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Measurements and performance evaluations of natural ester and mineral oil-immersed identical transformers

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ABSTRACT

The use of natural esters as an insulating liquid has become popular since the early 2000s. Studies in the literature emphasize the superiority of natural esters as compared to mineral oils. In these studies, the prominent properties of natural esters are presented as being environmentally friendly, safe, and delaying the aging of cellulosic insulation material. Although there is no doubt in terms of their characteristics, such as being environmentally and safe, exaggerated comments are made about the delay of aging of the paper material used in the insulation of transformer windings. This is because comparative experimental applications on mineral oil and natural esters are carried out under artificial and equal conditions provided in the laboratory environment. Whereas, performing these experiments on identical transformers will give more realistic results. In this study, two identical transformers were designed and equipped with precision fiber optic temperature sensors. Temperature differences that vary depending on the load between high voltage and low voltage windings were measured with a high degree of accuracy for both identical transformers. Besides these measurements, physical and chemical changes were analyzed on samples taken from insulation liquids. It was observed that the physical and chemical properties of the insulation liquids directly affect the operating performance of the transformers. Thanks to the differences in viscosity of insulating liquids, the heat dissipation due to losses in the windings were different for both transformers. Both heat distribution and temperature differences in the windings varied depending on the loading factors. Considering all these factors together, comprehensively evaluations were made on the aging rate of cellulosic insulation and the service life of the transformers.

1. Introduction

Transformers are one of the critical components of the power transmission and distribution system in terms of function and effect area. Although there has been no change in the operating logic of transformers for many years, there have been diversifications in terms of materials, protection, and monitoring technologies [1–4]. Solid and liquid insulating materials used in transformers have also been developed and diversified to ensure a longer and safer operation [5–8]. Three different prominent insulating liquids that can be mentioned to date are mineral oils, silicone oils, and esters [4,8].

Mineral oils, which are widely used because of their low cost in terms of providing electrical insulation in the industry, have some disadvantages such as limited biodegradability and low fire point [9–11]. Although silicone oils that emerged in the following years are prominent in terms of their properties such as high flash/fire point and thermal stability, they have high viscosity at high temperatures, and also the very low biodegradability is still a drawback [12]. Other options are synthetic esters and natural esters. Esters are environmentally friendly insulation liquids in addition to their high performance in operation [13]. They have higher oxidation and thermal stability as well as hygroscopic features. However, since synthetic esters are derived by chemical processes, they are more expensive than natural esters, which are derived from plants, and therefore, their usage rate is more limited. Many transformer manufacturers have designed and introduced natural ester immersed transformers due to size and weight limitations. There are many positive statements in the literature regarding the use of natural ester instead of mineral oil in transformers. In many studies, there is the illusion that all of these positive statements occur at the same time [14–16]. However, manufacturers realize the design according to the

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customer's demand by considering the benefits regarding operation performances that are important for them. These benefits can be better understood with a distinction, as shown in Fig. 1. Using natural esters instead of mineral esters allows the load capacity of the transformers to be increased. This situation increases the operating temperature of the transformer considerably. But, due to the chemical advantage of the natural ester, there is no reduction in the service life of the transformer, compared to the mineral oil-filled transformer [17,18]. In practice, it can be seen that the loading capacity of mineral oil-filled transformers currently in use is increased by filling the natural ester. Another option is that the natural ester filled transformer can be designed to be smaller in size than the mineral oil-filled transformer to transfer the same power [4,18]. This option is especially relevant for special applications with space shortages such as wind turbines, energy storage areas. The last option is to prolong the service life of the transformer. It is known that the identical transformer filled with natural ester instead of mineral oil will provide a longer service life for the same loading conditions [4,19].

The critical parameter to be monitored is the temperature changes due to load variations. The temperature is directly related to the operating performance of the transformer and provides clear information about the heat transfer capabilities of insulating liquids [20,21]. Therefore, it is important to measure the temperature quickly and accurately. In practice, temperature measurement is done using three different sensor types as RTD/Pt100, thermocouple, and fiber-optic technology [22,23]. In recent years, fiber optic sensor systems have been preferred in experimental applications and especially in critical units, because of their ease of installation in narrow locations and their ability to measure accuracy [24].

Especially the accurate measurement of the hot-spot temperature is very important for calculating the loss of life and estimating the remaining service life of the transformer correctly. Thermal characteristics of different insulating liquid immersed transformers will change due to their different physical and chemical properties such as viscosity values, thermal capacities, heat transfer coefficients, etc. [5,13,16,23,25]. This will certainly reveal different results for different liquid insulation-immersed identical transformers, in the loss of life calculations made by the Arrhenius equation basis. However, accelerated aging studies in the literature are not performed on real transformers due to cost constraints. This situation may cause some misunderstandings or interpretations. In the literature applications, paper samples are placed in the same steel vessels containing different liquid insulations. Then, aging experiments are carried out in the test oven, where the same artificial thermal conditions are prepared [25–27]. Whereas, different temperature values will be measured in the windings of identical transformers with different insulating liquids depending on the same loading conditions. This reveals that the results obtained in conventional accelerated aging experiments should be analyzed together with the results obtained from thermal tests on transformers.

