Influence of Thermal Ageing on Dielectric Properties of Natural Ester Oil-impregnated Paper

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***Abstract*— Mineral oil is widely used as a dielectric liquid in high voltage direct-current (HVDC) converter transformers because of its excellent electrical insulating and cooling properties. Due to the low biodegradability and high fire risk of mineral oil, natural ester oil is gaining considerable interest as a potential alternative for HVDC converter transformers. This requires more information thorough understanding of the electrical behaviours of natural ester oil under various conditions. This paper compares the impact of thermal ageing on the space charge characteristics of natural ester oil-impregnated paper to mineral oil-impregnated paper. During thermal ageing, although the increased acidity caused by the natural ester oil led to more charge accumulation in natural ester oil-impregnated paper compared to the mineral oil, the natural oil-impregnated paper showed a higher DC breakdown voltage.**

***Index Terms*— mineral oil, natural ester oil, space charge, thermal ageing, pulsed electroacoustic method (PEA), DC breakdown**

I. Introduction

THE HVDC transmission system is becoming more vital as energy demand sharply rises. HVDC technology for long-distance transmission, asynchronous interconnections and long submarine cables is widely acknowledged as being economically and technically advantageous [1]. The HVDC converter transformer is the most crucial component of the HVDC power transmission system in regard to reliable and sustainable operations [2]. Unlike conventional transformers, HVDC converter transformers operate in complicated conditions where AC, DC, and DC polarity reversal stresses exist [3]. Particularly under DC conditions, it is easy for dielectric materials to accumulate space charges, which can enhance the local electric field and accelerate ageing or possibly cause premature breakdown [2]. The performance of an HVDC converter transformer primarily depends on its insulation system. The primary insulating materials of an HVDC converter transformer are cellulose and mineral oil.

Cellulose functions not only as an electrical insulator but also as mechanical support, winding tube, and spacer block [4]. Mineral oils are generally recognised as an outstanding dielectric liquid and cooling medium for high voltage power transformers [5]. However, mineral oils are non-renewable resources produced from crude petroleum reservoirs, and they are nonbiodegradable, which has a harmful influence on health and the environment [5]. In addition, mineral oils typically have a flash and fire point of 160°C–180°C, so they are highly flammable [6]. Therefore, this environmental awareness demands the substitution of mineral oils in HVDC converter transformers.

Natural ester oil is one of the most promising candidates to replace mineral oils for HVDC converter transformers. They are produced from plentiful renewable resources, such as soybean and rapeseed, which are fully biodegradable [6]. Furthermore, natural ester oil has a relatively higher flash and fire point (above 300°C) than mineral oil, reducing fire risk significantly [6].

Transformer oil and cellulose are subject to electrical, mechanical, and thermal stresses and degrade over time during the operation of transformers [7]. When transformers are exposed to long-term thermal stress, cellulose can become brittle and might break away from the transformer winding, causing sludge to accumulate [7]. Additionally, due to the effect of thermal ageing, water can be created as a by-product, and local carbonisation of the paper can increase conductivity, which can lead to overheating and conductor failures [7]. Natural ester oils are resilient to fire, easily biodegradable, and devoid of corrosive sulphur compounds [8]. In addition, it has been verified that ester-based fluids improve the lifespan of cellulose insulation, offering additional advantages to transformers. Even so, further information is still required regarding the dielectric performance of natural ester oil

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through DC electric fields, as ester oils are predominantly used in distribution transformers [8]. The thermal ageing effect on mineral oil-impregnated paper has been actively investigated [3]. By comparing with the mineral oil-impregnated paper, this article explores how thermal ageing affected the space charge characteristics of the natural ester oil-impregnated paper.

II. METHODOLOGY

A. Sample Preparation

In this experiment, two different types of transformer oils were used, i.e., Midel eN 1204 (natural ester oil) and Shell Diala 3S ZX-IG (mineral oil). The physicochemical properties of natural ester oil and mineral oil are detailed in Table I. For this study, Kraft paper with a thickness of 100μm was used.

TABLE I
PHYSIOCHEMICAL PROPERTIES OF NATURAL ESTER OIL AND MINERAL OIL

Property	Natural Ester Oil (Midel eN 1204)	Mineral Oil (Shell Diala 3S ZX-IG)
Fire Point (°C)	>350	-
Flash Point (°C)	>315	136
Pour Point (°C)	-31	-57
Density at 20°C (g/cm^3)	0.92	0.88
Viscosity at 40°C (mm^2/s)	28.8	8
Biodegradability (%)	>90	<10

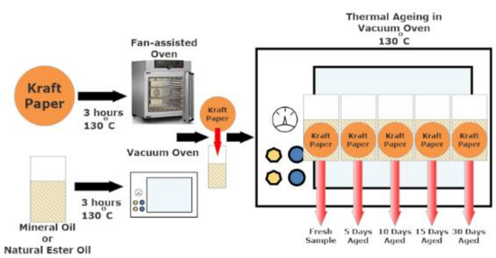


Fig. 1. Sample preparation for the thermal ageing process.

