Continuous thermal overloading capabilities of ester oil transformers in oil directed cooling conditions

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Abstract— **The prediction of temperature distribution in ester oil (natural and synthetic ester oil) filled transformer due to different types of cooling modes are important for thermal designer in order to utilize the ester oil benefits of biodegradable, fire safety substations and continuous overloading capabilities with respect to mineral oil. It is still a technical challenge for ester oil to utilize in transformers since higher viscosity of ester oil will leads to reduce the heat transfer process mainly in convection. With ester oil in a transformer, there will be reduction of convection fluid currents which leads to higher temperature in top temperature oil and winding temperature rise in ester oil filled transformers. In this paper, the effects of mineral oil and ester oil on top oil rise, winding rise and hot-spot temperature arising from their potentially different thermal properties are investigated using Thermal hydraulic network model (THNM) on 60/75/90MVA, 220/33kV transformer. The power losses are calculated from FEM based simulations for thermal analysis using THNM model. The direct impact of oil flow rate and total pressure drop over the windings in oil directed (OD) cooling modes are analyzed under rated loading and 120% continuous overloading capabilities (108MVA) with respect to mineral oil.**

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

I. INTRODUCTION

The prediction of hot-spot temperature (highest temperature in the winding) is of great interest for thermal designer and utilities since it will cause thermal degradation of the insulation [1]. The uncontrolled hot-spot temperature resulting from poor thermal design or continuous overloading of the transformer above the design value of temperature limits will leads to deterioration of winding insulation and resulting in a complete thermal failure of the transformer [1,2]. Hence, hot-spot temperature is the main parameter to estimates the continuous over loading capabilities and longevity of the transformer (with the exception of premature failure) [1-5].

In the recent years, transformer filled with ester oils are increasingly being used as dielectric coolant in addition to traditional mineral oil for transformers due to its advantages of reduced fire, eco friendly, extended life of transformer and continuous over loading capabilities [1-2]. The physical, chemical and thermal properties of ester oil are different from mineral oil [6,7]. In order to get the continuous overloading capabilities of ester oil, prediction of the temperature distribution and hot-spot temperature within the transformer winding is crucial due to higher viscosity of ester oil. Hence, it will be great interest for thermal designer to estimate the thermal parameters of transformer during normal and continuous over loading conditions in ester oil with respect to mineral oil.

Different types of cooling methods for transformer are generally developed based on quantity of heat to be handled with a suitable heat exchanger [1,2,8]. Hence, thermal performance of transformer windings relies on the continuous circulation of oil through different cooling modes between radiator / cooler and winding. In oil forced/natural (OF/ON) cooling modes of transformer, oil flow and heat transfer are strongly interconnected. Hence, buoyancy force and hot-streak dynamics play major roles to estimate the oil flow distribution. In OD cooling modes, oil flow and heat transfer are weakly interconnected [1,2]. Hence, the oil flow and temperature distribution in disc-type transformer windings are analyzed in 60/75/90MVA, 220/33kV transformer under the influence of mineral oil, natural ester oil and synthetic ester oil on different cooling modes of ONAN/KNAN, ONAF /KNAF and ODAF/KDAF. THNM models are used based on physical principles of conservation of mass, momentum and energy to estimate the prediction of top oil temperature, winding gradient, oil flow rate and hot-spot temperature above ambient temperature thereby avoiding expensive experiments. THNM model provides the temperature distribution in very short time with an intermediate thermal solutions and accuracy between simple design principles and computational fluid dynamics (CFD) [7].

II. TRANSFORMER OIL

The oil flow distribution in a disc type of winding in a power transformer has an direct impact on the thermal performance of transformer which, in conjunction with power loss distribution in the transformer winding (copper loss and stay loss), determines the location and amplitude of hot spot temperature [1,2,8-10]. Hence, principle for cooling of transformer is transferring the generated heat due to power losses from core and windings to an appropriate heat transfer agent such as liquid dielectrics (oil). The liquid dielectric will carry the temperature through both convection and conduction principles generated from different types of windings and core to external cooling components of radiator, conservator and cooling fans. The dissipation of heat is usually facilitated by continuous circulation of oil between the winding and the cooler/radiator. Hence, selection of appropriate heat transfer agent to act as a coolant is essential for transformer application [6,7].

Significant experience has been gained to determine the physical, chemical and thermal properties of commonly used petroleum based mineral oil [6], With increasing interest in ester oil as a substitute for mineral oil, it is important to ensure that ester oil has adequate and acceptable properties for transformer applications since the chemical composition of ester oil is different from mineral oil. Generally, viscosity of the oil plays a major role in cooling, other than specific heat and thermal conductivity mainly in naturally cooled systems [6]. Ester oil has three times viscous in nature with respect to mineral oil. The oil flow rate will be lower and further influence (or worsen) the thermal performance of transformer (Table I). In addition, the thermal conductivity is higher than mineral oil and it will support for heat dissipation at some extend. If the temperature of the oil is increases, naturally viscosity and thermal conductivity will decreases linearly whereas the specific thermal capacity increases. In addition, higher viscous nature of ester oil may be useful to suppress the reverse flow of oil in oil directed cooling modes and flow distribution will be more uniform at the cost of a higher pressure drop [1,2]. Ester oil has higher temperature stability to provide the higher overloading capabilities and greater solubility of water than mineral oil.

