Temperature Rise Analysisin Synthetic Ester Oil in 20/0.4 kV Distribution Transformers of 2500 kVA

Abstract:Currently, all electrical systems from the distribution system require the use of transformers,which are equipped with environmentally friendly transformer oil.A Transformer is an electrical equipment that is used to increase and decrease voltage in alternating current (AC) systems, both single phase and three phase. This equipment is made up of several main components such as iron cores, windings and cooling fluid. Transformer oil itself functions as a coolant for the primary secondary winding and as insulation between windings. However, as the load increases and the transformer ages, the temperature and performance of the transformer oil tend to decrease. In addition to the two primary and secondary windings in a transformer, there is also a liquid inside that functions as a coolant and insulator, namely transformer oil of the synthetic ester type.This oil actively protects the transformer from overheating caused by current flow in the windings and iron core.The aim of this research is to test the highest oil temperature rise or the terms top-liquid temperature and top-liquid temperature rise in a distribution transformer with a scheme based on the IEC 60076-2-2011 standard, which is tested by means of current injection on the primary side while the secondary side is connected short. The results obtained indicate that the steady-state top-liquid temperature is 83.2°C and the top-liquid temperature rise is 54.47°C. This shows that the application of this type of transformer oil can effectively dissipate heat in a transformer, which in turn will contribute to increasing the transformer's lifespan and be environmentally friendly.

Keywords: Transformers, top-liquid temperature rise, steady state,Synthetic Ester Oil

INTRODUCTION

Since the twentieth century, alternating current (AC) electricity has been discovered. AC has advantages over direct current (DC), one of which is that AC electricity can be easily increased and decreased in voltage using a transformer. With a transformer, the need for AC electricity with varying voltages can be met according to the load it carries. Transformers have several important components, including coils and iron cores. The iron core acts as a conduit for the flux generated by the electric current in a coil.

The iron core of a transformer consists of thin steel plates that are integrated into one piece to reduce the heat caused by the current, and coils that function as current conductors. There are two coils in a transformer, namely the primary coil and the secondary coil. In accordance with Faraday's law of voltage induction, voltage will be induced from the primary coil to the secondary coil[S.N.Singgih et.al]. In addition to these two components, transformers contain a liquid material that functions as a coolant and insulator, namely transformer oil. This oil actively protects the transformer from excessive heating caused by the coils and iron core[J. Jumardin, et.al]. Research on breakdown voltage studies in transformers with oil cooling was conducted to determine the performance of the liquid insulation using several test schemes, ranging from temperature variations to water content in the oil, which was tested in a transformer oil test vessel with a specific gap distance, using Shell Dila-B and Nynas[I.N. OksaWinanta, et.al and D.B. Fachrurrozi, etc.] oils. In addition to using these oils, several studies attempted to replace the oil type with SAE 40 lubricant to determine the breakdown voltage when the oil temperature increased, with the result that as the temperature increased, the breakdown voltage also increased [A.Junaidi]. The use of mineral oil and natural ester as transformer coolants is done by observing the hot spot temperature measured using an optical fibre-based temperature sensor, then plotting the results into a curve and comparing them with the IEEE standard [D.Kweon, et. al.][R. Duan et.al.][N.A. Fauzi et al].

The use of ONAF (Oil Natural Air Force) in transformer cooling has been widely used. However, damage to the fan often occurs, so it is proposed to detect damage to the fan without installing a sensor. The method used is TOT (Top Oil Transformer) monitoring, in which the oil exponent is modelled and analyzed. The oil exponent data is monitored in real time using PSO (Particle Swarm Optimization) or ultrasonic sensing technology[L. Wang, et, al][H. Guo, et. al]. Research on the development of methods for predicting hot spots in transformer oil has been conducted based on fluid thermal field calculations using a learning model with machine learning support vector regression. The data was taken from twenty test samples of temperature increases [Y. Deng et. al.][M. Li, Z. Wang, et.al.] Oranalyzing temperature increases accurately to determine hot spots using the hybrid Dimensionless Least-Squares Finite Element Method and Upwind Finite Element Method with the assistance of Computational Fluid Dynamic software[G. Liu at.al.][M.Akbari, et.al] and also by creating computational modelling to observe thermal, flow, and electromagnetic phenomena to determine hot spots inside the transformer tank [B. Melka et al][W.V. Calil, et.al].

