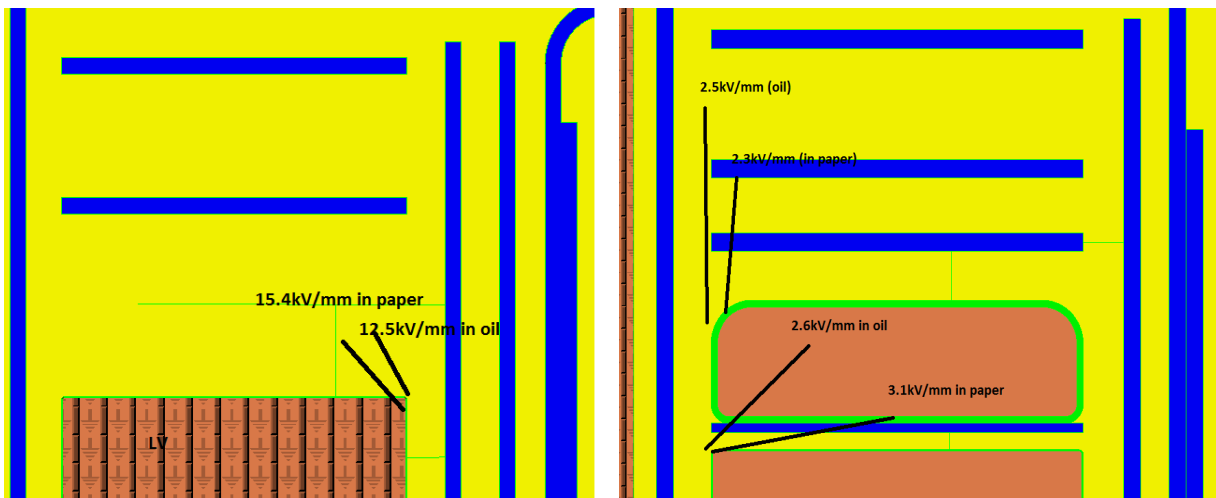
Fig. 6.14 Point stress at LV top insulation

6.4.4 OUTCOMES OF INSULATION ARRANGEMENT

- The electric stresses are checked under two main conditions:
 - In oil gaps
 - For point stress in windings
- Point stress is influenced by voltages applied and geometry of winding. The max point stress are given below. Acceptable value of point stress is 11-12kV/mm (Max).
 - 9.2kV/mm in paper over HV winding SER.
 - 9.8kV/mm in oil duct over HV winding SER.
 - 8.4kV/mm in paper over HV winding.
 - 7.3kV/mm in oil duct over HV winding.
 - 8.9kV/mm in paper over HV tap SER winding.
 - 9.3kV/mm in oil duct over HV tap SER winding.
 - 8.2kV/mm in paper over HV tap winding.
 - 7.1kV/mm in oil duct over HV tap winding.
- Stress between LV and HV winding at uniform field is 5.9kV/mm and Stress between tap and HV winding at uniform field is 5.7kV/mm
- Local stress does not occur only at ends of coils but geometric features also affect it. If higher stress is resulted due to combination of winding geometry and impulse voltages, extra solid insulation is needed for reducing oil stress.

- Cumulative stress curves have been plotted and comparison is done with Weidmann curves taken as reference defined by equation (2) & (3) as shown in Fig. for evaluating safety margins.
- Minimum safety margin is dependent on insulation quality, drying and impregnation process. Generally, 15% of safety margin in highly stressed portion of insulation is assumed to successfully pass impulse and induced overvoltage testing. For safety margin of overall transformer, minimum of all essential zone safety margins is considered. Hence safety margin of 20% is obtained which is greater than minimum required margin.
- End insulation is ideal if minimum margin is roughly equal for every duct. Otherwise angle rings or barriers are adjusted in such way that margin for resulting ducts are greater than some established limit.
- With consideration of stress imposed by standard impulse, special insulation is kept near winding conductors. If conductor paper insulation is increased to increase withstand capability against stress, it leads to reduction in series capacitance and increment in winding temperature. Hence, angle rings/caps are to be used. They perform the same purpose as is achieved by increasing radius of conductor. Angle rings/ caps are placed across equi-potential lines otherwise creepage stress along their surface may lead to reduction in withstand strength.
- Strength of insulation system is dominantly determined by strength of oil ducts in composite oil-paper insulation structure. Therefore, accurate designing of ducts and liquid-solid interface is essential.
- As solid insulation displays higher dielectric strength, but increasing its thickness in order to increase withstand capability leads to more stress in oil ducts.
- Dimensions of duct near to winding must be adequately decided as lesser width gives higher withstand strength but thermal performance should also be proper.
- As electric field distribution is non uniform at first duct at point of line terminal hence stress is to be accurately predicted.
- In case stress across an oil gap exhibits higher value as compared to the stress allowable, extra barrier is required to break oil gap hence increasing the strength of gap. Barriers display additional protection against propagation of streamer in oil.
- Stress at winding ends can be reduced using SER apart from constructive subdivision of oil gaps with barriers or angle rings. For eg. Fig 6.15 represents insulation modelling of LV top without and with SER. Point stress is found out to be as 15.4 kV/mm in paper

covering and 12.5 kV/mm in oil which is higher than the allowed point stress i.e. 11-12 kV/mm without SER. Hence, SER is used and it results in lowering down of stress to maximum of 3.1 kV/mm as shown in Fig.6.15



(a) Without SER

(b) With SER

Fig. 6.15 Influence of SER on LV winding top insulation arrangement

SER curvature (6mm) and SER paper covering needs to be maintained at any cause during SER manufacturing and assembly of all insulation arrangement. If there is any concern in the area of SER during manufacturing time of SER, quality team can increase the SER paper covering from 1.1mm to 1.5mm/1.6 mm in HV and Tap. It will be more safer in terms of safety margin other than point stress.

