Comparison of the Dielectric Properties of Soy-Based Natural Ester Oil and Mineral Oil Subjected to Accelerated Thermal Ageing

F. I. Asrin[1,2], S.A. Ghani[1*], I. S. Chairul[1], N. H. Rahim[1], N. A. Muhamad[3]
[1]Faculty of Electrical Technology and Engineering (FTKE), Universiti Teknikal Malaysia Melaka (UTeM), Melaka, Malaysia.
[2]TNB Labs Sdn. Bhd., Kajang, Malaysia.
[3]Faculty of Engineering, Universiti Teknologi Brunei, Jalan Tungku Link Gadong, BE1410 Brunei Darussalam
*corresponding author's email: sharinag@utem.edu.my

Abstract – Even though natural ester oils are recognised as sustainable alternative dielectric liquids to mineral oil in oil-immersed power transformers, their long-term dielectric properties under realistic dielectric liquid–solid insulation–metal interactions remain poorly understood. Currently, there are no well-established dielectric property degradation models, posing uncertainty in the long-term insulation reliability of oil-immersed power transformers. In this study, accelerated thermal ageing experiment was conducted on soy-based natural ester oil (FR3 fluid) and conventional mineral oil (MO) with solid insulations (kraft paper and pressboard, thermally upgraded paper (TUP) and pressboard) and metal catalysts (copper, iron, zinc, and aluminium catalysts) in sealed glass bottles to determine their dielectric properties in response to thermal ageing. Initially, these samples were pre-treated and tested in accordance with the IEC 60156 and IEC 60247 standards, where the samples were aged at 130 °C for 0, 250, 500, 750, 1000, 1250 and 1500 h. Periodic measurements were then conducted to determine the key diagnostic dielectric properties, namely, AC breakdown voltage (AC BDV), dissipation factor (tan δ), and volume resistivity. Despite the low dissipation factor and high volume resistivity, the mineral oil-based insulation systems demonstrated a significant decrease in AC BDV, suggesting low moisture tolerance. In contrast, the FR3-based insulation systems showed an improved and stable AC BDV despite their low volume resistivity and high dissipation factor, which aligned with the polar chemistry and better moisture scavenging of natural ester oils. Based on the results of the accelerated thermal ageing tests, the dielectric performance was most pronounced for the FR3–TUP system. The results showed that using FR3 fluid could improve the sustainability and long-term dielectric reliability of the transformer insulation. However, the results also indicated that the dissipation factor and volume resistivity should be interpreted by considering the fluid chemistry and moisture dynamics.

***Keywords**:* AC breakdown voltage; Accelerated thermal ageing; Dissipation factor; FR3 fluid; Insulation reliability; Mineral oil; Oil-immersed power transformer; Volume resistivity

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I. Introduction

The most common dielectric liquid used in oil-immersed power transformers is mineral oil (MO), which is derived from crude petroleum. Dielectric liquids are used in a variety of power equipment, such as tap changers, transformers, bushings, and circuit breakers. These dielectric liquids function to dissipate heat and quench arc discharge and serve as an electric insulator. To prevent excessive temperature rise, which can hasten ageing and cause premature failure of the insulation system, it is essential to provide effective heat dissipation, particularly in equipment with high loads. More importantly, dielectric liquids serve as practical diagnostic media to evaluate the condition of power equipment over the course of their useful life. The dielectric integrity and operational dependability of electrical insulation systems are heavily dependent on the dielectric liquid. Early warning signs of mechanical or electrical failure can be found by monitoring the dielectric properties of dielectric liquids. In oil-immersed power transformers, dielectric liquid samples can be collected during transformer operation without disrupting service, enabling continuous condition monitoring [1].

