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THE DC- AND AC-DIELECTRIC BREAKDOWN STRENGTH OF MAGNETIC FLUIDS BASED ON TRANSFORMER OIL

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The DC- and AC-dielectric breakdown strength of the transformer oil TECHNOL US 4000 based magnetic fluid was studied. The AC dielectric breakdown strength of the magnetic fluid was found to be not worse than that of the pure transformer oil. A better heat transfer provided by the use of magnetic fluids in transformers may result in the improvement of their operation.

Introduction. Magnetic fluids have been shown to provide both thermal and dielectric benefits to the power transformers. They can improve their cooling by strengthening the fluid circulation in the vicinity of the transformer windings, as well as they can increase the transformer capacity to withstand lightning impulses [1]–[2], and also minimize the effect of moisture on typical insulating fluids. The benefits of magnetic fluids may be utilized to design smaller, more efficient new transformers, or to extend the life or loading capability of existing units.

Since the magnetic fluid experiences a magnetically driven flow unlike oil, the results of efficient heat removal with such fluid could be expected. However, the results, showing the increased dielectric strength of the magnetic fluid, compared with the pure transformer oil, were surprising. The presence of foreign particles has a profound effect on the dielectric breakdown strength of liquid insulators [3]. Polarizable magnetic (e.g., magnetite Fe_3O_4) particles, which are of higher permittivity than the surrounding liquid, experience an electric force directed towards the place of maximum stress. With uniform field electrodes, the movement of particles is presumed to be initiated by the surface irregularities on the electrodes, which give rise to local field gradients. The accumulation of particles continues and tends to form a bridge across the gap, which leads to the initiation of breakdown. The magnetic dipol-dipol interaction between the particles has also to be considered, the aggregation of magnetic particles in an external magnetic field induced by the transformer windings influences the dielectric breakdown strength of a transformer oil based magnetic fluid. However, Segal *et al.* [2] found out that the presence of magnetic particles in transformer oil improved its dielectric properties by increasing the DC impulse breakdown voltage from 78 to 108 kV.

In our previous work [4], the DC dielectric breakdown strength of transformer-oil-based magnetic fluids was studied. Now the motivation was to investigate the AC dielectric breakdown in magnetic fluids and to compare it with the previous observations.

1. Experimental methods. The magnetic fluid used in experiments consisted of magnetite particles (mean magnetic diameter $D_{\mathrm{m}} = 8.6$ nm; standard deviation $\sigma = 0.15$), coated with oleic acid as a surfactant, dispersed in transformer oil TECHNOL US 4000 ($\varepsilon_r = 2.15$). The used volume concentration of magnetic particles $\Phi = 0.0025$ (saturation magnetization $I_{\mathrm{s}} = 1$ mT) was found in [4] as a concentration, at which the dielectric properties of magnetic fluids are better than those of the pure transformer oil. The dielectric breakdown strength was measured using properly shaped electrodes of a uniform gap of electric field Rogowski-profile [5]. The electrodes were 1.5 cm in diameter; the distance between the electrodes could be varied within the range of 0.1 to 1 mm. The generating circuits generated DC high voltages up to 10 kV. Two permanent NdFeB magnets with dimensions $5 \times 5 \times 0.3$ cm induced an external magnetic field up to 50 mT and this magnetic field was approximately uniform in the measured gap of the electric field. The time development of the breakdown was measured by an inductive probe and a programmable oscilloscope with its own memory. Each value of the dielectric breakdown strength was measured seven times and the maximum and minimum values were omitted in the calculation of its mean value, according to the rules of high voltage techniques [3]. The experimental error of the dielectric breakdown strength definition was $\pm 6\%$.

2. Results and discussion. The development of the AC dielectric breakdown in the magnetic fluid was compared with the development of the DC dielectric breakdown. Fig. 1 illustrates the time development of the DC dielectric breakdown. In this case, the onset of the measurable ionization leads to a complete breakdown of the gap. The onset of the breakdown appeared at $t \approx 11.93$ ns, it developed about 320 ps, until at $t \approx 12.25$ ns it was fully manifested. The electric energy of the dielectric breakdown depends on the distance between the

