MATERIAL COMPATIBILITY AND THERMAL ANALYSIS FOR PROCESS DEVELOPMENT GUIDELINES OF ESTER OIL TRANSFORMERS

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DECLARATION

I hereby certify that the work which is presented in dissertation entitled, "**MATERIAL COMPATIBILITY AND THERMAL ANALYSIS FOR PROCESS DEVELOPMENT GUIDELINES OF 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 as authentic record of my own work carried under the supervision of Dr. Jeyabalan Velandy, Manager, CG Power & Industrial Solutions Ltd., Mumbai and Dr. Prasenjit Basak, Associate Professor, EIED . 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.

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ABBREVIATIONS

ASTM	American Society for Testing and Materials
THNM	Thermal Hydraulic Network Modeling
NAS	National Aerospace Standard
FEM	Finite Element Method
HMA	High Molecular Weight Acid
LMA	Low Molecular Weight Acid
TS	Tensile Strength
DP	Degree of Polymerization
HT	High Tension
CT	Current Transformer
BDV	Breakdown Strength
NN	Neutralization Number
IFT	Interfacial Tension
DGA	Dissolved Gas Analysis
PCB	Pre-compressed Board
VPD	Vapour Phase Drying
CCA	Core Coil Assembly
IR	Insulation Resistance
PI	Polarization Index
DD	Dielectric Discharge
ONAN	Oil Natural Air Natural
ONAF	Oil Natural Air Forced
OFAN	Oil Forced Air Natural
OFAF	Oil Forced Air Forced
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
CFD	Computational Fluid Dynamics

ABSTRACT

Transformer insulation is a composite system made of insulating liquid and impregnable solid insulation. Generally, the mineral oil is used for insulating medium and cooling in transformers. Recently, there is a growing interest in ester oil transformer for fire safety, environmental friendly and continuous overloading capability in comparison to conventionally used mineral oil transformer. The high interest on ester oil transformer has led to several analyses aimed at prediction of their dielectric analysis, thermal analysis and process development.

In this study, material compatibility tests are performed as per ASTM D3455- 11 to check the compatibility between the insulating oil and the materials used in the transformer manufacturing such as varnishes, insulation paper, paint, gasket, core etc. for setting up the process guidelines for ester oil transformers. Further, the insulation resistance and dissipation factor of the transformer windings immersed in ester oil are measured. It reveals that the leakage current must be minimised to compensate the more dissipation factor effect of ester oil to make it commercial for transformer applications.

In order to utilize the ester oil as an alternative to mineral oil, the internal and external cooling modes in thermal analysis of transformer needs to be evaluated to get a continuous overloading capability advantageous of ester oil. In this dissertation work, thermal hydraulic network models (THNM) are effectively used to predict the oil flow distribution and the temperature distribution in 12.5/16 MVA, transformer and compared with mineral oil in steady state conditions. The oil flow rate within the winding, top oil rise, winding rise, gradient of the winding and hot spot temperature rise are calculated for both natural ester oil and synthetic ester oil with respect to mineral oil under air natural and air forced cooling modes. It is observed that the materials which are compatible with mineral oil need not to give the same behaviour with ester oil, therefore separate process guidelines must be designed. Due to more viscous nature of ester oil, rate of oil flow in transformer is slow and can be increased using zig-zag cooling method.

Keywords: Transformer, Ester oil, Compatibility, Ageing, Insulation resistance, Thermal analysis.

CHAPTER 1
INTRODUCTION

1.1 OVERVIEW

Transformers have been there over a century now, yet they are still a matter of interest to research enthusiasts. Insulation design is an integral part of transformer manufacturing. Particularly, in the case of high voltage transformers insulation design becomes a critical factor ensuring the desired operation of high tension (HT) transformers. The quality and reliability of transformers weigh heavily on controlled manufacturing processes, good design practices and the use of proper insulating materials. Recently, there is a growing interest in ester oil transformer for fire safety, environmentally friendly and continuous over loading capability in comparison to conventionally used mineral oil transformer [1]. The high interest on ester oil transformer has led to several analyses aimed at prediction of their dielectric and thermal analysis for the process improvement in the transformers. Therefore, the aim of this study is to design guidelines for the process improvement of ester oil transformers considering mineral oil transformer guidelines as the reference.

The verification and testing of insulation design are important for optimizing the material cost as it deeply affects the reliable performance of the transformer. The steady rise in the transmission level voltage ratings calls for higher voltage rated transformers, which in turn demands better insulation quality leading to higher cost allocation for transformer insulation [2]. Also, Insulation space have impacts on the quantity of oil used in transformer along with the price of active parts like the core and the copper used in transformer manufacturing. Keeping environmental ecosystem in mind, the transformer insulation which is primarily based from the wooden products, optimization of the transformer must be done. In addition to this, design engineers face new challenges with the higher MVA ratings of transformers which is reflected in the weight and size of transformers, causing this equipment to approach or exceed the allowed transport limits. Aforementioned explanations along with increasing competition in the market are accountable for persistent efforts being made to expand the insulating content effectively. This can be concluded the margin between the operating stress levels and withstand levels is diminishing. This draws attention from global academia and professionals, to research for accurate evaluation of stress levels at critical electrode configurations under different test conditions and voltage levels. The use of advanced computational tools such as finite element method (FEM) is turning out to be evaluative for accurate calculation of stress. Further, stresses levels are collocated with withstand capability which are recognized based on previously collected experimental data [3].

Mineral oil is considered to be the most commonly used coolant and insulating medium in transformer. The past studies show that liquid insulation system can be effectively used at or above voltage ratings of 1000 kV. Excellent dielectric strength of paper and pressboard impregnated with oil makes the mineral oil as the most important part of transformer insulation system. The non-hazardous dielectric and self -extinguishing properties of silicon-based oils have attracted the manufacturers to use these oils as replacement for Askarels [4]. Contrastingly, higher cost of silicon-based oils acts as a preventing factor for its widespread use. Also, super-biodegradable vegetables seed-based oils are gaining popularity in environmentally sensitive areas. The recent years have witnessed great technological advancements in gas immersed transformers. Sulfur-hexa Fluoride (SF_6) features high dielectric strength and is non-flammable. These properties of SF_6-Transformers make them the extremely advantageous in area where fire hazard is likely to occur. Also, specific gravity of SF_6 gas is less that results in reduced weight of transformers. The dielectric breakdown strength of SF_6 gas is positively related with the operative pressure; more the pressure, more will be the dielectric strength. On the other hand, thermal time constant and the heat capacity of the SF_6 gas are lesser than that of the transformer oil, which results in low capacity to withhold the overload conditions [5-7].

As a cooling and electrical insulation medium within the transformers, the oil can provide two features. Most transformers are traditionally used with mineral oil as an insulating medium. The petroleum originated mineral oil cannot be biologically degraded, and has a low fire and flash point. With strong requirement for fire safety, generators are now accessible with additional liquids such as natural esters.

To prevent catastrophic failure of a transformer, it is essential to monitor the condition of the paper. Measuring mechanical strength is the finest technology for determining ageing of the paper because this property is not affected by electrical characteristics. Paper samples from in-service transformers cannot nevertheless be obtained. Thus, the conditions of the paper by evaluating by-products of paper ageing by oil such as Furanic Compound Analysis (FCA) and Dissolved Gas Analyses (DGA) are determined using non-intrusive methods [8, 9].

The transformer life is considered to be depicted by the performance of its insulating paper. Several techniques have been created to depict the paper ageing, including intrusive and non-intrusive. However, the most precise depiction is renowned for intrusive techniques such as the Tensile Index (TI) and Degree of Polymerization (DP) tests. Paper samples for TI or DP measurement cannot be taken from the transformers which are still in operation and can only be taken by scrapping transformers. The layer profiles in the multilayer inter disc winding insulation in addition to conventional winding configurations have been analysed. The main focus has always been to determine the end-of-life assessment of the transformer. The dielectric properties of the scrap paper have been studied in addition to mechanical strength in attempt to check the impact of ageing on the dielectric strength of the solid insulation. Paper ageing produces various by-products like moisture, furanic compounds, methane and acids. The acids generated by oil are mainly low molecular acids (LMA) and that by the paper is high molecular acids (HMA). The process of ageing is being accelerated by the production of these acids. The study is needed to check the impact of the acids on the ageing of paper in mineral oil. The information about LMA's characteristics to remain in paper is a means of measuring the chemical property of the insulating paper of the scrapped transformer. This understanding can be utilized to determine the dispersion of LMA along the various layers of winding of the transformer.

The properties of different types of oils that has been utilized in the transformer application has been discussed below:

- Mineral Oil: The popular insulating oil used in a transformer is mineral oil. It consists of crude petroleum from vegetables stored and decayed, or water's effect on metal carbides. It is a complicated blend of carbohydrate and hydrogen with a little sulphur and nitrogen [8]. Mineral oil consists of various hydrocarbon kinds such as paraffins, naphthens, aromats and polyaromates. Paraffin hydrocarbons show a straight chain or branch setup, which is a significant variety in chemical properties unlike a cyclic form of the naphthenic compound. The paraffin composition is prone to water and sludge production oxidation products. It has a decent coefficient of viscosity. The naphthenic compound called cycloalkanes has a less temperature characteristic. The composition of the loop could be five, six or seven carbon. Ring buildings with double alternating bonds are aromatic molecules. They are completely distinct chemically and physically from paraffinic and naphthenic molecules. In its aromatic state almost all of the sulfur and nitrogen in oil are available. As monoaromates and polyaromates both, aromates may be available. There are several aromatic rings neighbouring to each other straight from Polyaromates [10]. Most mineral oils are saturated hydrocarbons with single C-C valence bonds. Carbon electrons are linked. The saturated compounds are more stable in chemical than the relevant unsaturated compounds.

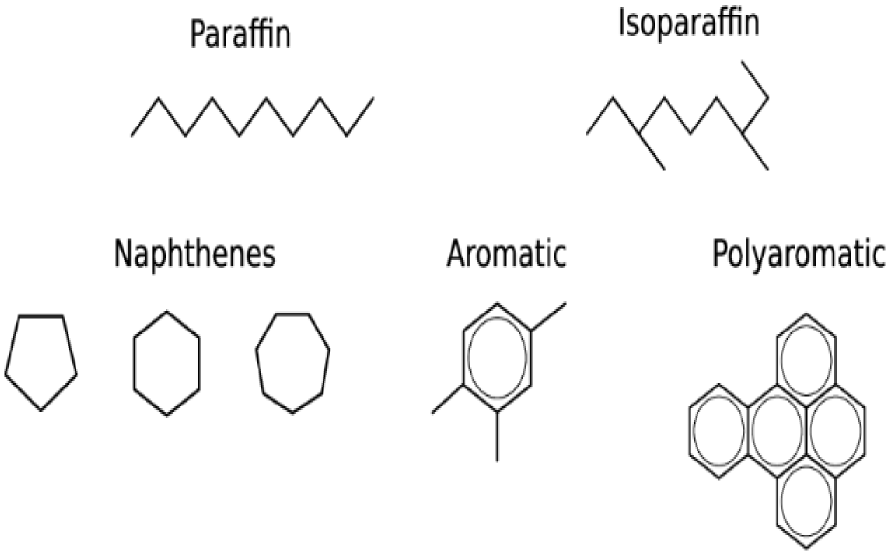

Fig. 1.1 Mineral Oil structure [8]

- Natural Ester: Glycerols and fatty acids recognized as triglycerides are natural esters. There are even numbers of carbon dioxide atoms in the fatty acid sections. This is a normal consequence of fat biosynthesis in which molecules are constructed at a moment of up to two carbon atoms at a time. The typical triglyceride structure in which groups (R, R′, R″) comprise of C8-C22 bonds is shown in figure 1.2. The transformer's natural ester is triglyceride fatty acid form. Linear strings 14–22 carbon lengthy, 0-3 double bonds are the elements of the fatty acids. Due to the composition of its molecule, natural ester could be oxidised or hydrolysed. Dual C-C valence bonds in organic ester might encourage oxidation while the COOH valence bonds might lead to hydrolysis [12, 13].

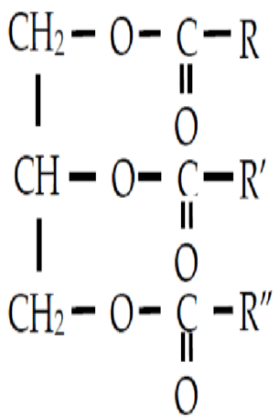

Fig. 1.2 Triglyceride structure [8]

DECLARATION

I hereby certify that the work which is presented in dissertation entitled, "**MATERIAL COMPATIBILITY AND THERMAL ANALYSIS FOR PROCESS DEVELOPMENT GUIDELINES OF 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 as authentic record of my own work carried under the supervision of Dr. Jeyabalan Velandy, Manager, CG Power & Industrial Solutions Ltd., Mumbai and Dr. Prasenjit Basak, Associate Professor, EIED . 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.

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1.2 NEED ANALYSIS

The insulating oil plays a significant role in determining transformer insulation performance and its characteristics. As ester oil is becoming increasingly popular as a potential alternative to mineral oil for transformer applications, therefore the proper assessment of the oil properties are required for designing an ester oil transformer. The need to carry out the project has been discussed in the following points:

- The compatibility of interior components used in transformer construction is conducted to ensure the right insulation performance. These tests are necessary as incompatibility of these materials with insulating oil might cause various troubles such as the rubber used in seals and gaskets may get deteriorated and lead to oil leakage.
- Due to more leakage current in the ester oil transformers, dissipation factor and insulation resistance characteristics are determined to design an insulating system for the ester oil transformers.
- The higher viscosity and density of ester oil with respect to mineral oil will increase the top oil temperature rise, winding rise and higher hot spot temperature at top of the winding.

The higher viscosities of ester oil would increase the impregnation time of solid insulation during transformer manufacturing time and reduce the cooling efficiency during the transformer operation at site. Therefore, it is still a technical challenge for ester oil to use in transformers. Hence, the purpose of this project is to design process guidelines, insulation and cooling arrangement for the ester oil transformers.

1.3 ORGANIZATION OF THE DISSERTATION WORK

Chapter 1- Introduction

This chapter provides the brief idea about the transformer insulations and their importance in the reliable operation of transformer. The various types of insulating oils used in the transformer are discussed in this chapter and their comparison has been done in order to highlight the need of using ester oil which is vegetable oil instead of using conventional petroleum based mineral oil.

Chapter 2 – Literature Survey

This chapter highlights the literature related to the compatibility check of transformer construction materials. Very less work has been done in this area as the project involves the compatibility analysis of ester oil filled transformers which is new in market and research is still going on in this area. Further based on the literature survey, various gaps that were present in the study are discussed, based on which the main objectives of the project are written.

Chapter 3 - Material Compatibility of Ester Oil Transformers

This chapter discusses the proposed methodology as specified in ASTM standards for the compatibility studies. List of materials and type of insulating oil used in the studies has been discussed in this chapter. Different types of tests being performed in order to consider the material compatible with particular oil has also been discussed in this chapter. The limiting criteria based on which material is said to be compatible or incompatible is given in this chapter followed by experimental result obtained and their practical implementations.

Chapter 4 – Insulation Resistance Testing of Ester Oil Transformers

This chapter gives the importance of carrying out insulation resistance testing of transformer winding. It discusses the methodology, results and practical implementations after doing Insulation resistance and capacitance/dissipation factor testing of the winding immersed in different insulating oils.

Chapter 5 - Thermal Analysis of Ester Oil Transformers

This chapter provides the importance of thermal studies for designing cooling and insulation arrangement for the transformers filled with ester oils. Ester oil due to its more viscous nature, takes time to dissipate the heat and temperature increases as compared to mineral oil. Therefore, simulations have been performed to check the changes in the ester oil transformers with respect to mineral oil transformers.

Chapter 6 – Conclusion

This chapter gives the summary of the work being carried out in the dissertation work. It presents the need of the work done in future. This chapter also discusses the work planned throughout the dissertation followed by the list of achievements/ publications, references and plagiarism report.

CHAPTER 2
LITERATURE SURVEY

2.1 INTRODUCTION

One of the fundamental insulation materials for oil-filled transformers are paper and pressboard. The benefits of these materials is their excellent electrical and heat characteristics. The winding conductors are generally covered with paper to provide inter-disc and inter-turn insulation. It is well recognized that a collapse at a reduced voltage may happen under a large oil gap as there is a strong probability that the weakest point is found and this effect is generally called volume effect. Pressboard is used to split oil quantities into narrower oil spaces as a spacer and obstacle to improve oil's dielectric strength. If a flash happens in an oil gap since the voltage is removed from the remaining oils gaps, a complete failure may be prevented [11-14].

The insoluble impurities like sludge could collect and prevent oil stream that could eventually encourage hotspot and boost the paper's ageing rate. Due to the properties like water scavenging and hydrolytic protection of the natural ester oils, the rate of ageing of paper is slow as compared to the mineral oil. However, the strength of natural ester is small in oxidation, where physical and chemical properties can alter under severe conditions and impact its efficiency as an insulated fluid [15, 16].

In this section, a brief study of various material compatibility tests being performed on various transformer insulating oils like dielectric strength, resistivity, dissipation factor, moisture, interfacial tension, dissolved gas analysis (DGA) and the effect of ageing of materials has been presented. After that the thermal performance of transformer, the concept of heat dissipation and the cooling methods to dissipate heat for reducing hotspot temperature of the transformer has been discussed. In the later stage, this chapter includes the various research gaps based on the previous work done and then discusses the objectives of the study.

2.2 COMPATIBILITY STUDIES OF TRANSFORMER

The main aim towards the material compatibility studies is to predict the behaviour of various transformer construction materials like pre-compressed board, insulating glue, wax, insulating papers such as thermally upgraded paper, nomex paper, crepe paper etc., nuts and bolts with the ageing of oil or in order words how these materials behave when come in contact with the insulating oil [8, 9].

It is necessary to determine their nature in contact with oil as it is the foremost criteria towards setting up the design guidelines for transformer manufacturing. If a material that is found to be incompatible, used in transformer that may result in disastrous effects. Incompatibility may lead to the reduction in breakdown voltage, increase number of faulty gases that in the long run may prove fatal for the transformer applications.

In [7], it is given that as age of transformer increases, its mechanical, electrical and chemical properties get affected. There are two ways to determine the mechanical strength of the insulating oil, they are degree of polymerization (DP) and tensile strength (TS). These properties cannot be defined for on-site transformer therefore; they do not give the true measure of transformer life. The withstand capability or dielectric strength of the insulating oil is considered to be a true measure to validate the age of the transformer. LMA, a chemical property is a clear indicative for the life assessment of the transformer.

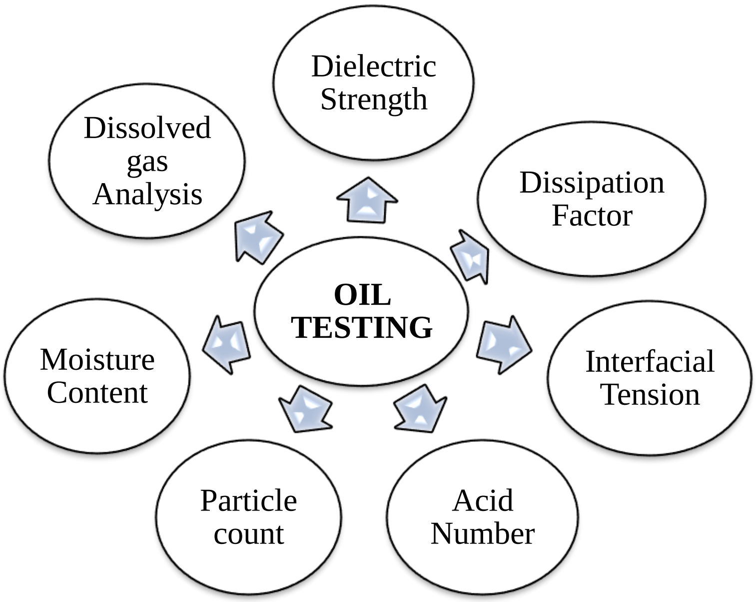


Fig. 2.1 Various Tests for Oil

To determine the breakdown voltage of the insulating oil under high voltage applications. Voltage is increased at the rate of 2 kV/s till the breakdown occur and the average of six readings is taken as final BDV [10, 11]. Dissipation factor test is performed to the dielectric losses in the oil at 90°C. The degradation of both oil and the solid insulation is mainly affected by the presence of moisture content in the oil [12, 13]. Karl Fischer method in which iodine solution reacts with water in the oil is used to calculate the ppm level. IFT is the measure of hydrophilic materials present in the insulating oil that may affect the chemical, physical and electrical properties of the oil [14, 15]. The presence of particles of different sizes affect the electrical properties of the oil, therefore particle count test is performed to determine the oil condition after conditioning. Total acid number is calculated used potentiometric method, in which the volume of KOH (potassium hydroxide) required to attain certain pH value, as per the standards 10 pH is attained for the sample [16, 17]. Color test is used to see the change in color of the oil in contact with a particular material. This setup works on Gardener scale that changes color from light brown to dark brown [18, 19]. DGA is an important test in the determination of amount of various gases present in the oil that may lead to severe faults in the transformer. Based on their amount present in the oil, severity and type of fault can be predicted and the risk of transformer failure can be avoided [20-23].

2.3 EFFECT OF AGEING ON TRANSFORMER PERFORMANCE

2.3.1 Ageing of cellulose

The anhydro β-D-glucopyranatic components in cellulose are connected to each other. A glycoside oxygen linkage, one of the parameters contributing to the mechanical strength of the paper, connects the repeating unit of the glycoside [24]. The glucose circle is linked to a cellulose fiber via the hydroxyl groups. 90% cellulose, 6-7% hemicellulose, lignin and pentosane are used in insulating papers. As it has more rate of polymerization of 2000, alpha cellulose is usually used as the primary source of cellulose. If the hemicellulose concentration in paper is greater than 10%, the tissue resistance will be impacted. For additional force and flexible, lignin offers more flexible fiber binding [13-17]. The paper is mostly produced of soft wood because its flexibility and strength are higher than hardwood. In addition, softwood has far more fiber than hardwood. Fiber is obtained from multiple units, consisting of amorphous and crystalline-associated cellulose [14]. The different types of insulating papers used in transformer applications has been described as follows:

a) Kraft Paper

Kraft paper is produced by the sulfate process from unbleached softwood pulp. A paper which is mildly alcaline because of the sulphate contents produced as a consequence of this method. Depending on the maker the method of producing paper varies. The paper's performance and accuracy rely on the sort of production method [15]. The overall operation begins with the production of a frozen fiber wood pulp mat. Next, a big quantity of water has been blended with the pulp paper to eliminate any residual chemical residue. Further, the moist fiber is crushed, leading to' hydrogen bonding' between cellulose molecules [8], which leads to a refining procedure. In cellulose products, hydrogen bonds are generally linked to the electronnegative nucleus by binding hydroxyl group (OH). Hydrogen bonds between bones or between fibrils do not generally differ with hydrogen bonds between cellulose. All chemical or physical waste that may occur during the refining phase will not be eliminated by extensive washing of sophisticated fiber. The final stage is to translate the cellulose and water combination into a paper on the spinning cylindrical device. The heat and strain in the process of progressing to the roll [8] can be used to control the size, thickness and humidity of the paper.

b) Crepe paper

Creped document is one of the oldest papers for unique purposes. It is manufactured by uneven near crimping, which improves its frame density and device extensibility. The link guide or electrostatic load control bands are normally used. It can be extended to allow the paper on the uneven outline to be used. The drawback of the crepe paper is that it loses its extensibility over moment and may lead to the loss of some of the link or joints embedded in this paper and not the tightness of its application [14, 15].

c) Thermally upgraded paper

The thermally upgraded document is another form of special purpose paper. It is produced by incorporating stabilisers that improve its strength in temperatures and reduce thermal degradation. Through this method, the cellulose OH groups connect to the cyanoethyl-ethyl ether clusters. Another way to eat water and neutralize oils produced from oxidation of oil and fabric is by adding fragile organic bases, such as dicyandiamide, urea or melamine during production. Thermally upgraded paper has as its primary purpose to speed down the ageing process and increase the transformer's maximum operating temperature [15].

d) Diamond dotted paper

For implementation where elevated mechanical strength is required, diamond spotted paper is used. The paper is produced with thermo-resin by covering the ordinary kraft paper and then curing the resin subsequently. The diamond pointed form comes from pre-coated paper in a diamond structure with two phases of resin. The diamond-painted resin produces a wide binding layer that allows paper to be washed and oil-impregnated efficiently [15].

