Magnetic fluid as cooling and insulation medium for high power transformers

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Abstract: - The development of electric breakdown in magnetic fluids (MFs) has been analyzed. MFs have been consisted of magnetic particles (Fe_3O_4) of nanometric size, coated with oleic acid as a surfactant, dispersed in transformer oil. The electro-physical processes, which appear at action of the DC electric field and constant magnetic field on MFs, were observed. These processes have effect on electric breakdown. The especial attention was devoted to state in MFs before breakdown, during breakdown and post breakdown.

Key-Words: - Mineral oil, Magnetic fluid, Dielectric breakdown, High power transformer,

1 Introduction

The transformer oil cools and provides part of the electrical insulation between internal live parts. The oil has to be stable at high temperatures so that a small short or arc will not cause a breakdown or fire. For large power transformers, the oil-filled tank may have radiators through which the oil circulates by natural convection so it improves cooling. Very large or high-power transformers (with capacities of millions of watts) may have cooling fans, oil pumps and even oil to water heat exchangers. These highly efficient transformers allow power to be transmitted over long distances. Failure of just one unit can have immensely damaging consequences to its owner on an economic front, to the public because of our dependence on power and even to the environment. Each transformer in a small network may cost EUR 10 000, while a large transformer could cost considerably more, into the millions. High-power or high-voltage transformers are bathed in transformer oil - a highly refined mineral oil that is stable at high temperatures. Large transformers to be used indoors must use a non-flammable transformer design liquid. Formerly, PCB (polychlorinated biphenyl) was used as the liquid in which the windings, an essential part of the device, were immersed to keep them cool. PCB is highly stable and non-flammable, making it eminently suitable for use in transformers, particularly those used inside buildings. Unfortunately it also turned out to pose significant hazards to health and to the environment and was banned from use in new products in the late 1970s. Even so, it is estimated that there are still some 30 million units in use worldwide that employ PCBs as the dielectric. Their disposal poses a significant problem. Today, nontoxic, stable silicone-based or fluorinated hydrocarbons may be used, where the added expense of a fire-resistant liquid offsets additional building cost for a transformer vault. Other less-flammable fluids such as canola oil may be used but all fire resistant fluids have some drawbacks in performance, cost, or toxicity compared with mineral oil. As previous discuss, transformer oil is primarily used to cool the transformer, it also helps to reduce the formation of corona discharge within high voltage transformers. By cooling the windings, the insulation will not break down as easily due to heat. To ensure that the insulating capability of the transformer oil does not deteriorate, the transformer casing is completely sealed against moisture ingress. Thus the oil serves as both a cooling medium to remove heat from the core and coil, and as part of the insulation system. Typically, transformers perform best at temperatures below 55^0C above the ambient temperature.

Power transformers are one of the most dangerous electrical equipments because of the large quantity of oil they contain, which is in direct contact with high voltage elements. Under such circumstances, low impedance faults that result in arcing can appear in transformer tanks once the oil loses its dielectric properties. Oil is then vaporized and the generated gas is pressurized because the liquid inertia prevents its expansion. The pressure difference between the gas bubbles and the surrounding liquid oil generates a dynamic pressure peak, which propagates and interacts with the tank. The dynamic pressure peak interactions with the tank structure generate reflections, which build up static pressure. Then, the static pressure rises leading to tank explosion and possible fire resulting in very expensive damages for electricity facilities, possible environmental pollution and human life risks. Traditional power transformers contain thousands of liters of mineral oil. These oil-filled transformers pose a significant environmental and safety risk due to oil spills and fire respectively. Such hazards result from combustible gases, produced when oil is heated, which can cause the transformer to explode, releasing thousands of liters of burning oil and asphyxiating smoke. Transformer explosions can cause significant financial loss including the loss of consent to operate the plant.