The growing global emphasis on sustainable energy systems has led to the adoption of environmentally friendly dielectric liquids such as natural ester oils. Despite their renowned biodegradability and fire resistance [2], little is known on the long-term performance and thermal ageing behaviour of soy-based ester oils used as dielectric liquids in oil-immersed power transformers [3]. Previous studies on natural ester oils are focused on either short-term thermal ageing or on the dielectric properties of natural ester oils compared with those of MOs, often overlooking interactions with other solid insulations such as kraft paper, thermally upgraded paper (TUP), and pressboard. In addition, some studies are only focused on conventional kraft paper. This solid insulation directly affects the lifetime of oil-immersed power transformers transformer as it is irreplaceable once the transformer unit is constructed [4]. Previous studies on natural ester oils are focused on short-term thermal ageing. For example, Cristina Méndez et al. [5] conducted thermal ageing for only 1008 h at 150 °C. These studies primarily focus on simplified systems and do not fully consider the combined interactions between the dielectric liquid, solid insulation, and metallic components present in practical transformer environments.

In addition to dielectric liquid, solid insulations are present in oil-immersed power transformers in the form of kraft paper, TUP, and pressboard. Solid insulations are typically made of cellulose, which comes from natural plant sources and has been used in electrical insulation applications for over a century. Solid insulations are often made from chemically treated wood pulp, which is available in a variety of thicknesses to meet various insulation needs. Wood-pulp-based paper provides adequate electrical and mechanical qualities for transformer insulation and are easily moulded or wrapped around the copper windings, enabling flexible dimensional modifications [6].

Although natural ester oils have been widely investigated as potential dielectric liquid alternatives to MOs, there are limited studies that have systematically examined the dielectric properties of dielectric liquid–solid insulation–metal catalyst systems in response to prolonged thermal ageing. In particular, the interactions between natural ester oil, solid insulations, and metal catalysts under prolonged thermal stress remains insufficiently understood. Therefore, the aim of this study was to evaluate and compare the long-term dielectric properties of dielectric liquid–solid insulation–metal catalyst systems subjected to prolonged thermal ageing to simulate the environment in an actual oil-immersed power transformer. This study focused on three key dielectric properties (AC breakdown voltage (AC BDV), dissipation factor (tan δ), and volume resistivity), which were measured periodically to assess the behaviour of the dielectric liquids.

II. Methodology

A. Design of the Accelerated Thermal Ageing Experiment

Accelerated thermal ageing was conducted using sealed 1-L Schott Duran borosilicate glass bottles with an overall height of 230 mm (with screw cap attached) and outer diameter of 101 mm (SKU number: DWK218015455-10EA). Two types of screw caps were used (blue polypropylene screw caps and red high-temperature polybutylene tetraphthalate screw caps), depending on the number of hours required for accelerated thermal ageing. Each glass bottle contained 800 mL [7], [8] of dielectric liquid (MO (Hyrax Oil) or natural ester oil (FR3 fluid, Cargill), solid insulations (kraft paper and pressboard, TUP and pressboard), and metal catalysts (copper, iron, zinc, and aluminium catalysts) to simulate the dielectric liquid–solid insulation–metal interactions present in industrial oil-immersed power transformers. The glass bottles were placed in a temperature-controlled oven. Fig. 1 shows the photograph of the dielectric liquid–solid insulation–metal catalyst systems investigated in this study while Fig. 2 shows a close-up view of the system.

Previous studies have indicated that metals, particularly copper and iron, significantly influence dielectric liquid oxidation, acidity formation, and cellulose degradation behaviour [9], [10], [11]. Based on these findings, in this study, multiple metal catalysts were incorporated within the dielectric liquid–solid insulation systems to reflect the catalytic effects observed in practical oil-immersed power transformer environments. Metal catalysts were introduced in the form of metal powders. Commercially available aluminium, zinc, iron, and copper powders (purity ≥ 99%, reagent grade) were used in this study. Copper (product code: C0249) and iron (product code: C1406) powders were procured from HmbG Chemicals, whereas zinc powder (product code: C0906) was sourced from Bendosen. Aluminium powder (product code: 8912-30) was supplied by R&M Chemicals.

