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RESEARCH ARTICLE

On Highlighting the Merits of Gas-to-Liquid Transformer Oil Under Accelerated Thermal Aging and Faults: Electrical and Physio-Chemical Properties

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ABSTRACT Mineral (MO) oil has long been utilized as a dielectric and cooling medium in high-voltage power transformers due to its low cost and availability. Recently, there has been a great trend toward the use of gas-to-liquid (GTL) oil due to its purity, chemical consistency, and better performance than conventional oils. This study aims to investigate the normal and abnormal thermal impacts on GTL and MO oil types. In this regard, this paper presents two parts. Firstly, it studies a comprehensive evaluation of the aging characteristics under normal conditions of GTL oil in comparison to conventional MO. Aged oil samples were obtained using a laboratory-based accelerated aging test, for simulating the thermal stress during the transformer's operation. Hence, the two oil types are subjected to different aging durations (i.e., 3, 6, and 10 days). These aged and fresh samples were tested for AC breakdown voltage, dielectric dissipation factor, permittivity, and resistivity as electrical testing. Additionally, as chemical and physical testing, moisture and acidity are measured for fresh and aged samples of two of these oil types. Besides, optical spectroscopy measurements have been used for insulating oil assessment; these kinds of measurements point out the existence of overall aging byproducts, including sludge formation, which can negatively impact the oil properties including physio-chemical and electrical properties. The used optical techniques include Ultraviolet-visible absorption and photoluminescence tests. Secondly, thermal faults impact as abnormal conditions is generally evaluated through dissolved gas analysis as a chemical test, where it is utilized to measure the gas concentrations for the two oils under abnormal conditions test after the thermal heating test. This study concluded that the electrical and physio-chemical properties of GTL oil with aging have superior results compared to MO oil.

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INDEX TERMS Mineral oil, gas to liquid, aging, electrical properties, chemical properties, optical techniques, oil assessment, decomposition byproducts.

I. INTRODUCTION

Power transformers are the most important component of the electrical power network. During their operations, transformers are subjected to electrical, thermal, and chemical stresses that affect transformer oil degradation and may lead to catastrophic transformer failures and system outages [1]. Oil acts as an insulating liquid and cooling medium in the transformer. its condition reflects crucial data concerning the oil itself as well as the transformer's health and operating condition [2]. Mineral oils (MO) have been used in power transformers for over a century due to their low cost and good dielectric performance. But it can have contaminations with flammable gaseous and compounds such as oxygen and Sulphur which can cause degradation of oil and interfacing solid material [3]. Hence, in recent years, there have been great efforts towards either improving the mineral oil properties through additives or using other oil types with better properties. The enhancement of oil properties shall be reflected in the oil condition and hence the transformer oil assessment which shall increase the transformer service lifetime [1].

Regarding using additives, nanoparticles have been used to develop oil-based nanofluids with superior properties compared to the base oil. Using nanofluids could improve the thermal properties of transformer oil [4], [5], [6], [7]. The investigated thermal properties are thermal conductivity and heat transfer coefficient. Among different types of nanoparticles, carbon-based nanoparticles (carbon, carbon nanotubes, graphene, and graphene oxide) exhibited the highest percentages in the thermal properties of transformer oils. On the other hand, nanofluids could improve the dielectric properties of transformer oil. These dielectric characteristics include breakdown strength, dielectric dissipation factor (DDF), in addition to partial discharge inception voltage [8], [9], [10]. In spite of successful enhancement in transformer oil when using additives of nanoparticles, their practical application in real transformers is still a challenging issue due to long-term stability problems.

Regarding using other oil types, ester oils have been presented as a substitution for mineral oil. Natural ester has the lowest average and hotspot temperatures, but the highest pressure drops [11], [12]. By studying the gelling phenomena in natural esters, it has no discernible effect on the failure rate of liquid breakdown voltage and paper degradation [13]. A previous study presented the effect of mixing natural ester oil with mineral oil. It concluded that the best technical solution for improving the properties of an insulating system at the moment is this mixing [14]. In spite of the multiple benefits of ester oils, their cost limited their application on a wide scale [11], [12], [13], [14].

Recently, to produce hydrocarbon transformer oils, a new technology known as Gas-To-Liquids (GTL) has emerged,

which involves the conversion of natural gas into a hydrocarbon liquid primarily composed of iso-paraffins [15], [16]. This transformation is achieved through the application of the Fischer-Tropsch technique, enabling methane gas to be converted into a range of fluid products, including high-quality base oils suitable as transformer oil. This type of oil offers consistent performance, improved thermal properties, excellent resistance to degradation, and high purity and is essentially free of Sulphur and aromatics compared with conventional mineral oils that reduce the dielectric strength of the transformer oil. Additionally, an experimental study has been presented and concluded that sulfur corrosion had a considerable effect on decreasing the performance of transformer insulation long-term [16], [17].

In [18], the effect of aging on GTL performance has been studied and compared with a mineral oil type, through a laboratory accelerated aging. It concluded that the aging effects of GTL are similar to mineral oil in terms of moisture in addition to acidity. Nevertheless, the colour of GTL changed more slowly than that of the mineral oil. In [19], GTL oil was studied in comparison with the other three oil types of non-naphthenic and naphthenic. According to their composition analysis, the GTL oil is quite different from non-naphthenic and naphthenic oils, especially the alkanes content. GTL has lower mass fraction characteristics (< 0.0002%), higher flash points, and lower density. Regarding the tests of thermal property and lightning breakdown, GTL is more resistant to impulse breakdown voltage and has higher capacity and thermal conductivity. GTL oil type is not corrosive sulfur risk and less substance hazardous to the environment. It can reduce the total oil-filled power transformers and other electric equipment weight. According to [20], in GTL, water is more rapidly spread because of its difficulty in forming association structures with molecules of water. Other recent studies focused on different aspects of GTL performance including partial discharges (PDs), aging, space charge, and lightning impulse breakdown voltage (LIBV) can be found in Refs. [21], [22], [23], [24], and [25]. For instance, the authors of [15] and [26] have focused on assessing the performance of GTLs considering the PDs' behaviour which can be affected by moisture content. In turn, the authors of [27], [28], and [29] have studied the impact of thermal aging and temperature distribution on the operation of GTLs compared with other traditional oils. Moreover, other authors have intensively tested GTL oil against LIBV, space charge, and streamer characteristics in uniform fields under positive and negative lightning impulses [30], [31], [32]. Generally, the findings illustrated that the GTL oil has a superior property and has a higher lightning impulse breakdown voltage, in contrast to a lower acceleration voltage rather than the MO. This is because, in comparison to MO,

GTL oil has a significant reduction in aromatic content [33], [34], [35].

To the best of our knowledge, there are few studies that have been presented in the literature for studying GTL electrical performance. Hence, this topic is open for research, and to cover this gap in the literature, it is necessary to present extensive experimental studies. Hence, this paper presents a comprehensive experimental study for testing the GTL as a fresh oil sample and an aged sample. Diala S4 ZX-I is used as GTL oil, which has not been studied in literature before. The aging sample is important to study the effect of aging on the oil properties. The presented experimental study is valuable for estimating the transformer health index based on oil assessment and hence, the transformer condition monitoring and lifetime, which is a base for proactive maintenance. Hence, it is important to study the electrical, chemical, and physical properties variation with the in-service operation to assess the oil condition.

The first part of this paper presents a comprehensive experimental study of the electrical, physical, and chemical properties under normal and accelerated aging conditions of GTL oil (i.e., Diala S₄ ZX-I) that compared to one of the most common mineral oils (i.e., Diala S₂ ZX-A). Electrical tests include AC breakdown voltage, dielectric dissipation factor, permittivity, and resistivity. On the other hand, chemical measurements focus on assessing moisture content and acidity levels. Further, optical spectroscopy measurements are conducted to analyze the overall aging byproducts, including sludge formation, along with their emission status. The used optical techniques are the Ultraviolet-visible (UV-Vis) absorption test and the photoluminescence (PL) test. Fresh and aged oil samples are used in testing to estimate the oil quality with aging. Aged oil samples were prepared by putting them in a vacuum oven for 24 hours before thermal aging to keep these oil samples at a low level of moisture. Then, put in the oven at 120 °C, where 1 day of laboratory aging is approximately equivalent to 1-year in-service aging, for simulating the thermal stress during this duration.

 TABLE 1. Accelerated aging durations of test sample and the equivalent in-service aging.

Aging Condition	Duration in days	Equivalent years		
Subject to 120 °C	3 days	3 years		
	6 days	6 years		
	10 days	10 years		

Before the accelerated aging process, there was no further treatment performed on the oils. These oil samples are subjected to different aging durations (3, 6, and 10 days). The second part of this paper presents the analysis of dissolved gas analysis (DGA) within the oil samples. It is used to measure the main gas concentrations. Further, the DGA test aimed to expose the oils to an abnormal condition (thermal fault \sim 300 °C) and to study the effect of thermal fault on the concentration of the gases generated.

II. EXPERIMENTAL SAMPLES, SET-UP, AND PROCEDURES

In this paper, two types of insulating oils are adopted for the study; a fully inhibited mineral oil (MO) Diala S_2 ZX-A and a Gas-To-Liquid (GTL) Diala S_4 ZX-I. In this section, the laboratory test procedures are presented including the accelerated aging test, oil breakdown voltage test, dielectric dissipation factor test, permittivity, and conductivity tests. Additionally, to simulate an abnormal condition (thermal fault) for the DGA test, the immersed heating element test at 300°C is presented.

