Thermal hydraulic network model for prediction of oil and temperature distribution in ester oil transformer under air natural and air forced cooling conditions

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***Abstract*— Recently, there is a growing interest in ester oil transformer for fire safety, eco-friendly and continuous over loading capability in comparison to conventionally used mineral oil transformer. The high interest on ester oil transformer has led to several analysis aimed at prediction of their dielectric analysis, thermal analysis and process development. 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 paper, Thermal Hydraulic Network Model (THNM) are effectively used to predict the oil flow distribution and the temperature distribution in 12.5/16MVA, 132/11kV transformer and compared with mineral oil in steady state conditions. The total oil flow rates of mineral oil and ester oil oils are compared with same winding geometry, power loss distribution (resistive losses in the winding conductors, winding eddy loss and stray loss) in a cooling mode. The power losses are calculated using finite element method (FEM) based simulation software and utilized for thermal analysis in THNM model. 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.**

***Keywords*—Transformer, Transformer oil, Ester oil, Thermal analysis, Thermal model, Winding insulation, Temperature rise.**

I. Introduction

Mineral oil is 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 [1-6]. However, mineral oil has some limitations in terms of fire safety, environmental impact and continuous overloading capabilities [5, 6]. Recently, ester oils are considered as an alternative to mineral oils for transformers. The technical challenge in the usages of ester oils are insulating properties and cooling properties different from mineral oil and it might change the design, manufacturing and impregnation process of transformer [5,6]. If the transformer utilities are considered to use the ester oil as an alternative of mineral oil for a transformer, then it is important to understand the characteristics of ester oil by transformer manufacturer. The prediction of thermal behavior of ester oil is one of the main criteria at design stage to utilize the ester oil in transformer due to higher viscosity since heat run test is one of the factory witness tests to validate the thermal behavior.

The higher viscosity and density of ester oil with respect to mineral oil will increases the top oil temperature rise, winding rise and higher hot-spot temperature at top of the winding even ester oil has higher specific heat and thermal conductivity [5]. Hence, higher viscosities and density 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 to use ester oil in transformers. In this paper, 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 mineral oil transformer of 12.5/16MVA, 132/11kV. Thermal hydraulic network model are used to estimate temperature distribution within the transformer winding.

II. Transformer Oil under Consideration

Mineral oil is a mixture of various hydrocarbon molecules having various structures such as paraffinic, naphthenic and aromatic. Naphthenic based mineral oil has more readily oxidized than paraffinic oil. The main advantages of mineral oil are better heat transfer, good oxidation stability and high dielectric strength. However, mineral oils have poor biodegradability and low flash/fire points [1-4].

Natural ester oil is derived from natural plants (vegetable seeds). The ester linkage has three different C18 fatty acid chains which will contain one, two or even three double bonds based on viscosity of the oil [5, 6]. The greater number of double bonds will lead to lower oxidation stability and higher molecular weight of natural ester oil results in considerable increase in viscosity in comparison to mineral oil which have much lower molecular weight. The increase in viscosity of the oil will reduce the cooling performance of transformer.

Synthetic ester oil is manufactured synthetically by reaction of four acid groups with pentaerythritol forming with four ester groups [5]. The saturated group presents in synthetic ester oil provide molecule structure offering high oxidation stability.

III. THERMAL MODELING 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 model and Computational fluid dynamics (CFD) model [5,6]. Reliable thermal modeling approaches are needed for thermal design analysis of transformer and it is required for the transformer designer at design stage to meet the customer guarantees values.

A. Computational fluid dynamics

Generally, numerical method based CFD models are used to solve the governing differential equations for oil flow analysis and heat transfer analysis [5-8]. Hence, CFD calculation provides more information to thermal designer due to distributed parameter models. In addition, the calculation time of oil flow distribution and the temperature distribution for a complete transformer geometry will be very long for several hours or days and even not possible to solve the geometry. Hence, CFD calculation is not suitable at the stage of design.