Large, high-power transformers, in particular, need to have a built-in cooling facility to transport heat from the interior. Thus, one of the numerous ways of classifying transformers is according to cooling type. For example, for power transformers rated up to a nominal kVA, natural convective air-cooling, often fan-assisted, is adequate. Traditionally, oil transformers relied on highly refined mineral oil as a cooling medium, while with the latest generation cast resin transformers the transformer core is insulated by a thin coating of inorganic material. Over the last decade the remarkable advances in materials technology and manufacturing methods have fostered the popularity of cast resin transformers, particularly in fire-sensitive locations such as high-rise structures, hospitals, and public buildings where the transformer is located indoors and a fire outbreak would be particularly hazardous because of the high density of people.

Transformers have traditionally used mineral oil, which acts as an insulating and cooling medium. The insulating oil fills up pores in fibrous insulation and also the gaps between the coil conductors and the spacing between the windings and the tank, and thus increases the dielectric strength of the insulation. Transformer in operation generates heat in the winding, and that heat is transferred to the oil. Heated oil then flows to the radiators by convection. Oil supplied from the radiators, being relatively cool, cools the winding. There are several important properties such as dielectric strength, flash point, viscosity, specific gravity and pour point and all of them have to be considered when qualifying certain oil as transformer oil. The quality of the oil is very important.

2 Problem Formulation

The insulation fluids in power transformers perform two main functions–insulating, i.e. preventing the flow of electric current between conductive components, and cooling, i.e. they conduct the heat out of active transformer components (i.e. out of both electric windings and transformer core) [1,2]. The rate of transferring this heat from the transformer interior to its walls and its subsequent dissipation into surroundings is the two factors that limit the current density in transformer windings and thus define its size and weight for a given power rating [3]. For currently used insulation fluids, especially those with high dielectric strength (highly refined mineral oils ~ transformer oils), a low thermal conductivity is typical, resulting in low-efficiency cooling, limitation of current intensity and higher price of the transformer. The heat transfer in such fluids is performed by standard thermal convection due to vertical thermal gradients. In magnetic insulation nanofluids an increased heat transfer was expected due to the thermo-magnetic convection, originating in the interaction of magnetic nanofluid with magnetic field generated by current flow in the windings. The temperature dependence of the saturation magnetization and the presence of non-uniform magnetic field are the basis for a convective flow of magnetic nanofluid in an electromagnetic device [4]. A power transformer is an ideal example of such device as both conditions are intrinsically present. However, following the existing knowledge, the addition of foreign particles into transformer oil should have detrimental influence on its dielectric strength and therefore a well-established practice is to clean the transformer oil up to the highest available degree. Nevertheless it has been showed experimentally [5,6], that magnetic nanofluids of suitable composition and magnetic particle concentration not only increase the heat transfer by thermal and magnetic convection, but they also have higher dielectric strength than ordinary insulation nanofluids. Here it has to be noted that the average size of magnetic particles (a few nanometers) is 2 to 3 orders of magnitude smaller than the particles normally found in transformer oil. Heat generated by the transformer windings and its magnetic core produces the temperature gradients within a space, which is also under effect of non-uniform magnetic field. The source of both the heat and magnetic field is the AC current in the winding. As it was mentioned, the results of former studies showed that the heat transfer in electromagnetic devices can be increased significantly using magnetic nanofluids that contain magnetic particles of nanometric sizes dispersed in transformer oil. The thermal conductivity magnetic nanofluid depends linearly on the solid loading. Segal and Raj [6] have performed an extensive temperature mapping on two small distribution transformers filled with transformer oil and magnetic nanofluid. They found out that below a limit magnetization (~50 G) of magnetic nanofluid, where the normal fluid flow is not inhibited by a strong magnetic interaction, the enhanced heat transfer from within the windings significantly decreases the maximum temperature inside the transformer. The experiments showed that magnetic nanofluid dramatically affected the heat transfer within and in the immediate vicinity of windings with a current exceeding a critical value. The temperature distribution in magnetic nanofluid surrounding the winding changes so that the hot fluid is completely displaced from the hot region that is placed close to the winding surface. The origin of such flow is in the magnetic interaction between magnetic field of the winding and magnetic liquid, while it depends on the concentration of magnetic particles and thus on the saturation magnetization. A major factor affecting the insulation fluid in a power transformer is the heat generated by the loaded windings. Therefore the effect of enhanced operation temperature on the physical and insulating properties of magnetic nanofluids was studied [7]. A magnetic nanofluid sample, based on transformer oil, was subjected to the thermal aging conditions modeled after a typical power transformer where the insulation fluid is expected to retain its dielectric performance for about 40 years of continuous service. Following the well-known Arrhenius relationship the “life in service” for up to 40 years at 105^{o}C corresponds to holding the sample in sealed jars for 10 weeks at 185^{o}C. Even longer aging, 34 and 50 weeks at 185 ^{o}C, showed no degradation of thermal or colloidal stability of used magnetic nanofluid. The understanding of the relationship between the imposed magnetic field, the magnetic nanofluid flow and the temperature distribution is a prerequisite for a design of any apparatus involving thermomagnetic convection. While extensive experimental researches in the field were conducted for more than a decade, the study of the mechanisms involved in the heat transfer in magnetic nanofluids was mainly aimed at the macroscopic scale [8-12]. The microscopic interactions started to be considered only recently [13,14]. The research in this field can benefit also from recent results presented in the open literature that state that the possible mechanisms that may affect the convective heat transfer in nanofluids (similar to the case of magnetizable nanofluid in zero magnetic field) are the transport mechanisms associated to the relative (slip) velocity developed by the nanoparticles with respect to the carrier fluid, such as: inertia, Brownian diffusion, Soret effect, Magnus effect, fluid drainage and gravity. Also, several other mechanisms are related to the larger increase in the effective thermal conductivity for a very low volume fraction ($\Phi \leq 1\%$) of solid nanoparticles of less than 10 nm in size, like ballistic transport of energy carriers within nanoparticles, formation of nanoparticles structures through agglomeration (in fractal-like shape), clustering and networking [15-16].