A. LABORATORY-BASED ACCELERATED AGING TEST /ACCELERATED AGED OIL SAMPLES PREPARATION

Oil aging conditions cause an irreversible and slow change in the properties of the insulating oil. As occurs in in-service transformer oil, it gradually loses its stability and becomes oxidized and decomposed. Oxygen and water are two well-known major factors that accelerate the aging process in transformer oil. Oxygen can be found in dissolved form in oil and water, and presented in cellulose paper. Hence, the electric fault and the temperature are two factors that accelerate oil aging. Within the oil of the transformer, moisture redistribution can be produced by increasing temperature. Further, temperature variations may also result in changes in the electrical, chemical, and physical properties of the transformer oil [36], [37], [38].

Hence, the in-service transformer is subject to different stresses that shall affect the oil's electrical, chemical, and physical properties. Note that the addition of cellulose paper and copper into various oil samples corresponds to the real situation in transformers aging, where these materials exist together with oil; however, in this study, we exclude the copper catalyst effect to focus on the impact of aging on the oil paper insulation system only.

Studying these effects, of oil aging and degradation, helps in the assessment of transformer oil conditions. For studying these properties of the Diala S₂ and Diala S₄ oils, the preparation of aged oil samples with different aging durations is required. In this paper, the accelerated aging is prepared in the laboratory for the two tested oil (Diala S2 as a MO and Diala S₄ as a GTL) samples with immersed paper in it to simulate the actual transformer condition. The preparation steps and stages of the oil samples, firstly, all oil samples of the two oil types (Diala S₂ and Diala S₄) are prepared by putting them in a vacuum oven for 24 hours before thermal aging to remove the absorbed water by circulating the transformer oil through a heated vacuum-extraction unit and to keep these oil samples at a low level of moisture. Then, three samples of each oil type were subject to accelerated aging at 120°C under semi-sealed conditions for different durations (3, 6, and 10 days) using a heating oven [39], [40], [41], [42].

The half-life rule of thumb was followed when conducting the accelerated aging test. It claims that every 7 °C increase in operating temperature causes the aging rate of transformer oil to double. The transformer oil is thought to operate at a reference temperature of 60 °C. As a result, one day of accelerated aging in a heating oven is comparable to 380 days (about one day) of practical oil aging in a field transformer when the accelerated aging test is conducted under the heating condition at a temperature of 120 °C. Equations (1) and (2) indicate that subjecting the oil sample for 24 hours in an oven at 120 °C is equivalent to one day (about 380 days) of aged transformer oil. Table 1 shows the accelerated aging durations of the test sample and the equivalent years as in-service conditions [39], [40], [41], [42].

Accelerated Aging Factor =
$$\frac{120^{\circ}C - 60^{\circ}C}{7^{\circ}C} = 8.57$$
 (1)

Time Factor
$$= 2^{8.57} = 380$$
 (2)

B. EXPERIMENTAL SETUP AND PROCEDURES

In this section, the experimental setup and procedures for measuring the breakdown voltage (BDV) and the dielectric dissipation factor (DDF) of the two oil types. Furthermore, the relative permittivity and resistivity are calculated based on the measured DDF for the fresh and aged oil samples. In addition, the optical absorption and emission measurements performed using UV-Vis and PL spectroscopy techniques are presented and described. Also, the immersed heating thermal fault test for the two oil types is performed.

1) BREAKDOWN VOLTAGE TEST

The oil breakdown voltage (BDV) or the dielectric strength is the maximum voltage at which the insulating oil has the ability to withstand the electrical stresses [43], [44], [45]. The breakdown voltage test has been prepared in accordance with the IEC 60156 standards [46], [47]. The measuring tool is the fully automatic oil tester (Model BAUR DTA 100 C). The oil tester electrodes are mushroom-shaped made of copper and spaced at a 2.5 mm distance. The oil samples were subjected to a breakdown voltage test with 2 kV/s of voltage ramp rate [46], [47]. Furthermore, there is a good correlation between the breakdown voltage of oil samples and the moisture content inside those samples, which will be discussed later in subsection III-C.

2) DIELECTRIC DISSIPATION FACTOR (DDF) TEST

The dielectric dissipation factor (DDF) is used to evaluate the oil quality [47], [48], [49]. Using Keysight E4980A precision LCR meter, the dielectric dissipation factor test was carried out in accordance with IEC 60247 as shown in Fig. 1. Furthermore, it shows the schematic diagram of the test configuration [50]. Using the measured capacitance (C_p) and the resistance (R_p) by the LCR meter, the oil dielectric dissipation factor (tan δ) is calculated as follows, for the aged and fresh samples:

$$\varepsilon' = \frac{tC_P}{A\varepsilon_0} \tag{3}$$

$$\varepsilon'' = \frac{t}{2\pi f \varepsilon_0 R_P A} \tag{4}$$

where t is the sample thickness, f is the frequency, A is the electrode surface area, ε_0 is the permittivity of free space, ε' is the dielectric coefficient ε'' is the dielectric loss. Hence, the relative permittivity ε_r and the conductivity are calculated as follows, for the aged and fresh samples:

$$\varepsilon_r = \varepsilon' - j\varepsilon'' \tag{6}$$

$$\sigma = 2\pi f \ \varepsilon_0 \varepsilon'' = \frac{t}{R_P A} \tag{7}$$

Also, the oil resistivity can be calculated as it is the inverse of the conductivity. Equation (4) shows that the dielectric loss changes with the source frequency [51]. Moreover, there is a close relationship between the DDF of oil samples and the acidity of those samples, which will be explained later in subsection III-C.



FIGURE 1. Photograph of the E4980A precision LCR meter, and schematic diagram of the experimental set-up.

3) ACIDITY AND MOISTURE MEASUREMENTS

When water desorption raises the local concentration of gases in the transformer oil, it can increase the likelihood of bubble formation. Thus, measurements of acidity and moisture for oils extracted from fresh and old samples of two oil kinds are shown in this section. The samples were obtained using volumetric syringes, and their moisture and acidity were assessed. For moisture, the acceptable limits are less than or equal to 50 ppm before oil treatment and less than or equal to 20 ppm after oil treatment according to IEC 60814 std [52]. For acidity, the acceptable limits are less than or equal to 0.03 for new oil and less than or equal to 0.1 for used oil according to IEC 62021 std [53].

4) UV-VISIBLE SPECTROSCOPY TEST

UV-Vis. spectroscopy has light beams of different wavelengths that can pass through oil samples and hence can measure how much light can be absorbed by many atoms. The obtained results of the UV-Vis test point out the diluted liquids, mainly gas and chemical absorbances. Such optical absorption technique has the ability to give information on the byproducts' composition and their concentration. According to the Beer-Lambert relation, the change in intensity of the light, due to absorption in a sample, is computed by the absorbing type's number. The absorbance (A) can be determined according to equation (8):

$$A = -\log T = a.b.c \tag{8}$$



FIGURE 2. UV-Vis spectroscopy technique: (a) photograph of the spectrophotometer, and (b) Schematic diagram of the experimental set-up.



FIGURE 3. Schematic diagram of the PL experimental set-up.

where *T* is the transmittance parameter that quantifies the amount of light passing through a substance. It is calculated by dividing the intensity of transmitted light by the intensity of the incident light. The factors *a*, *b*, and *c* represent the absorptivity of absorbing species, the path length that the light travels through the substance, and the concentration of absorbing species (gm/l), respectively [51], [54], [55], [56], [57].

To perform the measurements, a double-beam UV-Vis spectrophotometer (Shimadzu Scientific Instruments Incorporated, Tokyo, Japan), model UV 2600, is used, as shown in Fig. 2.a. Furthermore, Fig. 2.b illustrates the schematic diagram of the test configuration.

5) PHOTOLUMINESCENCE (PL) SPECTROSCOPY TEST

The PL spectroscopy test is simpler and has a lower cost than other techniques. The PL measurements yield an emission band that is much narrow and more sensitive than that of the absorption spectrum [58], [59]. In this paper, the two optical measurements have been used for more accurate detection of the aging byproducts [58], [59], [60]. Fig. 3 shows the schematic diagram of the experimental setup of the PL technique.

6) IMMERSED HEATING THERMAL FAULT TEST

One of the most used chemical tests for oil fault identification is the dissolved gas analysis (DGA), where low-concentrated gases are produced during ordinary operation, such as methane (CH₄), carbon monoxide (CO), hydrogen (H₂), ethylene (C₂H₄), carbon dioxide (CO₂), ethane (C₂H₆) and acetylene (C₂H₂). These low-concentrated gases are generated with higher concentrations when faults occur in the transformer [61].

The usual incipient thermal faults in transformer oil are classified as high (T3), medium (T2), and low (T1) as follows: T1 (300°C), T2 (300°C–700°C), and T3 (>700°C). In this study, the samples are subjected to a medium thermal fault. This test aims to detect the dissolved gases in the two oil types (Diala S₂ and Diala S₄) after their exposure to the thermal heating test, hence comparing the dissolved gases in the two oil types. The fresh oil samples of the two oil types (Diala S₂ and Diala S₄) have been prepared for the test, by putting them in a vacuum oven for 48 hours and left under vacuum for about 2 hours.