B. Thermal hydraulic network model

THNM model are generally based on lumped parameter models and it consists of a hydraulic network model and a thermal network model to describe the oil flow and heat transfer in rather coarse networks [5-8]. In hydraulic network model, mass conservation and pressure equilibrium in each closed oil flow loops are considered to calculate the oil flow distribution in the winding. In 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 [5-8]. Therefore, the effects of conduction and convection are conveniently lumped into thermal resistance for oil flow. It provides oil flow distribution and the temperature distribution as an intermediate solution between simple design rules and complex CFD calculations [8]. Hence, the determination of the oil flow distribution and the temperature distribution in transformer in steady state is mainly performed by using THNM model and it based on past experiences in ester oil and mineral oil.

IV. THERMAL HYDRAULIC NETWORK MODELING OF TRANSFORMER

The thermal performance of transformer mainly based on external and internal cooling components working together. Hence, transformer thermal components are divided into internal components (steel core, windings with their supporting structure and finally the transformer insulations) and external components (radiators, conservator, external pumps and cooling fans) for thermal analysis.

A. Internal Winding models

Thermal modeling with transformer geometry input plays a vital role for accurate calculation of the thermal performance at the design stage without error. The first internal component of transformer is the steel core. In THNM, transformer is subdivided into smaller elements like oil channels, conductors, etc., and each element is formed as simple algebraic equations based on conservation of mass, energy etc., [2]. It allows the designer to calculate the thermal performance in a few seconds or minutes.

The geometry of a disc type of low voltage (11kV) and high voltage winding (132kV) consists of thermally upgraded paper covered conductors are used in this transformer. The winding model geometries such as number of discs, number of turns, conductor dimensions, radial cooling duct, height of the winding, axial cooling duct and end insulation are modeled with considering actually shrinkage after vapor phase drying and impregnation process of transformers.

The inter disc conductor are separated by 4.2mm (average) radial spacers for HV winding and 2.8mm (average) radial spacer for LV winding to form horizontal (radial) cooling ducts. Axial dovetailed strips are used at both inside and outside of the winding (6.5mm for LV and HV winding) and pre-compressed board (3mm cylinders), onto which the winding is wound in winding former to form vertical (axial) cooling ducts. Hence, the oil flows vertically upward from bottom of the transformer through radial and axial cooling ducts.

B. 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, external cooling medium and ambient temperature [2]. The heat transfer coefficient from the radiator surface to the external cooling medium determines the required total radiator surface area. In this transformer, the center to center height of 4 numbers of radiator and number of plates per radiator are 2200mm and 20 respectively. The width of hot dipped galvanized radiators is 520mm. The heat dissipation per section of radiator at oil temperature of 50ºC is 851Watss in air natural and 1438Watts in air forced conditions. The cooling surface area of the section is 2.64m^2.

Three phase, 50Hz, 500Watts, 900RPM external cooling fans are mounted at the horizontal position to increase the heat dissipation through the radiator. External cooling fan will perform as a heat exchanger which is used to maximize heat dissipation from the radiator to external cooling medium. In this paper, 610mm diameter with volumetric flow of 10450m^3/hr fan is selected.

C. Thermal operating conditions

The thermal ageing of conductor paper covering, pressboard insulation and liquid dielectric 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 are taken as 50°C, 55°C respectively based on customer specifications [3,4].

The thermal properties of mineral oil (Transol) and ester oil as a function of temperature are obtained from curve fittings techniques of the measured data provided in the oil manufacturers catalogues. With the data provided by the natural ester oil manufacturers of FR3 & BioTransol, density (kg/dm^3), dynamic viscosity (mm^2/s), thermal conductivity (W/mK) and specific heat of the oil (J/kgK) are utilized based on temperature for the thermal analysis using THNM models.

V. TRANSFORMER ANALYSIS RESULTS

A. Power Loss distribution in the winding

The oil flow distribution in conjunction with power loss distribution of transformer windings will decide the cooling performance in a disc-type transformer winding. The thermal stress in solid and liquid insulation occurs due to power losses (no load and load loss) generated in the transformer and the imperfect cooling system provided in the transformer. The power losses in the transformer winding and core act as a heating source. Therefore, accurate prediction of power losses is main criteria for thermal analysis.

