INFLUENCE OF MAGNETIC NANO PARTICLES ON THE BREAKDOWN VOLTAGE OF TRANSFORMER OIL

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Abstract: In this study, we have investigated how the volume concentration of magnetic nanoparticles in the fluid and how the effect of magnetic field applied to the fluid affect the dielectric breakdown voltage by measuring AC (60Hz) breakdown strength of the fluids in accordance with IEC 156 standard. It is found that the dielectric breakdown voltage of pure transformer oil is around 12 [kV] with the gap distance of 1.5mm. In case of our transformer oil-based nanofluids with $0.0008<\Phi<0.006$ and without magnetic field, the dielectric breakdown voltage shows above 30 [kV], which is 2.5 times higher than that of pure transformer oil. Moreover, in case of the fluid with magnetic field, the dielectric breakdown voltage increases above 40 [kV], which is 3.3 times higher than that of pure transformer oil. However, in the case when the volume concentration of magnetic nanoparticles is above around 0.006, the dielectric breakdown voltage decreases reversely. It might be considered that the increase of the dielectric breakdown voltage of our transformer oil-based nanofluids is because conductive nanoparticles act as electron scavengers in electrically stressed transformer oil-based nanofluids converting fast electrons to slow negatively charged particles.

1 INTRODUCTION

The insulation fluids in power transformers perform two main functions; insulating and cooling. The highly refined mineral oils (transformer oils), typically used as insulating fluids [1, 2], have low thermal conductivity and thus perform low cooling efficiency. It has been shown that the heat transfer in electromagnetic devices can be substantially improved by using magnetic fluids consisting of magnetic nanoparticles suspended in transformer oil.

A magnetic nanofluid, so-called ferrofluid, is a stabilized colloidal material which contains nanoparticles within a carrier fluid. Ferrofluids have three main constituents; ferromagnetic particles such as magnetite and composite ferrite, a surfactant (i.e., emulsifier, to keep the magnetic nanoparticles from clumping. Some are used to oleic acid, citric acid, and tetramethylammonium hydroxide) and a base liquid such as water or oil (see Fig. 1) [3]. The surfactant coats the ferromagnetic particles, each of which has a diameter of about 10 nm. This prevents coagulation and keeps the particles evenly dispersed throughout the base liquid. Its dispersibility remains further stable when the magnetic field is applied adequately. Fluids with the suspended nanoparticles are called nanofluids,

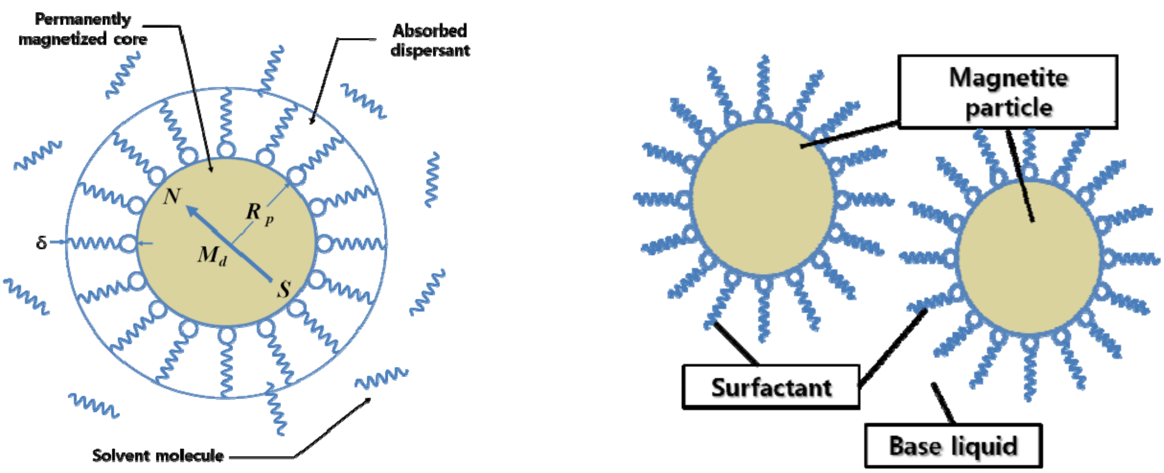


Figure 1: Schematic of the magnetic particles in ferrofluids

a term proposed by Choi [4] in 1995. Nanofluids can be considered to be the next-generation heat transfer fluid as they offer exciting new possibilities to enhance heat transfer performance compared to pure liquids. The much larger relative surface area of nanoparticles, compared to those of conventional particles, should not only significantly improve heat transfer capabilities, but also should increase the stability of the suspensions. Also, nanofluids can improve abrasion-related properties as compared to the conventional solid/fluid mixture.

