Thermal performance of ester oil transformers with different placement of cooling fan

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Transformer technology in R & D

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Abstract—Ester oil is becoming a substitute to replace mineral oil for transformers due to higher fire safe, environmental friendly, higher thermal stability and or longer insulation life (transformer life). The chemical composition and molecular structure of ester oil groups of natural ester oil and synthetic ester oil are entirely different from commonly used petroleum based mineral oil. The higher viscous nature of ester oil will increase the oil temperature rise, winding temperature rise, winding gradient and hot-spot temperature due to less convective heat transfer. Hence, the internal and external cooling modes of transformer needs to be analyzed extensively by transformer manufacturer to get an advantage of ester oil for transformer applications. In this paper, Thermal Hydraulic Network Model (THNM) is utilized to predict oil temperature rise and winding temperature rise, oil flow rate and hot-spot temperature on 12.5/16MVA, 132/11kV transformer winding geometry with different types of ester oil and comparing its results with mineral oil under steady state conditions. In addition, effect of different types of cooling fan mounting arrangements (vertical and horizontal manner) on 4 radiators with 3 cooling fan and 4 radiators with 4 fan are analyzed and its results are compared for ester oil and mineral oil. Temperature rise test is also performed to validate the THNM results.

Keywords—Transformer winding, Ester oil transformer, Thermal analysis, Thermal modelling of transformer, Winding insulation, Temperature rise test.

I.   INTRODUCTION

The objective of transformer thermal design is to estimate the magnitude and location of hot-spot temperature within the technical specification provided by customer [1-5]. Hence, determination of thermal performance of transformer is crucial for factory witness test mainly on ester oil filled transformer [2-4]. In recent years however, significant attention has been paid on ester oil for transformer applications, it becomes imperative to compare the thermal performance of ester oil with mineral oil filled transformer. It is also important for asset management of transformer during the operation [5,6].

Generally, viscosity (mm²/s), density (kg/dm³), specific heat capacity (J/kg°C) and thermal conductivity (W/m°C) of the oil are the main thermal parameters will decide the cooling performance of transformer. In addition, it is also important how external and internal cooling components are working together during the operations. Since, ester oil is more viscous nature than mineral oil, it reduces the oil flow rate. In oil natural cooling mode, viscosity factor worsens the situations [5,6]. If the transformer utilities are interested to utilize the benefits of ester oil for environmental protection and higher fire safety in substations, then transformer manufacturer needs to know the thermal characteristics of ester oil for transformer applications at the time of thermal design in order to prove that ester oil filled transformer will operate as per extended guaranteed life through temperature rise test at factory.

The objective of this paper is to estimate the thermal performance parameters (oil flow rate, oil temperature rise, winding temperature rise and hot-spot temperature) above atmospheric temperature for natural ester oil and synthetic ester oil transformer due to various placement of cooling fan arrangement on radiator using 12.5/16MVA, 132/11kV transformer. The thermal performance parameters result are compared with mineral oil at 16MVA base. In addition, the temperature distribution along with location of hot-spot temperature is estimated based on THNM model at the stage of thermal design and its results are compared with temperature rise test.

II.   TRANSFORMER OIL UNDER CONSIDERATION FOR THERMAL ANALYSIS

Mineral oils are mixture of liquid hydrocarbon molecules obtained from crude oil by different methods of distillation and refining process and it has various structures of paraffinic, naphthenic and aromatic. The significant experience has been gained by researcher, transformer manufacturer and utilities to understand physical, chemical and thermal properties of the mineral oil. The advantages of mineral oil are good heat transfer agent, better oxidation stability, higher breakdown strength, low cost and wide availability [1-6]. However, mineral oil is failed to provide the crucial combination of fire safety and environmental protection properties for transformer at substations since it has lower value of biodegradability and fire point. Hence, in the recent years transformer manufacturers and utilities have started to use ester oil filled transformers as a fire safety and bio degradable product.

Natural ester oil is mainly derived from renewable vegetable seeds of rapeseed, soybean and sunflower. It has a very low carbon footprint and higher moisture saturation level than mineral oil. Depends upon oil viscous, natural ester oil can have three different C18 fatty acid group of chains (glycerol backbone bonded) and it contains two or even three double bond chemical structure [6,7]. At a given temperature, natural ester oil protects the solid insulation mainly insulating paper upto 5-8 times longer than mineral oil. Since, natural ester oil has unique ability to draw out the moisture/water from insulating paper, it helps to extends the life of the transformer. Synthetic ester oil is basically derived synthetically by reaction of acid groups [5]. Synthetic ester oil is highly effective solution in cold climate area since it has lower pour point (-56˚C) than natural ester oil.

