

# Electrical Aging of Insulation Oils

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**Abstract-** In this investigation we have carried out a comparative electrical aging study of a natural ester, a synthetic ester, a bio-sourced hydrocarbon fluid and a conventional mineral oil. Repeated electrical discharges were applied to the oils and the resulting physical, chemical, and dielectric changes were characterized. General effects of aging include yellowing, increased water content, reduced viscosity and increased dielectric loss. Whilst the aged oils continue to meet the requirements of the applicable IEC standards for service aged oils after the maximum period of aging, the synthetic ester is less resistant to electrical aging than the natural ester, whilst the biofluid and mineral oil offer comparably good performance.

## I. INTRODUCTION

Insulating liquids are widely used both as a dielectric and as a cooling medium in most high voltage transformers. Whilst there have been many studies on the factors that affect breakdown strength of the oil, far less data exists concerning the consequences of repeated electrical breakdown events which could contribute towards the aging of the oil. Such “electrical aging” is usually simulated in the laboratory by applying high voltage impulses to an electrode system which is located either within or above the oil.

Early reports on electrical aging focused on silicone oils [1, 2] and dodecylbenzene [3], due to their use in cable terminations and reports of oil blackening in failed cable ends. In our own investigations [4-6], visible blackening of silicone oil was accompanied by increased dielectric loss, reduced AC breakdown strength, and increased electrical conductivity. Crucially we showed that the rate of aging was correlated to the average discharge power [6] - that is short duration, high energy discharges were more deleterious to the oil than long duration, low energy discharges, and aging is cumulative.

Of more relevance to transformers are studies on the electrical aging behavior of mineral and ester oils [7-13]. N’Cho et al. [7] investigated the electrical aging behavior of a mineral oil, a natural ester oil and a synthetic ester oil. All oils were visibly yellowed after aging with the synthetic ester showing the greatest increase in dielectric loss and mineral oil the least. All the tested oils emitted gasses during aging, but the gassing tendency of natural ester oil was significantly lower than that of the synthetic ester oil. Reffas et al. [8] contrasted the effects of thermal and electrical aging on olive oil - the changes during thermal aging were ascribed to evaporative loss of water and oxidation leading to increased acidity and viscosity. In contrast, electrical aging reduced the acidity and viscosity which was attributed to a lack of oxidation and molecular changes, such as fragmentation which arise from the energetic discharges, whilst

the dielectric loss was reduced, possibly due to a loss of water. Hamdi et al. [9] compared the electrical aging behavior of a series of mixtures of mineral oil and natural ester oil. It was found that the gassing tendency of the mixtures increased with increasing ester oil content but that fluids containing a higher proportion of ester oil were less discolored after aging. Elsewhere Zhang et al. [10] studied the effects of electrical aging on two natural ester oils and a mineral oil. A total of 5 - 20 breakdowns were performed, and it was noted that the resulting oils were visibly discolored with significantly less gassing evident in the natural ester oil compared to the mineral oil. Loisel et al. [11, 12] compared the electrical aging behavior of a mineral oil, a natural ester and a synthetic ester. The gassing tendency of the natural ester oil was reported to be the lowest out of the three oils whilst that of synthetic ester was higher than that of mineral oil, a finding which agrees with most of the previous investigations. Comparing ester oils with mineral oils, it was observed that mineral oils are more resistant to thermal aging whilst ester oils are more resistant to the effects of electrical aging, despite their higher gassing tendency [13].

Herein we have carried out a comparative electrical aging study of a natural ester (NE), a synthetic ester (SE), a bio sourced hydrocarbon fluid (BF) and a mineral oil (MO) using repeated electrical breakdowns. The resulting physical, chemical, and dielectric changes were characterized, the results were compared to the relevant IEC standards for service aged oils and the relative aging resistance of the various oils was then determined.