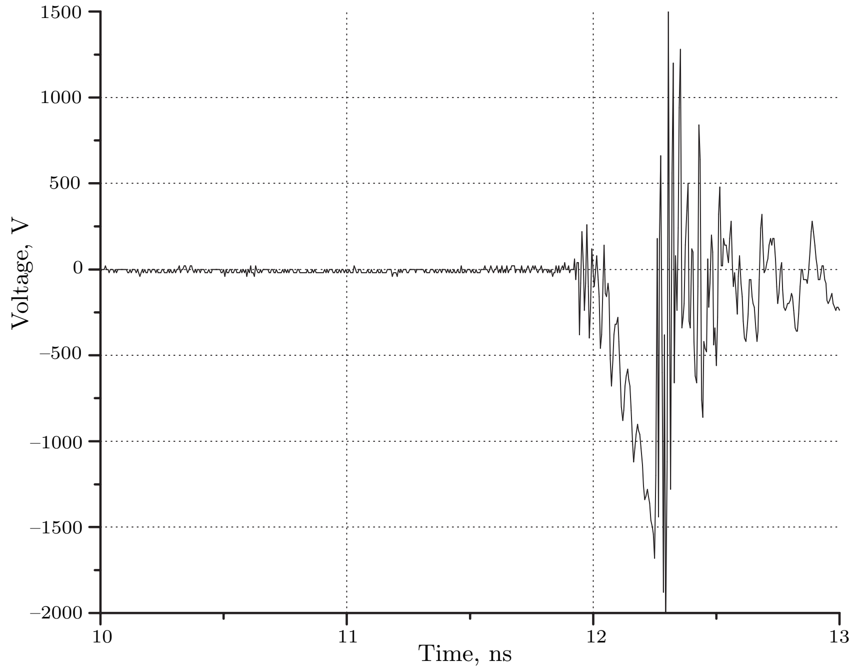

Fig. 1. Development of the DC dielectric breakdown in the magnetic fluid.

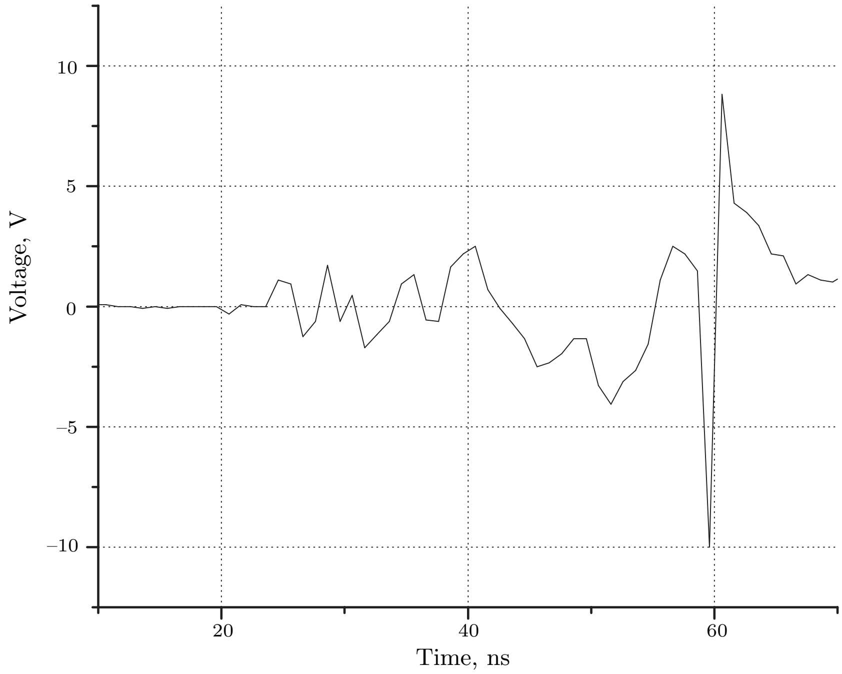

Fig. 2. Development of the AC dielectric breakdown in the magnetic fluid.

electrodes, but its values for $H = 0$, $\mathbf{H} \parallel \mathbf{E}$ or $\mathbf{H} \perp \mathbf{E}$ were of the same order of tens μJ.

The time development of the AC dielectric breakdown in the magnetic fluid is shown in Fig. 2. In this case, various manifestations of luminous and audible