Due to differences in properties of ester oil with well known mineral oil properties, it is important to understand that ester oils have adequate and acceptable thermal properties other than prediction of dielectric strength under impulse voltage excitations and power frequency excitations for transformer applications. Hence, thermal properties of mineral oil, natural ester oil and synthetic ester oils as a function of temperature are obtained from various oil manufacturers. The linear piecewise method is used to define density, viscosity, specific thermal capacity and thermal conductivity of transformer oils with respect to temperature. With the thermal properties data provided by the oil manufacturer thermal analysis are performed on 12.5/16MVA, 132/11kV transformer geometry with different types of ester oil to estimate the optimum placement of cooling fan for transformer applications.

III. ENERGY TRANSFER IN TRANSFORMER

The heat transfer principle in a transformer takes place by conduction, convection and radiation. The heat transfer pathway in transformer is shown in Fig.1.
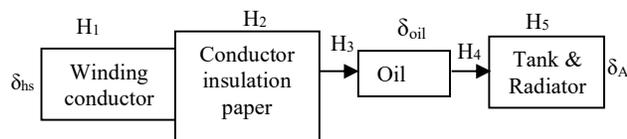

Fig.1. Energy transfer path in transformer

Where,

H_1– Conduction principle through winding copper and core
H_2–Conduction principle through kraft paper or thermally upgraded paper
H_3 –Convection principle from conductor insulation to oil
H_4 – Convection principle from oil to tank
H_5 – Convection/ radiations principle through the tank/radiator
δ_{hs} – Hot-spot temperature
δ_{oil} – Top oil temperature rise
δ_A – Atmospheric temperature

Generally, the heat transfer principles inside the core (magnetic properties) and windings are mainly by conduction process which is governed by Fourier's law and it is a linear in nature based on thermal conductivity of copper (approximately $380Wm^{-1}K^{-1}$), core and temperature difference between the surfaces in contact for heat conduction [7-10]. The thermal conductivity of copper conductor is higher than thermally upgraded kraft paper as a conductor insulation (approximately $0.2Wm^{-1}K^{-1}$). Hence, temperature gradient inside the copper conductor can be neglected. Since thermally upgraded kraft paper thickness will be very less (mm) on the conductor, temperature variations across the conductor insulation of paper is also generally neglected.

The heat transfer within the oil medium is mainly based on convection process as well as conduction due to fluid currents in the oil. Convection process is generally very complicated phenomenon since it is based on density and viscosity, thermal resistivity of the oil and temperature difference between the heated surface and coolant etc., The convection heat transfer rate are generally expressed by Newton's law of cooling [9-11]. The amount of convection fluid currents in the oil also based on viscous of oil. If the movement of oil is faster due to lesser viscous in nature, then convective mode of heat transfer will be more faster. As oil is a high viscous nature, there will not be more convection mode of heat transfer as in the case with non viscous nature of oil. Hence, due to utilization of natural ester oil and synthetic ester oil, there will be reduction of convection fluid currents which leads to higher temperature distribution in ester oil filled transformers than mineral oil transformer [6,7]. Hence, it will be interest for the transformer manufacturer to know the temperature distribution at the stage of thermal design.

The heat transfer from tank surface to atmosphere is by convection principle of heat transfer (air) and radiation principle (tank radiates heat to atmosphere). In transformer, radiation does not occur in most of the case, it is accompanied by convection. The surface of the transformer tank radiates heat to the atmosphere.

IV. TRANSFORMER UNDER CONSIDERATION FOR THERMAL ANALYSIS

The reliable thermal modelling techniques are particularly very useful for thermal designer during design stage to meet the customer guarantee values before manufacturing the transformer. The accurate thermal modeling is required for investigating convective heat transfer in cooling ducts and prediction of hot-spot temperature value and its location. THNM model is used in this paper to predict the hot-spot temperature to evaluate the temperature profile of transformer [11-17].