In addition to the inclusion of metal catalysts, both dielectric liquid and solid insulations were incorporated into the thermally aged systems in this study to reflect the actual oil-immersed power transformer environment. Two types of dielectric liquids were considered in this study, namely, FR3 fluid (which is a natural ester oil) and conventional MO. The solid insulations comprised kraft paper (Nine Dragons Paper Industries (Leshan) Co. Ltd.), TUP (Tomoegawa Co. Ltd.) Pressboard was also added as a constant variable. Prior to drying, the kraft paper and TUP were cut into dimensions of 10 cm × 10 cm (length × width, area: 100 cm²) [7] with a mass of 16 g per sample. The pressboard was prepared with a mass of 64 g per sample and was cut into smaller pieces to accommodate the glass bottle geometry and dielectric liquid volume. These materials were included in the thermally aged systems to represent commonly used transformer insulation systems and to evaluate the dielectric properties of MO and FR3 fluid under comparable thermal ageing conditions.

To ensure that all samples met the required initial conditions prior to thermal ageing, pre-treatment was performed on the dielectric liquid samples. The properties of the dielectric liquids were verified against the IEC 62770 standard (which specifies a moisture content of less than 200 ppm for natural ester oils) and against the ASTM D3487 standard for MO (which specifies a moisture content of less than 35 ppm). The moisture content of the dielectric liquid samples was determined according to the IEC 60814 standard using a Karl Fischer coulometric titrator (Metrohm 851 Titrando) with 801 magnetic stirrer. The results were reported in parts per million (ppm). Pre-treatment was carried out if the dielectric liquids failed to comply with the aforementioned standards. Because the moisture content was a critical parameter, nitrogen gas was purged over the surface of the dielectric liquids to degas and dehydrate the dielectric liquids [12]. Nitrogen purging was performed at a rate of 1.50 L/min for 1 h. Nitrogen purging was conducted until the moisture content of the dielectric liquids met the requirements stipulated in the standards.

Proper drying of the solid insulations will minimize moisture in the system, which has been shown to significantly influence thermal ageing behaviour, which in turn, affects the repeatability of the experiment [13]. The thicknesses of the kraft paper, TUP, and pressboard were critical parameters as they determined the drying durations in compliance with the BS EN 60641 standard (British Standard for Pressboard and Presspaper for Electrical Purposes). The materials were dried at 105 ± 5°C [8] in a ventilated oven. The kraft paper and TUP were dried for 12 h [7], whereas the pressboard was dried for 48 h, depending on their thicknesses, which were 0.25, 0.27, and 1.64 mm, respectively. After drying, all of the solid insulation samples showed a decrease in mass, indicating that moisture and volatile components had been effectively removed. The pressboard samples had an average mass loss of ~8.58%, whereas the kraft paper samples had an average mass loss of ~6.34%. These results showed that the pre-treatment effectively conditioned the solid insulations prior to dielectric liquid impregnation and accelerated thermal ageing. This step was crucial to minimize moisture-induced variability during the thermal ageing process.

After the solid insulations were prepared, the metal catalysts were added into the dielectric liquid samples, weighing 2.0 g for copper and iron, and 0.4 g for aluminium and zinc. The dielectric liquid–solid insulation–metal catalyst systems were then blanketed with nitrogen gas [12] at a rate of 0.75 L/min for 5 min to minimize moisture and dissolved gases. Subsequently, the samples were left in a cool, dark place at room temperature for 24 h to ensure uniform impregnation of the solid insulations. Recent dielectric liquid–solid insulation ageing studies have extensively documented similar impregnation techniques to reduce variability brought on by partial wetting and uneven moisture distribution [14], [15].