## II. EXPERIMENTAL

### A. Electrical aging apparatus

The equipment used in our previous investigations on silicone oil [4, 5] was modified to provide a waveshape that is comparable to that expected from an electrical breakdown event in a typical AC ramp to breakdown tester as employed by other authors to age oils [1, 9, 10, 11, 12]. Standards such as ASTM D877 and IEC 60156 stipulate that the current must be interrupted within half an AC cycle (pulse width  $\leq 10$  ms) with a trip current  $\leq 10$  mA. A schematic of the revised system is shown in Fig. 1 where the capacitor connected across the transformer primary provides pulse shaping and the relay was replaced with a solid-state switch. The steady state primary current was set to 0.5 A to maximize the open circuit secondary voltage (28 kV) and the switching frequency was 1 Hz. On the high voltage side, a spark plug (Champion RN9YC) with an electrode gap of 0.3 mm was immersed in the oil to be aged.

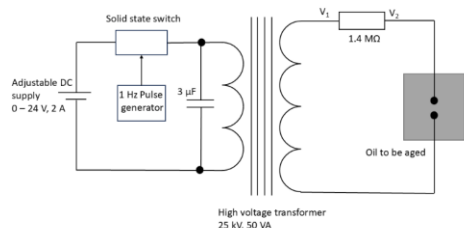


Fig. 1. Schematic of the modified electrical aging apparatus.

Measurements ( $V_1$ ,  $V_2$ ) taken across the included ballast resistor from a good number of discharges ( $> 20$ ) showed a consistent breakdown voltage of  $\sim 7$  kV and an initial current of  $\sim 5$  mA which decayed to zero over 10 ms. This corresponds to a peak power of 35 W and an integrated energy per discharge of  $45 \pm 10$  mJ. Aging of 20 ml oil samples was performed at  $40^\circ\text{C}$  (to reduce the viscosity of the ester fluids) under constant stirring for periods of 4, 8 and 16 h following previously established protocols [4-6].

### B. Analysis of aged oils

The acid number of 1 ml oil samples was determined according to IEC 62021-2 using toluene/isopropanol as solvent, naphtholbenzein as indicator and titrating with KOH solution. Water content of 1 ml oil samples was measured by direct injection into a GR Scientific Aquamax KF titrator which utilizes the potentiometric method, according to IEC 60814.

UV/Vis spectroscopy was performed on 10 ml oil samples loaded into a quartz cuvette (path length 10 mm) which was then inserted into a Perkin Elmer Lambda 35 spectrometer for analysis. Viscosity measurements were performed according to ASTM D445 on 20 ml oil samples placed into a calibrated glass viscometer tube - Paragon Scientific,  $C = 0.9328 \text{ mm}^2/\text{s}^2$  (UKAS) held in a water bath maintained at  $20 \pm 1^\circ\text{C}$ .

Determinations of the relative permittivity and dielectric loss were undertaken at room temperature according to IEC 60247; a test cell composed of a cup-plate arrangement with included 0.1 mm PTFE spacer was used to undertake measurements on 1 ml samples. The test cell was connected to a Solartron 1296 dielectric interface linked to a Schlumberger SI1260 dielectric analyzer controlled by a PC running SMART software.

## III. RESULTS

### A. Visual observations – turbidity and gassing

A visual examination (Fig. 2) revealed the oils became progressively more yellowed after aging. Before aging NE exhibited a pale-yellow color whilst the remaining oils are colorless and SE exhibited the greatest change in color due to aging, whilst BF shows the least change. Turbidity (color) is defined according to published color charts (ASTM D1500) and after a fixed period of aging, N'Cho et al. [7] reported values of around 1.0 for SE, 1.5 for MO and around 2.2 for NE which indicates that significantly increased coloration is exhibited by NE as we observe here. Other reports confirm that yellowing occurs but do not provide any quantitative data [7-9, 11].