This study aims to reveal the comparative operating performance of two different insulating liquid immersed identical transformers. The study has three critical originalities: (i) to compare the heat transfer performance of insulating liquids via high-precision fiber-optic temperature sensors installed in both the HV and LV windings. (ii) to analyze the changes in physical, chemical, and thermal performances in the experimental process. (iii) to propose a relative curve/function for making solid insulation (paper) aging calculations considering the heat transfer ability depending on the type of insulation liquid for the identical transformers. The stages of design, measurement, and results are discussed in the following headings, respectively.

2. Prototype transformer design and measurement system

In this study, two identical single-phase transformers were designed, as shown in Fig. 2. The only difference between these transformers was the insulating liquids used. Since this is a comparison study, the label values of the mineral oil-immersed transformer were taken as reference, and it was given in Table 1 for both transformers. In both transformers, the low voltage windings were short-circuited and supplied with a short-circuit voltage through the high-voltage windings by the converter.

2.1. The temperature measurement system

The use of fiber technologies has increased as the cost gradually reduces to reasonable levels, and the measurement can be taken directly from the hottest point in transformers. Besides, optical fiber probes are produced from a dielectric material and can be placed in any conductive or insulating locations. In this study, fiber-optic probes (Neoptix – Φ 400 μm sensitive area) were used to measure temperature in windings (HV and LV locations) and oil more accurately with low transmission loss. The aim was not only to monitor the hot-spot temperature but also to obtain data about heat transfer from different points. In case of failure of other fiber cables, spare fiber ends were also placed in the system. The main components of the temperature measurement system are fiber optic sensors, external extension cables, fiber-optic sensor transducer, and computer interface software.

2.2. The dielectric liquid selection

There are two main reasons for the use of liquid insulators in transformers. The first is to strengthen further the electrical insulation between the windings themselves and other metallic parts. They interact with the cellulosic material and also improve their insulating properties. The second is to quickly transfer the heat generated in the windings and core through the conduction and convection to the outside of the tank. These properties may vary depending on the insulation liquids used. Within the scope of the study, mineral oil (Nynas Lyra X), which is still widely used due to its low cost, and natural ester (Cooper FR3), whose

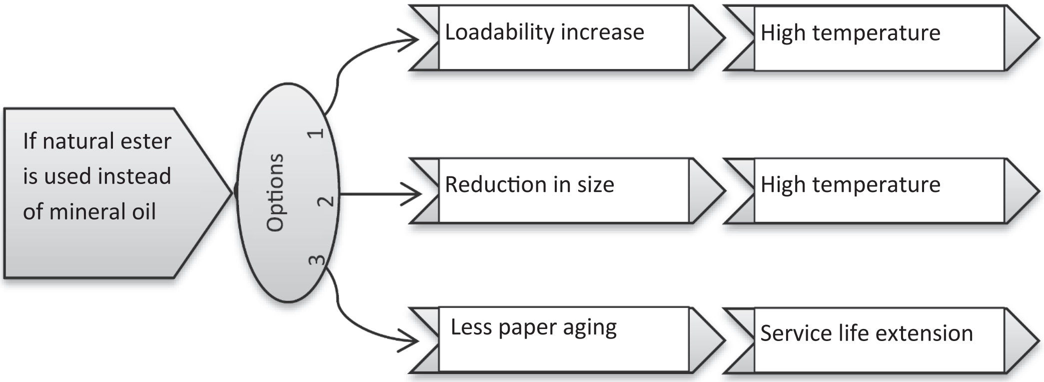

Fig. 1. Operating benefit options of using natural ester as the insulating liquid instead of mineral oil.