Following the immersion procedure, the glass bottles were sealed and placed in a temperature-controlled oven for the accelerated thermal ageing experiment. The samples were aged at 130 °C for predetermined periods (0, 250, 500, 750, 1000, 1250, and 1500 h). Before the dielectric property tests, the samples were retrieved from the oven at the end of each ageing duration and left to settle at room temperature for 1 day [8]. This accelerated thermal ageing experiment was carried out to simulate the long-term thermal stress of actual oil-immersed power transformers within a practical time frame. To evaluate the deterioration of electrical insulation performance under thermal ageing, the AC BDV, dissipation factor, and volume resistivity of the dielectric liquid samples were analysed. These parameters were selected as they collectively described the dielectric strength, dielectric losses, and charge transport behaviour of transformer dielectric liquids. Fig. 3 shows the flow chart of the methodology adopted in this study.

Fig. 1. Photograph of the dielectric liquid–solid insulation–metal catalyst systems placed in a temperature-controlled oven for the accelerated thermal ageing experiment.

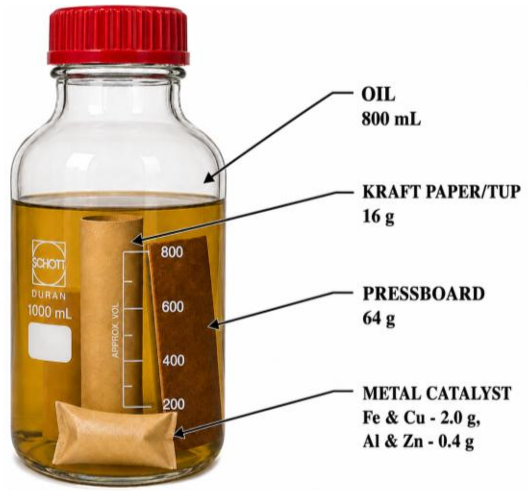

Fig. 2. Close-up view of the materials used in the accelerated thermal ageing experiment.

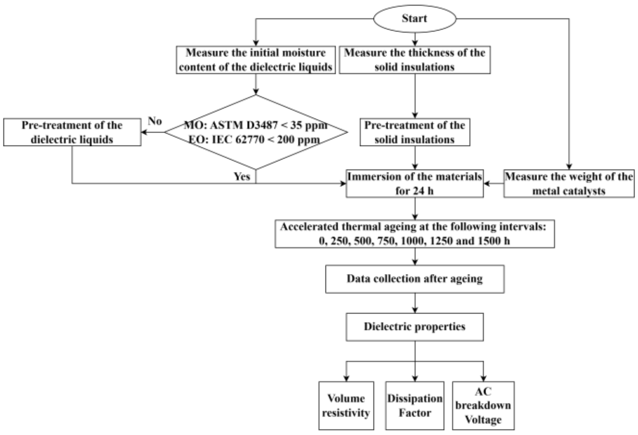

Fig. 3. Overview of the methodology adopted in this study.

B. Investigation of the Dielectric Performance Deterioration of FR3-based and MO-based Insulation Systems Subjected to Prolonged Thermal Ageing

AC Breakdown Voltage (AC BDV)

The AC BDV is defined as the maximum electric field or applied voltage that the dielectric liquid can withstand before electrical breakdown occurs. In this study, the AC BDV was measured in accordance with the IEC 60156 standard [8], [16], [17] using an automatic AC BDV voltage tester (Megger OTS100AF) equipped with standard spherical electrodes with a gap distance of 2.5 mm. In this study, the reported AC BDV value represents the arithmetic mean of six consecutive AC breakdown voltage measurements. The equipment was calibrated every month to ensure it was fit for service.

Dissipation factor (tan δ)

The Dissipation factor (tan δ) represents the ratio of dielectric losses to the total electrical energy stored in the dielectric liquid when subjected to an alternating electric field and reflects the energy dissipation due to polarization and conductive losses. In this study, the dissipation factor was measured at 90 °C in accordance with the IEC 60247 standard [8], [17] using an Eltel dielectric loss measurement system, which was calibrated on 8th August 2025. The measurements were performed using a standard liquid test cell with parallel plate electrodes at a fixed spacing, and an AC test voltage at the power frequency was applied. The Dissipation factor values were recorded after thermal stabilisation of the dielectric liquid samples and reported as dimensionless values, analysed as a function of the thermal ageing duration. The same instrument was also used for volume resistivity testing.