TABLE I. THERMAL PROPERTIES OF TRANSFORMER OIL

Thermal parameters of oil at 20ºC	Mineral oil	Ester oil	
		Natural ester oil	Synthetic ester oil
Density in kg/m³	0.89	0.91-0.92	0.97
Kinematic viscosity in mm²/sec	22	78-97	70
Thermal conductivity in W/kgºC	0.126	0.160-0.167	0.144
Specific heat in J/kg ºC	1860	1943	1880

III. TRANSFORMER WINDING UNDER CONSIDERATION FOR THERMAL ANALYSIS

Thermal modeling of transformer plays a major role for the thermal performance of transformer during thermal design stage [11-14]. The transformer components can be separated into internal and external components for thermal modelling of transformer. All components outside tank are external components like radiators, condenser bushings, conservator, external cooling pumps and fans. Internal components are components inside the transformer main tank like core, windings with their supporting insulation structure, solid insulations and liquid insulations. The thermal performance can be decided based on how external and internal cooling components will work together.

A. Internal cooling mode of transformer

The transformer rating of 60/75/90MVA, 220/33kV YNyn0, 3phase 3 limb are considered for thermal overloading capabilities of ester oil filled transformer. The geometry of a disc type of low voltage (33kV), high voltage winding (220kV) with tap winding (coarse and fine) consists of thermally upgraded paper covered copper conductors. The quantification of the bulging mainly in conductor insulation depends upon quality of the conductor, type of winding, insulation thickness and width of the conductor. If the bulging is high, then there will be a reduction of cooling duct causing an end effect increase of conductor temperature. In this study, the effect of bulging is also considered based on manufacturing practice to decide the radial depth of the windings. To extend the life of the ester oil transformer, thermally upgraded paper are considered for winding conductors in order to get the benefits of ester oil.

In disc type transformer winding, oil is circulated through a given radial and axial cooling duct to carry the heat from winding to external cooling medium [1,2,15-21]. Hence, oil flows vertically upward from bottom of the winding to top of the windings through radial and axial cooling ducts. The horizontal oil ducts between discs plays a significant role to transfer the heat from the windings than vertical ducts since the width of the vertical cooling ducts are much shorter and it has only a single contact surface with the heat source. Therefore, oil flow distribution in the radial cooling duct and axial cooling duct should be designed to match with loss distribution. Hence, design and dimensioning of axial and radial cooling ducts has been judiciously done in this transformer, which is based on typical manufacturing practices [1,2]. Hence, radial cooling duct of 3mm for LV winding of continuous double disc with epoxy bounded CTC and 4.5 mm for HV winding of counter shield disc winding is provided.

A relatively more uniform flow distribution is always desired in OD cooling mode through proper placement of oil guiding washer and oil seal (oil guiding strips) to avoid potential localized overheating. Hence, 1.5mm thickness of oil guiding washer and oil seal are used inner diameter and outer diameter of each winding to cool the windings effectively at the entrance and exit of each oil circulation pass. The oil guiding washer and oil seal will act as a oil stopper in a vertical duct from one side and it will allow the oil to pass into or out from the opposite side. Hence, oil flow is directed in a zig-zag fashion with 6 passes in LV windings and 9 passes in HV windings. Hence, the location and number of oil guiding washers are properly selected based on past experiences with THNM model analysis.

B. External cooling mode of transformer

In this 60/75/90MVA, 220/33kV transformer, center to center height of 16 radiator (hot dipped galvanized) and number of fins per radiator are 3100mm and 30 respectively. The radiator 520mm width is utilized in this transformer. The heat dissipation per fins at oil temperature of 50ºC is 851Watss in air natural and 1438Watts in air forced conditions. The cooling surface area of the fins are 2.64m². A 3 phase, 50Hz, 500Watts, 900RPM fans are mounted at the horizontal position [5,6]. In this paper, 36inch marathon make 415V, 3 phase, 50Hz with volumetric flow of 22100m³/hr fan is selected.

For oil OD cooling mode, oil is pumped from the radiators and delivered to the bottom of the transformer windings. In addition, the static pressure drop over a disc type of winding will decide the pump selection for oil forced and directed cooling modes [22]. The higher rated pump capacity (higher oil velocity) will provide higher rate of heat dissipation. In this transformer, 6 inch, 1800LPM, 1.2kW, 415V, 3phase 50Hz, BC-30/1 is considered for the analysis.

C. Transformer power loss estimation

The generation of heat in the winding is mainly due to core loss, resistive losses (I^2R loss) in copper strands and stray loss due to leakage/high current field within the transformer once the transformer is energized. The resistive losses are directly proportional to resistivity of the material, whereas the winding eddy loss due to leakage field is inversely proportional to resistivity. The loss distribution can be calculated independently with consideration of winding geometry, transformer loading level and leakage flux distribution, etc., Due to uneven distribution of electrical losses within transformer, the temperature profile within the transformer will not be uniform because of the non-uniform oil flow distribution and its the cooling structure. The accurate prediction of power losses (noload and load) distribution is the main criteria for thermal analysis. In this paper, the main focus is on oil flow and heat transfer processes in the winding with given loss distribution using FEM based technique.

