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RESEARCH ARTICLE

Comparative Analysis of Breakdown Voltage, Temperature Rise, and Production Cost of Using Mineral Oil and Synthetic Ester in 33 MVA 132/33 kV Power Transformers

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Abstract

In support of achieving the net zero emission target in the power sector, the selection of environmentally friendly transformer insulating oil is very important. This study presents a comparative analysis of the dielectric and thermal performance between mineral oil and synthetic ester oil. The breakdown voltage (BDV) test was conducted with a variation of rest time of 1 minute and 10 minutes. In addition, temperature rise tests were conducted on a 33 MVA capacity power transformer with a voltage of 132/33 kV. Temperature rise testing is carried out on synthetic ester oil and mineral oil through thermal simulation with identical transformer specifications, the goal is that there are no distinguishing variables in the test. The test results show that at a rest time of 1 minute, synthetic ester oil produces fluctuating BDV values, with some data being below the minimum threshold of 60 kV according to IEC 61203 standards. In contrast, mineral oil (MO) showed stable and consistent dielectric performance. At a rest time of 10 minutes, both types of oil showed stable BDV values with low standard deviations. In terms of thermal performance, mineral oil produced a lower temperature rise than synthetic ester oil (SE), indicating better cooling efficiency. The study will also analyze the impact of transformer dimensions due to the different transformer oils used, which will result in the price of the transformer. The findings provide technical insights for manufacturers and users in selecting transformer oils that support environmental sustainability without compromising the reliability of power transformers.

Keywords: Synthetic ester oil, mineral oil, breakdown voltage, temperature rise, power transformer

1. Introduction

Power transformers are one of the most vital components in electric power transmission and distribution systems[1]. One important part of the transformer is the transformer oil which functions as an electrical insulation medium and thermal coolant. The choice of transformer oil type greatly affects the performance, efficiency, and operational life of the transformer[2]. Mineral oil has been widely used due to its good dielectric properties and relatively low cost. However, being derived from petroleum, mineral oil has low biodegradability and contributes to carbon emissions[3]. With increasing demands for sustainability and net zero emission targets in the power sector, synthetic ester oils are being developed as a more environmentally friendly alternative due to their biodegradable properties and low carbon footprint[4], [5]. However, synthetic esters have several limitations, such as high viscosity which makes it difficult for gas bubbles to dissipate after dielectric testing and hygroscopic nature, which potentially reduces the insulation performance of synthetic ester oil. Therefore, this research will conduct dielectric testing, namely breakdown voltage and temperature rise on mineral oil and synthetic ester oil to determine the cooling performance of each transformers oil.

Previous studies on transformer oil performance have generally focused on the characteristics of breakdown voltage (BDV) against variations in oil temperature and distance between electrodes[6], [7]. Some studies show that increasing temperature can affect the decrease in dielectric strength[8]. However, most of these studies did not vary the rest time between BDV tests. While the physical characteristics of ester oil which has a higher level of viscosity or viscosity, this results in gas bubbles formed after the breakdown voltage testing process takes longer to disappear when compared to mineral oil. Gas bubbles that have a smaller permittivity than oil can result in a weakening of the insulating ability of synthetic ester oil.

Previous studies on temperature rise in power transformers have generally focused on the relationship between operating temperature and the life of paper insulation and overall transformer life[9]. Some studies only focus on certain parts of the transformer, such as its windings or tanks, while others focus on mathematical modeling or numerical simulation of temperature rise based on design parameters and operating loads[10]. In this study, direct temperature rise testing was conducted on a 33 MVA capacity power transformer with a voltage of 132/33 kV filled using synthetic ester oil. Measurements were made based on applicable transformer testing standards, by monitoring the top oil temperature, winding hot-spot temperature, and temperature distribution during nominal loading conditions. To compare the thermal performance of mineral oil, thermal simulations were conducted using transformer models that have identical technical specifications, such as operating voltage, nominal power, impedance, core loss, and load loss. With this combined method of actual testing and simulation, a more comprehensive picture of the thermal characteristics of each type of insulating oil is expected. This approach allows an objective evaluation of the cooling efficiency and heat release capability of synthetic ester oils versus mineral oils under identical operating conditions, thus providing a sound technical basis for oil type selection decisions for power transformer applications.

Therefore, this study aims to comprehensively evaluate the dielectric and thermal performance characteristics of mineral oil (MO) and synthetic ester (SE) oil. Tests were conducted on BDV with two variations of rest time, namely 1 minute and 10 minutes, to see the effect of rest time on the insulating ability of synthetic ester oil and mineral oil. In addition, temperature rise testing was also conducted on a power transformer with a capacity of 33 MVA and a voltage of 132/33 kV. The temperature rise tests for synthetic esters and mineral oil were simulated using the same technical parameter data. It is intended that there are no distinguishing variables that affect the temperature rise test results. Temperature rise testing on mineral oil and synthetic ester aims to determine the type of transformer oil that has better cooling capabilities. The results of this testing can serve as a reference for selecting the type of insulation paper for transformer windings. In this study, an analysis was also conducted on the dimensions of transformers using mineral oil and synthetic esters, as transformer dimensions can influence the primary material requirements in the manufacturing process, such as silicon steel (iron core), copper for windings, and transformer oil volume. Primary materials have a direct impact on the final cost of the transformer. Therefore, through this study, it is hoped that an understanding of the balance between reliability and economic efficiency in transformers using synthetic ester oil and mineral oil can be obtained. Thus, a more comprehensive picture can be obtained in selecting the appropriate type of insulating oil, based on technical performance and transformer cost considerations.

2. Mineral and Synthetic Ester Oil for Power Transformers

Tests were conducted on a 33 MVA capacity power transformer with a voltage of 132/33 kV, using two different types of transformer oil, namely mineral oil and synthetic ester oil. The first test carried out is the breakdown voltage (BDV) test for each type of oil, which aims to evaluate the dielectric performance of mineral and synthetic ester oil. The second test is the temperature rise test on power transformers with synthetic ester oil, which is carried out directly using testing equipment in the field. Meanwhile, the temperature rise test on mineral oil was conducted through thermal simulation, using identical transformer specifications, including operating voltage, nominal power, and core and load loss parameters. The temperature rise simulation was performed using thermal hydraulic network modeling (THNM).

2.1 Thermal Hydraulic Network Modeling (THNM)

Thermal Hydraulic Network Modeling (THNM) is a technique used to simulate the thermal behavior of transformers, particularly focusing on oil flow and temperature distribution within the transformer [11]. It utilizes an electrical analogy to model the hydraulic and thermal networks, enabling the prediction of hot-spot temperatures and overall thermal performance. THNM allows for precise calculation of temperature distribution within the transformer, which is crucial for determining its lifespan and performance. By analyzing thermal behavior, THNM enables designers to optimize transformer design for better cooling and reduced losses [12]. THNM helps identify potential hotspots and thermal issues, enabling proactive maintenance and reducing the risk of transformer failure.

This method involves the creation of a network model that represents the internal components of the transformer and their interactions in terms of heat transfer and fluid flow (oil). The following is the mechanism of thermal hydraulic network modeling [13],

a) Hydraulic Network:
This part of the model simulates the flow of oil through the transformer's various channels and passages. It uses an electrical analogy, where oil flow is represented by electrical current and pressure by voltage.
b) Thermal Network:
This part models the heat transfers between the transformer's active parts (windings, core) and the cooling oil, as well as heat dissipation to the environment.
c) Coupling:
The hydraulic and thermal networks are coupled, meaning that the oil flow affects the heat transfer and vice versa. For example, increased oil flow can carry away more heat, lowering the temperature, while higher temperatures can affect the oil viscosity and flow rate.

2.2 A Methodological Approach to the Study of Mineral and Synthetic Ester Oil

See figure 1, the second step is to read and analyze the specifications given by the customer for example power, voltage, no-load loss, load loss, and impedance of the power transformers. The third step is to design the transformers according to the specifications, to design this transformer is done using power transformers calculation. From designing an ordinary transformer, an initial picture is obtained, so that in the fourth step it is necessary to re-analyze it to suit the economic aspects and technical aspects so that when these two aspects have not been fulfilled, a redesign will be carried out again. In the fifth step, fabrication begins, namely the manufacture of tanks, iron cores, and transformers windings. The manufacturing of the tank is done by the vendor. The sixth step is to fill the transformers oil into the tank. In the seventh step is to do the purification of transformers oil, purification is to clean the transformers oil from particles and water content contained in the transformers oil. This aims to make the oil test results match the specifications so that a factory acceptance test (FAT) can be carried out. However, when the transformer oil test is below standard, purification must be performed again[14].