Volume Resistivity

Volume resistivity is defined as the intrinsic resistance of the dielectric liquid to charge conduction under an applied direct current electric field. In this study, volume resistivity measurements were conducted at 90 °C in accordance with the IEC 60247 standard [16] using the same Eltel dielectric measurement system configured for volume resistivity testing. The same electrode configuration was employed to ensure consistency between the dielectric loss and volume resistivity results. The volume resistivity values were obtained under steady-state conditions and reported in ohm-metres (Ω·m) as a function of the thermal ageing duration.

III. Results and Discussion

AC Breakdown Voltage (AC BDV)

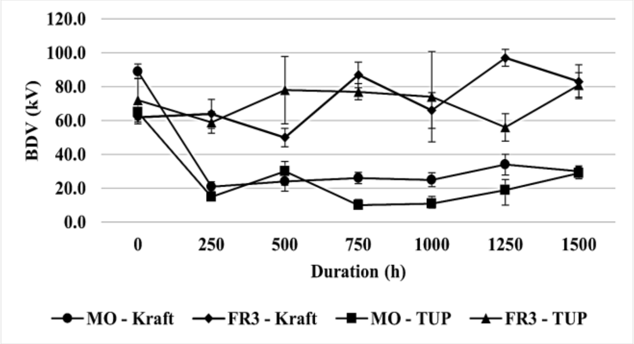

Fig. 4. AC BDV (kV) vs. the thermal ageing duration (h); n = 6 per point; data markers: FR3–TUP (■), FR3–Kraft paper (●), MO–TUP (▲), MO–Kraft paper (◆). The error bars represent ± standard deviation.

Fig. 4 shows the variation of the AC BDV with respect to the thermal ageing time duration for all dielectric liquid–solid insulation–metal catalyst systems tested in this study. The reported values represent the arithmetic mean of six consecutive measurements (n = 6), where the error bars represent the ± standard deviation, indicating the measurement repeatability. For the MO–TUP and MO–Kraft paper systems, a significant reduction in the AC BDV was observed during the early stages of thermal ageing. For the MO–Kraft paper system, the AC BDV decreased abruptly from an initial value of 89 kV to 21–26 kV between 250 and 1000 h. A similar trend was observed for the MO–TUP system, where the AC BDV declined from 65 kV to 10–11 kV at 750–1000 h. The rapid deterioration in the AC BDV is contributed by the limited oxidation stability and moisture tolerance of MO, which leads to the formation of degradation by-products, thus reducing its dielectric strength. Although partial recovery in the AC BDV was observed at prolonged thermal ageing durations (e.g., 29–34 kV at 1500 h), the values remained significantly lower than the initial AC BDV, indicating irreversible degradation of the insulation system. In contrast, the FR3–TUP and FR3–Kraft paper systems exhibited a markedly different thermal ageing behaviour. The FR3–Kraft paper system showed a progressive increase in the AC BDV from an initial value of 62 kV to a maximum of 97 kV at 1250 h, followed by a slight reduction to 83 kV at 1500 h. Similarly, the FR3–TUP system demonstrated relatively stable AC BDV, with values ranging between 72 and 81 kV throughout the thermal ageing period, aside from a temporary reduction at 1250 h. The improved dielectric performance of the FR3–TUP and FR3–Kraft paper systems is attributed to the higher moisture solubility of the FR3 fluid, which reduces the formation of free water and minimizes its detrimental effect on the dielectric strength [2]. This characteristic leads to a greater stability in the AC BDV of the FR3–TUP and FR3–Kraft paper systems unlike that observed for the MO–TUP and MO–Kraft paper systems. Overall, the results showed that the FR3 fluid outperformed the conventional MO in terms of dielectric stability and resistance to the thermal ageing [2], [18].