2.3.2 Paper ageing accelerators

The presence of moisture, oxygen and acids form the major parameters for the paper degradation as shown in Figure 2.2.

The detail study about the effect of the paper ageing parameters on paper degradation has been discussed below: -

a) Water

Paper degradation rates with a weight of 4% of moisture are 20 times greater than wet paper degradation level [20, 21]. The ageing test was carried out at different temperatures of 60°C to 130°C, with a control of 0.47% of original paper moisture contents, 1.11% and 1.92% by weight [59]. The ageing level rises with the original increase in paper moisture content between 0.47% and 1.92%.

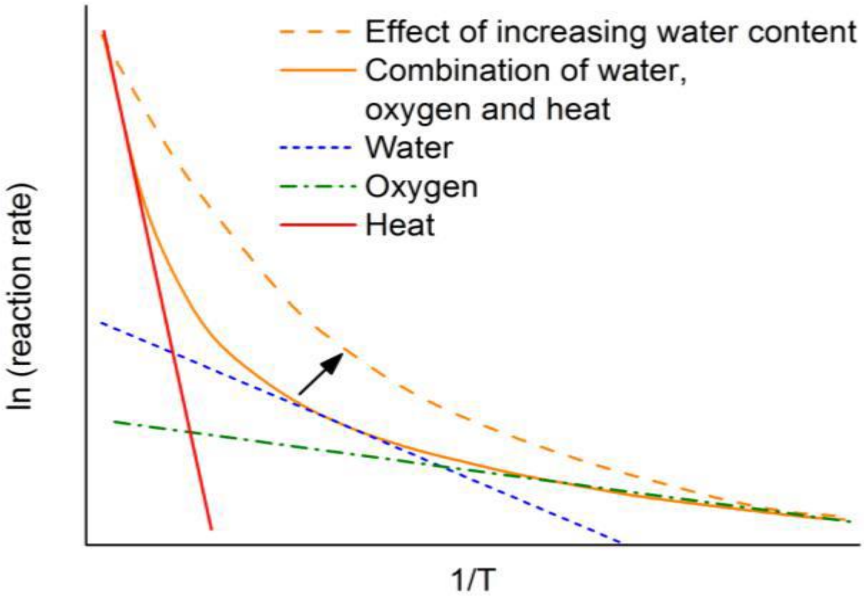


Fig. 2.2 Paper ageing with time [8]

b) Oxygen

If the system's oxygen can be lowered from 2000 ppm to 300 ppm [20], the ageing rate will be lowered by a change of 16. Other trials have found that oxygen can boost the ageing level by 2.5 for paper of 0.3 to 5% moisture level. With the existence of copper that might accelerate the oxidation of the paper, the ageing rate will increase more [20, 22]. Different oxygen conditions were introduced over the oil layer in the cans to monitor the impact of various amounts of oxygen current during ageing. In order to maintain the pressure throughout the ageing experiment, the bottles have been pressurised at a certain interval (initially once per day and later less frequently). The ageing speed rises with the growing amount of oxygen can be seen.

c) Combination of water and oxygen

The mixture of water and oxygen decrease the level of paper ageing at small temperatures. This reduces the response between water and cellulose by the hydrogen bonding water and oxygen to produce a protective impact [20]. The inhibitors impact of oxygen could be greater at work levels of a transformer and the oxygen material in the oil might be increased, which could effectively decrease the ageing level by avoiding that water in oil migrates to paper [20].

d) Acids

The degradation level of paper relies on the acid separation rate [18]. The rate of dissociation relies on the dissociation capacity of certain acids such as LMA [17]. The dissociated acid raises the H+ level in the scheme and speeds up the document depolymerisation method. By dissociating the carboxylic acids, water might assist to raise the concentrations of H+ [18].

2.4 THERMAL PERFORMANCE OF TRANSFORMER

The production of a transformer specification requires a general knowledge of the different types and the solutions that are in common usage. While some decisions are purely dependent upon end-user requirements, others may depend upon on the internal transformer properties, or are obtained from National and International Standards. It is therefore important to understand the main transformer parameters and the Standards that regulate them [24].

The main parameters that will define a transformer and which should be specified by the customer are:

- Installation altitude above sea level: The normal service condition relating to altitude is height above the sea level not exceeding 1000 m. Installation at higher altitude effects both the cooling and dielectric performance and must be considered in design.
- Temperature of ambient air or cooling medium: Normal service conditions are defined by a multiplicity of ambient air or ambient water temperature limitations.

Where air is the heat dissipation medium, the defined limits for temperature are between -25°C to 40°C. The monthly average of the hottest month should not exceed 30°C. Local ambient temperatures less than the normal minimum will require particular attention in respect of some construction materials [25, 26]. Temperatures in excess of any upper limits will require a level of thermal compensation to be built into the design.

2.4.1 Concept of heat dissipation

The heat produced in a body is dispersed to the environment and the surrounding air. The use of the word ambient temperature in an electrical circuit is comparable to the reference point. With reference to radiation, the air pressure and the ground on which the energy is radiated by the hot bodies are the standard temperature. The ambient temperature is the temperature of the bulk of the air too far away to be affected by the thermal field in other forms of heat dissipation like conduction, natural and artificial convections. Only when most heat is dispersed through convection, like in transformers, is the use of ambient temperature. In each case the body's heat is dissipated by one or more possible methods of heat dissipation, namely conduction, convection and radiation, to the surrounding medium [26-28].

- Conduction: It can be described as the transition of energy due to the difference of temperature when the bodies are in contact to each other.
- Convection: Because of the circulating fluid flows from one region into another, convection can be described as heat transfer in the gas or liquid.
- Radiation: The ignition and distribution of electricity in the shape of electrons or clouds may be specified as thermal radiation.

Newton’s Law of Cooling: Losses are generated in different parts of electrical machine, as the heat of the device is increasing. The heat generated in the device is equivalent to the heat that leaves its bottom by convection and radiation, and the device then continues to maintain a constant temperature. This is called the Newton’s law of cooling. This is another way of preserving energy.

2.4.2 Heat dissipation in transformers

The energy produced in different components of the transformer is dispersed in different steps into the environment. The production of heat takes position mainly in the transformer core and windings and this heat must be transmitted first of all to the outside ambient. In the core and windings, the heat transfer is conducted from the core to the oil. The thermal transition inside the oil is by convection, and the thermal transport is carried through conduction between hot oil and the thermal exchanger. When thermal conversion is carried by the insulating paper, because the interaction with the hot surface is uncommon, the distribution of energy primarily depends on the circumstances of the oil flow, i.e. whether the flow is steam line or turbulent and on the situation of the surface. The coolant has a much lower heat conductivity than the metallic parts. The transformer reservoir also partially dissipates the radiation-generated energy in addition to being absorbed with the thermal exchanger sides. Radiation in the transformer usually does not happen alone, and is followed by convection in almost every situation. Because dark metal designs trigger more radiation, all the electrical devices generally have a gray color painting with dark shiny designs in attempt to decrease the temperature increase by big thermal dissipation [27, 28].

During transformer operation, the bottom oil temperature is less as compared to top oil temperature which leads to non-uniform distribution of heat transfer across the transformer winding discs. This energy in the water must be drained by internal instruments and chilled water returned to the transformer. There should be no humidity or gasses entering the transformer. This causes it a significant problem to cool the transformer. Depending on the amount of heat that is to be processed, various heating techniques are used with appropriate heat exchangers.

- Oil Natural Air Natural (ONAN) Cooling: The natural heat produced by convection in the air produces heat movement in the oil. The hot oil at the top of the tank is distributed via pipes, which cool down around the pipes, straight down to the underside of the tank. The use of radiators and fins can improve the cooling of the transformer.
- Oil Natural Air Forced (ONAF) Cooling: The thermal transfer between hot oil and the colder environment through the thermal pipes for large transformers where the power supplied by the water is large can be increased by way of the water explosion obtained from the vents. They push water across the hole, push out the warm air and sweep in colder oil and thereby make heat exchange between the oil and the internal water more efficient.
- Oil Natural Water Forced (ONWF) Cooling: The oil can be cooled via the radiator pipes instead of using an aerial squeeze, because water is more efficient energy transfer medium but only when there is an availability of natural water head is present. For transformers in hydro-power plants, this technique is less expensive and effective.
- Forced and directed oil cooling (zig-zag cooling): The normal flow of air is inadequate in large transformers to cool the transformer and it is used forcibly. The oil guiding washers are also used to guide the oil flow in oil ducts, which guarantee a faster and more effective transmission of heat from the windings into the oil. Therefore, depending on the transformer loading, the selection of cooling arrangement is selected.

2.4.3 Consequence of heat build-up

Heat build-up in the transformer can cause the following undesirable consequences:

- Solid insulation of the windings gets deteriorated which causes short circuit.
- With heat, electrical properties of insulating oil get affected damaging insulation quality.
- Gases are generated due to dissociation of chemical bonds of the insulating oil.
- The pressure inside the tank increases and may cause even explosion with excessive increase in heat.
- Chances of transformer failures due to explosion.
- Thermal and electrical properties of the transformer parts may change.

2.5 ESTER OIL AS AN ALTERNATIVE TO MINERAL OIL

Now-a-days technology is switching towards renewable energy resources, similarly research is going on for a new transformer insulating oil that is biodegradable and gives more fire safety to both person and equipment. Ester oils are coming in latest trend and possess various advantages as an insulating oil over mineral oil used in transformers [6, 11-13]. Ester oil have the following advantages over the mineral insulating oil;

- Ester oils are proved to be 99% biodegradable whereas mineral oil is only 28% biodegradable.
- Ester oil have more fire point than petroleum based mineral oil which increases the overloading capacity of the transformer.
- Mineral oil transformers burn as an explosion giving no time to operate the shutdown switch whereas in case of ester oils, person have the time to manual shutdown the plant saving the life of people as well as equipment.
- Due to more viscosity, around 5% noise reduction is there in case of ester oil transformers as compared to mineral oil transformers.
- Ester oils have high water saturation level, i.e. they can hold more moisture as compared with mineral oil, therefore don’t allow moisture to penetrate into the solid insulation, hence increasing the life of the insulation and the transformer.
- Due to more thermal stability, clearances required between the transformer winding and insulation arrangement is less in ester oil transformers, resulting in the reduction of transformer size.

Despite various advantages, Ester oil have certain disadvantages like less oxidation stability because of which ester oil transformers are prescribed to be used under sealed conditions as ester oil gets oxidized easily in contact with oxygen. Research is going on to increase the oxidation stability of ester oils.

2.6 GAPS IN RESEARCH

The work discussed so far includes the testing of transformer construction materials with mineral oil. Following are the gaps or the less explored areas in the field of designing process guidelines for manufacturing transformers are:

- Compatibility of transformer construction materials with natural and synthetic ester oils.
- Compatibility of solid insulating materials have been focused in the literature, and very less literature is available on liquid insulating materials.
- Effect of ageing on breakdown voltage, dissolved gases and acid number of transformers insulating oil.
- Method to improve thermal performance of the ester oil transformers is still a part of ongoing research.

2.7 OBJECTIVES OF STUDY

The main goal of this project is to set process guidelines for ester oil filled transformer using the material compatibility and thermal modelling. Based on the gaps in research, following objectives have been set for the project:

1) Compatibility analysis of ester oil with transformer construction materials for the development of process guidelines of ester oil transformers.
2) Prediction of generation of gases in ester oil to avoid misleading results in the transformer.
3) Prediction of winding strength through insulation resistance and dissipation factor testing of the transformer and finding out the ways to reduce leakage current in the ester oil transformer.
4) Thermal analysis of ester oil transformer windings for designing insulation and cooling arrangement.

CHAPTER 3
MATERIAL COMPATIBILITY OF ESTER OIL TRANSFORMERS

3.1 INTRODUCTION

Insulation design is an integral part of transformer manufacturing. Particularly, in case of high voltage transformers, insulation design becomes a critical factor ensuring the desired operation of HT transformers. The quality and reliability of transformers weigh heavily on controlled manufacturing processes, good design practices and the use of proper insulating materials. The verification and testing of insulation design are important for optimizing the material cost as it deeply affects the reliable performance of the transformer. Broadly, insulation in any power equipment can be solid, liquid or gaseous [1-3]. Insulating oil in transformer application plays dual role; one as insulating medium and other as a coolant. Conventionally, mineral oil is used in the transformers but now-a-days ester oil have gained importance in the transformer insulating applications due to their higher fire point, better thermal performance, and biodegradability [1, 4-7]. It is necessary to determine the nature of transformer construction materials in contact with the new insulating oil as it is the foremost criteria towards setting up the process guidelines for transformer manufacturing.

Compatibility between the materials used in the transformer manufacturing such as varnishes, insulation paper, paint, gasket, core etc. and ester oil must be taken into account for selection of suitable materials and also for setting up the process guidelines for ester oil transformers in the real operation to maintain its reliable operation. If a material that is found to be incompatible, used in transformer that may result in disastrous effects. Incompatibility may lead to the reduction in breakdown voltage, increase number of faulty gases that in the long run may prove fatal for the transformer applications [8-11].

In this chapter, effect of liquid insulation with the various transformer construction materials has been discussed and the results can be used as the base guidelines by transformer manufacturers using these liquids. This study is expected to help in making right choice of materials of construction of transformer besides helping to reject non-compatible materials.

3.2 EXPERIMENTAL SETUP

Compatibility studies of transformer construction materials are considered to be an important parameter in assessing the transformer performance during both normal as well as abnormal conditions. If a material that is not compatible with the insulating oil, it would lead to severe faults and in the later stage can damage the whole transformer. Transformer, being considered as the heart of the power system, must be properly designed and maintained for the safe and reliable operation. Detailed method as described in ASTM D3455 has been followed for testing compatibility [29, 30]. Briefly, the procedure involves the preparation of test specimen for testing and then keeping the sample in contact with the oil for 164 hrs and then performing tests on the sample specimen and the oil. Corresponding blank experiments are carried out wherein the oil is aged without material. In addition to all the electrical tests mentioned in the standards, DGA has also been performed in this study in order to determine the extent of gas generation in different oils when they are aged in contact with a particular material. This is an important parameter since it can separate fault gases in a transformer from those generated because of material plus oil alone. Figure 3.1 shows the flow chart for the procedure followed for material compatibility. Following sections discuss about the detailed procedure and corresponding tests to be done for deciding compatibility status of a material.

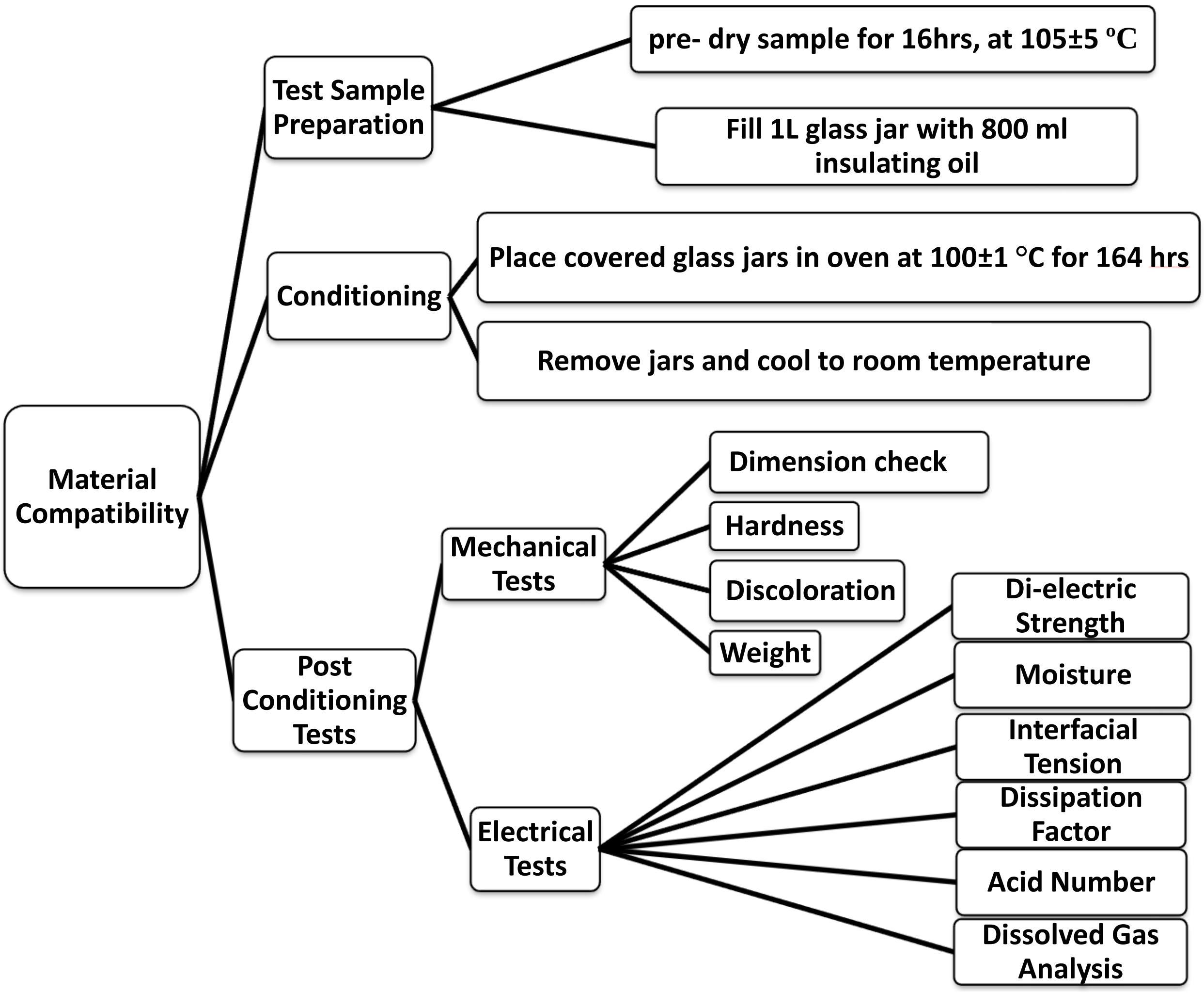


Fig. 3.1. Flowchart of material compatibility test procedure

Table 3.1: List of transformer construction materials considered for compatibility testing

Sr. No.	**Material**	**Application in Transformer**
1	Core laqor	Insulation at core edges
2	Silphos rod	Used for coil support
3	Paper on Conductor	Paper on winding conductors
4	Fiber glass rod	Used for coil support
5	Thermally upgraded paper	Paper on winding conductors with more thermal stability
6	Wax	Insulation to frame structure
7	CT cloth cover	Used in CTs in bushings
8	Perma wood	Mechanical support on which Core coil assembly is fixed
9	Loctite	Adhesive used for fix insulating paper on conductors
10	Radiator Paint	Used for painting tank
11	Diamond Dotted paper	For winding insulation (dry type transformers)
12	Fiber glass tape	To keep core stacks together
13	COPS Bag	Air bag in conservator for transformer breathing
14	Nomex Paper	Providing insulation between the windings and between winding and frame
15	Pre-compressed board	High density board for providing electrical insulation
16	Haldoo wood	Provides mechanical support to core
17	MS Stopper	Used as frame support
18	Insulating Tape	Tape to provide mechanical support to the windings
19	Cotton Tape(B)	Used in joints, high insulation applications
20	Cotton Tape(A)	Used to tightening core coil assembly
21	Crepe Paper	High tensile strength paper used in irregular bends
22	Crepe Paper Tube	Used to insulate lead terminals
23	Teflon washers	To avoid oil leakage at high temperature
24	Edge strip paper	For providing mechanical support to the conductor
25	Nitrile Damping Washer	Gaskets to avoid oil leakage
26	Gasket	Gaskets to avoid oil leakage
27	Oil gauge glass (MOG)	showing oil level in conservator tank
28	Blackodised HT Bolt	Used for tightening frame parts
29	HDG Fastener	Used for tightening frame parts
30	ZPP Fastener	To tighten transformer tank
31	SS Bolts	Used for tightening frame parts

3.2.1 Types of insulating oils and transformer construction materials used for testing

The main aim is to study the material compatibility to predict the behaviour of various transformer construction materials like kraft paper, CT cloth cover, nitrile damping washer, fiber glass rod, insulating tape with the insulating oil.

The three insulating oils (mineral oil, natural ester and synthetic ester) having different physical, chemical and electrical properties have been used. Mineral oil having petroleum-based origin contains a mixture of paraffinic, naphthenic and aromatic compounds. Ester oils can be classified as natural ester oil (originated naturally from vegetable seeds) and Synthetic ester oil (synthetically processed with acids). Considering mineral oil as the reference, natural ester and synthetic ester oils have been compared for the transformer applications. The list of transformer construction materials along with the respective application in transformers has been given in Table 3.1. The compatibility results are of general applicability and may be used for any electrical insulation applications to avoid failures.

Table 3.2: Limits of ester and mineral oil before and after the tests

Property	**Limit (Ester oil, ASTM D6871)**	**Limit (Mineral oil, ASTM D3455)**	**ASTM method**
Color	1.0	0.5	D 1500
Fire point, min ºC	300	155	D 92
Flash point, min ºC	275	145	D 92
Pour point, max ºC	-10	-40	D 97
Density 92ºC(kg/m³)	960	875	D 1296
Moisture saturation, 20 ºC	1100 ppm	55 ppm	D 1533
Acid Number, mg KOH/g	0.06	0.03	D 974
Viscosity (40 ºC)	30	9.2	D 445
Dielectric breakdown Voltage (kV) At 50 Hz	>75	>70	D 877
Dissipation factor 25 ºC	0.2	0.001	D 924
Resistivity 10^12 Ω-cm	20	200	D 924

3.2.2 Preparation and conditioning of test specimen

The insulating oil used to carry out compatibility testing should be processed properly to meet the respective limits given in Table 3.2 for mineral. The testing is done to replicate the real transformer in operation, therefore the ratio of material to oil should be taken as per the real transformer.