Fig. 1 depicts the methodology for investigating how thermal ageing degrades transformer oil-impregnated paper by comparing natural ester oil and mineral oil. The Kraft papers were placed in the fan-assisted oven, whilst the transformer oils (natural ester oil and mineral oil) were placed in the vacuum oven for 3 hours at 130°C. This reduced the amount of water in Kraft paper and transformer oils to minimise the influence of moisture. Then, the degassed Kraft papers were respectively impregnated with degassed natural ester oil and mineral oil for 24 hours in a vacuum oven. Afterwards, samples were thermally aged by heating them to 130°C in a vacuum oven [9]. When each sample attained the specified ageing durations (0 days, 5 days, 10 days, 15 days, and 30 days), it was removed from the vacuum oven for the rest of the measurements.

As seen in Fig. 2, as thermal ageing progressed, the colour of natural ester and mineral oils became darker compared to fresh oils.

Fig. 2. Discolouration of natural ester and mineral oils during thermal ageing.

TABLE II
MOISTURE CONCENTRATIONS IN NATURAL ESTER OILS AND MINERAL OILS DURING THERMAL AGEING

Ageing Time (days)	Moisture Concentrations in Natural Ester Oil (ppm)	Moisture Concentrations in Mineral Oil (ppm)
Day 0	32.27	6.43
Day 5	33.91	6.96
Day 10	31.48	5.9
Day 15	37.48	5.23
Day 30	39.33	6.26

1mL of oil was added to Aquamax Karl Fischer titrator to monitor the changes in moisture in fresh and aged natural ester oil and mineral oil, as shown in Table II. Throughout thermal ageing, natural ester oils maintained moisture concentrations between 31.48 and 39.33 ppm, whereas mineral oils had moisture concentrations between 5.23 and 6.96 ppm.

B. Acids Number Measurements

The acidity of the oil was measured via titration in accordance with ASTM D-974. To determine the acidity of aged natural ester oil and mineral oil, a titration solvent was prepared by mixing 49.5ml of isopropyl alcohol and 0.5ml of water. Then, 0.25g of 1-naphtholbenzein was placed in a 25ml titration solvent to prepare the indicator solution. Afterwards, 1ml of aged oil, 50ml of titration solution, and 0.25ml of indicator solution were mixed. Then, the KOH solution, which is a mixture of 0.3g of potassium hydroxide, 0.5g of barium hydroxide, and 300ml of isopropyl alcohol, has slowly added until the colour goes from green to a stable orange.

C. Degree of Polymerisation Measurements

According to ASTM D4243, the DP of thermally aged natural ester oil-impregnated paper and mineral oil-impregnated paper was measured. 15mg of thermally aged natural ester oil-impregnated paper or mineral oil-impregnated paper was placed into distilled water, which was sonicated for 10 minutes to disperse and fully wet. Afterwards, the solution was placed into a sealed glass bottle and stirred magnetically for 20 minutes at room temperature. After adding 10ml of bis(ethylenediamine) copper (II) hydroxide solution, the mixture was stirred for at least 4 hours at room temperature. Then, the solution for DP measurement was deposited into a viscometer tube and placed into a viscometer bath at 20 °C. After allowing the temperature to stabilise for at least 30 minutes, five viscosity measurements were taken, and the DP was calculated according to the standard.

D. DC Conductivity Measurements

To assess the quasi-DC conductivity of oil-impregnated papers, the polarisation depolarisation current (PDC) technique with Omicron Spectano 100 was applied. The measurement of quasi-DC conductivity was then completed using $200V_{DC}$. The quasi-DC conductivity predominantly occurs in the low-frequency region.

E. PEA Method

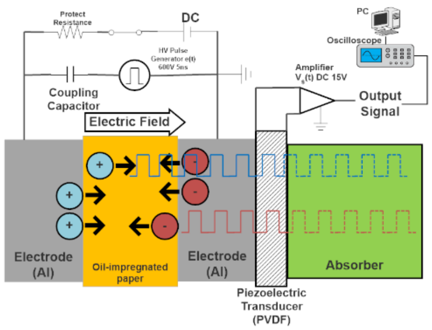


Fig. 3. A summary of the PEA system.

One of the most popular non-destructive techniques for measuring space charge profiles is the pulsed electroacoustic (PEA) method [10]. This method can perform a quantitative and qualitative investigation of charge dynamics because it does not create physical damage to dielectric substances.

