Type of Contribution:
Research Paper
Review Paper
Case Study

ENERGY: JURNAL ILMIAH ILMU-ILMU TEKNIK
Vol. 15, No. 2 (2025) pp 309-323
DOI: 10.51747/energy.v15i2.15215

E-ISSN: 2962-2565

This article contributes to: Sustainable Development Goals 9 Industry, Innovation and Infrastructure

Comparison of Breakdown Voltage and Aging of Kraft Paper in Transformers Immersed in Mineral Oil, Natural Ester, and Synthetic Ester

Hanifiyah Darna Fidya Amaral[1]*, Galuh Prawestri Citra Handani[1], Rahman Azis Prasojo[1], Reyhan Fadhlur Rahman[1], Satria Lutfi Hermawan[1], Ruwah Joto[1], Afidah Zuroida[1], Ahmad Hermawan[1], Irwan Heryanto/Eryk[1]

[1] Electrical Engineering Department, State Polytechnic of Malang, 65141, **Indonesia**

*hanifahdarna@polinema.ac.id

Abstract

Transformers are critical components in electrical power systems that rely on insulation oil and paper to ensure reliable and long-lasting operation. This study aims to compare the performance of kraft insulation paper immersed in three types of transformer oil, namely mineral oil, natural ester, and synthetic ester, through the accelerated thermal aging method. Evaluation was carried out based on tensile strength and water content testing in accordance with the IEEE C57.100-2011 standard, as well as breakdown voltage testing in accordance with the IEC 60156-2018 standard. Tests were conducted with samples taken at intervals of 24, 240, 480, and 720 hours at 150°C. The results showed that insulation paper soaked in mineral oil experienced a 34% decrease in tensile strength, while natural ester and synthetic ester oils showed tensile strengths of 66% and 52%, respectively. In the water content test, natural ester showed the best performance with the lowest water content (5.19%), followed by mineral oil (7.47%) and synthetic ester (46.70%). In the breakdown voltage test, natural ester had the highest breakdown voltage of 66.26 kV, followed by mineral oil at 63.96 kV and synthetic ester at 41.14 kV. Estimated insulation life based on lifetime regression showed that natural ester has a lifetime of up to 37.9 years, synthetic ester 25.6 years, and mineral oil 20.5 years. In addition, in transformers operating at 130°C, natural ester insulation oil can increase loading up to 20% higher than mineral oil and has a 15-20°C higher operating temperature. This study recommends the use of kraft insulation paper impregnated with natural ester and synthetic ester oils as an alternative to mineral oil, because both are superior environmentally friendly alternatives compared to mineral oil. Both oils

Article Info
Submitted: 2025-10-20
Revised: 2025-11-07
Accepted: 2025-11-29
Published: 2025-11-30

Publisher
Universitas Panca Marga

have better mechanical strength and insulation, lower water content, and can slow down transformer aging. Furthermore, these ester oils are non-flammable, biodegradable, and reduce the risk of failure due to excessive heat or discharge, thereby increasing the reliability and lifespan of the transformer. With these properties, ester oils support safer and more sustainable operations for the power system.

Keywords: Mineral Oil, Natural Ester, Synthetic Ester, Tensile Strength, Water Content, Breakdown Voltage

1. Introduction

Transformers are vital components in electrical power systems that are increasingly needed as the demand for clean and environmentally friendly energy grows [1]. Transformer oil functions as an insulation and cooling medium, absorbing heat from the windings and transferring it to cooling fins, as well as extinguishing arcs during electrical discharges [2]. Heat is generated by the current flowing through the transformer windings [3]. There are two types of insulation oil: mineral oil based on petroleum and ester oil based on plants [4]. Mineral oil has good temperature stability but is less environmentally friendly and has a low flash point [1]. Meanwhile, ester oil is divided into natural ester derived from plants and synthetic ester resulting from the chemical reaction of alcohol with organic acids. Both types of ester are biodegradable and have high flash points as well as humidity tolerance [5], [6], [7].

The oil–paper insulation system greatly affects the reliability of power and distribution transformers [8]. The lifespan of a transformer is primarily determined by the quality of the oil-impregnated insulation paper [9]. This study, titled "Comparison of Breakdown Voltage and Aging of Kraft Paper in Transformers Immersed in Mineral Oil, Natural Ester, and Synthetic Ester," aims to compare the performance of kraft paper in three types of oil through an accelerated thermal aging method to evaluate the lifetime of transformers using three different types of insulating oils. This research uses kraft paper, which is widely used because it has good impregnation capability, high electrical performance, is easy to form, and is more resistant to oxidation compared to TUP (Thermally Upgraded Paper). Kraft paper can withstand temperatures of 105°C –120°C, and during normal transformer operation it can endure up to 98°C at the maximum hot-spot temperature of the upper winding [10]. The laboratory experiment uses the accelerated thermal aging method to compare the lifetime of transformers using three different types of insulating oils—mineral oil, natural ester, and synthetic ester—and to conduct tests on transformer insulation paper, including tensile strength and water content based on IEEE C57.100-2011, as well as breakdown voltage according to IEC 60156-2018.

