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Research articles

Experimental study of AC breakdown strength in ferrofluid during thermal aging

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ABSTRACT

A colloidal ferrofluid (FF) with superparamagnetic iron oxide nanoparticles (SPION) has been investigated for the AC breakdown strength during the accelerated thermal aging test. Three volume concentrations of a transformer oil based FF were subjected to the accelerated thermal tests at the temperature 90 °C. AC breakdown strength (BDS) tests were carried out every 200 h period for up to 600 h. The breakdown probabilities were calculated according Weibull distribution function. Measured BDS populations were compared with a base carrier oil. The BDS median of the clear carrier oil has been observed to fall down 1.54 times, however for particular FF samples it dropped 2.31, 2.90 and 3.63 times, respectively, when comparing properties of the samples before testing with the samples after aging. Final BDS probability distributions show that the dielectrics withstand voltage of FF became lower than that of the carrier oil. The long-term thermal load of the particular FF is critical for its colloidal stability, which is deduced to be the main reason of such a significant BDS reduction. The impact of the thermal aging on the AC magnetic susceptibility is briefly documented, too.

1. Introduction

Nowadays, oil immersed power transformers are key components of the electrical networks worldwide. There are several certain properties of the insulating liquid for the power transformer which are identified as being very important: low viscosity, low pour point, high flash point, excellent chemical stability, high electrical field strength [1].

Typically, a refined mineral oil (MO) is used as an insulating and cooling fluid. Magnetic fluids, also known as ferrofluids (FF), have been seen as a potential successor of globally used MO due to their improved cooling and insulating properties [2]. A comprehensive review dealing specifically with the transformer-oil based nanofluids have been published recently [3]. As a dielectric fluid in power transformers, FF enhances the heat transfer by thermo-magnetic convection due to the interaction between magnetic particles and magnetic field around the windings [4–6].

The crucial requirement for FF insulation systems is to have the improved long-lasting capability and capacity to withstand high electrical field levels and the thermal stability (note that the power transformer insulation must be designed for a lifespan of 40 years or more [1]). In previous studies, they have been investigated either in the certain volume of as-prepared specific fluids [7–11] or in the impregnated cellulose pieces [12].

It is clear that for reliable and effective application of FF in power transformers the long term colloidal stability at operating conditions must be guaranteed. In general, the essential approach to determination of colloidal stability criteria consists in the dimensional reasoning. For FF, the interplay between various energies per particle, such as thermal energy, magnetic energy and gravitational energy is crucial for the long term stability [13].

Among the commonly used magnetic nanoparticles in FF, the superparamagnetic iron oxide nanoparticles (SPIONs) have been often studied for various potential applications. For the stabilization of SPIONs in FF several types of coating agents can be used. Regarding the MO based FF, the oleic acid belongs to the most frequently used surfactant besides other ones, such as starch, chitosan, etc. [14]. According to [15], the maximum hottest-spot winding temperature should not exceed 110 °C under a continuous ambient temperature of 30 °C. Recently, the analysis of thermal stability of SPIONs has revealed that weight loss is 7.5% and 0.9% for the hydrophylic or hydrophobic SPIONs, respectively, in the temperature 30–120 °C. However, the weight change is related to the evaporation of water adsorbed on the

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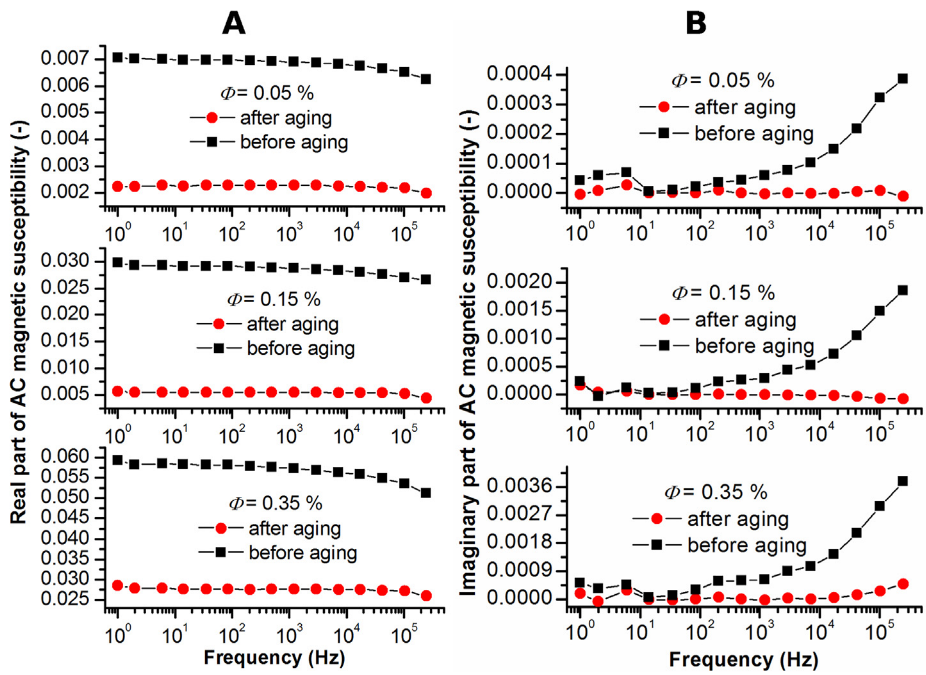