These fresh samples have been exposed to thermal fault for 1 hour by heating the oil sample up to 300°C, as a simulation of the in-service transformer thermal fault. A test cell of transparent Perspex of 400 ml volume and 7 cm height with a heating element was used. The heating element is made of a ferritic iron-chromium-aluminum alloy. The thermal fault has been simulated by supplying the heating element with a power of 300 W, leading the heating element to reach up to 300°C. A thermocouple type K has been used for monitoring the oil sample heating temperature. Fig. 4 shows the schematic diagram of the experimental setup. After the heating thermal fault test, the oil samples were collected and transferred to the Central Chemical Laboratories for detecting the dissolved gases according to IEC 60567 [61], IEEE Std. C57.104 [62], and [63].

III. RESULTS AND DISCUSSION

In this section, the results of testing the two oil types (Diala S_2 as a MO and Diala S_4 as a GTL) are presented and



FIGURE 4. Immersed heating thermal fault test: (a) Experimental set-up, and (b) Schematic diagram.



FIGURE 5. Aged oil sample color change: (a) Oil samples with 3 days aging duration, from left to right; Diala S₄ and Diala S₂ samples, (b) Diala S₂ oil samples, from left to right; 1- day and 10-days aging durations, and (c) Diala S₄ oil samples, from left to right; 1- day and 10- days aging durations.

analyzed. The results of the breakdown voltage, the dielectric dissipation factor, relative permittivity, and resistivity, for the aged and fresh samples of the two oil types, are presented and compared. In addition, the detected dissolved gases for the two oil types after the heating thermal test are presented. The UV-Vis absorption and the PL spectra of the aged and fresh samples are also presented.

A. OIL COLOR AND APPEARANCE

Oil color and appearance are one of the physical properties of the oil character. Also, it is used as a parameter in measuring the transformer oil condition assessment as it indicates the degradation changes in the oil chemistry. Generally, the lighter the color is the better oil as the color is changed due to the formation of contaminants, sludge, and byproducts [18].

Fig. 5 shows the variation and change in oil color with aging. Fig. 5.a shows the difference in color for two oil types (Diala S_2 and Diala S_4) with the same aging duration (3 days). This shows that the color is darker in Diala S_2 than the Diala S_4 , and hence, the formed by-products and contaminants in Diala S_4 are lower than in Diala S_2 . Besides, Fig. 5.b shows the difference in color for the same mineral oil sample (Diala S_2) with different aging duration (1 day and 10 days). Hence, for Diala S_2 samples with increasing the aging duration, the color becomes darker due to the formation of by-products and contaminants.

Fig. 5.c shows the difference in color for the same Diala S_4 oil sample with different aging durations (1 and 10 days).

B. ELECTRICAL PROPERTIES

This part presents the results of electrical properties measurements for identifying the oil quality. This includes measuring the breakdown voltage, dielectric dissipation factor, relative permittivity, and resistivity.

1) BREAKDOWN VOLTAGE

Breakdown voltage (BDV) has been measured for the fresh and different aged durations (3, 6, and 10 days). Also, this has been applied for the two oil types (Diala S₂ as a MO and Diala S₄ as a GTL). The results were analyzed, and the probabilities associated with various breakdown voltages were determined using Weibull distribution. The cumulative distribution function for a certain applied voltage "*x*" was computed as follows [64], [65], [66]:

$$f(x) = 1 - e^{-\left(\frac{p}{\alpha}\right)x} \tag{9}$$

where α and β are defined as the scale and the shape parameters, respectively. These parameters are calculated by equation (10):

$$\ln(\ln[\frac{1}{1-f(x)}]) = \beta \ln x - \beta \ln \alpha \tag{10}$$

Weibull distribution provides acceptable analysis and forecasting for breakdown with an extremely small number of tests.

At a probability of 50 %, the BDV refers to the mean value. While the BDV at the probability of 10 % indicates

the minimum permissible value of BDV, this is regarded as an indication of the transformer oil's reliability. Fig. 6 shows the BDV at a probability of 50% and 10%. For fresh mineral oil samples (Diala S₂) and GTL samples (Diala S₄), the BDV results are approximately equal; 78.5 kV and 78 kV at a probability of 50 %, besides 51.7 kV and 59.6 kV at a probability of 10 %, respectively. For oil samples with 3 days accelerated aging duration, the BDV value was decreased to 62.8 kV for Diala S2 and 50.6 kV for Diala S4 at a probability of 50 %. Additionally reduced to 40 kV for Diala S₂ and 43.6 kV for Diala S₄ at a probability of 10%. With increasing the accelerated aging duration to 6 days, the BDV continues to decrease and reached 46.6 kV for Diala S2 and 46 kV for the Diala S₄ at a probability of 50% while reached 36 kV for Diala S₂ and 38.6 kV for Diala S₄. Finally, with 10 days of accelerated aging, the BDV decreased to 42.9 kV for Diala S₂, while the BDV started to increase reaching 47.3 kV for Diala S_4 at a probability of 50%, while at a probability of 10% the BDV reached 34 kV for Diala S₂ and 40 kV for Diala S₄, respectively.



samples at different aging durations.

Comparing the mean value of BDV for the two oil types, the BDV for the two oil types were close in values from each other for fresh and at 6 days aging duration. There was a noticeable superiority for mineral oil BDV, at 3 days aging duration, with 124 % compared to Diala S₄. On the other hand, at 10 aging days, the Diala S₄ oil has a higher BDV of 110 % compared to mineral oil. Hence, the Diala S₄ oil type became better in dielectric strength by aging with a duration greater than 6 days.

Figure 7 presents the Weibull distribution for mineral oil samples (Diala S_2) with fresh samples compared to aged samples. The breakdown voltage was significantly reduced by aging. The breakdown voltage was decreased to 80 %, 59 %, and 54 % for the aged days, compared with the fresh oil sample. Mineral oil is self-oxidizable and with the presence of moisture, the oil starts oxidation which can be the main reason for the breakdown voltage decrease.

Figure 8 presents the Weibull distribution for (the Diala S_4 oil sample with fresh samples compared to aged samples. For the Diala S_4 oil sample, with 3 and 6 aging days, the breakdown voltage decreased to 64.8 % and 58.9 % compared



FIGURE 7. Weibull distributions of Diala S2 fresh oil sample with different accelerated aging durations (3, 6 and 10 days).

to the fresh oil sample BDV. Then, at 10 days of aging, the BDV got increased, higher than at 6 aged days, and reached 60.6 % of the fresh BDV value. This concluded that the breakdown voltage of the Diala S_4 oil type became better in BDV with an aging duration higher than 6 days. Diala S_4 is pure GTL oil, which is sulfur-free and has enhanced antioxidant performance providing good oxidation stability. The BDV decrement for 3 and 6 days may be attributed to the existence of any moisture in these samples that may be evaporated with more aging due to the oil heating. In addition, according to [18], the moisture content for the same GTL oil type increased first and then started to reduce with aging. This result may be the reason for increasing the breakdown voltage by aging.



FIGURE 8. Weibull distributions of Diala S4 fresh oil sample with different accelerated aging durations (3, 6, and 10 days).

Other aged oil samples for the same duration and the two oil types have been repeated again in the laboratory. These other samples have been tested for BDV, and the BDV trend of the Diala S_4 is still the same. The Diala S_4 breakdown voltage for the aged oil sample, higher than 6 days, returns in increase after the decrease in 3 and 6 days.

2) DIELECTRIC DISSIPATION FACTOR (DDF)

The dielectric dissipation factor is used in transformer oil condition assessment, as it refers to the existence of the conducting and impurities materials in oil. It has been measured for the fresh and aged oil samples with different aging durations (3, 6, and 10 days) of the two oil types (Diala S_2 and Diala S_4).

Figures 9 and 10 demonstrate the effect of changing frequency on the dielectric dissipation factor (DDF) for two oil types. These figures were obvious that the DDFs trend in change for two fresh oil samples (Diala S_2 and Diala S_4) is identical. Further, the DDF for the fresh oil sample of Diala S_4 is higher than Diala S_2 , but still below the tolerable limit. With different aging durations (3, 6, and 10 days), the DDFs for Diala S_4 have values lower than Diala S_2 with increasing the source frequency.



FIGURE 9. Dielectric dissipation factor of Diala S2 fresh oil samples and at different aging durations (3, 6, and 10 days).

Specifically, Fig. 9 shows the variation of DDF over a range of frequencies for Diala S_2 with fresh and aged oil samples with different aging durations. The fresh oil sample was found to have the lowest factor of dielectric dissipation. Then, the DDF increased as the aging test duration increased. This figure shows that the DDFs increase, with changing source frequency, with increasing the aged duration for the Diala S_2 oil sample.

Figure 10 shows the variation of DDF over a range of frequencies for Diala S_4 oil type with fresh and aged oil samples with different aging durations. The fresh was had a DDF value nearly close to the relevant DDF value of the aged oil samples. Hence, the DDF has a slight change with increasing the aging duration for the duration of 0, 3, and 6 days, then it increased significantly during the aging duration of 10 years. This is probably due to the decrease in moisture content after long aging as depicted in [18].



FIGURE 10. Dielectric dissipation factor of Diala S4 fresh oil samples and at different aging durations (3, 6, and 10 days).

Figure 11 shows the variation of the dielectric dissipation factor for the two oil types with fresh and aged duration

at the power frequency (50 Hz). Further, it shows that the DDF for Diala S_2 increased during the aging durations. At 10 aging days, the DDF decreased below the value at 6 days but was still higher than the fresh sample and 3 days of aging. Table 2 tabulates these values, where the DDF is 0.001035 for the fresh sample. With aging durations, the DDF reaches 0.001727, 0.002987, and 0.002524 for aging durations of 3, 6, and 10 days, which is below the acceptable limit.