This research aims to observe the highest increase in transformer oil temperature and the average temperature increase when testing with a transformer load of 4.7% of the nominal voltage of 20kV with a power capacity of 2500kVA conducted for 17 hours with the transformer connected to the short-circuited secondary side. The temperature increase data was then recorded by a data logger until a steady state was reached.

METHOD

This research phase will be divided into two parts, namely the data analysis phase [agus.] on the oil temperature increase equation, the average increase during *steady state*, and the increase and average oil temperature during one hour of nominal current injection in accordance with the IEC 60076-2-2011 standard. Figure 1 shows the transformer oil testing scheme that will be used in this research and the analyse of result is important for education and industry [agus et al] to get the best quality of new transforamtor oil.

Figure 1 shows a test diagram for a distribution transformer with a capacity of 2500kVA, 20kV/0.4kV, with an ONAN (*Oil Natural Air Natural*) cooling system, delta-star connection with no-load *losses* of 2048W and loaded *losses* of 40843.56W. The test scheme complies with the IEC 60076-2-2011 standard, which uses the short-circuit method.The voltage of the three-phase system is regulated using a three-phase variac, then the voltage is *stepped up* to 1kV, and the primary side current and voltage are measured using CT (*current transformer)* and PT (*potential transformer).*

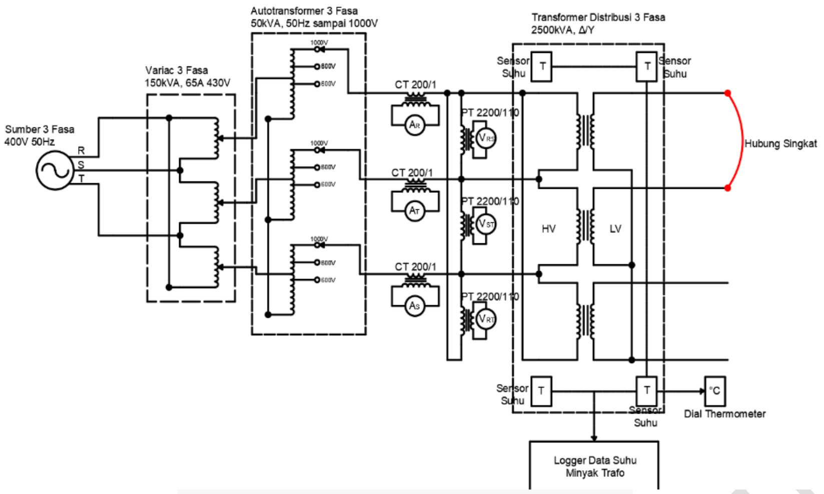

Figure 1. Transformer Oil Testing Scheme

During the test, a short circuit was applied to the secondary side, and the transformer was subjected to a test current in accordance with the , which calculated the total power loss. Oil temperature data was sampled over seventeen hours and stored in *a data logger*.

Highest Liquid/Oil Temperature (Top-Liquid Temperature)

Transformers contain oil that functions as a heat dissipater. When a transformer supplies a load, the current in the transformer increases. With the increase in the temperature of the transformer oil/fluid, the IEC 60076-2-2011 standard regulates the maximum increase. In this standard, the maximum oil temperature, also known as *the top-liquid temperature* (θ_0) , is determined through testing and measurement processes. Temperature readings are taken by installing a sensor inside the transformer, submerged in the liquid/oil at the top of the tank. The maximum temperature rise of the transformer oil/fluid or *top-liquid temperature rise* $(\Delta\theta_0)$) can be obtained from the difference between the highest measured temperature of the fluid/oil (θ_0)) at the end of the testing period, taking into account *the* total *losses* and external cooling temperature at the end of the testing period (θ_a) , using the following equation, based on IEC 60076-2-2011,:

$$\Delta\theta_0 = \theta_0 - \theta_a \quad (1)$$

The average liquid temperature rise $(\Delta\theta_{0m})$) is determined by the difference between *the average liquid temperature* (θ_{0m}) and the external cooling temperature (θ_a) , as follows:

$$\Delta\theta_{0m} = \theta_{0m} - \theta_a \quad (2)$$

For the *bottom-liquid temperature rise* $(\Delta\theta_b)$, it is determined by the difference between the bottom-liquid temperature and the external cooling temperature (θ_a) , as follows:

$$\Delta\theta_b = \theta_b - \theta_a \quad (3)$$

The different fluid temperatures are the average of the last hour's readings with total losses.

