The Influence of Magnetite Nano Particles on the Behaviour of Insulating Oils for Pulse Power Applications.

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***Abstract*- The effects of the addition of magnetite nanoparticles on the breakdown strength of three insulating liquids have been examined. The liquids considered are: a mineral transformer oil; a synthetic ester liquid, Midel 7131, and a specialist high permittivity liquid for pulse power applications THESO. The expected increases in breakdown strength were observed in the mineral oil and synthetic ester liquids. However in the case of the high permittivity liquid no significant changes in the breakdown strength were observed. Possible explanations for the differences in the observed behavior for the THESO insulating liquid are discussed.**

I. Introduction

Liquid insulation plays a significant role in the design and operation of pulse power systems as well as those involved in conventional power frequency systems. There is good evidence in the literature that the addition of magnetite (ferroferric oxide Fe_3O_4) nano particles to conventional transformer oils and to ester and synthetic ester liquids can lead to significant increases in breakdown strength [1,2,3]. This paper presents some findings as to the changes in d.c. and impulse breakdown strength due to the addition of magnetite nano particles to: a transformer oil (Grosvenor Oil Services); MIDEL 7131 a synthetic ester; and the specialist high dielectric constant THESO [4] insulating oil. These liquids were chosen because of previous work performed by the authors on their dielectric properties and breakdown behaviour and the possible interest in the pulse power community in the energy storage capabilities of the THESO insulating liquid [4].

II. Experimental

A. *Formulation of Test Fluids*

The magnetite nano particles used in the experiments reported in this paper came in the form of a ferrofluid supplied by Magnacol Ltd. The supplier quoted that the particle size as being 10nm on average. Oleic acid was used as a surfactant to allow colloidal dispersion of nano particles which were then suspended in a kerosene. The ferrofluid was mixed in differing concentrations with 60 ml samples of the insulating liquids. In the case of the transformer oil, the ferrofluid mixed readily with the oil and a stable suspension was formed. For the Midel 7131 and THESO insulating liquids it was necessary to treat the mixture in an ultrasonic bath to disperse the ferrofluid in the liquid and the magnetite particles tended to settle out of the liquid over a period of days. Therefore before any measurements were taken using these liquids the ultrasonic bath was used to re-disperse the nano particles in the liquid.

B. *Test Cell*

A point-plane test geometry was used to measure the breakdown strength of the oil ferrofluid mixtures, Fig.1. The diameter of plane electrode used was 12 mm and the needle extended 22 mm from its electrode. The radius at the tip of the stainless steel needle was ~100 µm and the separation between the tip of the needle and the plane electron was set to 2 mm. Quickfield modelling for this geometry has the field at the tip of the needle being 12.2 times the field expected in the corresponding plane parallel gap.

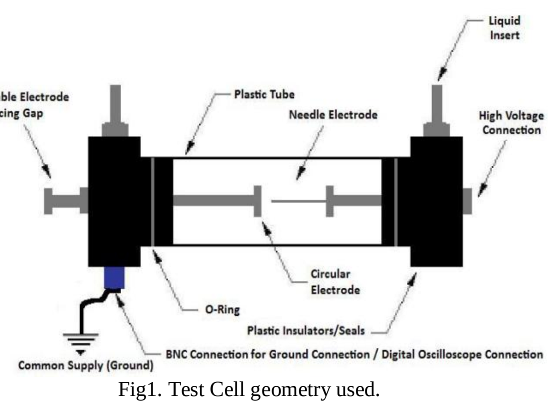

Fig1. Test Cell geometry used.

III. Experimental Results

A. *Breakdown Tests d.c.*

Fig. 2a shows the breakdown behaviour for the transformer oil as the concentration of nano particles was varied. The results are based on 15 measurements with the error bars indicating the standard deviation. The voltage ramp rate was 500 Vs^{-1}. The breakdown field is an average value based on the measured breakdown voltage divided by the separation between the tip of the needle and the ground electrode. There is a clear increase in the breakdown strength as the nano particle concentration is increased. Over the concentration range considered the breakdown strength is increasing from 6.7 $kVmm^{-1}$ to 10 kV mm^{-1}.