The power loss distribution is a scalar function (W/m3) over the volume of transformer. 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 [7, 8]. Therefore, empirical methods are not always feasible to calculate the losses accurately. The numerical technique has an ability to analyze the complex geometry and to determine copper losses (I^2R or resistive losses), winding eddy loss and stray losses by more precise than empirical methods. Hence, the copper losses, winding eddy loss are calculated for all the winding using FEM based techniques. "Fig 1" and "Fig 2" show the copper loss of the winding and eddy loss distribution of the transformer windings of transformer.

From "Fig 1" and "Fig 2", the following points are observed.

- 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.
- The copper losses in each disc of LV, HV and Tap are uniform from top to bottom of the disc.

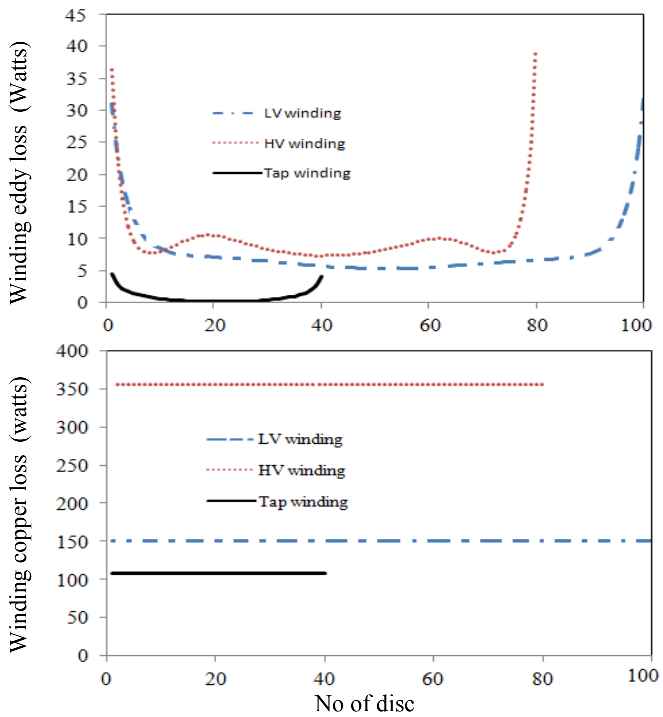


Fig 1. Power loss distribution in the winding for 12.5MVA base

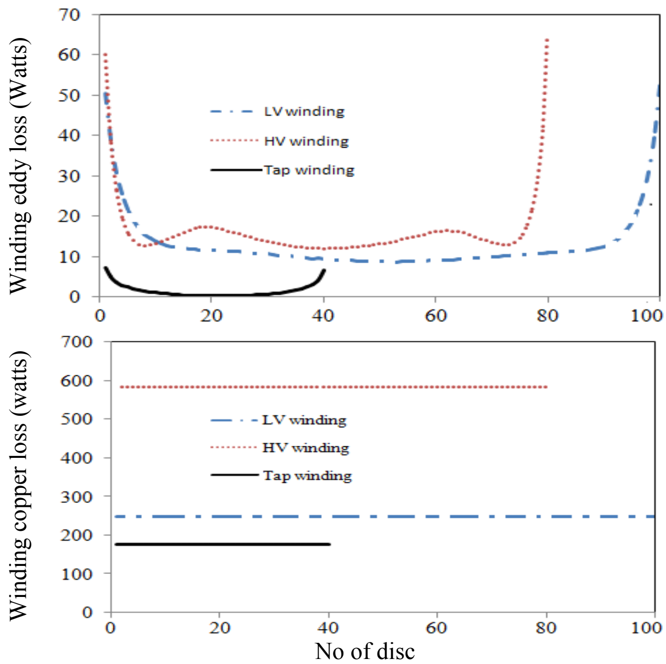


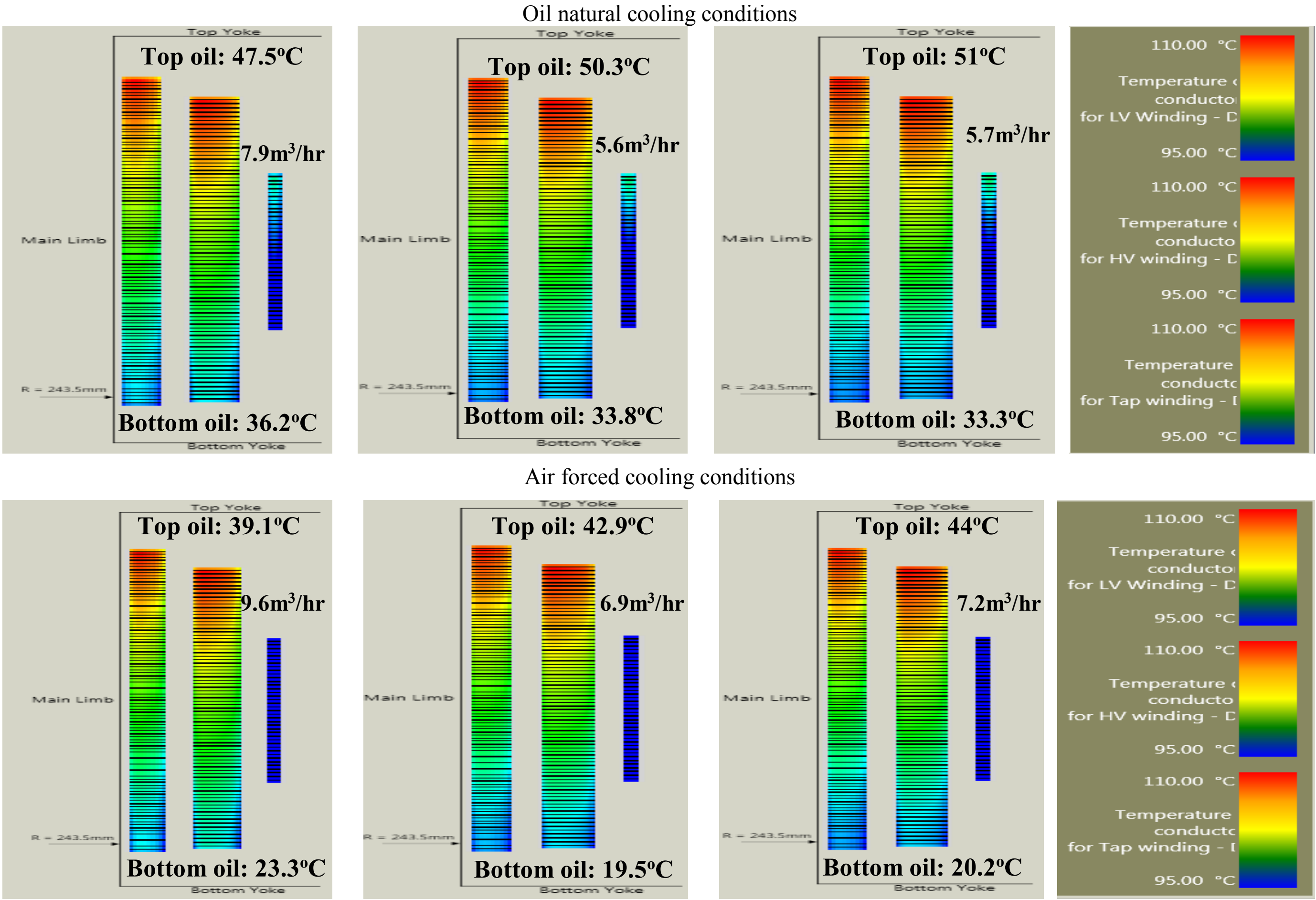
Fig 2. Power loss distribution in the winding for 16MVA base

B. Temperature distribution and oil flow rate analysis

Generally, viscosity of the oil is the main parameter which affects the thermal performance of oil for cooling purpose, other than specific heat capacity and thermal conductivity especially in naturally cooled systems [5,6]. 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. Since, the thermal conductivity of ester oil is higher than mineral oil, it will provide some compensation for heat dissipation.

The distribution of oil flow has a direct impact on the thermal performance of transformer based on cooling mode. In oil natural cooling mode, oil flow rate is based on thermosyphon force within the winding and the total pressure loss due to hydraulic loop [5,6]. In oil flow and temperature distribution calculation, Reynolds number (Pr), Prandtl number (Pp) and ratio between Grashof number (Pg) and square of Reynolds number (Pg/Pr^2) are dimensionless parameters [5,6]. The oil flow distribution depends upon Pr and Pg/Pr^2. For oil natural cooling mode, oil flow and transfer of heat are strongly coupled. Hence, Pr is more significant than Pp to calculate the oil flow and temperature distribution. The ratio of Pg and Pr^2 are directly related to buoyancy force which is the main driving force for oil flow [6] in oil natural mode.

