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The Investigation on the *E–J* Characteristics and the Role of Nanoparticle Concentration in Weakly Polar Magnetic Fluids

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The paper presents investigation on the magnetic fluids that are stable colloidal suspensions of single-domain magnetic particles in a liquid carrier of dielectrics nature. Studies were made on the electric field vs. current density, e.i. E–J characterization commonly observed in insulating liquids under uniform low electric or magnetic fields. High performance oil was used as the dielectric carrier. The experiments were carried out at different volume concentrations of magnetite nanoparticles up to 4%.

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1. Introduction

The technology and application breakthrough was achieved since magnetic fluids physical properties were uncovered. Early magnetic fluids have been synthesized for technical applications since the early sixties of twentieth century. Comprehensive review of application area has been published in [1]. Seals utilize magnetic field to attract and get-on the position. Accelerometers use change of displacement of magnetic particles in the fluid due to acceleration change. The list can continue by applications for printers, bearings, magnetogravimetric separation, dampers, magneto-calorimetric pumps, etc. [2]. Recent research on magnetic fluids (MFs) especially nanofluids (NF) offers improvements to high voltage equipment performance and reliability.

The research of transformer oil based MFs for high voltage applications has led to investigations on enhancing dielectric and thermal characteristics. Scientific teams have dealt with new dielectric nanofluids, which are manufactured by adding nanoparticle and surfactant to transformer oil. Last decade, researchers have published new investigations on transformer oil-based MFs with content of magnetite nanoparticles [3].

Nanoparticles in the fluid interact with the magnetic field around power transformer windings and improve their cooling. Moreover, the enhancement of the insulating characteristics has been observed. It is supposed that increased the lightning impulse withstand voltage is caused by enhanced electric field dissipation due to the presence of magnetite nanoparticles [4].

More detailed insight to pre-breakdown conduction development can be realized by analyze of E–J characteristics of newly developed dielectric nanofluids. Several volume concentrations of magnetite nanoparticles in MFs have been experimentally tested. Impact of concentration on characteristics of MFs is discussed.

2. Theoretical background

There are several basic phenomena with possible contribution to electrical conductivity in the MFs: the electrochemical dissociation, the boundary potentials on surfaces of colloidal nanoparticles, the existence of semiconductive or conductive particles in the fluid and, finally, ionization phenomena in insulating fluid matter. They are taken into account when analyzing conducting properties of MFs samples. The ionization is not present in the experiment; therefore it is not mentioned in the following paragraphs. In the case of mineral oil as carrier fluid, the electrochemical dissociation is caused by water (moisture) content which produce electrolysis. Several ppm of water content can cause raise of specific conductivity σ and influence overall current density J considerably, which can be analytically derived as differential form of Ohm's law. The specific conductivity σ depends on the free-charge density and appropriate mobility of free charges. For many current mechanisms in MFs, the E–J curve can be presented as a function of activation energy W_a and temperature T:

$$J = \frac{nq^2\delta^2\nu}{6kT} \cdot E \cdot \mathrm{e}^{-\frac{W_a}{kT}}, \tag{1}$$

where n is a number of particles, q is a charge, δ is mean distance between particles, ν is a oscillation frequency of particles, k is Boltzmann constant.

Colloidal particles are able to create electrical double layers (DL), which can be characterized by Stern model [5]. The electrode surface layer consists of ions adsorbed onto the electrode surface due to chemical interactions. The second layer comprises of ions attracted to the first layer due to Coulomb forces. In second layer, free ions move in the fluid due to electric attraction and thermal motion. Contribution of electrophoresis to current density in MF is

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$$J_e = \sigma_e E = \rho_e \mu_e E = q N_e \mu_e E, \tag{2}$$

where σ_e is electrophoretic conductivity, ρ_e is charge density, N_e is number of charge carriers. The mobility μ_e of particles can be derived from theory of electrophoresis.