A concept of the PEA system is depicted in Fig. 3. The PEA method comprises an HVDC supply that produces a high electric field across dielectric samples and a pulse generator that creates an acoustic wave through the interaction of charges [11]. The acoustic signal created by the motion of charges under the applied electric field propagates towards the piezoelectric transducer [11]. The piezoelectric transducer is composed of polyvinylidene fluoride (PVDF), which converts acoustic signals to voltage signals [11]. Then, the amplifier enhances the output voltage signal, which is transmitted to a PC for data analysis. The 5-LAB PEA system was used in this experiment to measure space charge profiles.

In this study, a single layer of natural ester oil-impregnated paper and mineral oil-impregnated paper with different ageing times were applied between two electrodes, respectively. A semi-conductive layer was inserted between oil-impregnated paper and the upper electrode to enhance acoustic impedance matching. In order to explore the space charge characteristics, a DC electric field of 20 kV/mm was applied for 60 minutes. The space charge dissipation was then recorded for 60 minutes after removing the applied DC voltage. Each test was conducted using a new sample to eliminate the possibility of the pre-stressed influence on charge formation in the oil-impregnated paper.

F. DC Breakdown Measurements

For DC breakdown measurements, each electrode incorporates a ball bearing to hold the oil-impregnated paper in place. The 350 µm-diameter ball bearings are put on brass rods with springs that hold the sample between the two electrodes in a horizontal position. Aged mineral oil-impregnated paper and natural ester oil-impregnated paper were submerged in mineral oil and natural ester oil, respectively. A sample of 100 µm thick was used, and 500 V/s of ramp rate was applied to it. On each sample, 20 different points were taken to measure DC breakdown.

III. Experimental Results

A. Acidity

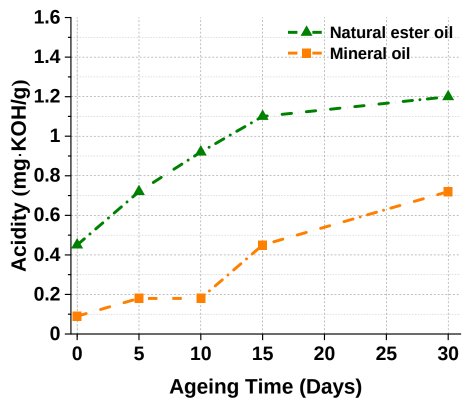


Fig. 4. Acidity of natural ester oil and mineral oil during thermal ageing.

Aged insulating paper and oil in transformers produce acids as by-products [12]. It is well known that acid in a transformer can accelerate the deterioration of an oil-paper insulation system [12]. Natural ester oil and mineral oil may have different chemical stability during thermal ageing due to their different properties.

Fig. 4 represents the acidity of natural ester oil and mineral oil during thermal ageing. As thermal ageing progressed, acid levels increased in both natural ester oil and mineral oil. The acid level of natural ester oil was considerably higher than that of mineral oil throughout thermal ageing. Natural ester oil increased from 0.45 mg·KOH/g to 1.2 mg·KOH/g, while mineral oil increased from 0.09 mg·KOH/g to 0.72 mg·KOH/g during 30 days of thermal ageing.

Natural ester oil has a triglyceride structure consisting of three fatty acids connected to a glycerol molecule [13]. Therefore, through hydrolysis, the water interacts with the triglycerides composing the natural ester to generate long-chain fatty acids [14]. In contrast, mineral oil mainly yields carboxylic acids through the oxidation of mineral oil or hydrolysis of Kraft paper during thermal ageing [15]. Unsaturated double bonds of fatty acids frequently undergo several active reactions, such as oxidation, which reduces the oxidation stability of natural ester oil [16]. Eliminating a hydrogen atom from the methylene group adjacent to a double bond can readily generate free radicals. Peroxy radicals are created when free radicals react quickly with oxygen. Then, the oxidation process can be furthered when the peroxy radical attacks other lipid molecules, removing a hydrogen atom to create hydroperoxide and another free radical [16]. Consequently, unsaturated double bonds and the hydrolysis process in natural ester oil produce more acids than in mineral oil. Nevertheless, natural ester oil mostly creates high molecular weight acids (HMA), whereas mineral oil primarily produces low molecular weight acids (LMA) [11]. Due to the lack of aggression and solubility in HMAs, they do not significantly contribute to the degradation of Kraft paper [17]. On the other hand, LMAs are more hydrophilic and corrosive and absorbed by Kraft paper, accelerating cellulose degradation [17].

During thermal ageing, natural ester oil mainly produces HMAs, which are not aggressive, but natural ester oil still produces more acids compared to mineral oil. Even though HMAs from natural ester oil are beneficial, they still have some impact on dielectric properties [18]. Thus, it is crucial to understand how the space charge characteristics of natural ester oil-impregnated paper are affected by the acidity that occurs during thermal ageing.