In this paper, the total oil flow rates, temperature distribution of mineral and ester oils are compared with same winding geometry with the same power loss distribution in an oil natural cooling mode and air forced cooling mode. "Fig 3" shows the temperature distribution of mineral oil and ester oil under oil natural and air forced conditions. The oil flow rate is shown in "Fig 4".From "Fig 3", the temperature distribution in the windings is not uniform because the non-uniform oil flow distribution and the uneven distribution of power losses ("Fig 1" and "Fig 2"). Hence, 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 [8-10].



Mineral oil | Natural ester oil | Synthetic ester oil | Temperature distribution

Fig 3. Temperature distribution and oil flow rate of mineral oil and ester oil

The total oil flow rate in the winding has more influence on oil flow distribution and the temperature distribution in oil natural cooling modes. The total oil flow rate is calculated by thermal driving force and the pressure drop in the oil circulation loop [6]. The static pressure drop in the oil circulation loop depends upon by the geometry of transformer, oil properties and oil flow rate. The static pressure drop over the winding has low magnitude in oil natural cooling mode [5].

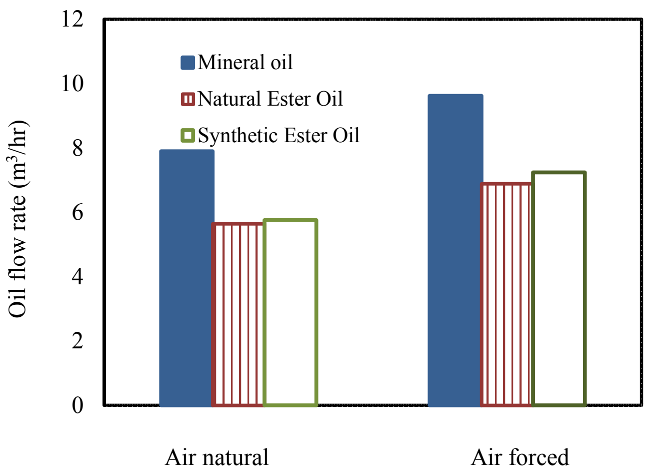


Fig 4. Rate of oil flow rate for air natural and air forced cooling

From “Fig 4”, following points observations are observed:

- In air natural conditions, the oil flow rate of natural ester oil and synthetic ester is 28.5% and 27% respectively which is lower than mineral oil respectively due to higher viscosity.
- In air forced conditions, oil flow rate of natural ester oil and synthetic ester oil are low by 28% and 24.5% respectively with respect to mineral oil.

C. Top oil temperature distribution

Top oil temperature has a great influence on the transformer operation life and overloading capacity. A lower value of top temperature rise will lead to increase the higher overload capability of transformer and reduces the thermal degradation of the insulation. In steady state conditions, the top oil temperature rise is directly proportional to power losses. “Fig 5” shows the top oil temperature of ester oil and mineral oil.

From “Fig 6”, the following points are observed.

- In air natural conditions, the top oil temperature of mineral oil is 6-7.5% lower than natural and synthetic ester oil.
- In air forced conditions, top oil temperature of natural ester oil 9.5% and 12.5% for synthetic ester higher than mineral oil. The top oil temperature of ester oil exceeds the limit of 50°C.