The ninth step is to conduct transformer oil sampling. This sampling must follow established procedures. Before collection, the sample storage container must be rinsed at least three times using the transformers oil to be taken. The goal is to avoid contamination from previous oil residues or dirt that may be present in the container. In addition, oil collection should be done with a small and steady flow. This is so that the oil sample is not mixed with surrounding gases or contaminated with dust particles from the surrounding environment. With the right procedure, the quality of the oil sample can be maintained and the test results become more accurate. The tenth step is to test the breakdown voltage (BDV).

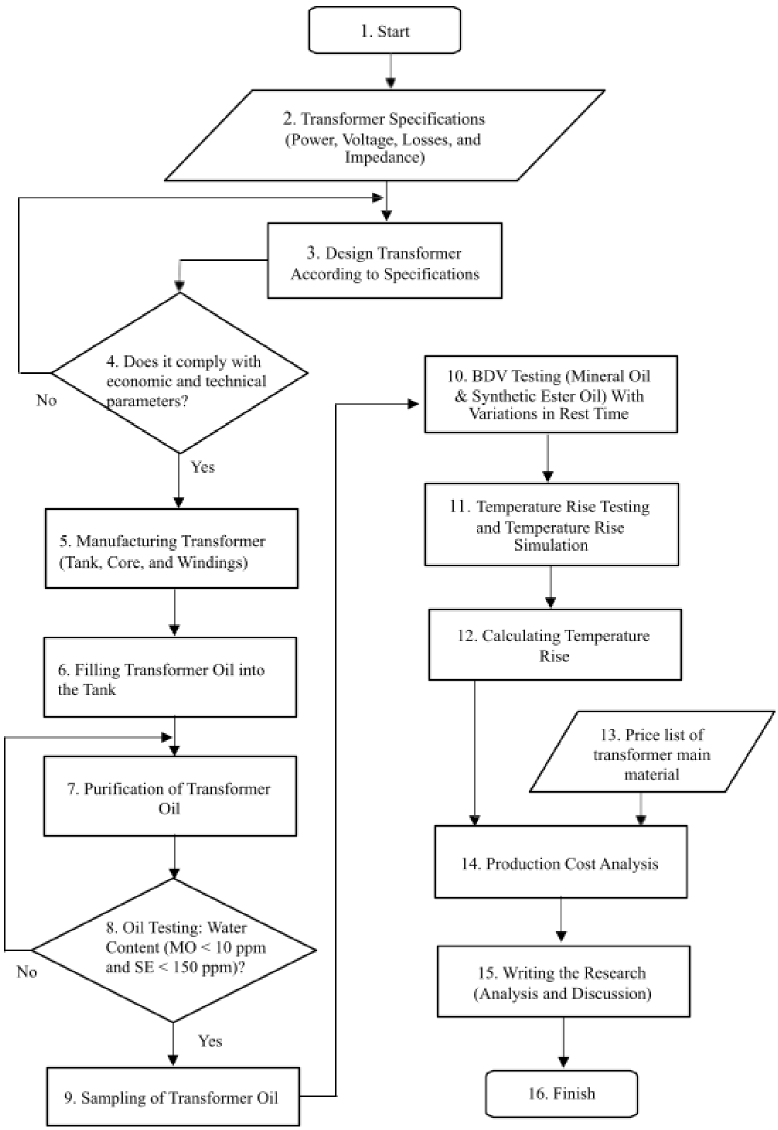

Figure 1. A methodological approach to the study of mineral and synthetic ester oil

This test is carried out with a variation of the rest time between each measurement. The purpose of this rest time variation is to determine the effect of rest time on the insulating ability of transformer oil. This test aims to evaluate the effect of rest time on the breakdown voltage value produced by the oil, so that a more comprehensive understanding of the dielectric characteristics of the transformer oil can be obtained. The eleventh step has two methods. The first method is to test the temperature rise directly on the power transformer. Meanwhile, the second method is done by simulation using thermal hydraulic network modeling (THNM).

This is done because it is not possible to replace different types of oil in one transformer. This test aims to see the ability or role of transformer oil in affecting transformer temperature. The twelfth step is to analyze and calculate the results of the previous temperature rise test. This calculation is based on the results of the temperature rise test. The goal is to obtain the value of the oil top surface temperature, HV winding temperature, LV winding temperature, and the highest temperature. The thirteenth step is to make observations to find out the price of tanks, iron cores, and the price of copper used to make the windings in the transformers. These prices are used in analyzing the production cost of the transformers. The fourteenth step is to analyze and calculate the production cost of the transformers using two different types of oil.

2.3 Water Content Test

Water content testing is carried out first before carrying out breakdown voltage testing. The purpose of this test is to ensure that the condition of the transformer oil–both mineral oil and synthetic ester oil–is within the appropriate water content standard before breakdown voltage testing is carried out. The water content testing standard refers to IEC 60422 for mineral oil and IEC 61203 for synthetic ester oil. The maximum allowed moisture content in mineral oil is 10 ppm, while for synthetic ester oil is 150 ppm. This moisture content test was conducted using the Megger KF-Lab Karl Fischer tool, which works based on the Karl Fischer titration method. The working principle of this tool involves a chemical reaction between water, iodine (I_2), sulfur dioxide (SO_2), organic bases, and alcohol in an organic solvent. This reaction proceeds stoichiometrically, allowing accurate measurement of moisture content down to the microgram level[15].

$$H_2O + I_2 + SO_2 + 3C_5H_5N \rightarrow 2C_5H_5N.HI + C_5H_5N.SO_3 \tag{1}$$

$$C_5H_5N.SO_3 + CH_3OH \rightarrow C_5H_5NH.SO_4CH_3 \tag{2}$$

A total of 1 mL of oil sample is put into the Megger KF-Lab Karl Fischer device, then it will mix with iodide and sulfur dioxide solutions. Iodine (I_2) is produced through the electrolysis process and will react with water in the sample, according to the chemical reaction shown in Equations (1) and (2). The iodine formed is directly proportional to the amount of electric current used, in accordance with Faraday's Law, as shown in the following equation:

$$2I^- - 2e^- \rightarrow I_2 \tag{3}$$

Under stoichiometric conditions, one mole of iodine will react with one mole of water, as described in Equation (1). Based on this calculation, it is known that 1 mg of water is equivalent to 10.72 coulombs. Therefore, the amount of water in the sample can be determined based on the total electric current (number of coulombs) required during the electrolysis process.

The KF-Lab Megger device will use a current integrator to calculate the total current consumed, then determine the equivalent amount of water based on Faraday's Law, and finally display the test results in units of micrograms of water[15]. Figure 2 is the KF-lab megger tool and the process of entering the sample into the KF-lab megger tool.

Figure 2. Water content testing on oil using Megger KF-Lab

2.4 Voltage Breakdown Test

The breakdown voltage test in this test uses the Baur DTA 100 Dielectric Strength Test Set. This tool has voltage specifications up to 100 kV. This tool uses a mushroom-shaped electrode, see Figure 3 The breakdown voltage test in this study will be carried out with rest time variations, namely 1 minute and 10 minutes. The standard procedure for breakdown voltage testing is set out in IEC 60156[16]. The test results refer to IEC 60422 for mineral oil and IEC 61203 for synthetic ester oil. For the oil to be used in this transformer (33 MVA 132/33 kV) the breakdown voltage value should not be less than 60 kV.

Breakdown voltage (BDV) in power transformers is a crucial parameter that plays a role in assessing how strong the dielectric ability and reliability of the insulation system in the face of high voltage. The BDV value is influenced by various aspects, such as the type of insulating material used, the quality and condition of the insulating oil, the shape and configuration of the electrodes, and external factors such as environmental temperature and humidity.

Below are presented some of the main mathematical models used to estimate and evaluate breakdown voltage values in power transformers. To estimate the breakdown voltage in transformer oil and solid insulating materials, one approach used is an empirical model based on Paschen's Law, which was originally developed for gaseous dielectrics, but has also been applied to liquid media such as transformer oil. This model illustrates the relationship between breakdown voltage and electrode spacing and the pressure or density of the insulating medium[17].