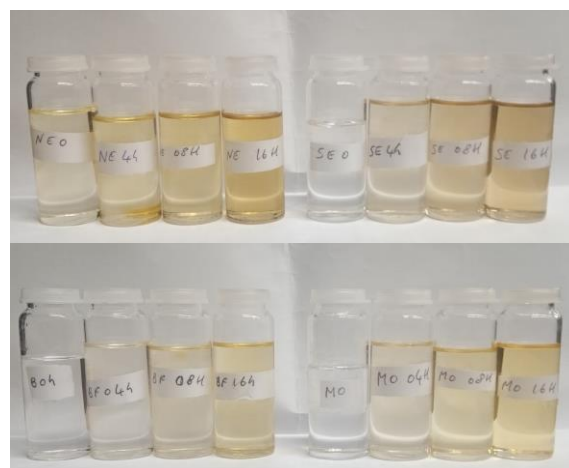


Fig. 2. Photo of the aged oils, aging times are 0, 4, 8 and 16 h and from top left to bottom right the oils are NE, SE, BF and MO.

The aged oils exhibited a pungent ozone like smell and gassing is widely reported during electrical aging [1, 3, 7, 9, 10-13]; the evolved gases are composed of hydrocarbons such as  $\text{CH}_4$ ,  $\text{C}_2\text{H}_4$ ,  $\text{C}_2\text{H}_2$ ,  $\text{H}_2$  and  $\text{CO}$  [10, 11] and in some cases  $\text{O}_2$  and  $\text{CO}_2$  [12, 13]. In our experiments very little gassing was observed from MO or BF, some bubbling was observed from NE and profuse bubbling was observed from SE. This agrees with other comparative studies [7, 9, 10, 12, 13], however no attempt was made to analyze the evolved gases here.

### B. Chemical changes due to aging

Fig. 3a shows that there is no significant change in the acid number after electrical aging. Only one of the published reports measured the acidity of electrically aged oils [8] and here, the value was slightly reduced in an olive oil which was acidic to begin with (3 mgKOH/g). The values remain significantly less than the acceptance limits specified in the IEC standards for natural ester oil ( $< 0.5$  mgKOH/g) [14], synthetic ester oil ( $< 2.0$  mgKOH/g) [15] and mineral oil ( $< 0.1$  mgKOH/g) [16].

The oils were supplied to us in sealed bottles and show a consistent oil relative humidity of  $\sim 10\%$  (Fig. 3b) [17]. After 16 h aging, the water content of the two ester fluids (NE and SE) stabilizes to a somewhat higher oil relative humidity of  $\sim 13\%$  but is unchanged in BF and MO. This behavior is consistent with other studies [7] which show a slight increase in water content of ester oils following aging. The water content of both ester-based fluids remains well within IEC acceptance limits for service aged oils;  $< 300$  mg/kg for NE [14] and  $< 400$  mg/kg for SE [15] whilst that of MO (which is followed closely by BF) is close to the acceptance limit of 20 mg/kg [16].

### C. Physical changes due to aging

In all four oils, a shift of absorption edge towards longer wavelengths (Fig. 4a) occurs as the fluid becomes gradually yellowed [10-13], see also Fig. 2. The spectra of SE show a significant level of absorbance at longer wavelengths (arrowed, Fig. 4a) which was not evident in the corresponding spectra from NE, BF or MO; this is indicative of particle formation, a general consequence of electrical aging [4-6, 10-13], with one author confirming a high particle count in synthetic ester [10].