FIGURE 11. DDF of Diala S2 and Diala S4 fresh oil samples and at different aging durations (3, 6, and 10 Days-aging) at 50 Hz power frequency.

On the other hand, the DDF for Diala S₄ at 3 and 6 aging days is lower than the relevant value for the fresh oil sample. However, the results remain close to each other during 0, 3, and 6 days of aging durations. At 10 aging days, the DDF significantly increased over the DDF during 0, 3, and 6 days of aging durations. Table 2 presents these values, where the DDFs are 0.001727 for the fresh sample. With aging, the DDF is 0.00135, 0.001197, and 0.003149 for aging durations of 3, 6, and 10 days. This test concluded that the dielectric dissipation factor for Diala S₄ was not affected by aging up to 6 days of aging. At 10 aging days, the DDF of Diala S_4 increased with values greater than the DDF of Diala S_2 . For Diala S₂, the DDF increases with aging up to 6 days of accelerated aging, then it reduces during 10 days of aging. As well as breakdown voltage, the dielectric dissipation factor was affected by the changing in moisture during aging duration which varies by aging according to [18]. Generally, the aged byproducts in Diala S₄ are lower than the Diala S₂.

3) RELATIVE PERMITTIVITY AND RESISTIVITY

The oil relative permittivity and resistivity are calculated based on the DDF measurements for the fresh and aged oil samples with different aging durations (3, 6, and 10 days). The oil's relative permittivity is an indication of the dielectric polarization intensity. The oil resistivity is the inverse of the conductivity which is an indication of the oil quality [67].

Table 3 presents the relative permittivity and the conductivity of the fresh and aged oil samples with durations for the Diala S_2 and Diala S_4 . The relative permittivity, for the fresh and aged oil samples, of the Diala S_2 is slightly higher than the Diala S_4 ; 106 % for fresh and 103.5 %, 102.1 %,

	Mineral oil (Diala S ₂)			GTL oil (Diala S₄)		
	C _P (Farad)	$R_P(\Omega)$	DDF (tan δ)	C _P (Farad)	$R_P(\Omega)$	DDF (tan δ)
Fresh Sample	6.79 E-11	4.52 E+10	0.0010355	6.35 E-11	2.9 E+10	0.001727
3 years Sample	6.75E-11	2.73E+10	0.0017271	6.39 E-11	3.67 E+10	0.001358
6 years Sample	6.66E-11	1.60E+10	0.0029871	6.37 E-11	4.18 E+10	0.001197
10 years Sample	6.65E-11	1.90E+10	0.0025244	6.42 E-11	1.57 E+10	0.003149

TABLE 2. DDF of Diala S2 and Diala S4 fresh oil samples at different aging durations (3, 6, and 10 years) at 50 Hz power frequency.

TABLE 3. Relative permittivity and conductivity of Diala S_2 and Diala S_4 fresh oil samples at different aging durations (3, 6, and 10 years) at 50 Hz power frequency.

	Mineral	oil (Diala S2)	GTL oil (Diala S4)		
	ϵ_r	$\sigma\left(\Omega^{-1}\right)$	ε _r	$\sigma\left(\Omega^{-1}\right)$	
Fresh Sample	2.02	2.21E-11	1.898936	3.45E-11	
3 years Sample	2.01	3.67E-11	1.908	2.73E-11	
6 years Sample	1.988	6.25E-11	1.902	2.39E-11	
10 years Sample	1.987	5.28E-11	1.917	6.35E-11	

and 102.1 % for 3, 6, and 10 days aged duration, respectively, as demonstrated in Figure 12.a. So, with oil aging, the relative permittivity of Diala S_4 is in increases while, for the Diala S_2 , the relative permittivity is in decreases.



FIGURE 12. (a) Relative permittivity, and (b) resistivity of MO (Diala S_2) and GTL (Diala S_4) with fresh and aged oil samples with different aging durations (3, 6, and 10 years) at 50 Hz power frequency.

Figure 12.b shows the resistivity of the fresh and aged oil samples with different aging durations (3, 6, and 10 days).

The resistivities of fresh and aged Diala S_4 oil samples have an incremental increase with aging until the duration 6 days of aging, after this duration, it started to decrease. while a decrease in the resistivity of the fresh and aged Diala S_2 samples. The oil resistivity is an indication of the aged byproducts; Figure 12.b means that the formed by-products in Diala S_4 are lower than those formed in the Diala S_2 with aging until duration 6 days of aging.

C. MOISTURE AND ACIDITY MEASUREMENTS

The moisture and acidity for the samples of two oil types (fresh and aged samples) have been recorded. The moisture measurements for fresh, 3 days, 6 days, and 10 days of aging, respectively, were 26.383, 25.179, 38.551, and 39.778 (ppm) for Diala S_2 and 16.54, 15.8035, 22.616, and 29.69 (ppm) for Diala S_4 . This illustrated that the moisture for Diala S_2 and Diala S_4 were within the permissible limits for fresh and aged samples, but Diala S_2 has a quick effect by aging compared to the other oil types. Also, Fig. 13.a illustrated that the water content in Diala S_4 was lower than that of Diala S_2 on (3 days, 6 days, and 10 days) of aging and fresh samples. This is regarded as one of the biggest threats to the lifespan of transformer oil. Moisture does lower the oil breakdown voltage and can raise the temperature of the windings, which can subsequently result in a short circuit.

The acidity measurements for fresh, 3 days, 6 days, and 10 days of aging, respectively, were equal to 0.02728165, 0.032743659, 0.02730219, and 0.027295865 (mg KOH/g) for Diala S₂ and 0.017795736, 0.02374558, 0.035622857, and 0.017824902 (mg KOH/g) for Diala S₄. The acidity results show that, for Diala S₂ and Diala S₄, the measurements affected by aging and within the permissible limits except for 3 days and 6 days of aging for Diala S₂ and Diala S₄, respectively, see Fig. 13.b. Generally, these chemical results ensured that Diala S₄ has a less chemical effect by aging compared to MO oil type. These results explained the reason for the change in the results of breakdown voltage and DDF.

The moisture and acidity seem to have a close relationship with the electrical properties of the two oil types, i.e., Diala S_2 and Diala S_4 . From Fig. 6 and Fig. 13.a, the breakdown voltage is effectively correlated with the moisture content. where the breakdown voltage of oil samples decreases when the aging duration reaches 10 days, see Fig. 6. Otherwise, the moisture increases with the aging duration rise, see Fig. 13.a. This is due to the presence of the moisture content inside the oil samples causing an effective reduction in the breakdown



FIGURE 13. (a) Moisture, and (b) Acidity of MO (Diala S_2) and GTL (Diala S_4) with fresh and aged oil samples with different aging durations (3, 6, and 10 years).

voltages of those oils [68], [69]. Furthermore, from Fig. 11 and Fig. 13.b, the DDF for the Diala S_2 sample increases when the aging duration reaches 10 days, see Fig. 11. This is due to the Diala S_2 sample having high oxidation causing growth in acids inside the oil, see Fig. 13.b, resulting in high DDF due to the aging process [70].

Regarding the Diala S₄ sample, the DDF slightly decreases (approximately kept constant) until the aging duration reaches 6 days because this oil type has a lower aromatic component and behaves as resistant to thermal aging with a slight effect until 6 days. The physical mechanism behind that is the GTL transformer oil (Diala S₄) typically has a lower aromatic content compared to mineral oil (Diala S₂). Aromatics are hydrocarbon compounds that are more prone to oxidation and degradation at high temperatures. By reducing the aromatic content, GTL oil exhibits improved thermal stability, which helps to mitigate the effects of thermal aging. By reducing the aromatic content in GTL transformer oil, the oil exhibits improved thermal stability. This means that it is less prone to oxidation and degradation when exposed to high temperatures. The lower aromatic content helps mitigate the effects of thermal aging, which is the gradual degradation of the oil due to prolonged exposure to elevated temperatures.

However, during the aging period of 6 to 10 days, a noticeable decrease in acids can be observed, as depicted in Fig. 13.b, while the DDF experiences a sharp increase, as shown in Fig. 11. This reduction in acids can be attributed to prolonged thermal aging. As GTL transformer oil (Diala S_4) undergoes extended thermal aging, the DDF

may exhibit a significant increase due to the conversion of acids into sludge. This transformation occurs as a result of the oxidation process, where neutralized acids are converted into larger and more complex molecules, which are less soluble in the oil. Consequently, these molecules are more likely to precipitate as sludge, resulting in low acidity. It is worth noting that the moisture content had no impact on the DDF since its presence in the oil samples was minimal, in ppm range. The reduction in acidity due to sludge formation is validated by the increased area under UV-Vis spectroscopy curves. This increase indicates a higher presence of decomposition byproducts from the sludge formation process.

D. OPTICAL SPECTROSCOPY RESULTS

1) UV-VISIBLE SPECTROSCOPY RESULTS

UV-Vis spectroscopy measures the optical absorption of the byproducts as a function of wavelength. Hence, it is used to identify the atomic or molecular structure of chemical compounds and quantify the concentrations of these compounds [71], [72].

