POWER TRANSFORMER DESIGN USING BIODEGRADABLE OIL STUDY FOR SUSTAINABILITY

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Article Info

Article History:
Recieved Sep 04, 2024
Revised Sep 17, 2024
Accepted Okt 28, 2024

ABSTRACT

To achieve net carbon zero in the electrical transmission and distribution industry, design, manufacturing, and materials advancements are essential, particularly for power transformers. Traditional mineral oil, used for insulation and cooling, poses environmental challenges due to its non-biodegradability, low fire point, and lack of eco-friendliness. Alternative insulating fluids, both synthetic and natural esters, offer improved fire safety and environmental compatibility. Recent research has enhanced understanding of ester fluids' electrical, thermal, and chemical properties, yet limited research, unestablished testing methods, and experience hinder adoption. This study explores the design and manufacturing challenges of power transformers using ester-insulating oil compared to those filled with mineral oil, focusing on weight, dimensions, cost, and the impact of smart monitoring systems on performance, longevity, maintenance, and reliability. The study also examines the influence of renewable energy and micro-grids on designing and manufacturing ester oil-filled transformers. This comparison aims to guide both customers and manufacturers in evaluating the suitability of ester-filled transformers for specific applications, ultimately contributing to more informed decision-making and advancing the industry's sustainability goals. The study showed the weights of some of the critical design parameters of a transformer design with ester oil to those of mineral oil for the same transformer rating and guaranteed parameters. In this case, the overall footprint is bigger for high-voltage transformers.

Keywords: *Biodegradable oil; sustainability; power transformer design*

ABSTRAK

Untuk mencapai nol karbon bersih di industri transmisi dan distribusi listrik, kemajuan desain, manufaktur, dan material sangat penting, utamanya pada transformator daya. Minyak mineral tradisional, yang digunakan untuk isolasi dan pendinginan, menimbulkan tantangan karena sifatnya yang non-biodegradabilitas, memiliki titik api rendah, dan kurang ramah lingkungan. Cairan isolasi alternatif, baik ester sintetis maupun ester alami, menawarkan keamanan kebakaran dan kompatibilitas lingkungan yang lebih baik. Penelitian terbaru telah meningkatkan pemahaman tentang sifat listrik, termal, dan minyak ester, namun penerapannya terhambat oleh penelitian, metode pengujian dan pengalaman yang terbatas. Studi ini mengeksplorasi tantangan desain dan manufaktur transformator daya yang menggunakan minyak isolasi ester dibandingkan dengan yang menggunakan minyak mineral, dengan fokus pada berat, dimensi, biaya, dan dampak sistem pemantauan cerdas terhadap kinerja, umur pemakaian, pemeliharaan, dan keandalan. Studi ini juga meneliti pengaruh energi terbarukan, jaringan mikro-grid pada desain dan manufaktur transformator berisi minyak ester. Tujuannya untuk memandu pelanggan dan produsen dalam mengevaluasi kesesuaian transformator berisi ester untuk aplikasi tertentu, yang pada akhirnya berkontribusi pada pengambilan keputusan yang lebih tepat dan memajukan tujuan keberlanjutan industri. Studi menunjukkan bahwa bobot beberapa parameter penting dari desain transformator oli ester sama dengan bobot oli mineral untuk rating transformator yang sama dan parameter yang diizinkan. Dalam kasus ini, footprint keseluruhan lebih besar untuk transformator tegangan tinggi.

Kata Kunci: *Minyak biodegradable; keberlanjutan; desain transformator tenaga*

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1. INTRODUCTION

Transformers are an important part of electrical power systems equipment [1] and need them even more in the future to increase the need for cleaner and environmentally friendly energy. Transformers need to be well manufactured, with appropriate alternate materials, and be reliable and environmentally safe. Conventional power transformers are filled with mineral oil for insulation and cooling purposes, but the use of mineral oil is disadvantageous in several ways. In contrast, new-age dielectric coolants, which are composed of an ester-based insulating oil, offer carbon-free credentials, a low fire risk, full biodegradability, lower ageing rate of the cellulose in the pressboard barriers in the transformer, and compatibility with high-temperature insulation, all of which contribute to their superiority compared with mineral oil [2]. Recent studies have allowed manufacturers to better understand the electrical, thermal, and chemical properties of ester fluids [3, 4]. Earlier studies have highlighted the challenges in dielectric and thermal design considerations and their impacts on power transformers with ester fluids [5, 6]. However, they lack the quantitative comparison and thus do not help in developing a clear design guideline.