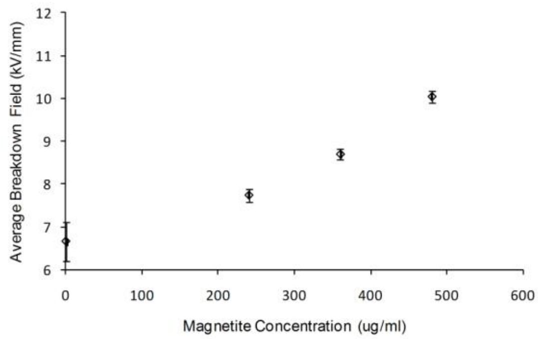

Fig.2a Positive d.c. breakdown behaviour of transformer oil

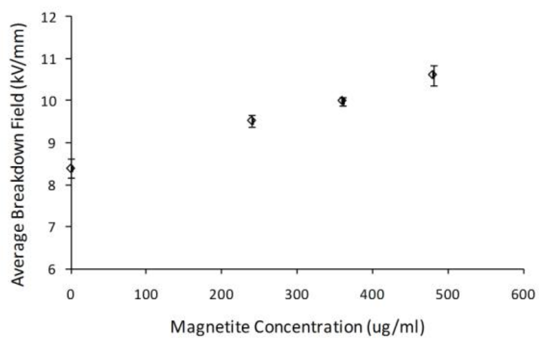

Fig.2b Negative d.c. breakdown behaviour of transformer oil

Fig. 2b shows the d.c. breakdown behaviour for the mineral oil based on 15 measurements. As expected the breakdown strength is higher under these conditions. As the magnetite concentration is varied the breakdown strength increases from 8.4 to 10.6$kVmm^{-1}$.

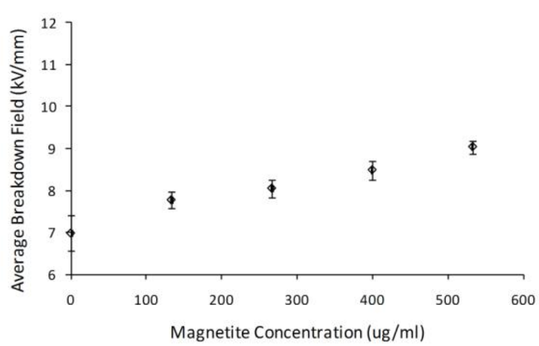

Fig.3a Positive d.c. breakdown behaviour of Midel oil

Fig. 3a shows the positive d.c. breakdown behaviour for the Midel 7131 synthetic ester liquid based on 30 measurements, again the breakdown voltage increases as the concentration of magnetite particles was increased, with the voltage increasing from 7 to 9 $kVmm^{-1}$. Fig. 3b shows the breakdown behaviour of this oil under negative d.c. conditions, again the breakdown strength are in general higher than under positive polarity with an increase observed in the breakdown strength from 11.5 $kVmm^{-1}$ to 14 $kVmm^{-1}$ over the range of magnetite concentrations considered.

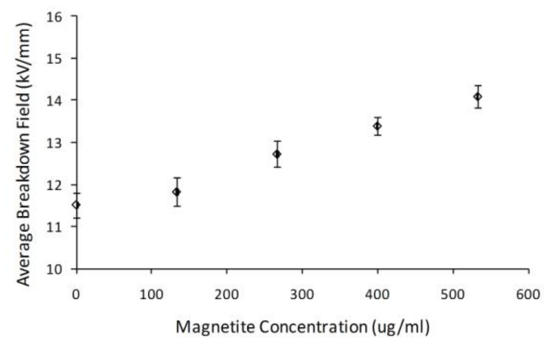

Fig.3b Negative d.c. breakdown behaviour of Midel oil

Fig. 4a shows the behavior of the positive d.c. breakdown behavior of the THESO insulating liquid based on 30 measurements.