A. Transformer geometry

The detailed transformer geometry for thermal modeling is required as input parameters to calculate the thermal performance in order to get better accuracy in the results. The main internal component of transformer for thermal modelling are core and windings. Low voltage (LV), high voltage (HV) and tap windings of 12.5/16MVA, 132/11kV transformers are manufactured as disc type of windings. The radial cooling ducts (key spacer) between disc, thickness of axial ducts (at the inner and outer diameter of the winding) play an vital role in heat dissipation from the windings. The radial cooling are 4.2mm (average value) for HV winding and 2.8mm (average value) for LV winding is used in this transformer [17]. Vertical cooling ducts are placed within the core, LV winding, HV winding and tap winding in such a way to create an efficient distribution of oil flow for better cooling of each component. Therefore, for a given viscosity of the oil, the flow of oil from bottom to top of the winding based on dimensions of radial and axial cooling ducts along with winding geometry arrangements [6,7].

The thermally upgraded paper is used in conductor insulations. The thermally upgraded paper will reduce hydrolysis effect and enhance thermal resistance to increase the insulation ageing rate [6,7,17]. Hence, life of a transformer is not compromised in conductor paper in spite of higher temperature rise limit for ester oil. The transformer winding geometry such as inter turn insulation, inter disc insulation, radial key spacer, axial cooling duct, phase to phase insulation, insulation between HV & LV winding, top and bottom end insulation etc., are modeled properly with considering actual shrinkage of cellulose based insulation (kraft paper, pressboard, permawood) after drying and impregnation process of transformers.

B. Powerloss calculation

The first step prior to thermal analysis on transformer winding using THNM model comprises the calculation of the magnitude and distribution profile of power loss (noload and load loss). The temperature rises are mainly occurs due to combine effect of no load losses (voltage related effect) and load losses (current related losses) in the transformer during operations. The scalar function of power loss over the volume of transformer is converted into heat during operation which will create thermal stresses inside the transformer.

The heat generated by core (W/m^3) in a transformer is calculated by ratio of core loss and core volume. The resistive losses (Joule's law) along the winding height will be uniform because of the current which goes through the windings uniformly. The winding eddy losses will concentrate more on the top and bottom part of the winding based on conductor dimensions due to higher leakage fields in radial direction than axial compared to middle portion of the windings. Hence, the distribution of eddy current loss will not be uniform at top and bottom of the windings. In this study, the complex nature of winding eddy loss and stray losses in the magnetic structures are calculated using FEM based techniques than empirical methods and results of 16MVA base is given in Fig. 2.
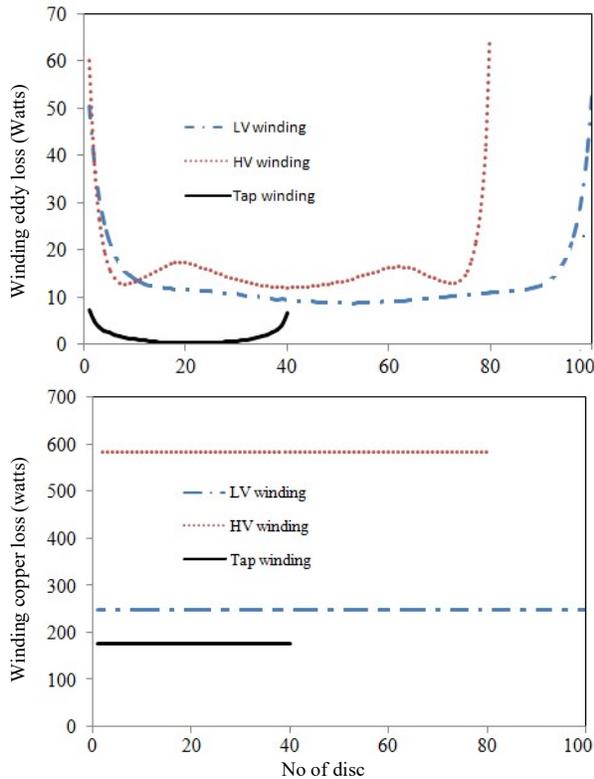