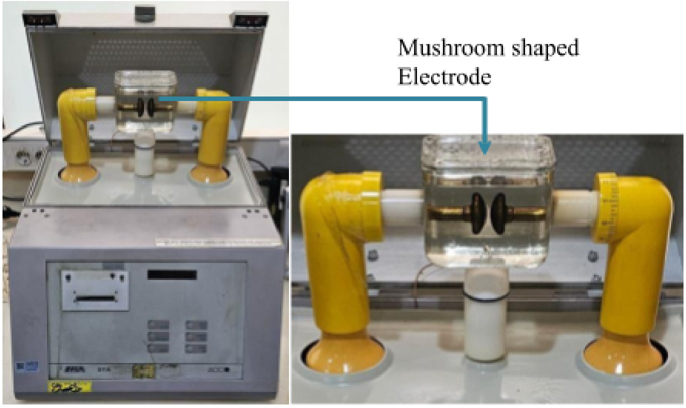

Figure 3. Baur DTA 100 Dielectric Strength Test Set

$$V_{BD} = \frac{B.p.d}{1n(A.p.d) - 1n(1n(1 + \frac{1}{\gamma_{SC}}))} \tag{4}$$

V_{BD} : Breakdown voltage
p : Pressure (atm)
d : Gap distance between electrode (mm)
A, B : Constants depending on the dielectric medium
γ_{SC} : Secondary electron emission coefficient

The streamer model is used to explain how breakdown voltage (BDV) is formed in liquid media such as transformer oil, when there is a high electric field between the electrodes.

$$V_{BD} = k.d^n \tag{5}$$

k : A constant that depends on the type of oil, temperature, humidity conditions, and electrode geometry.
n : Exponent (typically between 0.6 to 0.9)

The breakdown voltage (BDV) of transformer oil can decrease significantly if moisture and contaminants are present in the oil.

$$V_{BD} = V_{BD0}.e^{-(\alpha C + \beta W)} \tag{6}$$

V_{BD0} : Breakdown voltage of pure oil (kV)
C : Concentration of contaminant (ppm)
W : Moisture content (ppm)
α, β : Empirical coefficient (determined through experimentation)

The breakdown voltage (BDV) of transformer oil will tend to decrease exponentially as the temperature increases.

$$V_{BD}(T) = V_{BD0}.e^{-\lambda(T-T_0)} \tag{7}$$

V_{BD0} : Breakdown voltage at reference temperature T_0
λ : Temperature coefficient (determined through experiment)
T : Operating temperature (°C)

The shape of the electrode also affects the BDV value so that it can approach the model below

$$V_{BD} = \frac{E_{BD}.d}{1 + \frac{d}{r}} \tag{8}$$

E_{BD} : Dielectric strength of oil (~10–20 kV/mm for clean oil)
r : Radius of curvature of the electrode (mm)

The breakdown voltage does not have a fixed value because it is affected by various random factors, such as microcontamination, gas bubbles, or inhomogeneity in the insulating oil. Therefore, the statistical properties of the breakdown voltage need to be analyzed using a distribution model. One of the most common distribution models used in this analysis is the Weibull distribution[18]. The following is the mathematical model.

$$P(V) = 1 - e^{-\left(\frac{V}{\eta}\right)^{\beta}} \tag{9}$$

$P(V)$: The probability of breakdown at voltage (V)
η : Scale parameter (characteristic breakdown voltage)
β : Shape parameter (shows the trend of failure rate)

2.5 Temperature Rise Test

Temperature rise testing is carried out with the aim of knowing the cooling performance or cooling ability of the power transformer[19]. This test was conducted on a power transformer with a capacity of 33 MVA and a working voltage of 132/33 kV. Tests were carried out using two different types of transformer oil, namely synthetic ester oil and mineral oil. However, testing with mineral oil is done through simulation using identical transformer specifications. This aims to avoid any distinguishing variables in the test. Temperature rise testing is regulated in the IEC 60076-2 standard. The following are the steps in temperature rise testing.

a) Make connection as per test connection diagram. See figure 4.
b) Put temperature sensor on the top cover, top radiator, bottom radiator and surrounding transformer.
c) Put tap position to tap with maximum losses.
d) Measure cold winding resistance as a base of average winding temperature calculation.

e) The temperature rise test will be performed by the short circuit method, supplying the transformer in order to obtain the total losses.
f) The no load loss at 110% of rated voltage shall be applied when determining the total losses.
g) Inject maximum total losses until top oil temperature rise in steady state condition, where the change of temperature in one hour is less than 1 K and has remain there for 3 hours.
h) Record all data voltage, current, losses and temperature in every hour.
i) Reduced to rated current after the above condition is obtained, keep for one hour. If the different between test current and rated current is less than 10%, by an agreement reduced to rated current is not necessary.
j) Shut down the power supply and start winding resistance measurement.
k) Calculate average winding temperature, hot spot temperature and top oil temperature.

The number and position of temperature sensors for measuring top oil are adjusted according to the power capacity of the transformer used. The aim is to ensure accurate temperature measurement at the hottest part of the oil in the tank, so that the performance of the cooling system can be properly assessed. Transformers with a capacity of 100 MVA or more are equipped with three temperature sensors. For transformers with a capacity between 20 MVA to less than 100 MVA, two temperature sensors are used, while transformers with power below 20 MVA use one temperature sensor at the top of the oil. In this test, two temperature sensors are used because the transformer under test has a capacity of 33 MVA, so it falls into the medium category. The sensors are placed at two different points on the top of the transformer tank, namely on the HV side and LV side.

And there are 4 ambient temperature sensors placed around the transformer with a distance of 2 meters. See figure 5

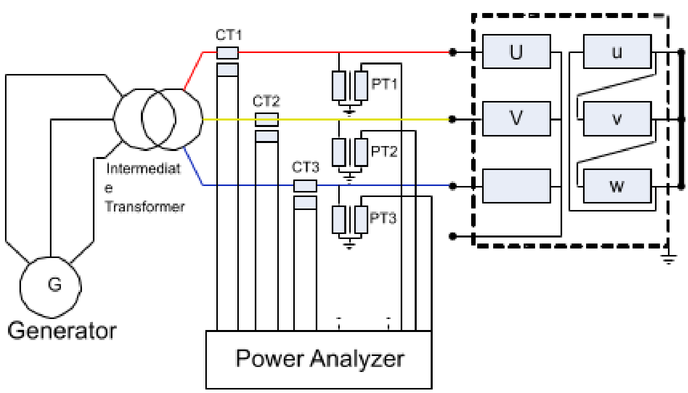

Figure 4. Temperature Rise Test Connection Diagram

The working temperature in the transformer is influenced by various factors, both from inside and outside the system. In general, the increase in temperature in the transformer occurs due to the accumulation of energy lost during the process of converting and distributing electrical power.

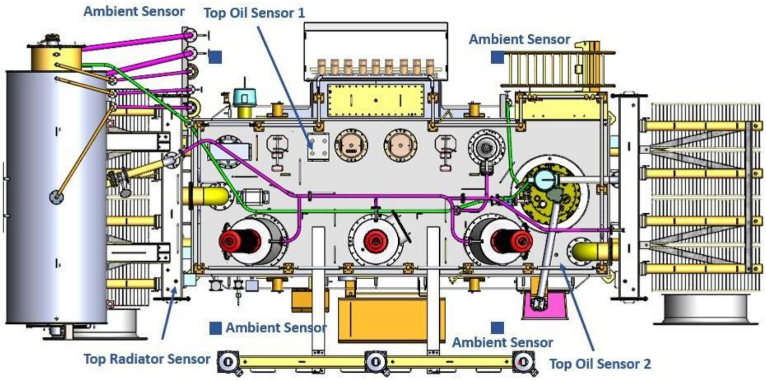

Figure 5. Temperature Rise Test Sensor Position

Some of the main factors that play a role in this temperature increase include no-load losses, load losses, the type of insulating oil used, and the cooling system applied to the transformer. No-load losses are energy losses that occur when the transformer is under voltage but is not carrying load current[20]. These losses are generally caused by hysteresis effects and eddy currents in the iron core, and are constant as long as the input voltage does not change[21]. This is in contrast to load losses, which occur when the transformer starts delivering current to the load. This type of loss is variable and will increase as the current increases, because its magnitude depends on the square of the current (I^2R)[22]. The type of insulating oil used also plays an important role in temperature control. Each type of oil has different thermal characteristics, such as heat conductivity, viscosity, and heat absorbing capacity. For example, synthetic ester oil has a higher flash point and different heat transfer characteristics compared to mineral oil. These differences will affect the speed and efficiency of heat release from the inside of the transformer to the tank surface and eventually to the ambient air. So here is the mathematical model.

