Electrical aging of silicone oil

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***Abstract*—In view of its widespread use in cable terminations, new results pertaining to electrical aging (i.e. exposure to repeated electrical discharge events) of silicone oil are reported. A new piece of equipment allowed the discharge characteristics to be controlled and the resulting blackening was correlated to the change in dielectric properties. End of life conditions were determined and the feasibility of a simple optical probe was explored. This could give the operator warning of when the oil is excessively aged, allowing remedial action to be taken.**

Keywords—silicone oil, ageing, electrical discharges

I. INTRODUCTION

Silicone oil (poly(dimethyl siloxane)) is used in certain applications where its unique characteristics, such as high temperature stability, low toxicity, water repellent ability and low flammability are of benefit. In view of its widespread use in high voltage cable terminations [1], which may see partial discharge (PD) activity in service, electrical aging studies have been carried out in the laboratory [2-5]. In these experiments oils are subjected to repeated electrical discharges and decomposition products such as hydrogen, methane, carbon-monoxide and various cyclic poly(dimethyl siloxanes) along with a solid sludge have been reported [2]. Elsewhere [3] oil taken from failed terminations was reported to be blackened in appearance and contained "a dense mist of very fine particles". Further studies report similar blackening along with increased dielectric loss [4], decreased electrical breakdown strength and increased electrical conductivity [5]. The reported blackening effects of electrical aging are similar in dodecylbenzene [6].

In view of its applications in small (traction) transformers, thermal aging studies of silicone oils have also been carried out [3-5, 7-8]. In contrast to electrical ageing, blackening does not occur in these systems [4, 5] or in comparable dodecylbenzene systems [9], indicating that blackening is specifically related to electrical aging. In accelerated laboratory aging studies a number of cyclic poly(dimethyl siloxanes) and gaseous products were reported, but in different proportions to those found after electrical aging [7] . The resulting degradation in the dielectric properties of the oil was attributed to oxidation occurring at the high aging temperatures used (>200 ^{o}C) [8]; however such extreme temperatures are unlikely to be found in traction transformers and certainly not in cable terminations [1].

Analysis of cable termination failures indicates that the oil is blackened, pointing at electrical aging [3]. Laboratory studies indicate that this diagnosis is reasonable since only a few hours exposure to electrical discharge activity at room temperature is required to cause blackening and a deleterious effect on the dielectric properties [4, 5]; such effects were confirmed elsewhere [10] where particulates were added to new oil.

The discharge characteristics used in these laboratory aging experiments are far from the typical PD behaviour which might be expected in a cable termination, this indicates a need to elucidate the effects of the discharge characteristics on aging. Here we report on a new investigation using a capacitor-discharge aging rig which permits both the energy and duration of the discharge events to be controlled. Oils were aged and UV/Vis spectroscopy was used to quantify the resulting blackening, whilst dielectric spectroscopy was used to assess the change in dielectric properties. Correlations between the discharge energy, discharge duration, the extent of blackening and increased dielectric loss were explored. The feasibility of a simple optical probe for online condition monitoring of cable terminations is then discussed.

II. EXPERIMENTAL

A. Electrical ageing

A commercial silicone oil (Dow Corning 200/20CS) was used as supplied. To permit the control of discharge energy and duration a capacitor discharge aging apparatus was constructed (Fig. 1). The high voltage vacuum relay was driven at 1 Hz for consistency with earlier work [4, 5], the necessary voltage being provided by a Glassman high voltage supply through a protection resistor *R'*. The storage capacitor *C* and discharge resistor *R* together control the discharge characteristics. The aging cell was composed of a glass beaker into which 20 ml of oil was placed and suspended in the oil was a spark plug (Champion RN9YC) with an electrode gap of 0.3 mm (± 5%) which served as the discharge source. Whilst similar

