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Experimental study on the dielectric breakdown voltage of the insulating oil mixed with magnetic nanoparticles

Jong-Chul Lee[a]* and Woo-Young Kim[b]

[a]*School of Mechanical and Automotive Engineering, Gangneung-Wonju National University, Wonju 220-711, Korea*
[b]*Graduate School of Automotive Engineering, Gangneung-Wonju National University, Wonju 220-711, Korea*

Abstract

In this study, we have measured the dielectric breakdown voltage of transformer oil-based nanofluids in accordance with IEC 156 standard and have investigated the dielectric breakdown performance with the application of an external magnetic field and different volume concentrations of magnetic nanoparticles. It is confirmed that the dielectric breakdown voltage of pure transformer oil is about 10 kV with a gap distance of 1 mm between electrodes. In the case of our transformer oil-based nanofluids with $0.08\% < \Phi < 0.39\%$ (Φ means the volume concentration of magnetic nanoparticles in the fluid), the dielectric breakdown voltage is three times higher than that of pure transformer oil. Furthermore, when the external magnetic field is applied under the experimental vessel, the dielectric breakdown voltage of the nanofluids is above 40 kV, which is 30% higher than that without the external magnetic field.

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1. Introduction

The insulation fluid in power transformers performs two main functions; insulating and cooling. The highly refined mineral oils (transformer oils), typically used as insulating fluids, have low thermal conductivity and thus perform low cooling efficiency [1]. 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 oils [2].

A magnetic nanofluid, so-called ferrofluid, is a stabilized colloidal material which contains nanoparticles within a carrier fluid. As shown in Fig. 1, a ferrofluid has three main constituents; ferromagnetic particles such as magnetite and composite ferrite, a surfactant such as oleic acid, citric acid, and tetramethylammonium hydroxide, to keep the magnetic nanoparticles from clumping and a base liquid such as water or oil. The surfactant coats the ferromagnetic

* Corresponding author. Tel.: +82-33-760-8766; fax: +82-33-760-8761.
E-mail address: jclee01@gwnu.ac.kr

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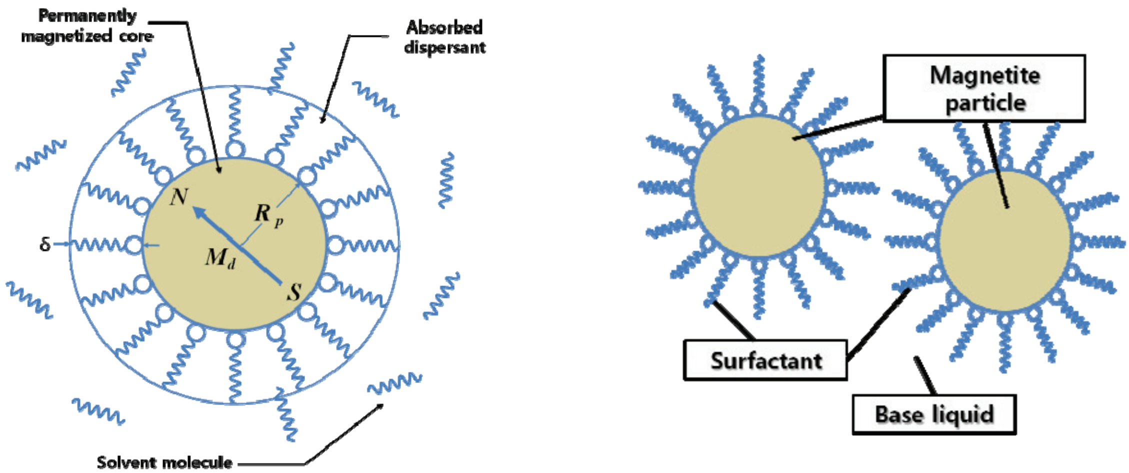


Fig. 1 Schematic sketch of the magnetic particles in a ferrofluid [3]

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 [3]. 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 [4]. 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.