$$P_{CU} = I^2R \tag{10}$$

From the copper loss equation above, the total heat generated is as follows,

$$Q_{gen} = P_{cu} + P_{fe} \tag{11}$$

The heat generated in the transformer is released to the environment through three main mechanisms, namely convection, radiation, as well as the help of cooling systems such as oil, air, or forced cooling. This heat release process is known as heat dissipation, which can generally be modeled using Newton's cooling law approach[23]. This approach allows estimation of the heat release rate based on the temperature difference between the transformer surface and the ambient temperature.

$$Q_{diss} = hA(T - T_{amb}) \tag{12}$$

h : Heat transfer coefficient (depends on cooling medium)
A : Surface area for heat dissipation,
T : Transformer temperature
T_{amb} : Ambient temperature

The temperature rise in the transformer is controlled by the principle of heat balance, which is expressed through the thermal energy balance equation. This equation illustrates that the amount of heat generated from internal losses must be equivalent to the heat absorbed by the system and released to the environment through the cooling mechanism. In other words, the transformer temperature will increase until an equilibrium condition between heat in and heat out is reached.

$$C\frac{dT}{dt} = Q_{gen} - Q_{diss} \tag{13}$$

Where:
C : Thermal capacitance of the transformer
$\frac{dT}{dt}$: Rate of temperature change

So that the substitution of the equations Q_{gen} and Q_{diss}

$$C\frac{dT}{dt} = P_{cu} + P_{fe} - hA(T - T_{amb}) \tag{14}$$

At steady state, where there is no change in temperature with respect to time ($\frac{dT}{dt}$ = 0) the system reaches thermal equilibrium.

$$T_{ss} = T_{amb} + \frac{P_{cu} + P_{fe}}{hA} \tag{15}$$

The temperature rise (ΔT) is:

$$\Delta T = T_{ss} - T_{amb} = \frac{P_{cu} + P_{fe}}{hA} \tag{16}$$

In transformers that use oil as an insulating and cooling medium, the heat transfer process is generally described through a two-stage thermal model. This model helps understand how heat moves from the inside of the transformer to the surrounding environment. The first stage is heat transfer from the windings, which are the main source of heat due to load losses, to the surrounding oil. This oil serves to absorb heat from the windings and lower the temperature of the active components. After the heat has transferred to the oil, the next stage is the transfer of heat from the oil to the external environment, namely through the walls of the transformer tank. At this stage, heat is released to the surrounding air through the processes of convection and radiation, which can occur naturally or be assisted by fans (forced cooling), depending on the cooling system used.

$$C_w\frac{dT_w}{dt} = P_{cu} - h_{wo}A_w(T_w - T_o) \tag{17}$$

$$C_o \frac{dT_o}{dt} P_{fe} + h_{wo} A_w (T_w - T_o) - h_{oa} A_o (T_o - T_{amb}) \quad (18)$$

Where:
T_w : Winding Temperature
T_o : Oil Temperature
h_{wo} : Winding to Oil heat transfer coefficient
h_{oa} : Oil to Ambient heat transfer coefficient

2.6 Dimensional Comparison of Transformers with Synthetic Ester and Mineral Oil

The type of insulating oil used in a power transformer plays an important role in determining how well its insulation system works. Each oil has different dielectric characteristics, and this affects the safety distance required between windings, as well as between windings and ground. Therefore, the choice between mineral oil, synthetic esters, or natural esters is not just a matter of materials, but also has a direct impact on the physical design and safety level of the transformer. If the oil used has a high insulating ability, then the distance between conductive components can be made tighter. This allows for a more compact and lightweight transformer design. Conversely, if the dielectric capability is lower, then greater spacing is required to maintain safe operation[24]. This adjustment has a direct impact on the overall physical size of the transformer. The larger the size or dimensions of the transformer, the higher the production costs required both in terms of raw materials, manufacturing processes, and shipping. This research simulates the physical design comparison of two transformers with the same power and voltage specifications, but using different types of insulating oil: mineral oil and synthetic ester oil. The purpose of this simulation is to examine the extent to which differences in oil characteristics affect design requirements. Some of the important parameters analyzed include tank size (length, width, and height), volume and weight of copper for windings, and silicon steel material requirements at the core of the transformer. With this research, it is hoped that a clearer understanding of the influence of the thermal and dielectric capabilities of each type of oil on the physical design and production cost estimation of transformers will be obtained.

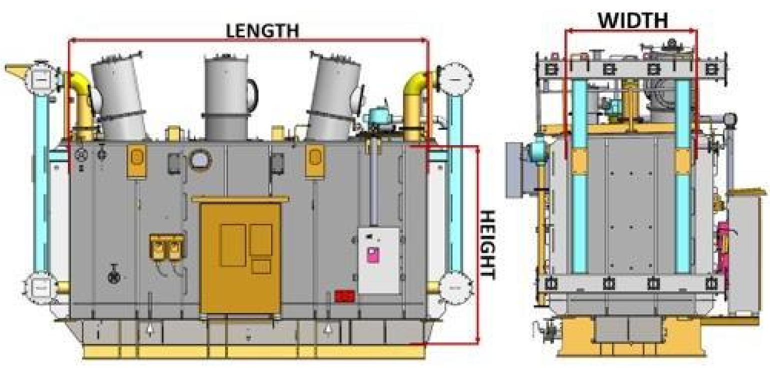

Figure 6. Dimension Transformer

3. Results and Discussion

3.1 Water Content Test Results

Before conducting breakdown voltage (BDV) testing on mineral oil and synthetic ester oil, it is necessary to test the water content. The purpose of this test is to ensure that the oil to be tested has a water content in accordance with the established standards, so that the test results can be comparable. Based on the test results, the water content in mineral oil is 3.65 ppm, while in synthetic ester oil it is 65.97 ppm. In accordance with the IEC 60422 standard, the maximum limit of moisture content in mineral oil is 10 ppm, while in IEC 61203 for synthetic ester oil the maximum is 150 ppm.

If the moisture content in both types of oil exceeds these limits, then a treatment process must be carried out first, such as vacuum, filtering, or heating, to reduce the moisture content to within the permissible limits. Looking at the water content test results, it can be concluded that both types of transformer oil have met the IEC standards regarding water content, so they are ready for BDV testing.

Table 1. Water Content Result

No	Oil Type	Water Content (ppm)	Standard IEC (ppm)
1	Mineral Oil	3.65	< 10
2	Synthetic Ester Oil	65.97	< 150

3.2 Voltage Breakdown Analysis and Results - Rest Time 1 minute

Table 2 and Table 3 present the breakdown voltage test results with a rest time of 1 minute. Table 2 is the test result on mineral oil, which shows no significant voltage variation. Meanwhile, Table 3 is the test result on synthetic ester oil, which shows a voltage variation or anomaly. To facilitate analysis, the data in both tables will be presented in the form of a diagram.

Table 2. Mineral Oil with Rest Time 1 Minute

Mineral Oil	Rest Time 1 Min					
	First	Second	Third	Fourth	Fifth	Sixth
Time 1	09.45	09.46	09.47	09.48	09.49	09.50
1	98.9 kV	95.1 kV	96.6 kV	97.9 kV	95.4 kV	96.3 kV
Time 2	09.55	09.56	09.57	09.58	09.59	10.00
2	100 kV	95.7 kV	95.4 kV	100 kV	96.4 kV	90.1 kV
Time 3	10.49	10.50	10.51	10.52	10.53	10.54
3	99 kV	93.4 kV	96.3 kV	96 kV	100 kV	98.8 kV

As explained earlier, the procedures for testing breakdown voltage (BDV) are regulated in the IEC 60156 standard. However, the reference standard for the test results differs depending on the type of insulating oil used. For mineral oil, the test results refer to the IEC 60422 standard, while for synthetic ester oil, the results refer to the IEC 61203 standard.

Table 3. Synthetic Ester Oil with Rest Time 1 Minute

Synthetic Ester Oil	Rest Time 1 Minute					
	First	Second	Third	Fourth	Fifth	Sixth
Time 1	14.12	14.13	14.14	14.15	14.16	14.17
1	87.7 kV	83.7 kV	92.4 kV	49.9 kV	91.7 kV	100 kV
Time 2	14.52	14.53	14.55	14.56	14.57	14.58
2	22.4 kV	91.4 kV	88.3 kV	95.2 kV	97.6 kV	77.7 kV
Time 3	14.59	15.00	15.01	15.01	15.02	15.03
3	92.4 kV	75.2 kV	88.4 kV	71.9 kV	84.9 kV	58.6 kV

In this test, transformer oil was used in a power transformer with a capacity of 33 MVA with a voltage of 132/33 kV. Based on the applicable standards, the BDV value in mineral oil with an electrode spacing of 2.5 mm must exceed 60 kV. In this case, synthetic ester oil has the same minimum eligibility limit, which is above 60 kV.