In previous results obtained in the study of the DC and AC dielectric breakdown strengths of magnetic nanofluids with different saturation magnetization and different orientations of electric and magnetic fields showed, that magnetic nanofluids based on transformer oil ITO !)) and TECHNOL US 4000 have better dielectric properties than pure transformer oil if volume concentration of magnetic particles is smaller than 0,01 (I_S < 4 mT) [17-20, 23-24]. This fact is in agreement with observations of Segal and Raj [4], who observed this improvement in the study of DC impulse breakdown in magnetic nanofluids. To conclude it can be said, that special magnetic nanofluids could be suitable for the use as an insulation and cooling liquid in power transformers.

3. Experimental methods

For the experiments we have used magnetic fluids with magnetite particles coated with oleic acid as a surfactant dispersed in transformer oil ITO 100. The volume concentrations of magnetic particles were defined precisely. The lognormal particles size parameters were D_v = 8.6nm and standard deviation σ = 0.15.from VSM magnetization measurements. For the observation of agglomeration processes a drop of magnetic fluid was sandwiched between two parallel glass cover slips with the thickness d = 20μm and placed normal to the optic axis of the microscope. The optical microscope was equipped with a video camera. Helmholtz coils parallel to the magnetic fluid film plane produced a magnetic field of up to 50 mT. Dielectric breakdown strength measurements were carried out using appropriate shaped electrodes of a uniform gap of electric field-Rogowski profile [4]. The size of the electrodes was approximately 1.5 cm in diameter with the possibility to change the distance between electrodes in range of 0.1-1mm. The generating circuits generated high voltages up to 10 kV. Two permanent NdFeB magnets with sizes 5x5x0.3 cm produced the external magnetic field up to 50mT and the magnetic field was approximately uniform in measured gap of electric field. Experimental set up is on Fig.1. Each point of dielectric breakdown strength of the magnetic fluid 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 [21]. The experimental error of determination of dielectric breakdown strength was ±4%.