This paper aims to establish the impacts on the thermal and dielectric design of the power transformers filled with ester fluids by establishing a quantitative comparison with mineral oil-filled transformers. The first part of the research analyses the thermal performance of the power transformers filled with ester and mineral oil using Thermal Hydraulic Network Model (THNM) [7]. A detailed quantitative comparison is established. The results confirm the elevated temperature rises for Ester Oil-filled transformers, which were established in earlier studies. Design, its challenges, and its impact on ester oil. This study verifies and establishes the advantages of using a directed oil flow cooling methodology for ester oil. The following section details the quantitative comparison of dielectric design safety margins between ester-filled and mineral oil-filled power transformers. The results further confirm the conclusions established in earlier experimental studies[6, 8]. Eventually, an impact on the overall footprint of the transformer is highlighted due to the thermal and dielectric design requirements for ester oil. The results of this research can be used to establish reliable design guidelines for transformer designers without the need for simulation for individual designs. Thus, this can help save a huge amount of time at the design stage. Additionally, a user can make a well-informed decision when buying a transformer with ester fluid.

Figure 1 Typical Insulation Arrangement in Power Transformer

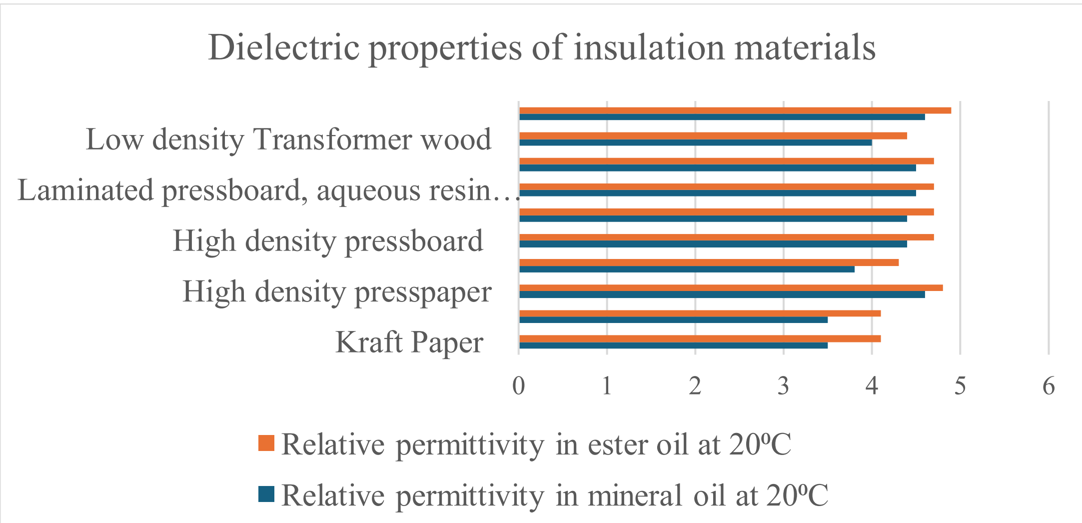


Figure 2 Properties of Insulation Material Used in Oil Filled Transformer

Table 1 Comparison of Properties of Mineral Oil and Ester Oil

	Units	Mineral oil (nynas lybra iec60296)	Synthetic ester midel 7131 iec61099	Natural ester Cargil fr3 Iec62770
General properties				
Density at 20ºc	Kg/m^3	875 (max. 895)	970 (max. 1000)	920 (max.1000)
Specific heat at 20ºc	J/kg-k	1860	1880	1883
Thermal conductivity at 20ºc	W/m-k	0.126	0.144	0.167
Kinematic viscosity at 40ºc	Mm^2/s	9.6 (max. 12)	28 (max. 35)	34 (max. 50)
Kinematic viscosity at -20ºc	Mm^2/s	-	1400 (max. 3000)	650
Kinematic viscosity at -30ºc	Mm^2/s	1100 (max. 1800)	-	-
Pour point	ºc	-51 (max. -40)	-60 (max. -45)	-21 (max. -10)
Flash point	ºc	152 (min. 135)	26 (min. 250)	260-270 (min. 250)
Fire point	ºc	170	316 (min. 300)	350-360 (min. 300)
Fire hazard classification (iec 61100)		O	K3	K2
Biodegradability at 28 days				
Oecd 301f	%	Na	>89	>99
Oecd 301d	%	< 10	-	-
Oecd 301b	%			95-100
Water content	Mg/kg	< 20 (max. 30)	50 (max. 200)	4-50 (max. 200)
Water solubility at 20ºc	Ppm	55	1100	2700
Electrical properties				
Breakdown strength iec 60156, 2.5 mm	Kv	40-60	>75	47
		Min. 30 (untreated)	Min. 45	Min. 30
Permittivity at 20ºc		2.2	3.2	3.2

2. RESEARCH METHODS