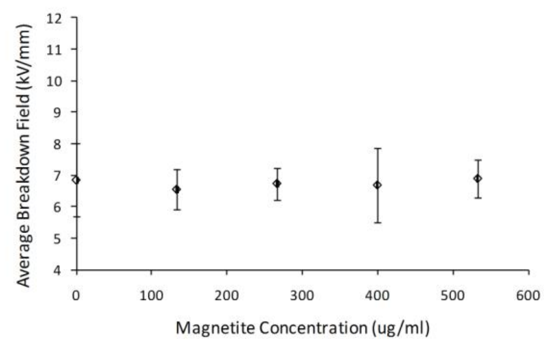

Fig. 4a Positive d.c. breakdown behavior of THESO liquid

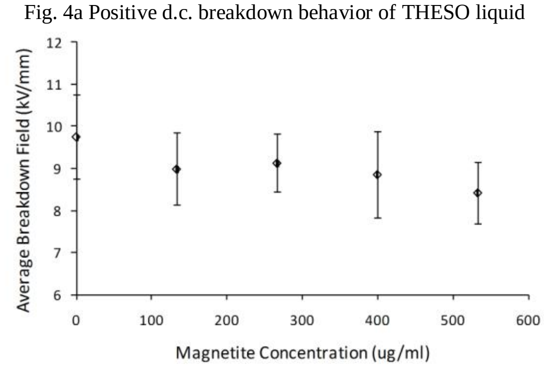

Fig. 4b Negative d.c. breakdown behavior of THESO liquid

Unlike the mineral oil and the synthetic ester, no significant changes are observed in the breakdown strength as the magnetite concentration is varied. However a larger variation in the measured values of breakdown strength as shown by the standard deviation occurs compared to the mineral oil and synthetic ester samples. A similar behavior is seen for the negative polarity d.c. breakdown, Fig. 4b, with small variations in the breakdown strength as the magnetite concentration is varied with perhaps an indication that the breakdown strength is decreasing. The behavior of the breakdown voltage against shot number was examined for both negative and positive polarities and the variation appeared to be random with no discernable trend that would indicate conditioning or instability in the magnetite suspension.

B. Breakdown Under Impulse Conditions.

Measurements of the breakdown strength of the Midel 7131 and THESO liquids have also been performed for differing concentrations of magnetite. The impulse was produced using a simple capacitive pulser with a rise time to peak voltage of ~50 ns. The data presented in this section is based on 30 measurements and the average breakdown strength was calculated in same manner as in section A above.

Fig. 5a shows the behavior of the breakdown strength for the Midel synthetic ester liquid for positive polarity impulses. As under d.c. conditions the breakdown strength increases as the magnetite concentration is increased changing from 17.7 to 20.49 kVmm^{-1}. Fig. 5b shows the behavior for the synthetic ester liquid under negative impulse conditions were again an increase in the breakdown strength is observed as the magnetite concentration is varied, changing from 22.1 to 28.4 kVmm^{-1}.

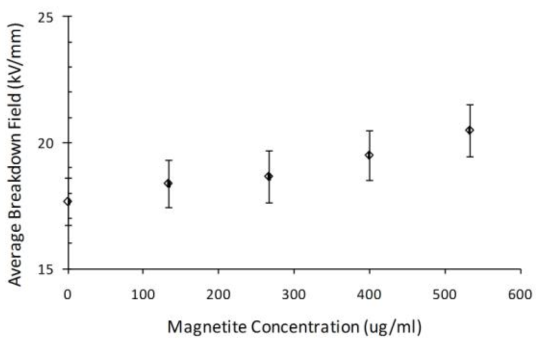

Fig.5a Positive impulse breakdown behaviour of Midel oil.

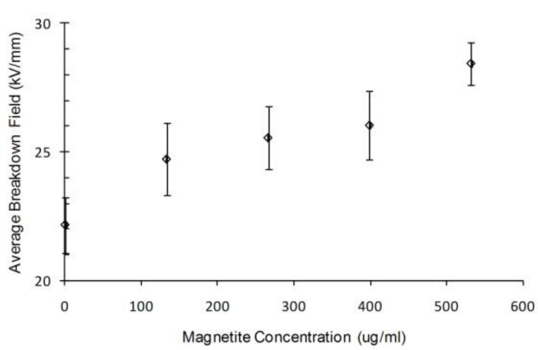

Fig.5b Negative impulse breakdown behaviour of Midel oil

Fig. 6a shows the impulse breakdown data for the THESO liquid under positive impulse conditions and Fig. 6b shows the behavior for negative impulses. As with the results obtained for this liquid under d.c. conditions the breakdown strength seems independent of the concentration of magnetite nano particles present in the system. The observed breakdown strength being 14.1 kVmm^{-1} for positive impulses and 19.4 kVmm^{-1} for negative impulses.

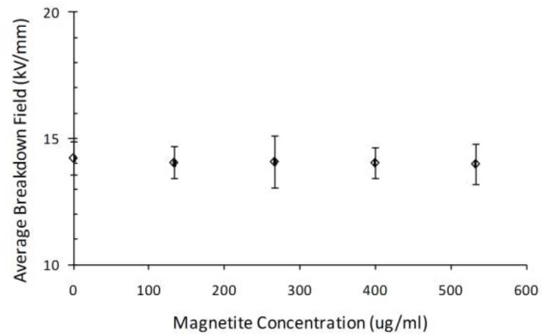

Fig.6a Positive impulse breakdown behaviour of THESO liquid.

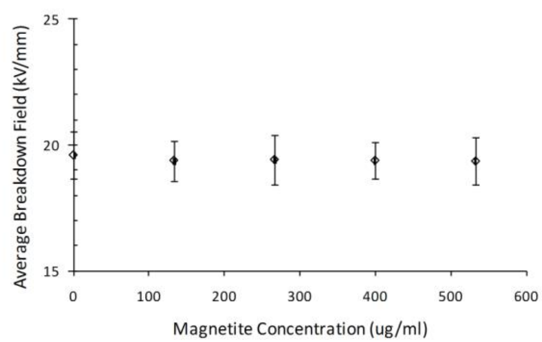

Fig.6b Negative impulse breakdown behaviour of THESO liquid.