B. Degree of Polymerisation

Cellulose consists of alpha-D-glucose units, and the degree of polymerisation (DP) is measured by the number of monomer glucose units, which for new paper might range from 1100 to 1600 [19]. However, after drying and oil impregnation, the DP number may decrease by 10% of its initial value [19]. Thermal ageing is a primary factor that reduces the DP via depolymerisation. When cellulose is depolymerised, the linkages are broken through hydrolytic decomposition and ring structure breakdown, which produces by-products such as CO, CO_2, and water [19]. By lowering the DP, cellulose's mechanical strength is consequently diminished. Therefore, it is crucial to comprehend how different effects of natural ester oil and mineral oil on cellulose's mechanical strength during thermal ageing.

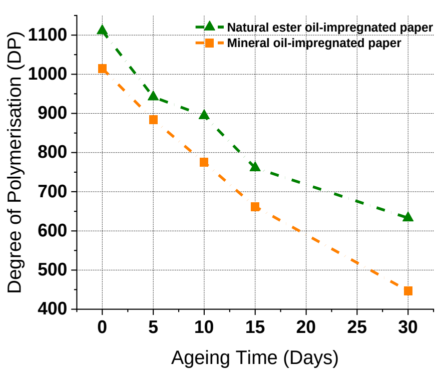


Fig. 5. Degree of polymerisation of natural ester oil-impregnated paper and mineral oil-impregnated paper during thermal ageing.

The degree of polymerisation of natural ester oil-impregnated paper and mineral oil-impregnated paper with different thermal ageing times is depicted in Fig. 5. The DP of both oil-impregnated papers gradually decreased as thermal ageing progressed. The DP of natural ester oil-impregnated paper decreased from 1111 to 633, whilst the DP of paper with mineral oil-impregnated paper reduced from 1015 to 447. The results indicated that natural ester oil had a slower rate of cellulose degradation than mineral oil.

Pyrolysis of cellulose may produce water as a by-product, which can react with the natural ester oil [19]. As a result, the natural ester oil may be able to dissolve more water, which generates more long-chain fatty acids [18]. Consequently, paper with natural ester oil may be drier than paper with mineral oil during thermal ageing. Moreover, unlike mineral oil, acids generated from natural ester oil are not aggressive towards cellulose. These effects may result in a slower degradation process for paper impregnated with natural ester oil.

Clearly, there are still many other factors to consider when analysing cellulose's mechanical strength during thermal ageing. However, according to the results, natural ester oil can protect cellulose more effectively than mineral oil as it absorbs more water and produces non-aggressive acids.

C. DC conductivity

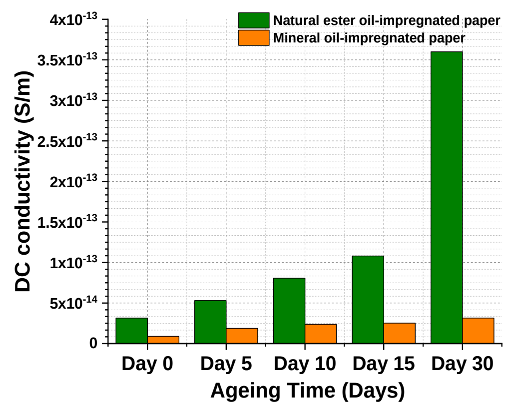


Fig. 6. DC conductivity with different thermal ageing times.

Fig. 6 shows that the DC conductivity of both the natural ester oil-impregnated paper and mineral oil-impregnated paper increased as thermal ageing progressed. During 30 days of thermal ageing, the DC conductivity of the natural ester oil increased from $3.14 \times 10^{-14} S/m$ to $3.6 \times 10^{-13} S/m$, whilst the mineral oil-impregnated paper showed that dc conductivity increased from $8.96 \times 10^{-15} S/m$ to $3.14 \times 10^{-14} S/m$. The results found that the DC conductivity of the natural ester oil impregnated-paper was much higher than that of the mineral oil-impregnated paper under thermal ageing conditions. The DC conductivity of the natural ester oil-impregnated paper rose 11.46 times from its initial state to day 30. However, after 30 days of thermal ageing, the DC conductivity of mineral oil-impregnated paper increased by only 3.5 times.

The water solubility of natural ester oil is significantly greater than that of mineral oil. In other words, natural ester oil interacts with water more vigorously during the thermal ageing period and creates more fatty acids than mineral oil. Consequently, this hydrophilic characteristic and the production of a greater amount of acid can improve the mobility of charges, resulting in a significantly greater increase in the DC conductivity for the natural ester oil-impregnated paper under thermal ageing conditions.