Conventionally, oil-filled power transformers are designed and manufactured using mineral oil as insulating and cooling material, cellulose-based pressboard, and transformer wood. Figure 1 shows the main insulation between windings using cylinders and potential rings. We first summarize the dielectric properties of the insulation materials, and the chemical and thermal properties of insulating oils used in the power transformers. We compare the properties of ester oil with those of mineral oil, as shown in Table 1. These properties are established in the literature and the ester oil manufacturer's datasheet[3, 4, 9, 10]. These properties will be later used for modelling the cooling and dielectric designs of power transformers filled with ester and mineral oil. Figure 2 shows these dielectric properties as established by the international standard IEC [9, 11-14]. Figure 2 shows the dielectric properties of ester oil is higher than those of mineral oil.

The thermal performance is evaluated with the help of the Thermal Hydraulic Network model [7] for ester and mineral oil-filled power transformers in section 2.1. The chemical and thermal properties highlighted above are used to create these models. Impact on thermal performance is evaluated for different types of cooling methods incorporated in the power transformer, they are ONAN – Oil natural air natural, ONAF – Oil natural Air forced, ODAF – Oil directed Air forced. The impact is summarized as a quantitative comparison of the thermal parameters between the ester and mineral oil-filled power transformers. The results are also compared with the established conclusions in earlier literature. Section 2.2 evaluates the impact on the dielectric performance of a power transformer filled with ester oil. Insulation design with the dielectric properties shown in Figure 1 are modelled in FEM software. The results of this study are compared with those of a similar study performed with mineral oil. A quantitative comparison of the safety margins in dielectric design between ester and mineral oil-filled power transformers is produced. These outcomes are also in line with the experimental studies done in the literature for AC and impulse breakdown of ester fluids [6, 8].

Brief information on the selection of accessories and components for ester-filled transformers is provided in section 2.3. Eventually, the overall impact of thermal and dielectric design on the size and weight of the power transformer is summarized.

2.1 Cooling Design

As can be seen in Table 2, the Viscosity of ester fluid is higher than mineral oil. THNM modelling shows a higher viscosity, resulting in reduced flow rate and oil velocity in transformer windings. In addition, a higher temperature difference along the winding height is caused. This is shown in Figure 3 and Figure 4 by comparing the various cooling parameters between mineral and ester oil for ON (oil natural) cooled transformers. The other design parameters are kept the same between the two designs. In Figure 5, a comparison is made for an OD transformer.