The material used should be clean and dry. The following steps were followed for Preparation of test specimen and its conditioning [29]:

1. Preconditioning of test specimens at 105 ± 5 ^{0}C and 10 mbar vacuum for 16 hours to remove the surface moisture and preserved in vacuum desiccators.
2. Drying Glassware at 120 ± 1 ^{0}C for 5 hours and preserving it in vacuum desiccators.
3. Nitrogen through oil is being bubble dried for 10 minutes and the glass jars are then covered and placed in oven at 100 ± 1 ^{0}C for 164 hours.
4. After taking the glass jars out from the oven, the tests on insulating oil and test specimen are being performed.

3.2.3 Post Conditioning Tests

After the preparation of test sample and its conditioning, sample is taken out from the glass jar filled with oil, using a pair of tongs. Then tests are performed on the insulating oil and on the transformer construction material used in a particular compatibility experiment.

The two types of tests are being performed: one on the insulating oil and other on the construction material [26-28]. They are defined as follows:

a) Electrical Tests: The changes in the oil properties are considered to be an important deciding parameter for determining the compatibility status of the oil. The properties of oil such as its breakdown strength, dielectric losses, presence of polar contamination, moisture, acid and stray gases before and after the conditioning are determined.

    - Dielectric Breakdown Voltage (BDV): The withstand strength of the insulating oil when high voltage is applied across it define its dielectric breakdown strength (kV). It provides the information about the presence of moisture and other oxidation products produced as a result of any chemical instability between the material and the oil [31, 32].
    - Dissipation Factor: This test is done to determine the dielectric losses due to leakage current through the oil deteriorated its dielectric properties. Dissipation factor (in %) and resistivity (Ω-cm) of the oil is evaluated during this test. More value of dissipation factor indicates more losses, more resistivity means a smaller number of free electrons resulting in lower losses [33, 34].
    - Interfacial Tension (IFT): It defines the presence of hydrophilic particles in the insulating oil which results in its degradation in terms of its chemical, physical and

electrical properties resulting in reduction in BDV, more dielectric losses [35, 36]. It basically measures the force required to pull platinum ring from oil layer upward which is floating at the top of the water layer. It is expressed in mN/m.

- Acid Number (NN): Neutralization Number (in mg KOH/ gm) also termed as Acid Number is the evaluated as the amount of potassium hydroxide solution (KOH in mg) required to neutralize the amount of acidic content present in the insulating oil [37. 38]. More the amount of KOH utilized to neutralize the solution, more will be the acidic content present in the oil due to the presence of contaminants with the ageing of oil in contact with the construction materials.
- Color: The changes in the color of oil before and after its conditioning is one of the parameters analyzed during compatibility studies. The color change can be seen with naked eyes otherwise various instruments are also available to determine the change in color [39, 40].
- Dissolved Gas Analysis (DGA in ppm): Gases are evolved due to the breakdown of insulating materials inside the transformer. The dispersion of such gases indicate the nature of electrical fault, and the fault severity can be further determined through the rate of gas generation. The information regarding the gas generation proves to be an important measure to avoid the risk of transformer [41, 42]. In the material compatibility, DGA is not the deciding parameter for determining the compatibility status rather it proves to be a supporting test used to determine the rate of generation of gases in the insulating oil in contact with a material. If the rate of generation of gases is more, chemical composition of the material along with the other material and oil properties are thoroughly revised to avoid the transformer failure in the long run [43, 44].

b) Mechanical tests: The transformer construction materials used in the transformer should be compatible with the insulating oil. Along with checking the oil parameters, material properties are equally important to avoid the transformer failure. Any changes in the material dimensions beyond the acceptable limits are not preferred for the transformer applications. Therefore, following tests are performed on the materials before and after the conditioning and are compared to determine the change [29].

- Swelling or Dimension Change (in mm): Length, width, thickness and weight of the test sample should be checked before and after the conditioning.

- Hardness check (in shore): Hardness should be checked and the material before and after the conditioning should maintain the same hardness level.
- Discoloration: Test sample must maintain almost the same color before and after the conditioning in order to complete the compatibility test with the transformer oil.
- Brittleness: Some materials become brittle after conditioning due to their long contact with the insulating oil. This should be carefully checked in order to declare the material compatible.

If both Oil and material parameters are within the limits as given by ASTM D3455 (for mineral oil) and ASTM D6871 (for ester oil), then that material is said to be compatible with the insulating oil. Experiments are carried out in triplicate to declare a material to be compatible or incompatible. Blank experiments are carried out for each oil wherein the oil is aged for 164 hours without any material. Ideally, for a material to be compatible, the oil parameters aged in material should not be very different from the blank values. However, the oil to material ratio and its exposure to oil in actual transformer should be taken into account and allowances may be made accordingly to oil parameters. Judgments on specific material compatibility will be based on the considerations explained as above.

3.3 RESULTS AND DISCUSSIONS

Electrical and mechanical tests are performed to evaluate the compatibility status of transformer construction materials with different insulating oils. The results of individual tests have been discussed in this section and a comparative result are reported for different oils. The basic guidelines on which the compatibility decision is taken are to check the dimensional changes in the material before and after its ageing with insulating oil followed by analysing the corresponding changes in oil properties. After analysing all the properties, if changes in two or more properties exceed the limits as mentioned in Table 3.3, then the material is declared as incompatible. Detailed interpretation of experimental data for kraft paper and nitrile damping washer has been shown in Table 3.4 which, on the basis of percentage change in the oil and material properties before and after conditioning, decides the compatibility status of a particular material.

Other materials such as CT cloth cover, fiber glass rod and insulating tape give unsatisfactory results in case of esters as compared to mineral oil. However, the weight to volume ratio of these materials to oil in the transformer is very small. Therefore, their effect can be neglected in transformer applications but should be taken into consideration for the applications where ratio of these materials in contact with oil is more. For example, in case of transformer applications, quantity of CT cloth cover used is very small but in case of CTs in which the cloth quantity used is larger, this material should be replaced with other material that is compatible with the ester oil in order to avoid transformer failure [2-7, 11-17].

Table 3.3: Compatibility limits for oil properties

Sr. No.	Oil Properties	Permissible limits
1	Dielectric strength	28 kV min
2	Dissipation Factor	1.1% max change
3	Interfacial Tension	38 mN/m min
4	Acid Number	0.03 mg KOH max change
5	Color	0.5 max change

The considerations applied for deciding on compatibility is presented here taking nitrile damping washer and kraft paper as an example. For kraft paper, the dimensional changes are in the range 0.2% - 1% which is almost negligible in case of transformer applications. But in case of Nitrile damping washer, the percentage changes in the dimensions are in the range of 0.7% - 18% which cannot be neglected. Further, it can be observed that for mineral oil these changes are negligible 0.7% - 1% as compared with ester oils in contact with nitrile damping washer.

After checking the material properties, oil properties in contact with both the materials are analysed. It has been observed that there is significant increase in dissipation factor, acid number, DGA and decrease in dielectric breakdown voltage, interfacial tension for nitrile damping washer whereas these changes are negligible for kraft paper. Considering the changes in material and insulating oil properties compatibility status of a material is determined. Based on the results, kraft paper is declared as compatible for all the insulating oils and nitrile damping washer as incompatible with ester oil whereas found to be compatible with mineral oil. Similar criteria are followed for deciding compatibility of other transformer construction materials in contact with an insulating oil.

The quality of nitrile rubber gasket is critically dependent on the composition of the polymer. Normally the acrylonitrile (ACN) content varies from 15% to 50% in the polymer. The higher the ACN content, the higher the resistance to oil. The mechanical properties like compression set, hardness improve making it suitable as a gasket for systems where oil is in contact. The supplier needs to carefully optimize the composition to suit each application need.

Hence the quality of the gasket can vary significantly from vendor to vendor. Therefore, gasket from every vendor has to be evaluated carefully to determine suitability and compatibility with oil. If the quality is not right, resistance to oil will come down causing swelling and abnormal dimensional changes. From the unusually abnormal dimensional changes (35% change in weight) as observed in the Table 3.3, it appears that the vendor has supplied a bad quality of gasket. Therefore, the chemical composition of the materials to be used must be properly observed to get accurate compatibility results and hence avoiding transformer failures.

A detailed description along with the graphical representation of the various tests involved to predict the behaviour of an incompatible material is discussed below taking nitrile damping washer as an example. Further, the increment percentage in the oil parameter for all the three insulating oils is also compared to decide the best suitable oil in a transformer.

a) Dielectric Breakdown Strength (in kV): The breakdown strength of insulating oil is indicative of the voltage withstand capability of the insulating oil under high voltage application. Insulating oil in contact with an incompatible material may contain certain dissolved impurities which can affect dielectric strength of the oil.

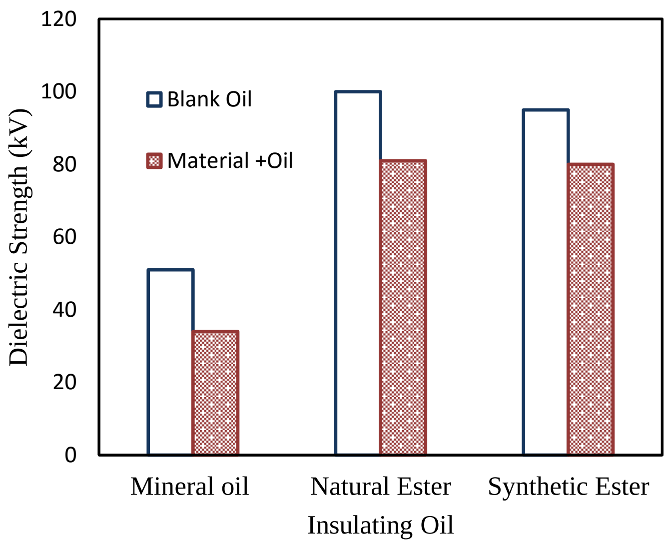


Fig. 3.2. Change in dielectric strength of insulating oil

From Figure 3.2, following conclusions for nitrile damping washer can be drawn:

- Dielectric breakdown strength of mineral oil is less than that of the ester oil
- For mineral oil, there is around 10% decrease in breakdown voltage.
- The percentage changes in breakdown strength in case of natural and synthetic ester oil are 19% and 15% respectively.

Therefore, the change in breakdown strength of nitrile damping washer are more in case of ester oil as compared to mineral oil.

Table 3.4: Analysis of results obtained from compatibility testing

Tests on oil and material	**Mineral oil**			**Natural ester oil**			**Synthetic ester oil**		
	Blank oil	**Kraft paper + oil**	**Nitrile Damping washer + oil**	**Blank oil**	**Kraft paper + oil**	**Nitrile Damping washer + oil**	**Blank oil**	**Kraft paper + oil**	**Nitrile Damping washer + oil**
Dielectric Strength (kV)	51	45	34	100	92	81	95	90	80
Dissipation Factor (%)	0.019	0.02	0.02	0.38	0.4	0.84	0.69	0.72	0.77
Interfacial Tension (mN/m)	43	40	38	24	23	22	29	26	25
Acid Number (mg KOH/gm)	0	0	0	0.06	0.06	0.06	0.029	0.042	0.088
Color	0.5	0.5	0.5	0.2	0.2	0.2	0.5	0.5	0.5
DGA (ppm)	0	1	2	11	21	95	1	2	3
% change in Length	--	0.7	0.8	--	0.5	6	--	0.3	7
% change in width	--	0.6	0.7	--	0.4	4	--	0.2	6
% change in thickness	--	0.6	3	--	0.5	18	--	0.4	13
% change in weight	--	1	1	--	0.4	35	--	0.4	25
Compatibility Status		Yes	Yes		Yes	No		Yes	No

b) Dissipation factor (in %): Pure Esters have higher amount of dissipation factor as compared to pure mineral oil which is due to the inherent chemical property of the ester linkage. Therefore, the percentage increase in the oil parameter after ageing with material over the value of the same oil parameter aged without material is taken for deciding the behaviour of the material with insulating oil instead of the absolute increase in values [13].

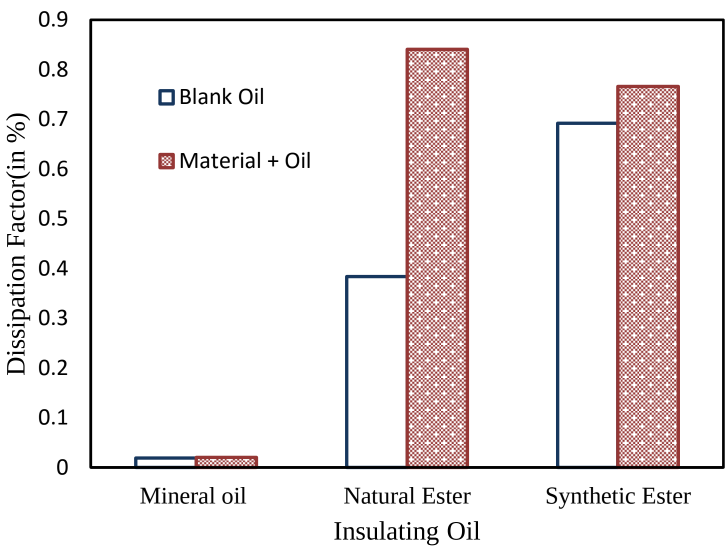


Fig. 3.3. Change in dissipation factor of insulating oil

Following inferences are drawn from Figure 3.3:

- Dissipation factor of blank mineral oil is less than that of both natural as well as synthetic ester oils.
- There are significant variations in dissipation factor of natural ester (approx. 120%) whereas for synthetic ester is 11%.
- For mineral oil, the change is 0.5% which is acceptable as per the standards.

Therefore, dissipation factor is an important parameter to determine the compatibility status of a material.

c) Interfacial Tension (in mN/m): IFT measures the presence of polar impurities in an oil. As Mineral oil is non-polar in nature, even small polar quantity in mineral oil has significant effect on the IFT value, whereas esters themselves are polar in nature and hence IFT is not much sensitive to polar impurities as compared to mineral oil [14].

From Figure 3.4, following conclusions are observed:

- For mineral oil, there is around 11% decrease in IFT.
- The percentage changes in IFT in case of natural and synthetic ester oil are 8% and 14% respectively.

Hence, IFT is more sensitive to mineral oil impurities as compared to ester oil and cannot be used as the only parameter to decide compatibility for ester oils.

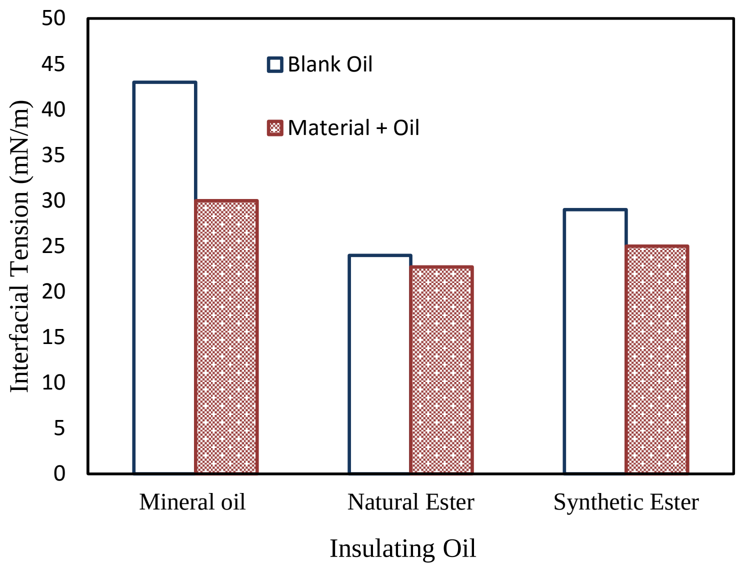


Fig. 3.4. Change in Interfacial Tension of insulating oil

d) Acid Number (in mg KOH/gm): Neutralization number also termed as acid number measures the amount of fatty acids present in the oil sample [15]. These acids in the oil can come into contact with solid insulation and cause its degradation

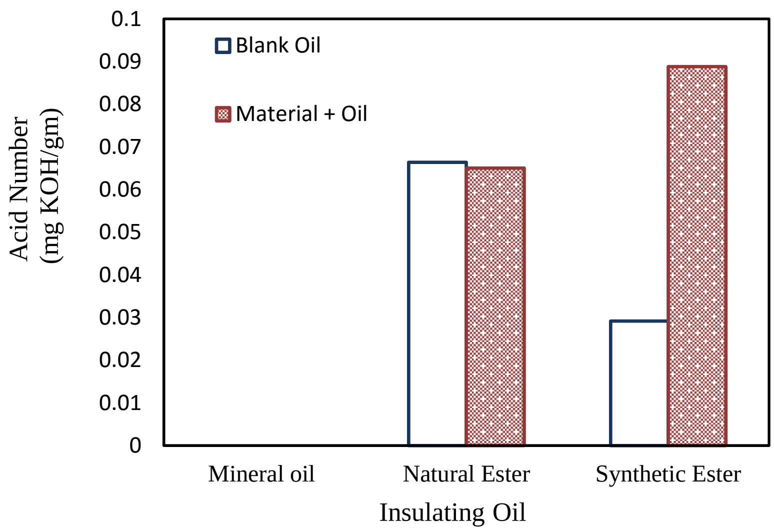


Fig. 3.5. Change in Acid Number of insulating oil

From Figure 3.5, following inferences are taken:

- The base value of ester oil itself are higher than that of mineral oil
- Almost negligible changes in acid number for both mineral and natural ester oil

- Acid number is almost doubled for synthetic ester oil.

Therefore, in case of synthetic ester, acid value is very sensitive to ageing with materials.

e) Color: The test involves the comparison of oil sample color with color code that shows color change from light yellow to dark brown. This test alone is not sufficient to decide the compatibility of a particular material with the insulating oil. It is found that oil sample of the material which is not compatible shows no color change before and after the test whereas oil sample of a compatible material showed a change in color [16].

f) Dissolved Gas Analysis (in ppm): DGA [17] is done to analyse the rate of gas generation in the transformer oil when aged in contact with a particular material. In practice, there are chances that an incompatible material generates gases in the transformer which in the long run may give misleading results for the identification of fault in the running transformer. Transformer failures are related to fault gases whereas DGA arising from materials & oil interaction can only cause confusion in interpreting DGA fault gases. The gases observed in the material compatibility studies are not fault gases nor are they considered to be a deciding criterion for material compatibility. Therefore, the objective of our DGA studies is to avoid the chances of misinterpretation of fault gases if generated in a transformer in operation. DGA has been performed in addition to various electrical and mechanical tests as mentioned in the material compatibility standard with the objective as stated.

Following are the interpretations from Figure 3.6:

- The concentration of stray gases in esters is more in reference to mineral oil
- Synthetic ester behaves like mineral oil in DGA results with low stray gas concentrations
- Higher rate of generation of DGA gases in natural ester with respect to the blank oil

Hence, in case an incompatible material is used in the transformer, the end-user of the transformer has to make use of this abnormal gas generation rates and make appropriate accounting of DGA in an actual transformer in operation.

Therefore, from the above results obtained from various tests for determining the compatibility studies, it can be stated that the presence of an incompatible material with the insulating oil have detrimental effects on the performance of transformer. So, care must be taken while using new materials or new insulating oil in the transformer.

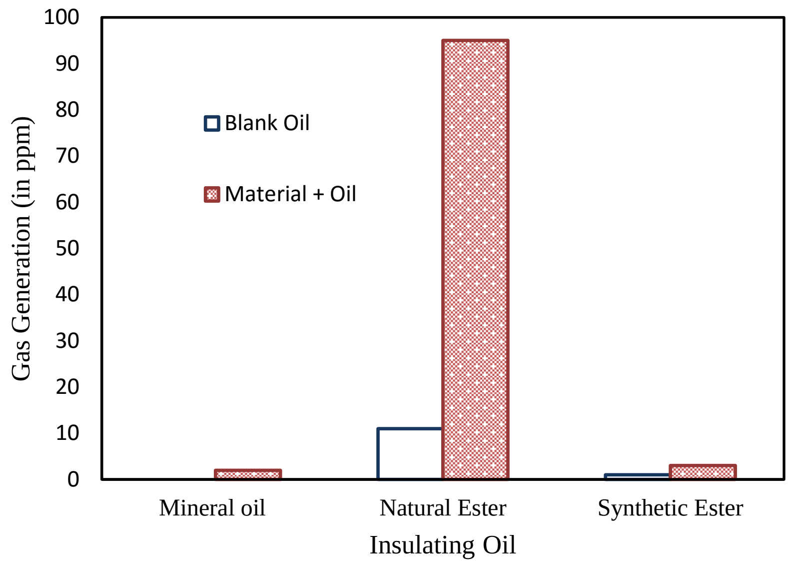


Fig. 3.6. Gas generation in insulating oil

g) Ageing of thermally upgraded paper

From the material compatibility results, it has been found that compatibility studies alone are not sufficient to determine the behaviour of transformer construction materials with the insulating oil. These studies have been further extended in order to evaluate the performance of transformer oil in contact with an incompatible material at different intervals of time and at different temperatures. Dissipation factor of the oil aged with thermally upgraded paper (TUP) at 70°C and 110°C for 0, 7, 14, 21 & 28 days are compared for mineral and ester oils. It is very important to predict the behaviour of paper on the winding conductors with insulating oil over a period of time as the life of solid insulation decides the life of transformer. Ageing studies are performed in order to determine this behaviour of materials in contact with the insulating oil over a long period of time [1, 8-10]. It is possible that mistakenly the incompatible materials are used in the transformers, therefore ageing has been performed with the materials to know how an incompatible material will behave in the operational transformer. This will help to avoid the losses occurring in the transformer**.** Dissipation factor is defined as the loss factor due to the presence of leakage current through the insulation. It is important as it provides the condition and dielectric strength of the insulating oil. More the value of dissipation factor (dissipation factor), more dielectric losses are there in the insulation and its quality becomes poor. Experiments have been performed [13] and results are shown in the form of graph in which dissipation factor values for different insulating oils at different intervals of time has been compared.