Oil Temperature Rise Correction

At this stage of temperature rise correction, the result is calculated from the highest oil temperature minus the external temperature, which is then multiplied by the power or current injected into the transformer. If using the power value, the total power loss value is multiplied by equation (1). According to the IEC 60076-2-2011 standard, the power loss equation is determined as follows:

$$\left(\frac{TotalRugiDaya}{RugiDayaPengujian}\right)^{x} \quad (4)$$

The average temperature rise in the transformer windings relative to the average oil temperature when the transformer is not in operation is:

$$\left(\frac{RatingArusNominal}{Arus\ Pengujian}\right)^{y} \quad (5)$$

Meanwhile, the magnitude of the temperature rise at the highest hot spot on the transformer winding relative to the winding temperature at the hot spot when the transformer is not in operation is:

$$\left(\frac{RatingArus\ \ Nominal}{ArusPengujian}\right)^{z} \quad (6)$$

Where the values x, y, and z are the exponent values in the temperature increase during testing in *steady-state* conditions, and the value x is a constant determined based on the type of transformer cooling. Table 1 shows the constant values specified in the IEC 60076 standard.

Table 1. Correction Exponent Values for Temperature Rise Test Results

TYP	**Transformer Distribution**	**Medium and High Power Transformers**			
	ONAN	ONAN	ONAF	OF..	OD..
	0.8	0.9	0.9	1.0	1.0
	1.6	1.6	1.6	1.6	2.0
	-	1.6	1.6	1.6	2.0

Where:A is the exponent x (for the top temperature). B is the exponent y (for the average winding temperature), C is the exponent z (for the winding temperature gradient), ONAN = *Oil Natural Air Natural (*transformer cooling system), ONAF = *Oil Natural Air Force (*transformer cooling system), OF = *Oil Forced* OD = *Oil Directed*

From equation (1), if substituted into equation (4), the average temperature rise is:

$$\Delta\theta_0 = \theta_0 - \theta_a \left(\frac{TotalRugi\ \ Daya}{RugiDayaPengujian}\right)^{0,8} \quad (7)$$

Table 1 contains the constant values used for temperature rise testing with a transformer power rating of at least 2500kVA or above.

RESULTS AND DISCUSSION

In this research, the results of calculations and temperature rise tests on transformer oil will be discussed. Table 2 shows the *nameplate* data of the transformers is used.

Table 2. Transformer *Nameplate* Data

Primary Voltage		20 kV
Secondary Voltage		400 V
Number of Phases		3
Power Capacity		2500 kVA
Frequency		50Hz
Vector Group		Dyn-5
Primary Current Rating		72.17 A
Secondary Current Rating		3608.44 A
Cooling Type		ONAN

The testing procedure involved injecting a nominal current of 72.168A into the primary side of the transformer winding. The primary current rating was 72.16A, so substituting this into equation (1) and then into equation (5) gives:

$$\Delta\theta_0 = \theta_0 - \theta_a \left(\frac{Total\ Rugi\ Daya}{Rugi\ Daya\ \ Pengujian}\right)^{1,6} \quad (8)$$

Using equation (7), where the highest oil temperature ((θ_0) is 67.6°C and the external *cooler/ambient average* temperature (θ_a) is 30.37°C, the oil temperature increase is 37.24°C. The highest oil temperature (θ_0), highest temperature rise ($\Delta\theta_0$), and highest average temperature rise ($\Delta\theta_{01}$)) tests were conducted for 16 hours with the primary side of the transformer supplied with 4.7% of the nominal primary side voltage. The following is a graph of the highest oil temperature test versus time reaching a *steady state.*