Fig.2. Power loss distribution in the winding for 16MVA base

V. COOLING FAN MOUNTING ARRANGMENTS IN RADIATOR

The hot dipped galvanized radiator is used to draw out the heat due to power losses at top portion of tank and re-circulate the cooled oil back into the tank bottom using external radiators as well as cooling fan. Four radiator with 520mm width, 2200mm height, 23 plates per radiator is mounted in the tank. The cooling surface area of the section and heat dissipation per section at 50°C is 2.64m^2 and 851 watts

respectively. The commonly used cooling fan mounting configurations on radiator (Fig.3 and Fig.4) in transformer by various manufacturers are horizontal (mounted at the sides of radiators assembly) and vertical arrangements (at the bottom of the radiator assembly). Transformer manufacturers are interested generally to estimate thermal parameters based on different cooling fan mounting arrangement on radiators for ester oil transformer and comparing the thermal parameter results with mineral oil. In this transformer, 3phase, 50Hz, 900RPM, 500watts, 610mm diameter with volumetric air flow of 10450m^3/hr cooling fan is utilized. The combinations of cooling fan mounting arrangements are given in Table I and II.
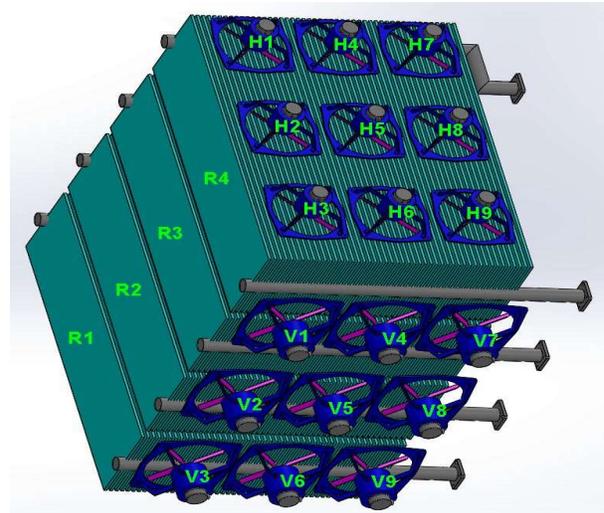

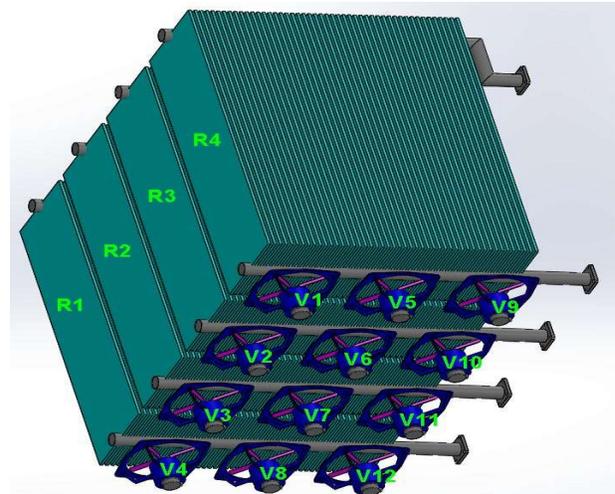Fig.3. Various positions of 4 radiator 3 cooling fan configurations on the radiators.

Fig.4. Various positions of 4 radiator 4 cooling fan configurations on the radiators.

VI. THERMAL ANALYSIS RESULTS OF TRANSFORMER

The thermal operation limits of mineral oil are used in this paper based on customer technical specifications. The maximum ambient temperature value of 50°C is considered based on ambient temperature of site as specified by customer. The top oil rise, winding rise limits are 50°C, 55°C respectively.

TABLE I. EXCITATION OF 4 RADIATOR 3 COOLING FAN ARRANGEMENTS

Cooling fan mounting arrangement on radiators	Test configurations	Excitations of cooling fan on R4 side
Horizontal positions	H1	H1, H2, H3
	H2	H4, H5, H6
	H3	H7, H8, H9
	H4	H7, H9, H2
	H 5	H1, H3, H8
	H 6	H3+, H5, H7&
	H7	H7,H5,H3
	H8	H1, H5, H9
	H 9	H7, H9, H2*
	H10	H1, H3, H5 *
Vertical positions	V1	V7, V8, V9
	V2	V1, V2, V3
	V3	V4, V5, V6
	V4	V7, V9, V5
	V5	V8, V1, V3
	V6	V1,V5,V9
	V7	V7,V5,V3

* indicates cooling fan mounted on R1 side radiator.
+ indicates H3 fan is moved between H3 and H6.
& indicates H7 fan is moved between H4 and H7.