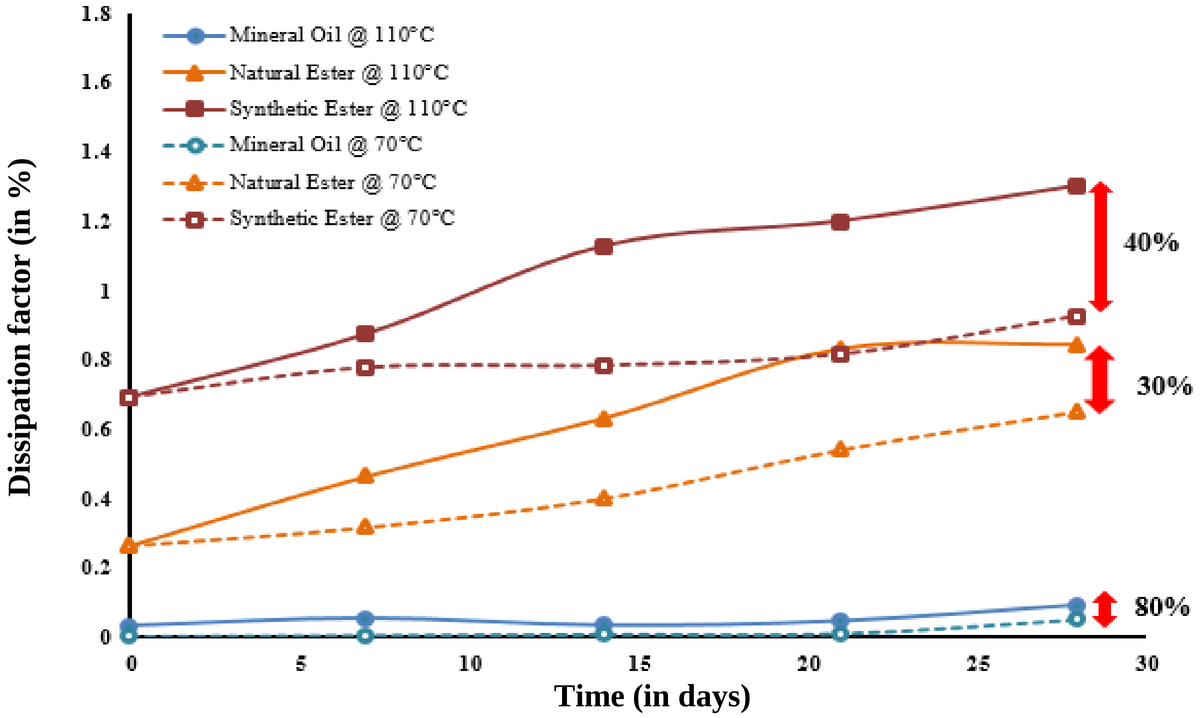


Fig. 3.7. Effect of ageing on dissipation factor

Following results are drawn from the Figure 3.7.

- Dissipation factor of blank mineral oil is less than that of natural ester and synthetic ester have highest dissipation factor
- Mineral Oil is highly affected by increase in temperature (80% increase in dissipation factor from 70°C to 110°C)
- Increase in dissipation factor with temperature for natural ester and synthetic ester is 30% and 40% respectively.
- Ageing of TUP with time increases dissipation factor by 36%, 32% & 6% for mineral, natural ester and synthetic ester oil respectively.

Therefore, both time and temperature are significant parameters on which properties of oil depends. With time and increase in temperature dissipation factor of the insulating oil increases showing the ageing of oil. Therefore, from the ageing results obtained, it can be stated that ageing studies are important to evaluate the performance of transformer over a period of time for its reliable and safe operation.

The use of TUP instead of normal kraft paper has been recommended in the ester oil transformers based on the ageing results obtained. As life of ester oil transformers is more and they can operate at high temperatures, therefore to make reliable operation TUP which can withstand more temperature as compared to kraft paper (conventionally used) is being used.

3.4 CONCLUSION

Material Compatibility is considered to be an important guiding factor for material selection and setting up the process guidelines of a transformer. Incompatibility may lead to the increase in dissipation factor, resulting in reduction in the dielectric strength of the oil, increase in dielectric losses resulting in the increase of fault gases that in the long run may prove fatal for the transformer applications. Further, it is observed that the chemical composition of a material to be used in transformer plays an important role and must be properly checked as per the applications for avoiding misleading results in the compatibility studies. From the experimental results, core laqour is found to be incompatible with ester oil. Therefore, its use in the ester oil transformers has been stopped. The use of TUP instead of normal kraft paper has been recommended in the ester oil transformers because of its thermal stability at high temperatures as compared to conventionally used kraft paper.

CHAPTER 4
INSULATION RESISTANCE TESTING OF ESTER OIL TRANSFORMERS

4.1 INTRODUCTION

Transformers are considered to be the heart of the whole power system. Generally, a transformer is used to change the voltage (boost or reduce) level based on the application. There are therefore two primary kinds of transformers, step-up and step-down which differ in the number of turns in the windings. Taking mineral oil transformer results as reference the reliability of ester oil transformers is being determined. Ester oil possess more dissipation factor than mineral oil due to its high viscosity. The variations in the insulation resistance and dissipation factor of the transformer windings in contact with the ester oil with respect to mineral oil are the two important parameters of these studies. Low dissipation factor is highly desirable for the transformer customers to avoid leakage current while the transformer is in operation [45, 46].

Due to the incompatible material present in the transformer, it will lead to increase in the DGA content in the oil which as a result reacts with the solid insulation and deteriorates it. This results in decrease in winding insulation and more dissipation factor will result in more leakage current. Therefore, these tests play an important role to avoid the transformer failures.
In this chapter focus is to provide a brief idea about the increase in leakage current in the ester oil transformers and further the results are used to reduce the leakage current losses.

4.2 WINDING PREPARATION BEFORE TESTING

The transformer must be properly processed before performing any test to avoid the misleading results due to the presence of any dirt particles and moisture.
In this section, details about the winding preparation before carrying out testing has been discussed. The winding after manufacturing, is being dried in vacuum to keep the moisture level within the specified limits in the standards, then it is placed in the tank properly sealed and then oil is filled under vacuum.

4.2.1 Winding configuration

Transformer winding is a main component of the transformer and care is taken while their manufacturing. Various types of windings based on the applications such as voltage, power rating is being used in the transformers. A continuous disc winding with dimensions (90 x 665) mm consisting 32 discs each having 10 turns (total number of turns in the winding are 320) has been manufactured to perform various tests on the windings. The width of each turn is 3.22 mm and the bare conductor is 1.68 mm thick. Therefore, each conductor have paper covering of 1.54 mm (width of each conductor turn – thickness of bare conductor). In order to make the calculation easy, turns ratio have been taken as unity that means both HV (high voltage) and LV (low voltage) windings have same number of turns. The HV and LV windings as shown in Figure 4.1 are separated by 1.5 mm high density pressboard sandwiched between two axial spacers (5.2 mm towards LV and 6.5 mm towards HV). The main difference between the two windings (HV and LV) is that 10 taps from HV winding are taken out each connected to the individual bushing to perform testing (as shown in Figure 4.2). After completing the manufacturing process of the winding and before going for its testing following processes are being done on the windings.

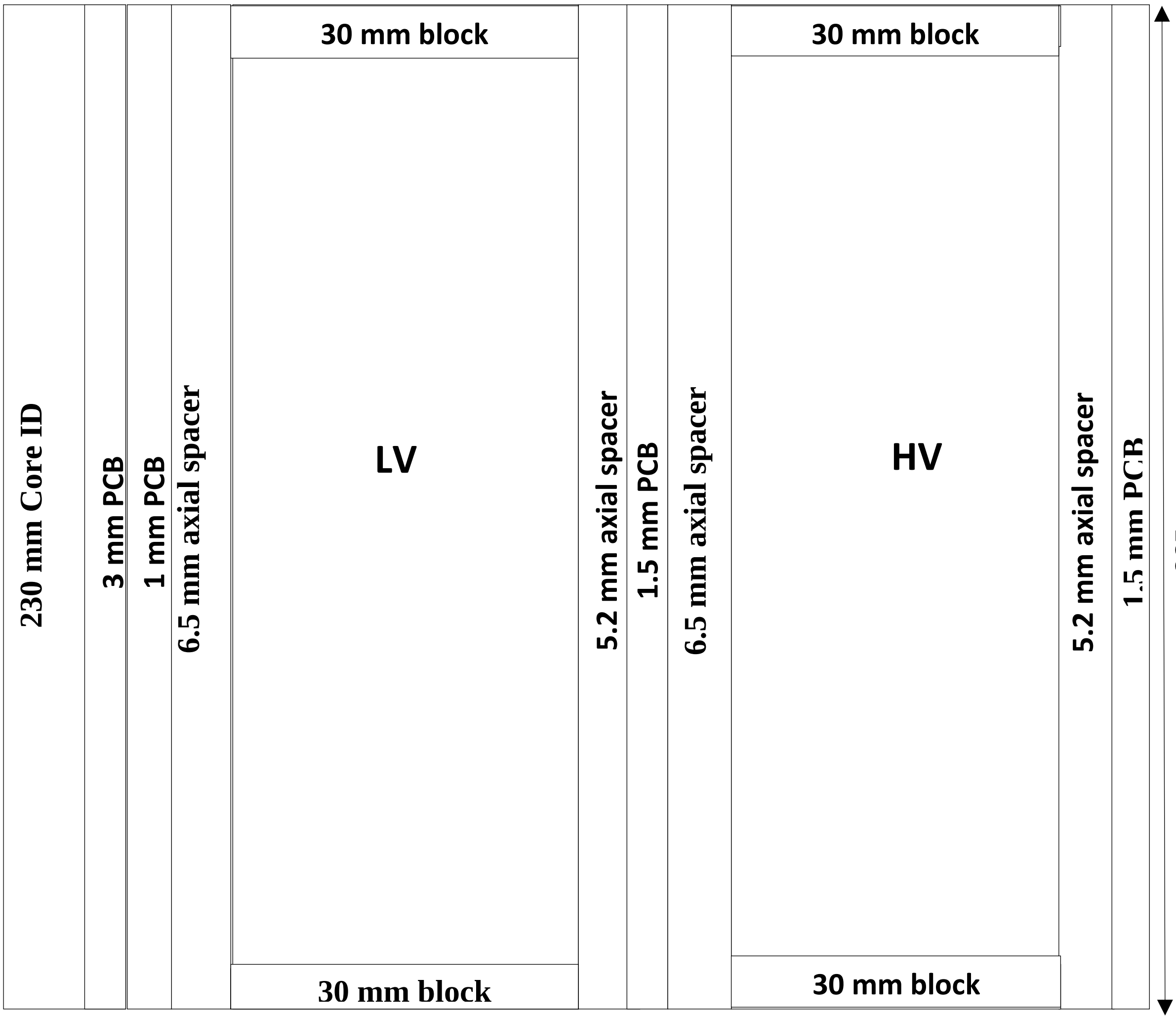


Fig. 4.1. Schematic diagram of winding

Fig. 4.2. Continuous disc winding used for testing

4.2.2 Vapour phase drying

Vapour phase drying or commonly known as VPD is a technique in which vacuum is used instead of air for reducing moisture content from the transformer windings. The thermal conductor is a low-viscosity liquid steam such as kerosene with an elevated flash point, instead of air. The steam is cooled by the use of electric heater in a room during vapour processing and is moved over a core coil assembly (CCA) inside for drying [1, 2].

The water vapours therefore condense on the material and are recirculated in the system as a solvent. In addition to a vacuum chamber and a vacuum pull system, such as vacuum pump, root pumps, etc., which are part of the standard vacuum system, the vapour phase drying systems have an evaporator and condenser system. For this purpose, the scheme comprises therefore of a solvent heat transport scheme composed of retention, evaporation, condensation, filtration, solvent feedback and regulator.

The steps involved in the VPD process are:

- Preparation: Before the solvent is drawn into the evaporator and heated to 130°C, the complete evaporator and condenser are placed in full vacuum at 5 torr stage. The VPD vacuum chamber is also used with 5 torr vacuum. The CCA is held with a pitch to help the solvent drain. Above 130ºC, there is decrease in the degree of polymerization of solid insulation in the windings. Therefore, the temperature in VPD should not exceed 130ºC.

- Heating and Drying: After all oxygen is removed, heating begins. For the solvent vapours to reach the vacuum chamber and condense on the charged washing layer, these valves are maintained closed. The condensation discharges heat and the charged weight temperature thereby improves water evaporation. For recirculation, the combination of water and solvent flows out. Drying process continues for 24 hrs.
- Reduction of pressure: During this phase, the supply is stopped of solvent vapour and the majority of solvents absorbed by the insulation are re-evaporated, condensed into the condenser and then returned to the evaporator. The pressure in the vessel remains 15-20 torr during this phase.
- Applying vacuum: This is the last phase of the process following the pressure reduction phase. The pressure in the chamber again reduced and should not exceed 0.1 torr. Water extraction is regularly tracked and documented. The process comes to end when the water extraction rate reached to a value less than or equal to 0.5%.

After VPD, Core Coil Assembly and other active parts of the transformer after clamping are placed in the tank. They are locked in such a direction that any disturbance or vibration will not cause any movement inside the tank.

4.2.3 Impregnation of oil

After tanking, the active parts are impregnated with transformer insulating oil so that the air bubbles that remain in the insulation material can be removed. Air bubbles may contribute to the localized breakdown [1, 2]. Before filling the transformer oil in the tank, the insulating oil should be degassed, dried and filtered and should be in limits as per the Table 4.1 to avoid failures due to impurities in the oil.

Table 4.1: Limits considered for oil filling in the tank

Sr. No.	**Oil Properties**	**Specified acceptable limits**		
		Mineral oil	Natural ester oil	Synthetic ester oil
1	Moisture content	≤5 ppm	≤55 ppm	≤55 ppm
2	Dielectric breakdown strength (2.5 mm/kV)	>70 kV	>75 kV	>80 kV
3	Dissipation Factor	0.005	0.2	0.25

Depending on the dimensions, type and temperature of the oil, the time of impregnation of pre-compressed wood is 24 hrs under vacuum of 0.5 torr pressure. Increased oil temperatures lead to reduced viscosity, which increases impregnation velocity.

A large temperature distinction between the winding and the oil filled can alter the pressure of clamping (as shown in Table 4.2). Therefore, during impregnation, oil temperature needs to be maintained near to the winding temperature.

Table 4.2: Clamping pressure before and after Impregnation

Sample temperature prior to impregnation (ºC)	Oil temperature prior to impregnation (ºC)	Clamping pressure direction
20	20	→
80	20	↘
20	80	↗
80	80	→

Completing the oil sprinkling from the edge of the tank roof helps prevent the development of bubbles and trap inside windings. Winding-trapped air particles might produce partial discharges or electrical faults afterwards. Oil filling speed is an essential element. The increase in oil velocity needs to be restricted to allow the oil to correctly complete all the vacuum within the insulation windings. Table 4.3 shows the limits for various parameters that must be taken into consideration while oil filling.

Table 4.3: Process parameters for oil filling

Sr. No.	Parameters	Specified limits
1	Position of oil inlet on transformer	At top directed against tank wall
2	Average oil filling speed(mm/hour)	<150 mm/hour (calculated based on oil volume in the tank and tank height)
3	Oil temperature difference with winding temperature (Δ˚C)	max 10˚C
4	Filling level	Active parts should remain completely immersed in oil

4.3 TESTING OF WINDINGS

Various tests are being performed on the transformers to assure its quality. All the performance parameters are verified and examined for the values guaranteed and within the accessible tolerances. A series of tests being categorised as: A) Routine testing B) Type testing

C) Special Testing should be carried out in advance of declaring a transformer healthy and reliable for operation. Routine tests are important tests that needs to be performed on all the transformers, Type tests are based on the customer requirements [2]. This project focuses on two important tests being performed on the transformers i.e. Insulation resistance and capacitance/ Dissipation factor of transformer windings. Insulation resistance test provides the information about open or short winding connections and the corresponding faults. Dissipation factor provides the amount the leakage current flowing in the transformer and the deterioration of the winding insulation.

4.3.1 Insulation resistance testing

To avoid electrical shocks and to ensure staff safety, it is very essential to test the insulation resistance of an electrical equipment. It is useful in identifying isolation deterioration so that repair work such as: vacuum cleaning, steam cleaning, drying and rewinding can be scheduled. It also helps to assess the repair quality before returning the machinery to service. Several maintenance tests are used to evaluate the insulation quality.

Insulation Resistance test is being conducted at or above rated voltage to determine if the winding is deteriorating at low resistance between winding and ground or between the windings. This test should be carried out before and after repair or maintenance. For future comparison reasons, the test information standardised to 20°C should be registered. The value of the voltage used for measurement is accurately defined by the use of a constant voltage source.

The mega-ohmmeter or megger is used to find insulation of the transformer winding. The Megger is basically an ohmmeter with a built-in direct current generator, a high-range resistance meter. Specially designed with both present and voltage coils, this meter allows to read real ohms directly, regardless of the real voltage applied. The megger is a tiny, mobile tool that gives a direct reading of the resistance to insulation in Ω or MΩ. The resistance should generally be read in the MΩ range in order to be regarded as excellent isolation.

Reading is generally done for 15, 60 & 600 seconds by applying a constant test voltage. The operator should note down the winding temperature so that the reading can be corrected to a 20°C base temperature [45, 46].

By estimating resistance of transformer winding starting with one HV transformer bushing then onto the next, transformer resistance testing can uncover a lot of data about the transformer.

The following five connections are being performed for single phase transformer winding to determine the insulation resistance of the winding and their schematic diagram has been shown in Figure 4.3.

a) High voltage winding to low voltage winding and ground: The winding insulation resistance between high voltage winding (HV) and low voltage winding (LV) keeping LV and tank both at ground potential is being determined.
b) Low voltage winding to high voltage winding and ground: The winding insulation resistance between HV and LV keeping HV and tank both at ground potential is being determined.
c) High voltage winding to low voltage winding: This connection is used to determine insulation strength between HV and LV.
d) High voltage winding to ground: The insulation strength between HV and ground is being determined.
e) Low voltage winding to ground: The insulation strength between LV and ground is being determined.

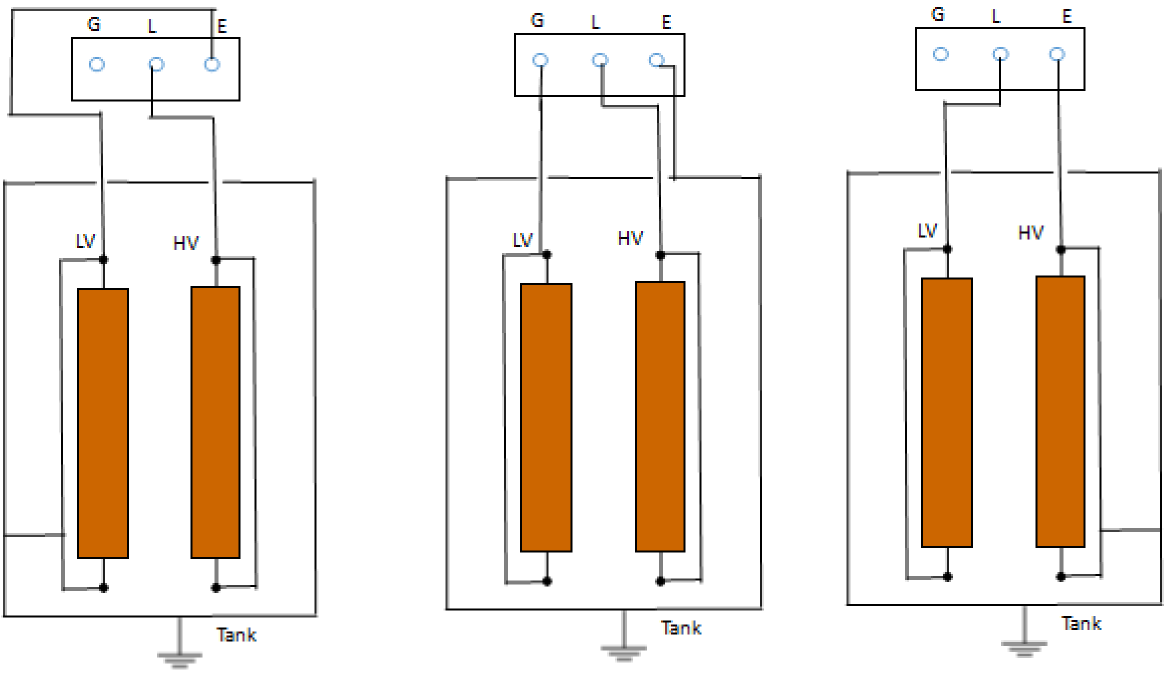
Further, the strength of transformer winding is determined by defining a numeric ratio known as Polarization Index (PI). PI is defined as the ratio of 10 min insulation resistance value and 1 min insulation resistance value.

$$PI = \frac{10\ \mathrm{min}\ insulation\ resistance}{1\ \mathrm{min}\ insulation\ resistance} \qquad \text{Eq. 4.1}$$

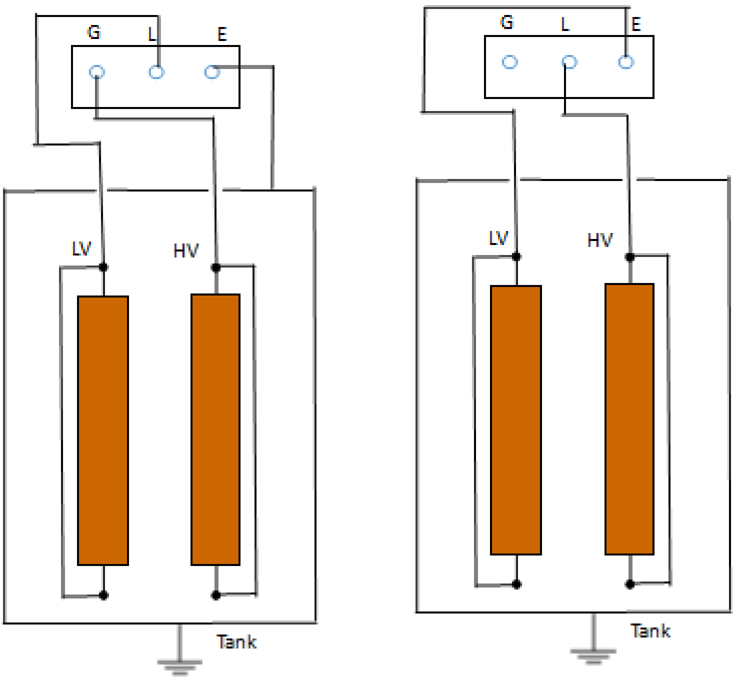
The rate of increase of leakage current is faster in case of damaged insulation than the absorption current, therefore PI value will be less for the poor insulation. More is the PI, good will be the insulation strength of the transformer winding. Based on the values of PI as described in Table 4.4, quality of transformer winding can be determined.