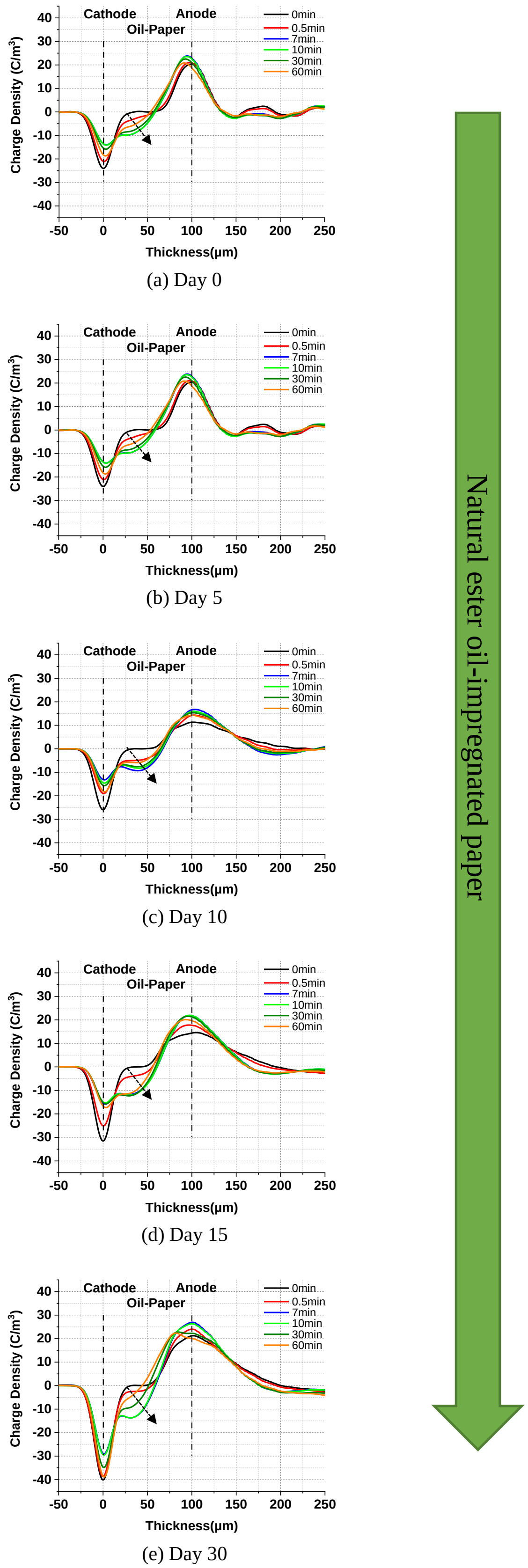


Fig. 7. Space charge characteristics of natural ester oil-impregnated paper during thermal ageing.