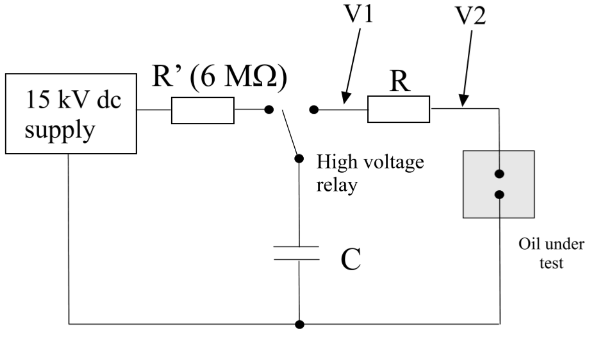

Fig. 1. Schematic of the electrical aging equipment

arrangements composed of opposing copper or aluminium wires were trialled, electro-mechanical movement caused reliability problems. A storage oscilloscope was used to collect voltage waveforms *V1* and *V2* through Keithley 1:1000 high voltage probes. From these waveforms and the known value of *R*, the current and instantaneous power were derived and finally, through integration, the total energy of the discharge event [4].

B. *Characterisation*

Before testing, the aged oil was briefly stirred to homogenise. UV/Vis spectroscopy was then immediately undertaken using a Perkin Elmer Lambda 35 spectrometer and the oil was placed within a quartz cell for analysis (10 mm path length). Dielectric loss measurements were performed using a Solartron 1296 dielectric interface linked to a Schlumberger SI 1260 impedance-gain-phase analyser. Measurements were made at 25 °C (unless otherwise stated) using a plate-cup geometry; 33 mm electrode diameter and 0.1 mm thickness (maintained by a PTFE spacer).

III. RESULTS

A. *Calibration*

A total of ten discharges were used to calibrate the equipment for each combination of *R* and *C*. Fig. 2a shows that the discharge energy is related solely to the value of the storage capacitor *C* and is independent of *R*. Using the capacitor equation $E = \frac{1}{2}CV^2$ with $V = 15$ kV and $C = 4$ nF gives a stored energy of 0.45 J; comparison to the measured energy indicates a typical efficiency of ~15 %. Maximum and minimum discharge times were limited by either the switching time of the relay (~300 ms) or the relay contact bounce time (~3 ms), therefore, Fig. 2b represents the useful working range of the apparatus. Here the discharge time is approximately 5*RC*.

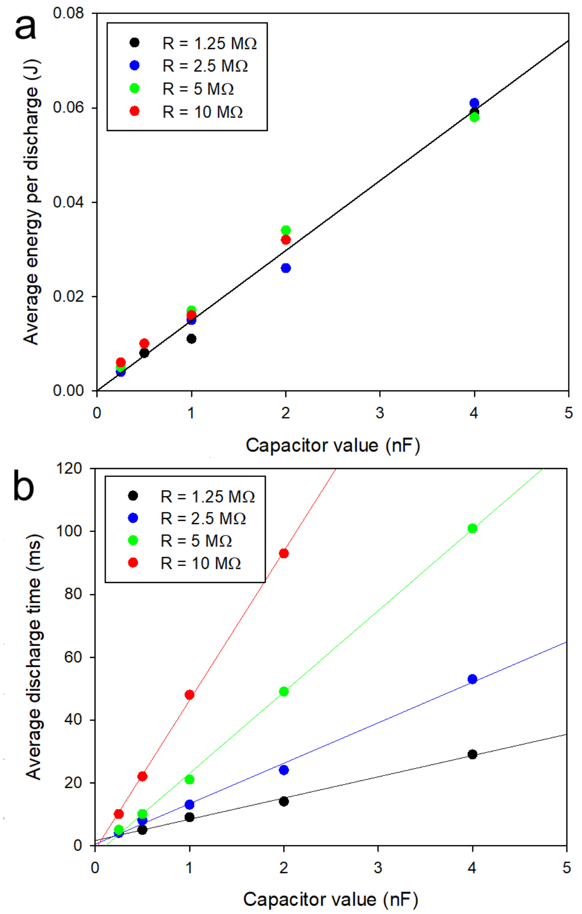

Fig. 2. Calibration results; (a) energy per discharge, (b) discharge time.