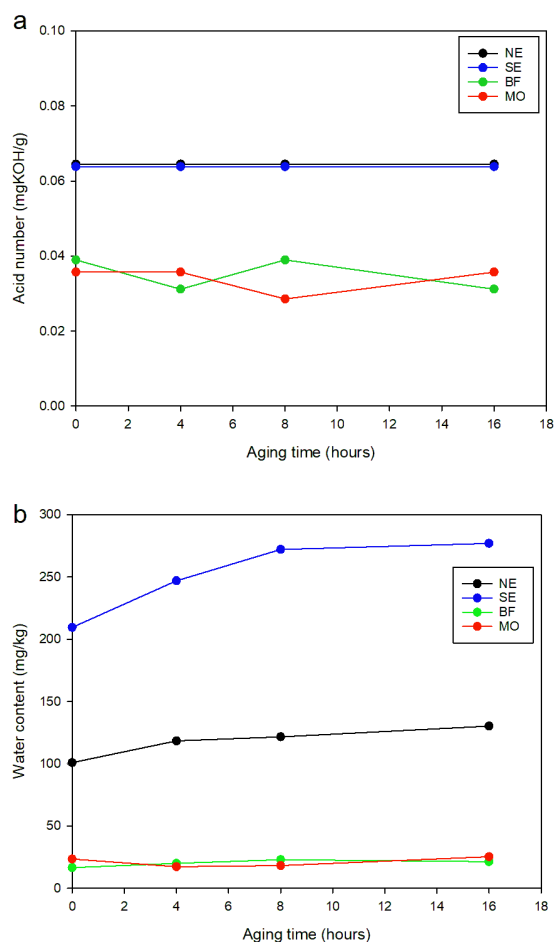


Fig. 3. Measurements of (a) acid number and (b) water content.

To quantify the changes in optical absorbance across all four oils, the wavelength corresponding to an absorbance of 0.3 has been plotted against aging time in Fig. 4b. The general trends with fluid type are in line with other studies [7, 8, 9, 13] which indicate a higher turbidity in natural ester oil and lower values in mineral oil. Significantly a greater change in turbidity is exhibited by SE compared to NE, which along with its greater propensity to produce particles and gas during aging, indicates that NE exhibits a better resistance to electrical aging than SE.

Viscosity values in Fig. 4c (uncertainty  $\pm 3 \text{ mm}^2/\text{s}$ ) show that both NE and SE exhibit a slight decrease following aging ( $1 \text{ mm}^2/\text{s}$ ). One study [8] reported comparable behavior in an electrically aged olive oil, attributing the change to molecular fragmentation. The values do not exceed IEC limits [14-16].

#### D. Changes in dielectric properties due to aging

Values at 50 Hz were extracted from the datasets and are summarized in Fig. 5. The values of relative permittivity (Fig. 5a) are consistent with expectations [8] being lower in BF and MO than in NE and SE but are unchanged after aging. The dielectric loss, which is very low initially ( $< 10^{-3}$ ), is increased after aging (Fig. 5b); the greatest increase, to a value of nearly  $10^{-2}$ , occurs in SE whilst MO and BF both exhibit the smallest increase after aging to  $< 2 \times 10^{-3}$ .