Figure 14 shows the UV-Vis absorption spectra of the fresh and aged oil samples over the wavelength range of 200 nm to 600 nm for two oil types (Diala S₂ and Diala S_4). It is noticed that the light absorption starts to occur at $\lambda = 450$ nm, for both fresh and aged oil samples, and then increases gradually at wavelengths < 450 nm for Diala S₂, Fig. 14.a. As seen, the UV-Vis absorption spectrum of the fresh oil sample shows the lowest absorbance magnitude along with the investigated wavelength range for Diala S₂. It also observes that, with increasing aging duration, the absorbance values increase gradually with an absorbance level higher than that for the fresh oil sample, Figure 14.a. It is found that, over the wavelength range from 200 to 400 nm, the absorbance peak value is 4.4 for fresh oil samples, 4.6 and 4.78 for 3 and 10 days, respectively, Figure 14.a. Hence, the absorbance increases with increasing aging duration due to the aged byproducts. This is agreed with the electrical dielectric dissipation factor test.

For Diala S₄, the absorbance spectrum has a pulse-like shape with a peak value at $\lambda = 300$ nm and was found to decrease rapidly at $\lambda = 350$ nm. This was due to its free from sulfur which had a peak that appeared in the far UV spectrum. Moreover, the peak has a narrower band compared with that of the Diala S₂ sample, Figure 14.b.

We also observe that the absorption spectrum of the fresh oil sample has a lower absorbance level for Diala S_4 . The latter is found to increase gradually with aging (where the absorbance level becomes higher than that for the fresh oil sample), Figure 14.b. The peak absorbance is 0.05 for the fresh oil sample, 0.55 and 1.15 for 3 and 10 days, respectively. Hence, for Diala S_4 , the absorbance is lower in magnitude and has a narrower band compared with Diala S_2 . Hence, it can be concluded that Diala S_4 oil has a higher performance compared with Diala S_2 oil as the formed aged byproducts concentrations are lower than that in the mineral oil type.



FIGURE 14. UV-Vis. absorption spectra of fresh and aged Diala S2 and Diala S4 oil samples: (a) MO, and (b) GTL oil.

From Figure 14, the area under the UV-Vis spectrum curve over wavelength from 200 to 600 nm, which indicates the decomposition aging byproducts (i.e., sludges), can be estimated according to ASTM D6802 standard [73]. For Diala S_2 , the area under the curve for fresh oil, 3 days aging, and 10 days aging is 705.038 a.u., 759.406 a.u., and 863.91 a.u., respectively, see Fig. 14.a. Where the area under the curve of 3 days aging oil and 10 days aging oil is slightly increased compared with S_2 fresh oil.

Furthermore, for Diala S₄, the area under the curve over wavelength from 200 to 600 nm for fresh oil, 3 days aging, and 10 days aging is 2.764 a.u., 8.869 a.u., and 12.217 a.u., respectively, see Fig. 14.b. In which, the area under the curve of 3 days aging oil and 10 days aging oil is sharply increased compared with S₄ fresh oil. It can be concluded that when the oil aging increased until 10 days, the decomposition byproducts increased, resulting in a high amount of sludges. Also, the decomposition byproducts for aging Diala S₄ are sharply increased compared with aging Diala S₂ and the fresh oil ones (i.e., fresh S₂ and S₄). This means that the amount of sludge in Diala S₄ is larger than in Diala S₂, which obvious that the aging byproducts for Diala S₄ increased sharply over 10 days of aging, which confirms that the acidity is decreased, and sludge is formed, as discussed in sub-section III-C.

2) PL SPECTROSCOPY RESULTS

PL measurement is based on detecting the radiation emitted from a molecule or an atom due to an electronic transition occurring from a high energy level to a lower energy level [58]. Figure 15 shows the normalized PL spectra of the fresh and aged oil samples over the wavelength range between 475 nm to 750 nm for Diala S₂ oil type while at 350 nm to 600 nm for Diala S₄. For Diala S₂, the luminescence starts at 750 nm, and then the PL intensity increases for $\lambda < 750$ nm until it reaches the maximum intensity at $\lambda = 500$ nm, see Fig. 15.a. The PL spectrum is shifted to higher intensities and becomes broader over wavelengths 700 nm to 500 nm with increasing aging duration for Diala S₂ (with constant peak emission intensity), see Fig. 15.a.



FIGURE 15. PL Spectrum of fresh and aged MO and GTL oil samples: (a) MO, and (b) GTL oil.

For Diala S₄, the PL starts at $\lambda = 500$ nm, and then the emission intensity increases at $\lambda < 500$ nm until reaching the maximum PL intensity at $\lambda = 380$ nm, Figure 15.b. With increasing aging duration of Diala S₄, the PL intensity is approximately the same as for the fresh oil sample, which has no significant change with aging, see Fig. 15.b.

Two main parameters were used for quantitative analysis of the PL spectrum [58]; the full width at half-maximum (FWHM) and the enclosed area under PL spectra. The FWHM is estimated from the PL spectrum. It is estimated by measuring the difference in wavelength on the x-axis that is corresponding to half of the normalized PL intensity on the y-axis. For Diala S₂, the FWHM is 38 nm for the fresh oil sample, 42 nm, 50 nm, and 55 nm for the aged oil samples with 3, 6, and 10 aged days, respectively, see Fig. 16. While for Diala S₄, the FWHM is approximately constant with a value of 28 nm, Figure 16. This expresses that the concentration of the aged byproducts in Diala S₄ is constant with increasing aging durations, while it is increased linearly in Diala S_2 .



FIGURE 16. The FWHM of fresh and different duration aged oil of Diala S2 and Diala S4.

Figure 17 shows the estimation of the area under the PL spectra; its increase refers to an increase in the decomposition byproducts concentration. For Diala S_2 , it is 49 a.u. for fresh oil samples and 53, 63, and 73 a.u. for aged durations 3, 6, and 10 days, respectively. While, for Diala S_4 , the areas under the PL curve were approximately constant at 40 a.u. This reflects an incremental increase in the byproduct's concentration with aging for Diala S_2 compared with a constant byproduct's concentration for the Dialal S_4 sample, see Fig. 16 and Fig. 17.



FIGURE 17. The area under PL spectra for fresh and different duration aged oil of Diala S2 and Diala S4.

Moreover, it is concluded that there is no obvious increase in the intensity or the area under the PL curve in contrast to the UV-Vis spectrum curve. This is due to the aging byproducts formed by PL spectroscopy in Diala S_4 oil containing nonemitting molecules, which means the S_4 oil has a lower aromatic component without changing the oil color and behaves as resistant to thermal aging, resulting in improving the oil stability compared with the Diala S_2 oil.

E. CHEMICAL PROPERTIES RESULTS (DISSOLVED GAS ANALYSIS) UNDER ABNORMAL CONDITIONS

The results of dissolved gases for two oil types (Diala S_2 as a MO and Diala S_4 as a GTL) are presented in Table 4 after subjecting the oil samples to a heating thermal test. According to the central laboratory, the diagnosis of the two oil types after the heating thermal test is normal because the gases concentrations did not exceed the limits according to IEEE Std. C57.104 [62].

 TABLE 4. Concentrated gases of MO (Diala S2) and GTL oil (Diala S4) with ppm.

Dissolved Gasas (ppm)	H2	CH₄	C ₂ H ₆	C ₂ H ₄	C ₂ H ₂	СО	CO ₂
Diala S2	2	8	8	11	0	93	1013
Diala S4	6	3	3	9	0	22	606

The concentrated gases H₂, CH₄, C₂H₆, C₂H₄, and C₂H₂ are 2, 8, 8, 11, and 0, respectively for Diala S₂. While these dissolved gases are 6, 3, 3, 9, and 0, respectively for Diala S₄ as shown in Figure 18.a. Hence, the concentrated gases CH₄, C₂H₆, and C₂H₄, of Diala S₂ are greatly affected by thermal fault compared with Diala S₄ oil type. While H₂ is affected by a thermal fault with a higher value, for Diala S₄ oil type compared with mineral oil type. For Diala S₂, extensive studies concluded that methane (CH₄), ethane (C₂H₆), and ethylene (C₂H₄) are the dominant gases and most effective gases in the case of thermal fault [1], [2], [3], [62], [74], [75], which coincide with our results. Diala S₄ has not been used studied in a wide range; hence, by subjecting Diala S₄ to a thermal fault, H₂ is also affected by a thermal fault in addition to the other gases (CH₄, C₂H₆, and C₂H₄). In addition, carbon dioxide (CO₂) and carbon oxide (CO) concentrations have been presented as shown in Table 4 and Fig. 18.b. The concentration of CO for Diala S2 was 4.2 times Diala S4. Also, CO₂ concentration for Diala S₂ was 1.6 times Diala S₄. This ensures that Diala S₄ has lower carbon emissions, effectively, compared to Diala S₂.

IV. PHYSICAL AND CHEMICAL MECHANISMS

Thermal stress can trigger chemical reactions that can result in the creation of carbon that has been freed from C-H bonds, in addition to this, carbon release increases the transformer oil's dielectric losses [76], [77]. In the GTL oil type, Fischere-Tropsch synthesis was used for polymerizing the hydrogen and carbon parts into molecules with long chains. Through a series of chemical processes, several hydrocarbons were produced using this technology, ideally having the formula (C_nH_{2n+2}) . Alkanes are produced through the more useful reactions by equation (11):

$$(2\mathbf{n}+1)\mathbf{H}_2 + \mathbf{n}\mathbf{C}\mathbf{O} \to \mathbf{C}_{\mathbf{n}}\mathbf{H}_{2\mathbf{n}+2} + \mathbf{n}\mathbf{H}_2\mathbf{O}$$
(11)

The primary distinction between these two oils is that a GTL oil is almost entirely made up of branched paraffins (99%), which are relatively simple branching iso-alkanes, while the naphthenic mineral oils are primarily made up of naphthenic hydrocarbons (poly-cycloalkanes), with only a small amount of iso-alkanes and n-alkanes (84%), as shown in Fig. 19 [77], [78].