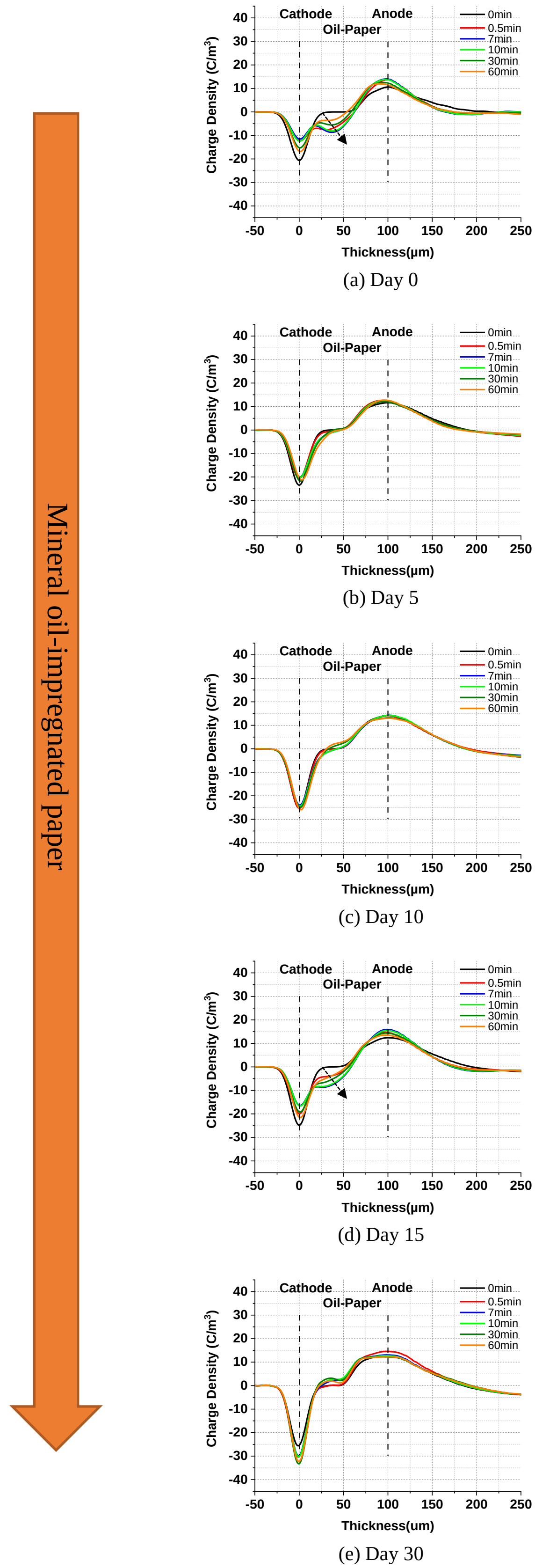


Fig. 8. Space charge characteristics of mineral oil-impregnated paper during thermal ageing.

D. Space Charge Characteristics

Space charge accumulation has been identified as a critical challenge in dielectric materials under DC conditions [20]. The presence of space charge enhances the local electric field, causing dielectric materials to degrade or possibly breakdown prematurely [20].

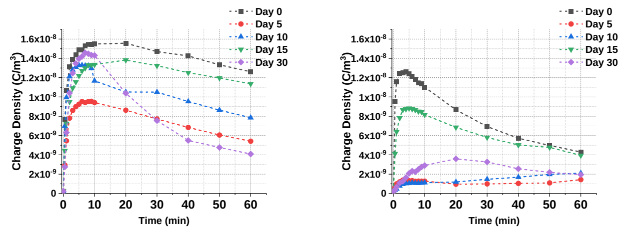
Fig. 7 and Fig. 8 represent space charge characteristics of natural ester oil-impregnated paper and mineral oil-impregnated paper under thermal ageing conditions. After applying DC voltage, the electric potential barrier between electrodes and oil-impregnated paper lowered. Therefore, when DC voltage was supplied, obvious homocharges were injected from electrodes into oil-impregnated papers.

In Fig. 7(a), when the natural ester oil-impregnated paper was in its fresh condition, negative charges were injected into it, and these charges eventually accumulated in the middle of the sample. This reduced the peak charge density near the cathode, whereas the negative charge accumulated in the middle, which induced positive charges, thereby increasing the peak charge density near the anode. After 5 and 10 days of thermal ageing in Fig. 7(b) and (c), the space charge characteristics of the natural ester oil-impregnated paper were similar to the fresh condition. Nonetheless, after 15 days, as shown in Fig. 7(d) and (e), more negative charges penetrated into the middle of the natural ester oil-impregnated paper. Because of the increased charge mobility, more negative charges were injected from the cathode, and more positive charges were injected from the anode when thermal ageing reached 30 days. Due to the recombination effect between negative and positive charges in the middle of the natural ester oil-impregnated paper, negative charges gradually decreased over time, while the positive charge accumulated in the middle. As a result, the positive charges that accumulated in the middle of the natural ester oil-impregnated paper induced negative charges adjacent to a cathode, increasing the cathode's peak charge density.

Like fresh natural ester oil-impregnated paper, when a DC voltage was applied, negative charges were injected and accumulated in the middle of the fresh mineral oil paper-impregnated paper, as shown in Fig. 8(a). However, when thermal ageing reached 5 and 10 days in Fig. 8(b) and (c), it was observed that fewer negative charges were injected into the middle of the mineral oil-impregnated paper as compared to the fresh condition. As thermal deterioration progresses, this leads to loss of moisture retention as cellulose loses fibre flexibility [21]. Therefore, it is believed that fewer negative charges were injected during the deterioration period of 5 and 10 days due to the lower amount of moisture in the cellulose than in the fresh condition. However, the loss of water retention of cellulose may increase brittleness, which causes a decrease in mechanical strength [20]. As the ageing period reached 15 days, as shown in Fig. 8(d), negative charges were injected again into the middle of the mineral oil-impregnated paper with increased acidity. When the thermal deterioration period reached 30 days in Fig. 8(e), the high acidity increased the charge mobility, resulting in the positive charge from the anode accumulated in the middle of the mineral oil-impregnated paper. Consequently, positive charges accumulated in the middle of the paper, inducing negative charges near the cathode, and increasing the peak charge density of the cathode.

Moisture is the most hazardous by-product regarding transformer operation, but when the cellulose is in the dry state, the properties of transformer oil are the most crucial factor for space charge properties during the ageing period. According to the results, the generation of fatty acids due to the water affinity of the natural ester oil led to an increase in conductivity and more space charge accumulation in the natural ester oil-impregnated paper during thermal ageing.