The widespread use of transformer oil for high voltage insulation and power apparatus cooling has led to extensive research work aimed at enhancing both its dielectric and thermal characteristics. A particular innovative example of such work is the development of dielectric nanofluids. These materials are manufactured by adding nanoparticle suspensions to transformer oil, with the aim of enhancing some of the oil's insulating and thermal characteristics [5-8]. Because of these advantages, many studies have been carried out to develop the nano-insulation oil.

Electrical breakdown testing of magnetic nanofluids found that for positive streamers the breakdown voltage of the nanofluids was almost twice that of the base oils during lightning impulse tests. The lightning impulse withstand results obtained by V. Segal et al. of increased transformer oil breakdown strength with the addition of conducting nanoparticles for two common transformer oils (i.e., Univolt 60 and Nytro 10X) and their related experimental data of breakdown voltage are arranged in Table 1. Also, the propagation velocity of positive streamers was reduced by the presence of nanoparticles, by as much as 46% for Univolt-colloid nanofluid [8]. The results are important because a slower streamer requires more time to cross the gap between electrodes to cause breakdown. This allows more time for the applied impulse voltage to be extinguished. These results are very important in that it indicates that the presence of the magnetic nanoparticles in the oil samples inhibits the processes, which leads to electrical breakdown. The results found by V. Segal et al. are in direct conflict with conventional wisdom and experience

Table 1 Results of impulse voltage withstand testing in 25.4 mm gap system [10]

	Breakdown Strength (kV)		Time to breakdown (μs)		Average streamer velocity (km/s)	
Working fluids	positive	negative	positive	negative	positive	negative
Univolt 60 pure oil	86	170	12	27	2.12	0.94
Univolt-colloid nanofluid	157	154	26	15	0.98	1.69
Nytro 10X pure oil	88	177	16	23	1.59	1.10
Nytro-colloid nanofluid	156	173	25	17	1.02	1.49

Table 2 Properties of OT-4 and EFH-1

	Volume resistivity (Ω·m, 300K)	Density (g/ml, 300K)	Viscosity (cP, 300K)
OT-4	2×10^{16}	0.8370	13.73
EFH-1	5×10^{8}	1.1725	4.925

regarding the breakdown of dielectric liquids, where the presence of conducting particulate matter in a dielectric liquid is expected to decrease the breakdown voltage [9]. 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 [10]. Also, the dielectric breakdown strength of the oil-based nanofluid is not verified systematically yet. But in order to demonstrate the specific applications of nanofluids, many studies have been progressed by numbers of researchers in various fields. Especially, O'Sullivan et al. demonstrates that conductive nanoparticles behavior 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 [11, 12]. Also, they 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 [13].

In the present study, we confirm that dielectric breakdown performance of oil-based nanofluids with various values of volume concentration of nanoparticles in the oil-based nanofluids and the external magnetic field applied under the test vessel using the experimental apparatus.

2. Experimental details

2.1 Preparation of transformer oil-based nanofluid

In order to prepare transformer oil-based nanofluids, we control the concentration of magnetic nanoparticles through the mixing of EFH-1 with OT-4. The mineral oil (KS C 2301, 1-4), OT-4, is commonly used as high-voltage, high-capacity insulating oil in transformers and the magnetic nanofluid developed by Ferro Tech Co., EFH-1, are mixed to produce our transformer oil-based nanofluid. Main properties influencing heat transfer and dielectric breakdown strength of the common transformer oil, OT-4, and the magnetic nanofluid, EFH-1, were measured and these properties are listed as shown in Table 3. Due to the magnetic nanoparticles, the electrical conductivity and the

(a) Dielectric breakdown measurement device (BA75)

(b) Test vessels

Fig. 2 Dielectric breakdown measurement device and test vessels for experiments [14]

Table 3 Saturation magnetization with volume concentration of magnetic nanoparticles