The tests were carried out at 90°C for 24 hours (initial condition) and 150°C for 240, 480, and 720 hours. From the results of this study, it is expected that the comparison of the quality of kraft insulation paper immersed in different types of transformer insulating oils can be determined.

2. Methods

This study discusses the testing of insulation paper tensile strength, water content, breakdown voltage, and the lifetime calculation of insulation paper immersed in mineral insulating oil, natural ester, and synthetic ester under accelerated aging conditions. The research process began with preparing samples of mineral insulating oil, natural ester, synthetic ester, and kraft insulation paper in 12 Duran bottles of 500 ml (400 ml of oil per bottle) with an oil-to-paper ratio of 3:1 according to [11]. Pretreatment was performed by heating the oil at 110°C for 24 hours (with the bottles open) to remove dissolved air, and drying the paper at 70°C for 7 hours until the moisture content reached 0.25%, as stated in [11]. The samples then underwent accelerated thermal aging in an oven at 90°C for the initial condition (Sample 1, 24 hours) and at 150°C for Samples 2, 3, and 4 with durations of 240, 480, and 720 hours. After these four sampling stages, tests were conducted on the insulation paper, including tensile strength and water content, as well as breakdown voltage testing for the three types of oil.

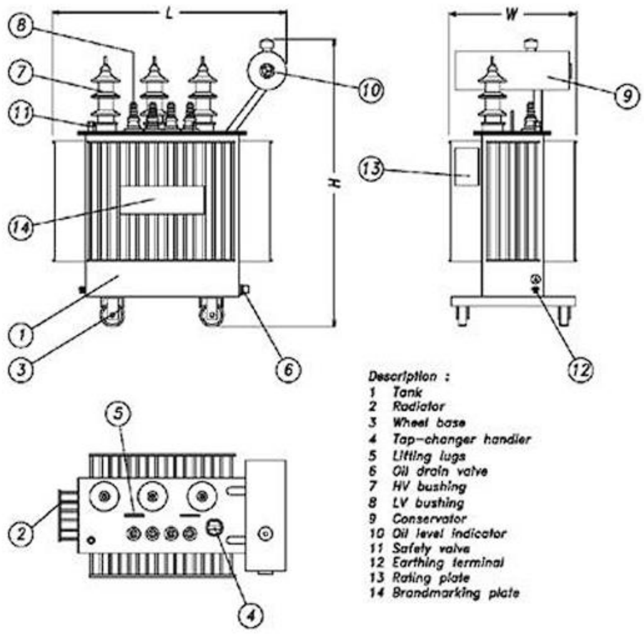

Figure 1. Transformer

2.1 Transformer

Transformers are electrical equipment consisting of an iron core and windings based on the principle of electromagnetic induction and can increase voltage with the same frequency according to [12]. In voltage transformation, the transformer uses the principle of electromagnetic induction through three main components: the primary winding, secondary winding, and iron core, as seen in **Figure 1**. When alternating current flows through the primary winding, it generates a magnetic flux that flows through the iron core, which then induces the secondary winding. As a result, the secondary winding experiences a potential difference at both ends [13]. Heat in the transformer is caused by the current flowing through the transformer windings [3].

2.2 Accelerated Thermal Aging of Transformer

Accelerated Thermal Aging is an experimental method that accelerates time and increases the temperature value. The purpose of Accelerated Thermal Aging is to study the aging behavior of oil and insulation paper due to the influence of temperature and time, as well as to observe changes in the physical, chemical, and dielectric characteristics of the oil and insulation paper used [14].

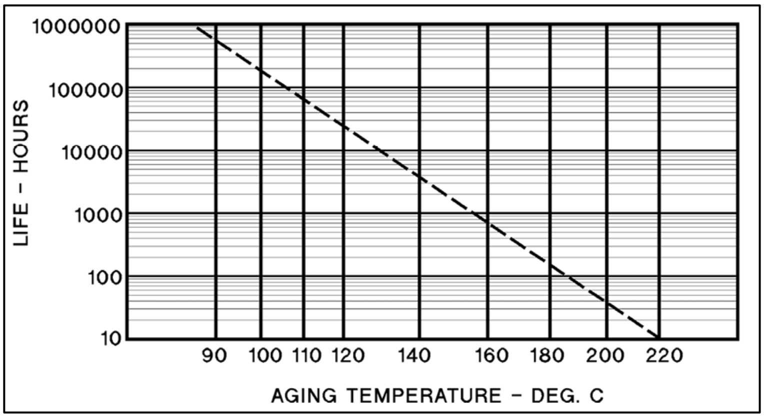

Figure 2. Minimum Expected Life Curve For Closed Tube Test On Cellulose Insulation Material Immersed In Liquid (50% Reduction From Tensile Strength) IEEE C57.100 2011

Based on **Figure 2**, the Minimum Expected Life Curve for Closed Tube Test on Cellulose Insulation Material Immersed in Liquid (50% Reduction from Tensile Strength) IEEE C57.100 2011, it can assess the thermal endurance of paper insulation material against high temperatures until the tensile strength drops below 50%. The causes of accelerated insulation aging are overload on the transformer and high temperature due to the failure of the transformer cooling system [15]. There are several options for temperature variations for aging, namely 150°C, 165°C, and 180°C according to the standard [11].