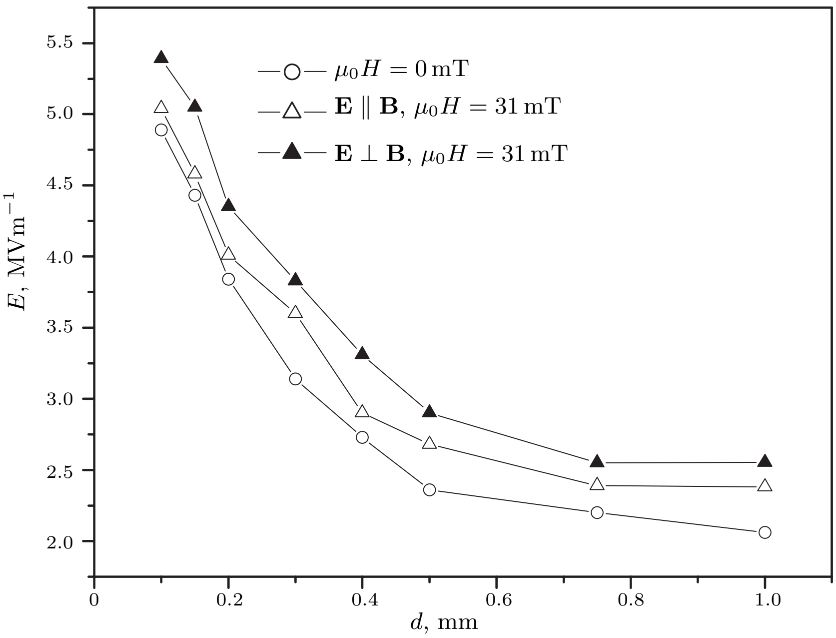

Fig. 3. The AC dielectric breakdown strength vs. the distance between electrodes for the magnetic fluid ($\Phi = 0.0025$, $I_s = 1$ mT) at $H = 0$, $\mathbf{H} \parallel \mathbf{E}$ and $\mathbf{H} \perp \mathbf{E}$.

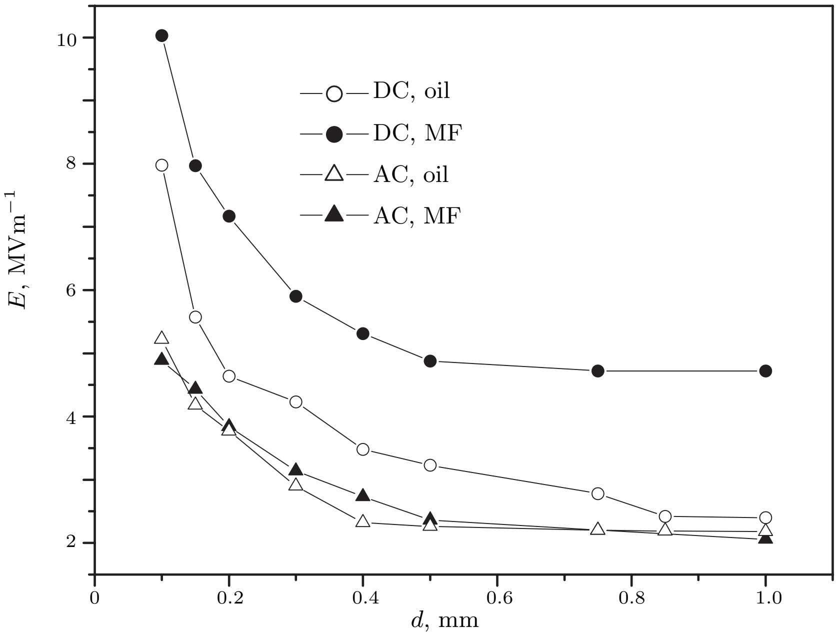

Fig. 4. The DC and AC dielectric breakdown strengths of the magnetic fluid ($\Phi = 0.0025$, $\mu_0 H = 0\,\mathrm{mT}$) and pure transformer oil.

discharges were observed long before the complete breakdown occurred. These discharges, which may be transient or steady state, are known as "coronas" and in Fig. 2 they are visible in the form of oscillations of bigger amplitude, followed by a complete dielectric breakdown. The AC dielectric breakdown strength of the magnetic fluid as a function of the distance between the electrodes in a uniform electric gap was investigated for $H = 0$ and in the magnetic field of $H = 31\,\mathrm{mT}$, oriented parallel and perpendicular to the electric field. As Fig. 3 shows, in all three cases the decrease of the dielectric breakdown strength E_c with the increasing d was observed. This is in agreement with theoretical predictions of Gupta and Sen [5], who studied the dielectric breakdown in a semi-classical bond percolation model for a non-linear composite material. The measured DC and AC dielectric breakdown strengths of the magnetic fluid, compared with the DC and AC dielectric breakdown strengths of the pure transformer oil, are shown in Fig. 4. The DC dielectric breakdown strength of the studied magnetic fluid was found to be higher than that of the pure transformer oil and AC breakdown strength remains comparable with that of transformer oil, but not worse.

3. Conclusions. Observations of the time development of the AC dielectric breakdown in the magnetic fluid have shown the presence of luminous and audible discharges long before the complete breakdown occurred, while for the DC dielectric breakdown a complete breakdown of the gap next to the onset of measurable ionization is typical.

The AC dielectric breakdown strength of the magnetic fluid was found to be not worse than that of the pure transformer oil. Considering a better heat transfer, provided by magnetic fluids, their application in power transformers may lead to the improvement of the operation of these devices.

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