Fig. 1. Real magnetic susceptibility spectra (A) and imaginary magnetic susceptibility spectra (B) measured on the ferrofluid samples before and after the accelerated thermal aging test. The measurements were performed at room temperature (23 °C) in magnetic field intensity of 400 A/m.

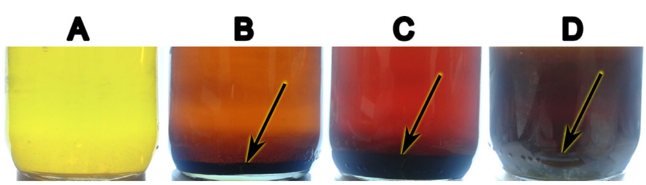

Fig. 2. The decomposition of the FF after the aging test. A – pure MO; B – FF05; C – FF15; D – FF35.

nanoparticles [16]. It seems that the problem of a possible FF decomposition in the above mentioned temperature range is documented only rarely. The questions are: Is the FF decomposition the issue in the transformer thermal profile? What will happen if so? Surely, the examination of long-term thermal aging/stability is the essential procedure for any FF to be used as an insulating fluid in power industry application.

Our motivation is to investigate the rapid degradation when heated FF interfaces with the air. The situation was briefly mentioned a long time ago [17]. However, the process at the temperature under 100 °C has not been documented yet. This is an important issue because in the open breather systems the aging starts at less than 100 °C [18]. We confirm the increased breakdown field strength in the FF at the initial stage of the tests. However, the critical issue regarded the long term stability of FF insulation has been addressed. BDS of FF are compared with those of the carrier MO which was subjected to the same test conditions.

The impact of the accelerated aging experiments on the FF magnetic susceptibility is reported, too.

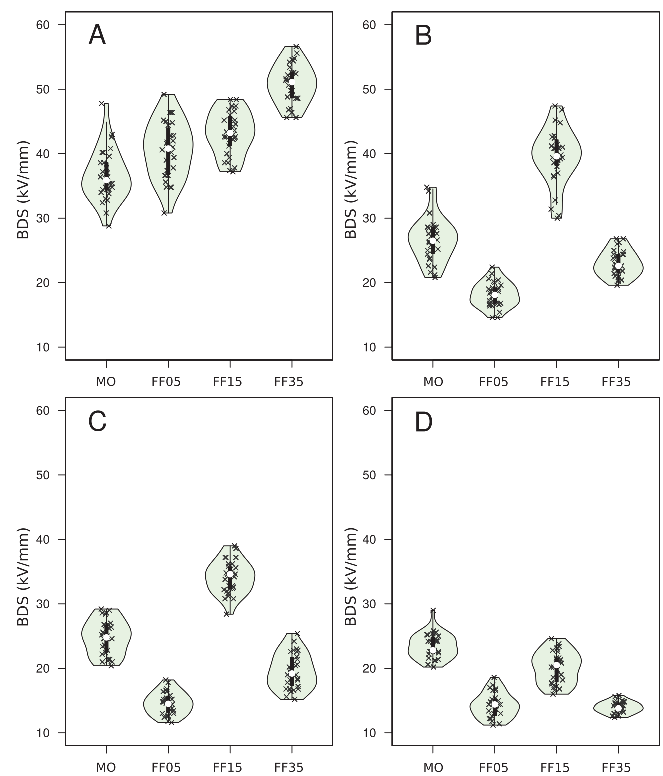

Fig. 3. AC breakdown strength aging statistics plot with measured data distributions. Panel A – initial state of the samples. Panels B–D represent the results after 200, 400, 600 h of the accelerated thermal aging, respectively.

2. Theoretical background

As the paper presents the impact of the FF thermal aging on dielectric breakdown and magnetic susceptibility, it is valuable to consider relevant mechanisms usually present in FF and contributing to the investigated properties.

In FFs, the magnetic susceptibility at low magnetic fields is sensitive to several parameters, e.g. the size of the magnetic nanoparticles, the nanoparticle material, and the nanoparticle concentration. By measurements of frequency dependent complex magnetic susceptibility $\chi(\omega)$, which is vital for an understanding of the dynamic behavior of FFs, the relaxation mechanisms have been often identified [19]. There are two mechanisms through which the magnetic moment of nanoparticles in FFs can align (relax) with the applied magnetic field [20]. In