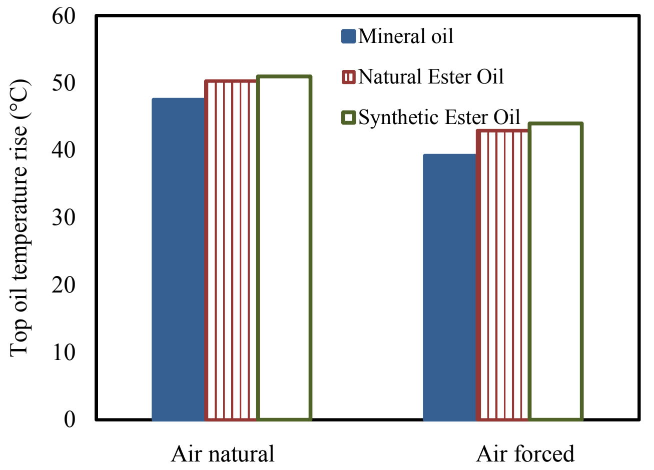


Fig 5. Top oil temperature rise for air natural and air forced cooling

D. Average winding rise distribution

A lower oil flow rate within the in the winding will increases the winding temperature gradient. The average winding temperature is generally obtained by resistance method during heat run test of transformer at manufacturing locations. In disc type transformer winding, the oil is circulated through cooling ducts in radial and axial directions to carry the heat from winding and core to the external cooling medium [8-14]. "Fig 6" shows the average winding rise distribution of LV and HV winding for mineral oil and ester oil transformer.

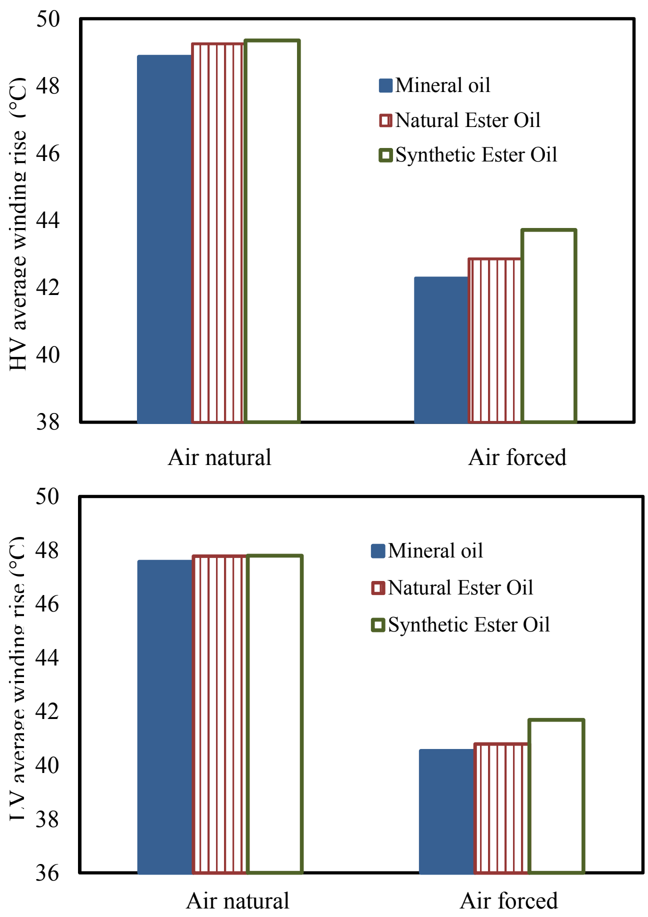


Fig 6. Average winding rise for air natural and air forced cooling of LV winding and HV winding

From "Fig 6", following points observations are observed

- Under air natural conditions the average winding temperature rise is around 0.5ºC-0.7ºC lower for mineral oil as compared to natural and synthetic ester oil for both LV and HV winding. Hence, the average winding rise of LV and HV under air natural condition is comparable between mineral oil and ester oil.
- Under air forced conditions, synthetic ester oil has higher average winding temperature rise than natural ester oil and mineral oil. The difference between synthetic ester oil and mineral oil is 0.5-1.2ºC for both LV and HV winding.

E. Hot-spot temperature rise

The thermal performance of the transformer is generally decided based on hot-spot temperature which is used to estimate the life expectancy of transformer. For oil immersed transformers, hot-spot temperature rise over the ambient temperature is mainly controlled by the geometry of the winding, power loss distribution with in the windings, oil flow rate into radial cooling ducts and oil properties. A primary objective of transformer thermal design 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 addition, the hot-spot factor is also one of the main factors in thermal diagram to estimate the hot-spot temperature in heat run test data [5, 6, 10]. In addition, hot-spot factor for oil natural cooling mode is mainly based on Pp, Pr and Pg/Pr^2 [5,6]. Hence, an effective hot-spot factor of 1.3 is utilized.