Table 4.4: Winding condition based on polarization index

Condition	**PI (polarization Index)**
Dangerous	<1
Poor	1-1.1
Questionable	1.1-1.25
Fair	1.25-2
Excellent	>2



(a) (b) (c)



L	E	G
Line	Earth	Gaurd

(d) (e)

Fig. 4.3. Schematic Diagram of winding connections during Insulation resistance testing; a) High voltage winding to low voltage winding to ground, b) High voltage winding to ground and low voltage winding guarded, c) Low voltage winding to high voltage winding to ground d) Low voltage winding to ground and high voltage winding guarded, e) High voltage winding to low voltage winding

4.3.2 Capacitance/ Dissipation factor testing

Due to ageing, the insulation losses increase in the form of heat. The level of deterioration is determined by the power factor or dissipation factor. The diagnostic tests are being performed on the insulation of transformer windings to evaluate their deterioration. Capacitance/ Dissipation factor testing is based on the fact that winding insulation in its pure state behaves as a capacitor. Dissipation factor is defined as the ratio between resistance and the capacitive reactance of the transformer winding. Whenever there are faults in the winding, leakage current starts following and the capacitance decreases. Due to this, capacitive reactance also decreases, resulting in more dissipation factor and therefore more losses. Hence, in order to avoid the failures due to leakage current, these tests are being performed [45, 46]. There are three components of current flowing through the transformer winding:

a) Capacitance Charging current: It is part of the current that rises when voltage across the insulation winding (capacitance) increases from zero to rated value.

b) Leakage Current: It is the resistive part of the current that flows from the winding insulation on the application of high voltage across it. Lower is the value of leakage current, better is the insulation quality.

c) Absorption Current: The dipoles in the insulation are randomly distributed in the different directions when the electric stress is applied across an insulation and align themselves in the same direction after some time under the electric field. Hence, initially current drawn is more and decreases gradually (within 5 to 10 minutes) after the polarization of dipoles. Therefore, absorption current is the current drawn by the winding insulation when the dipoles are aligning on the application of electric field.

Hence, these three components of current add to give the total current flowing through the winding insulation.

An index used to define the quality of the winding in terms of current flowing through it is known as dielectric discharge (Table 4.5) and is defined mathematically as:

$$Dielectric\ discharge\ (DD) = \frac{current\ flow\ after\ one\ minute\ (nA)}{Test\ voltage(V) * Capacitance(pF)} \qquad \text{Eq. 4.2}$$

Because of the internal connections, the phases cannot be measured separately. Therefore, there are three measurable capacitances as shown in Figure 4.4, one between the high voltage winding and ground ($C_{H\text{-}G}$), other is between the high voltage and low voltage windings ($C_{H\text{-}L}$) and the third is between the low voltage winding and the ground ($C_{L\text{-}G}$).

Table 4.5: Winding condition based on dielectric discharge

Condition	**DD (Dielectric Discharge)**
Good	<2
Questionable	2-4
Poor	4-7
Bad	>7

For determining Capacitance and dissipation factor of the transformer winding, different configurations are used.

a) GST (Ground Specimen Test): In this test, leakage current flowing through the ground is measured keeping High and Low voltage windings earthed.

b) UST (Ungrounded Specimen Test): Leakage current flowing between high and low voltage winding keeping ground at earth potential is being measured.

c) GST-G (Ground Specimen Test with Guard): In this part, total leakage current through HV, LV and ground is being noted.

The sum of all the parameters (capacitance, dissipation factor, watt losses) from UST and GST must be equal to the respective parameters obtained from GST-G mode otherwise there is some malfunctioning in the test performed. The schematic diagram of all the connections for determining Capacitance/ Dissipation factor of the transformer winding has been shown in Figure 4.5.

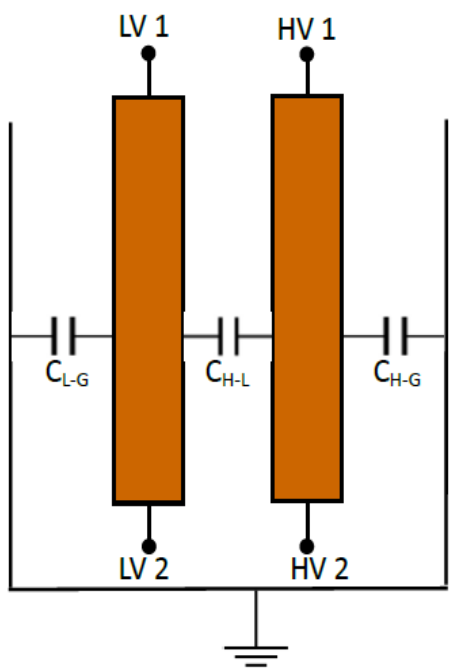
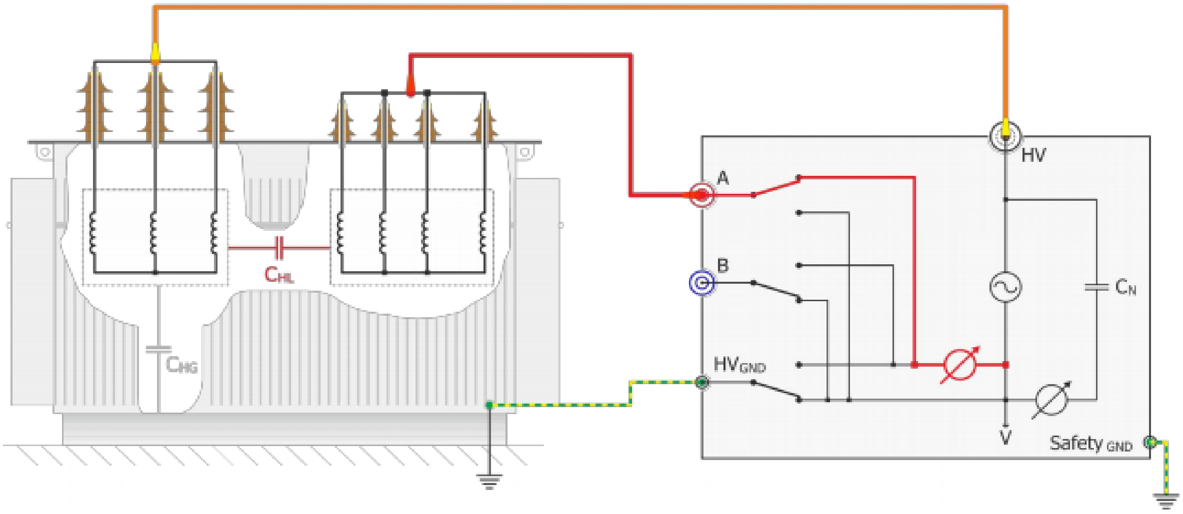
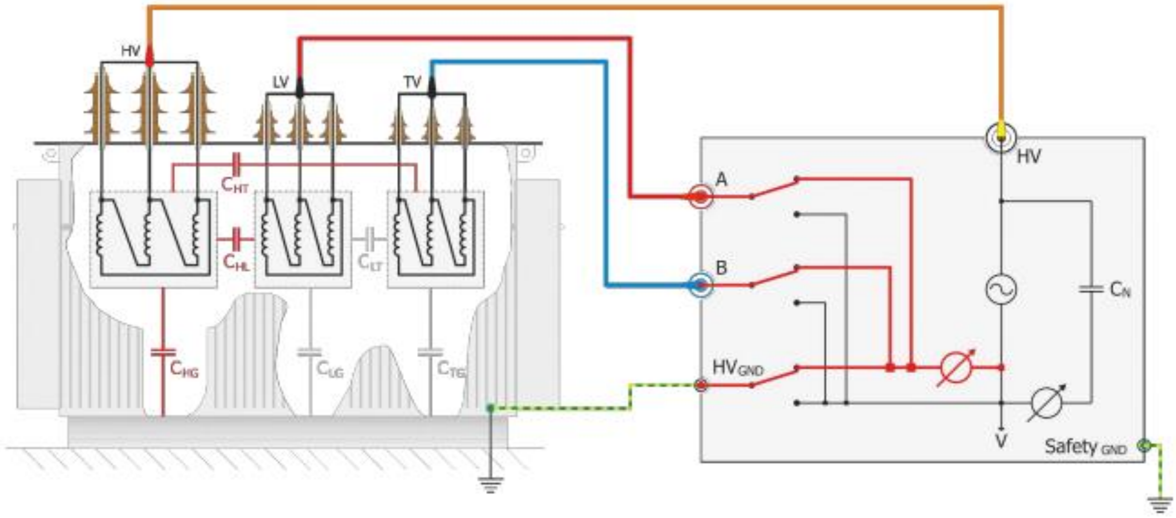


Fig. 4.4. Different capacitances formed between the transformer windings and ground



(a)



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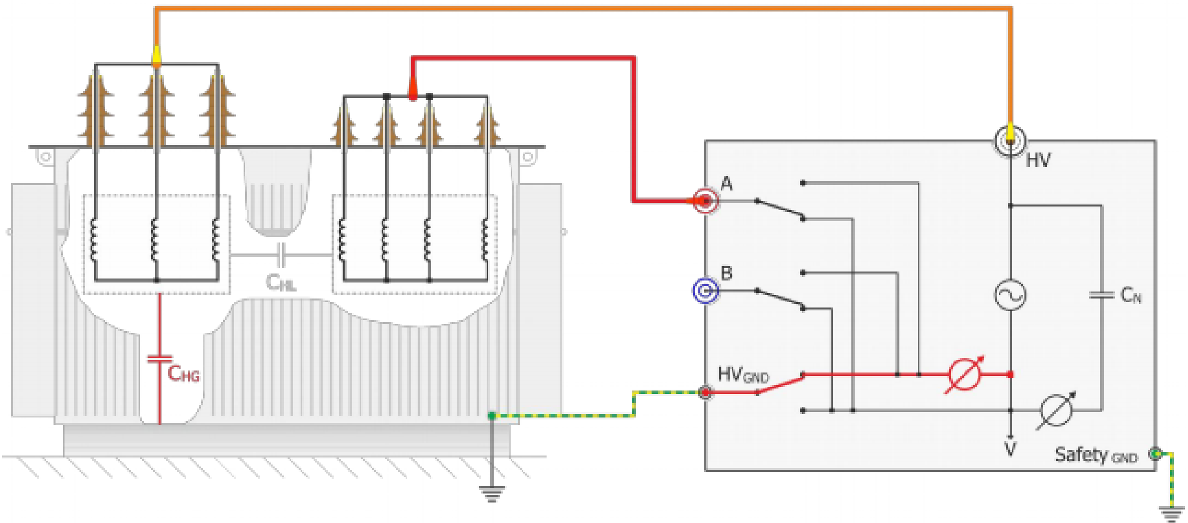


(c)

Fig. 4.5. Schematic Diagram of winding connections during Capacitance/ Dissipation factor testing a) UST b) GST c) GST-G [46]

4.4 RESULTS AND DISCUSSIONS

After drying, the transformer windings are immersed in different insulating oils and readings of winding insulation resistance and capacitance values are recorded. All the results are then compared with the reference mineral oil readings.

4.4.1 Insulation resistance

Insulation resistance at different time intervals giving a constant voltage across the windings is taken and corresponding PI value is calculated (as shown in Table 4.6 for mineral oil and Table 4.7 for natural ester). Continuous rise in resistance over time (as shown in Figure 4.6) is a measure of excellent isolation due to absorption. For a visible charge effect, the time duration by good insulation is longer when compared to the time required to charge the insulation capacity. The presence of moisture or contaminants on insulation includes the impact of absorption with a large level of leakage at a fairly steady value resulting in low strength reading (R= E / I).

Table 4.6: Insulation resistance values at different time intervals (mineral oil)

Details	Applied voltage (kV)	Insulation resistance (GΩ)			
		15s	60s	600s	PI
HV-E	5	1.58	3.71	10.4	3.34
LV-E	5	2.62	4.33	7.45	1.72
HV-LV	5	3.24	6.06	18.9	3.12

Table 4.7: Insulation resistance values at different time intervals (natural ester oil)

Details	Applied voltage (kV)	Insulation resistance (GΩ)			
		15s	60s	600s	PI
HV-E	5	0.9	1	1.4	1.4
LV-E	5	1	1.2	2.5	2.08
HV-LV	5	1.6	2	4	2

From the results, it can be fairly seen that PI of Mineral Oil is more as compared to Ester Oil. This is due to lower dissipation factor and viscosity of mineral oil due to which Insulation resistance is more. It must be noted that for the winding insulation to possess excellent insulating properties, PI should be greater than 2. In the Figure 4.5, PI for both the insulating oils show values greater than and equal to 2 which results in excellent winding insulation. If the PI comes less than 1.25, preventative measures must be taken in order to avoid the insulation failure and to save the transformer for serious damage.

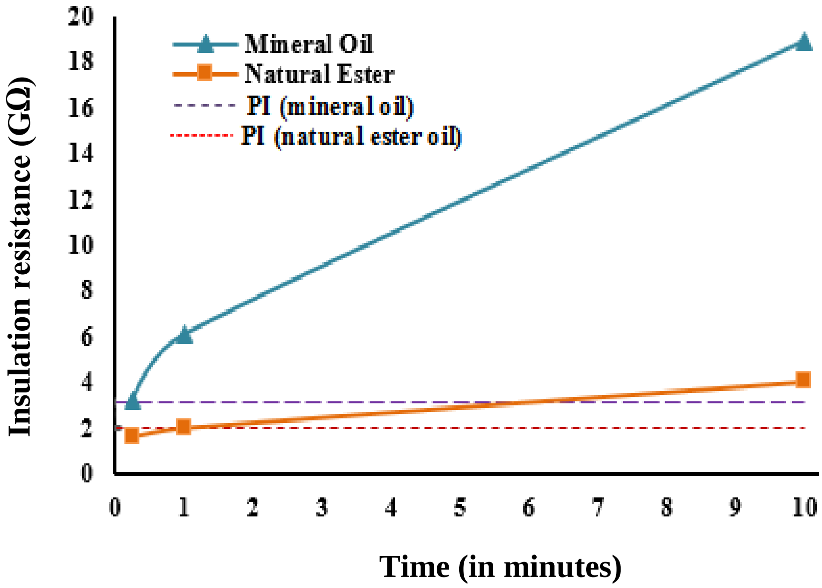


Fig. 4.6. Comparison of Insulation resistance of mineral and ester oil transformers

Therefore, it can be stated that Insulation Resistance is a simple and important test to evaluate the winding insulation. On the application of small DC voltage across the winding sections, current through the winding is being measured the ratio of which gives the dc winding resistance. From the skin effect calculations, ac resistance can be calculated with the information of dc resistance.

4.4.2 Capacitance/ Dissipation factor

The capacitance formed between the windings provides the healthiness of winding insulation. In this test, AC voltage at low frequency is applied to determine the dielectric losses in the transformer. For a particular voltage level applied across the winding results of capacitance and dissipation factor are taken across LV winding and ground (UST), LV – HV winding (GST) and HV winding ground (GST-G) as shown in Table 4.8 and 4.9.

Table 4.8: Capacitance and Dissipation factor values for mineral oil

Details	Applied Voltage (kV)	Capacitance (pF)	Dissipation factor (%)
UST	5	2528	0.369
GST	5	2186	0.455
GST-G	5	658.7	0.642

Table 4.9: Capacitance and Dissipation factor values for natural ester oil

Details	Applied Voltage (kV)	Capacitance (pF)	Dissipation factor (%)
UST	5	2721.27	0.669
GST	5	2439.64	0.705
GST-G	5	1986.86	0.854

From Figure 4.7, it is observed that the capacitance values of transformer winding immersed in mineral oil are almost double than that with ester oil. Similarly, ester oil immersed windings have more dissipation factor as compared with mineral oil immersed windings.

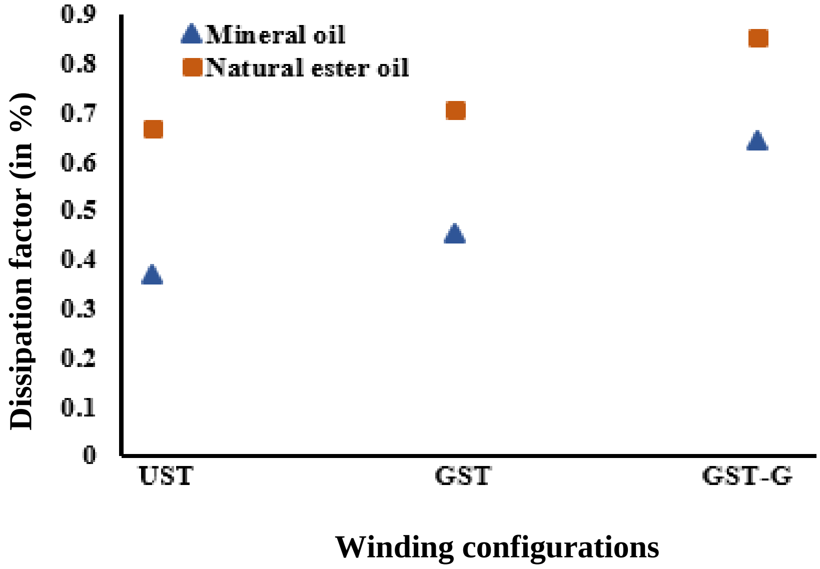


Fig. 4.7. Comparison of dissipation factor of mineral and ester oil transformers

4.5 CONCLUSION

Insulation resistance of ester oil transformers is lesser than mineral oil transformers whereas dissipation factor is almost double than that of mineral oil transformers. Mineral oil due to low fire point I^2R losses are more due to which windings gets heated up and hotspot gets formed even at lower temperature which in the later stage can damage the winding insulation. Generally, mineral oil filled transformers give good insulation resistance values but the loss due to I^2R is more as compared to dielectric loss, therefore this effect of ester oils cannot be overcome by mineral oil. Further research is going on in the designing of ester oil transformers to reduce these dielectrics loses. Insulation barriers are being used at the winding corners where the chances of leakage current are more. If the path followed by the leakage current is stopped, it will reduce the dissipation factor losses overcoming this limitation of ester oil filled transformers.

CHAPTER 5
THERMAL ANALYSIS OF ESTER OIL TRANSFORMERS

5.1 INTRODUCTION

Mineral oil is the most commonly used insulating oil in transformers. Hence, a significant amount of research has been performed on thermal analysis of mineral oil in different cooling modes from low voltage transformer to high voltage [1-4]. However, the main limitation of mineral oil has some limitations in terms of fire safety, environmental impact and continuous overloading capabilities. Recently, the ester oils are increasingly considered as an alternative to mineral oils used in transformers. The technical challenge that usages of ester oils are insulating properties and cooling properties of ester oil different from mineral oil and it might change the design, manufacturing and impregnation process of transformer. Since, the chemical compositions and molecular structure of ester oil is different from mineral oil it becomes imperative to predict the behavior of ester oil and their impact on thermal design of transformer. If the transformer manufacturer is considered to use the ester oil as an alternative of mineral oil for a transformer, it becomes important to understand the oil properties. The prediction of thermal behavior of ester oil is one of the main criteria at design stage to utilize the ester oil for transformer application due to higher viscosity since heat run test is one of the factory tests to verify the thermal behavior of ester oil transformers.

The higher viscosity and density of ester oil with respect to mineral oil will increases the top oil temperature rise, winding rise and higher hotspot temperature even ester specific heat and thermal conductivity of ester oil is more as compared to mineral oil. Hence, the higher viscosities of ester oil would increase the impregnation time of solid insulation during transformer manufacturing time and reduce the cooling efficiency during the transformer operation at site. Therefore, it is still a technical challenge for ester oil to be use in power transformers. In this chapter, an attempt has been made to estimate the oil flow distribution and the temperature distribution of the natural ester oil and synthetic ester oil and it is compared with to mineral oil. The temperature profile of the winding under different operating and geometrical conditions is being predicted using Thermal Hydraulic Networks Models [47-50]. The main things that come in mind while comparing the thermal performance of petroleum based mineral oil with vegetable-based ester oils are:

a) How the temperature profile of the transformer is being affected by the thermal properties of different oils?

b) How will the solid insulation degrade with the thermal performance? Generally, in case of mineral oil paper ages 5-8 times faster as compared to ester oil.

Thermal modelling of Transformers guarantees the life of the transformer. If a transformer is externally too heated, the insulation products will degrade more quickly and the transformer's operating life is reduced. According to IEC 60076-7, insulation of non-thermally upgraded paper halves with every 6°C increase in temperature.

5.2 THERMAL PERFORMANCE OF TRANSFORMERS

The temperature rise in the winding and oil are indicative of the thermal performance of the transformer. The transformer is said to be thermally stable if the temperature rises are within the limits. Due to various losses in the transformer (load, no-load and stray losses), the temperature profile gets disturbed resulting in temperature rise which again increases the losses and this process going on and cause transformer failure. Therefore, it becomes important to evaluate the thermal performance of the transformer for its safe and reliable operation. With the thermal modeling, information about the hotspot temperature and end life of the transformer is obtained.

Various cooling methods for maintaining temperature profile and the temperatures conditions used to define the thermal stability of the transformer are described further in this chapter.

5.2.1 Cooling methods

The heat produced in the transformer must be transferred to an external cooling medium if the transformer is to be maintained in a desired state of thermal equilibrium (not exceeding a guaranteed limit). Whilst the actual design specification for cooling equipment is complex and depends, in addition to the heat dissipating requirements, on the application and size of transformer, its environment etc., a general classification of cooling types according to some key parameters has been developed. According to IEC and IEEE standards, a four-letter code identifies the different cooling methods of liquid-immersed power transformers [1]. These codes are described below in Figure 5.1. For example, ONAN means Oil (O) Natural (N) Air (A) Natural (N) cooling.