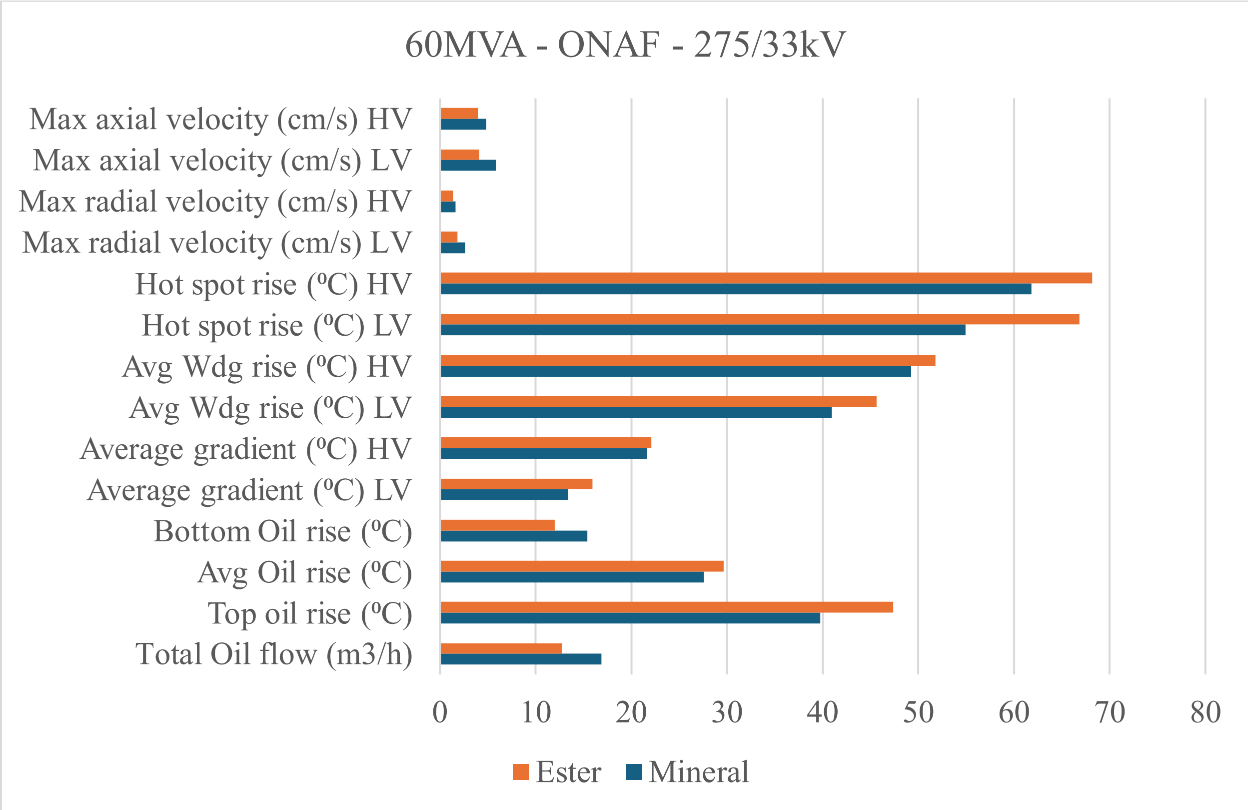


Figure 3. Cooling Design Parameters for ON Design 60MVA with Mineral & Ester Oil.