2.3 Insulation Paper Testing

In this insulation paper testing, it examines the physical and chemical changes that occur in the insulation paper used. The main failure of transformers is caused by the weak mechanical strength of the paper due to aging or stress. The strength of the paper depends on the fiber strength and, more importantly, the inter-fiber bonding strength. This testing also includes the influence of temperature factors, environmental conditions, and humidity that affect both the oil and the paper [16]. The insulation paper tests conducted include tensile strength and water content.

2.3.1 Tensile Strength

Tensile strength is the ability of a material to withstand tensile force until it reaches the point of failure or breakage. Tensile testing using a universal tensile tester as shown in **Figure 3**. In transformer insulation paper testing, tensile strength is measured to understand the characteristics of the paper during the accelerated thermal aging process [9]. According to the standard [17], if the tensile strength is below 50% of the initial value, the transformer is considered to have reached the end of its life. The tensile strength is given by the following equation [18]:

$$\sigma = \frac{F}{A} \quad (1)$$

Description:

σ = Strain (N/m² atau Pa)

F = Force (N)

A = Surface Area (m²)

$$\%TS = \left[\frac{t_i}{t_0}\right] x100\% \quad (2)$$

Description:

%TS : Tensile Strength (%)

t_i: Tensile strength value after aging (KgF)

t_0 : Initial tensile strength value (KgF)

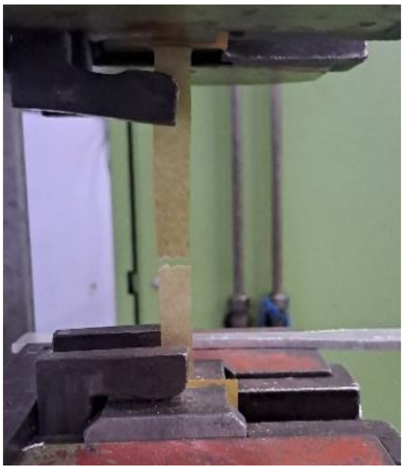

Figure 3. Tensile Strength Testing

2.3.2 Water Content

Water content in insulation paper and oil is one of the main factors influencing the aging process [20]. Water content testing using a universal water content test tool as shown in **Figure 4**. The purpose of checking the water content is to measure the amount of moisture present in the transformer insulation paper. The sources of this moisture can come from two main factors: the surrounding environment and the degradation that occurs in the insulating oil and paper [21].

Figure 4. Water Content Testing

2.4 Breakdown Voltage

Breakdown voltage is the maximum voltage that a dielectric material can withstand before insulation failure occurs, as seen in **Figure 5**. The main purpose of this test is to detect electrically conductive contaminants in the oil, such as water, dirt, fibers, or wet cellulose particles. The breakdown voltage testing is conducted in accordance with the IEC 60156-2018 standard, where the minimum allowed limit is ≥30 kV/2.5 mm [22].

Figure 5. Breakdown Votage Testing

2.5 End of Life Transformer

A transformer also has a service life or age, referred to as its Life. The transformer's lifespan is influenced by changes or excessive increases in load, which cause high temperatures. If the high temperature persists continuously and is not promptly addressed, it can cause failure or damage to the transformer beyond its tolerance limits. To prevent temperature increases in the transformer, appropriate materials such as insulation inside the transformer should be selected. This insulation needs to be verified through aging tests to estimate the transformer's lifespan. According to standard [17], the reduction in transformer life is caused by certain temperatures over a specific period. The equation used to estimate the transformer life is as follows:

$$LIFE = EXP[\frac{15000}{T+273} - 28{,}082] \tag{3}$$

Description:

LIFE : Service life in hours

T : Heating temperature (°C)

The calculation of LIFE at each sample point during the aging duration uses the equation:

$$\%LIFE = \frac{t_i}{t_r} x100\% \tag{4}$$

Description:

t_i: Effective life calculated at 150°C

t_r: Duration of aging (hours)

The calculation of the life ratio of transformer (*r*) insulation paper uses the following equations:

$$r = \frac{\%LIFE\ Synthetic\ Ester}{\%LIFE\ Mineral} \tag{5}$$

$$r = \frac{\%LIFE\ Natural\ Ester}{\%LIFE\ Mineral} \tag{6}$$

3.Results and Discussion

3.1 Comparison of Tensile Strength (TS) Results on Kraft Insulation Paper Immersed in Mineral Oil, Natural Ester, and Synthetic Ester

Tensile strength testing was conducted on kraft insulation paper that had been immersed in mineral oil, natural ester, and synthetic ester. The resulting tensile strength values are shown in **Figure 6**.