Dissipation factor (tan δ)

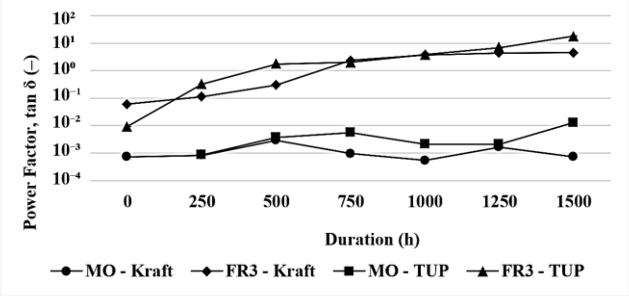

Fig. 5. Dissipation factor (tan δ) at 90 °C vs. the thermal ageing duration. The results are presented on a logarithmic scale.

To further evaluate the dielectric behaviour of the FR3 fluid and MO, the variation of the dissipation factor with respect to the thermal ageing duration was analysed. Fig. 5 shows the variation of the dissipation factor throughout the accelerated thermal ageing experiment for the MO–TUP, MO–Kraft paper, FR3–TUP, and FR3–Kraft paper systems. The error bars for the dissipation factor were not visually prominent due to the relatively small standard deviation compared with the logarithmic scale of the y-axis. The results indicated that the dissipation factor values were consistently higher for the FR3–TUP and FR3–Kraft paper systems with a larger rate of increase during thermal ageing compared with those for MO–TUP and MO–Kraft paper systems, as also observed in other studies [19], [20], [21].

For the MO–TUP and MO–Kraft paper systems, the dissipation factor values remained consistently low throughout the accelerated thermal ageing experiment. It is evident that the dissipation factor values were extremely low throughout thermal ageing duration for the MO–Kraft paper system, ranging from 0.000540 to 0.00295. In contrast, the MO–TUP system exhibited slightly higher dissipation factor values between 0.000870 and 0.00551 up to 1250 h, followed by an increase to 0.0128 at 1500 h, indicating the onset of advanced thermal ageing effects. This behaviour reflects the low dielectric losses inherent in the non-polar MO systems. However, low dissipation factor values do not always indicate insulation stability since the breakdown processes in the MO–TUP and MO–Kraft paper systems are influenced by moisture build-up and oxidation.

In contrast, the FR3–TUP and FR3–Kraft paper systems exhibited a pronounced increase in the dissipation factor throughout the accelerated thermal ageing experiment. The FR3-Kraft paper system displayed a significant and progressive increase in the dissipation factor, increasing from 0.0615 to 4.53 from 0 h to 1500 h. A significant increase was observed after 500 h. Similarly, the FR3–TUP system exhibited a steep and sustained increase in the dissipation factor throughout the accelerated thermal ageing experiment, increasing from 0.00924 at 0 h to 18 at 1500 h, where a noticeable increase was apparent during the early thermal ageing stages. This behaviour is due to the polar nature of the FR3 fluid, which causes larger dielectric losses and increased charge carrier mobility with respect to thermal ageing.

Despite the higher dissipation factor values observed for the FR3–TUP and FR3–Kraft paper systems, the AC BDV results revealed that the dielectric strength of these systems was maintained. This indicates that the increase in the dissipation factor is due to the intrinsic dielectric properties and thermal ageing behaviour of the FR3-based insulation systems, rather than a degradation in the insulation performance.

Overall, the dissipation factor results showed that the chemical composition of the dielectric liquid had a considerable effect on the dielectric loss behaviour and should be understood in conjunction with other diagnostic metrics such as AC BDV and volume resistivity.