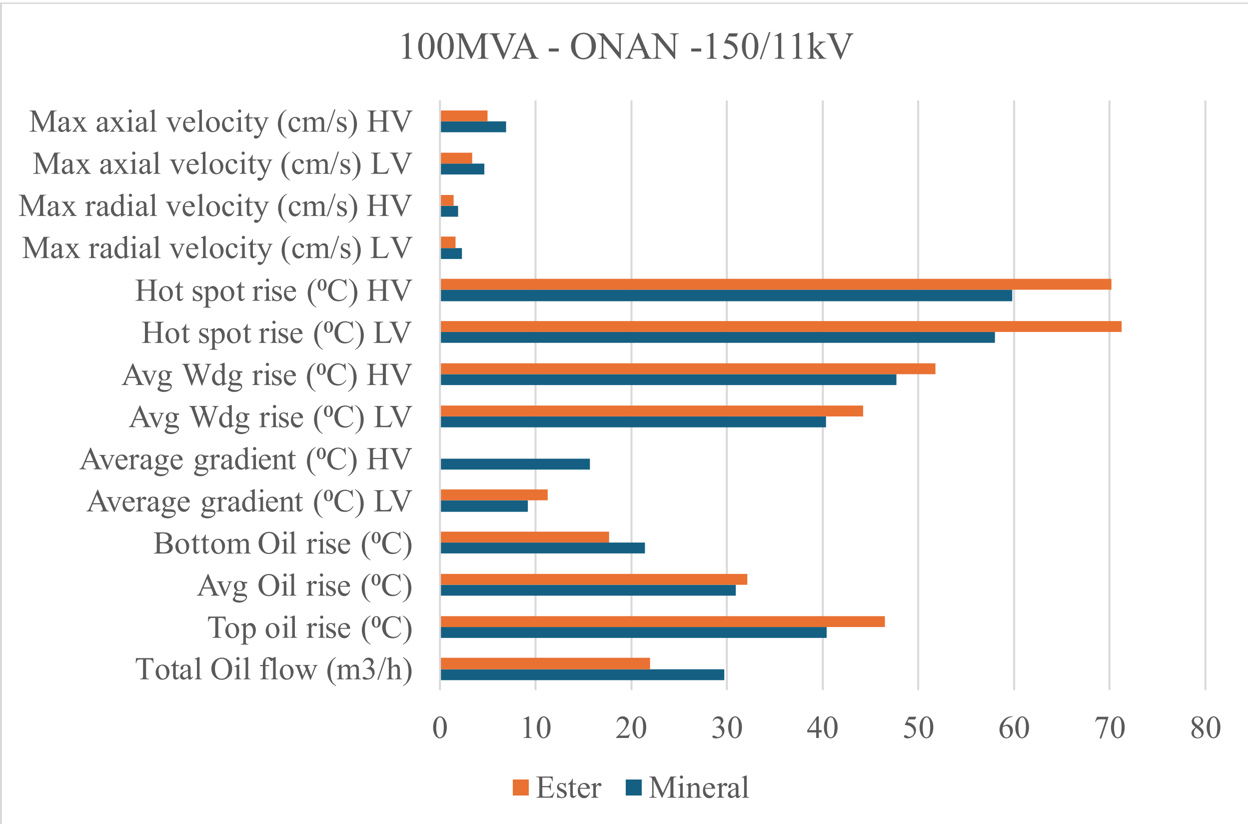


Figure 4 Cooling Design Parameters for ON Design 100MVA with Mineral Oil & Ester Oil.