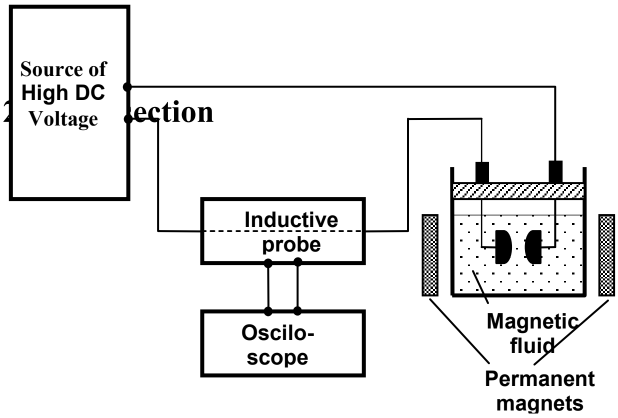

Figure1: Experimental set up

3. The influence electrical and magnetic field on magnetite nanoparticles

On the base of superposition of electrical and magnetic field acting on liquid medium containing the clusters of magnetic nanoparticles we can obtain the tout force in the form:

$$\vec{F} = q.\vec{E} + q.\vec{v}x\vec{B} \qquad (1)$$

Since we are interesting about $\vec{E}$ || a $\vec{E}$ ⊥, we can write vector velocity **v** and intensity of electrical field **E** into parallel and perpendicular directions and equation can be expressed in the form:

$$m(c)\frac{d\vec{v}_{\parallel}}{dt} + m(c)\frac{d\vec{v}_{\perp}}{dt} = q.\vec{E}_{\parallel} + q.\vec{E}_{\perp} + q.\vec{v}_{\parallel} \times \vec{B} + q.\vec{v}_{\perp} \times \vec{B} \qquad (2)$$

Critical value of transversal field *E(x)* can be obtained by comparison of transversal $v_e(x)$ and diffusion $v_{dif}(x)$ *velocity*. If the stability is disturbed, electric breakdown appears. Then it is possible to write

$$N(x) = N(\infty)\exp\left[\frac{\varepsilon_0 \varepsilon_{r_0} r^3 \left(E^2(x) - E^2(\infty)\right)}{2kT}\right]. \qquad (3)$$

This equation (3) shows to exponential increasing of particle concentration in DC electrical field and by that current increasing at pre-breakdown area in strong and week electrical field boundary at 10^6-10^7 Vm^{-1}. During exponential increasing of current it formed breakdown canal from one electrode to other in magnetic fluids. As we suppose that the building of breakdown canal is carried out at constant temperature, the main role is played by the permittivity and the value of local intensity of electrical field. E(x).

4. Results

Measurements showed that concentration of nanoparticles (Fe_3O_4) in MFs influences not only relative permittivity of MFs but their electric conductivity too. The aggregation of magnetic particle (Fig.2) was observed by optical and electron microscope.

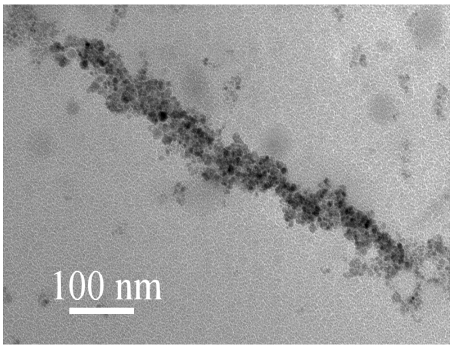

Figure 2: The example of the magnetic particles aggregation in magnetic fluid with concentration of magnetic particles f= 0.25%.

It was observed that clusters of magnetic particles in external magnetic field have shape of needles with average length in interval 100-300 μm in dependence on both values of external magnetic field and concentration of magnetic particles. As result aggregation process influences relative permittivity of MFs, concentration of magnetic particles in MFs and value of applied magnetic field. The saturation of a cluster length of magnetic particles was reached after 3 minutes. The dependence of relative permittivity of MF on concentration of magnetic particles (Fig.3) and dependence of breakdown electric intensity on distance between electrodes (Fig.4) were observed too.