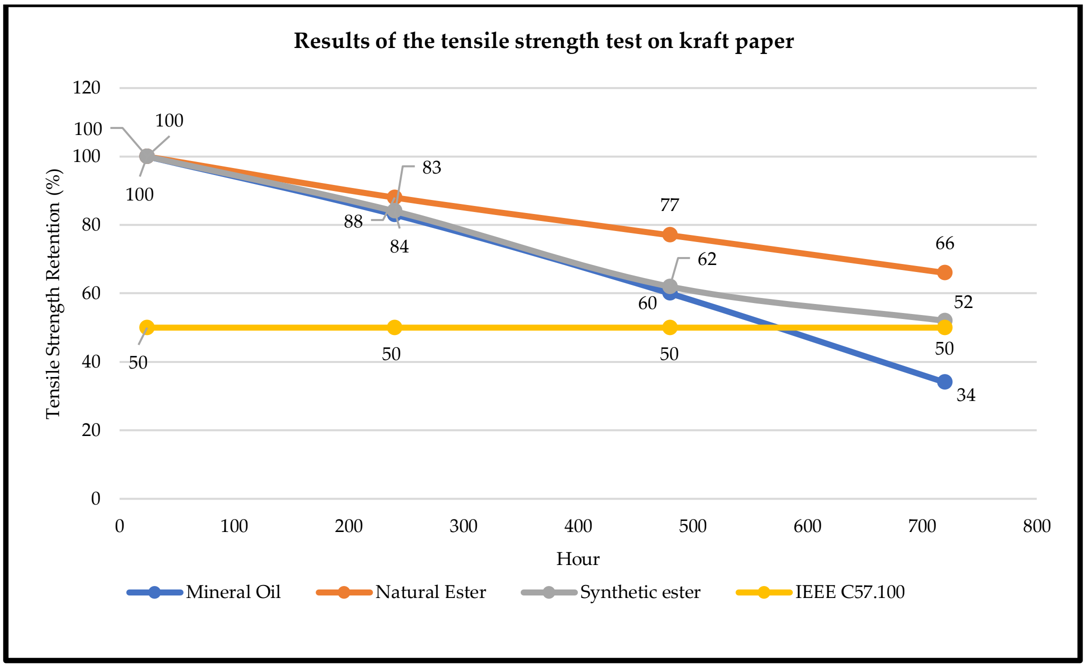

Figure 6. Tensile Strength Test Results of Kraft Paper

Based on **Figure 6**, which shows the tensile strength test results of kraft paper, a decrease in tensile strength is observed during the aging period at 150°C for 720 hours. Paper immersed in mineral oil experienced a significant reduction from 100% (at 24 hours) to 34% (at 720 hours), falling below the minimum threshold of 50% according to IEEE Standard C57.100-2011, which indicates the end of insulation life. According to [22], a tensile strength degradation below 50% is considered the threshold for transformer failure. In contrast, kraft paper immersed in natural ester showed a gradual decrease to 66%, and synthetic ester to 52%, both of which remained above the standard limit. The results indicate that under high-temperature and long-duration aging conditions, both ester oils are more resistant to thermal degradation compared to mineral oil. Natural and synthetic esters demonstrate a better ability to maintain the molecular structure and physical properties of kraft paper than synthetic and mineral oils at high temperatures and long aging durations. Thus, it can be concluded that natural ester and synthetic ester provide better protection against the mechanical degradation of kraft paper compared to mineral oil.

3.2 Comparison of Water Content (WC) Results on Kraft Insulation Paper Immersed in Mineral Oil, Natural Ester, and Synthetic Ester

Water content testing was conducted on kraft insulation paper that had been immersed in mineral oil, natural ester, and synthetic ester. The resulting water content values are shown in **Figure 7**.