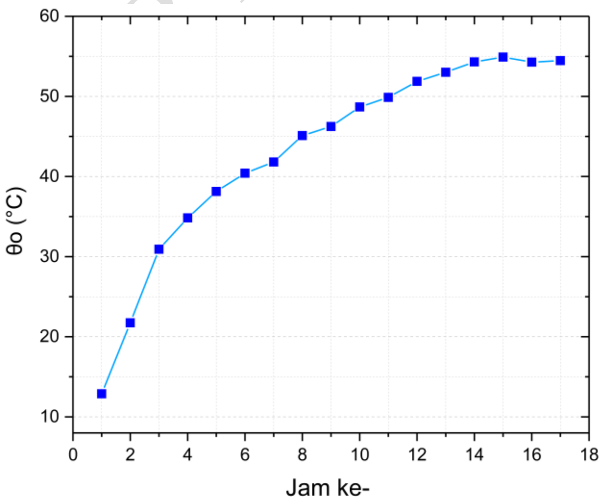

Figure 2. Test graph of the highest oil temperature (θ_0) over time

Figure 2 shows the graph of the highest oil temperature increase function over the seventeen-hour test period. The test was conducted to reach the highest temperature point under steady-state conditions. Under these conditions, the temperature reached a steady state at 83.2°C. Next is the test of the highest average oil temperature with a test period of seventeen hours, as shown in Figure 2.

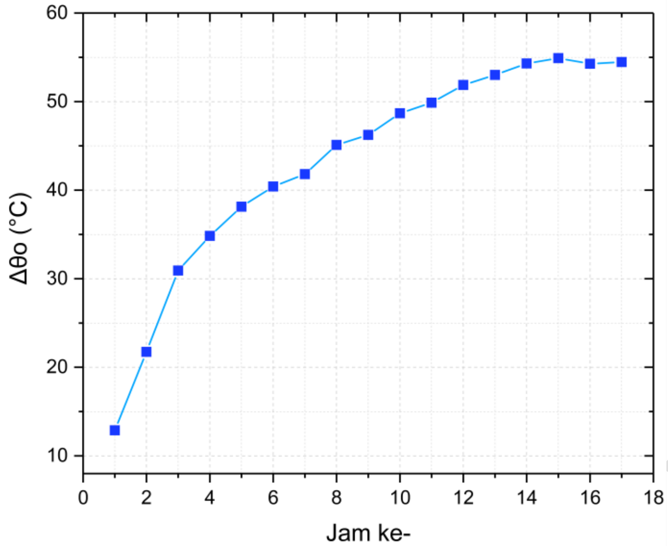

Figure 3. Graph of Oil Temperature Rise Test ($\Delta\theta_0$) s Versus Time

Figure 3 shows that the temperature rise, which is theoretically derived from equation (7), was then plotted as a function of time over seventeen hours to reach a steady state with a maximum temperature of 54.47°C. Figures 3 and 5 are the results of documenting the transformer oil temperature measurements using *a temperature logger* and *dial thermometer*.

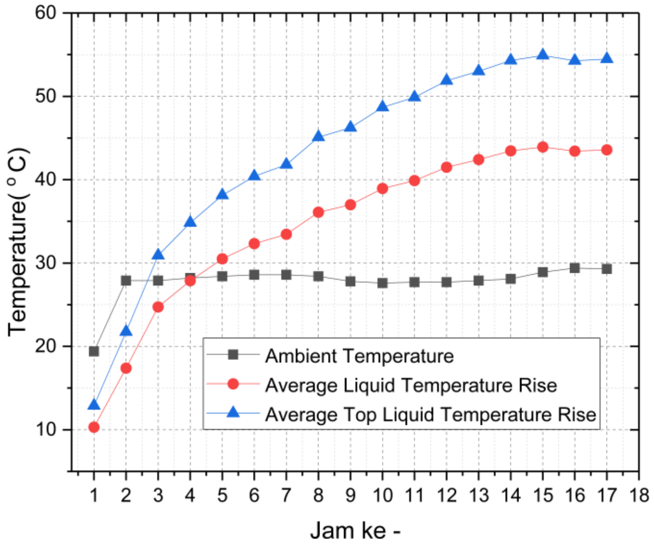

Figure 4. Comparison Graph of Oil Temperature Rise ($\Delta\theta_0$) s) Over Time