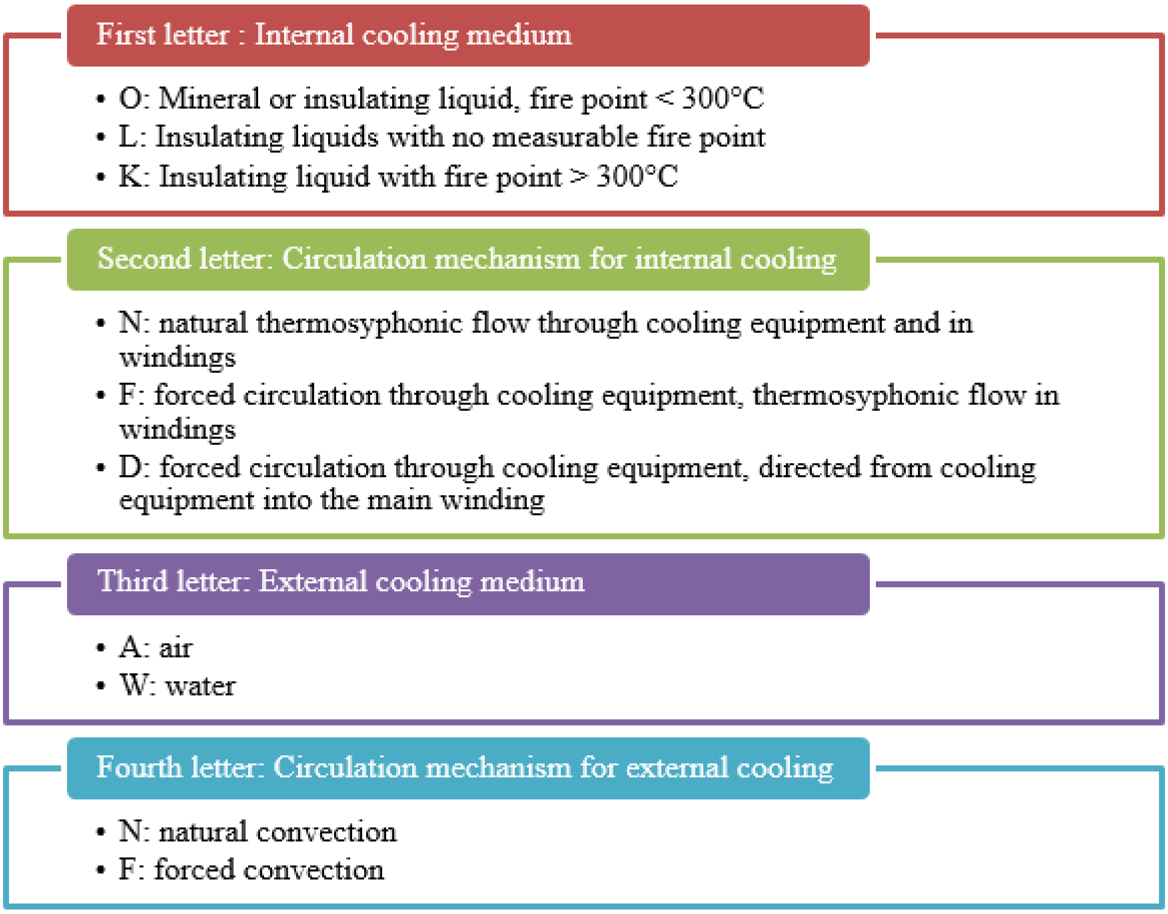


Fig. 5.1. Four Letter coding for cooling in transformers

a) Natural circulation of oil

In the simplest case, ONAN cooling is achieved by natural circulation driven by the temperature difference between the oil in the tank, and that in the radiators (as shown in Figure 5.2). By adding fans to this cooler, ONAF, the efficiency of the external heat transfer can reduce the oil temperature in the radiator. The greater temperature difference increases the oil flow rate and the cooling is further improved [47, 48]. In practice, the improved heat removal efficiency of the fans in ONAF cooling allows the use of a cooler with a smaller surface area than that for ONAN. The disadvantages are that it requires an auxiliary power supply, control and protection and may increase the noise level.

b) Forced circulation of oil

Pumps may be used to increase the oil circulation. This improves the heat transfer to the external cooling medium and reduces considerably the temperature difference between the top and the bottom of the radiators thereby lowering the oil temperature rise in the top parts of the transformer (as shown in Figure 5.3). In the case of forced type cooling, oil circulates in to the windings by convection therefore the local oil temperature at the top of the windings may be greater than that measured at the top of the transformer. This requires special attention to be taken in the assessment of winding temperature. For high power transformers, it can be advantageous to direct the oil circulation through the windings; this is the OD cooling mode. The greater oil velocity inside the windings improves the heat transfer between copper and oil and lowers the copper-oil temperature gradient [47, 48]. It also reduces the top oil temperature rise within the winding and therefore the hot spot rise is much reduced compared to the OF cooling mode.

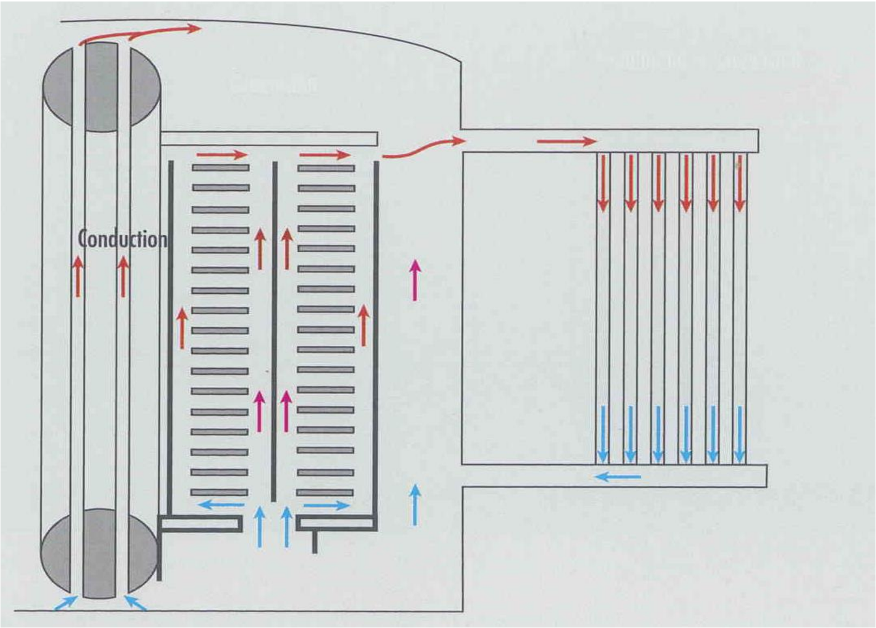


Fig. 5.2. Schematic diagram of natural cooling in transformers [1]

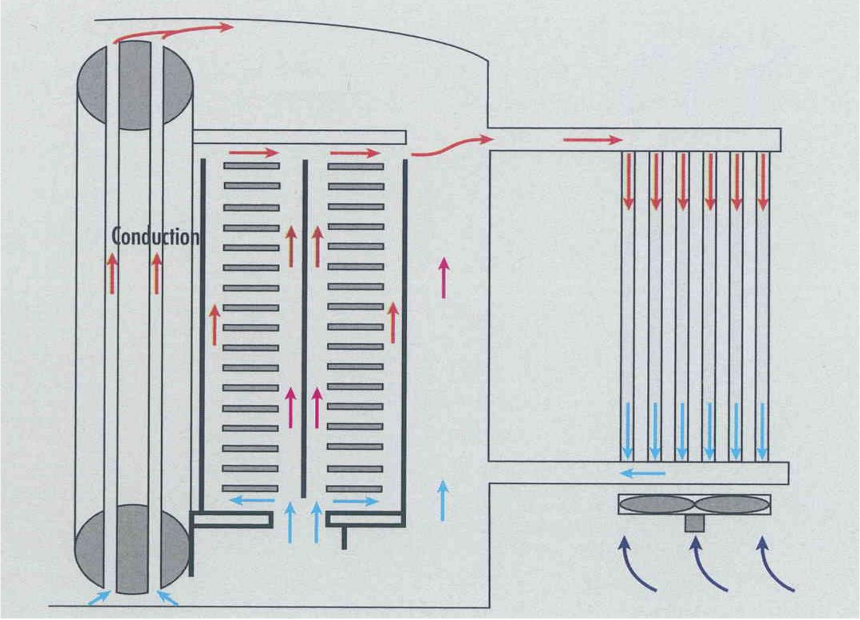


Fig. 5.3. Schematic diagram of forced cooling in transformers [1]

c) Zig-Zag circulation of oil

Natural flow uses the heat generated when the oil is heated, rises through the windings and as it cools down falls through the radiators. In forced non-directed cooling, oil is forced to flow from radiator to the bottom of the winding and then passes along the vertical oil ducts over and below the winding conductors. Radial ducts connect the axial ducts father and nearer to the core. Due to the temperature difference from top to bottom of the winding there is very less oil flow along the axial ducts and oil tries to follow the radial path from bottom to top of the winding (as shown in Figure 5.4). Due to this, cooling of the transformer windings is not uniform due to non-uniform distribution of oil flow.

This limitation is being eliminated in directed cooling or zig-zag cooling. Zig-Zag cooling (as shown in Figure 5.4) is a directed cooling in which direction of oil flow is directed by the use of oil barrier washers. It is same as oil forced and oil natural cooling methods with the addition of oil duct washers to provide proper flow of oil in all the directions and includes all the discs of the winding [47, 48]. Therefore, oil is being circulated uniformly reducing the heat and therefore the losses in the windings. The use of this method decreases the winding temperature which is highly desirable for the safe and reliable operation of the transformer.

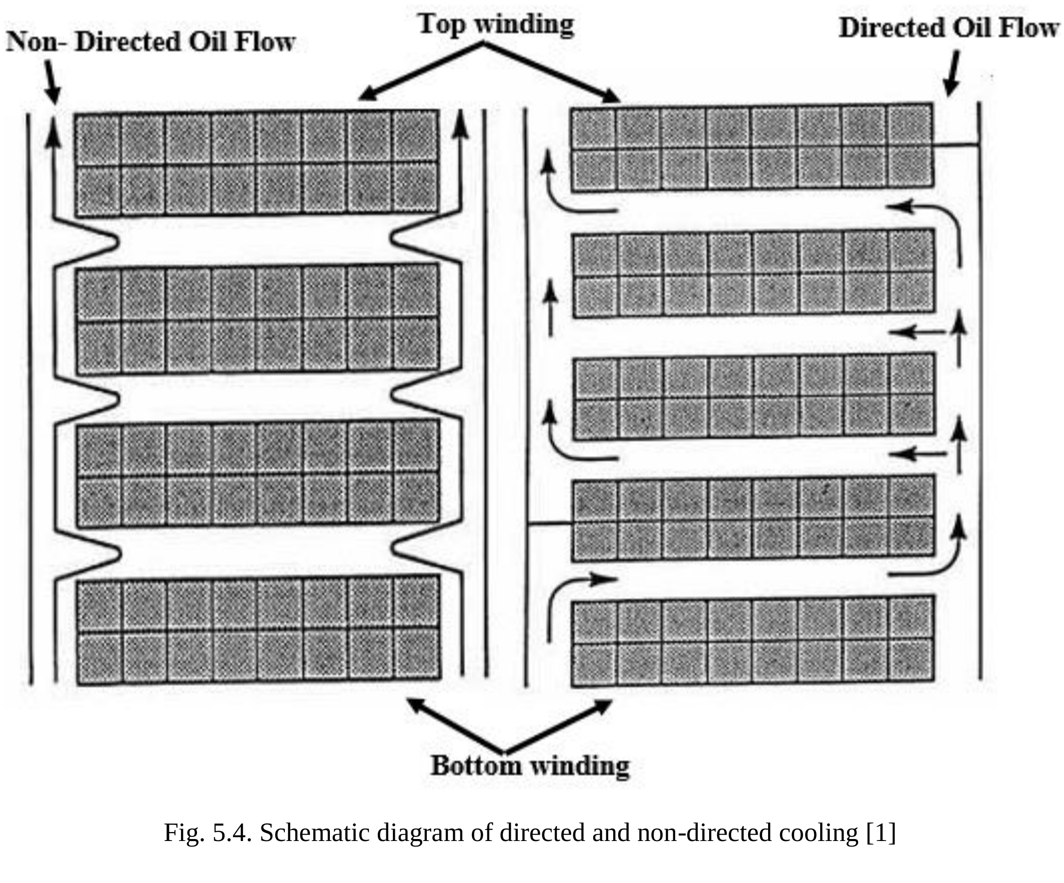


Fig. 5.4. Schematic diagram of directed and non-directed cooling [1]

5.2.2 Effect of temperature rise

During operation, a transformer generates energy losses within its core, windings and associated structures. These energy losses cause the various components to become hotter than the surrounding external ambient temperature. The operating temperature of the transformer is the sum of ambient temperature and the temperature rise inside the transformer.

In order to preserve the integrity of the equipment it is important that the operating temperatures of certain parts of the transformer are restricted to defined levels. In particular, this applies to the oil and the solid insulation system. All the components in the insulation system have a thermal classification that indicates their maximum operating temperature. Above these temperatures the solid insulation system will begin to degrade at a greater rate than normal, leading to a premature "end of life" of the insulation system and eventually to failure of the transformer [48-50].

The transformer oil acts as both a coolant and as an insulating medium. From a dielectric point of view, if the oil becomes too hot, it will start gassing and the gas will soon saturate the oil locally and form bubbles. Equally, hot solid insulation can evolve gas bubbles if sufficient moisture is present. These bubbles will impair the insulating properties of the oil.

Oil properties, such as viscosity and volume, change with temperature. At low temperatures natural oil movement can become sluggish and this would impair the cooling properties. The change in oil volume across the full operating temperature range has to be allowed for in the mechanical design of the transformer. It is, therefore, necessary to have knowledge of both the ambient temperature characteristics of the particular site and the permitted temperature rises, in order to determine the operating temperatures of each of the components.

Measurement of the temperature rises forms part of the type testing process and hence provides evidence that the equipment meets the relevant standards and is thermally capable of a long and reliable life span. Mainly three types of temperature limits are being given by the customer as per their applications. They are:

a) Top Oil (Liquid) Rise: This is the difference between the oil (liquid) temperature at the top of the tank and the ambient temperature.
b) Average Winding Rise by Resistance: This is the difference between the average winding temperature and the ambient temperature. The average winding temperature is measured by the resistance method and includes extrapolation back to the point of shutdown.
c) Hot Spot Temperature Rise: This is the difference between the hottest-spot winding temperature and the ambient temperature.

5.3 THERMAL MODELLING OF TRANSFORMERS

During transformer design phase, the determination of temperature distribution in the winding is typically based on either empirical formulae or thermal models of thermal-hydraulic network models and CFD models. Thermal model will help the thermal designer for predicting the temperature distribution with better accuracy than empirical formulae in order to meet the expected life time of the transformer. Hence, reliable thermal modelling approaches are crucial for thermal design analysis of transformer and required for the transformer designer at design stage to meet the customer guarantees values [48-50].

- CFD: Generally, numerical method (finite element method, finite volume method, finite difference method etc.) based CFD models are used to solve the governing differential equations for oil flow analysis and heat transfer. Hence, CFD calculation provides more information to the thermal designer due to distributed-parameter models. However, CFD calculation is not suitable at the stage of design since it requires specialized techniques for meshing the elements and calculation. In addition, the calculation time of rate of oil flow and the temperature profile for a complete transformer geometry will be very long for several hours or days and even not possible to solve the geometry. Hence, it is not a reliable model at the stage of design of transformer.
- THNM: The thermal hydraulic network model is based on lumped-parameter models and consists of a hydraulic network model and a thermal network model to describe the oil flow and heat transfer in rather coarse networks. In hydraulic network model, mass conservation and pressure equilibrium in each closed oil flow loops are considered to calculate the rate of oil flow in the winding. In the thermal network, the fundamental of conservation of thermal energy is effectively utilized at each node in the network and heat transfer equation is used to each closed oil flow path. In addition, temperatures are considered as a voltage source and power losses of the transformer is considered as current sources in thermal network. Hence, the effects of conduction and convection are conveniently lumped into thermal resistance for oil flow. It provides rate of oil flow and the temperature profile as an intermediate solution between simple design rules and complex CFD calculations. Hence, the determination of the oil flow rate and the temperature distribution in transformer in steady state is mainly performed by THNM model and it based on past experiences in ester oil and mineral oil [49].

The thermal performance of the transformer mainly based on external and internal cooling components working together. Hence, the transformer thermal components are divided into internal inside the transformer components (steel core, transformer windings with their supporting structure and finally the transformer insulations) and external outside transformer main tank components (cooling radiators, protection and relaying devices, transformer bushings, the conservator, external pumps and fans) for thermal analysis using THNM.

5.3.1 Internal winding model

Thermal modelling with transformer geometry input plays a vital role to calculate the thermal performance at the design stage without error and it becomes an important fact for both manufacturers and utilities consider the ester oil as an alternative of mineral oil. The first internal component of the transformer is the steel core. A laminated steel core links the primary and the secondary windings through the magnetic field and consider as a cylinder. In THNM, transformer is subdivided into smaller elements like oil channels, conductors, etc. and where for each element simple algebraic equations are setup like conservation of mass, energy etc. It allows the designer to calculate the thermal performance in a few seconds or minutes.

A 16 MVA, power transformer has been taken for carrying out the analysis. The winding as shown in Figure 5.5 consists of low voltage, high voltage and tap winding.

The geometry of a disc-type of low voltage and high voltage winding consists of thermally upgraded paper covered conductors are used in this transformer. The winding model geometries such as number of discs, conductor dimensions, radial cooling duct, and height of the winding, axial cooling duct width are modelled with considering actually shrinkage after vapour phase drying and impregnation process of transformers. The inter disc conductor are separated by 4.5 mm radial spacers for HV winding and 3mm radial spacer for LV winding to form horizontal (radial) cooling ducts. Axial dovetailed strips are used at both inside and outside of the winding (6.5 mm for LV and HV winding) and pre-compressed board (3 mm cylinders), onto which the winding is wound in winding former, to form vertical (axial) cooling ducts. The oil from the radiator passes along the axial duct followed by the radial movement, then to axial and radial and this way reaches top of the winding and to the radiator again. This process goes on in this sequence, resulting in dissipating heat through the radiators and lowering the temperature inside the transformer.

The tank and core dimensions, cooling arrangement and the operating conditions are fed as an input to the software to get the temperature profile of the transformer. The operating conditions in Figure 5.6.

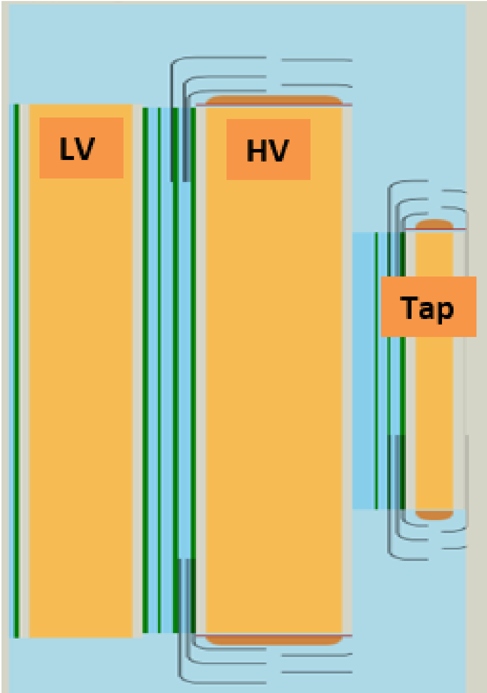


Fig. 5.5. Winding configuration for thermal analysis

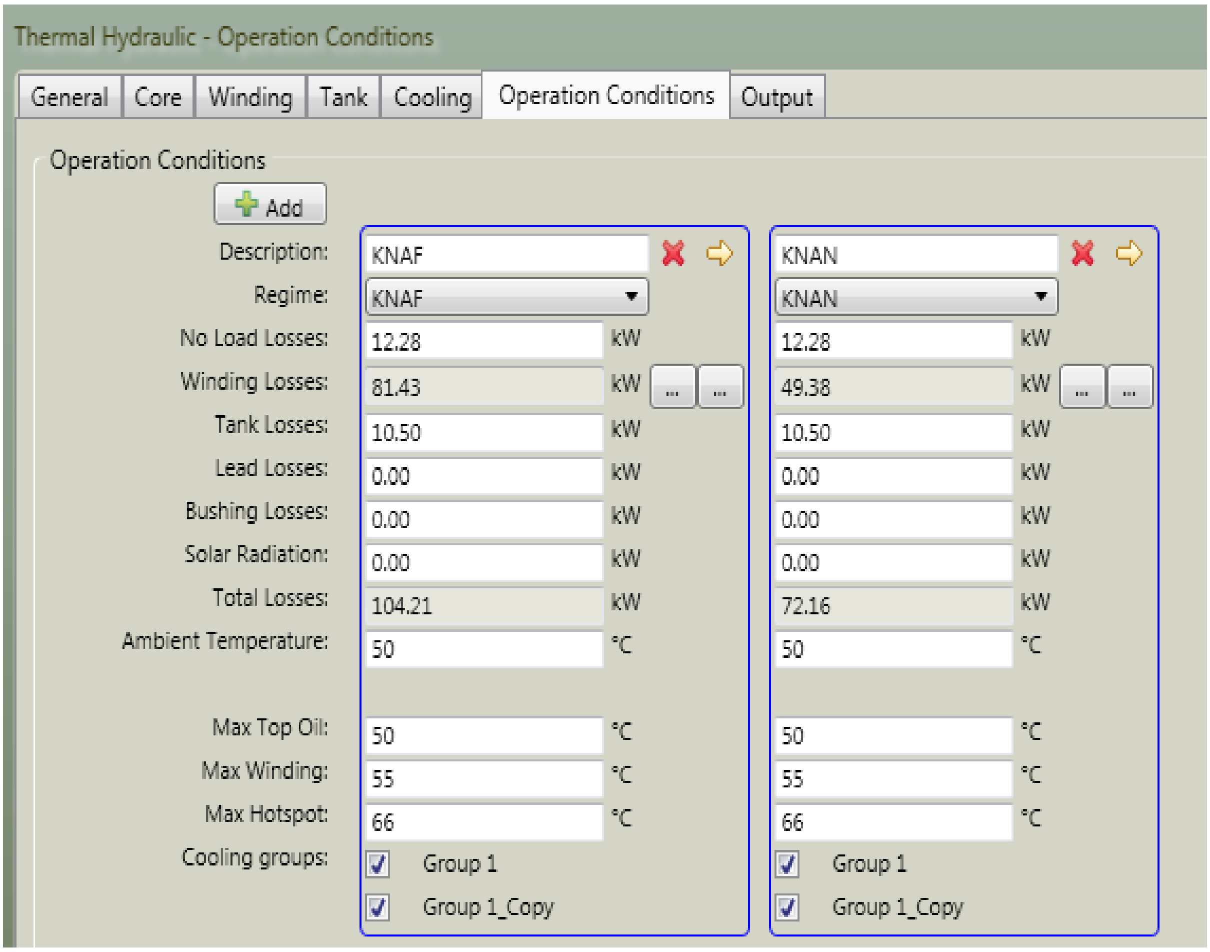


Fig. 5.6. Operating conditions for the transformer

5.3.2 Thermal operating conditions

The thermal ageing of conductor paper covering in transformers depends upon their operating temperatures at site. The thermal operation limits of mineral oil are considered for ester oil transformers to ease the comparative analysis among them. Hence, the ambient temperature is kept constant at its maximum possible value as 50°C. The maximum value of top oil temperature, winding temperature rise and hotspot rise are taken as 50°C, 55°C & 66°C respectively. The thermal properties of mineral oil and ester oil is taken from the catalogues provided by the oil manufacturer which is represented as a function of temperature and is obtained from curve fittings techniques of the measured data.

5.3.3 External cooling models

Transformer oil carries the heat through both convection and conduction generated by power losses from winding to the radiator. The transferred heat through the radiator depends on oil flow rate, total surface area, and external cooling medium and ambient temperature. In this transformer, the center to center height of the radiator and no of plates per radiator is 2200 mm and 20 respectively. The heat transfer coefficient from the radiator surface to the external cooling medium determines the required total radiator surface area. The selected domestic radiator is a double panel radiator with 2200 mm length and 0.7 m height. The datasheet of the radiator indicates that under normal domestic heating conditions with mean water temperature of 50°C, the radiator is able to dissipate 4000 W. External fans are mounted at the horizontal position to increase the heat dissipation through the radiator. External fans are act as a heat exchanger which is used to maximize heat dissipation from the radiator to external cooling medium.