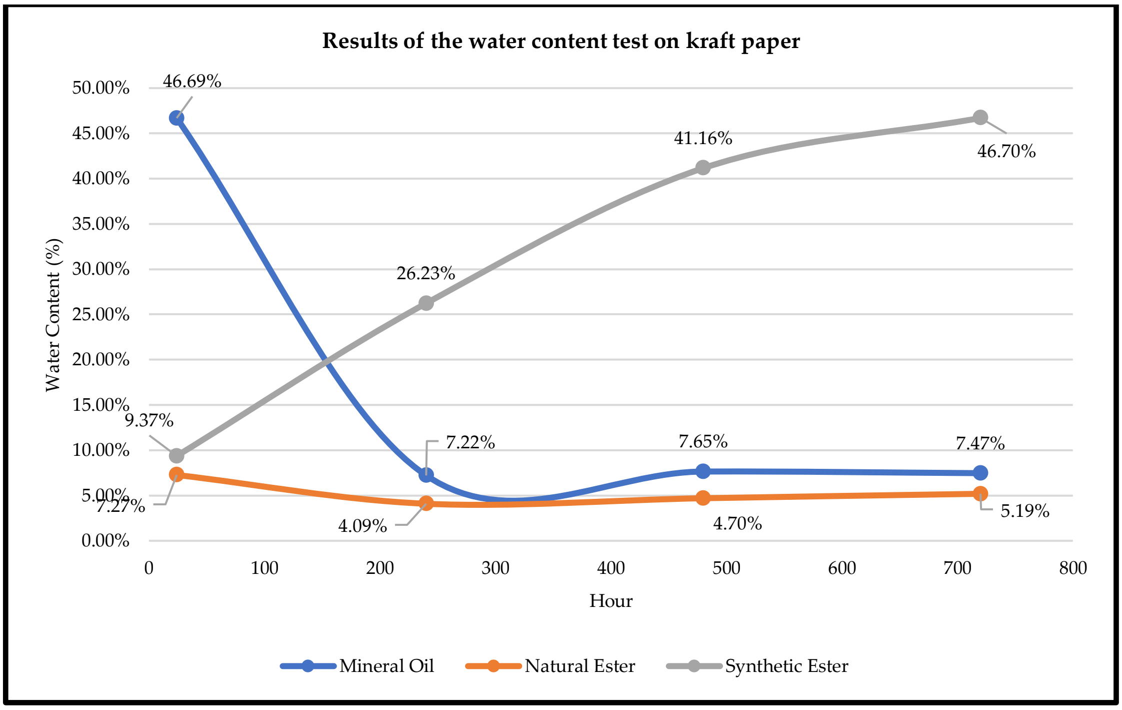

Figure 7. Water Content Test Results of Kraft Paper

Based on the moisture content test results for kraft paper immersed in three types of insulating oils, there is a significant difference in the moisture trend during the aging process at 150°C. The moisture content in kraft paper can accelerate insulation degradation and reduce dielectric properties, potentially leading to transformer failure. Paper immersed in mineral oil showed a drastic decrease in moisture content from 46.69% (at 24 hours) to 7.47% (at 720 hours). Paper immersed in natural ester maintained the most stable and lowest moisture level, decreasing from 7.27% to 5.19%, making it the most effective at keeping moisture low. In contrast, paper immersed in synthetic ester experienced a significant increase in moisture content from 9.37% to 46.70%, which is considered an anomaly because synthetic ester is generally expected to have lower water absorption than mineral oil. According to [23], the moisture content of synthetic ester insulating oil should be lower than that of mineral oil, following the order: natural ester < synthetic ester < mineral oil. This anomaly is likely caused by non-optimal initial oil conditions or inadequate paper pretreatment, resulting in higher initial moisture content. Overall, natural ester demonstrated the best performance in maintaining moisture stability in kraft insulation paper. Chemically, natural esters exhibit strong thermal stability, allowing them to withstand extreme temperatures without significant degradation. In addition, their resistance to oxidation is a major advantage, enabling insulation performance to last longer than mineral oil [24].

3.3 Comparison of Breakdown Voltage Results for Mineral Oil, Natural Ester, and Synthetic Ester

Breakdown voltage testing was conducted on mineral oil, natural ester, and synthetic ester insulating oils. The resulting breakdown voltage values are shown in Figure 8.