Based on the test results of the mineral oil, BDV values ranged from 90.1 kV to 100 kV, with an average of 96.7 kV and a standard deviation of ±2.6 kV, see table 7. These values indicate a very stable dielectric performance, as all test results are above the minimum feasible limit (60 kV). The in Figure 8 shows a relatively constant distribution of test results, with no significant fluctuations between measurement points. This stability indicates that the mineral oil used has good dielectric characteristics.

This is because no froth or air bubbles are formed after the Breakdown Voltage (BDV) test. Even if froth or gas bubbles were to form, they can quickly rise to the surface of the oil and disappear immediately. Thus, the presence of bubbles does not have a significant impact on the insulating ability of mineral oil. One of the main factors supporting this condition is the relatively low viscosity of mineral oil. The low viscosity allows the movement of gas bubbles to be faster towards the surface, thus minimizing the possibility of trapping bubbles between the test electrodes. As a result, the resulting BDV values tend to be more stable and are not easily disturbed by physical disturbances such as the presence of froth. This condition can be observed in Figure 7.a, which shows the appearance of the space between the electrodes shortly after the BDV test was conducted. It can be seen that there is no froth or bubbles left between the electrodes, which supports the test results with consistent BDV values.

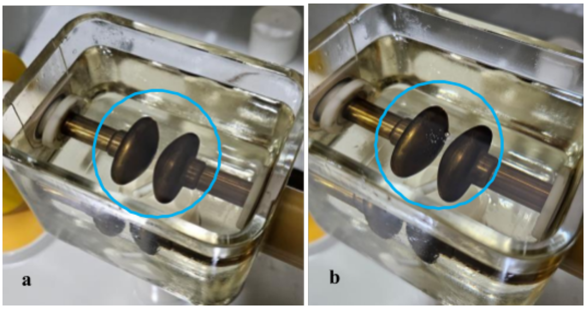

Figure 7. a) Mineral Oil after BDV test, b) Synthetic Ester after BDV test

Meanwhile, the test results for synthetic ester oil show a much larger variation in BDV values, as shown in Table 3 BDV values ranged from 22.4 kV to 100 kV, with an average value of 80.5 kV and a standard deviation of ±19.6 kV. There were three test points, namely the 4th, 7th, and 18th tests that produced values below the eligibility threshold, amounting to 49.9 kV, 22.4 kV, and 58.6 kV, respectively.

The extreme fluctuations in the synthetic ester oil test results are shown by the green line in Figure 8, indicating instability in its dielectric performance. One possible cause of this instability is the formation of froth or gas bubbles during the BDV testing process. Since the rest time between tests is relatively short, at only 1 minute, the gas bubbles formed have not had time to fully rise to the surface and dissipate. As a result, when the next test is performed, the froth or bubbles are still between the electrodes, as shown in Figure 7b, thus disrupting the insulation path and lowering the BDV value. This condition explains why the BDV value of synthetic ester oil tends to be inconsistent. This is exacerbated by the higher viscosity of synthetic ester oil compared to mineral oil, which causes the movement of gas bubbles to the surface to be slower.

Based on the data presented in Table 4, it is known that under all tested temperature conditions, the kinematic viscosity value of synthetic ester oil is consistently higher than that of mineral oil. This indicates that, in general, synthetic ester oil has a higher level of thickness across various operating temperatures. Kinematic viscosity is one of the important parameters in assessing fluid flow capability, which directly affects cooling efficiency and oil movement within the transformer system.

In the composition of 100% MO and 0% SE, the test was carried out entirely using mineral oil without any synthetic ester mixture. Conversely, in the composition of 0% MO and 100% SE[25], the entire test was conducted using pure synthetic ester oil without any mineral oil mixture. The viscosity differences recorded between these two types of oil can be used to evaluate the cooling performance and dielectric stability of the transformer under various temperature conditions, considering that viscosity also affects the oil's ability to absorb and transfer heat from the transformer core and windings to the outer surface of the tank.

Table 4. Kinematic Viscosity Mineral and Synthetic Ester Oil

Kinematic Viscosity v ($mm^2.s^{-1}$)					
Proportion of mineral oil (MO) and synthetic ester (SE)		Temperature			
		25°C	40°C	60°C	80°C
100 % MO	0 % SE	17.08	9.59	5.37	3.42
0 % MO	100 % SE	55.14	28.25	14.02	8.11

3.3 Voltage Breakdown Analysis and Results - Rest Time 10 minute

The following are the results of testing mineral oil and synthetic ester oil with a pause or rest time of 10 minutes. The purpose of this test aims to determine the effect of pause or rest time on the insulation ability of mineral oil and synthetic ester oil.

Table 5. Mineral Oil with Rest Time 10 Minute

Mineral Oil	Rest Time 10 Minute					
	First	Second	Third	Fourth	Fifth	Sixth
Time	10.44	10.54	11.04	11.14	11.24	11.34
1	91.9 kV	88.3 kV	99.6 kV	95.5 kV	99.7 kV	101 kV
Time	12.13	12.23	12.33	12.43	12.53	13.03
2	101 kV	99.2 kV	91.7 kV	96.5 kV	99.7 kV	91.6 kV
Time	13.17	13.26	13.37	13.47	13.57	14.07
3	98.7 kV	100 kV	99.7 kV	98.8 kV	90.9 kV	93.4 kV

Table 6. Synthetic Ester Oil with Rest Time 10 Minute

Synthetic Ester Oil	Rest Time 10 Minute					
	First	Second	Third	Fourth	Fifth	Sixth
Time	14.01	14.11	14.21	14.31	14.41	14.51
1	86.2 kV	97.2 kV	94.8 kV	87.4 kV	91.5 kV	84.8 kV
Time	15.00	15.10	15.20	15.30	15.40	15.50
2	97.0 kV	94.3 kV	96.5 kV	95.7 kV	94.0 kV	93.6 kV
Time	16.02	16.12	16.22	16.33	16.43	16.53
3	86.3 kV	93.2 kV	99 kV	93.1 kV	93 kV	98 kV

Based on the breakdown voltage (BDV) test results with a rest time of 10 minutes, it shows an increase in stability in both types of insulating oil when compared to the results when the rest time is only 1 minute. In this condition, the average BDV value for mineral oil was recorded at 96.5 kV, with a maximum value of 101 kV and a minimum value of 88.3 kV, see figure 8. The standard deviation of 4.1 kV shows that the mineral oil test results are quite consistent and stable, without large deviations between test points. Meanwhile, synthetic ester oil also showed a more stable performance than before. The average BDV value was recorded at 93.1 kV, with a maximum value of 99 kV and a minimum value of 84.8 kV. The standard deviation of 4.3 kV shows a relatively even and stable distribution of values. There were no BDV values below the minimum feasible limit (60 kV), in contrast to the results when the rest time was only 1 minute, where several test points were below the limit. This data shows that by extending the rest time between tests to 10 minutes for both mineral oil and synthetic ester oil, the dielectric performance becomes more stable. This additional lag time allows the froth or gas bubbles formed during the previous testing process to rise to the surface and dissipate, especially in synthetic ester oil which has a higher viscosity.

Froth or gas bubbles that appear in the transformer oil can cause anomalies in breakdown voltage testing or trigger failure during impulse testing in the Factory Acceptance Test (FAT). The presence of froth or gas bubbles results in two different permittivity (ε) values in the insulating medium, namely the permittivity of the transformer oil (both mineral oil and synthetic ester oil) and the permittivity of the gas (air) in the bubble.

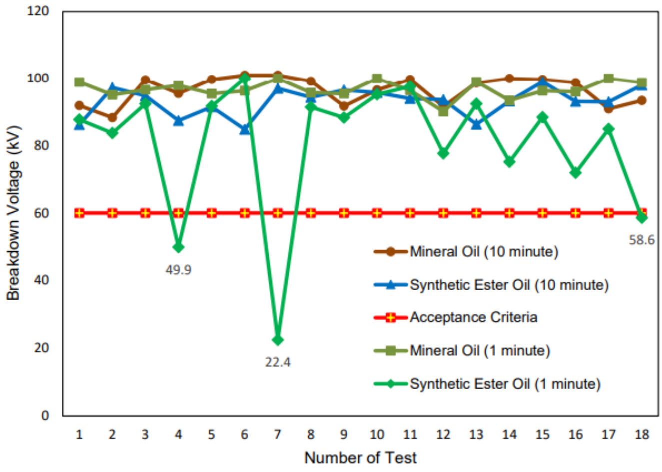

Figure 8. Pareto of BDV Testing with Rest Time 1 and 10 Minute

This test can provide a reference in the implementation of impulse testing during the Factory Acceptance Test (FAT). The results show that a longer rest time is needed for transformers that use synthetic ester oil, in order to avoid potential failures during impulse testing.