5.4 RESULTS AND DISCUSSIONS

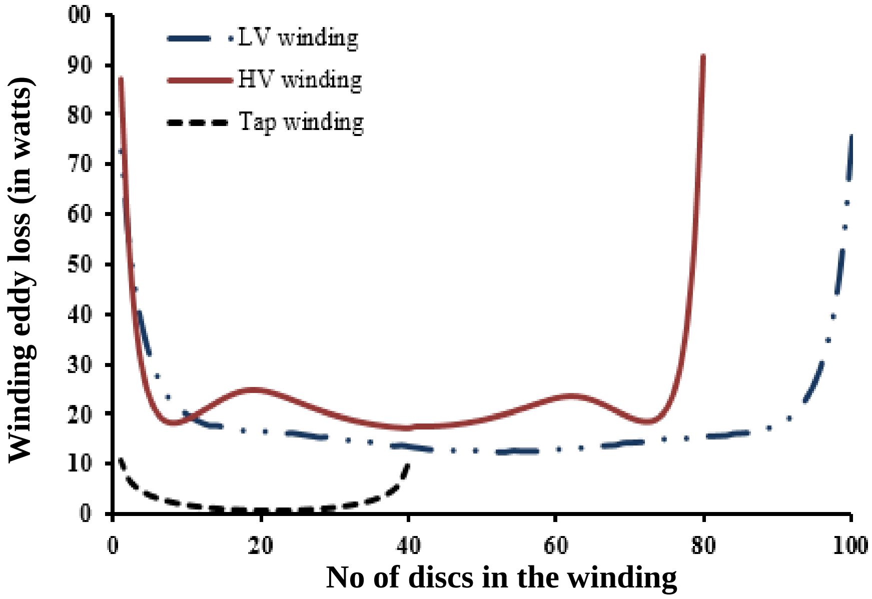
In this section, focus has been done on comparing oil flow rate, top oil temperature, average winding temperature rise and the hotspot temperature rise for the mineral, natural ester and synthetic ester oil transformers. Due to more viscosity, oil flow rate and therefore, the heat dissipation rate of the ester oil becomes slow resulting in rise in temperature sometimes beyond the specified limits. Therefore, the study will provide relevant information about the cooling arrangement required for designing ester oil transformer to maintain the temperature profile for the safe and reliable operation. The results obtained are shown in Table 5.1 wherein temperature profiles of transformer winding for three different oils under various cooling modes have been compared.

Table 5.1: Comparison of transformer thermal properties for differed insulating oils

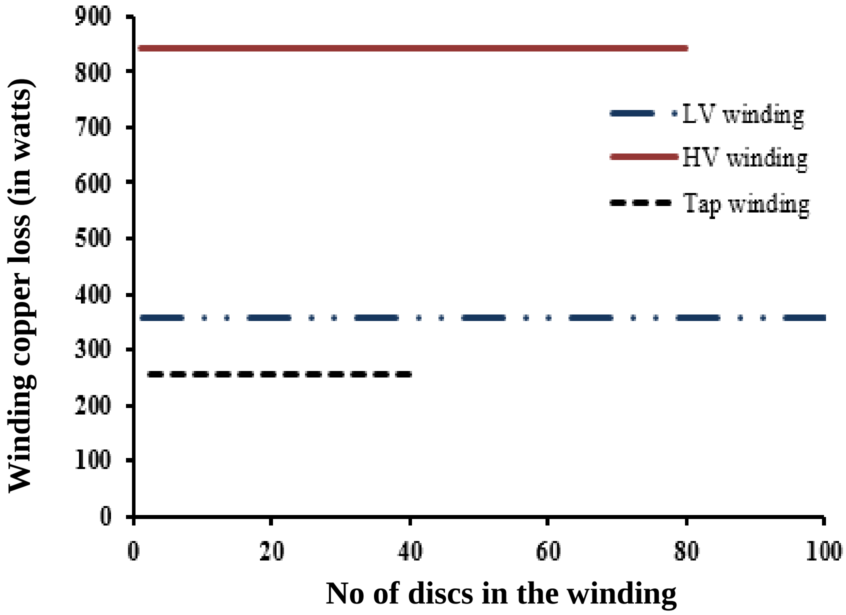
Properties of transformer after Thermal analysis		**Mineral oil**				**Natural ester oil**				**Synthetic ester oil**			
		Non-Directed Cooling		**Directed cooling**		**Non-Directed Cooling**		**Directed cooling**		**Non-Directed Cooling**		**Directed cooling**	
Cooling methods		**ONAN**	**ONAF**	**ONAN**	**ONAF**	**KNAN**	**KNAF**	**KNAN**	**KNAF**	**KNAN**	**KNAF**	**KNAN**	**KNAF**
Total oil flow (m^3/h)		7.9	9.6	8.6	10.4	5.6	6.9	6	7.4	5.7	7.2	6.2	7.8
Top Oil temperature (°C) Limit: 50°C		47.5	39.2	47	38.5	**50.3**	43	49.7	42	**50.1**	44	**50**	43
Average oil temperature (°C)		41.8	31.2	41.8	31.1	42	31.2	42	31	42	32	42.1	32
Bottom oil temperature (°C)		36.2	23.3	36.6	23.8	33.8	19.5	34.3	20.1	33.3	20.2	34	21
Top – Bottom temperature difference (°C)		11.3	15.8	10.4	14.7	16.5	23.5	15.3	21.9	17.7	23.8	16.5	22.1
Average winding rise (°C) (Limit: 55 °C)	LV	47.6	40.5	47.9	41	47.8	40.8	48.2	41.4	47.8	41.7	48.3	42.3
	HV	48.8	42.3	49.6	45.6	49.7	42.8	52.5	47.2	49.3	43.7	52.7	48
	Tap	45	36.3	45.3	36.8	44	34.6	44.4	35.3	43.8	35.4	44.3	36
Testbay gradient (°C)	LV	5.7	9.3	6.1	9.8	5.7	9.6	6.2	10.3	5.7	9.6	6.2	10.3
	HV	7	11	7.8	14.5	7.2	11.6	10.5	16.1	7.21	11.6	10.6	16.1
	Tap	3.2	5.1	3.6	5.7	1.9	3.5	2.4	4.2	1.7	3.3	2.2	4.1
Hot spot temperature rise (°C) (Limit: 66 °C)	LV	55.2	52.8	56	54	55.3	53.4	56.4	60.8	55.3	54.3	56.4	56
	HV	58	56.8	60	65	58.7	58.2	66.4	68.5	58.9	59	66.8	69.3
	Tap	51.6	45.9	51.7	46	52.8	47.5	52.8	47.5	53.3	48.4	53.3	48.4

5.4.1 Transformer winding loss distribution

Thermal stress occurs due to the electrical losses generated within the transformer and the imperfect cooling system of the transformer. Therefore, power losses in the transformer winding and core acts as a heating source. Therefore, accurate prediction of power losses is main criteria for thermal analysis. The power loss distribution of the transformer winding is not uniform from top to bottom of the winding with quasi-uniform resistive losses along the winding and eddy current losses concentrating on the top and bottom part of the winding. Hence, empirical formulae are not feasible to calculate the losses accurately.



(a)



(b)

Fig. 5.7. Power loss distribution in the winding (a) eddy loss (b) copper loss

The numerical technique has an ability to simulate and analyse the complex geometry and to determine copper losses, winding eddy loss and stray losses more precise than empirical methods. Hence, the copper losses, winding eddy loss are calculated for all the winding using FEM based techniques. The stray losses calculated accurately using magnetic analysis and fed as an input to the THNM models.

From the Figure 5.7 (a) and (b), the following points are observed:

- For the eddy current losses, if the leakage magnetic flux is properly controlled by using proper conductor selections to reduce its radial component, the eddy current losses in the winding can generally be reduced to less than 20% of the resistive losses.
- The copper losses in each disc of LV, HV and Tap are uniform from top to bottom of the disc. The copper loss of each disc for LV winding, HV winding and tap winding are 248 W/disc, 584 W/disc and 180 W/disc respectively.

5.4.2 Thermal Analysis

Generally, viscosity of the oil is the main parameter to affect the thermal performance of oil for cooling purpose, especially in naturally cooled systems other than specific heat capacity and thermal conductivity. Ester oil has higher viscosity than mineral oil and it will leads to reduce the oil flow, further influence (or worsen) the cooling effect of a transformer oil natural mode. Since, thermal conductivity of ester oil is higher than mineral oil, it will provide some compensation for heat dissipation. For ON cooling modes of mineral oil and KN cooling modes of ester oil, the flow of the oil is driven by buoyancy forces.

The hot-streak dynamics play a main role to predict the oil flow and temperature distributions. The Figure 5.8 provides the comparison of rate of oil flow and temperature distribution in mineral and ester oil transformers under oil natural conditions. The temperature distribution in the winding is not uniform based on power loss distributions from bottom to top of the windings. Hence, the top of the winding reaches the maximum temperature and it normally undergoes the severest thermal ageing of paper and oil which leads to reduce the life expectancy of the transformer insulation.

The Figure 5.9 provides the comparison of rate of oil flow and temperature distribution in mineral and ester oil transformers under oil forced conditions and are then compared for directed and non-directed cooling. It has been seen that the rate of oil flow increases and temperature rise decreases by using oil guiding washers at different positions of the windings to direct the flow of oil for uniform oil distribution along all the discs of the windings.

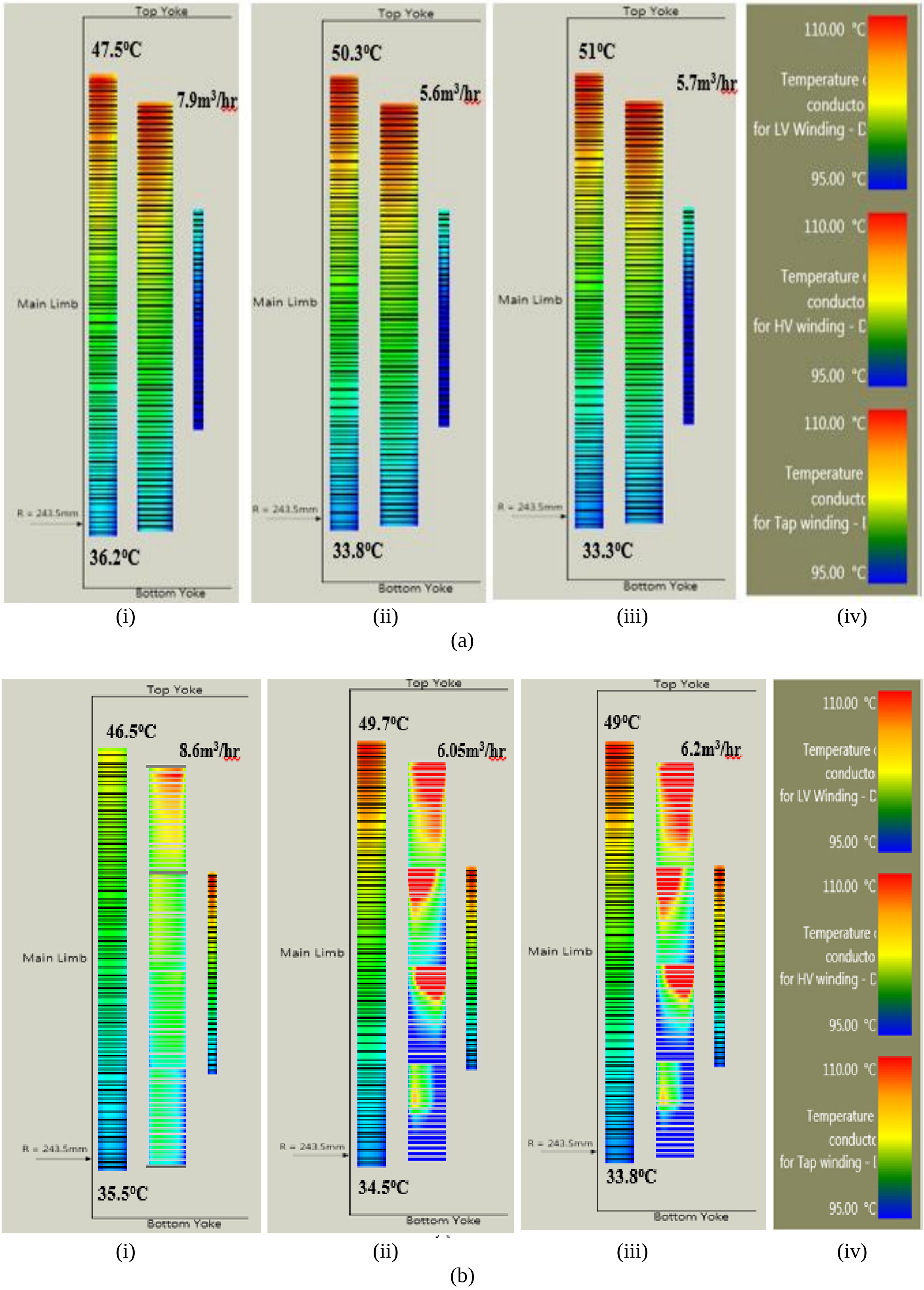
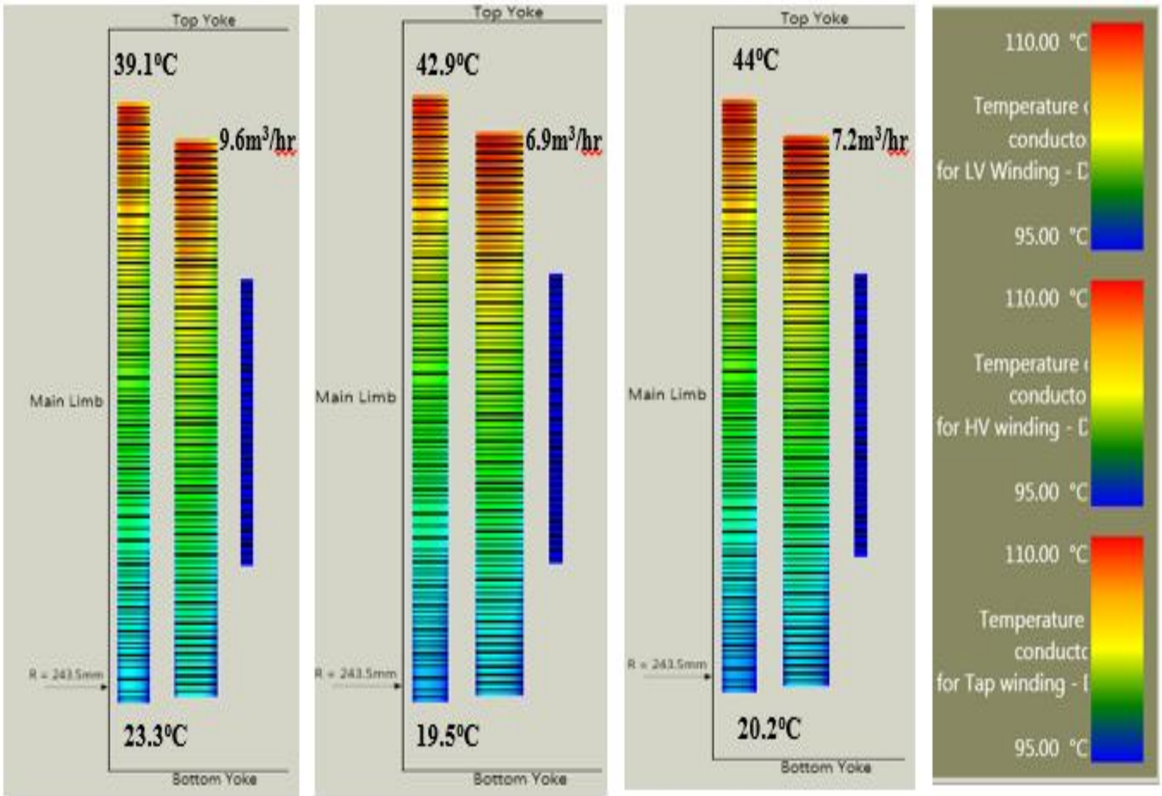
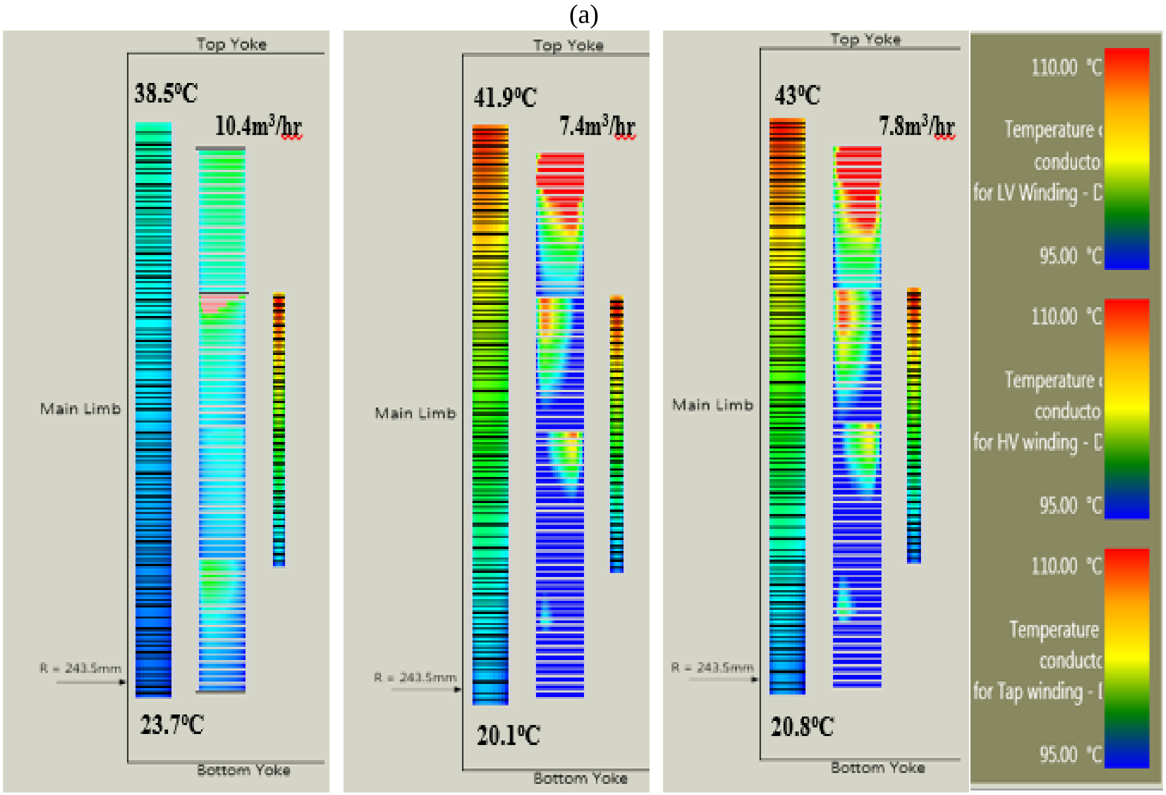


Fig. 5.8. Temperature distribution and oil flow rate of mineral oil and ester oil transformer of 12.5 MVA
(i) Mineral oil, (ii) Natural ester oil, (iii) Synthetic ester oil, (iv) Temperature distribution
(a) non-directed oil natural cooling (b) directed oil natural cooling



(i) (ii) (iii) (iv)

(a)



(i) (ii) (iii) (iv)

(b)

Fig. 5.9. Temperature distribution and oil flow rate of mineral oil and ester oil transformer of 16 MVA
(i) Mineral oil, (ii) Natural ester oil, (iii) Synthetic ester oil, (iv) Temperature distribution
(a) non-directed oil forced cooling (b) directed oil forced cooling

From the analysis on 12.5/16 MVA transformer, the oil flow rate of ester oil is about 28% higher than mineral oil and top oil temperature rise is increased above 2.5°C with respect to mineral oil in air natural cooling mode conditions. In air forced condition, the top oil temperature is increased around 3-4°C in ester oil.

5.4.3 Oil flow rate analysis

The cooling performance of the transformer is greatly affected by the distribution of oil flow across the winding. Furthermore, a static pressure drops across the winding which are in parallel determines a hydraulic division of oil. Hence, the total oil flow rates of mineral and ester oils for the same winding geometry with the same power loss distribution in an ON-cooling mode are estimated. The development of the oil flow rate is impacted by the thermoplastic power in the winding and the total pressure lower in the hydraulic transformer loop under liquid natural conditions (ON or KN). The total rate of oil flow provides the effects of viscosity of ester oil on oil flow distribution and temperature distributions using by THNM simulations (in Figure 5.10).

From Figure 5.10, following observations are drawn:

- The oil flow rate (m^3/h) for mineral oil is 28% more than that of natural and synthetic ester oil due to their more viscous nature.
- Oil flow rate is increased by 8% by changing directed cooling from non-directed cooling.

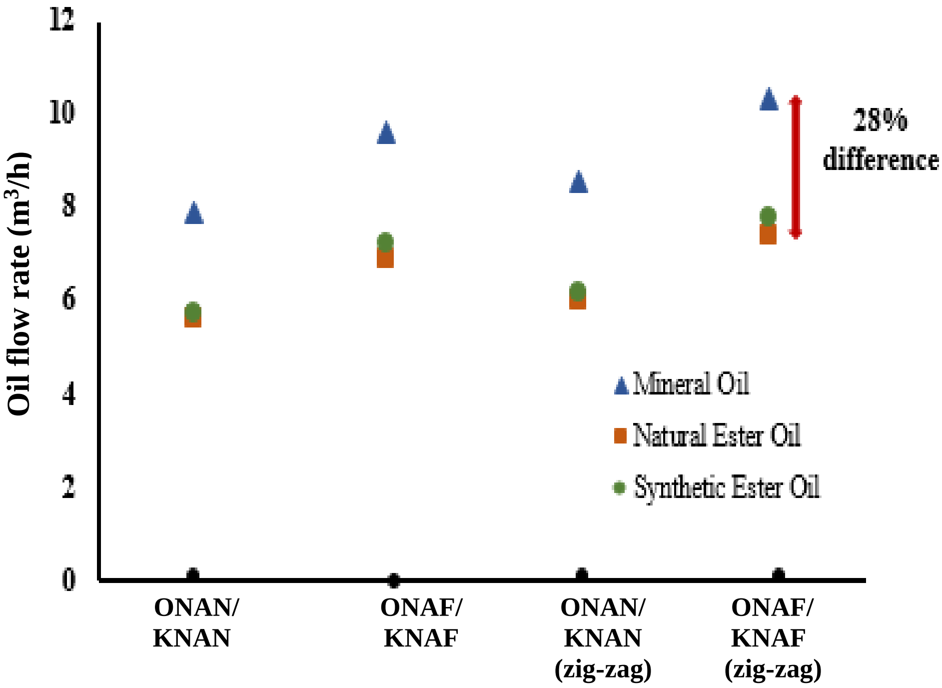


Fig. 5.10. Rate of oil flow at different cooling modes

5.4.4 Top oil temperature rise distribution

The difference between the oil (liquid) temperature at the top of the tank and the ambient temperature is known as top oil temperature rise.