OT-4 [ml]	EFH-1 [ml]	MNP's volume concentration [%]	Saturation magnetization [G]
300	0	0	0
300	5	0.082	0.328
300	10	0.162	0.648
300	15	0.238	0.952
300	20	0.312	1.248
300	25	0.385	1.54

density of EFH-1 is higher than that of OT-4. EFH-1 used in this study has various material properties as follows. MNP's volume concentration and saturation magnetization of transformer oil-based nanofluids prepared are shown in Table 2. The value of initial susceptibility is indicated to the 1.70, the flash point of EFH-1 is 92°C and the pour point is -94°C. The volatility of this ferrofluid is 9% at 50°C for one hour.

2.2 Measurements of dielectric breakdown voltage

In order to measure the dielectric breakdown voltage with various values of volume concentration (0.08% < Φ < 0.39%) of magnetic nanoparticles in the mixed nanofluid, the testing is done 60 times for each of the volume concentration according to IEC 156 standard using the dielectric breakdown measurement device, BA 75 (see Fig. 2). Figures 3 show the main components of BA 75 consist of test vessel, a pair of electrode and the permanent magnet (about 250 mT), etc. The mixed nanofluid and a pair of electrodes are installed inside a glass vessel. When the mixed nanofluid is filled to the vessel, the inside of test vessel is not transparent because the magnetic nanoparticle is black as shown in Fig. 2(b). The gap distance between electrodes in the test vessel are set to be 1 mm,

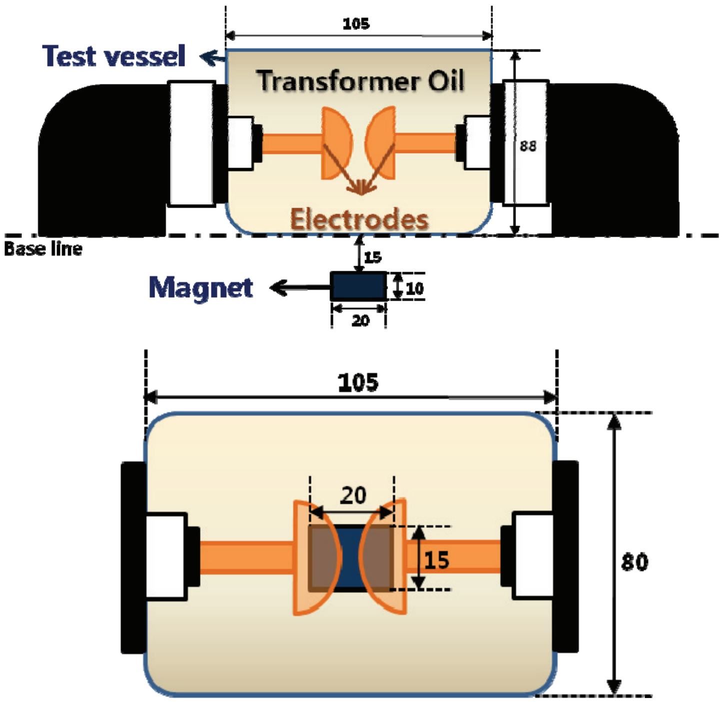
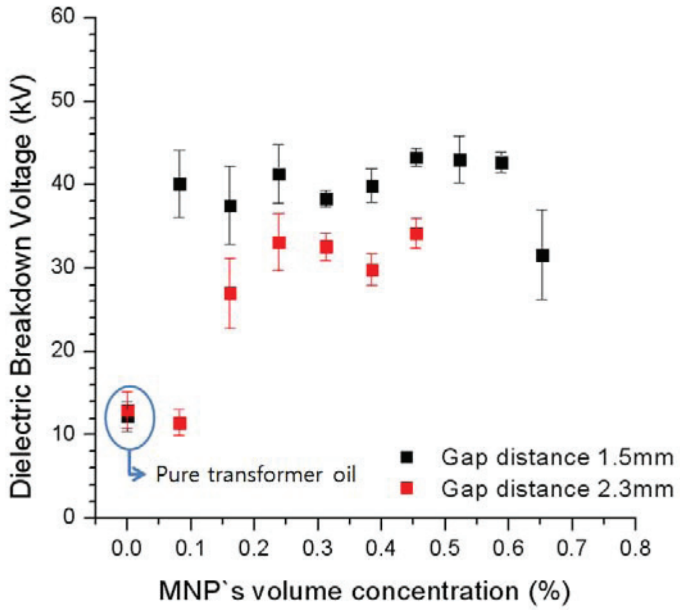