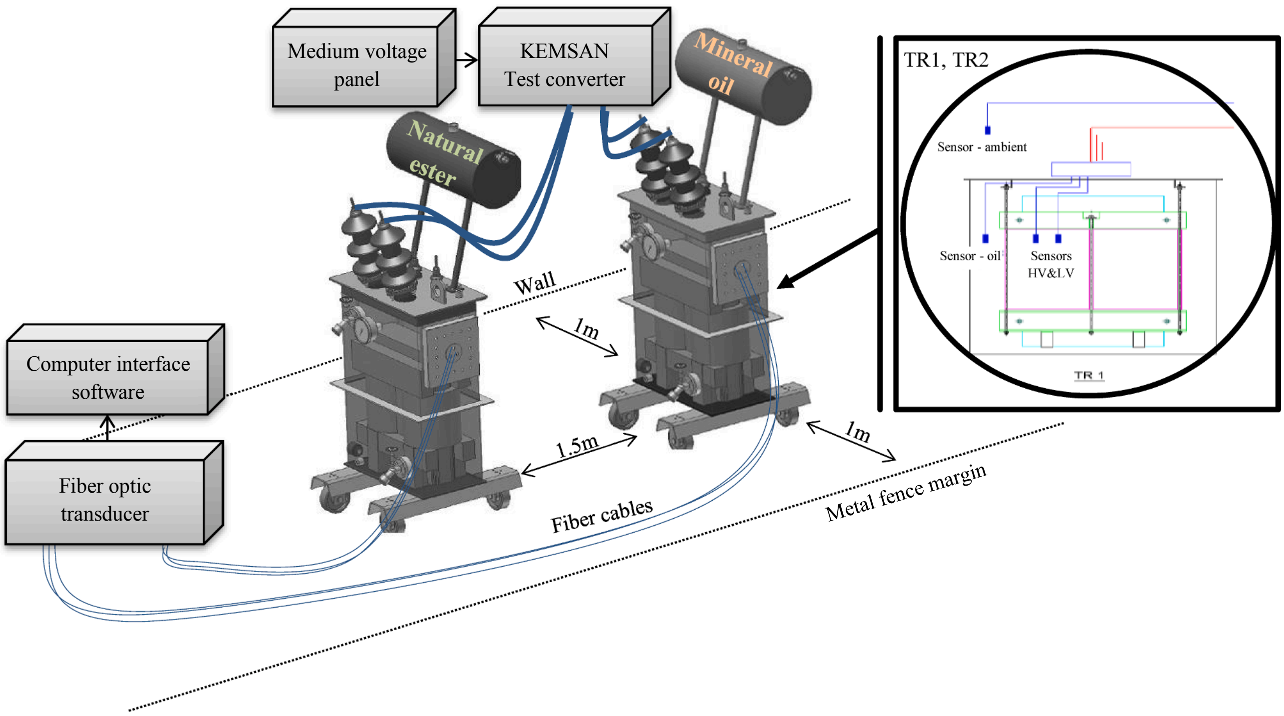

Fig. 2. Identical transformer and temperature measurement system design.

Table 1
Identical transformer specifications.

Single Phases	TR1	TR2
S [kVA]	50	50
U [kV] ; f [Hz]	20/0.4 ; 50	20/0.4 ; 50
Uk %	5	5
Tank	Gas padded hermetic/Flat walled tank	Gas padded hermetic/Flat walled tank
Liquid insulations	Mineral oil (Nynas Lyra X)	Natural ester (FR3)

usage rate is increasing day by day due to its environmental/safety properties, have been preferred. Fig. 3(a) and (b) are frequently encountered in the literature and experimentally confirmed in many studies for mineral oil and natural ester [28–30]. They indicate the temperature-dependent aging change of the thermally-upgraded paper in MO and NE. In Fig. 3(a), the degree of polymerization (DP) of thermally reinforced papers, which are kept at a constant temperature of 170 °C for 4000 h, is given for both insulating liquids. DP is an important indicator that gives information about mechanical strength and, therefore the life of the paper [28]. It can be seen from this graph that the natural ester has a slower aging curve. In Fig. 3(a), considering the ratio of time values corresponding to each DP value, Fig. 3(b) can be obtained for different temperature values. Fig. 3(b) per-unit values are drawn regarding MO, and it shows the life-changing of the papers in MO and NE for each temperature value. The known permissible hot-spot temperature value for mineral oil-immersed transformers in the standards is 110 °C, and in this case, the unit life of the insulation paper is considered as 1pu, as shown in Fig. 3(b). For the same temperature value, the per-unit life of the paper increases approximately eight times in the natural ester compared to the mineral oil. In similar studies, this increasing rate is stated to be between 5 and 8 times for different natural esters and different temperature values. However, these experimental results about natural esters in the literature do not provide clear information about the service life of transformers. Because these experiments are carried out in the same test environment and at the same temperature values for different insulating liquids. However, in a transformer in operation, the volume of the isolation liquid is large and there is freedom of circulation

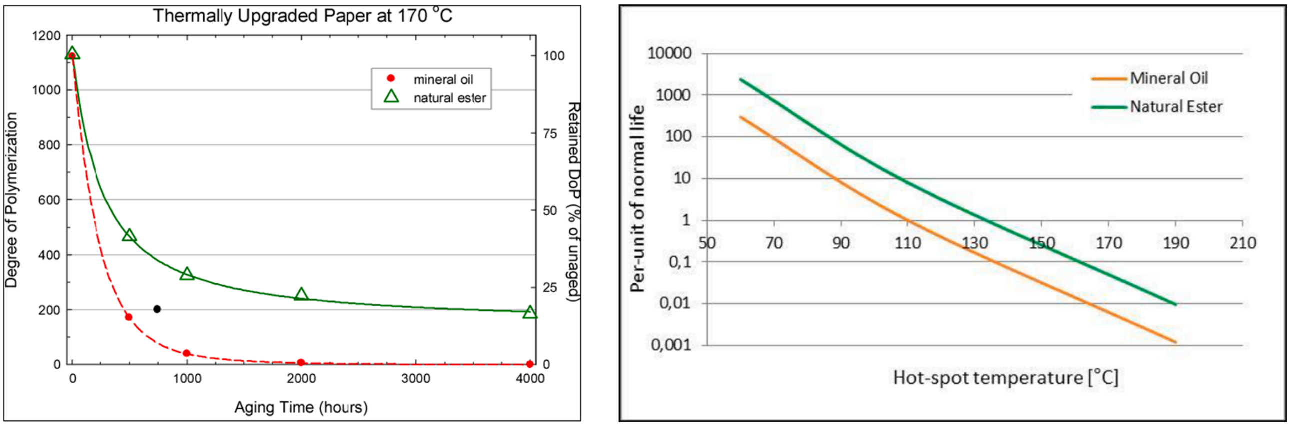

Fig. 3. (a) Comparative per-unit life curves and (b) degree of polymerization of paper for MO and NE insulation liquids [28–30].

between the windings and channels belonging to the tank. Since the physical and chemical properties of insulating liquids will be effective in circulation, different outcomes will arise in transformers using these insulating liquids than the results obtained in classical aging experiments.