The period of construction of electric discharge up to total breakdown was observed. This quantity was studied

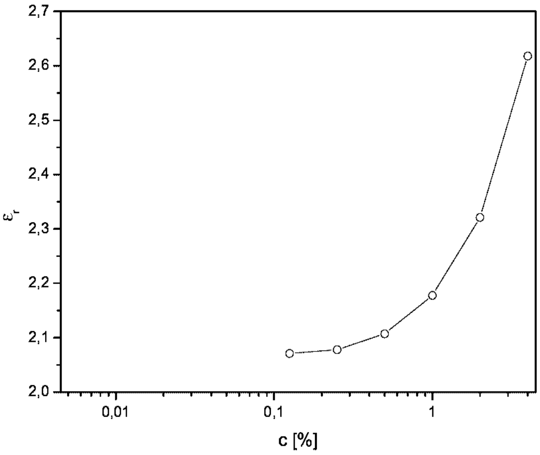

Figure 4: The effect of volume concentration of magnetic particles on relative permittivity of MFs.

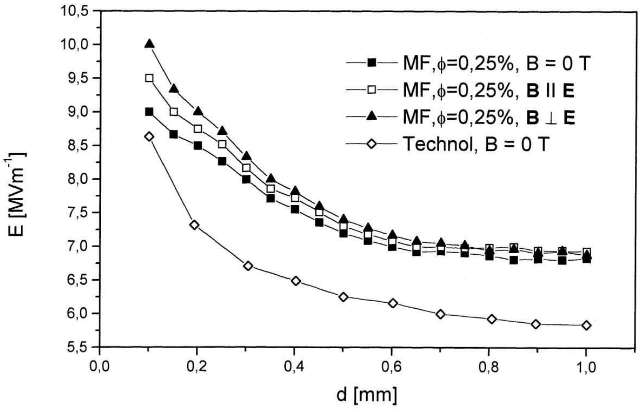

Figure 5: Dielectric breakdown strength vs. distance between the electrodes for magnetic fluids Φ =0,0025 and I_s=1mT

at continual increasing of voltage in homogeneous DC electric field [22] in different materials (air, transformer oil ITO 100 and magnetic fluids with volume concentrations of magnetic particles 0.125%.

The experiments were carried out in different orientation of **E** and **H** (**E**||**H**, **E**⊥**H** and **H =0**). The courses of time dependence of current in MF with magnetic particles concentration of value 0.125% are illustrated on (Fig.5-9). The periods of pre-breakdown state in investigated MF were in interval 150-220 ns what correspond to time needed for creating of an electric breakdown channel. The typical mark of quasi-exponential course is rise of an avalanche discharge (Townsed). This effect was observable in transformer oil ITO 100 for all concentrations of magnetic particles in MF and during observation pre-breakdown state in air too (Fig.5). While period needed on neutralization of avalanche in air is approximately 0.8-0.1 ns the same period for MF is approximately 1-3 ns. The clusters of magnetic particles arising as a result of magnetic field create in their surrounding micromagnetic fields that interact with existing electric field what influences shape of curve of exponential increasing of current. (Fig.7). This effect is depressed by macroscopic imposed magnetic field what can be observed in Fig.7. The course of time dependence of electric channel in observed interval (500 ns) can be divided into 3 regions.