Figure 4 shows that the ambient air temperature in the testing environment was relatively stable at 27.75 °C. At the start of the test, the temperature was 19.4 °C.
The average temperature rise of the insulating oil throughout the transformer when operating above ambient temperature showed a rise pattern in accordance with the IEC 60076-2-2011 standard. This metric reflects the overall temperature rise in the oil throughout the transformer, including the middle and lower parts. Meanwhile, the averagetemperature rise of the insulating oil, particularly in the upper part of the transformer (top liquid temperature rise), when operating above ambient temperature. This metric focuses more on the temperature rise that occurs in the upper part of the transformer, which is often the area

where the temperature tends to be higher due to the thermal effects of the transformer's operating process. From Figure 4, it is clear that the above conditions have a greater increase compared to other areas.

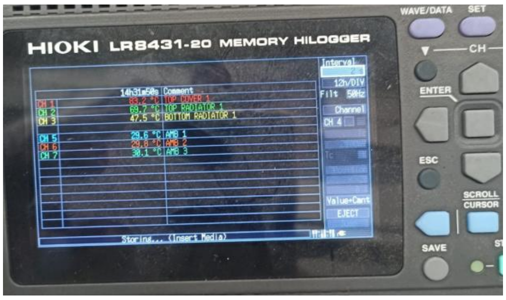

Figure 5. Measurement Results Using *a Thermometer Logger*

Figure 6. Measurement Results Using *a Dial Thermometer*

In Figures 5 and 6, the transformer oil temperature was measured by taking *samples* over a period of seventeen hours. The results are measurements taken when the temperature was stable at 83.2°C.

CONCLUSION

From these research conducted, the analysis and testing of transformer oil temperature rise in accordance with IEC 60076-2 standards showed that in the highest temperature test $((\theta_0))$ of oil over time under steady-state conditions, the highest temperature reached 83.2°C, and the resultof the Temperature Rise Test $(\Delta\theta_0))$ of Oil over Time showed a temperature of 54.47°C under steady-state conditions.

References

A. Junaidi, “Effect of Temperature Change on Breakdown Voltage in Liquid Insulation Materials,” *Teknoin*, vol. 13, no. 2, pp. 1–5, Dec. 2008, doi: 10.20885/teknoin.vol13.iss2.art1.

Agus Sofwan, Methodology Research and Development, (2025), ISBN, 978-623-8730-810, Saba Jaya Publisher, Indikator Keberhasilan Produk Research and Development, P 199-201.

Agus Sofwan, R. Kun Wardana Abyoto,Baskoro Abie Pandowo MetodologI Penelitian Pendidikan (Kuantitatif & Kualitatif), (Mei 2025), ISBN 978 623 8730 70 4 Saba Jaya Publisher, HIPOTESIS PENELITIAN, P 87-100.

B. Melka *et al.*, “Effective Cooling of a Distribution Transformer Using Biodegradable Oils at Different Climate Conditions,” *IEEE Transactions on Dielectrics and Electrical Insulation, vol. 30, no. 4, pp. 1557–1565, Aug. 2023* vol. 30, no. 4, pp. 1557–1565, August 2023, doi: 10.1109/TDEI.2023.3282561.

D. B. Fachrurrozi, S. P. Hadi, and F. Danang Wijaya, “Effect of temperature change of liquid isolator based on composite diala b oil and palm oil as transformer oil,” *2019 Int. Conf. Inf. Commun. Technol. ICOIACT 2019,* pp. 789–793, 2019, doi: 10.1109/ICOIACT46704.2019.8938485.

D. Kweon, K. Koo, J. Woo, and Y. Kim, “Hot spot temperature for 154 kV transformer filled with mineral oil and natural ester fluid,” *IEEE Transactions on* vol. 19, no. 3, pp. 1013–1020, June 2012, doi: 10.1109/TDEI.2012.6215107.