IV. HEAT TRANSFER PRINCIPLE

The heat transfer modes are mainly by conduction, convection and sometimes by radiation [1,2,16,17]. If the transformer is energized the heat sources are generated due to power losses which will cause the oil and winding temperature to rise above the ambient temperature. According to heat transfer theory, heat will transfer from the hottest temperature mainly at winding conductor to atmospheric temperature ($T_{ambient}$) through windings, insulation paper, oil, tank and external radiators based on winding coolant arrangement.

The conduction principle within each copper strand is negligible due to higher thermal conductivity and small size of the copper strand used in the windings. The heat transfer from the core to oil and windings to oil is considered as conduction process since they are designed to be in good contact. The temperature drop across the conductor insulation due to the conduction heat transfer principles can be calculated by Fourier's law of thermal conduction. The thermal conductivity of oil-impregnated paper insulation is temperature dependent [16,17]. The rate of heat conduction through a copper conductor is proportional to temperature gradient across the paper insulation and heat transfer area of paper insulation and it is given by.

$$\Delta\theta = Q \bullet R = k_p \frac{dT}{dX}$$
(1)

Where,

$\Delta\theta$- Local heat flux density at the hot-spot location (W/m^2)
Q- Average heat flux in all the discs (W/m^2)
R- Ratio of hot-spot heat flux to average heat flux
  -Ratio of power loss at the hot-spot to average power loss
k_p- Paper thermal conductivity (W/m.^{o}C)
dT- Temperature gradient across conductor insulation (^{o}C)
dX- Thickness of thermally upgraded paper insulation (m)

The heat dissipation from core and windings occurs mainly due to convection mode of heat transfer. The convection process within the oil is generally very complicated phenomenon since it is dependent upon physical properties of oil and physical situation [1,2,16,17]. The convection heat transfer rate is generally expressed by

Newton's law of cooling for prediction of highest temperature in oil domain. The basic relationship for heat transfer by convection as

$$Q = hA\left(T_{surface} - T_{oil}\right)$$
(2)

Where, h- Local heat transfer coefficient at hot-spot in oil domain (W/m^2.^{o}C)
A- Surface area in m^2
$T_{surface}$- Hot-spot temperature in fluid domain (^{o}C) - object's surface temperature
T_{oil} - Bulk oil temperature surrounding the hot-spot (^{o}C)

If viscosity of the oil is higher, then convection process will be lesser for heat transfer. Hence, due to utilization of ester oil for transformer applications, there will be reduction of amount of convection fluid currents. The heat dissipation from tank occurs by both radiation and natural convection. The cooling of externally mounted radiators will also occurs by radiation principle. In addition, radiation will be very less with respect to convection principle. The entire radiator surface does not participate in heat transfer mechanism by radiation [16,17]. The heat transfer by radiation is expressed by Stephan-Boltzmann law:

$$P = \eta E S_A\left(T_{radiating\ surface} - T_{ambient}\right)$$
(3)

Where,

η- Stephan-Boltzmann constant (5.67×10^{-8} W/(m^2 ^{o}C))
E - Surface emissivity factor
S_A - Surface area for radiation in m^2
$T_{radiating\ surface}$- Average temperature of radiating surface (^{o}C)
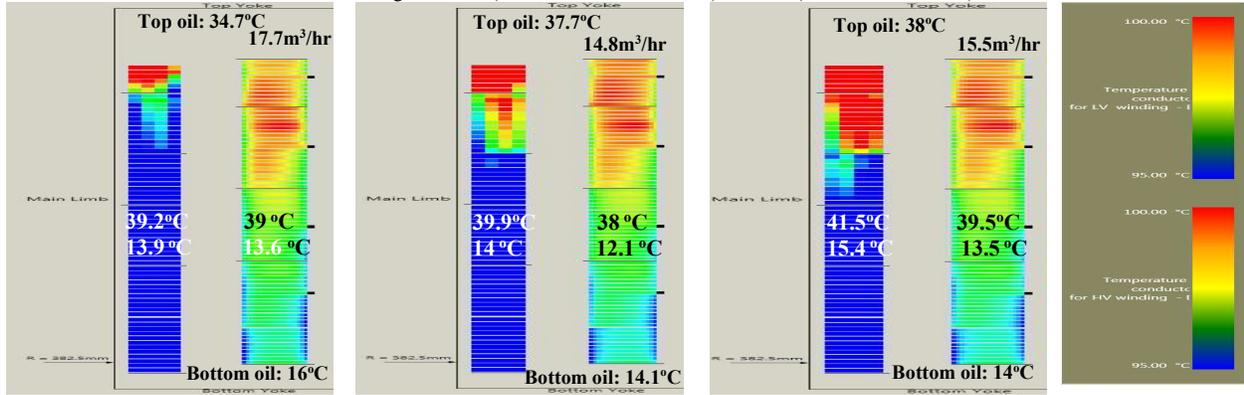
V. TRANSFORMER ANALYSIS RESULTS

If the thermal performance of transformer is well taken care at the time of design, then it provides lower top oil, average winding rise and hot-spot temperatures. The oil flow distribution and pressure drop over the winding due to different thermal properties of mineral oil and ester oil are important for thermal analysis for the following reasons.