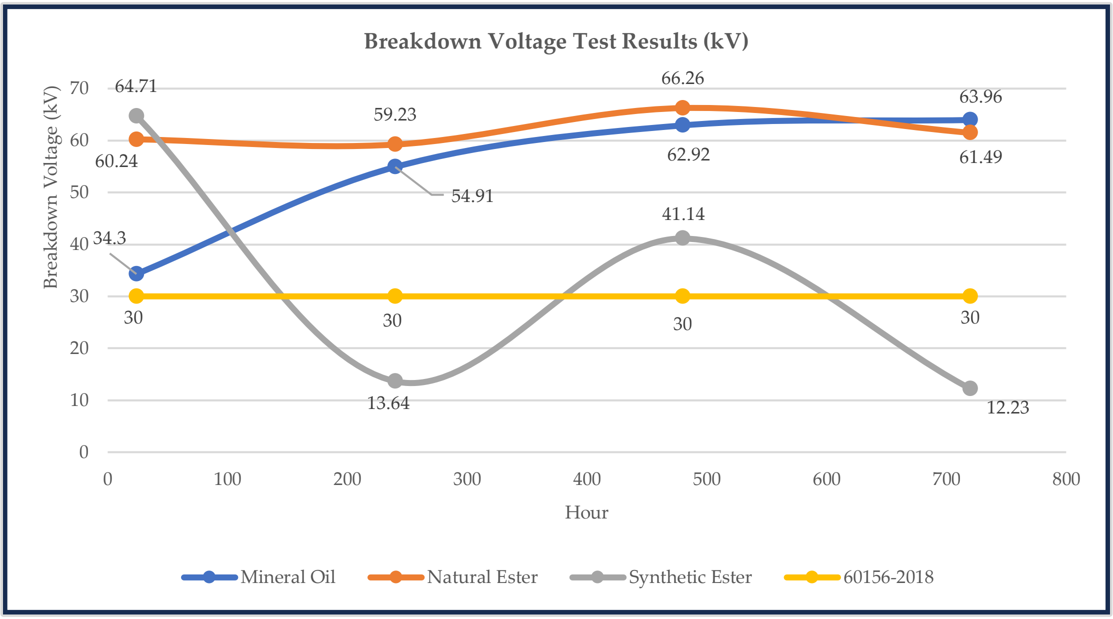

Figure 8. Breakdown Voltage Test Results

Based on the breakdown voltage test results for the three types of insulating oils, there were clear differences in both increases and decreases, as shown in Figure 8. The breakdown voltage of mineral oil increased from 54.91 kV (at 24 hours) to 63.96 kV (at 720 hours). Natural ester oil showed a higher breakdown voltage than mineral oil, increasing slightly from 60.24 kV to 61.49 kV over the same aging period. In contrast, synthetic ester oil experienced a significant decrease in breakdown voltage, from 64.71 kV (at 24 hours) to 12.23 kV (at 720 hours), which is below the IEC 60156-2018 standard of 30 kV. This is considered an anomaly because synthetic ester is generally expected to have a higher breakdown voltage than mineral oil. According to [25], synthetic ester insulating oil should have a higher breakdown voltage than mineral oil, following the order: natural ester < synthetic ester < mineral oil. This anomaly may have occurred because the oil condition could not be fully verified, and the initial pretreatment stage was too short, resulting in high moisture content in the oil. Overall, natural ester demonstrated the highest and most stable breakdown voltage. These results indicate that natural ester oil excels in resistance to thermal aging and high temperatures, thereby maintaining its insulating capability better than both mineral oil and synthetic ester.

3.4 Analysis of the Lifetime of Kraft Insulation Paper Based on Tensile Strength (TS) Testing During Accelerated Aging Immersed in Mineral Oil, Natural Ester, and Synthetic Ester

Based on the lifetime calculation results, the estimated remaining life of the transformer can be determined using accelerated thermal aging. However, this calculation requires several data points, such as the temperature used, as well as the strength of the transformer insulation paper, which is assessed through tensile strength testing. The following are the calculation steps that need to be performed.

3.4.1 Determining the End of Life Calculation According to IEEE C57.100 2011

Based on Equation (3) with a temperature of 150 °C, the End of Life calculation results according to IEEE C57.100 2011 are 1601.975 hours. The estimated effective life until failure of the transformer insulation paper after accelerated aging is 1601.975 hours (approximately 66 days) at a temperature of 150 °C. However, in this research, a shorter duration of 720 hours (approximately 30 days) is used with the same temperature. The 720-hour duration is taken from a journal on transformer insulation experiments conducted by [17], which used 720 hours (30 days) with insulation paper sample collection at 24 hours, 240 hours, 480 hours, and 720 hours at 160 °C, as well as 720 hours at 150 °C conducted by [22].

3.4.2 Determining the Calculation of %LIFE per Sample (240 hours, 480 hours, 720 hours)

Based on Equation (4), the calculation results for %LIFE for each sample are obtained, and Tabel 1. Calculation of %Life Per Sample shows the %LIFE values and Tensile Strength Retention for the three insulation papers that have been immersed in oil with different aging durations. At 240 hours, the percentage of life per sample is 14.981%, at 480 hours it is 29.963%, and at 720 hours it is 44.944%. From these %LIFE values, it can be seen that there is an increase in the percentage of life per insulation paper sample as the aging time increases; this increase indicates a decrease in the quality of the insulation paper used. Therefore, the %LIFE value is not merely a statistical figure, but rather an important piece of data that supports decision-making in transformer maintenance and operational planning based on predictions of the paper insulation degradation level.

Tabel 1. Calculation Of %Life Per Sample

Aging (Hour)	Tensile Strength Retention (%)			%LIFE
	Mineral Oil	Natural Ester	Synthetic Ester	
0	100	100	100	0
240	83	88	84	14,981
480	60	77	62	29,963
720	34	66	52	44,944

3.4.3 Determining the Regression Calculation for Delta Lifetime from Tensile Strength Retention Results and %LIFE Calculations

The delta lifetime regression calculation is used to determine the difference in service life of kraft insulation paper that has been immersed in mineral insulating oil, natural ester, and synthetic ester, and to estimate the tensile strength retention results and service life (lifetime) of the kraft insulation paper after accelerated aging. This allows for a more accurate estimation of the transformer's age based on the condition of the insulation. This calculation uses the Minitab application; the following shows the calculation results and display from the Minitab application by inputting data on tensile strength retention results and %LIFE from the types of mineral insulating oil, natural ester, and synthetic ester.