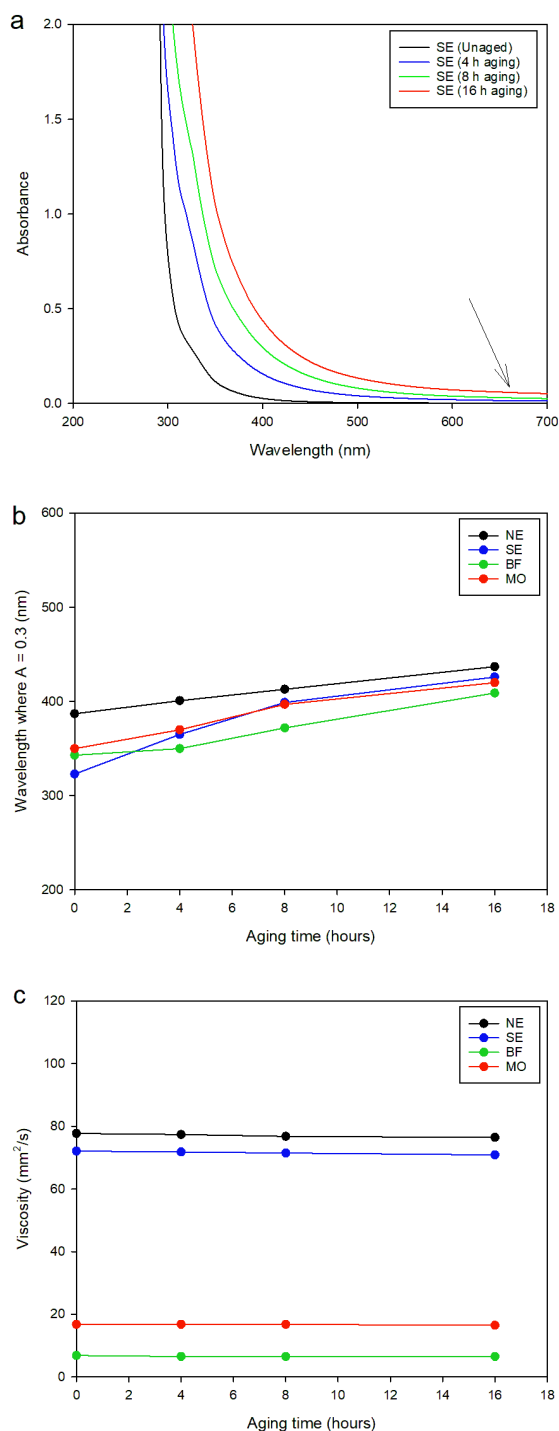


Fig. 4. (a) UV/Vis spectra, (b) comparison plot, (c) viscosity values.

In silicone oils [2, 4-6] and ester and mineral oils [7, 9] a similar invariance in relative permittivity and increase in dielectric loss was reported after aging. In the most useful comparative study [7], measurements were made at  $100^\circ\text{C}$  so the absolute values cannot be directly compared with our data, however, the same ranking was observed with synthetic ester exhibiting the greatest increase (a factor of 7), followed by natural ester (doubled) and finally mineral oil (hardly changed).

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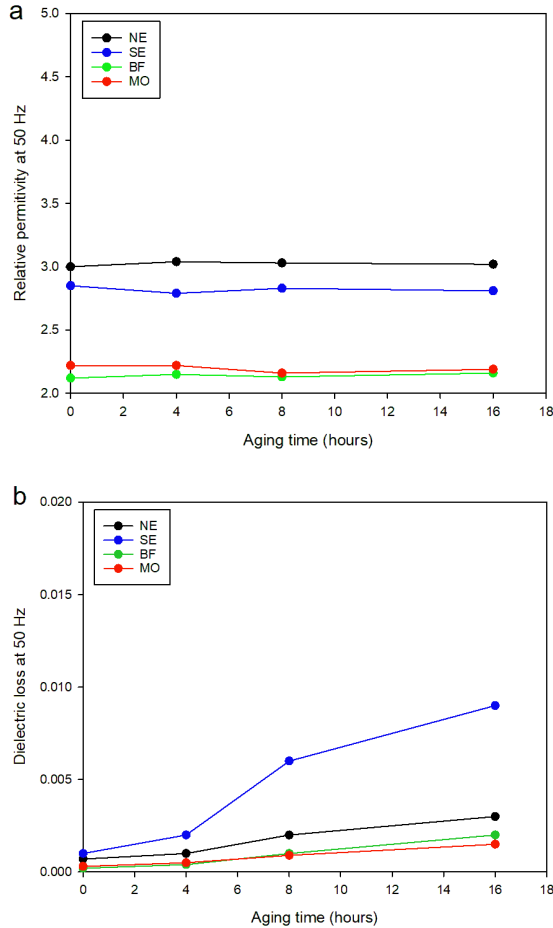


Fig. 5. Measurements of (a) relative permittivity, (b) dielectric loss.

Considering whether the aged fluids would still be fit for service in a high voltage transformer, the IEC standard for service aged synthetic ester oil [15] stipulates a maximum value of 0.01 at room temperature which is not exceeded here.

## IV. CONCLUSIONS

Electrical aging of a natural ester (NE), a synthetic ester (SE), a biofluid (BF) and a mineral oil (MO) was carried out using repeated electrical breakdowns at a rate of 1 Hz for up to 16 h.

All the oils were visibly yellowed by aging and SE exhibited the highest gassing tendency, NE an intermediate level and BF and MO the least. The water content of the two ester oils increased by ~20 % and optical absorption measurements indicated that SE produced particulate matter and exhibited the greatest change of turbidity on aging. The viscosity of the ester fluids was decreased slightly, which suggested some molecular fragmentation was occurring due to the energetic discharges.

In terms of changes in both color and dielectric loss, SE is clearly less resistant than NE to electrical aging whilst BF and MO exhibit comparably good performance. All the aged oils remained compliant with IEC standards for service aged oils even after 16 h of aging (approx. 57,600 breakdown events).