- Oil flow rate is directly related to thermal performance and a more uniform oil flow distribution is highly preferred to avoid hot-spot temperature.
- The total pressure drop over a winding with total oil flow rate in the winding will determine oil split among windings (LV, HV and tap winding in the same phase) connected hydraulically in parallel in ON modes [22].
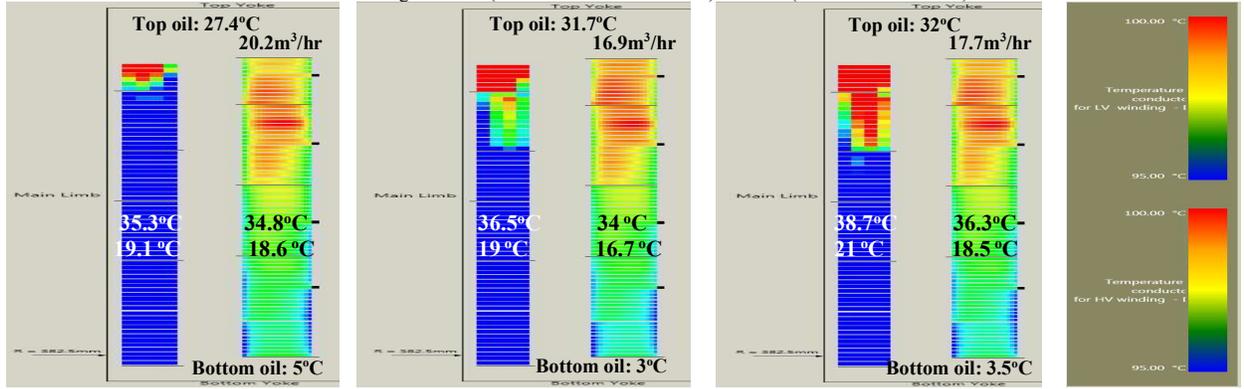
A. Temperature distributions and oil flow rate

The oil flow distribution in conjunction with power loss distribution will determine the temperature distribution within the windings other than ambient temperature, transformer design, loading conditions and cooling provided. The temperature of transformer filled with ester oil is higher than transformer filled with mineral oil and this temperature difference is highlighted in Fig.1. Fig.1(a) & (b) provides the temperature distribution, oil flow rate, top and bottom oil temperature and winding temperature rise of transformer. The temperature distribution within the windings is not uniform due to uneven power losses distribution. Since, viscosity of ester oil is higher, top oil rise, winding rises of LV and HV windings are increased due to lesser oil flow rate and reduction of convection fluid currents [22].
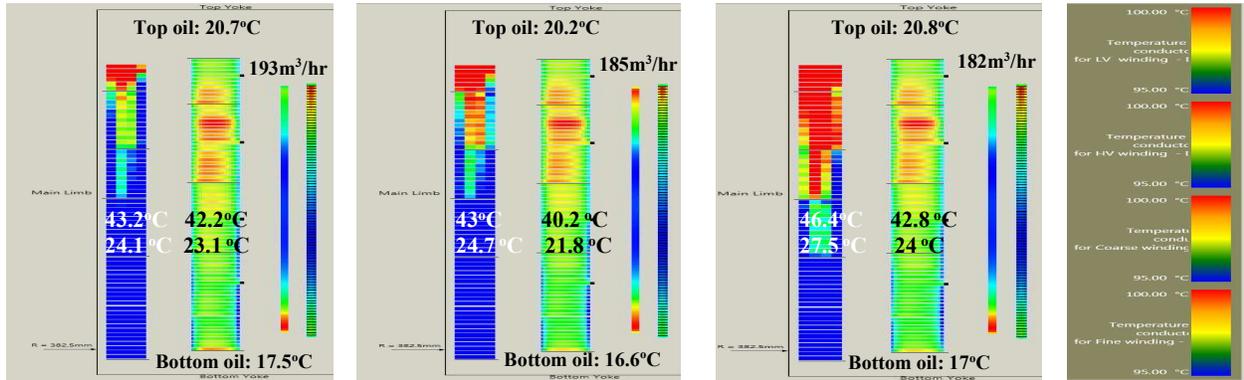
63MVA rating – ONAN (for mineral oil transformer) / KNAN (Ester oil transformer)
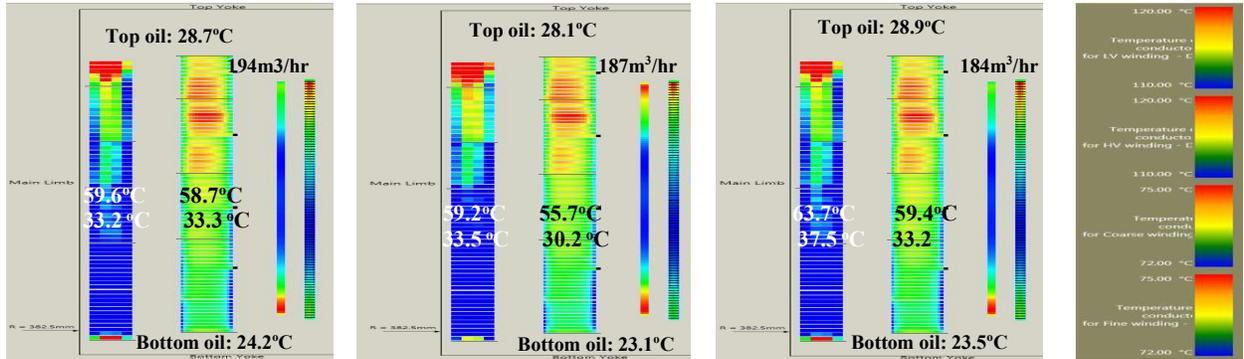
Top oil: 34.7°C 17.7m³/hr 39.2°C 39 °C 13.9 °C 13.6 °C Bottom oil: 16°C