Table 7. Statistic BDV – Rest Time 1 and 10 Minute

BDV (kV)	Rest Time 1 minute		Rest Time 10 minute	
	Mineral Oil (kV)	Synthetic Ester Oil (kV)	Mineral Oil (kV)	Synthetic Ester Oil (kV)
Average	96.7	80.5	96.5	93.1
Max Value	100	100	101	99
Min Value	90.1	22.4	88.3	84.8
Standard Deviation	± 2.6	±19.6	4.1	4.3
Acceptance	0 from 18	3 from 18	0 from 18	0 from 18

Impulse testing is one type of dielectric test that is destructive, because it involves high voltage spikes in a short time that can cause permanent damage to the internal insulation of the transformer if it does not meet the standards. Therefore, failure in impulse testing will have a serious impact, both in terms of time, repair costs, and product quality reputation. Considering the higher viscosity characteristics of synthetic ester oil and its tendency to produce froth that takes longer to dissipate, providing adequate rest time is crucial. This is to ensure that the oil condition is fully stabilized before the impulse test is conducted, so that the risk of failure can be minimized.

3.4 Temperature Rise Performance of Mineral Oil and Synthetic Ester Oil

Temperature rise tests are carried out to ensure that the transformer cooling system, especially the circulation of insulating oil, works in accordance with the design that has been designed. This test aims to evaluate the efficiency of heat transfer from the winding and core of the transformer to the cooling medium, as well as measure the thermal stability of the transformer when operating under certain load conditions. In this study, temperature rise tests were carried out on two types of transformers based on the type of insulating oil, namely transformers with synthetic ester oil and transformers with mineral oil. For transformers with synthetic ester oil, tests were carried out on two cooling system conditions, namely at 23.1 MVA (KNAN) and 33 MVA (KNAF) loads. The KNAN system (Oil and Air Natural Cooling) relies on the natural circulation of oil and air, while the KNAF system (Oil and Air Natural Cooling with Fan Assistance) uses fans to assist air circulation to improve cooling efficiency. Meanwhile, tests on transformers with mineral oil were conducted under ONAN 23.1 MVA and ONAF 33 MVA load conditions. The ONAN system fully relies on the natural circulation of both oil and air, while the ONAF system uses a fan to accelerate the flow of cooling air, although the oil still circulates naturally. The results of this test were then compared with the maximum temperature rise limits set by the buyer. These limits generally refer to international standards such as IEC 60076-2 or customer technical specifications.

Tables 8 show the guaranteed values provided by the customer. Therefore, the results of the temperature rise test must not exceed these guaranteed limits. If any measured values exceed the guaranteed limits, a penalty must be paid to the customer.

Table 8. Temperature Rise Limit

No	Temperature Rise	Guarantee
1	Top Oil Rise	55 K
2	Winding Rise HV	90 K
3	Winding Rise LV	90 K
4	Hot-Spot Rise	105 K

Based on the results of the temperature rise test, it was found that the transformer with a capacity of 33 MVA and a voltage rating of 132/33 kV using mineral oil exhibited a lower temperature rise compared to a transformer with identical specifications using synthetic ester oil. This difference indicates that the cooling performance of the mineral oil-based transformer is more effective in transferring heat from the core and windings to the cooling system than that of the transformer using synthetic ester oil.

Based on the test results on a transformer with a load of 23.1 MVA, it was found that there is a difference in temperature rise value between the use of synthetic ester oil and mineral oil. In the winding temperature parameter, the use of synthetic ester oil produces a temperature 1 K higher than mineral oil. Furthermore, in the average oil temperature, a difference of 0.4 K was recorded, where the average oil temperature was also higher when using synthetic ester oil. The most striking difference occurs in the top oil temperature, with a difference of 4.9 K, indicating that the top of the oil in the transformer becomes hotter when using synthetic ester oil compared to mineral oil.

Table 9. Performa Temperature Rise Synthetic Ester Vs Mineral Oil

Temperature Rise Test	Synthetic Ester		Mineral Oil	
	23.1 MVA (KNAN)	33 MVA (KNAF)	23.1 MVA (ONAN)	33 MVA (ONAF)
Winding Temp (K)	44.9	47.2	43.9	45.1
Average Oil Temp (K)	31.9	28.9	31.5	27.2
Top Oil Temp (K)	47.5	50.6	42.6	43.1
Hot-Spot Rise (K)	64.4	79.6	58.8	66.3

While at the hot-spot rise, which is the point with the highest temperature in the transformer winding, the difference recorded was 5.6 K, where synthetic ester oil again showed a higher value.

Overall at a load of 23.1 MVA, these results show that transformers with the same specifications produce a higher temperature rise when using synthetic ester oil than mineral oil. When using synthetic ester oil, there is a higher temperature rise compared to the use of mineral oil in all test parameters. The increase in winding temperature was 2.3% higher than when using mineral oil. For the average oil temperature, the difference was 1.3% higher when using synthetic ester oil. Furthermore, in the top oil temperature parameter, synthetic ester oil showed an 11.5% higher temperature rise, which was the most significant difference. Finally, for the hot-spot rise, it was 9.5% higher compared to the use of mineral oil.

In testing transformers with a load of 33 MVA, in the winding temperature parameter, transformers with synthetic ester oil showed a temperature of 47.2 K, while transformers with mineral oil produced 45.1 K. This shows that the temperature in the winding is 2.1 K or 4.6% higher when using synthetic ester oil. For average oil temperature, synthetic ester oil produces a temperature of 28.9 K, while mineral oil records a value of 27.2 K, so there is a difference of 1.7 K or 6.2% higher in the use of synthetic ester oil. Meanwhile, at the top oil temperature, which is the highest temperature on the top surface of the oil, synthetic ester oil recorded a value of 50.6 K, while mineral oil produced 43.1 K. This difference is quite significant, which is 7.5 K or 17.4% higher when using synthetic ester oil.

The most striking difference occurs in hot-spot rise, which is the temperature increase at the hottest point of the winding. Synthetic ester oil produces a value of 79.6 K, while mineral oil is only 66.3 K, showing a difference of 13.3 K or 20% higher when using synthetic ester oil.

3.5 Dimensional Comparison of Transformers with Synthetic Ester and Mineral Oil

This analysis and research are carried out on power transformers with the same specifications with different transformer oils, the aim is to find out the differences in dimensions and material requirements for 33 MVA 132/33 kV transformers that use synthetic ester oil and mineral oil, so that from the simulation results using power transformers calculation the results are as follows.