3. Performance evaluations

3.1. Thermal performances

The short-circuit current was first set to a level below the rated current. And after the transformer reached the steady-state condition, the temperature values at different locations were measured by fiber optic sensors, as shown in Fig. 4. Secondly, the same process was repeated by upgrading the short circuit current at a constant value above the rated current. Measurements were performed simultaneously for both identical transformers. Unlike literature, the temperature values of HV and LV windings and the differences between them were achieved to compare the thermal performances of the NE and MO immersed-identical transformers.

As known, if there is difficulty in transferring heat, the temperature tends to increase. This is directly related to the thermal resistance of the material. In the equations proposed in standard approaches for transformers, thermal resistances are taken as constant even in liquid insulations. However, the thermal resistance of the liquid insulating material is influenced by physical changes, in particular, viscosity (μ). Instead of the standard approach, a dynamic thermal model based on the temperature-viscosity relationship proposed by D. Susa may give more realistic results, as shown in Fig. 5 and related equations [31,32]. Where: q is the heat source (W), c is the specific heat capacity (Wh/kg°C), ρ is the density of the media ($\mathrm{kg/m^3}$), T is the thermal resistance (°C/W), and it can be expressed as a function depending on the viscosity$T(\mu)$,n is the nonlinear parameter, θ is the temperature (°C), and it is achieved by $\theta = Tq^n$, the thermal capacitance is calculated by $C = c\rho$ (W.min/°C).

$$q_{tot} = C_{tot} \times \frac{d\theta}{dt} + \left(\frac{\theta - \theta_{amb}}{T_{tot}}\right)^{1/n} \tag{1}$$

$$C_{tot} = C_{eq} + C_{liquid} \tag{2}$$

$$T_{tot} = T_{eq} + T_{liquid} \tag{3}$$

$$T_{tot} \cong T_{liquid} = T(\mu) \tag{4}$$

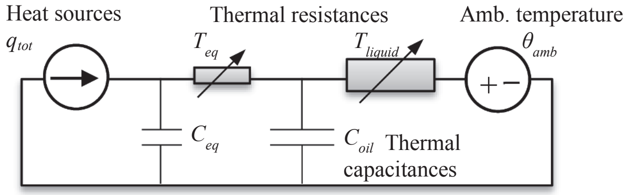

Fig. 5. Heat flow and simplified thermal-electrical analogy.

Fig. 4. The actual measurement and test system.

In Susa's model, other physical variables except for viscosity, are considered as constant. However, the thermal capacity and thermal conductivity parameters are not constant, and these physical parameters also affect the thermal time constant of the insulating liquids and the temperature values at different locations. In other words, both transient and steady-state temperatures are directly affected by these physical parameters. Also, this situation may lead to deviations between the data obtained from the model and the actual measurements. Therefore, the most accurate results can be achieved with high-precision optical fiber sensors. Temperature measurements in the designated regions were carried out after the system became thermally steady-state, and then the temperature differences were obtained. The comparative experimental measurement results are shown in Fig. 6. The temperature differences between the HV and LV windings for both transformers show the heat transfer-ability of the liquid insulations. Accordingly, the heat transfer performance of natural ester is worse than that of mineral oil. The differences between LV and HV winding temperatures at both test currents are larger in natural ester immersed transformer. As the load factor increases, in the natural ester-immersed transformer, the temperature difference between LV and HV winding becomes more than the mineral oil-immersed identical transformer.

3.2. Physical and chemical performances

According to the results of the test performed on identical transformers, natural esters have more difficulty in removing the heat generated in the windings than mineral oils. This is mainly due to the viscosity differences between the insulating liquids. Typically, as the temperature increases in each liquid insulation, the viscosity value decreases exponentially. However, when the comparative viscosity changes depending on the temperature are examined for both insulating liquids, a nearly linear curve is obtained, as shown in Fig. 7. This indicates that the response characteristics of the MO and NE insulation liquids to the temperature change are the same. Insulating liquid with low viscosity is often more advantageous in terms of cooling performance. Because this facilitates the transfer of heat through convection. Therefore, MO that can circulate more easily in the transformer tank is better in heat transfer than natural esters.