By studying the GTL oil type produced by Fischere-Tropsch technology, the oil produced is of higher acetane



FIGURE 18. Concentrated gas of MO (Diala S2) and GTL oil (Diala S4) oil samples: (a) Five dissolved gases Concentration, and (b) CO and CO₂ concentration.



FIGURE 19. Representative primary ingredients of; (a) mineral oil, (b) GTL oil.

number and free from sulfur and low emission of carbon. Thus, the formation of other substances does not occur soluble in oil. Accordingly, GTL emits little aromatics, little nitrogen oxide, little carbon monoxide, little hydrocarbon, and little particulate matter.

By discussing the results for mineral oil compared to GTL, it is noticed that the Diala S_4 oil still has the same color by aging as the fresh sample, or it has very low changes in the color. This is attributed to the very low impurities in Diala S_4 . Hence, the Diala S_4 has a lower degradation rate in its bonds compared with mineral oil. Additionally, with regard to the other physical measurements as density and viscosity in addition to electrical properties, such as withstand voltage and DDF, the result concluded that the rate of change of Diala S_4 as GTL oil is very limited at different durations of aging. Unlike the other type of Diala S_2 as mineral oil, this can be explained because GTL oil is free of sulfur, as it is one of the elements that affect the properties of oils in the aging process.

Whereas, by studying the chemical properties, it is noticed that there is a difference in the moisture and acidity measurements of the two types of oils over different aging durations, as shown in Figure 13. This indicates that the chemical compositions of these oils, i.e., Diala S_4 as GTL and Diala S_2 as mineral oil, are affected by thermal aging.

On the other hand, under the abnormal conditions with medium thermal fault type, the dissolved gas analysis result showed that the two types of oils were not affected by the thermal fault, as the concentration of gases remained within the permissible limits, and this is due to the low carbon emission of these oils, as showing in Figure 18. Hence, it can be concluded that the DGA test is not effective for these oils under thermal fault.

Additionally, the physical bonds of Diala S_2 oil were evaluated by UV-Vis and PL spectroscopy, as the results of lower absorbance for GTL oil compared to the other type, showed that when the external radiation incidents on the mineral oil atoms. These atoms are excited, and this results in electrons and ions being freed, also these ions increase the dielectric losses of the insulating oil. On the other hand, due to GTL oil's strong physical bonds, fewer electrons emitted can be negligible (see Figures 15, 17, and 18). Hence, the dielectric losses were less than that of the other mineral oil types.

V. CONCLUSION

A comprehensive experimental work for studying the behavior of two insulating oils (Diala S_2 as mineral oil and Diala S_4 as GTL oil) is presented. Fresh and aged oil samples have been used in testing for studying the oil quality and its properties due to aging. To the best of our knowledge, this extensive experimental study has not been reported in the literature. The electrical, chemical, and physical properties of the two oil samples have been measured and can be summarized as follows:

- For Diala S₂, the BDV mean value is decreased with aging (3, 6, and 10 days), where the breakdown voltage of Diala S₂ is decreased by aging. While, for Diala S₄, the BDV is decreased with an aging duration of 3 and 6 days. Then, BDV returns to increase at 10 aging days with a value higher than the aged sample (6 days) of oil itself, and also higher than the relevant value of Diala S₂. Hence, the BDV of Diala S₄ is increased and improved after 10 aging days.
- The dielectric dissipation factor of Diala S_2 increases with aging with a value higher than the DDF for fresh oil samples. While the DDF of Diala S_4 has slightly decreased lower than the DDF of the fresh sample. Up to 6 days of aging, the DDF of Diala S_4 was not affected by aging and is better than the relevant value of Diala S_2 as the aged byproducts in Diala S_4 are lower than the Diala S_2 , at 10 days of aging, its DDF significantly increased with compared to its value at 3 and 6 days of aging.

- The relative permittivity for the fresh and aged oil samples of the Diala S_2 is slightly higher than the relevant value of Diala S_4 . However, with oil aging, the relative permittivity of Diala S_2 is slightly increased while, for Diala S_4 , the relative permittivity is slightly decreased.
- For the chemical and physical tests, Diala S₄ has less effect than mineral oil by aging.
- Up to 6 days of aging, the resistivity for the fresh and aged oil samples of the Diala S_4 is higher than the relevant value of Diala S_2 . Also, with aging, the resistivity of Diala S_4 is slightly increased, while the resistivity of Diala S_2 is slightly decreased. At 10 days of aging, the resistivity of Diala S_4 reduced to a value less than Diala S_2 at 10 days of aging.
- The detected concentrated gases CH_4 , C_2H_6 , and C_2H_4 , of Diala S_2 , are increased with heating thermal fault compared with the Diala S_4 oil type. In the case of Diala S_4 , H_2 is affected by a thermal fault in addition to the other gases (CH_4 , C_2H_6 , and C_2H_4). Also, carbon dioxide (CO_2) concentration for Diala S_2 was 4.2 times Diala S_4 , and CO_2 concentration for Diala S_2 was 1.6 times Diala S_4 . This ensures that Diala S_4 has lower carbon emissions compared to Diala S_2 .
- For aged oil samples, the UV absorption spectra are gradually increased, with increasing aging duration, compared with the fresh oil sample. This is due to the formed aged byproducts.
- Using PL spectroscopy, the FWHM and area under the PL curve are constant for Diala S₄ fresh and aged oil samples. This is due to the aging byproducts formed by PL spectroscopy containing non-emitting molecules, which means the Diala S₄ oil has a lower aromatic component without changing the oil color and behaves as resistant to thermal aging, resulting in improving the oil stability compared with the Diala S₂ oil.

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REFERENCES

- P. Bohatyrewicz, J. Płowucha, and J. Subocz, "Condition assessment of power transformers based on health index value," *Appl. Sci.*, vol. 9, no. 22, p. 4877, Nov. 2019.
- [2] A. D. Ashkezari, H. Ma, T. K. Saha, and C. Ekanayake, "Application of fuzzy support vector machine for determining the health index of the insulation system of in-service power transformers," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 20, no. 3, pp. 965–973, Jun. 2013.
- [3] P. K. Maiti and M. Chakraborty, "Dissolved gas analysis of thermally aged mineral oil and vegetable oil based nanofluids," in *Proc. IEEE Int. Conf. Properties Appl. Dielectric Mater. (ICPADM)*, Johor Bahru, Malaysia, Jul. 2021, pp. 53–56.
- [4] D. A. Mansour, E. M. Shaalan, S. A. Ward, A. Z. El Dein, H. S. Karaman, and H. M. Ahmed, "Multiple nanoparticles for improvement of thermal and dielectric properties of oil nanofluids," *IET Sci., Meas. Technol.*, vol. 13, no. 7, pp. 968–974, Sep. 2019.
- [5] A. Ghaffarkhah, M. Afrand, M. Talebkeikhah, A. A. Sehat, M. K. Moraveji, F. Talebkeikhah, and M. Arjmand, "On evaluation of thermophysical properties of transformer oil-based nanofluids: A comprehensive modeling and experimental study," *J. Mol. Liquids*, vol. 300, Feb. 2020, Art. no. 112249.