3. Experimental procedure and results

The measuring cell was provided by Rogowski shaped electrode edges to eliminate E-field inhomogeneity. In order to investigate E–J performance in basic mutual orientations of electric and magnetic fields (parallel and perpendicular), the permanent magnet holders has been installed at cell's walls. Low fields were chosen for experiments. The maximum of electric field applied was $E = 5 \cdot 10^5$ V/m and magnetic field was static of value $B = 40$ mT. The experiments were carried out at different volume concentrations of magnetite nanoparticles of mean diameter 9 nm as follows: 0.25%, 0.5%, 1.5% and 4%. MFs, based on inhibited transformer oil ITO 100 carrier, were free of agglomerations due to van der Waals and magnetic forces by a layer of acid oleic surfactant. In the frequency range from 1 Hz to 250 kHz there were no Brown relaxations observed at room temperature. MFs without aggregates are therefore supposed. For each sample, the data analyzed were collected in four quadrants of E–J plane. An example is shown in the Fig. 1.

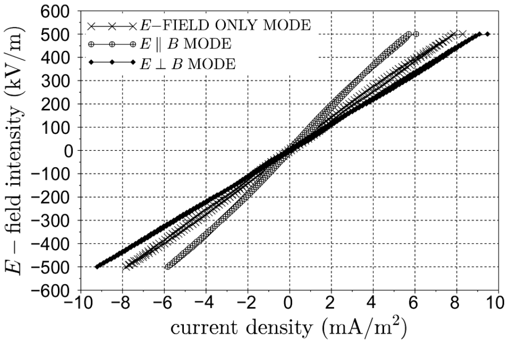

Fig. 1. E–J plot in four quadrants for MF with volume concentration 1.5%.

TABLE

Numerical characterization of electrical current flow in MFs samples under electrical and magnetic fields.

Electrical current flow J(mA/m^2) in MFs samples for $E = 5 \cdot 10^2$ kV/m and $B = 40$ mT					
mode/conc.	0.00%	0.25%	0.50%	1.50%	4.00%
E−only	$3.7 \cdot 10^{-2}$	$3.12 \cdot 10^{-1}$	2.79	8.28	$1.57 \cdot 10^{-1}$
$E \parallel B$	$3.2 \cdot 10^{-2}$	$3.04 \cdot 10^{-1}$	2.81	6.06	$1.45 \cdot 10^{-1}$
$E \perp B$	$2.3 \cdot 10^{-2}$	$2.03 \cdot 10^{-1}$	3.08	9.47	$1.58 \cdot 10^{-1}$

To demonstrate the nanoparticle concentration influence on current density, results are shown in the Table. Related to Table, the great dynamics of nanoparticle impact on current density in MFs is shown in the Fig. 2. It is supposed, that there are two dominant reasons that lead to current flow raise. The first is coupled with number of charge carriers in the liquid volume. The second is the influence of electric or magnetic fields. Magnetite particles have their own magnetic moments so that magnetic field causes self-assembly of colloidal particles. Different types of particle clusters are assembled. "*When an external field is applied to a colloidal suspension, the particles obtain a dipole moment as a result of the contrast of the dielectric constant or magnetic susceptibility of the particles with that of the fluid*" [6]. That is why electric field causes creation of magnetite particles clusters, too.

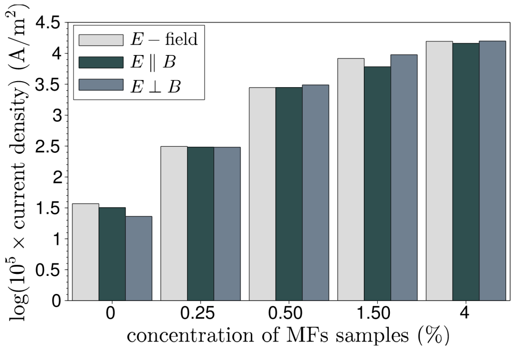

Fig. 2. The raise of current density related to volume concentration.

4. Concluding remarks

The leakage current due to magnetite nanoparticles was found to be increased with their volume concentration.

These results confirm that the nanoparticles are the dominant paths for the leakage current, moreover thermal effect should be taken into account. To explain more precisely the influence of electric or magnetic fields to overall conductance, more experiments should be done. This is important to qualify it when high electric and magnetic fields are supposed to be applied, e.g. in the case where magnetic fluid is to be applied in power transformers.

Acknowledgments

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