B. *UV/Vis spectroscopy*

After electrical aging, the oils became hazy then noticeably darkened and Fig. 3a shows typical as-collected spectra from a set of aged oils ($C = 2$ nF and $R = 2.5$ MΩ). Owing to the

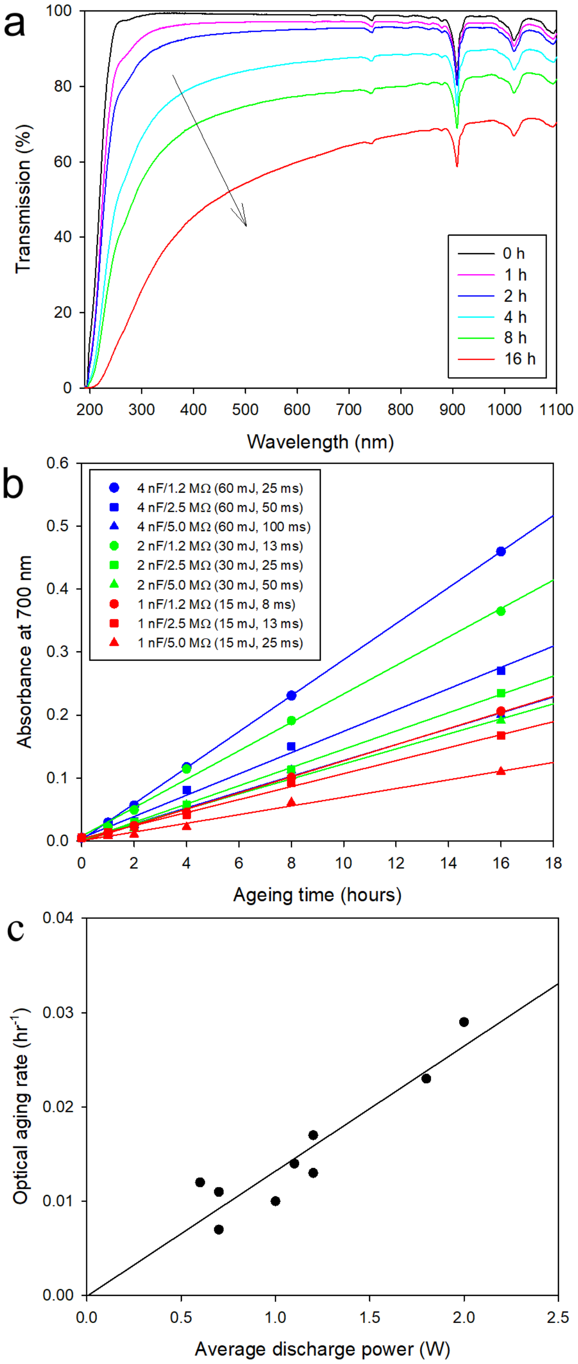

Fig. 3. UV/Vis results; (a) raw data, (b) absorbance as a function of aging time, (c) optical aging rate as a function of average power.

formation of particles, optical scattering and a reduction in optical transmission occurs over all wavelengths. Assuming the particles are simple Rayleigh scatterers, an estimate of their concentration is given by their optical absorption at any fixed wavelength. In the example shown in Fig. 3b, a wavelength of 700 nm was selected for a comparison over nine different aging conditions. The absorbance increases linearly with aging time, indicating that the effect is cumulative and results in a progressive increase in scatterer concentration.

Clearly, whilst any form of electrical discharge activity will age the oil given sufficient time, high energy, short duration discharges (i.e. high *C*, low *R*) result in a greater aging rate, indicating that the discharge power is an important variable. To quantify this, the gradient of each of the fitted lines in Fig. 3b was taken as a measure of the "optical aging rate" and were plotted in turn against the discharge energy and duration, but no clear correlation was found. However, when the optical aging rate was plotted against the "average discharge power" (defined as the discharge energy divided by the discharge time) a very reasonable correlation was obtained (Fig. 3c). This confirms that the average power of the discharge controls the aging rate.

C. *Dielectric spectroscopy*

Aging results in increased dielectric loss at all frequencies and an example of the as-collected data is shown in Fig. 4a (*C* = 4nF, *R* = 2.5 MΩ); the gradient of the fitted lines is -1 within the experimental uncertainties. Using these fits as a guide, the value of dielectric loss at power frequency (50 Hz) was extracted and plotted for the nine different aging conditions in Fig. 4b. The behavior is rather similar to that shown in Fig. 3b; the dielectric loss increases linearly with aging time and increasing the discharge energy (larger *C*) or reducing the discharge duration (smaller *R*) again results in an increased aging rate.