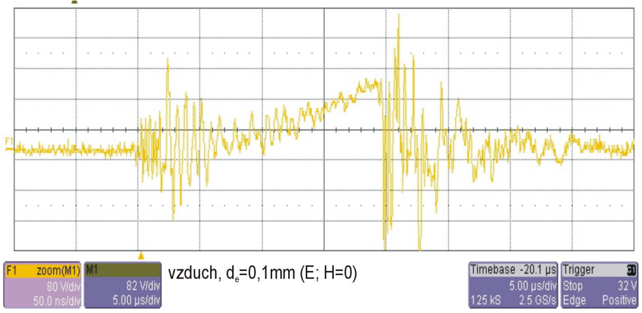

Figure 5: The time dependence of current in air

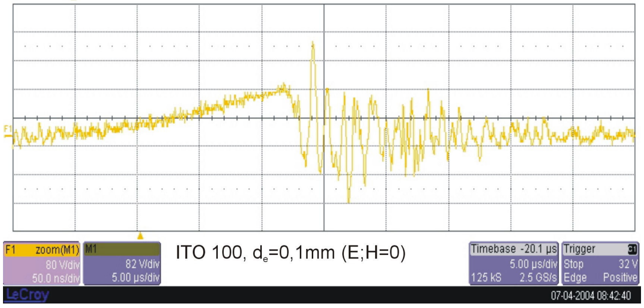

Figure 6: The time dependence of current in transformer oil ITO 100.

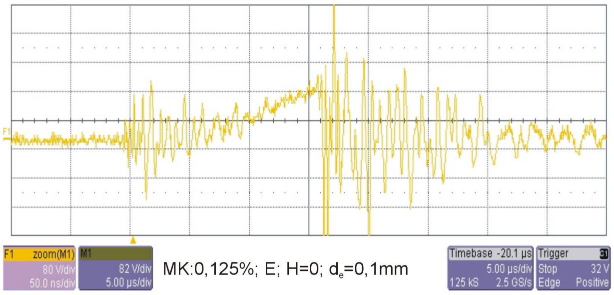

Figure 7: Time dependence of current in MF

In region of weak electric field (less then 10^7Vm^{-1}) is carried out orientation of dipoles of weak polar, resp. polar material and also weak bounded electric charged particles direction of electric intensity without irrespective of existence external magnetic field, when electric intensity is greater than 10^7Vm^{-1} current increases exponentially in breakdown channel with transition from avalanche to streamer and leader kind of current discharge. The multiply oscillations of impulses rise in last phase (after creating of conductive channel); these oscillations last 2-3 ns and their amplitude exceed three times current amplitude in pre-breakdown region; the fade wade of oscillation effect has also exponential transition from avalanche to streamer and leader kind of current discharge. The multiply oscillations of impulses rise in last phase (after creating of conductive channel);

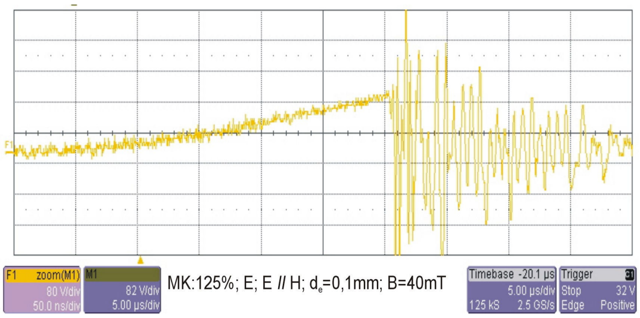

Figure 9: Time dependence of current in MF in external magnetic field $E \parallel H$

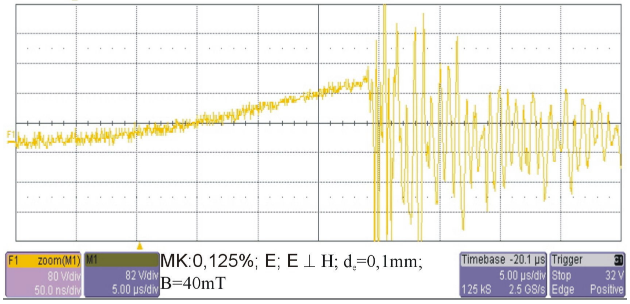

Figure 10: Time dependence of current in MF in external magnetic field $E \perp H$

these oscillations last 2-3 ns and their amplitude exceed three times current amplitude in pre-breakdown region; the fade wade of oscillation effect has also exponential attribute with lasting time equal to period of increasing density up to electric breakdown.

5. Conclusion

This contribution is a theoretical introduction supported by experiments. There was studied the creation of electric channel that represents the track of electrical breakdown. The electro-physical accounting for building of conductive channel was one on base a time change of concentration of electric charge carriers in dependence on their positions. Theses effects have been studied in coexistence of electric and magnetic field.

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