Fig. 3 Dielectric breakdown voltage with different MNP's volume concentrations

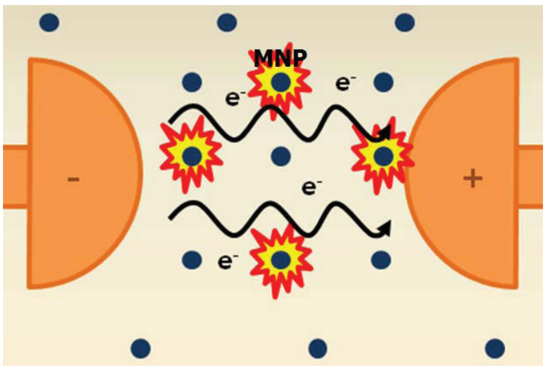
and the voltage build-up rate is 1.0 kV/s. Measurement for each of different volume concentrations of the magnetic nanoparticles is performed to calculate the average value and the standard deviation with following two equations and the volume concentration of magnetic nanoparticles can be estimated by the last equation as following:

$$MNP's\ volume\ concentration = \left(\frac{V_N \times 0.05}{V_O + V_N}\right) \times 100 \tag{1}$$

where MNP means the magnetic nanoparticle, V_o is the volume of transformer oil, V_N is the volume of nanofluid, and 0.05 means that the amounts particle contains 5% in the nanofluids [14].



(a) Dielectric breakdown voltage with MNP's volume concentrations



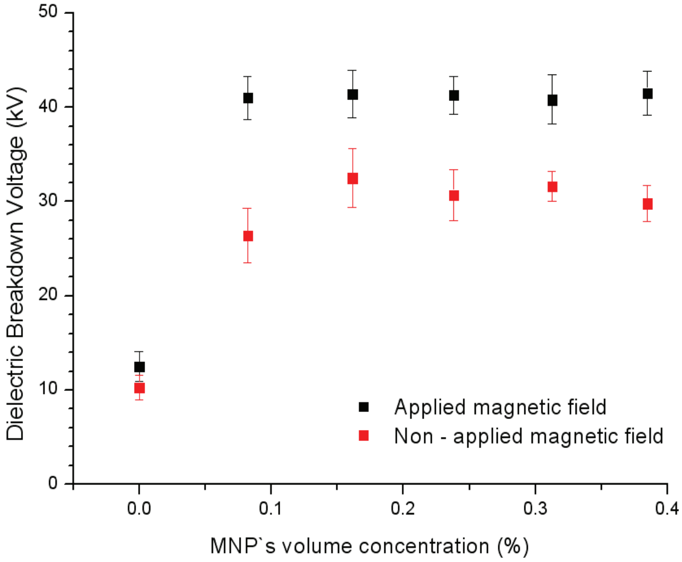
(b) Schematic of MNPs as electron scavenger

Fig. 4 Dielectric breakdown voltage with MNP's volume concentrations (top) and schematic of MNPs as electron scavenger (bottom)