E. Total Charge Amount



(a) Natural ester oil-impregnated paper

(b) Mineral oil-impregnated paper

Fig. 9. Total amount of charge during thermal ageing.

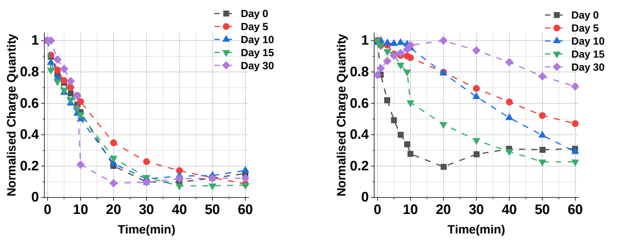
Fig. 9 depicts the total charges in the natural ester oil-impregnated paper and mineral oil-impregnated paper for 60 minutes with different thermal ageing periods. To observe the impact of thermal ageing on space charge accumulation in the sample, the charge density at electrodes was exempted. Accordingly, the total amount of charge is limited to the oil-impregnated paper. Based on Equation (1), the total amount of charges was determined [20].

$$Q_{total} = \int_0^d |\rho| \cdot S dx \tag{1}$$

where, Q_{total} is the total amount of charge, d is the thickness of oil-impregnated paper, S is the area of the electrode. Both oil-impregnated papers had the largest amount of charges when they were in a fresh state and a smaller amount of charges accumulated after thermal ageing. Then, the total amount of charge accumulated in the natural ester oil-impregnated paper gradually increased as thermal ageing progressed. However, when the mineral oil-impregnated paper reached 15 days of thermal ageing, the total charges rose due to increased acidity. The recombination effect reduced the total amount of charges after 30 days, but positive charges began to accumulate in the middle of the mineral oil-impregnated paper due to the increased acidity and DC conductivity.

F. Space Charge Decay

Fig. 10 shows space charge decay between natural ester oil-impregnated paper and mineral oil-impregnated paper under thermal ageing conditions. During thermal ageing, the natural ester oil-impregnated papers exhibited faster charge decay rates than the mineral oil-impregnated papers. Due to the presence of polar ester groups in its chemical structure, the hydrophilic nature of natural ester oil can create extra charge transport pathways, which can make it easier to move charges. This can lead to a reduction in charge-trapping properties and an increment in charge mobility, eventually leading to a faster charge decay.



(a) Natural ester oil-impregnated paper (b) Mineral oil-impregnated paper

Fig. 10. Space charge decay (normalised charge quantity)

Therefore, natural ester oils are probably better suited for high voltage applications, which require rapid charge decay to mitigate space charge accumulation, such as the polarity reversal effect.

G. Electric Field Distortion Rate

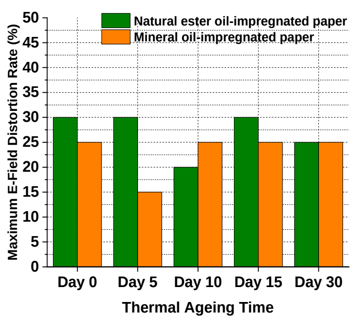


Fig. 11. Electric field distortion rate in oil-impregnated papers under thermal ageing conditions.

The space charge accumulation can enhance the electric field in specific areas of the oil-paper insulation system, hence accelerating its deterioration. Fig. 11 illustrates maximum electric field distortion rates in oil-impregnated papers under thermal ageing conditions. Equation (2) was used to determine the maximum electric field distortion rate.

$$Electric\ Field\ Enhancement = \frac{E_{max} - E_{applied}}{E_{applied}} \times 100\ (\%) \qquad (2)$$

During the 30-day thermal ageing period, natural ester oil-impregnated papers had a maximum field distortion of 20-30%, while mineral oil-impregnated papers had a maximum field distortion of 15-25%. Compared with the fresh condition, when the thermal ageing period reached 30 days, the maximum electric field distortion rate of the natural oil-impregnated paper was reduced by 5%, and the mineral oil-impregnated paper had the same maximum electric field distortion rate as the fresh condition. Eventually, when the thermal ageing reached 30 days, they had the same maximum field distortion.

H. DC breakdown

Fig. 12 describes the DC breakdown voltages of the natural ester oil-impregnated paper and mineral oil-impregnated paper. The DC breakdown voltage of the fresh natural oil-impregnated paper was 18.04 kV, and after 5 days of thermal ageing, it was 14.14 kV. After that, the DC breakdown voltage decreased slightly until a thermal ageing period of 30 days was reached.