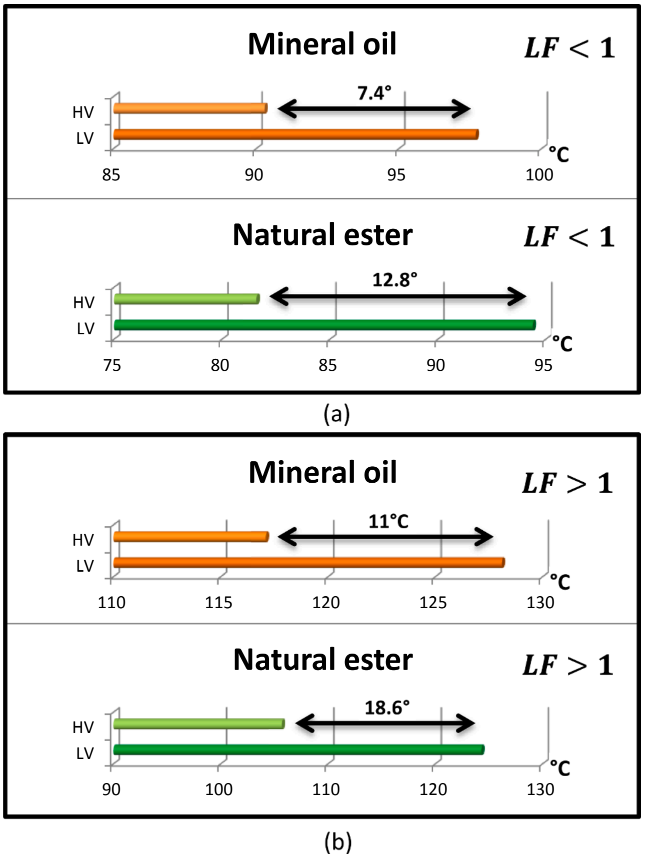

Fig. 6. The temperature difference between LV and HV windings (a) for LF < 1 (b) for LF > 1.

During the experimental schedule, which lasted several weeks, different physical and chemical tests were applied to the samples taken from transformers. One of these was the water content test. The water saturation level of natural ester was quite high in comparison with that of mineral oil. Therefore, the water level absorbed from the insulation paper was observed to be high for all weeks, as shown in Fig. 8. This is a positive feature for the natural ester; because the reduction of the water content on the cellulosic insulation material means that the service life of the transformer is extended. Water molecules in liquid and solid isolation are affected by loading conditions. Depending on the loading, the water passes from the paper on the surface of the heated windings to the insulating liquid or passes from the insulation liquid into the paper due to the decrease of the winding temperature. In this process, the cellulosic insulation material is subjected to some physical and chemical disrupting effects (oxidation, acidity, hydration-dehydration, etc.) in which water acts directly or indirectly as an accelerator. Increasing water content in insulating liquids over time accelerates the process of paper degradation caused by water, exponentially reducing the service life of the transformer. It is stated in the literature that mineral oils are affected much more negatively than the natural esters by the increase in the amount of water [33,34].

The acceleration rise of the total dissolved gases in oil-immersed transformers is important for possible fault monitoring. Total dissolved gases were measured on samples taken from both transformers and presented, as shown in Fig. 9. As seen in Fig. 9, the total gas increase in mineral oil is higher. It is not possible to make any comments only by considering this figure since the chemical structure of the insulating liquids used is different. The important thing is the proportion and accelerations of the increase of the gases occurring in the liquid insulation used in each transformer. For both transformers, gas production rates are nearly parallel to each other, and it is seen that gas rates have an increasing trend over time.

One of the most important tests that provide information about the condition of the insulating liquid is the breakdown voltage test. Considering the average values of the measurements made for breakdown voltage tests, relatively natural ester was found to be better, as shown in Fig. 10. It is known that the breakdown voltage test results are affected by many physical and chemical parameters of the liquid insulation to be tested [34,35]. Especially water content and temperature parameters in the isolation liquid are essential in this respect. When Figs. 8 and 10 are examined together considering weekly changes, it can

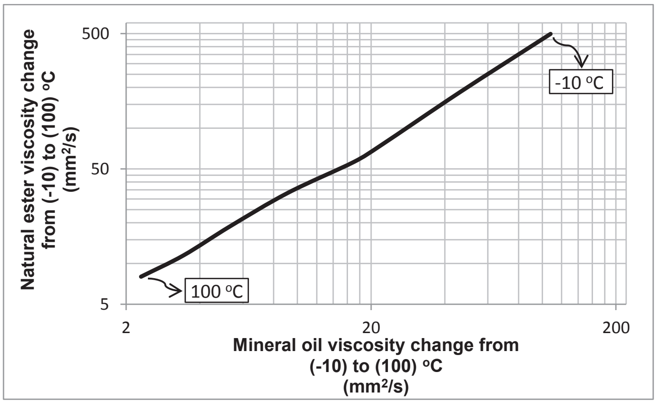

Fig. 7. The viscosity changes for MO and NE insulation liquids.

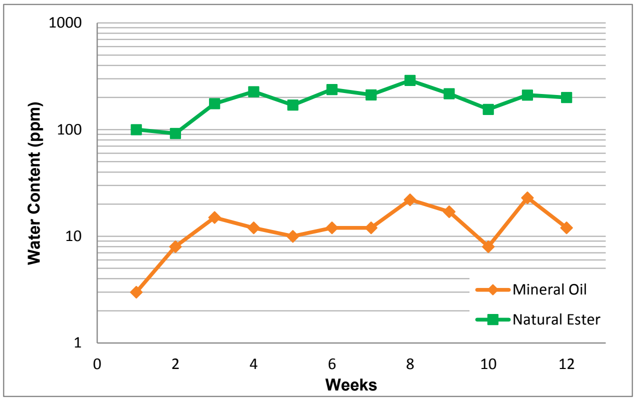

Fig. 8. The comparative water content changes for MO and NE insulation liquids.