Top oil: 37.7°C 14.8m³/hr 39.9°C 38 °C 14°C 12.1 °C Bottom oil: 14.1°C

Top oil: 38°C 15.5m³/hr 41.5°C 39.5°C 15.4 °C 13.5 °C Bottom oil: 14°C

75MVA rating – ONAF (for mineral oil transformer) / KNAF (Ester oil transformer)

Top oil: 27.4°C 20.2m³/hr 35.3°C 34.8°C 19.1 °C 18.6 °C Bottom oil: 5°C

Top oil: 31.7°C 16.9m³/hr 36.5°C 34 °C 19 °C 16.7 °C Bottom oil: 3°C

Top oil: 32°C 17.7m³/hr 38.7°C 36.3°C 21 °C 18.5 °C Bottom oil: 3.5°C

90MVA – ODAF (for mineral oil transformer) /KDAF (Ester oil transformer)

Top oil: 20.7°C 193m³/hr 43.2°C 42.2°C 24.1 °C 23.1 °C Bottom oil: 17.5°C

Top oil: 20.2°C 185m³/hr 43°C 40.2 °C 24.7 °C 21.8 °C Bottom oil: 16.6°C

Top oil: 20.8°C 182m³/hr 46.4°C 42.8 °C 27.5 °C 24 °C Bottom oil: 17°C

108MVA – ODAF (for mineral oil transformer) / KDAF (Ester oil transformer)