Repeating the same analytical process undertaken on the UV/Vis data, the equivalent set of "dielectric aging rates" were extracted from the fitted lines shown in Fig. 4b. Similarly, plots of this parameter against discharge energy or time did not reveal any clear correlation, however, there was again a good correlation with the average discharge power (Fig. 4c). The data indicate that the increase in optical absorbance, which occurs primarily due to scattering from fine particles within the oil, is closely correlated to the increased dielectric loss. Thus the scattering can be used to evaluate the condition of the oil.

D. *Towards an optical diagnostic tool*

Let us now investigate the feasibility of an optical diagnostic tool for condition monitoring of plant. Such a tool would measure absorbance over a known path length (here 10 mm) at a specific wavelength (here 700 nm). A signal can then be provided to the operator if the absorbance exceeds a certain level, remedial action or oil replacement can then be carried out before failure occurs. It was found here that the optical absorbance is correlated directly to the measured dielectric loss (Fig. 5a) and the gradient of the fitted line is 0.053 ± 0.007. The precise gradient could be influenced by contaminants or moisture in the oil so it is essential to establish a similar calibration using service aged oils prior to deployment.

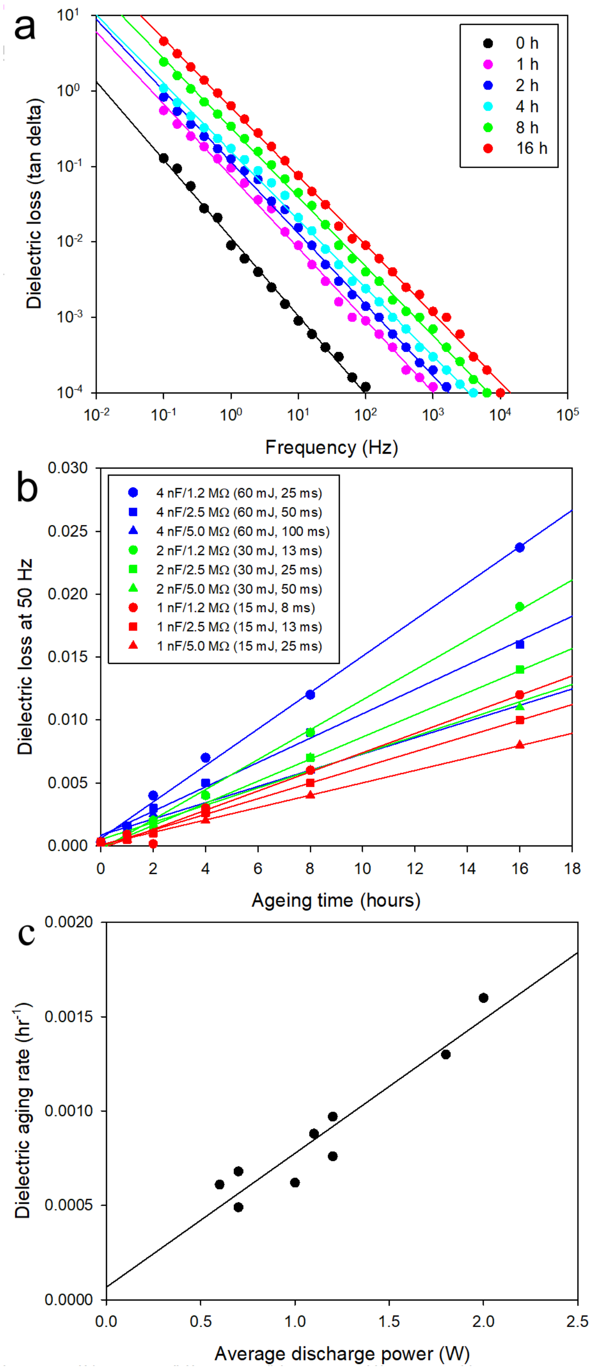

Fig. 4. Dielectric spectroscopy results; (a) raw data, (b) dielectric loss as a function of aging time, (c) dielectric ageing rate as a function of average power.