6.5 CONCLUSION

As this chapter deals designing insulation for ester oil and evaluating their key points, safety margin determination has been discussed based on calculation of design insulation level (DIL) and cumulative stress and comparing with weidmann strength curves. It has been evaluated that safety margin of 20% has been obtained which display proper insulation arrangement. Role of solid barriers breaking oil gaps have been discussed along with implementation of angle ring/cap.

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

The objective of this dissertation work is to assess behavior of ester oils under impulse voltage application considering area effect and combination of electric stress i.e. axial and radial stress, thermal performance of ester oils and their permittivity effect on frequency response analysis along with insulation design of transformers.

Research areas covered in this work are as follow:

- Standard impulse testing of inter disc insulation of winding
 - Effect of positive and negative polarity on breakdown in quasi-uniform field
 - Study of electric field geometry via two models i.e. Model A (Axial stress) and Model B (Combination of axial and radial stress)
 - Comparison of breakdown voltages of insulating liquids considering Model A and Model B
 - Evaluation of electrostatic stress through FEM for insulating liquids considering Model A and Model B and different combination of solid insulation.
- Thermal performance of transformer insulation liquids
 - Evaluation of hotspot and top liquid temperature of insulating liquids through temperature rise test
 - Transformer application of higher temperature limits of ester liquids
- Frequency response analysis of insulating liquids
 - Evaluation of difference in permittivity of ester and mineral oil
 - Evaluation of effectiveness of graphical and numerical parameter analysis in SFRA interpretations.
- Insulation design of transformer
 - Evaluation of design insulation level, cumulative stress and optimum safety margin
 - Insulation arrangement for reduction in stress in insulation components

7.1 CONCLUSION OF MAJOR FINDINGS AND RESULTS

- There is no significant polarity effect in quasi-uniform field i.e. in interturn and interdisc geometry.
- Combining radial and axial electric field in a single design criterion, so called combined stress has a big impact on HV transformer design. Because no widely accepted breakdown theory of interaction of solid and liquid insulation exists, research of the radial electric field influence to axial electric field is done experimentally, through emulation via Model A and Model B which simulate both electric fields. Combination of axial and radial stress leads to higher stress in insulation and hence breakdown occurs at lesser voltage.
- Higher the stressed area, higher is probability of breakdown. This is known as area effect which is evaluated using wedge shaped model. Considering area effect in interdisc insulation of transformer winding, ester oil demonstrated lesser breakdown voltage in comparison to mineral oil and reduction is about 0.15-0.2 pu.
- Due to comparable permittivity of solid insulation impregnated with ester oil, stress in oil is reduced in case of ester oil application with respect to mineral oil. However, stress at winding edges have increased in ester oils.
- Since failure of insulating material is function of risk and hence statistical techniques are extensively utilized for estimating dielectric strength of insulation at low probability of failure.
- Accounting to higher viscosity of ester oil, higher temperature rise limits are observed experimentally through temperature rise test. However, higher temperature results in increased ageing of cellulose. But ester oils because of their hydrophilic nature have higher rate of water absorption than mineral oils, hence results into lesser ageing of cellulose upto four times. This increase life of transformer while operating at same hotspot temperature as of mineral oil or same operation at higher temperature without need of under loading transformer or increase in cooling capacities.
- As permittivity difference of ester oils with respect to mineral oil affects stress distribution in solid and liquid insulation, this also affect impedance of transformers. Through SFRA of ester oil transformers, resonant frequencies at lesser frequencies are observed as higher permittivity lead to higher capacitance.

As graphical analysis requires expertise of personnel hence numerical parameters are proved to be less time consuming and more precise in evaluating deviation in frequency response of ester oil with respect to mineral oils.

- To discuss effect of numerous factors such as dielectric, thermal constraints and processing of insulation, cumulative stress is calculated to evaluate safety margin with respect to weidmann design curves.
- As design of power transformer majorly depends on insulation condition, materials, geometry and composition. Hence, various aspects are evaluated regarding minimization of stress in insulation and increment in safety margin are discussed.

7.2 FUTURE SCOPE

As this dissertation work elaborates dielectric, thermal and electric properties of ester oils both experimentally and analytically, in detail. However, there is further scope of research in this work for more understanding of nature of alternate transformer insulation liquids.

- 1.To develop similar models to characterize the switching impulse strength of windings.
- 2.Influence of residual charges need to be investigated to understand physics of degradation of oil-solid insulation system
- 3.Considering the possible over voltages occurring in HVDC system.
- 4.Thermal modeling of ester oil transformers.
- 5.Development of transformer model or algorithm from obtained SFRA results for better understanding of change of electrical and physical parameters of windings.
6. Optimization of ester oil transformers on basis of developed design guidelines.
7. Algorithm to detect the location and occurrence of the faults at multiple locations along the winding.

LIST OF PUBLICATIONS/ACHIEVEMENTS

1. Research paper entitled as A.Garg, T.Sharma ,A.Jain, “Statistical synchronization technique for transient signal analysis during impulse testing of transformers” has been submitted in IEEE Transactions on Power delivery (Revision 1)
2. Research paper entitled as A.Jain, T.Sharma, A.Garg,“ A spot light visualization for detection of transient signals during impulse testing of transformer” has been communicated to International Journal of Power and Energy Conversion (IJPEC)
3. Selection for PhD in IIT Roorkee.

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