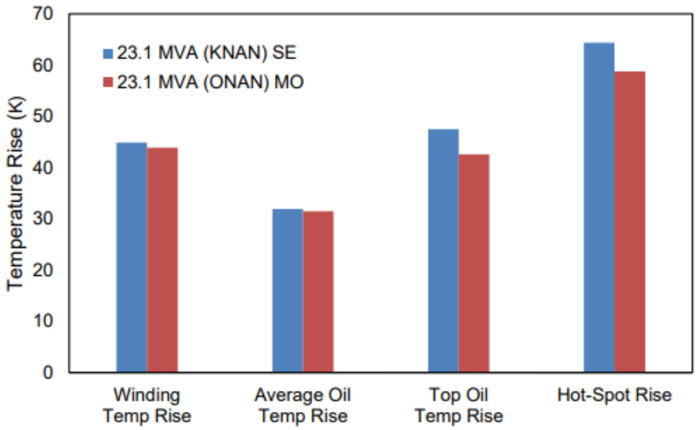

Figure 9. Performa Temperature rise SE Vs MO 23.1 MVA

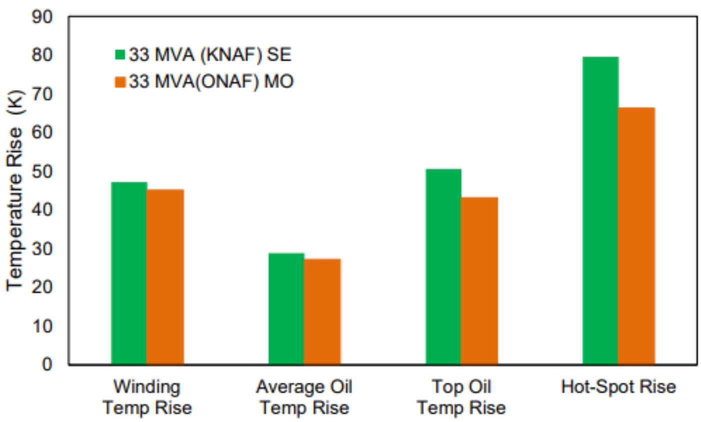

Figure 10. Performa Temperature rise SE Vs MO 33 MVA

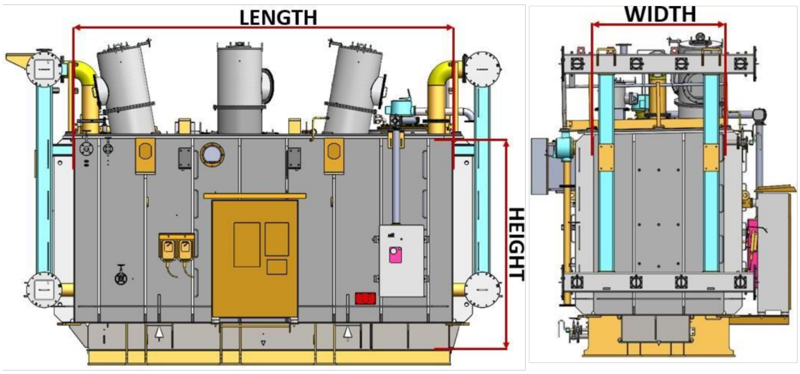

Figure 11. Dimension Transformer

Table 10. Dimension Comparison of SE Vs MO Transformer

Description	Length (mm)	Height (mm)	Width (mm)
Mineral Oil	4491	1471	2540
Synthetic Ester Oil	4633	1547	2665

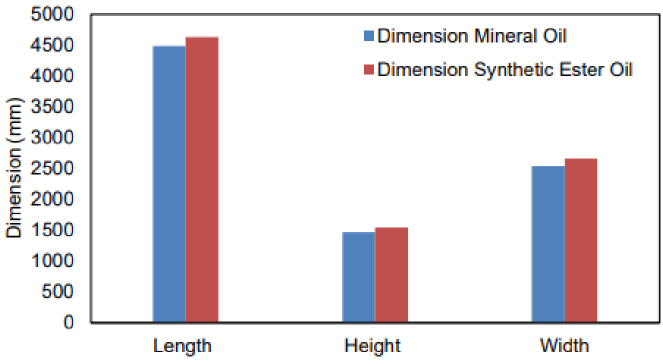

Figure 12. Dimension Comparison of SE Vs MO transformer

From the simulation results it is known that the transformer using synthetic ester oil has larger dimensions. From the test results it is known that the length of the transformer using synthetic ester oil is 142 mm or 3.2% longer than the transformer using mineral oil, the height of the transformer using synthetic ester oil is 76 mm or 5.2% higher than the transformer using mineral oil, and the width of the transformer using synthetic ester oil is 125 mm or 4.9% wider than the transformer using mineral oil.

This is because synthetic ester oil has a lower breakdown voltage value compared to mineral oil at the same gap or distance. This underlies that transformer that use synthetic ester oil must have a clearance distance between winding to winding, winding to ground greater than transformers that use mineral oil with the same power and working voltage, namely in this study 33 MVA 132 / 33 kV transformer[24].

With larger transformer dimensions, the material requirements will also increase, especially in main materials. This increase includes the use of more copper for the windings, more silicon steel for the transformer core, and a larger volume of insulating oil to fill the transformer tank. The increase in the volume and size of these components certainly has an impact on increasing the cost of transformer production.

The use of synthetic ester oil in transformers leads to an increase in material requirements compared to the use of mineral oil. The need for silicon steel increases by 556 kg or 4.5%. In the low voltage winding, the copper increase is relatively small, only 3 kg or 0.11%, which can be categorized as insignificant. However, in the high voltage winding, there is an increase of 351 kg of copper or 8.3%, and in the tapping winding, an increase of 48 kg or 6.8%. In addition, the volume of insulating oil also experiences a significant increase of 3,545 kg or 27.33%.

Table 11. Transformer Main Material Comparison

Description	Main Material	
	Mineral Oil (kg)	Synthetic Ester Oil (kg)
Silicon Steel	12428	12984
LV Winding (Copper)	2640	2643
HV Winding (Copper)	4188	4539
Tapping Winding (Copper)	702	750
Oil Transformer	12972	16517

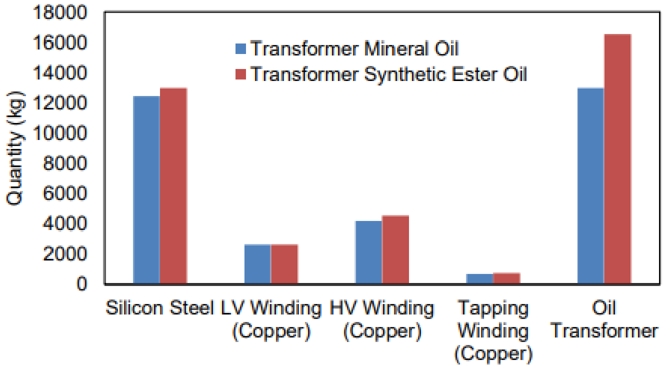

Figure 13. Transformer Main Material Comparison

This increase certainly has a direct impact on the production cost and selling price of the transformer, especially due to the increased need for main materials such as copper, silicon steel, and insulating oil. On the other hand, the advantage of synthetic ester oil lies in its biodegradability and lower carbon footprint compared to mineral oil, making it a more environmentally friendly option. Therefore, even though the initial cost of the transformer becomes higher, this can be considered in the context of improving environmental safety, compliance with environmental regulations, and contributing to the reduction of carbon emissions in the energy sector.

3.6 Transformer Production Cost

Based on the main material data of transformers that use synthetic ester oil and mineral oil, an overview of the difference in production costs can be obtained when viewed from the main material. The assumption is that all supporting materials used are the same and have the same price. It is known that the price of copper as of May 16, 2025 based on the LME Copper website is 9,534 USD/kg[26], the price of silicon steel is 2,268 USD/kg, the price of mineral oil is 1.6832 USD/kg, and the price of synthetic ester oil is 6.20 USD/kg. Thus, it can be calculated the difference in production costs between transformers using synthetic ester oil and transformers using mineral oil in terms of main materials.

Table 12. Production Cost of Mineral Oil Transformer

Main Material	Quantity (Kg)	Price per Kg (USD)	Total Price (USD)
Silicon Steel	12428	2.268	28,186.704
LV Winding (Copper)	2640	9.534	25,169.760
HV Winding (Copper)	4188	9.534	39,928.392
Tapping Winding (Copper)	702	9.534	6,692.868
Oil Transformer (MO)	12972	1.683	21,834.470
Total Cost			121,812.194

Table 13. Production Cost of Synthetic Ester Oil Transformer

Main Material	Quantity (Kg)	Price per Kg (USD)	Total Price (USD)
Silicon Steel	12984	2.268	29,447.712
LV Winding (Copper)	2643	9.534	25,198.362
HV Winding (Copper)	4539	9.534	43,274.826
Tapping Winding (Copper)	750	9.534	7,150.5
Oil Transformer (SE)	16517	6.200	102,405.400
Total Cost			207,476.800

Based on the results of the calculations that have been carried out, it is known that there is a significant cost difference between the 33 MVA 132/33 kV transformer using synthetic ester oil and the transformer using mineral oil. The cost difference amounts to USD 85,664.61, which indicates that the transformer with synthetic ester oil is about 70% higher than the transformer using mineral oil. This cost difference is mainly due to two important factors. First, in terms of unit price, synthetic ester oil has a much higher market value than mineral oil. Based on the data, the price of synthetic ester oil reaches USD 6.20 per kilogram, while the price of mineral oil is only USD 1.683 per kilogram and the amount of insulating oil required for synthetic ester transformers is greater than that of mineral oil transformers.