TABLE II. EXCITATION OF 4 RADIATOR 4 COOLING FAN ARRANGEMENTS

Cooling fan mounting arrangement on radiators	Test configurations	Excitations of cooling fan on R4 side
Vertical positions	V1	V1, V2 ,V3, V4
	V2	V5, V6 ,V7, V8
	V3	V9, V10 ,V11, V12
	V4	V12,V3,V10, V1
	V5	V12*, V3,V2,V9*
	V6	V11,V10, V3,V2

V12*- between R1&R2, V9* - Between R3&R4

The power losses will cause degradation of winding insulation which is leads to reduction of tensile strength and dielectric performance of the conductor insulation. For a transformer design engineer, prediction of temperature distributions at various disc or turn positions becomes interesting since it is very important for thermal ageing of insulating materials. Hence, the temperature distribution inside the transformer winding at every disc middle turn of turn in LV, HV and tap are predicted under air natural (AN) and air forced (AF) cooling modes and it is shown in the Fig. 5. From Fig.5, the temperature profile within the windings is not distributed uniformly because of uneven power losses distribution (mainly due to winding eddy loss) within the winding. 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 (for mineral oil)/ KNAN (for ester oil) and ONAF (for mineral oil) / KNAF (for ester oil) conditions. It indicates that, overall inlet oil flow rate is lower for ester oil and it leads to increase the higher hot-spot temperature in both LV and HV windings.

In oil natural cooling modes, the oil flow is mainly depends on buoyancy forces and hot streak dynamics. The prediction of oil flow and heat transfer in an oil natural cooling mode of transformer is more challenging task than oil directed winding because the hydraulic system and thermal system are fully interconnected well and therefore need not be considered separately. The oil flow, temperature distributions and hot-spot temperature are mainly controlled by dimensionless parameters of Reynolds number (Pr, ratio of the inertia to viscous forces), Prandtl number (Pp, ratio of the momentum to thermal diffusivities) and ratio of Grashof number (Pg, the ratio of buoyancy forces to viscous forces) and square of Reynolds number, Pg/Pr^2 [6,7]. In oil natural cooling mode, Pg/Pr^2 governs oil flow and temperature distributions mainly as a dominant factor for flow and temperature distribution because it provides a measure of the ratio of buoyancy forces to inertial forces. Pr is more influential parameter than Pp to estimate the oil flow and temperature distribution of winding and oil since, oil flow and heat transfer are strongly coupled in oil natural cooling modes [6,7].
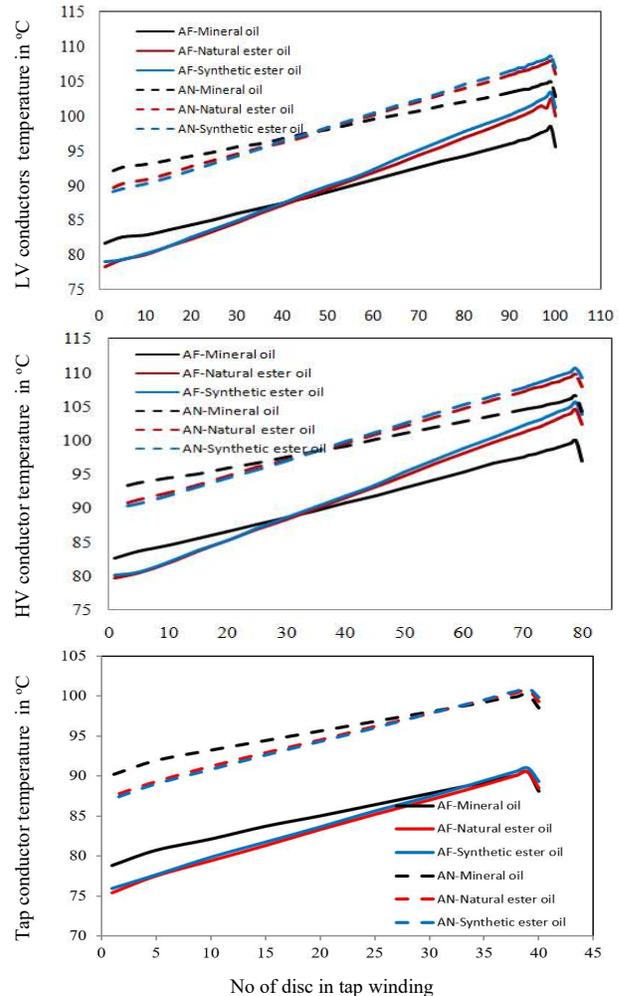