Oil-based magnetic nanofluids enable better cooling of transformers than pure transformer oil. Thermomagnetic convection is established in the presence of temperature and magnetic field gradient. This leads to the better thermal exchange between the core and the environment of a transformer and the more effective cooling. Due to the fact that the insulation oil has much lower thermal conductivity compared to water, it would be reasonable to expect substantially the more increasing heat transfer capability by adding solid particles when compared to water. Because of these advantages, many studies have been carried out to develop the nano-insulation oil. However, the development of nanofluids is still hindered by several factors such as the lack of agreement between results, poor characterization of suspensions, and the lack of theoretical understanding of the mechanism [5]. Also, the dielectric breakdown strength of the fluid is not verified systematically yet. But in order to demonstrate the nanofluids act, many studies have been progressed by numbers of researcher in various fields. Especially, O'Sullivan et al. demonstrates that conductive nanoparticles behaviour as electron scavengers in electrically stressed transformer oil-based nanofluids converting fast electrons to slow negatively charged particles through the use of numerical simulation methods [6,7]. Also, they were suggested an electrodynamic model which is presented for streamer formation in transformer oil-based nanofluids and found out that the fast electrons cause a propagating electric field wave that is the dominant mechanism in streamer propagation leading to electrical breakdown [8].

In the present study, we have investigated how the volume concentration of magnetic nanoparticles in the fluid and how the effect of magnetic field applied to the fluid affect the dielectric breakdown voltage by measuring AC (60Hz) breakdown strength of the fluids in accordance with IEC 156 standard.

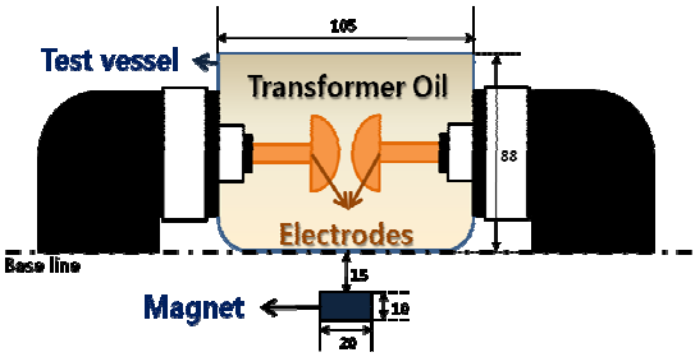
Table 1: Volume concentration of MNPs

OT-4 [ml]	EFH-1 [ml]	MNP's volume concentration [%]	Saturation magnetization [G]
300	0	0	0
300	5	0.08	0.32
300	10	0.16	0.64
300	15	0.23	0.95
300	20	0.31	1.24
300	25	0.38	1.53
300	30	0.45	1.81
300	35	0.52	2.09
.	.	.	.
.	.	.	.

2 EXPERIMETNS

In order to perform this study, we make the magnetic nanofluids through the mixing EFH-1 with OT-4. OT-4, this mineral oil (KS C 2301, 1-4) is commonly used for a high-voltage high-capacity insulating oil in transformers, and EFH-1, the magnetic nanofluid developed by Ferro Tech Co. in U.S.A., are mixed to be used as our transformer oil-based nanofluid. Due to the magnetic nanoparticles, the electrical conductivity and the density of EFH-1 is higher than that of OT-4. Also, EFH-1 used in this study has various material properties as following. The medium of EFH-1 is

(a) Dielectric breakdown measurement device



(b) Test vessel (unit: mm)

Figure 2: Dielectric breakdown measurement device and test vessel for experiments

used to transformer oil (highly-refined mineral oil), the corresponding saturation magnetization with various values of volume concentration of magnetic nanoparticles is shown as Table 1. The value of initial susceptibility is indicated to 1.70, the flash point of EFH-1 is 92°C and the pour point of it is minus 94°C. The volatility of the fluid is 9% at 50°C for one hour.