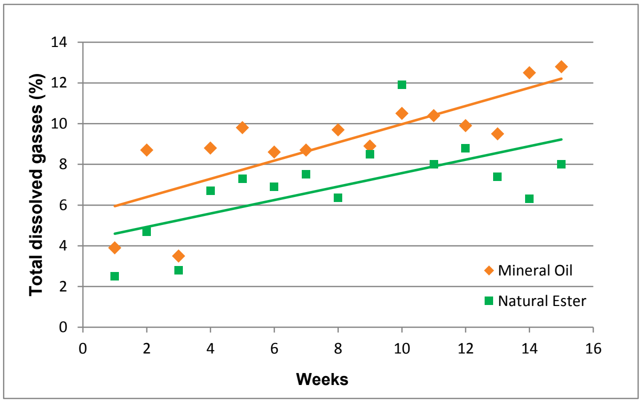

Fig. 9. Total dissolved gas rising for MO and NE insulation liquids.

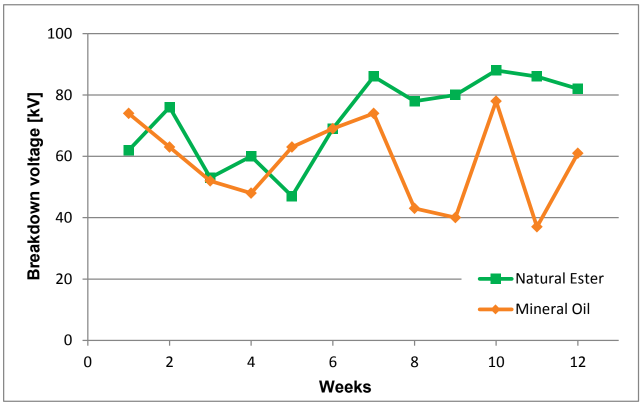

Fig. 10. Breakdown voltages for MO and NE insulation liquids.

be seen that there is a negative correlation between the water content in oil and the breakdown voltage. The dielectric distortion voltage of mineral oils is more affected by the amount of water content it contains than the natural ester.

The measurements shown in Table 2 were performed on the insulation liquids before and after the experimental processes. Each of the parameters in the table gives information about the quality of the oil. Since the experimental process was completed at levels close to the rated load in approximately four months, no significant physical and chemical differences were observed in the isolating liquid (for before and after) samples taken from both transformers. However, it is possible to understand that there is also a slight deterioration in both insulating liquids in terms of all their physical and chemical properties. As seen in the table, the dielectric dissipation factor (DF) has higher values in natural esters than mineral oils. Also, the rate of change over time is higher than that of mineral oils. The color number is an old and reliable technique to determine the aging levels of the insulating liquids. However, since no significant aging occurred in the isolation fluids in this application, the color number scale difference was not detected. The Interfacial tension (IF) of natural esters is lower compared to mineral oils. However, the IF test, which gives healthy results in determining the quality of mineral oils, may not be used in the same precision due to the high hydrophilic nature of natural esters [36].

3.3. Service life performances

The service life of the transformer depends on many factors such as load conditions, climatic conditions, external/internal faults, design flaws, and operator errors. Many of these factors can be monitored and controlled by security/safety equipment. The effect of some factors is reduced by adequate protection. However, there is one factor that cannot be eliminated, which is the heat produced in the windings. Therefore, the standards define the normal service life of the power transformers depending on the temperature parameter. The normal life expectancy of distribution and power transformer is 20.55 years at 110 °C hot-spot temperature in related standards. In other words, the cellulosic material used to insulate the windings during this period will complete its functional life. The relationship among time, temperature, and loss of life can be expressed by Dakin's modified equation based on Arrhenius Reaction Rate Theory;

$$L = Ae^{B/\theta} \tag{5}$$

where: L is the per-unit life that can be defined as time slots, A is the derived constant based on the normal operating temperature (110 °C) of the insulating material, B is the aging rate constant, and θ is the temperature ($^{\circ}$K). If it is assumed that the temperature parameter in this equation will change over time depending on the load;

$$F_{AA} = e^{\left[\frac{15000}{383} - \frac{15000}{\theta_H + 273}\right]} (pu) \tag{6}$$

where: F_{AA} is the aging acceleration factor, θ_H is the hot-spot temperature (°C), the aging rate constant B = 15000 is taken according to the standard IEEE-C57.91-2011. The percent life loss *%LoL* can be defined

Table 2
The characteristics of insulating liquids before and after the experimental processes.

Characteristics	Test Methods	Units	Mineral oil		Natural ester	
			Before running	After running	Before running	After running
			Measured Values	Measured Values	Measured Values	Measured Values
Dielectric DF at 90 °C	IEC 60247	Numerical	0.00401	0.00712	0.03105	0.03337
Color Number	ISO 2049	–	0.5	0.5	0.5	0.5
Acidity	IEC 62021-1	mgKOH/g oil	0.0009	0.0093	0.0144	0.0227
Interfacial Tension at 25 °C	ISO 6295	mN/m	35.4	34.1	25	24.4

for a certain period in Eq. (7);

$$\%LoL = 100 \times \frac{1}{T}\int_{0}^{T} F_{AA}dt \tag{7}$$

Following these equations, the service life performance of both transformers can be evaluated. The hot-spot temperatures of both transformers were different from each other because the insulation liquids used in the transformers were different. Typically, when the transformers are not in operation, the temperature difference is 0°K at the hot spot locations for both transformers. As the load factor of the transformers increases, the difference between the hot-spot temperatures increases. In that case, a generalizable curve can be drawn for identical transformers with different insulating oils, as shown in Fig. 11. This curve gives relative information $\gamma = F_{AA}(MO)/F_{AA}(NE)$ about the aging accelerations for identical transformers when natural ester and mineral oil are used.