G. Liu, Z. Zheng, X. Ma, S. Rong, W. Wu, and L. Li, “Numerical and Experimental Investigation of Temperature Distribution for Oil-Immersed Transformer Winding Based on Dimensionless Least-Squares and Upwind Finite Element Method,” *IEEE Access*, vol. 7, pp. 119110–119120, Aug. 2019, doi: 10.1109/ACCESS.2019.2937548.

H. Guo, Y. Sun, Z. Zhang, G. Gu, X. Yang, and D. He, “A Transformer Hot Spot Fault Diagnosis Method Combining Ultrasonic Sensing Technology and PSO-SVM Algorithm,” *Proc. - 2023 Int. Conf. Power Syst. Technol. Technol. Adv. Constr. New Power Syst. PowerCon 2023*, no. September, pp. 1–4, September 2023, doi: 10.1109/PowerCon58120.2023.10331236.

I. 60076-2-2011, *International Electrotechnical Commission*, vol. 2003. 2003.

I. N. Oksa Winanta, A. A. N. Amrita, and W. G. Ariastina, “Study of Breakdown Voltage of Transformer Oil,” *J. SPEKTRUM*, vol. 6, no. 3, p. 10, Oct. 2019, doi: 10.24843/spektrum.2019.v06.i03.p02.

J. Jumardin, J. Ilham, and S. Salim, “Study of Patchouli Oil Characteristics as an Alternative to Transformer Oil,” *Jambura J. Electr. Electron. Eng.*, vol. 1, no. 2, pp. 40–48, 2019, doi: 10.37905/jjeee.v1i2.2881.

L. Wang, W. Zuo, Z. X. Yang, J. Zhang, and Z. Cai, “A Method for Fans’ Potential Malfunction Detection of ONAF Transformer Using Top-Oil Temperature Monitoring,” *IEEE Access*, vol. 9, pp. 129881–129889, September 2021, doi: 10.1109/ACCESS.2021.3114301.

M. Akbari and A. Rezaei-Zare, “Transformer Bushing Thermal Model for Calculation of Hot-Spot Temperature Considering Oil Flow Dynamics,” *IEEE Transactions on Power Delivery, vol. 36, no. 3, pp. 1726–1734, 2021,* vol. 36, no. 3, pp. 1726–1734, 2021, doi: 10.1109/TPWRD.2020.3014064.

M. Li, Z. Wang, J. Zhang, Z. Ni, and R. Tan, “Temperature Rise Test and Thermal-Fluid Coupling Simulation of an Oil-Immersed Autotransformer under DC Bias,” *IEEE Access*, vol. 9, pp. 32835–32844, 2021, doi: 10.1109/ACCESS.2021.3060632.

N. A. Fauzi *et al.*, “Detection of Power Transformer Fault Conditions using Optical Characteristics of Transformer Oil,” in *2018 IEEE 7th International Conference on Photonics, ICP 2018*, 2018, pp. 2017–2019. doi: 10.1109/ICP.2018.8533173.

R. Duan, “Real-Time Hotspot Tracing and Model Analysis of a Distributed Optical Fibre Sensor Integrated Power Transformer,” *IEEE Access*, vol. 10, pp. 57242–57254, May 2022, doi: 10.1109/ACCESS.2022.3177844.

S. N. Singgih and H. Berahim, "Analysis of the Effect of Temperature on AC and DC Breakdown Voltage in Transformer Oil," *J. Tek. Elektro*, vol. 1, no. 2, pp. 93–99, 2009.

W. V. Calil, P. D. P. Salazar, A. S. De Melo, and E. C. M. Costa, “An Efficient Procedure for Temperature Calculation of High Current Leads in Large Power Transformers,” *IEEE*

Access, vol. 8, pp. 222371–222376, October 2020, doi: 10.1109/ACCESS.2020.3044713.

Y. Deng *et al.*, “A Method for Hot Spot Temperature Prediction of a 10 kV Oil-Immersed Transformer,” *IEEE Access*, vol. 7, pp. 107380–107388, June 2019, doi: 10.1109/ACCESS.2019.2924709.