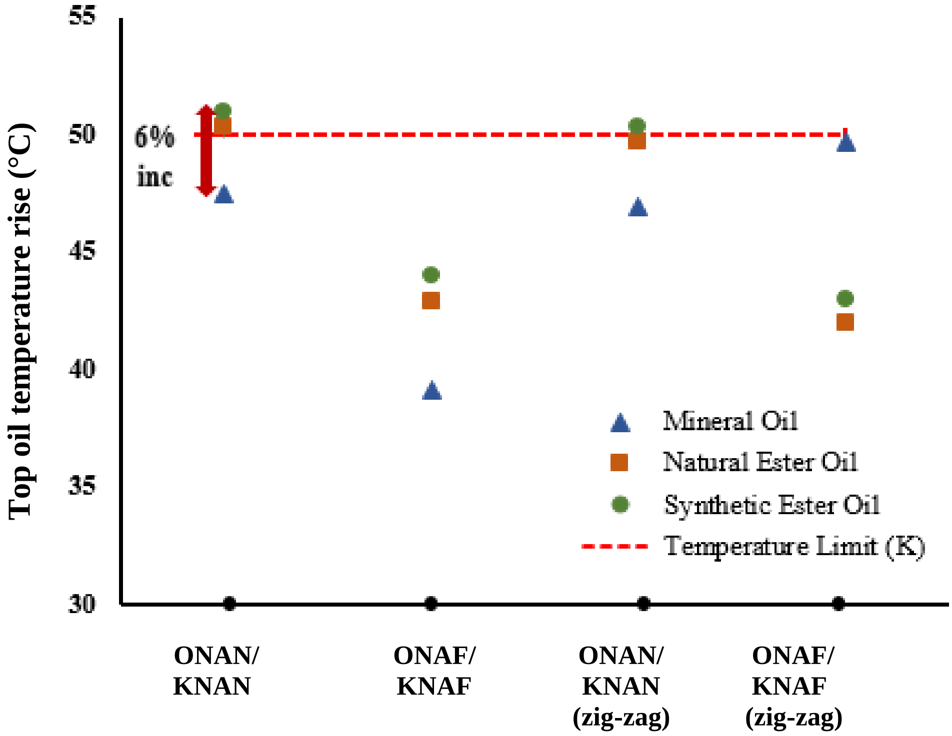


Fig. 5.11. Top oil temperature rise at different cooling modes

The observations from Figure 5.11 are:

- The top oil temperature of mineral oil is 6% lower than that of natural and synthetic ester oil.
- The oil temperature can be reduced by 2% in case of directed cooling.

The top oil temperature of ester oil in case of directed natural cooling is exceeding the limits (50°C).

5.4.5 Hotspot winding temperature rise distribution

The cooling performance of the transformer is generally performed to calculate the hot spot temperature which is an important parameter to evaluate the end life of the transformer. Hence, the main objective of designing thermal model of transformer is to identify the hot-spot temperature rise over ambient temperature for ester oil and compare the results with mineral oil at rated loading of transformer in steady state conditions. For oil immersed transformers, the hot spot temperature rise over the ambient temperature is mainly controlled by the geometry of the winding, power loss distribution, oil flow rate and oil properties. Further, the hotspot factor is an essential component that must be considered while designing thermal model for the determination of hotspot temperature from the temperature rise data. The hot-spot factor is affected by both the local power losses and local cooling efficiency at the hot-spot. The concept of hotspot factor becomes more empirical than theoretical which the assumption of linearity in the transformer thermal model.

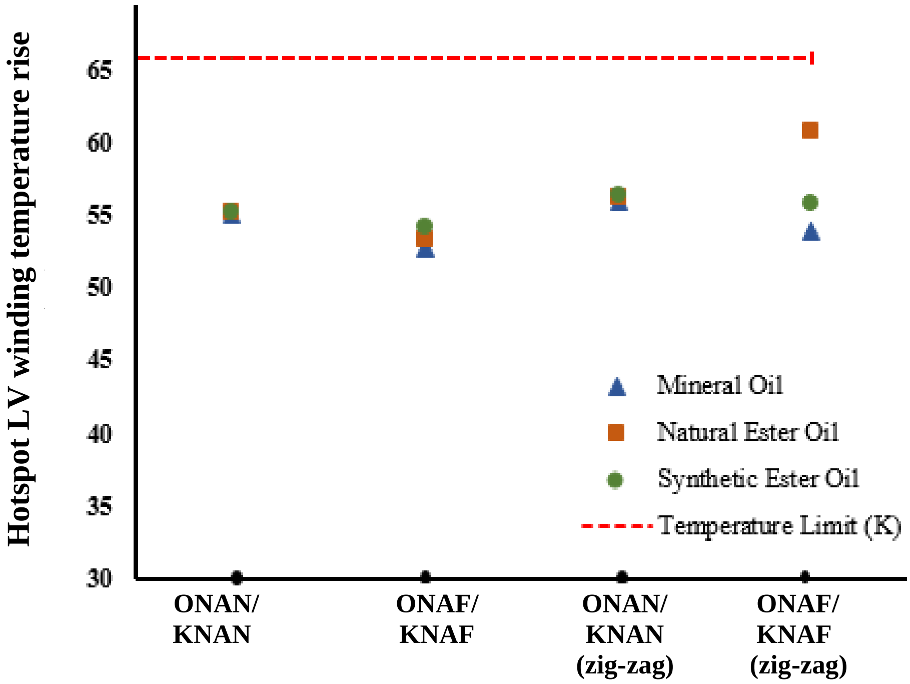


Fig. 5.12. Hotspot winding temperature rise for LV winding

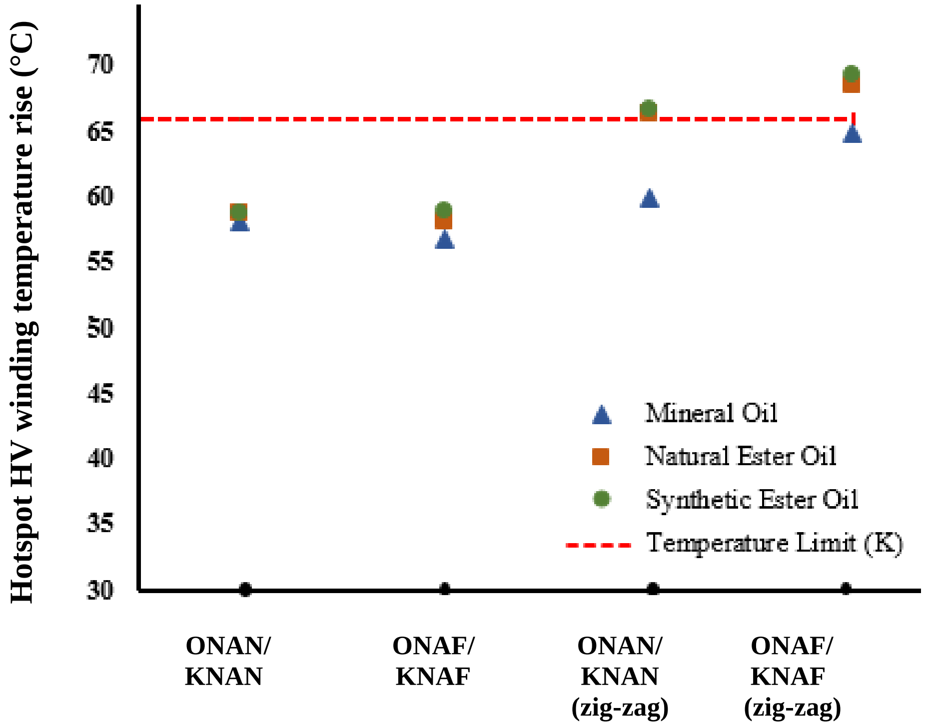


Fig. 5.13. Hotspot winding temperature rise for HV winding

The interpretations from Figure 5.12 & 5.13 are:

- The hotspot rise in temperature is 1% & 6% lesser in mineral oil as compared to ester oils for non-directed and directed cooling respectively.
- There is an increment of 13% hotspot winding temperature with the use of directed cooling as compared to non-directed cooling. In case of directed cooling, hotspot temperature rises for ester oil (both natural and synthetic) is exceeding the limit (66°C).

5.4.6 Average winding temperature rise distribution

The difference between the average winding temperature and the ambient temperature is known as average winding rise. The average winding temperature is measured by the resistance method and includes extrapolation back to the point of shutdown. In disc type transformer winding, the oil is circulated through cooling ducts in radial and axial directions to transport heat from within the winding to the external cooling medium.

Figure 5.14 & 5.15 provides the following information:

- The average winding temperature rise is around 0.5% higher for mineral oil as compared to natural and synthetic ester oil.
- There is a decrement of 15% in average winding temperature rise for forced cooling.

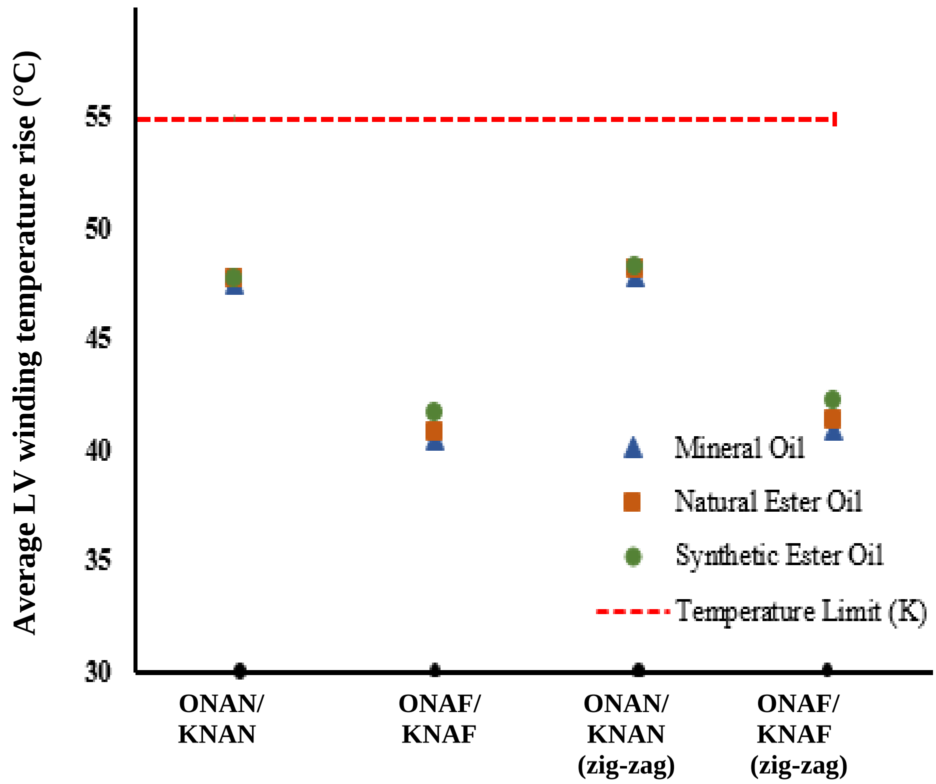


Fig. 5.14. Average winding temperature rise for LV winding

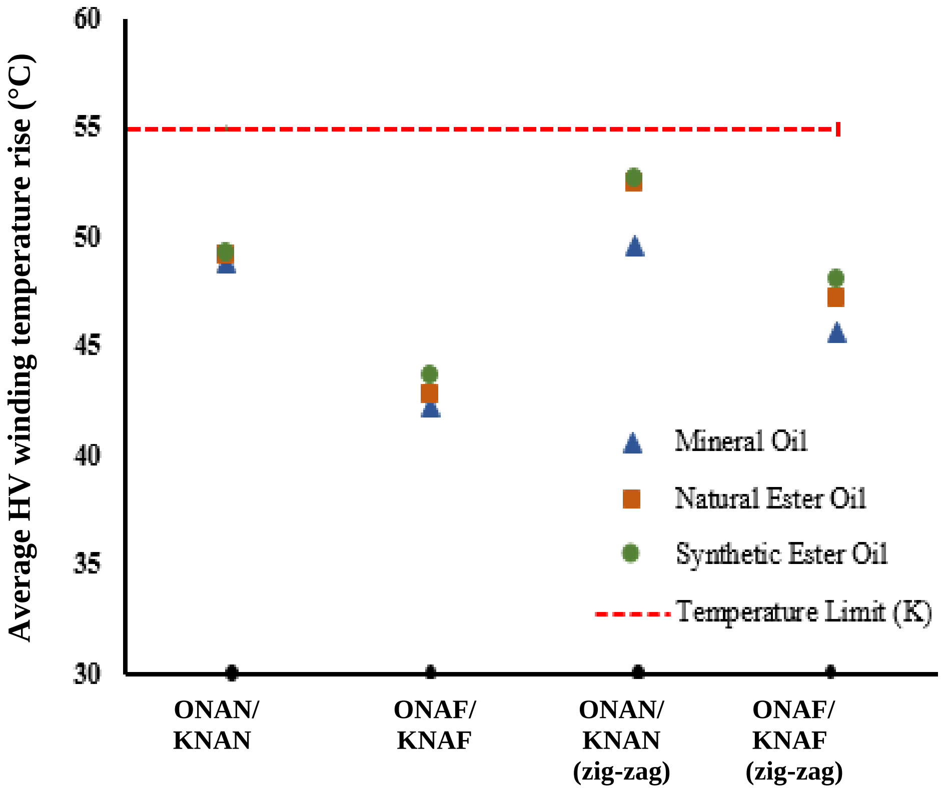


Fig. 5.15. Average winding temperature rise for HV winding

5.5 CONCLUSION

Determination of the temperature distribution within the transformer winding is crucial for both thermal design in the factory and thermal rating during the operation. The transformer filled with ester oil is becoming an option in place of mineral oil for a wide range of voltage levels in transformers. Therefore, the results obtained are universally applicable and of the simplest form as well. In addition, the dimensional analyses have provided insight into how the flow and temperature distribution patterns are controlled by the dimensionless controlling parameters, regardless of the transformer operational conditions and the coolant liquid types used.

For the prediction of the location and temperature of hotspot, thermal modeling is very important. The characteristics of hotspot inside the transformers is mainly being affected by the rate of oil flow and its distribution across the disc arrangement of the windings. Thermal modeling has been used when a basic knowledge of oil stream and the distribution of temperature within a transformer system is needed. Due to more viscosity of ester oils, ester oil transformers have lower oil flow rate and therefore lower heat dissipation rate as compared to mineral oil transformers.

CHAPTER 6
CONCLUSION

The objective of this thesis was to develop process guidelines for ester oil transformer through compatibility analysis of transformer construction materials, withstand strength of windings through insulation resistance testing and finally predication of thermal profile of the ester oil transformers under various cooling and loading conditions. Using experimental and simulation results, the research objective has been achieved and the major findings have been evaluated to design the transformer with new insulating oil.

The work done in the dissertation is discussed as:

A. Material compatibility of ester oil transformers
   i. Effect of incompatible materials on various oil properties that includes:
      - Dielectric breakdown strength
      - Dissipation factor
      - Interfacial Tension
      - Acid Number
      - Color
      - Dissolved Gases in the oil
   ii. Effect of ageing on solid insulation with the variation in temperature and time

B. Insulation resistance testing of transformers
   i. Prediction of effect on insulation resistance of transformer windings immersed in ester oil with respect to mineral oil
   ii. Prediction of effect on dissipation factor of transformer windings immersed in ester oil with respect to mineral oil

C. Thermal modelling of ester oil transformers
   i. Thermal performance of transformers under various cooling and temperature conditions
   ii. Thermal modelling using THNM simulations
   iii. Transformer winding loss distribution under natural and forced cooling
   iv. The rate of oil flow in the different insulating oils under various cooling conditions.
   v. The prediction of temperature profile i.e. top oil temperature rise, average winding rise and hotspot temperature rise for mineral and ester oils under directed and non-directed cooling

6.1 MAIN FINDINGS OF THE DISSERTATION

From the experimental and simulation results, it can be concluded that the before designing a transformer with a new insulating oil, material compatibility is the foremost step that needs to be considered. A material that have been used in conventionally used mineral oil transformer may or may not be compatible with the new oil. Experimental studies suggest that the incompatibility may lead to the increase in dissipation factor, resulting in reduction in the dielectric strength of the oil, increase in dielectric losses resulting in the increase of fault gases that in the long run may prove fatal for the transformer applications. Also, the misleading results obtained from nitrile damping washer testing, it becomes important to check the chemical composition of a material to be used in transformer as per the applications for avoiding misleading results in the compatibility studies.

Due to more dissipation factor of ester oil, it is found that the dielectric losses in the transformer insulation system are more as compared to mineral oil transformer. But dielectric losses are negligible as compared to I^2R losses which are predominant in mineral oil transformers.

Further, ester oil due to their more viscosity and density as compared with mineral oil, have low rate of oil flow which makes the process of heat dissipation across the discs of the winding slower resulting in increase in temperature. Determination of the temperature distribution within the transformer winding is crucial for both thermal design in the factory and thermal rating during the operation. The transformer filled with ester oil is becoming an option in place of mineral oil for a wide range of voltage levels in transformers. Therefore, the results obtained are universally applicable and of the simplest form as well. In addition, the dimensional analyses have provided insight into how the flow and temperature distribution patterns are controlled by the dimensionless controlling parameters, regardless of the transformer operational conditions and the coolant liquid types used.

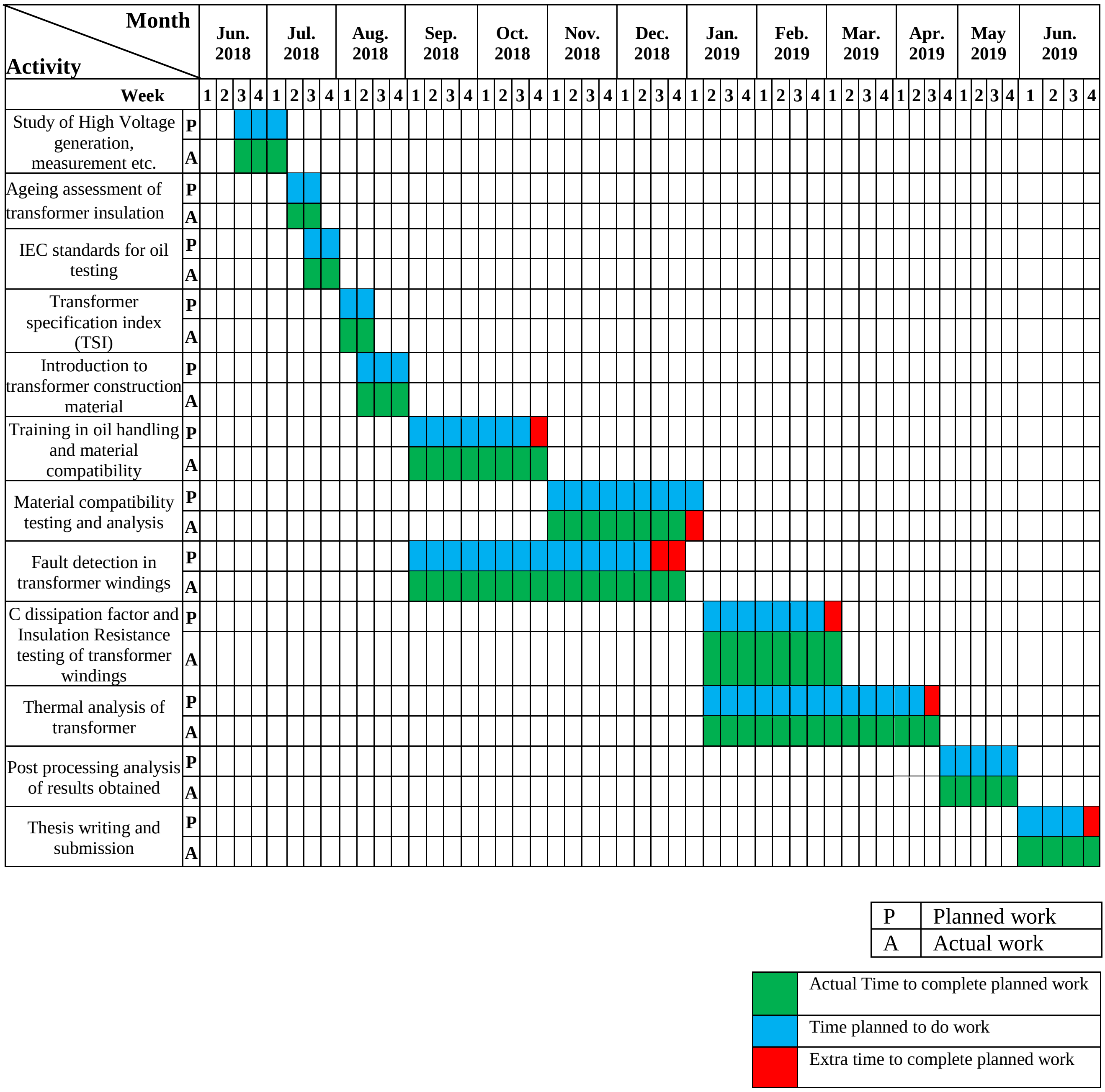
6.2 FUTURE SCOPE

The research work that can be carried out in future includes:

- The rate of oil flow in the ester oil transformers have been calculated using thermal hydraulic network modelling. In future, the simulation results need to be verified using experimental results
- The increase in temperature in ester oil transformers can be reduced further by using external cooling methods. Therefore, thermal optimization studies needs to be performed.

- Despite of various advantages, there are certain limitations of ester oil, major is less oxidation stability i.e. ester oil transformers can be used in sealed conditions only. In future, work can be done to improve the oxidation stability of the ester oil by the use of some additives.

6.3 WORKPLAN



LIST OF ACHIEVEMENTS / PUBLICATIONS

1. Awarded "**Gold Medal**" for scoring first position in M.E. Power Systems in the year **2018.**
2. **A. Garg**, A. Tiwary, P. Basak and A. Paramane, "Effect of Applied Voltage and Electromagnetic Shielding on Partial Discharge," *2018 International Conference on Computing, Power and Communication Technologies (GUCON),* Greater Noida, Uttar Pradesh, India, 2018, pp. 652-656.
3. **A. Garg**, T. Sharma, A. Jain and J. Velandy, "Statistical synchronization technique for transient signal analysis during impulse testing of transformers", has been submitted in *IEEE Transactions on Power Delivery* (Revision 1).
4. A. Jain, T. Sharma, **A. Garg** and J. Velandy, "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)* (under revision).
5. **A. Garg** and J. Velandy, "Thermal hydraulic network model for prediction of oil and temperature distribution in ester oil transformer under air natural and air forced cooling conditions" has been communicated to *IEEE 4th International Conference on Condition Assessment Techniques in Electrical Systems (CATCON 2019)* to be held at IIT Madras (21-23 November, 2019).
6. **A. Garg** and J. Velandy, "Compatibility of ester oil with transformer components and comparison with mineral oil" has been communicated to *IEEE 4th International Conference on Condition Assessment Techniques in Electrical Systems (CATCON 2019)* to be held at IIT Madras (21-23 November, 2019).
7. **A. Garg** and J. Velandy, "Nonlinear synchronization technique for high frequency transient signal analysis during impulse testing of transformers" has been communicated to *IEEE 4th International Conference on Condition Assessment Techniques in Electrical Systems (CATCON 2019)* to be held at IIT Madras (21-23 November, 2019).

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