III. Discussion

For both the mineral oil and the synthetic ester the addition of the magnetite nano particles have a significant effect on the breakdown behavior of the liquid under both d.c. and impulse conditions. Calculating the breakdown strength expected at a concentration of 400 µgmL^{-1} from the experimental data allows a comparison of the behavior to be made

TABLE I
COMPARISON OF CHANGES IN BREAKDOWN STRENGTH

Fluid	Test	Breakdown Field (kVmm^{-1})		
		0 µgmL^{-1}	400 µgmL^{-1}	% Change
Mineral Oil (Grosvenor)	+ve d.c.	6.60	8.92	35%
	-ve d.c	8.40	10.2	22%
Midel 7131	+ve d.c.	7.10	8.54	20%
	-ve d.c	11.4	13.4	18%
	+ve imp.	17.6	19.6	12%
	-ve imp.	22.6	26.7	18%

From Table I, it can be seen that the changes in breakdown strength under d.c. conditions appear to be greater for the mineral oil as compared to the synthetic ester liquid. Also it appears that the presence of the nano particles seems to have a greater effect on positive polarity breakdowns as compared with negative polarity breakdowns. No significant change in the breakdown strength of the THESO liquid was observed although there was a larger variation in the breakdown voltages measured for each nanoparticle concentration. There is however no evidence of conditioning occurring during each set of experimental tests and the scatter in the breakdown measurements for the pure liquid is similar to that observed for the liquid containing different concentrations of nano particles which suggests that the scatter observed may be associated with the properties of the liquid

Under impulse conditions the changes in breakdown strength for the synthetic ester are less significant and a greater effect is observed for negative impulses as compared with positive impulses.

Two mechanisms have been proposed as to how magnetite particles can affect the breakdown mechanisms in a liquid [3]:

A. Electron Trapping

The magnetite nano particles are known to be efficient at trapping electrons. This will have the effect of reducing electron multiplication within high field regions of the liquid impeding the breakdown mechanism. In addition the electron trapping process will have the effect of and introducing relatively slow moving negative particles into the liquid. These slow moving charges will introduce a space charge into the system which modifies the field distribution within the system.

B. Preventing Bubble Formation

Bubble formation in high field regions is known to play a significant role in the breakdown of liquid insulation. The presence of a relatively high concentration of particles in these regions may act to impede the formation of bubbles thus leading to an increase in the breakdown strength of the liquid.

Both of these mechanisms will be dependent on the concentration of the nano particles in the high field region where breakdown is being initiated. As the magnetite particles have a high permittivity they will tend to move toward these regions under the influence of the inhomogeneous field. A general expression for the expected concentration of high permittivity particles at a position *x*, *N(x)* under the influence of an inhomogeneous field is:

$$\frac{N(x)}{N_0} = \exp\left(\varepsilon_0 r^3 \left(\frac{\varepsilon_s - \varepsilon_l}{\varepsilon_s + 2\varepsilon_l} \right) \left(\frac{E(x)^2 - E_0^2}{2kT} \right) \right)$$

where N_0 is the average concentration of particles, ε_s and ε_l are the relative permittivities of the solid particles and the liquid, $E(x)$ is the electric field at x and E_0 is the average value of the electric field. The quoted permittivity for the THESO liquid is ~15, five times greater than the expected values for the mineral oil and synthetic ester liquids (2.2 ~ 3.8). This high permittivity would reduce the value of the term :

$$\left(\frac{\varepsilon_s - \varepsilon_l}{\varepsilon_s + 2\varepsilon_l} \right)$$

in the exponential equation above. Depending on the other parameters, in particular the effective radius of the nanoparticles, this could significantly reduce the expected concentration of nano particles in the high field region where breakdown is initiated. This may provide a partial explanation for the different behavior of the THESO insulating liquid when magnetite nano particles are present. However the validity of the assumptions made when deriving the equation above when applied to a system containing nano particles has not been established and the differences in other properties of the THESO liquid, in particular its conductivity [5], which differs significantly from the other liquids considered may also play a significant effect in the observed behaviour.

IV. CONCLUSIONS

The influence of magnetite nano particles on the breakdown strength of three liquids has been examined. For the mineral oil considered and the synthetic ester liquid significant changes in the breakdown strength were observed as a result of the addition of the nano particles. For the high permittivity THESO liquid no significant changes in the breakdown strength were observed over the range of nano particle concentrations considered.

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