When there is no temperature difference, the relative aging acceleration ratio is achieved as $\gamma \cong 1/8$, theoretically, and this value may even exceed “1” when the temperature difference increases, as shown in Fig. 11. However, even under overload conditions of identical transformers, the hot-spot temperature difference does not exceed 20 °C. Therefore, the relative aging acceleration ratio will be $\gamma < 1$ for the different liquid-immersed identical transformers. This means that in any case, the use of natural ester as the insulating liquid is more advantageous in terms of slow aging of the paper.

4. Conclusion

There are many experimental studies on insulation liquids in the literature. However, comparative analyses of insulation liquids in identical transformers are not available. In this study, two identical transformers with different insulating liquids were designed and equipped with a precision fiber optic cable measurement system. In this context, natural esters, which have been increasingly used as insulating liquids, and mineral oils, which are already widely used, were preferred. To determine the heat dissipation ability of insulation liquids, temperature differences were determined by fiber optic sensors placed in HV and LV windings. Also, physical and chemical changes of liquid samples taken from transformers every week were observed. The aging accelerations of the cellulosic insulation material used in transformers were analyzed according to the type of insulation liquid.

There is a well-known reality in the transformer industry: As the power values increase, the ratio of the insulation liquid cost to the transformer cost decreases. Therefore, the high costly insulation liquids such as natural ester to be used in power transformers should not be considered as a disadvantage, and instead, the benefits must be taken into consideration. In general, the use of natural ester for an identical transformer extends the service life of the transformer depending on the load conditions. However, exaggerated service life extension comments regarding the natural ester in the literature do not fully reflect the truth. Especially at low load factors, the use of natural esters in transformers provides a longer service life than that in the use of mineral oil. However, the increase rate in service life extension decreases as the load factor increases. In light of all the experimental studies, this study provides insights to manufacturers in terms of how performance changes when different insulating liquids are preferred, especially for identical transformers. Operators can estimate the service life of the transformer more realistically, taking into account the loading conditions and liquid insulation types. When the natural ester is preferred in the retrofilling process, the change in the operating performance of the transformer can be analyzed more accurately.

CRediT authorship contribution statement

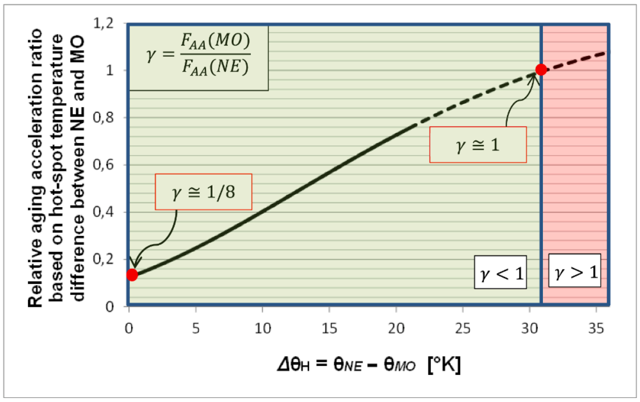

Fig. 11. Relative aging acceleration ratio based on the hot-spot temperature difference between NE and MO immersed identical transformers.

Yusuf Cilliyuz: Conceptualization, Validation, Formal analysis, Writing - review & editing. **Yunus Bicen:** Conceptualization, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Faruk Aras:** Methodology, Investigation, Writing - review & editing, Supervision. **Guzide Aydugan:** Conceptualization, Methodology, Validation, Resources, Data curation, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Kunicki Michał, et al. Modeling of the winding hot-spot temperature in power transformers: Case study of the low-loaded fleet. Energies 2019;12(18):3561.

[2] Biçen Yunus, Aras Faruk, Kirkici Hulya. Lifetime estimation and monitoring of power transformer considering annual load factors. IEEE Trans Dielectr Electr Insul 2014;21(3):1360–7.

[3] Lu Ping, et al. Real-time monitoring of temperature rises of energized transformer cores with distributed optical fiber sensors. IEEE Trans Power Delivery 2019.

[4] Asano Roberto, Page Stephane A. Reducing environmental impact and improving safety and performance of power transformers with natural ester dielectric insulating fluids. IEEE Trans Ind Appl 2013;50(1):134–41.

[5] Tokunaga Junko, et al. Comparative studies on the aging of thermally upgraded paper insulation in palm fatty acid ester, mineral oil, and natural ester. IEEE Trans Dielectr Electr Insul 2016;23(1):258–65.

[6] Fernández Inmaculada, et al. Thermal degradation assessment of Kraft paper in power transformers insulated with natural esters. Appl Therm Eng 2016;104:129–38.

[7] Prevost Thomas A, Oommen TV. Cellulose insulation in oil-filled power transformers: Part I-history and development. IEEE Electr Insul Mag 2006;22(1):28–35.

[8] Kweon Dongjin, et al. Hot spot temperature for 154 kV transformer filled with mineral oil and natural ester fluid. IEEE Trans Dielectr Electr Insul 2012;19(3):1013–20.

[9] Aljohani O, Abu-Siada Ahmed. Application of digital image processing to detect transformer bushing faults and oil degradation using FRA polar plot signature. IEEE Trans Dielectr Electr Insul 2017;24(1):428–36.