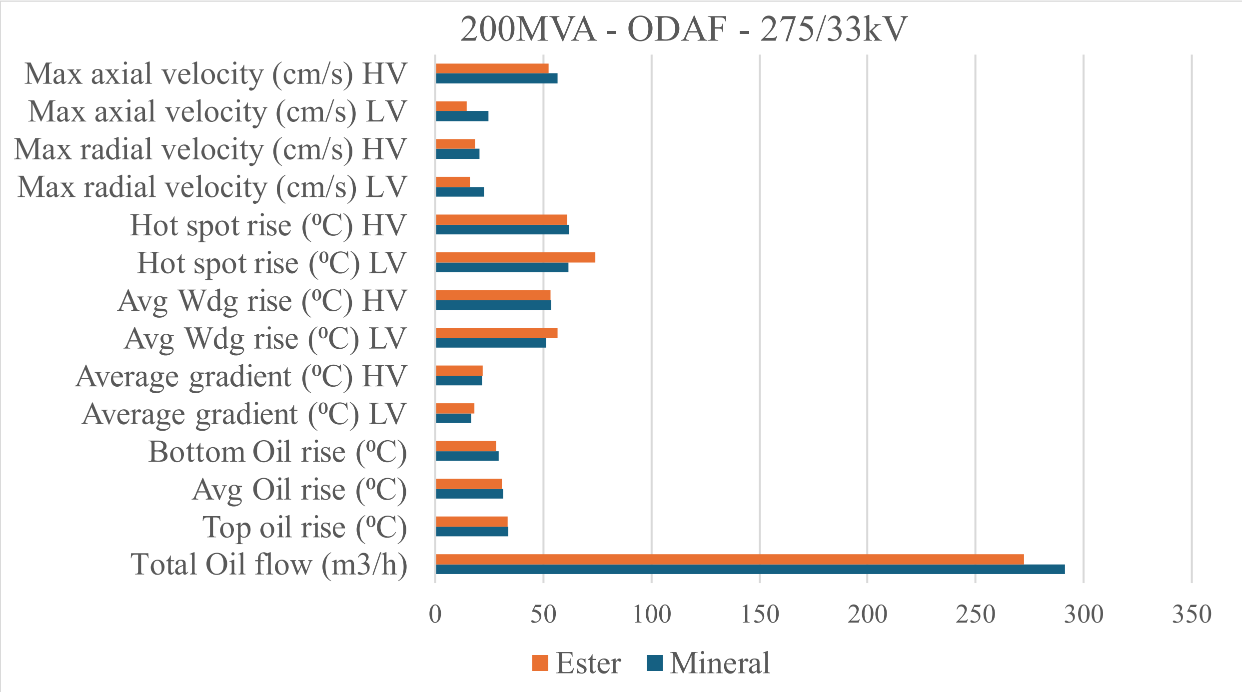


Figure 5 Cooling Design Parameters for OD Design 200 MVA with Mineral Oil & Ester Oil.

For the ester-filled transformer, the top oil temperature rise is 2 - 5^{0}C higher, the average winding rise is 2 - 3 ^{0}C higher, and the hot spot rise could be >10 ^{0}C higher in some cases, compared to mineral oil. In the case of an ester-filled transformer, design guidelines such as increased minimum radial duct thickness, increased minimum axial duct thickness, and increased number of oil guiding passes need to be implemented for better cooling efficiency. The impact on cooling design is more significant in ester oil-filled transformers with ON cooling than it is in OD-cooled designs. For ON cooling, the required number of radiators and fans will be higher than that required for mineral oil. This increase won't be very significant for OD cooling. This leads to a bigger transformer footprint.

2.2 Dielectric Design

Transformers designed with ester oil must withstand the same AC, lightning impulse, and switching surges as conventional mineral oil-filled transformers. The values of the breakdown voltage, when measured as per the IEC 60156 for mineral and ester fluids, are the same [5]. It was reported that the AC breakdown voltage, partial discharge inception voltage, and impulse breakdown voltage under a homogenous field are similar in ester oil and mineral oil. It also shows the differences in partial discharge patterns. The study performed in [15] shows that for quasi-uniform fields, the lightning impulse withstand for ester liquids is comparable with that of mineral oil. However, from the study in [6, 16], it is shown that very fast streamers are observed at much lower voltage in ester fluids compared to mineral oil. A lower breakdown voltage in long gaps is measured in these liquids, and a lower resistance to short-duration impulses is also observed compared to mineral oil. This is for both positive and negative waves. This is important for larger liquid gaps and higher impulse voltages. The results shown in [6] also show that the difference in breakdown strength starts departing by a larger value to those of mineral oil as the degree of inhomogeneity increases. A similar experimental outcome is also reported [8]. The performance of ester fluid is comparable to mineral oil. Under nonhomogeneous field distributions, the difference in dielectric performance becomes more important.

If there are no well-verified design criteria for ester oil, the general practice is to use an empirical approach by following the design curves of mineral oil with some adjustments on required safety margins. Special care is taken in the area of non-uniform field stress distribution, which usually occurs in the top and bottom end insulation, near the lead exits, near the leads in bulk oil, tap changer connection, and other places. The design rules will be different from manufacturer to manufacturer. The difference in allowed stress and actual stress is maintained over the design curve. There is a % difference between safety margins for ester oil design and mineral oil design in Table 2.

Table 2 Percentage Difference in Safety Margin Between Ester Oil and Mineral Oil Design

Insulation Location	% Difference in safety margin between Ester and Mineral oil designs
Radial Gap between windings	10%
Electrical stress in conductor paper	10%
Impulse withstand between discs	10%
End clearance	10%
Clearance in lead system (path >20 mm)	25%
Clearance to tank (path > 20 mm)	30%
Along the creepage path	30%

2.3 Selection Of Accessories & Components

1) Pump

The cooling design is impacted by the higher viscosity of the oil. The increase in thermal design parameters in the case of OD design is not significant. The data in Table 4 shows that a slightly higher pump flow rate is needed to compensate for the reduced oil flow and oil velocities.