Volume Resistivity

In addition to dielectric losses, volume resistivity measurements provide a deeper insight into the charge transport behaviour of the insulation systems under thermal ageing conditions. Fig. 6. shows the evolutions of the volume resistivity for the MO–TUP, MO–Kraft paper, FR3–TUP and FR3–Kraft paper systems throughout the accelerated thermal ageing experiment. In general, the volume resistivity decreased as the thermal ageing duration increased for all systems, with a more pronounced reduction observed for the FR3–TUP and FR3–Kraft paper systems. In contrast, the MO–TUP and MO–Kraft paper had comparatively higher volume resistivity values, consistent with previous studies [19], [22], [23].

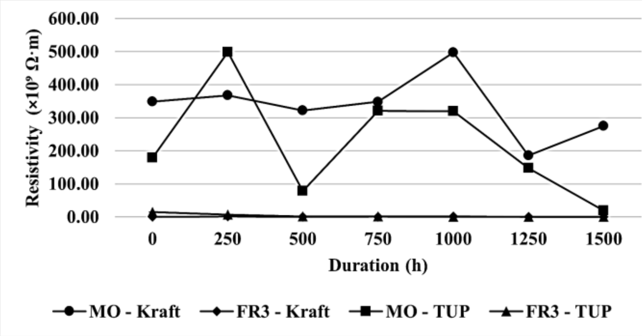

Fig. 6. Volume resistivity (Ω·m) at 90 °C vs. the thermal ageing duration (h). The error bars represent ± standard deviation.

The measurement instrument displays the direct current resistivity in Ω·cm using automatic range selection. To ensure consistency with the IEC 60247 standard, the volume resistivity values were converted and reported in SI units (Ω·m), using the conversion factor 1 Ω·cm = 0.01 Ω·m, and expressed in normalized scientific notation. In general, the volume resistivity decreased with the thermal ageing duration for all systems. The MO–TUP and MO–Kraft paper systems maintained comparatively higher volume resistivity values throughout the accelerated thermal ageing experiment, whereas the FR3–TUP and FR3–Kraft paper systems exhibited a more significant reduction. For the MO–Kraft paper system, the volume resistivity remained relatively high, ranging from 1.85×10^{11} Ω·m to 4.97×10^{11} Ω·m at 90 °C, without a consistent decreasing trend observed. A similar behaviour was observed for the MO–TUP system, where the volume resistivity decreased from 4.99×10^{11} Ω·m at 250 h to 1.88×10^{10} Ω·m at 1500 h. This gradual reduction is attributed to the accumulation of conductive ageing by-products.

In contrast, the FR3–TUP and FR3–Kraft paper systems exhibited significantly lower volume resistivity values. The volume resistivity for the FR3–Kraft paper system decreased from 6.70×10^{8} Ω·m at 0 h to 3.00×10^{7} Ω·m at 1500 h, whereas the volume resistivity for the FR3–TUP system decreased from 1.51×10^{10} Ω·m to 1.00×10^{7} Ω·m over the same thermal ageing duration.

Based on the aforementioned observations, it can be deduced that the volume resistivity behaviour is influenced by the chemical characteristics of the dielectric liquid as well as thermal ageing process. To interpret the findings of this study in detail, the AC BDV and dissipation factor results were supplemented by the volume resistivity results. The lower volume resistivity values observed for the FR3–TUP and FR3–Kraft paper were not directly associated with deterioration in the dielectric properties; rather, they were primarily contributed by the higher moisture absorption behaviour of the FR3 fluid.

The major factors controlling the dissipation factor (tan δ) and volume resistivity are associated with the mechanisms of moisture transfer, dielectric liquid polarity, and oxidation chemistry of the dielectric liquid–solid insulation system. The FR3 fluid has high moisture solubility due to its chemical structure, and thus, it has a high ability to absorb the produced moisture from the cellulose decomposition products, thereby increasing ion mobility in the FR3 fluid, resulting in higher dissipation factor values and lower volume resistivity values, as well as restraining the moisture content in the solid insulations [20]. This hypothesis was confirmed by the AC BDV measurements, which indicated improved and stable dielectric strength for the FR3–TUP and FR3–Kraft paper systems despite the lower volume resistivity values.