Fig.5. Temperature distribution of transformers for horizontal cooling fan arrangement due to configurations of H5

Fig.6 shows the oil flow rate, top oil temperature rise, winding temperature rise and hot-spot temperature of ester oil and mineral oil due to various cooling fan arrangements. In Fig.6, the oil flow rate in oil natural cooling modes are generally affected by thermosyphon pressure induced forces (thermosyphon force) within the winding structure and the total pressure loss will be based on hydraulic loop within transformer [6,7,14-17].
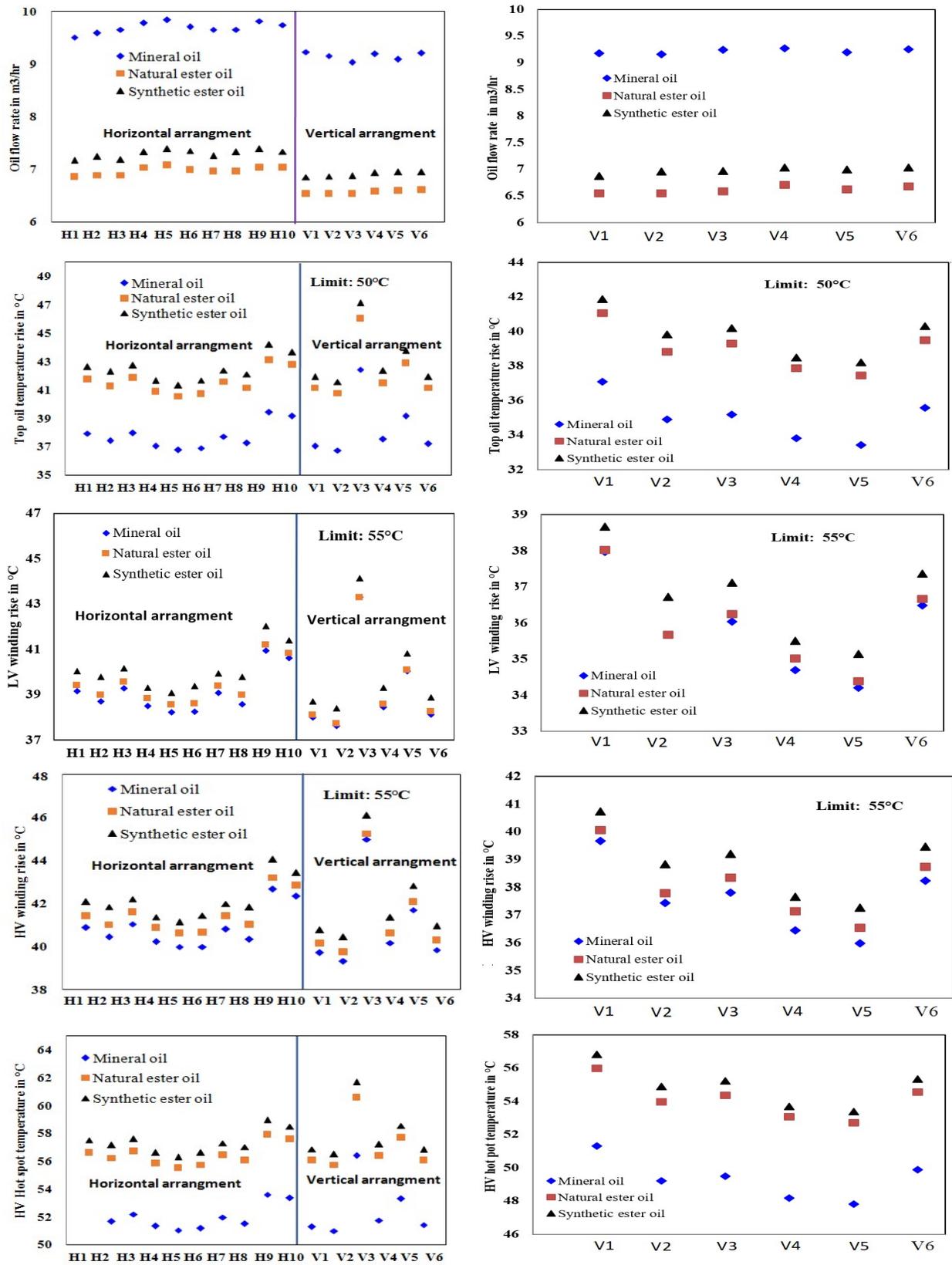
Fig.6. Oil flow rate, top oil temperature, winding rise and hot-spot temperature of ester oil and mineral oil due to various cooling fan arrangements