2) Tap changer

In addition, as highlighted in [8], an experimental result shows that a significant de-rating is to be applied when selecting a tap changer as they show lower resistance to AC as well as lightning. Selecting a higher voltage class tap changer would result in a bulkier tap change. The dimensions of the transformer have increased. If transformer insulating liquid is different from traditional mineral oil, the supplier must be informed.

3) Bushings

Power transformer application has limited development in the ester oil-filled condenser bushings. If you want to use a transformer filled with ester oil, you have to use either mineral oil-filled OIP bushings or an impregnated paper one. As far as alternate fluids are considered, there isn't much impact on the selection of bushing. For higher operating temperatures, special consideration should be given to the gasket material selection.

4) Material Compatibility

There are no incompatibilities between natural ester fluids and material used for mineral oil. The material used for mineral oil is generally compatible with synthetic esters. Only a few materials are recommended for use in a particular situation. A brief description can be found in [5], where the impact of using the ester with some conventional materials, along with recommendations, are discussed. A similar compatibility study is found in[17]. Most of the material is compatible with ester oil. However, it is important to check the nitrile rubber gasket's chemical composition to make sure it is compatible.

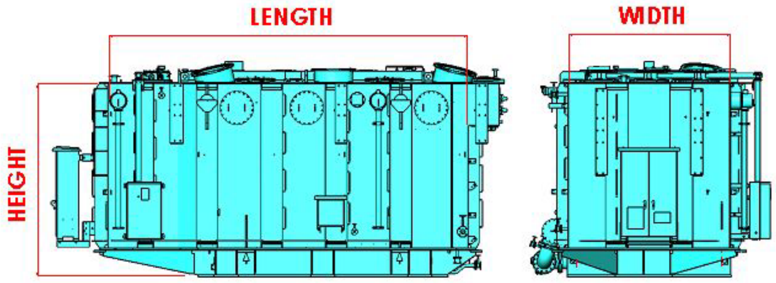
3. RESULTS AND DISCUSSION

3.1. Research Results

The data presented in section 2.1 shows that the use of ester oil in power transformer application leads to an increase in temperature rise values when compared to mineral oil-cooled transformers. THNM calculation also revealed a reduced oil flow, reduced velocity, and increased temperature difference along the winding height. An increase of 2-5 ºC for top oil rise, 2-3 ºC for average winding rise and approximately 10ºC for hot spot temperature rise is observed for the selected designs under study. It is observed the increase in the temperature rise values is significant in the case of ON cooled transformer. In the case of OD cooled transformer a, better cooling efficiency is observed. A dielectric design evaluation revealed that due to the formation of streamers at comparatively lower voltage and low voltage withstand in long inhomogeneous oil gaps, required safety margins are higher for ester oil-filled transformers. The difference between design safety margins for dielectric performance between mineral oil and ester oil-filled transformers can be as high as 30% in very long oil gaps. It is further observed that the oil gap of a length of more than 20 mm results in poor withstand.

3.2. Discussion

Based on the results of cooling evaluation using THNM, it is understood that the cooling design rules such as minimum radial duct thickness, minimum axial duct thickness, average height of winding section per oil guiding pass, selection of oil-directed cooling for ratings above a particular MVA capacity are required to be reviewed and revised by the manufacturer to improve cooling design efficiency.