On the other hand, the MO trapped moisture inside the cellulose, accelerating hydrolytic ageing, although the volume resistivity of the MO–TUP and MO–Kraft paper systems remained high while the dissipation factor remained low as the thermal ageing progressed [19]. The system behaviour can be further distinguished by oxidation, considering that MO develops electrically active short-chain acids whereas the long-chain fatty acids of the FR3 fluid are less dissociative and hence, have a moderating effect on the dielectric response [21]. One study [24] has shown that even a low level of oxidation coupled with the presence of long-chain fatty acids can greatly increase the dissipation factor. The findings of this study confirmed that the low volume resistivity of the FR3–TUP and FR3–Kraft paper systems could be considered as an indication of good moisture management rather than an indication of insulation performance. This affirmed the superiority of FR3 over conventional MO.

The findings of this study offer insight into transformer design, condition monitoring, and maintenance guidelines. The enhanced stability in the AC breakdown voltage for the FR3-based insulation systems, particularly the FR3–TUP system, indicates that proper selection of dielectric liquid–solid insulation system can mitigate the deterioration due to prolonged exposure to thermal stress [25], [26]. From a design perspective, the adoption of the FR3–TUP system can enhance long-term insulation reliability, especially in applications involving elevated operating temperatures [8], [26], [27].

From a condition monitoring standpoint, the higher power factor values and lower volume resistivity values of the FR3–TUP and FR3–Kraft paper systems should not be interpreted using acceptable criteria for MO-based insulation systems; rather, they should be interpreted using moisture-aware diagnostic criteria that account for the higher moisture solubility and polar chemistry of natural esters to prevent misclassification of the insulation condition [19], [25], [28]. In terms of maintenance, the ability of the FR3 fluid and other esters to retain more moisture in the oil phase and slow cellulose degradation supports the possibility of extended inspection and oil treatment intervals when diagnostic metrics such as AC BDV, dissipation factor, and volume resistivity are evaluated collectively rather than in isolation [25], [26], [27].

IV. Conclusion

In this study, the long-term thermal ageing behaviour of MO and FR3 fluids in the presence of solid insulations (kraft paper and pressboard, TUP and pressboard) and common metal catalysts (copper, iron, zinc, and aluminium catalysts) subjected to accelerated thermal ageing was investigated in a systematic manner. Based on the results, the FR3-based insulation systems exhibited improved and stable AC BDV compared with the MO-based insulation systems, which suffered from a pronounced decrease in the AC BDV over the thermal ageing duration.

The increase in dissipation factor and decrease in volume resistivity for the FR3-based insulation systems are mainly attributed to the polar nature of the FR3 fluid and its interactions with the thermal ageing by-products. Therefore, these parameters should not be interpreted in isolation as indicators of insulation failure. Instead, a comprehensive understanding of insulation performance should be evaluated by evaluating the AC BDV, dissipation factor, and volume resistivity concurrently.

It is crucial to note that this study was performed under controlled accelerated thermal ageing in the laboratory, which do not fully replicate the intricate mechanical, thermal, and electrical stressors encountered during transformer operation. Therefore, direct extrapolation of the findings to in-service transformer performance should be done with caution, even though the observed trends offer insightful information regarding the thermal ageing behaviour of the insulation system. The long-term dielectric performance of the FR3-based and MO-based insulation systems can be further assessed in future research that includes additional chemical diagnostics and system-level thermal ageing testing.

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Conflicts of Interest

The authors declare that there are no conflicts of interest that could have influenced the work reported in this paper.

Author Contributions

Author 1: Investigation, Formal analysis, Writing – Original draft; Author 2: Supervision, Writing – Review and editing, Investigation. Author 3: Writing – Review and editing. Author 4: Writing – Review and editing; Author 5: Visualisation, Project administration.

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