[10] Munajad Abi, Subroto Cahyo. Fourier transform infrared (FTIR) spectroscopy analysis of transformer paper in mineral oil-paper composite insulation under accelerated thermal aging. Energies 2018;11(2):364.

[11] Wilhelm HM, et al. Aging markers for in-service natural ester-based insulating fluids. IEEE Trans Dielectr Electr Insul 2011;18(3):714–9.

[12] Pukel Georg-Johannes, et al. Power transformers with environmentally friendly and low flammability ester liquids. e & i Elektrotechnik und Informationstechnik 2013:1–6.

[13] Martins M Augusta, Gomes A. Comparative study of the thermal degradation of synthetic and natural esters and mineral oil: effect of oil type in the thermal degradation of insulating kraft paper. IEEE Electr Insul Mag 2012;2(28):22–8.
[14] Perrier Christophe, Coulibaly Mamadou-Lamine, Marugan Marielle. Efficiency of ageing markers for different transformer insulation systems. 2016 IEEE International Conference on Dielectrics (ICD) 2016;vol. 2.
[15] Rycroft Mike. Vegetable oil as insulating fluid for transformers. Energize 2014: 37–40.
[16] Liao Ruijin, et al. A comparative study of thermal aging of transformer insulation paper impregnated in natural ester and in mineral oil. Eur Trans Electr Power 2010;20(4):518–33.
[17] Mehta Dhruvesh M, et al. A review on critical evaluation of natural ester vis-a-vis mineral oil insulating liquid for use in transformers: Part 1. IEEE Trans Dielectr Electr Insul 2016;23(2):873–80.
[18] Garcia Belen, et al. Studying the loss of life of natural-ester-filled transformer insulation: impact of moisture on the aging rate of paper. IEEE Electr Insul Mag 2017;33(1):15–23.
[19] Raymon A, et al. Enhancing the critical characteristics of natural esters with antioxidants for power transformer applications. IEEE Trans Dielectr Electr Insul 2013;20(3):899–912.
[20] Rosillo Miguel E, Herrera Carlos A, Jaramillo Guillermo. Advanced thermal modeling and experimental performance of oil distribution transformers. IEEE Trans Power Deliv 2012;27(4):1710–7.
[21] Moore Steven P, et al. Cold start of a 240-MVA generator step-up transformer filled with natural ester fluid. IEEE Trans Power Deliv 2014;30(1):256–63.
[22] Betta Giovanni, Pietrosanto Antonio, Scaglione Antonio. An enhanced fiber-optic temperature sensor system for power transformer monitoring. IEEE Trans Instrum Meas 2001;50(5):1138–43.
[23] Perkasa Caesar Y, et al. A comparison of the formation of bubbles and water droplets in vegetable and mineral oil impregnated transformer paper. IEEE Trans Dielectr Electr Insul 2014;21(5):2111–8.
[24] Arabul Ahmet Yigit, Arabul Fatma Keskin, Senol Ibrahim. Experimental thermal investigation of an ONAN distribution transformer by fiber optic sensors. Electr Power Syst Res 2018;155:320–30.
[25] Bandara Kapila, et al. Understanding the ageing aspects of natural ester based insulation liquid in power transformer. IEEE Trans Dielectr Electr Insul 2016;23(1): 246–57.
[26] Ortiz A, et al. The aging impact on the cooling capacity of a natural ester used in power transformers. Appl Therm Eng 2018;144:797–803.
[27] Yang Lijun, et al. Influence of vegetable oil on the thermal aging of transformer paper and its mechanism. IEEE Trans Dielectr Electr Insul 2011;18(3):692–700.
[28] McShane C Patrick, et al. Aging of paper insulation in natural ester dielectric fluid. 2001 IEEE/PES Transmission and Distribution Conference and Exposition. Developing New Perspectives (Cat. No. 01CH37294) 2001;vol. 2..
[29] Rapp Kevin J, Luksich J. Review of Kraft paper/natural ester fluid insulation system aging. 2011 IEEE International Conference on Dielectric Liquids. IEEE; 2011.
[30] McShane C Patrick, et al. Natural ester dielectric fluid development. IEEE/PES Transmission and Distribution Conference and Exposition. 2006.
[31] Susa Dejan, Lehtonen Matti, Nordman Hasse. Dynamic thermal modelling of power transformers. IEEE Trans Power Delivery 2005;20(1):197–204.
[32] Susa Dejan, Lehtonen Matti. Dynamic thermal modeling of power transformers: further Development-part I. IEEE Trans Power Delivery 2006;21(4):1961–70.
[33] Martin D, Wang ZD. A comparative study of the impact of moisture on the dielectric capability of esters for large power transformers. 2006 IEEE Conference on Electrical Insulation and Dielectric Phenomena. IEEE; 2006.
[34] Xiang Junru, Li Jian, Zhang Zhaotao. Influence of water content on the aging performance of natural ester-paper insulation. 2012 International Conference on High Voltage Engineering and Application. 2012.
[35] Rafiq M, et al. Use of vegetable oils as transformer oils–a review. Renew Sustain Energy Rev 2015;52:308–24.
[36] Lewand L. Laboratory testing of natural ester dielectric liquids. Neta World 2004: 1–4.