THE INFLUENCE OF MAGNETIC NANOPARTICLES ON DC- AND AC-DIELECTRIC BREAKDOWN IN TRANSFORMER OIL-BASED MAGNETIC FLUID

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Introduction. Magnetic fluids have been shown to provide both thermal and dielectric benefits to the power transformers. They can improve the cooling by enhancing the fluid circulation within transformer windings, as well as they can increase the transformer capacity to withstand lightning impulses [1]–[2], while minimizing along the effect of moisture in 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 an efficient heat removal with such fluid could be expected. However, the results, showing the increased dielectric strength of magnetic fluid, compared with a 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 electrical 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 that 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 produced 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 $D_m = 8.6\,\mathrm{nm}$; standard deviation $\sigma = 0.15$), coated with oleic acid as a surfactant, dispersed in transformer oil TECHNOL US 4000 ($\varepsilon_r = 2.15$). The volume concentration of magnetic particles was $\Phi = 0.0025$ (saturation magnetizations $I_s = 1\,\mathrm{mT}$). At this volume concentration the dielectric properties of the magnetic fluid are better than those of a pure transformer oil, as was found in [4], where the crossover from better to worse dielectric properties was observed in a magnetic fluid with $\Phi = 0.01$

($I_s = 4\,\mathrm{mT}$). The dielectric breakdown strength measurements were carried out 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 changed within the range 0.1 to 1 mm. The generating circuits indiced DC high voltages up to 10 kV. Two permanent NdFeB magnets with dimensions $5x5x0.3$ cm produced 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 determination was ±6%.

2. Results and discussion. The development of the AC dielectric breakdown in a magnetic fluid was compared with the development of the DC dielectric breakdown. An example of the time development of the DC dielectric breakdown is presented in Fig. 1. In this case the onset of the measurable ionization leads to complete breakdown of the gap. The onset of the breakdown appeared at $t \approx 11.93\,\mathrm{ns}$, it developed about 320 ps, until at $t \approx 12.25\,\mathrm{ns}$ it fully manifested itself. The electric energy of the dielectric breakdown depends on the distance between the electrodes, but its values for $B = 0$, $\boldsymbol{B} \| \boldsymbol{E}$ or $\boldsymbol{B} \perp \boldsymbol{E}$ were of the same order of tens $\boldsymbol{\mu}$ J.

The time development of the AC dielectric breakdown in a magnetic fluid is shown in Fig. 2. In this case various manifestations of luminous and audible 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 are visible in the form of oscillations with a 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 $\boldsymbol{B} = \mathbf{0}$ and in the magnetic field $\boldsymbol{B} = \mathbf{31}\mathrm{mT}$, oriented parallel and perpendicular

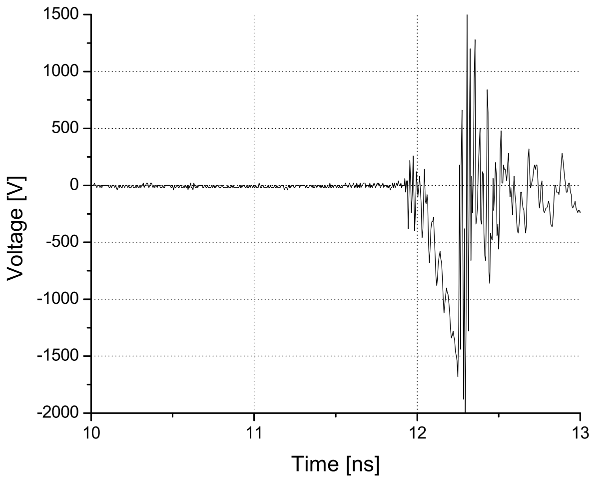

Fig. 1. The development of the DC dielectric breakdown in a magnetic fluid.