Results of the delta lifetime regression calculation per oil based on Minitab calculation results:

$$\text{Mineral Oil: } \%TS = 102{,}40 - 1{,}4752 \times \%LIFE \quad (7)$$

$$\text{Natural Ester: } \%TS = 99{,}700 - 0{,}7543 \times \%LIFE \quad (8)$$

$$\text{Synthetic Ester: } \%TS = 99{,}400 - 1{,}108 \times \%LIFE \quad (9)$$

The criterion for the end of life of insulation paper is the reduction of tensile strength to 50% of the initial condition [16]. The results of the regression calculation for delta lifetime per oil, based on Minitab calculations, are then used to calculate the regression of delta lifetime in the transformer using equations (7), (8), and (9). The result of %LIFE for kraft paper immersed in mineral oil is 35.52% of the effective age (66.7 days) until it is considered end of life. Therefore, kraft paper immersed in mineral oil is considered to reach end of life at 23.69 days. Meanwhile, the result of %LIFE for kraft paper immersed in natural ester oil is 65.88% of the effective age (66.7 days) until it is considered end of life. Therefore, kraft paper immersed in natural ester oil is considered to reach end of life at 43.94 days. Additionally, the result of %LIFE for kraft paper immersed in synthetic ester oil is 44.58% of the effective age (66.7 days) until it is considered end of life. Therefore, kraft paper immersed in synthetic ester oil is considered to reach end of life at 29.73 days.

3.4.4 Comparison of Lifetime Ratios from Mineral Insulation Oil, Natural Ester, and Synthetic Ester

Normal operation in transformers with thermally upgraded insulation paper, Kraft paper, cellulose pressboard, and mineral oil shows that the minimum service life is at least 20.5 years (180,000 hours) according to standard [17]. Based on this standard, the calculation results of the percentage ratio comparison between mineral insulating oil, natural ester, and synthetic ester using delta regression data from tensile strength results and %LIFE must be determined using Equations (5) and (6). The results show that the service life of Kraft paper immersed in synthetic ester oil is 1.25 times longer compared to mineral oil. Meanwhile, the service life of Kraft paper immersed in natural ester oil is 1.85 times longer than that in mineral oil.

The results of the percentage ratio comparison for the three types of oils based on service life indicate that natural ester insulating oil has the advantage, with an estimated service life of up to 37.9 years, followed by synthetic ester insulating oil with an estimated service life of up to 25.6 years. For mineral insulating oil, the service life can reach 20.5 years according to [17]. This higher service-life ratio typically leads to reduced maintenance costs and a lower need for transformer replacement in the long term. Current trends encourage the use of environmentally friendly insulating fluids in transformers, requiring electro-thermal studies, engineering evaluations, and real-time monitoring for the implementation of ester oils. Many older transformers are projected to be retrofilled from mineral oil to ester oil to improve fire security, consistency, and the remaining useful life [26]. However, it should be noted that other factors, such as actual load conditions and ambient temperature, also influence the implementation of ester oils. Additionally, the initial cost of insulating materials such as synthetic esters—which are relatively more expensive—must be considered, making further studies on the comparison of operational costs among the three types of oils essential.

4. Conclusion

Based on the results of the 720-hour aging experiment at 150°C, the kraft insulation paper of transformers immersed in mineral oil, natural ester, and synthetic ester demonstrates that natural ester and synthetic ester oils are superior in maintaining tensile strength retention at 66% and 52% respectively, while mineral oil only achieves 34%, which exceeds the IEEE C57.100 2011 standard limit. The water content in the paper immersed in natural ester is the best, whereas synthetic ester shows an anomaly with high water content due to a short pretreatment stage. The breakdown voltage of natural ester oil is also higher, but synthetic ester is low below the IEC 60156-2018 standard, likely due to oil conditions and initial processes. The highest estimated service life for the insulation paper is with natural ester at around 37.9 years, followed by synthetic ester at 25.6 years, and mineral oil at 20.5 years. At an operating temperature of 130°C, natural ester allows for 20% higher loading and an operating temperature 15-20°C higher compared to mineral oil. Therefore, the use of kraft paper immersed in natural ester and synthetic ester is recommended as an alternative to mineral oil to extend the transformer's service life and improve long-term durability.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

Funding - No funding information from the authors.

Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

Additional information - No additional information from the authors.

References

[1] A. Indarto, A. Bohra, S. Wahyudi, dan A. Dharmanto, "Trafo daya menggunakan minyak isolasi yang dapat terurai secara biologis," Hexatech J. Ilm. Tek., vol. 2, no. 2, pp. 49–55, 2023.

[2] J. Jumardin, J. Ilham, dan S. Salim, "Studi Karakteristik Minyak Nilam Sebagai Alternatif Pengganti Minyak Transformator," Jambura J. Electr. Electron. Eng., vol. 1, no. 2, pp. 40–48, 2019.

[3] PT. PLN (Persero), "Buku Pedoman Trafo Tenaga," Buku Pedoman Pemeliharaan Trafo Tenaga, pp. 1–142, 2014.

[4] G. R. K. Anggara, S. Prasetyono, dan R. M. Gozali, "Analisis Karakteristik Dielektrik Berbagai Minyak Nabati Sebagai Alternatif Isolasi Cair Untuk Transformator Tenaga," Jurnal Arus Elektro Indonesia, vol. 8, no. 1. pp. 1, 2022.