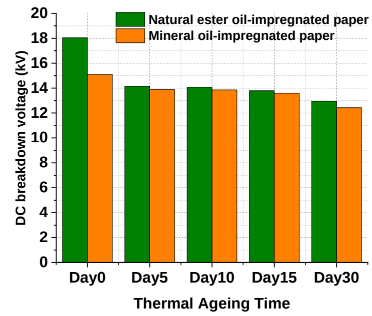


Fig. 12. DC breakdown voltages of oil-impregnated papers during thermal ageing.

However, the fresh mineral oil-impregnated paper has a DC breakdown voltage of 15.1 kV. Afterwards, the dc breakdown voltage of the mineral oil-impregnated paper slightly reduced as the thermal ageing process progressed. It was shown that the natural ester oil-impregnated paper had a higher DC breakdown voltage than the mineral oil-impregnated paper during thermal ageing. As the DP decreased due to thermal ageing, the DC breakdown voltage of natural oil-impregnated paper and mineral oil-impregnated paper was also reduced. Apart from the initial drop, the electrical strength of both oil-impregnated papers was slightly affected by further thermal ageing.

IV. Discussion

It is widely acknowledged that natural oils have much higher water affinity than mineral oils. Therefore, natural ester oils react with water to produce significantly more fatty acids than mineral oils as thermal ageing progresses.

Chemical ageing is another mechanism of ageing in Kraft paper. Kraft paper is composed of cellulose fibres, lignin, and other substances [4]. These materials have the potential to react with external chemicals like acids over time, which could result in a reduction in mechanical strength and an increase in electrical conductivity [22]. Thus, even though the total amount of space charge in the mineral oil impregnated-paper was less than that of natural ester oil-impregnated paper during thermal ageing, the DC breakdown strength was lower due to mechanical loss, which was harmed by LMA [22]. However, although the natural ester oil-impregnated paper produced a larger amount of acids than the mineral oil-impregnated paper, most acids produced by natural ester oil were HMA, which was not harmful to Kraft paper. The higher dielectric constant of the natural ester oil tends to have higher polarisability, which makes it a better solvent for polar and ionic compounds, so natural ester oil tends to absorb more polar compounds from Kraft paper compared to mineral oil [8]. Therefore, this possibly helps the natural ester oil aids to have higher breakdown strength of Kraft paper than mineral oil.

Although the amount of accumulated charge initially decreased due to a reduction of water retention in the natural ester oil-impregnated paper as thermal ageing progressed, the total charge amount increased again along with the increase in acidity. In comparison to mineral oil, natural ester oil exhibits a significantly lower ionisation potential, as demonstrated by [23]. Hence, natural ester oil requires a lower voltage to produce a substantial number of electrons than mineral oil. The ester group's greater ability to attract electrons may result in a greater impact on itself than the alkane in mineral oil, accelerating the transition from slow to fast charge injections [23]. As a result, natural ester oil generates a greater number of electrons and positive ions. During the thermal ageing period, even though more charges accumulated in the natural ester oil-impregnated paper than in the mineral oil-impregnated paper, the DC breakdown voltage was found to be greater in the natural oil-impregnated paper. This is likely because natural ester oils are more polar than mineral oils, so electrical stress in the liquid might be more evenly distributed. Therefore, the point of electric stress tends to shift from liquid to solid when Kraft paper is impregnated with mineral oil [8]. However, when Kraft paper is impregnated with natural ester oil, the point of electric stress tends to shift from a solid to a liquid, which partly explains why the oil-impregnated paper has a higher breakdown strength [8]. Nevertheless, both oil-impregnated papers that were subjected to thermal ageing did not suffer a significant reduction in their electrical strength. In addition, it demonstrated that natural ester oil has a slower DP reduction in cellulose than mineral oil, suggesting that it may provide a longer service life for cellulose.

Therefore, if the HVDC transformer is well sealed from moisture, natural ester oil has a remarkably high potential to replace mineral oil.

V. Conclusion

This study examined the effect of thermal ageing on the space charge characteristics of the natural ester oil-impregnated paper and the mineral oil-impregnated paper. The natural ester oil produced more acids than the mineral oil during thermal ageing, which may have contributed to more charge accumulation in the natural ester oil-impregnated paper. Nevertheless, both oil-impregnated papers did not experience a significant change in their electrical strength during thermal ageing. During thermal ageing, it was also discovered that the natural ester oil-impregnated paper had a higher DC breakdown voltage than the mineral oil-impregnated paper. Thus, if natural ester oil is protected well from moisture, it might replace mineral oil. Natural ester oil is a more environmentally friendly alternative to mineral oil. However, it is not yet as extensively employed in HVDC transformers as mineral oil. It is still a developing technology, and more studies are required to enhance the performance of natural ester oil so that it can fulfil the requirements of HVDC transformers.

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