Top oil: 28.7°C 194m3/hr 59.6°C 58.7°C 33.2°C 33.3 °C Bottom oil: 24.2°C

Top oil: 28.1°C 187m³/hr 59.2°C 55.7°C 33.5 °C 30.2 °C Bottom oil: 23.1°C

Top oil: 28.9°C 184m³/hr 63.7°C 59.4°C 37.5 °C 33.2 Bottom oil: 23.5°C

Mineral oil   Natural ester oil   Synthetic ester oil   Temperature

Fig.1 (a). Temperature distribution (Top and bottom oil, winding gradient and winding temperature) and total oil flow rate of mineral oil and ester oil.
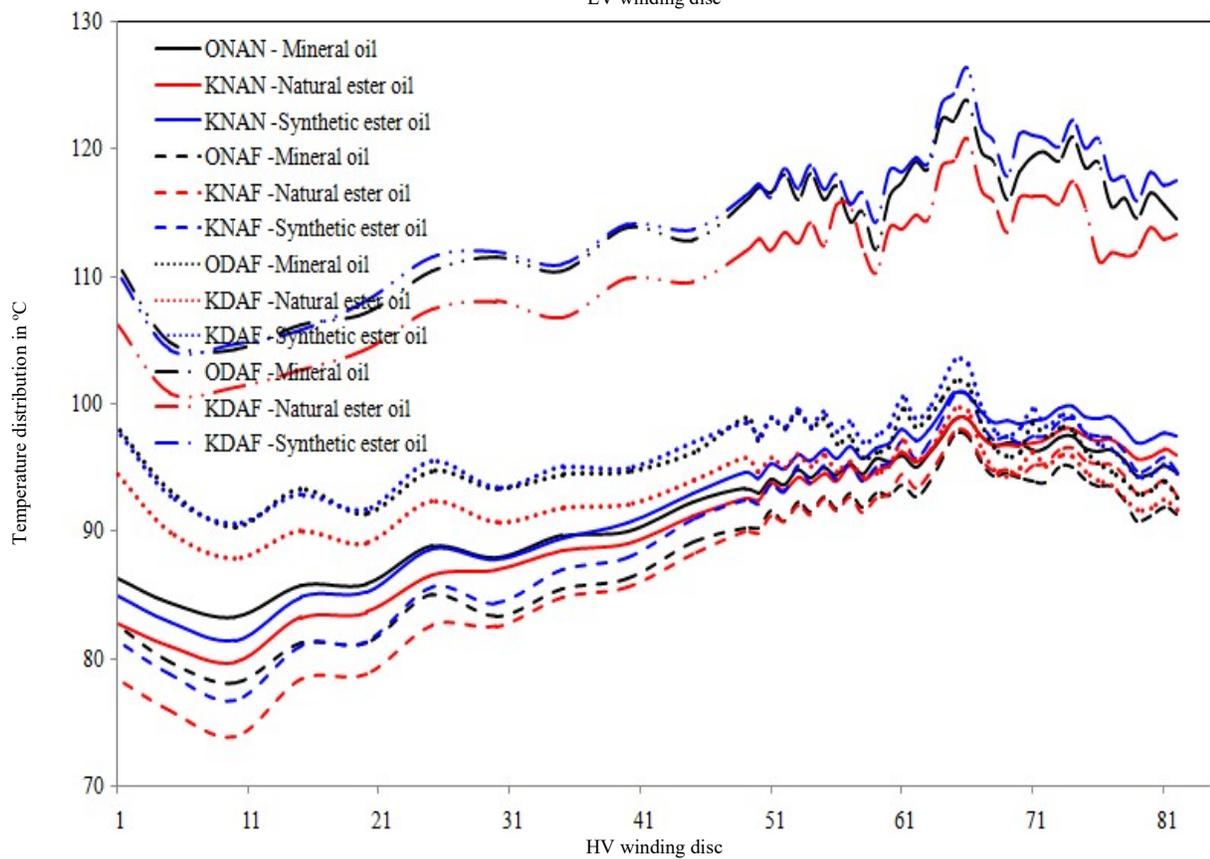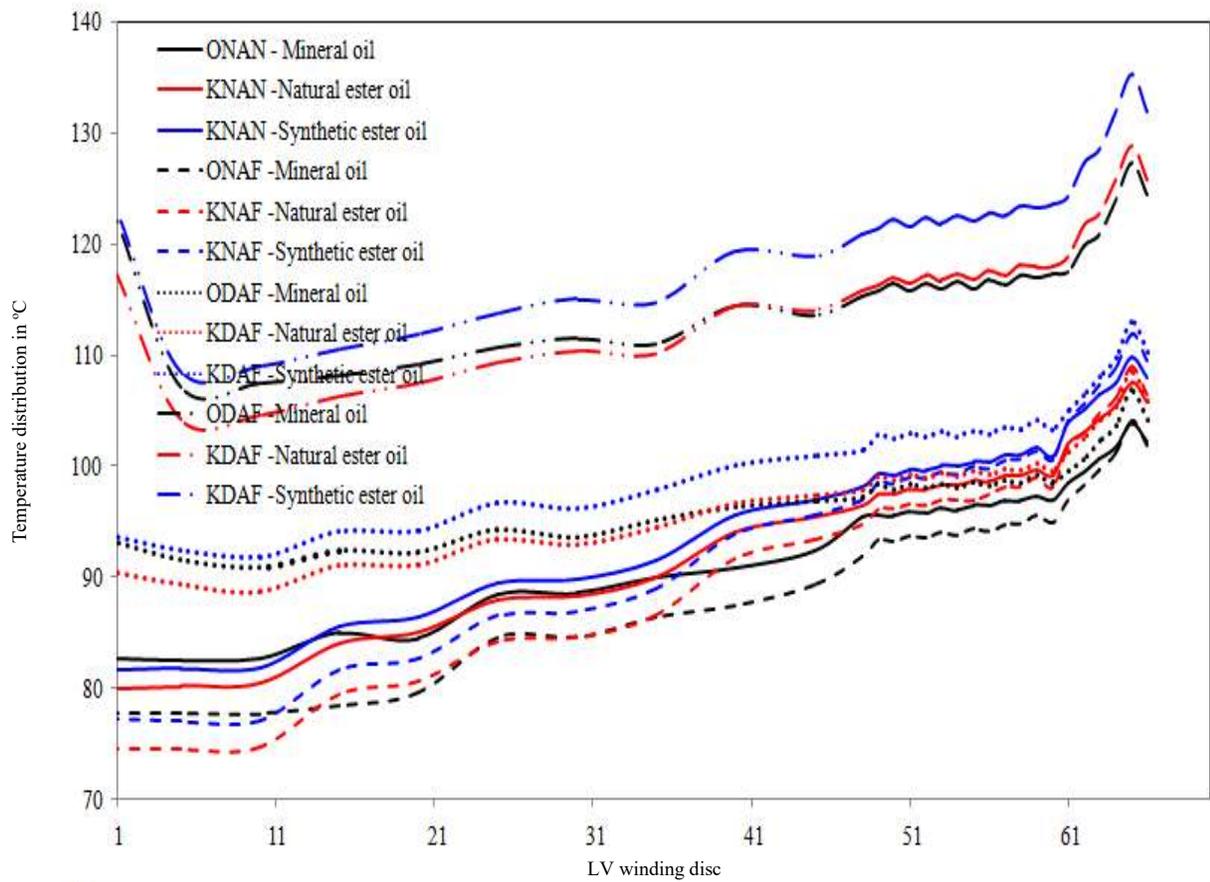
Fig.1(b). Temperature distribution of mineral oil and ester oil