[5] M. Srivastava, S. K. Goyal, dan A. Saraswat, "Ester oil as an alternative to mineral transformer insulating liquid," in ELSEVIER, 2021, pp. 2850–2854.

[6] J. Jacob, P. Preetha, dan S. T. Krishnan, "Review on natural ester and nanofluids as an environmental friendly alternative to transformer mineral oil," IET Nanodielectrics, vol. 3, no. 2, pp. 33–43, 2020.

[7] IEEE Std C57.155, IEEE Std C57.155. IEEE Guide for Interpretation of Gases Generated in Natural Ester and Synthetic Ester-Immersed Transformers IEEE Power and Energy Society. 2014.

[8] Duanaputri, Prasojo, Wiwaha, et al., "Pengembangan Uji Eksperimental Penuaan Dipercepat Sistem Isolasi Kertas Terendam Minyak Transformator," Elposys J. Sist. Kelistrikan, vol. 10, no. 3, pp. 142–145, 2023.

[9] R. A. Prasojo et al., "Evaluasi Kinerja Sistem Isolasi Transformator Kertas Kraft Terendam Minyak Mineral Pada Sel Uji Penuaan Termal Dipercepat," Elposys J. Sist. Kelistrikan, vol. 9, no. 3, pp. 87–92, 2023.

[10] CIGRE 323, Ageing of Cellulose in Mineral-Oil Insulated Transformers. 2007.

[11] IEC TS 62332-2, Electrical insulation systems (EIS) : thermal evaluation of combined liquid and solid components. Part 2, Simplified test. 2011.

[12] IEC 60076-1, Power Transformers - Part 1: General, vol. 2011. 2011.

[13] M. Tohari, B. Sukoco, dan M. Haddin, "Analisis Kondisi Transformator Daya

20Kv/150Kv Dengan Metode Uji Dissolved Gas Analysis (Dga) Di Pt.Pjb Pltu Rembang," Konf. Ilm. Mhs. Unissula 4, pp. 337–344, 2020.

[14] M. Ahmad, I. Daris, H. Rahmat, dan S. Suwarno, "Aging Behavior of Mineral Oil, Gas-to-Liquid (GTL), and Natural Ester Liquids in Presence of Cellulosic Materials," 2021 3rd Int. Conf. High Volt. Eng. Power Syst. ICHVEPS 2021, pp. 501–506, 2021.

[15] CIGRE 761, Power Transformers and Reactors. 2019.

[16] S. R. Arsad et al., "Water Content in Transformer Insulation System: A Review on the Detection and Quantification Methods," Energies, vol. 16, no. 4, 2023.

[17] IEEE C57100, IEEE Standard Test Procedure for Thermal Evaluation of Liquid-Immersed Distribution and Power Transformers, vol. 1999, no. January. 2011.

[18] R. Duanaputri, R. A. Prasojo, D. Wiranti, S. S. Wiwaha, D. N. Akbar, dan G. P. C. Handani, "Analysis and Experiments of Insulation Loss of Transformer Kraft Paper Based on Hotspot Variations," Int. J. Electr. Eng. Appl. Sci., vol. 6, no. 1, pp. 29–34, 2023.

[19] Wiley, Transformers Ageing. 2017. [Daring]. Available at: https://www.google.co.id/books/edition/Transformer_Ageing/tkkzDwAAQBAJ?hl=id&gbpv=1&dq=natural+ester+oil&pg=PA377&printsec=frontcover

[20] A. Syakur dan W. Lazuardi, "Penerapan Metode Interpretasi Rasio Roger, Segitiga Duval, Breakdown Test, dan Water Content Test untuk Diagnosis Kelayakan Minyak Transformator," Teknik, vol. 40, pp. 1, hal. 63–68, 2019.

[21] H. D. F. Amaral et al. 2024. "Karakteristik Tegangan tembus Pada Dielektrik Minyak Mineral Dan Minyak Ester Natural." Elposys J. Sist. Kelistrikan, vol. 11, no. 3, pp. 179–183, 2024.

[22] CIGRE WG A2.18, Guide For Life Management Techniques For Power Transformer. 2003

[23] Gasser, Hans Peter, Christoph Krause, Mark Lashbrook, dan Russel Martin. 2011. "Aging of pressboard in different insulating liquids." Proceedings - IEEE International Conference on Dielectric Liquids, 1–5. https://doi.org/10.1109/ICDL.2011.6015450.

[24] Dielectric Properties of Ester alami, Synthetic Ester Midel 7131, and Mineral Oil Diala D (June, 2012). IEEE Transactions on Dielectrics and Electrical Insulation, 19(3), 827-834.

[25] Jayyid, U. L. (2024). Studi Komparasi Minyak Mineral, Sintetik Ester, Dan Natural Ester Sebagai Isolasi Cair Pada Transformator. 23222368.

[26] M. Rafiq et al. 2020. "Sustainable, Renewable and Environmental-Friendly Insulation Systems for High Voltages Applications." Molecules, 25, 3901; doi:10.3390/molecules25173901