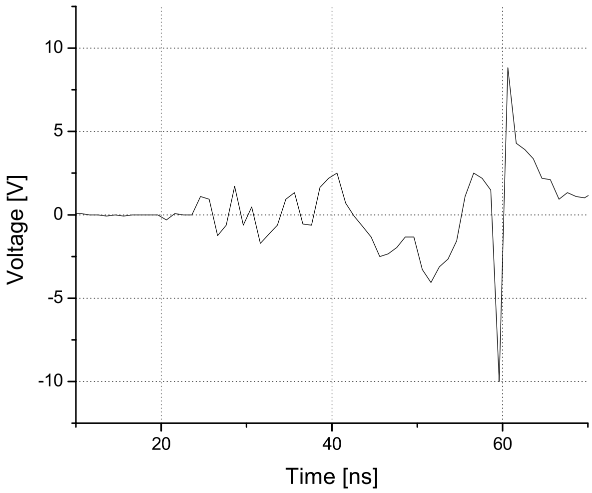

Fig. 2. The development of the AC dielectric breakdown in a magnetic fluid.

to the electric field. As Fig. 3 shows, in all cases the decrease of the dielectric breakdown strength $\boldsymbol{E_c}$ with the increasing $\boldsymbol{d}$ 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 comparison with the AC-dielectric breakdown strength of pure transformer oil confirmed better dielectric properties of the magnetic fluid in an external magnetic field.

The measured DC and AC dielectric breakdown strengths of the magnetic fluid at $\boldsymbol{B = 0}$, compared with the DC and AC dielectric breakdown strengths of pure transformer oil, are shown in Fig. 4. As the DC dielectric breakdown strength

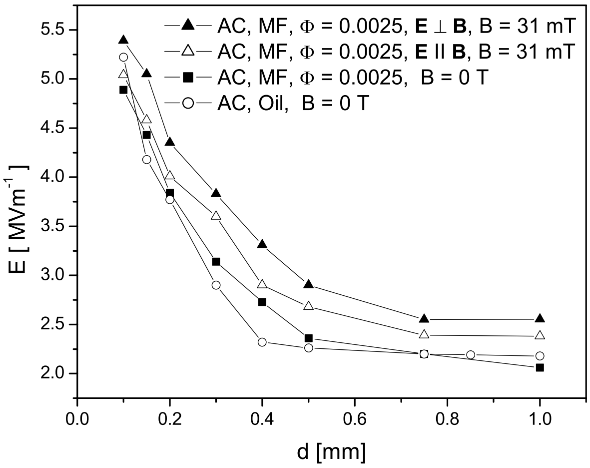

Fig. 3. The AC dielectric breakdown strength vs. the distance between the electrodes for a magnetic fluid ($\boldsymbol{\Phi = 0.0025}$, $\boldsymbol{I_s = 1}\,\mathrm{mT}$) at $\boldsymbol{B = 0}$, $\boldsymbol{B \| E}$ and $\boldsymbol{B \perp E}$.

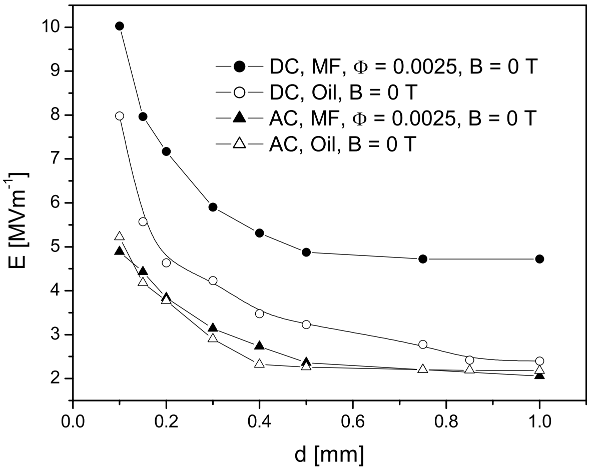

Fig. 4. The DC and AC dielectric breakdown strengths of a magnetic fluid ($\mathbf{\Phi = 0.0025}$) and pure transformer oil.

of the studied magnetic fluid was found to be higher than that of pure transformer oil, the AC breakdown strength remains comparable with that of transformer oil, but not worse.

3. Conclusion. The observations of the time development of the AC dielectric breakdown in the magnetic fluid based on transformer oil showed the presence of luminous and audible discharges long before the complete breakdown occurrence, while for the DC dielectric breakdown a complete breakdown of the gap next to the onset of measurable ionization is characteristic.

The comparison of the AC-dielectric breakdown strengths of pure transformer oil and a transformer-oil-based magnetic fluid showed better dielectric properties of the magnetic fluid in an external magnetic field and comparable, but not worse, at $\boldsymbol{B = 0}$. With regard to 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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