4. Conclusion

Based on the research results that have been conducted, it can be concluded that in the breakdown voltage (BDV) test with a rest time of 1 minute, the BDV value of synthetic ester oil showed instability, with three test conditions producing values below the acceptance criteria. This was caused by the presence of gas bubbles that had not completely dissipated during the short rest time. Meanwhile, under the same condition, the BDV value of mineral oil showed stability, with no test results falling below the acceptance criteria. In the BDV test with a rest time of 10 minutes, both synthetic ester oil and mineral oil showed stable BDV values without significant fluctuations. This indicates that a longer rest time allows entrapped gases to dissipate, resulting in more consistent test results.

In the temperature rise test, transformers using synthetic ester oil exhibited higher operating temperatures at both 23.1 MVA and 33 MVA loads compared to transformers using mineral oil. This becomes an important consideration in the selection of insulation paper types, as higher operating temperatures can accelerate the degradation of insulation paper and potentially shorten the lifespan of the transformer.

In addition, the 33 MVA 132/33 kV transformer using synthetic ester oil has larger physical dimensions compared to the transformer using mineral oil. As a result, the need for main materials such as copper, silicon steel, and insulating oil increases, which directly affects the production cost and selling price of the transformer. The production cost for transformers using mineral oil is USD 121,812,194, while the production cost for transformers using synthetic ester is USD 207,476,800. The production cost of synthetic ester oil transformer is about 70% higher than the production cost of mineral oil transformer.

Synthetic ester oil has some disadvantages in terms of technical and economic aspects, it has significant advantages in terms of biodegradability and a lower carbon footprint compared to mineral oil. Therefore, synthetic ester oil can be considered a more environmentally friendly alternative, and is worth considering in the context of improving environmental safety, complying with environmental regulations, and contributing to the reduction of carbon emissions in the energy sector.

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References

[1] A. Indarto et al. "Total cost of ownership analysis of 60 MVA 150/120 kV power transformer". In: *2017 15th International Conference on Quality in Research (QiR)*. International Symposium on Electrical and Computer Engineering. Nusa Dua: IEEE, 2017, pp. 291–295. DOI: 10.1109/qir.2017.8168499.

[2] A. Indarto et al. "Influence of different adhesives on partial discharge in power transformer winding cylinder insulation". In: *IEEE Transactions on Dielectrics and Electrical Insulation* 27.3 (June 2020), pp. 964–970. DOI: 10.1109/TDEI.2020.008533.

[3] X. Wang et al. "Review of Research Progress on the Electrical Properties and Modification of Mineral Insulating Oils Used in Power Transformers". In: *Energies* 11.3 (Feb. 2018), p. 487. DOI: 10.3390/en11030487.

[4] S. Ab Ghani et al. "Methods for improving the workability of natural ester insulating oils in power transformer applications: A review". In: *Electric Power Systems Research* 163 (Oct. 2018), pp. 655–667. DOI: 10.1016/j.epsr.2017.10.008.

[5] D. M. Mehta et al. "A review on critical evaluation of natural ester vis-a-vis mineral oil insulating liquid for use in transformers: Part 1". In: *IEEE Transactions on Dielectrics and Electrical Insulation* 23.2 (Apr. 2016), pp. 873–880. DOI: 10.1109/TDEI.2015.005370.

[6] D. Güneş et al. "Breakdown Voltage Estimation in Transformer Oils with Low-Cost Humidity Sensor". In: *Kocaeli Journal of Science and Engineering* 7.1 (May 2024), pp. 9–19. DOI: 10.34088/kojose.1115308.

[7] S. Shen, Q. Liu, and Z. Wang. "Effect of electric field uniformity on positive streamer and breakdown characteristics of transformer liquids". In: *IEEE Transactions on Dielectrics and Electrical Insulation* 26.6 (Dec. 2019), pp. 1814–1822. DOI: 10.1109/TDEI.2019.008168.

[8] D. Güneş et al. "Breakdown Voltage Estimation in Transformer Oils with Low-Cost Humidity Sensor". In: *Kocaeli Journal of Science and Engineering* 7.1 (May 2024), pp. 9–19. DOI: 10.34088/kojose.1115308.

[9] T. Li et al. "Study on the Method of Calculating Temperature Rise of Transformer". In: *E3S Web of Conferences*. Vol. 179. 2020, p. 01027. DOI: 10.1051/e3sconf/202017901027.

[10] S. Abdi et al. "Comprehensive Assessment of Transformer Oil After Thermal Aging: Modeling for Simultaneous Evaluation of Electrical and Chemical Characteristics". In: *Energies* 18.8 (Apr. 2025), p. 1915. DOI: 10.3390/en18081915.

[11] M. Novkovic et al. "Proof of the Concept of Detailed Dynamic Thermal-Hydraulic Network Model of Liquid Immersed Power Transformers". In: *Energies* 16.9 (Apr. 2023), p. 3808. DOI: 10.3390/en16093808.

[12] Z. R. Radakovic and M. S. Sorgic. "Basics of Detailed Thermal-Hydraulic Model for Thermal Design of Oil Power Transformers". In: *IEEE Transactions on Power Delivery* 25.2 (Apr. 2010), pp. 790–802. DOI: 10.1109/TPWRD.2009.2033076.

[13] L. H. Medeiros et al. "Thermal-Hydraulic Network Model for steady-state thermal analysis and design of power transformer magnetic cores". In: *Case Studies in Thermal Engineering* 64 (Dec. 2024), p. 105517. DOI: 10.1016/j.csite.2024.105517.

[14] A. Indarto et al. "The Effects of Vacuum and Oil Impregnation Duration on Partial Discharge of 167 MVA 500/150 kV Single Phase Power Transformer". In: *2019 IEEE 2nd International Conference on Power and Energy Applications (ICPEA)*. Singapore, Singapore: IEEE, Apr. 2019, pp. 61–65. DOI: 10.1109/ICPEA.2019.8818492.

[15] *IEC60814-Water Content*. International Electrotechnical Commission Standard.

[16] *IEC60156 BDV*. International Electrotechnical Commission Standard.

[17] A. M. Loveless and A. L. Garner. "A universal theory for gas breakdown from microscale to the classical Paschen law". In: *Physics of Plasmas* 24.11 (Nov. 2017), p. 113522. DOI: 10.1063/1.5004654.

[18] W. Yuan et al. "Weibull statistical analysis of size effects on the impulse breakdown strength in transformer oil". In: *2017 IEEE 19th International Conference on Dielectric Liquids (ICDL)*. Manchester: IEEE, June 2017, pp. 1–4. DOI: 10.1109/ICDL.2017.8124618.

[19] T. Li et al. "Study on the Method of Calculating Temperature Rise of Transformer". In: *E3S Web of Conferences*. Vol. 179. 2020, p. 01027. DOI: 10.1051/e3sconf/202017901027.

[20] W. B. Pramono et al. "Designing Power Transformer Using Particle Swarm Optimization with Respect to Transformer Noise, Weight, and Losses". In: *Designs* 7.1 (Feb. 2023), p. 31. DOI: 10.3390/designs7010031.

[21] J. C. Olivares et al. "Reducing losses in distribution transformers". In: *IEEE Transactions on Power Delivery* 18.3 (July 2003), pp. 821–826. DOI: 10.1109/TPWRD.2003.813851.

[22] M. A. Fatullah, A. Rahardjo, and F. Husnayain. "Analysis of Discharge Rate and Ambient Temperature Effects on Lead Acid Battery Capacity". In: *2019 IEEE International Conference on Innovative Research and Development (ICIRD)*. Jakarta, Indonesia: IEEE, June 2019, pp. 1–5. DOI: 10.1109/ICIRD47319.2019.9074667.

[23] P. Goscinski et al. "The Influence of Heat Transfer Coefficient of Insulating Liquids on Power Transformer Cooling Systems". In: *Energies* 16.6 (Mar. 2023), p. 2627. DOI: 10.3390/en16062627.

[24] Q. Liu and Z. Wang. "Streamer characteristic and breakdown in synthetic and natural ester transformer liquids under standard lightning impulse voltage". In: *IEEE Transactions on Dielectrics and Electrical Insulation* 18.1 (Feb. 2011), pp. 285–294. DOI: 10.1109/TDEI.2011.5704520.

[25] Z. Nadolny, G. Dombek, and P. Przybylek. "Thermal properties of a mixture of mineral oil and synthetic ester in terms of its application in the transformer". In: *2016 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*. Toronto, ON, Canada: IEEE, Oct. 2016, pp. 857–860. DOI: 10.1109/ceidp.2016.7785457.

[26] *westmetall . market data . prices/lme stocks . copper, tin, lead, zinc, aluminium, nickel, gold, fine silver*. https://www.westmetall.com/en/markdaten.php?action=table&field=LME_Cu_cash. Accessed: May 19, 2025.