From the Fig.1, the flow rate of ester oil is lowered by 12-17% with respect to mineral oil under ONAN / KNAN and ONAF/ KNAF conditions. The flow rate difference between mineral oil and natural ester oil is 3.5% to 6% under ODAF conditions. The bottom oil temperature of ester oil is lower than mineral oil. At the same time top oil temperature is higher for ester oil than mineral oil in ONAN /KNAN and ONAF/KNAF conditions. It indicates that, overall inlet oil flow rate is lower ester oil and it leads to increase the higher hot-spot temperature in both LV and HV windings.

The fundamental principles of Reynolds number (Pr), Prandtl number (Pp) and the ratio of Grashof number (Pg) and Reynolds number (Gr/Re^2) will also control the oil flow rate, temperature distribution and hot-spot temperature [1,2]. Fig.2 shows percentage of oil flow within the windings and percentage of total heating (winding loss in power loss) in the windings and Fig. 3 shows the volumetric oil flow in the transformer windings. The ratio Pg /Pr^2 governs the oil flow and temperature distributions as a more dominant factor than Pr and Pb in ON cooling mode because it provides a measure of the ratio of buoyancy forces to inertial forces. Pp is less influential than Pr. From Fig.2, oil flow and heat transfer is strongly interconnected in ON cooling modes. Hence, buoyancy force and hot-streak dynamic are main driving force and play a vital role for oil flow distribution and temperature distribution within the winding.
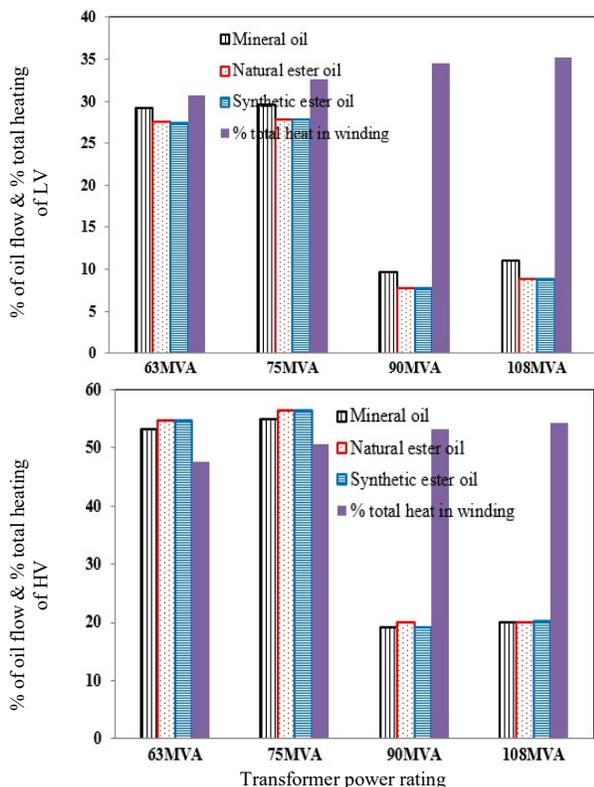

Fig. 2. Percentage of oil flow and Percentage of total winding heating of transformer

From Fig.2, oil flow and heat transfer are weakly coupled in OD cooling modes at 90MVA and 108MVA. For OF and OD cooling mode, the pressure generated by the pump dominates the oil flow pattern. Hence, the effects of hot-streak dynamics and buoyancy force will be less influential for OF and OD cooling mode. Hence, the oil flow rate must,

consequently, guarantee that the insulation temperature is kept below the allowable temperature as much as possible. Hot-spot temperature is a function of Re and Pr in OD cooling mode [1,2]. It indicates that, if Re is higher (i.e., higher oil flow rate) then oil flow will be uneven in OD cooling mode which will leads to reverse oil flow.
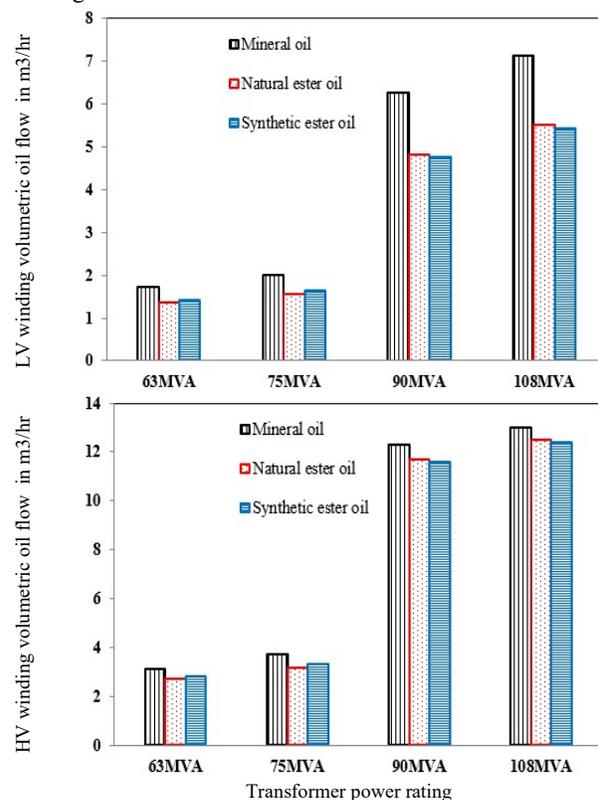