- [6] R. A. Farade, N. I. A. Wahab, D. A. Mansour, N. B. Azis, J. B. Jasni, V. Veerasamy, M. Thirumeni, A. X. R. Irudayaraj, and A. S. Murthy, "Investigation of the effect of sonication time on dispersion stability, dielectric properties, and heat transfer of graphene based green nanofluids," *IEEE Access*, vol. 9, pp. 50607–50623, 2021.
- [7] H. Alizadeh, H. Pourpasha, S. Z. Heris, and P. Estellé, "Experimental investigation on thermal performance of covalently functionalized hydroxylated and non-covalently functionalized multi-walled carbon nanotubes/transformer oil nanofluid," *Case Stud. Thermal Eng.*, vol. 31, Mar. 2022, Art. no. 101713.
- [8] J. Fal, O. Mahian, and G. Żyła, "Nanofluids in the service of high voltage transformers: Breakdown properties of transformer oils with nanoparticles, a review," *Energies*, vol. 11, no. 11, p. 2942, Oct. 2018.
- [9] E. G. Atiya, D. A. Mansour, and M. A. Izzularab, "Partial discharge development in oil-based nanofluids: Inception, propagation and time transition," *IEEE Access*, vol. 8, pp. 181028–181035, 2020.
- [10] B. Chakraborty, K. Y. Raj, A. K. Pradhan, B. Chatterjee, S. Chakravorti, and S. Dalai, "Investigation of dielectric properties of TiO2 and Al₂O₃ nanofluids by frequency domain spectroscopy at different temperatures," *J. Mol. Liquids*, vol. 330, May 2021, Art. no. 115642.
- [11] A. Santisteban, A. Piquero, F. Ortiz, F. Delgado, and A. Ortiz, "Thermal modelling of a power transformer disc type winding immersed in mineral and ester-based oils using network models and CFD," *IEEE Access*, vol. 7, pp. 174651–174661, 2019.
- [12] R. A. Prasojo, M. A. A. Putra, Ekojono, M. E. Apriyani, A. N. Rahmanto, S. S. M. Ghoneim, K. Mahmoud, M. Lehtonen, and M. M. F. Darwish, "Precise transformer fault diagnosis via random forest model enhanced by synthetic minority over-sampling technique," *Electr. Power Syst. Res.*, vol. 220, Jul. 2023, Art. no. 109361.
- [13] U. M. Rao, I. Fofana, P. Rozga, P. Picher, D. K. Sarkar, and R. Karthikeyan, "Influence of gelling in natural esters under open beaker accelerated thermal aging," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 30, no. 1, pp. 413–420, Feb. 2023.
- [14] M. N. Lyutikova, S. M. Korobeynikov, U. M. Rao, and I. Fofana, "Mixed insulating liquids with mineral oil for high-voltage transformer applications: A review," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 29, no. 2, pp. 454–461, Apr. 2022.
- [15] W. Lu and Q. Liu, "Prebreakdown and breakdown mechanisms of an inhibited gas to liquid hydrocarbon transformer oil under positive lightning impulse voltage," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 4, pp. 2450–2461, Aug. 2016.
- [16] H. S. Karaman, A. Z. El Dein, D.-E.-A. Mansour, M. Lehtonen, and M. M. F. Darwish, "Influence of mineral oil-based nanofluids on the temperature distribution and generated heat energy inside minimum oil circuit breaker in making process," *Nanomaterials*, vol. 13, no. 13, p. 1951, Jun. 2023.
- [17] S. R. Arsad, P. J. Ker, M. Z. Jamaludin, P. Y. Choong, H. J. Lee, V. A. Thiviyanathan, and Y. Z. Yang Ghazali, "Water content in transformer insulation system: A review on the detection and quantification methods," *Energies*, vol. 16, no. 4, p. 1920, Feb. 2023.
- [18] S. Y. Matharage, Q. Liu, Z. D. Wang, P. W. R. Smith, P. Mavrommatis, and P. Dyer, "Ageing assessment of a gas to liquid hydrocarbon transformer oil compared with an inhibited mineral oil," in *Proc. Int. Symp. High. Voltage. Eng. (ISH)*, Pilsen, Czech Republic, 2015, pp. 425–430.
- [19] W. Jianyi, L. Jinzhong, and Z. Shuqi, "Typical properties analysis of gasto-liquid transformer oil with natural gas as raw material," *High Voltage Eng.*, vol. 42, no. 9, pp. 2974–2979, 2016.
- [20] J. Wang, J. Li, S. Zhang, X. Liu, F. Gao, G. Jia, S. Bai, and J. Sun, "Study on water absorption behaviour of a new type of gas-to-liquid transformer oil," in *Proc. IEEE Int. Conf. High Voltage Eng. Appl. (ICHVE)*, Chengdu, China, Sep. 2016, pp. 1–4.
- [21] W. Lu, Q. Liu, and Z. D. Wang, "Pre-breakdown and breakdown mechanisms of an inhibited gas to liquid hydrocarbon transformer oil under negative lightning impulse voltage," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 5, pp. 2809–2818, Oct. 2017.
- [22] S. Y. Matharage, Q. Liu, and Z. D. Wang, "Aging assessment of Kraft paper insulation through methanol in oil measurement," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 3, pp. 1589–1596, Jun. 2016.
- [23] Y. Zhou, X. Huang, L. Zhang, Y. Zhang, Z. Zhou, and C. Teng, "Influences of temperature on space charge in gas-to-liquid oil-impregnated paper," in *Proc. IEEE Int. Conf. High Voltage Eng. Appl. (ICHVE)*, Beijing, China, Sep. 2020, pp. 1–4.
- [24] W. Lu, Q. Liu, Z. D. Wang, and P. W. R. Smith, "Lightning impulse breakdown performance of an inhibited gas-to-liquid (GTL) hydrocarbon transformer oil," in *Proc. IEEE 18th Int. Conf. Dielectric Liquids (ICDL)*, Bled, Slovenia, Jun. 2014, pp. 1–4.

- [25] Š. Hardon, J. Kúdelcík, and M. Gutten, "The dielectric spectroscopy of new generation of transformer oil shell," in *Proc. Int. Conf. Diag. Electr. Eng. (Diagnostika)*, Pilsen, Czech Republic, Sep. 2022, pp. 1–4.
- [26] Z. Liu, Q. Liu, Z. D. Wang, P. Jarman, Ch. Krause, P. W. R. Smith, and A. Gyore, "Partial discharge behaviour of transformer liquids and the influence of moisture content," in *Proc. IEEE 18th Int. Conf. Dielectric Liquids (ICDL)*, Bled, Bled, Slovenia, Jun. 2014, pp. 1–4.
- [27] M. Ahmad, I. Daris, H. Rahmat, and S. Suwarno, "Aging behavior of mineral oil, gas-to-liquid (GTL), and natural ester liquids in presence of cellulosic materials," in *Proc. 3rd Int. Conf. High Voltage Eng. Power Syst. (ICHVEPS)*, Bandung, Indonesia, Oct. 2021, pp. 501–506.
- [28] M. Meissner, E. Matic, S. Schober, M. Darmann, and M. Mittelbach, "Monitored migration of additives from thermally upgraded paper into various insulation liquids," in *Proc. IEEE 3rd Int. Conf. Dielectrics (ICD)*, Valencia, Spain, Jul. 2020, pp. 649–652.
- [29] X. Zhang, Z. Wang, Q. Liu, M. Negro, A. Gyore, and P. W. R. Smith, "Numerical investigation of influences of liquid types on flow distribution and temperature distribution in disc type ON cooled transformers," in *Proc. IEEE 19th Int. Conf. Dielectric Liquids (ICDL)*, Jun. 2017, pp. 1–4.
- [30] G. Mao, S. Li, S. Li, Z. Ge, L. Yang, and L. Jiang, "Effect of insulating oil on space charge characteristics of oil-impregnated paper under DC voltage," in *Proc. IEEE 3rd Int. Conf. Dielectrics (ICD)*, Valencia, Spain, Jul. 2020, pp. 443–446.
- [31] H. Yu, Q. Liu, Z. Wang, A. Hilker, C. Krause, and D. Walker, "Streamer and breakdown characteristics of transformer liquids in moderatelyuniform fields under negative lightning impulse," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 30, no. 4, pp. 1590–1597, Apr. 2023.
- [32] F. Stuchala and P. Rozga, "Comparative analysis of lightning properties of selected GTL based dielectric liquids under positive lightning impulse," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Quebec City, QC, Canada, Jun. 2023, pp. 1–4.
- [33] F. Stuchala and P. Rozga, "Breakdown and acceleration voltage of selected GTL based dielectric liquids under negative lightning impulse," in *Proc. IEEE 22nd Int. Conf. Dielectric Liquids (ICDL)*, Worcester, MA, USA, Jun. 2023, pp. 1–4.
- [34] H. Yu, Q. Liu, Z. Wang, C. Krause, and A. Hilker, "Effect of electric field uniformity on streamer and breakdown characteristics in a gas-to-liquid oil under positive lightning impulse," in *Proc. IEEE Int. Conf. High Voltage Eng. Appl. (ICHVE)*, Beijing, China, Sep. 2020, pp. 1–4.
- [35] K. Homeier, M. Imani, M. Kuhnke, T. Kinkeldey, and P. Werl, "Investigation on gassing behavior of various insulation liquids in power transformers," in *Proc. IEEE 20th Int. Conf. Dielectric Liquids (ICDL)*, Roma, Italy, Jun. 2019, pp. 1–4.
- [36] R. J. Densley and B. K. Gupta, "Effect of temperature on sensitivity of diagnostic tests on oil-impregnated paper insulation," in *Proc. IEEE Electr. Insul. Conf. Electr. Manuf. Coil Winding Conf.*, Cincinnati, OH, USA, Oct. 2001, pp. 601–604.
- [37] B. Pahlavanpour, M. Martins, and D. Eklund, "Study of moisture equilibrium in oil-paper system with temperature variation," in *Proc. 7th Int. Conf. Properties Appl. Dielectric Mater.*, Jun. 2003, pp. 1124–1129.
- [38] S. Abdi, A. Boubakeur, A. Haddad, and N. Harid, "Influence of artificial thermal aging on transformer oil properties," *Electr. Power Compon. Syst.*, vol. 39, no. 15, pp. 1701–1711, Oct. 2011.
- [39] T. Münster, P. Werle, K. Hämel, and J. Preusel, "Thermally accelerated aging of insulation paper for transformers with different insulating liquids," *Energies*, vol. 14, no. 11, p. 3036, May 2021.
- [40] F. Husnayain, M. Latif, and I. Garniwa, "Transformer oil lifetime prediction using the Arrhenius law based on physical and electrical characteristics," in *Proc. Int. Conf. Quality Res. (QiR)*, Lombok, Indonesia, Aug. 2015, pp. 115–120.
- [41] A. M. Alshehawy, D.-E.-A. Mansour, M. Ghali, M. Lehtonen, and M. M. F. Darwish, "Photoluminescence spectroscopy measurements for effective condition assessment of transformer insulating oil," *Processes*, vol. 9, no. 5, p. 732, Apr. 2021.
- [42] W. Sun, L. Yang, D. Feng, X. Zhao, and J. Li, "A new accelerated thermal aging test for over-loading condition transformer," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Montreal, QC, Canada, Jun. 2016, pp. 354–357.
- [43] A. Mohammad, "Condition assessment of transformer oil using optical spectroscopy," M.S. thesis, Dept. Power Mach. Eng., Tanta Univ., Tanta, Egypt, 2018.