To establish an end of life condition we have considered the guidance set out in IEEE C57.111 [11] which gives maximum allowable values of dissipation factor at 60 Hz. These were converted into dielectric loss values at 50 Hz (Table I) and these agree well with BS 7704:1993 [12]. The corresponding absorbance levels were then calculated (Table I) and here values of ≤ 0.05 clearly correspond to normal service aging. Oils in this regime range from water clear to hazy in appearance (vials 1 – 3 in Fig. 5b) and are quite difficult to distinguish

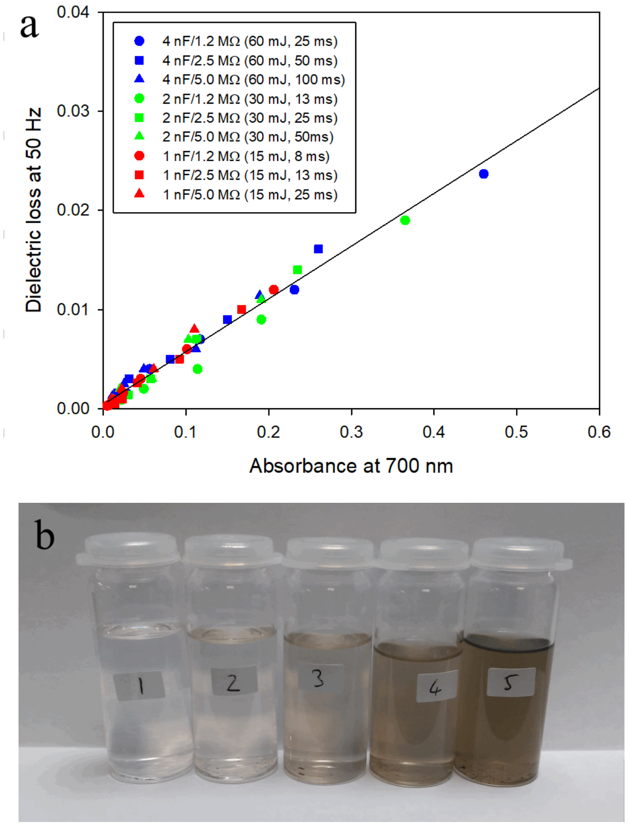

Fig. 5. (a) Correlation between dielectric loss and optical absorbance, (b) picture of oils aged using C = 2 nF, R = 1.2 MΩ; from left to right: new oil, 2 h, 4 h, 8 h and 16 h aging time.

visually. Only after aging past this point are the oils unambiguously blackened in appearance (vials 4 and 5 in Fig. 5b). The difficulty of making visual observations of the condition of normal service aged oils [3] suggests that an appropriately calibrated in-situ optical probe would be extremely beneficial for monitoring cable terminations.

It is interesting to note that to obtain an oil in end of life condition requires only 8 h of aging at our minimum energy level (C = 1 nF, R = 5 MΩ). Therefore, despite its excellent high temperature stability, silicone oil appears to be particularly susceptible to degradation from electrical discharge activity, even at low discharge energies, given sufficient time.

TABLE I. OIL CONDITION ACCORDING TO IEEE C57.111

Conditions	Allowable tan δ at 50 Hz	Optical absorbance at 700 nm	Description of oil condition
As supplied	1.3×10^{-4}	0.002	Water clear
New, in plant	1.4×10^{-3}	0.026	Slightly hazy
Used, in plant	2.7×10^{-3}	0.051	Hazy

IV. CONCLUSIONS

Electrical ageing was undertaken on silicone oil under conditions where the discharge energy and duration can be controlled. This process results in the formation of particles, which scatter over all wavelengths along with increased dielectric loss. These findings are in line with the applicable literature and crucially, as far as we can determine, there is no minimum energy under which aging does not occur - it occurs even at small energy levels given sufficient time and is cumulative with no obvious saturation.

The good correlation between the concentration of these particulates and the dielectric loss permits a simple optical diagnostic tool to be proposed for use in cable terminations. Using available standards we have established an end of life condition which could be used to warn the plant operator when remedial action is needed, before a failure event occurs.

Future work will focus on the chemistry of the aging process; to elucidate the chemical pathways applicable to the aging of silicone oils and to identify the chemical species responsible for the increase in dielectric loss. Crucially, this may point at suitable additives to mitigate the effects of aging and hence extend the lifetime of cable terminations.

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