Fig.3. Volumetric oil flow in the transformer

B. Hot-spot temperature rise distribution

The hot-spot is an indicator of the uniformity of the temperature distribution in the winding. The hot-spot temperature is affected by both the local power losses and local cooling efficiency at the hot-spot. The hot-spot temperature in the copper conductor of the winding can be regarded as the sum of the hot-spot temperature in oil domain and the temperature gradient across thermally upgraded kraft paper. Fig. 4 shows the LV and HV hot-spot temperature of mineral oil and ester oil due to different cooling modes. The hot-spot temperature in the copper conductor of the winding can be regarded as the sum of the hot-spot temperature in the fluid domain and the temperature gradient across thermally upgraded kraft paper .

As per IEEE C57-91 (1995) the insulation life of transformer will be based on hot-spot temperature. It will be normalized to insulation life at 110°C with mineral oil and thermally upgraded kraft paper (assuming 80°C winding hot-spot rise over a 30°C ambient). As per IEC 60076-14, IEEE C157.154, the allowable hot-spot temperature is 125°C-130°C with usage of ester oil and thermally upgraded kraft paper in transformer. It indicates that the increased hot-spot temperature of 15°C-20°C from base value of 110°C is possible without sacrificing the life and reliability of transformer when immersed with natural ester oil.
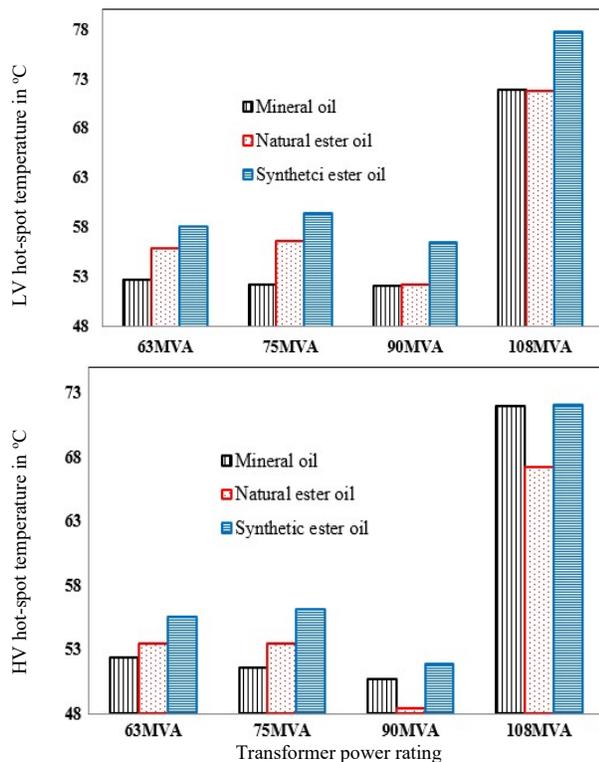
Fig.4. Hot-spot temperature in transformers

VI. CONCLUSION

The transformer filled with ester oil is becoming an option in place of mineral oil for a wide range of voltage levels in transformers. In addition, determination of the temperature distribution within the winding due to rated and continuous overloading capabilities of ester oil is required for transformer manufacturers in order to estimate the top temperature oil rise, winding temperature rise and hot-spot temperature during thermal design stage. In this paper, effects of three different types of oil (mineral oil, natural ester oil and synthetic ester oil) for transformer applications are considered.

For a given winding geometry of 60/75/90MVA, 220/33kV with given radiator configurations and a given load and noload loss, oil flow rate, top oil rise, winding rise and hot-spot temperature are calculated using THNM model due to higher viscous of ester oil [22]. The oil flow rate of ester oil is 12-15% lower than mineral oil. The oil flow rate and % total heating of transformer winding is weakly coupled in oil directed cooling modes. If the motion of oil is faster due to less viscous nature of oil properties, then convective principle will be faster. Hence, convection fluid currents will be lesser in ester oil which is leads to higher temperature distribution. The higher flow rate of ester oil does not necessarily result in a better thermal performance of transformer since, too high rate of oil flow will also lead to reverse oil flow in the oil pass bottom duct in oil directed cooling mode.

From the analysis, the existing thermal design guidelines of mineral oil is not applicable for ester oil for power transformer applications with considering continuous overloading capabilities. If retrofilling in existing mineral oil filled transformer are considered with ester oil for continuous overloading benefits, then analysis on thermal parameters are advisable based on winding geometry due to higher hot-spot temperature with considering conductor insulation of cellulose paper.

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