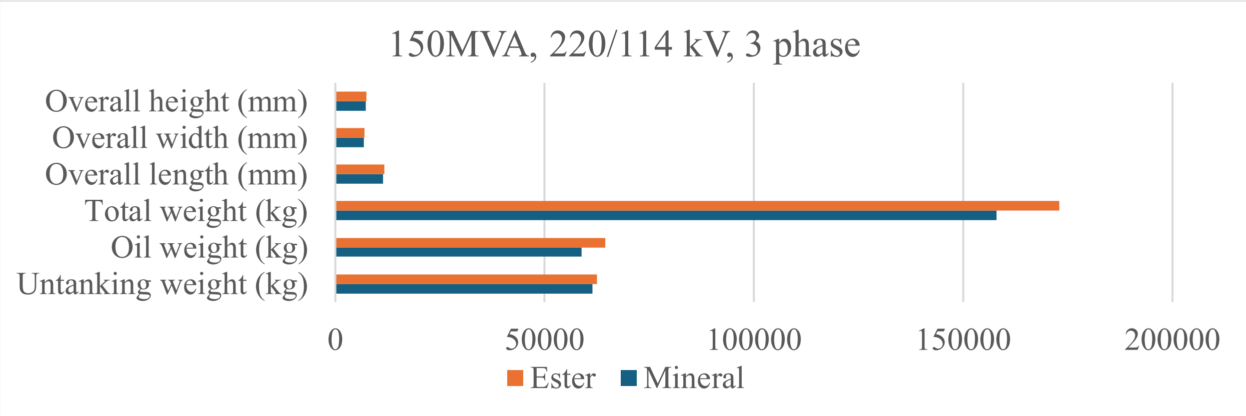


Figure 6 Comparison of weights and dimensions of mineral oil vs ester oil transformers

In general, a higher radial duct thickness and axial duct thickness are recommended with more oil passes along the winding height. For large power transformers above 100 MVA, oil-directed cooling mode is advised. It can be deduced that the cooling design footprint will be larger in the case of ester-filled transformers for on designs.

In the absence of verified design criteria, the dielectric design of the ester oil-filled transformers follows the design curves of the pd-free mineral oil transformers with additional de-rating factors. Particularly for the long oil gap and inhomogeneous fields such as winding top and bottom end insulation, lead exits, lead to tank, tap changer connection, bushing connections, etc., the resilience of ester oil is not as good as mineral oil. The increase in safety margin in the design has to be maintained. There will be an increase in internal insulation clearances. The de-rating of tap changers is required due to the lower dielectric strength of ester-filled transformers. The tap changer manufacturer needs to be consulted to select the appropriate class. This results in a higher class tap change compared to mineral oil-filled transformers. The above factors cause The dimensions and weight of the transformer to be increased. This increment is more significant for higher-capacity transformers. Figure 6 compares the weights of some of the critical design parameters of a transformer design with ester oil to those of mineral oil for the same transformer rating and guaranteed parameters. In the case of ester oil designs the overall footprint is bigger for high-voltage transformers.

4. CONCLUSIONS

It is possible to make the transformer application more sustainable and environmentally friendly by using bio-degradability and high fire safety. One of the challenges is adapting the ester fluids for the large power transformers. Some challenges in power transformer designs are caused by the use of ester oil for insulation and cooling. Revised design rules are required to increase the cooling design efficiency and reliability for ester oil-filled power transformers. Increased value of thermal parameters required an increase in the cooling ducts inside the windings and an increase in the cooling equipment such as radiators, fans, pumps, etc. This leads to an increased footprint of the transformer. The thermal design parameters are almost identical for oil-directed cooling designs. The optimum cooling design footprint is almost identical to mineral oil designs if you adopt oil-directed cooling for a larger rating transformer. Without an established breakdown theory of fluids, it is difficult to fully understand the breakdown properties. A comparison of the experimental results and the calculations produced here for the dielectric performance of ester oil with those of mineral oil gives some insight into the behaviour of ester fluid.

It is recommended to use the mineral oil design criteria with some de-rating for the dielectric design of ester oil-filled transformers. The derating is governed by the difference in safety margins highlighted in Table 2. The safety margins are increased to ensure reliability. The increase in dielectric clearance due to the increased safety margins is unavoidable. The manufacturer is advised to update the design rules and requires de-rating with experience. Due to the increased nature of inhomogeneity in an electrical field, it is necessary to choose a higher voltage class tap changer for the ester oil design compared to the mineral oil design. The combination of these factors results in a larger footprint in terms of weights and dimensions for ester oil designs compared to mineral oil designs of the same rating and guaranteed parameters. As the transformer's capacity increases, the increment becomes more significant.

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