- [44] S. S. M. Ghoneim, S. S. Dessouky, A. Boubakeur, A. A. Elfaraskoury, A. B. Abou Sharaf, K. Mahmoud, M. Lehtonen, and M. M. F. Darwish, "Accurate insulating oil breakdown voltage model associated with different barrier effects," *Processes*, vol. 9, no. 4, p. 657, Apr. 2021.
- [45] C. Pan, J. Tang, Y. Zhang, X. Luo, and X. Li, "Variation of discharge characteristics with temperature in moving transformer oil contaminated by metallic particles," *IEEE Access*, vol. 6, pp. 40050–40058, 2018.
- [46] S. Hassan, A. M. Emam, S. Ward, Z. A. Hamid, and M. Badawi, "Partial discharge detection inside transformer oils using on-line monitoring nanotechnology techniques," in *Proc. 20th Int. Middle East Power Syst. Conf. (MEPCON)*, Cairo, Egypt, Dec. 2018, pp. 452–454.
- [47] Insulating Liquid—Determination of the Breakdown Voltage at Power Frequency—Test Method, IEC Standard 60156, 2018.
- [48] A. Phalphale, K. Bhagat, and S. Nagare, "Investigation of transformer oil exposed to the atmosphere," *Int. J. Manag., Technol. Eng.*, vol. 8, no. 11, pp. 706–713, 2018.
- [49] O. Arikan, C. F. Kumru, and C. Kocatepe, "Measurement of the dielectric performance of an instrument transformer at different voltage and frequencies," in *Proc. Int. Conf. High Voltage Eng. Appl.*, Shanghai, China, Sep. 2012, pp. 451–454.
- [50] N. K. Mandavgade, S. B. Jaju, and R. R. Lakhe, "Measurement uncertainty evaluation of automatic tan delta and resistivity test set for transformer oil," *Int. J. Metrol. Quality Eng.*, vol. 3, no. 1, pp. 39–45, 2012.
- [51] Insulating Liquids Measurement of Relative Permittivity, Dielectric Dissipation Factor (TAN) and D.C. Resistivity, IEC Standard 60247, 2004.
- [52] Insulating Liquids—Oil-Impregnated Paper and Pressboard— Determination of Water By Automatic Coulometric Karl Fischer Titration, IEC Standard 60814, 2017.
- [53] Insulating Liquids—Determination of Acidity, IEC Standard 62021, 2014.
- [54] Y. Hadjadj, I. Fofana, J. Sabau, and E. Briosso, "Assessing insulating oil degradation by means of turbidity and UV/VIS spectrophotometry measurements," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 5, pp. 2653–2660, Oct. 2015.
- [55] M. A. Mehmood, J. Li, F. Wang, Z. Huang, J. Ahmad, and M. S. Bhutta, "Analyzing the health condition and chemical degradation in field aged transformer insulation oil using spectroscopic techniques," in *Proc. Int. Conf. Diag. Electr. Eng. (Diagnostika)*, Pilsen, Czech Republic, Sep. 2018, pp. 1–4.
- [56] M. Srinivasan and S. Burnwal, "UV visual spectral response of transformer oil under the impact of thermal and electrical stress," in *Proc. Fist Int. Conf. Adv. Sci. Innov. Sci., Eng. Technol. (ICASISET)*, Chennai, India, 2021, pp. 16–17.
- [57] D. L. Pavia, G. M. Lampman, G. S. Kriz, and J. R. Vyvyan, *Introduction to Spectroscopy*, 5th ed. Stamford, CT, USA: Cengage Learning, 2013.
- [58] D. Harvey, "Spectroscopic methods of analysis," in *Modern Analytical Chemistry*, 1st ed. New York, NY, USA: McGraw-Hill, 2000, pp. 384–388.
- [59] M. M. F. Darwish, M. H. A. Hassan, N. M. K. Abdel-Gawad, M. Lehtonen, and D. A. Mansour, "A new technique for fault diagnosis in transformer insulating oil based on infrared spectroscopy measurements," *High Voltage*, vol. 9, no. 2, pp. 319–335, Apr. 2024.
- [60] A. M. Alshehawy, D. A. Mansour, A. Rezk, and M. Ghali, "Impact of thermal aging of transformer oil on UV-vis optical spectrum and dielectric properties," in *Proc. 18th Int. Middle East Power Syst. Conf. (MEPCON)*, Cairo, Egypt, Dec. 2016, pp. 860–865.
- [61] Oil-Filled Electrical Equipment—Sampling of Gases and Analysis of Free and Dissolved Gases—Guidance, IEC Standard 60567, 2011.
- [62] IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers, IEEE Standard C57.104, 2008.
- [63] S. A. Ward, A. El-Faraskoury, M. Badawi, S. A. Ibrahim, K. Mahmoud, M. Lehtonen, and M. M. F. Darwish, "Towards precise interpretation of oil transformers via novel combined techniques based on DGA and partial discharge sensors," *Sensors*, vol. 21, no. 6, p. 2223, Mar. 2021.
- [64] S. Li, M. Karlsson, R. Liu, A. Ahniyaz, A. Fornara, and E. J. Salazar-Sandoval, "The effect of ceria nanoparticles on the breakdown strength of transformer oil," in *Proc. IEEE 11th Int. Conf. Properties Appl. Dielectric Mater. (ICPADM)*, Jul. 2015, pp. 289–292.
- [65] W. Yuan, T. Wang, H. Ni, M. Gao, Y. Ding, Y. Li, Y. Zhao, and Q. Zhang, "Weibull statistical analysis of size effects on the impulse breakdown strength in transformer oil," in *Proc. IEEE 19th Int. Conf. Dielectric Liquids (ICDL)*, Jun. 2017, pp. 1–4.
- [66] Y. Wang, S. Gong, and S. Grzybowski, "Reliability evaluation method for oil-paper insulation in power transformers," *Energies*, vol. 4, no. 9, pp. 1362–1375, Sep. 2011.

- [67] H. S. Karaman, D.-E.-A. Mansour, M. Lehtonen, and M. M. F. Darwish, "Condition assessment of natural ester-mineral oil mixture due to transformer retrofilling via sensing dielectric properties," *Sensors*, vol. 23, no. 14, p. 6440, Jul. 2023.
- [68] J. Wada, G. Ueta, S. Okabe, and T. Amimoto, "Influence of trace components contained in transformer insulating oil on various characteristics over time," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 20, no. 4, pp. 1388–1394, Aug. 2013.
- [69] M. Kohtoh, G. Ueta, S. Okabe, and T. Amimoto, "Transformer insulating oil characteristic changes observed using accelerated degradation in consideration of field transformer conditions," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 3, pp. 808–818, Jun. 2010.
- [70] S. S. Dessouky, D.-E.-A. Mansour, M. Shaban, and S. A. M. Abdelwahab, "Insulation performance enhancement of aged current transformers using nanofluids," *Int. J. Electr. Power Energy Syst.*, vol. 126, Mar. 2021, Art. no. 106613.
- [71] M. M. F. Darwish, M. H. A. Hassan, N. M. K. Abdel-Gawad, and D. A. Mansour, "A new method for estimating transformer health index based on ultraviolet-visible spectroscopy," in *Proc. 23rd Int. Middle East Power Syst. Conf. (MEPCON)*, Cairo, Egypt, Dec. 2022, pp. 1–5.
- [72] M. M. F. Darwish, M. H. A. Hassan, N. M. K. Abdel-Gawad, and D. A. Mansour, "Application of infrared spectroscopy for discrimination between electrical and thermal faults in transformer oil," in *Proc. 9th Int. Conf. Condition Monitor. Diagnosis (CMD)*, Nov. 2022, pp. 255–258.
- [73] Standard Practice for Describing and Measuring Performance of Ultraviolet and Visible Spectrophotometers, ASTM Standard D6802, ASTM E275, 2013.
- [74] S. A. Ward, A. EL-Faraskoury, M. Badwi, and S. A. Ibrahim, "A modified dissolved gas analysis technique as a diagnostic tool for faults in power transformers," in *Proc. 21st Int. Middle East Power Syst. Conf.* (*MEPCON*), Cairo, Egypt, Dec. 2019, pp. 639–644.
- [75] M. Badawi, S. A. Ibrahim, D. A. Mansour, A. A. El-Faraskoury, S. A. Ward, K. Mahmoud, M. Lehtonen, and M. M. F. Darwish, "Reliable estimation for health index of transformer oil based on novel combined predictive maintenance techniques," *IEEE Access*, vol. 10, pp. 25954–25972, 2022.
- [76] P. Havran, R. Cimbala, J. Kurimský, M. Rajňák, B. Dolník, D. Medved, and J. Király, "Dielectric relaxation response of electrical insulating liquids under different natures of thermal stress," *J. Mater. Res. Technol.*, vol. 25, pp. 1599–1611, Jul. 2023.
- [77] P. Havran, R. Cimbala, J. Király, M. Rajňák, S. Bucko, J. Kurimský, and B. Dolník, "Frequency-dependent dielectric spectroscopy of insulating nanofluids based on GTL oil during accelerated thermal aging," *Processes*, vol. 10, no. 11, p. 2405, Nov. 2022.
- [78] J.-C. Carrillo, H. Shen, F. Momin, O. Kral, H. Schnieder, and S. Kühn, "GTL synthetic paraffin oil shows low liver and tissue retention compared to mineral oil," *Food Chem. Toxicol.*, vol. 159, Jan. 2022, Art. no. 112701.



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