The oil flow rate of natural ester oil and synthetic ester oil have almost the same oil flow distributions ranges between 6.5 m³/hr to 7.3 m³/hr whereas mineral oil has relatively more uniform distribution of oil flow contributing to higher flow rates into pass top cooling ducts. With in ester oil, synthetic ester oil has higher flow rate than natural ester oil for the same liquid flow distributions.

A lower value of top oil temperature rise will provides good thermal performances which will leads to lower hot-spot temperature. The top oil temperature of ester oil is 10% higher than mineral oil. The larger hot-spot temperature at top of the winding will be generally due to uneven temperature distribution. The maximum temperature is located in the upper part of HV windings (79th disc) for mineral oil, natural ester oil and synthetic ester oil. It is found that under both cooling modes, the synthetic ester oil filled transformer oil has higher temperature than natural ester oil transformers due to higher viscosity nature. The difference between natural ester oil and synthetic ester oil is less than the difference between ester oils and mineral oil.

In oil natural cooling mode, the lower value of pass inlet velocity and higher values of copper losses will lead to more distorted oil flow and its results will be higher hot-spot temperature at top of the winding. Hence, increasing the pass inlet velocity will help to improve the oil flow distribution in order to avoid oil stagnation at bottom winding passes [6,7]. The viscosity of the oil affects the pressure drop with the winding geometry and it will influence the pass inlet velocity [18]. If a transformer is retro-filled with ester oil, the reduction of pass inlet velocity should be estimated beforehand in order to compare the performance of ester oil with respect to mineral oil.

VII. EXPERIMENTAL ANALYSIS

The thermal performance of transformer can be assessed by thermal modeling with THNM model and heat run test with optical-fibre sensor measurements where the hot-spot temperature is the most important thermal parameter. As per IEC standard, traditional assessment of transformer thermal performance is mainly relies on temperature rise test as a type test at factory, in which global temperature parameters (top oil temperature rise, bottom oil temperature rise and average winding temperature rises) are measured against atmospheric temperature under different loading conditions. The better thermal performance of transformers will be always lower top oil, winding rise and hot spot temperature. To validate the THNM results, heat run test of a transformer is conducted on 12.5/16MVA, 132/33kV natural ester oil transformer (Fig.7). Table III shows the different cooling fan mounting arrangements used for experimental validations with natural ester oil.

From experimental studies, it is found that the difference between THNM and experimental are within 1.5ºC-3ºC in all the cooling fan mounting arrangements. THNM results are higher than experimental data in most of the analysis on different fan mounting arrangements. In the experimental analysis on horizontal positions of configurations 6 shows the higher efficiency than configurations 4 as same results of THNM. Similarly, vertical position of configurations 4 shows better than configuration 2 in both THNM and experimental studies.

Fig.7. 12.5/16 MVA 132/11kV transformer with cooling fan arrangement position (H4) in radiator 4 side (R4).

TABLE III. TEST CONFIGURATIONS FOR EXPERIMENTAL ANALYSIS

Fan mounting arrangement on radiators	Test configurations	Excitations of fan at normal load conditions
Horizontal positions	Configuration -H4	H7, H9, H2
	Configuration -H6	H3, H5, H7
Vertical positions	Configuration -V2	V5, V6 ,V7, V8
	Configuration -V4	V12,V3,V10, V1