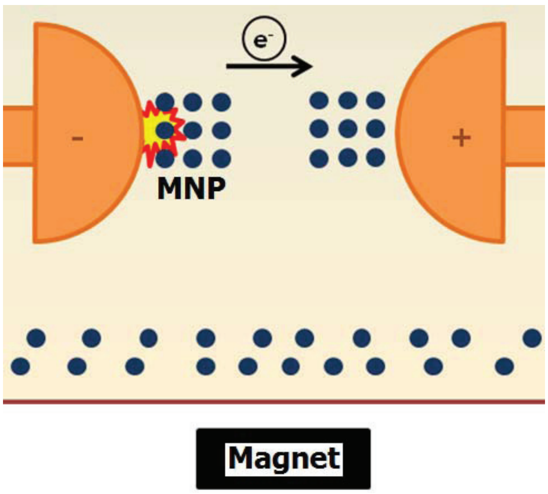
3. Results and discussion

In order to investigate the dielectric breakdown performance with the effect of external magnetic field, we installed a magnet, which is originally installed for stirring oils, under the test vessel (see Fig. 3). The average dielectric breakdown voltage of pure transformer oil, OT-4 is about 10 kV [14], this is lower value than that of IEC or KS on dielectric oil. This is due to the small gap distance between electrodes as we set to 1 mm for the limit capacity electrically of our experimental device (BA 75).

Figure 4 shows the experimental results with the various values of MNP's volume concentration and the change of gap distance between electrodes. Generally, increasing the gap distance between electrodes leads to a marked



(a) Dielectric breakdown voltage with MNP's volume concentrations



(b) Schematic of MNPs as electron scavenger

Fig. 5 Dielectric breakdown voltage with MNP's volume concentrations (top) and schematic of MNPs in case the external magnetic field is applied or not decrease of the dielectric strength [16]. As a result of the performed experiments with change of gap distance between electrodes, it is confirmed that the dielectric breakdown voltage with unit length of gap distance in case of 2.3 mm is less than in case of 1.5 mm.

Figure 5 shows the experimental results with change of volume concentration of magnetic nanoparticles and whether or not magnetic field. In case of non-applied magnetic field, the dielectric breakdown voltage is measured 26.4 kV as the volume concentration of magnetic nanoparticles (Φ) is 0.082%. It is two times higher than the case of Φ=0 which is measured around 10 kV. This trend is corresponded with those by Segal et al. [8], which were performed experimentally with Univolt 60 and Nytro 10X, commonly used to transformer oil. Increasing the dielectric breakdown voltage with to the added magnetic nanoparticles to transformer oil might be because the conductive nanoparticles affect as electron scavengers in electrically stressed transformer oil-based nanofluids changing fast electron into slowly negative charged nanoparticles. In other words, the extension of a net space charge zone at the streamer tip is hindered due to the slowly mobility of negative charged nanoparticles, and it is suppressed to the generated streamer propagation in the transformer oil for electric field propagation wave [13].

In case of the MNP's volume concentrations between 0.082% and 0.385%, the dielectric breakdown voltage has averaged 40.2 kV with the magnetic field, which is 30% higher than that of the non-applied magnetic field. It might be considered that the dielectric breakdown voltage is increased because the magnetic nanoparticles are not hold together but dispersed well by the external magnetic field. But, these phenomena are still interrupted by several factors such as the shortage of correlation between results, insufficiency description of suspension patterns, and the shortage of theoretical understanding of the mechanisms.

4. Conclusions

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 the measurement of dielectric breakdown voltage. We are confirmed if the gap distance between electrodes increase, the dielectric breakdown voltage with unit length of gap distance in the test vessel decrease. The dielectric breakdown voltage of pure transformer oil, OT-4, is measured around 10 kV, but the cases of transformer oil-based nanofluids with $0.08\% < \Phi < 0.39\%$ are measured two times higher than that of pure transformer oil, 30 kV. It might be considered that the added conductive nanoparticles affect 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. These phenomena are considered as the dielectric breakdown voltage of transformer oil-based nanofluid is increased because the magnetic nanoparticles are not hold together but dispersed well by the field.

In the future work, we will investigate how the direction of external magnetic field affects to the dielectric characteristics of transformer oil-based nanofluids and the numerical study should be conducted to streamer propagation with materials and properties of the magnetic nanoparticles.

Acknowledgments

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