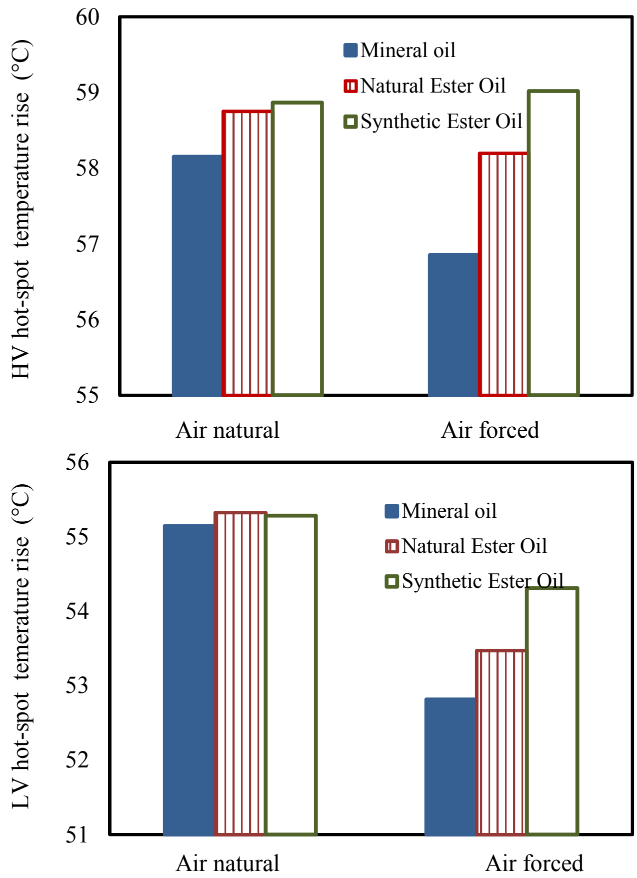


Fig 7. Hot-spot temperature of LV and HV winding under air natural and air forced conditions.

The interpretations from “Fig 7” are as follows:

- HV winding hot-spot temperature rise of ester oil is higher than mineral oil in air forced conditions. The different between natural ester oil and synthetic ester oil is 1°C in air forced conditions. In addition, the different between natural ester oil and synthetic ester oil is comparable at air natural conditions.
- LV hot-spot temperature rise of ester oil is comparable with mineral oil under air natural conditions. In air forced conditions, hot-spot rise in temperature of mineral oil is 0.6°C-1°C is lower than ester oil. The different between natural ester oil and synthetic ester oil is 1°C.
- The hot-spot temperature is located at the second disc from topmost disc for ester oil and mineral oil.

VI. CONCLUSIONS

The thermal performances of different of ester oil were compared with mineral oil for a given winding geometry and a given power loss distribution of 12.5/16MVA,132/11kV transformer. THNM model is used in this paper to predict the flow of oil and temperature distribution of ester oil transformer with respect to mineral oil. Total oil flow rate is used to predict the effects of viscosity of ester oil on oil flow distribution and temperature distributions. From the analysis on 12.5/16MVA,132/11kV transformer, thermal results of FR3 and BioTransol are comparable. The oil flow rate of mineral oil is about 28% higher than ester oil and top oil temperature rise is increased above 2.5^{0}C with respect to mineral oil in air natural cooling mode conditions. In air forced condition, the top oil temperature is increased around 3°C-4°C in ester oil.

The low value of oil flow rate of ester oil can cause local overheating in the transformer winding. To improve the thermal performance of ester oil transformer, total oil flow rate should be higher than mineral oil. The design engineer can increase the height difference between radiator centre and winding centre. Hence, mineral oil and ester oil are not comparable in terms of oil flow and temperature distributions due to effect of higher viscosity even specific heat and thermal conductivity is higher in ester oil. Different thermal design guidelines should be adopted for different oil for transformer applications. If the retrofilling of transformer with ester oil are considered for old transformer, then thermal aspects of ester oil needs to be made due to higher hot-spot temperature with conductor insulation of cellulose paper.

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