In order to measure the dielectric breakdown voltage in the transformer with various values of volume concentration (0.0008<Φ<0.0065) of magnetic nanoparticles in the transformer oil, the experiments have performed following by IEC 156 standard and we conducted repetitive experiments using the dielectric breakdown measurement device, BA75 (see Fig. 2 (a)). Figure 2(b) shows that the main components of BA75 consist of test vessel, a pair of electrode and the magnet, etc. The repetitive experiments are due to somewhat different experimental data for every time as we measured. Therefore, the work is conducted to find the average of all collected data in order to ensure the reliability of experimental results. The test dielectric oil and a pair of electrodes are installed inside a glass vessel. The inside of test vessel cannot be seen when EFH-1 is filled because the magnetic nanoparticles are black. The gap distance between electrodes in the test vessel are set to be 1 mm, and the voltage build-up rate is 1.0 kV/s. Measurement for each of different volume concentrations of the magnetic nanoparticles is performed to calculate the average value and the standard deviation with following two equations. And the volume concentration of magnetic nanoparticles (MNPs) can be estimated by the last equation as following:

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{1}$$

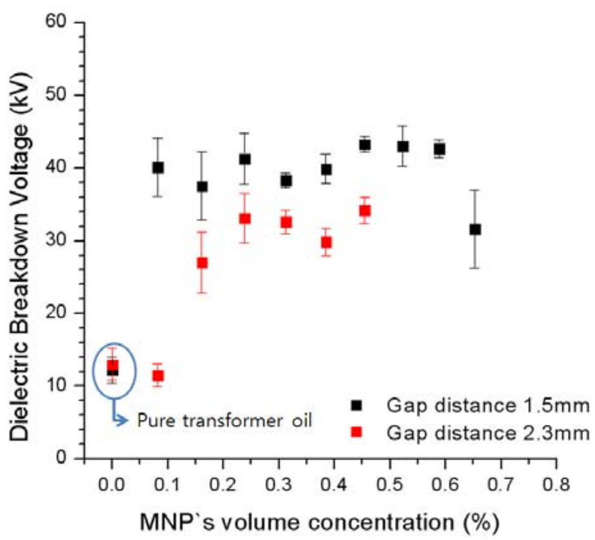
$$s = \frac{\sqrt{\sum_{i=1}^{2} X_i^2 - n\overline{X}^2}}{n-1} \tag{2}$$

$$\Phi = \left(\frac{V_N \times 0.05}{V_O + V_N}\right) \times 100 \tag{3}$$

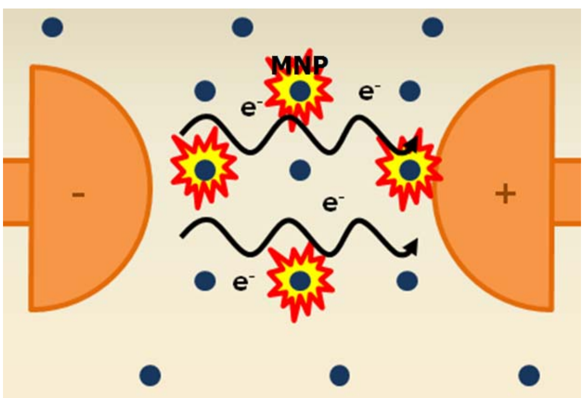
where: $\overline{X}$ = Average of results
s = sample standard deviation
X_i = i^{th} individual results
n = number of results
V_o = volume of transformer oil
V_N = volume of nanofluid
0.05 = the amounts of nanoparticle in the nanofluid
Φ = volume concentration of MNPs

3 RESULTS AND DISCUSSION

The dielectric breakdown voltages of the test dielectric oil for different volume concentrations of magnetic particles have been measured with a dielectric breakdown voltage measurement device. Also, in order to investigate dielectric breakdown performance with the effect of external magnetic field, we installed a magnet under the test vessel (see Fig. 2). As shown in Fig. 3(a), the average dielectric breakdown voltage of pure transformer oil is about 12 [kV], which is lower value than that of