VIII. OPTIMUM PLACEMENT OF COOLING FAN

The thermal performance of transformer is mainly decided by temperature rise of oil and windings; lower the value of temperature rises in heat run test, better is the thermal performance for achieving guaranteed value of transformer life. The copper conductor has higher mechanical strength than solid (kraft paper and pressboard) and liquid insulation (oil) up to a few hundred of degree celsius. The mineral oil will not loose the insulation properties considerably below around 140°C however conductor insulation of kraft paper will start to deteriorate greatly if its temperature increases above about 90°C [3-6]. The insulation failure could result in the uncontrolled overheating of the windings leading to deterioration of the conductor insulation and resulting in a thermal failure of the transformer [6]. Hence, dissipation of heat using radiator and proper placement of cooling fan on radiator plays one of the major roles for life expectancy of transformer. Therefore, based on the thermal analysis using 12.5/16 MVA 132/11kV transformer, heat dissipation factor ranking is given in the Figs.8 &9 for all the combination of cooling fan mounting arrangments.

From the Figs.8 & 9, it is found that for a given winding geometry of 12.5/16 MVA 132/11kV transformer with given radiator configurations and a given power loss of transformer winding, the raking of heat dissipations using the cooling fan will not change.
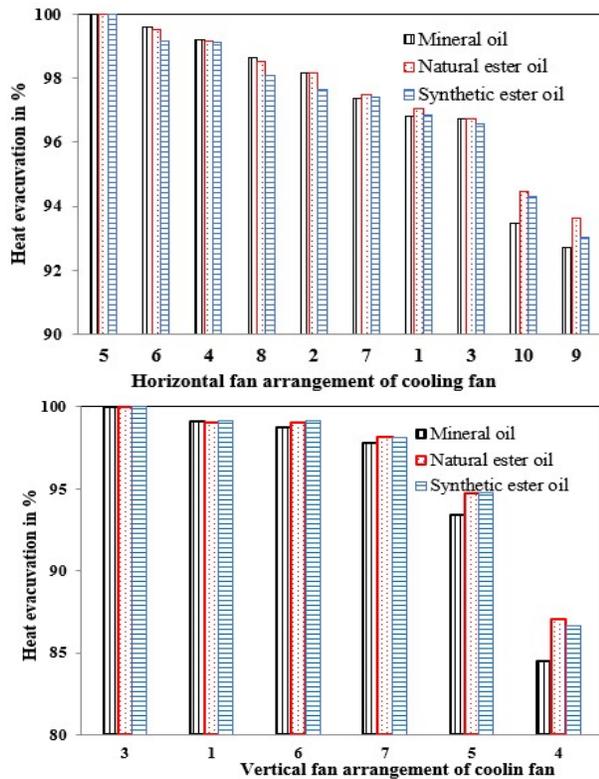
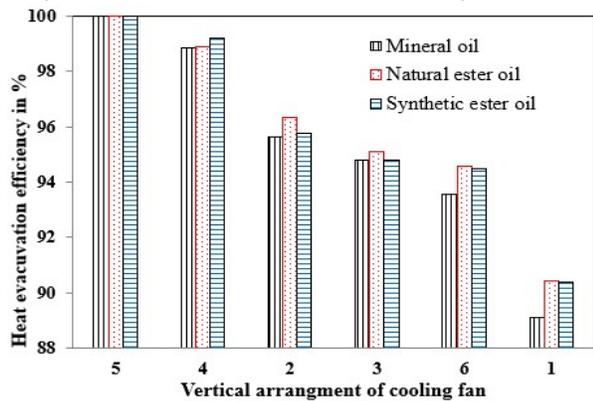Fig.8. Heat evacuation results of 4 radiator 3 fan arrangement results

Fig.9. Heat evacuation results of 4 radiator 4 fan arrangement results

IX.   CONCLUCIONS

The prediction of temperature distribution is one of the main criteria during thermal design stage to utilize different types of ester oil for transformer application. In this paper, the effects of three different oils (mineral oil, natural ester oil and synthetic ester oil) on the oil flow distribution and temperature distribution are investigated using 12.5/16MVA 132/11kV transformer. The performances of different of ester oil were compared under fixed power loss with respect to mineral oil filled transformer. The present study will be great interest for transformer manufacturers and utilities to understand the thermal performance of the ester oil transformers for various cooling fan mounting arrangement in the radiators. THNM model is utilized to predict the oil and winding temperature distribution along with oil flow rate and hot-spot temperatures and its results are compared with experimental analysis on typical power transformer of 12.5/16MVA, 132/11kV.

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