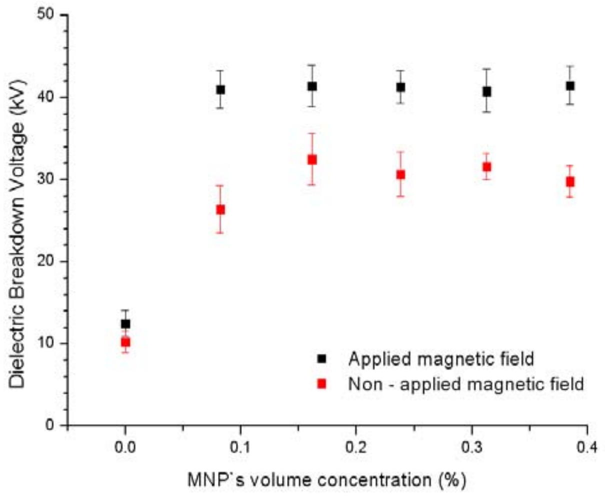


(a) Dielectric breakdown voltage

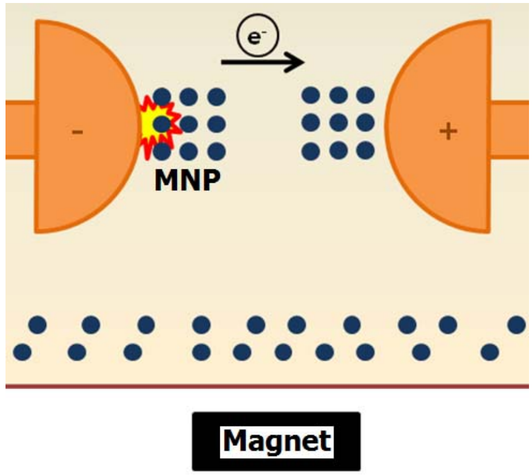


(b) Schematic of MAPs as electron scavenger

Figure 3: The effect of MNP's volume concentrations on the dielectric breakdown voltage



(a) Dielectric breakdown voltage



(b) Schematic of the mobility of MAPs

Figure 4: The effect of applied magnetic field on the dielectric breakdown voltage

KS standards on dielectric oil. This is due to the small gap distance between electrodes as we set to 1.5~2.3 mm for the limited capacity electrically of our experimental device.

When the magnetic nanoparticles are added in the fluid in case of $0.0008 < \Phi < 0.006$, the dielectric breakdown voltage increases above 40 [kV] with magnetic field as shown in Fig. 3(a). Our results are consistent with those by Segal et al. [9], which were conducted experimentally with Univolt 60 and Nytro 10X, commonly used transformer oil. These results are contrary to general ideas for the dielectric breakdown voltage since the conductive particles added decrease the dielectric breakdown voltage of the insulation materials. However, as it was explained by O'Sullivan et al. [6-8] that the increase of the dielectric breakdown voltage of our transformer oil-based nanofluids is because conductive nanoparticles act as electron scavengers in electrically stressed transformer oil-based nanofluids converting fast electrons to slow negatively charged particles as shown in Fig. 3(b).

In case of $\Phi > 0.006$, we can see that the dielectric breakdown voltage decreases reversely in Fig. 3(a). It might be considered that the added particles are attached on the surface of electrodes and form the chain each other because the distance between particles is too short for the stable dispersion in the fluid.

Generally, the more gap distance between electrodes increases, the less dielectric breakdown voltage per unit length of gap distance decreases. As a result of performed experiments with change of gap distance between electrodes, it is confirmed that the dielectric breakdown voltage per unit length of gap distance in case of 2.3 mm is less than in case of 1.5 mm.

Figure 4 shows the experimental results to investigate the effect of the applied magnetic field on the dielectric breakdown voltage of the fluid. In case of non-applied magnetic field, the dielectric breakdown voltage is around 30 [kV] as the particles are added as shown in Fig. 4(a). It is two times higher than that in case of the pure transformer oil. The dielectric breakdown voltage with the applied magnetic field is about 40 [kV] as explained before, which is higher than that in case of non-applied magnetic field. From our magnetic calculation, we might conclude that the increase of dielectric breakdown voltage by the applied magnetic field is due to the mobility of the magnetic nanoparticles. The particles in the field are easy to move near the electrodes where the breakdown is initiated as shown in Fig. 4(b). The moved particles to near surfaces will make formation of bubbles, molecular ionization and ultimately streamer propagation further into the liquid delayed for breakdown. Further studies should be required to investigate the motion of nanoparticles by the field included experimentally and numerically.

4 CONCLUDION

In the present study, we considered the effect of dielectric characteristics with the volume concentration of magnetic nanoparticles in the transformer oil-based nanofluid, the change of gap distance between electrodes, and the external magnetic field as measurement of dielectric breakdown voltage. We are confirmed if the gap distance between electrodes increase, the dielectric breakdown voltage per unit length of gap distance in the test vessel decrease. The dielectric breakdown voltage of pure transformer oil is around 12 kV, but the cases of transformer oil-based nanofluids with $0.08\% < \Phi < 0.4\%$ are two times higher than that of pure transformer oil, 30 kV. It might be considered that the added conductive nanoparticles act as electron scavengers in electrically stressed transformer oil-based nanofluids changing fast electron into slowly negative charged nanoparticles. Also, in case of the external magnetic field applied to the transformer oil-based nanofluids, it measured above 40 kV, and these results are 30% higher than that of the non-applied magnetic field. It might be considered that the increase of dielectric breakdown voltage by the applied magnetic field is due to the mobility of the magnetic nanoparticles. The particles in the field are easy to move near the electrodes where the breakdown is initiated where there are formation of bubbles, molecular ionization and ultimately streamer propagation further into the liquid for breakdown. Further studies should be required to investigate the motion of nanoparticles by the field included experimentally and numerically.

5 ACKNOWLEDGMENTS

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