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Effect of DC Voltage Ramp Rate on Breakdown in Ferrofluid Based on Transformer Oil

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In the presented experimental study, the transformer oil based magnetic nanofluids with iron oxide nanoparticles are tested for DC breakdown as a variable depended on voltage ramp rate at ambient conditions. The breakdown tests were performed on four samples of various concentrations of nanoparticles with 0, 0.05, 0.15, and 0.35 vol.%. The measurements were conducted in accordance with IEC 60897 by using needle to sphere electrode geometry. Carrier oil and ferrofluids were tested at negative needle polarity of electric potential towards grounded sphere and then vice versa. By utilizing the particular breakdown measurement method with a variable DC voltage ramp rate, a statistically large set of breakdown data was obtained. The data-sets were collected as a function of negative DC voltage ramp rates 470, 750, and 1100 V/s, respectively. The test results show that the higher is the ramp-rate of DC voltage, the higher is the dielectric breakdown strength. It has been found that with the negative needle — grounded sphere geometry, there was dielectric breakdown at higher voltage than the other way around. Also, the effect of nanoparticle concentration in the oil on the increasing dielectric breakdown strength was observed.

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PACS/topics: ferrofluid, dielectric strength, DC breakdown voltage

1. Introduction

The constant rise of electric energy consumption is pushing us toward using power transformers with higher power creating bigger demands on performance and reliability of the electrical insulation system of power transformers [1]. This is the reason why researchers are looking for a better alternative to oil and paper based electrical insulation systems [2]. In this context, the research on transformer oil based nanofluids has been growing rapidly during the last few decades [1]. The nanofluids came up as a potential substitute of mineral oils, and as an insulation and heat transfer fluid for high voltage equipment. Especially, the transformer oil based magnetic nanofluids (ferrofluids) may be regarded as the successor of transformer oil as they offer better thermal and dielectric properties [2]. Although much research has been conducted in the field of ferrofluid based dielectrics [3, 4], there are several challenges that we still face today. An important parameter, which is usually experimentally observed in dielectric ferrofluids, is the dielectric breakdown. It is known that at certain nanoparticle concentrations the ferrofluids may exhibit higher values of the breakdown strength as compared to pure transformer oil [5]. This effect is significantly dependent on the external magnetic field [6]. Just a few theoretical approaches have been proposed to explain the paradoxical dielectric behavior. Among them, the nanoparticle charge trapping model is becoming quite acceptable [7]. In this model, the streamer propagation velocity reduction due to the charged nanoparticles is considered as a key aspect. However, the experimental research has not been focused much yet on the breakdown mechanism in ferrofluids under various temporal and spatial conditions, which could shed light on the streamer dynamics.

This article is mainly focused on breakdown dielectric voltage (BDV) of the ferrofluid and the base transformer oil. Breakdown dielectric voltage was tested using DC voltage with a variable DC voltage ramp rate. Three different concentrations of nanoparticles diluted in transformer oil were tested with the following content of nanoparticles: 0.05, 0.15, and 0.35 vol.%. Results of BDV were compared and statistically evaluated.

2. Experiment

The ferrofluid samples tested for the DC BDV consist of a commercial transformer oil MOGUL TRAFO CZ-A and iron oxide nanoparticles stabilized by oleic acid. The preparation of the raw concentrated ferrofluid including the magnetic nanoparticle synthesis by chemical co-precipitation is described elsewhere [8, 9]. The samples investigated in this study were diluted from the concentrated ferrofluid at 60 °C. As mentioned earlier, the dilution procedure yielded the nanoparticle concentration of 0.05, 0.15, and 0.35 vol.%. The BDV tests on each sample were performed according to the international standard IEC 60897. In a testing vessel, the pair of needle-sphere electrodes was fixed with the inter-electrode separation

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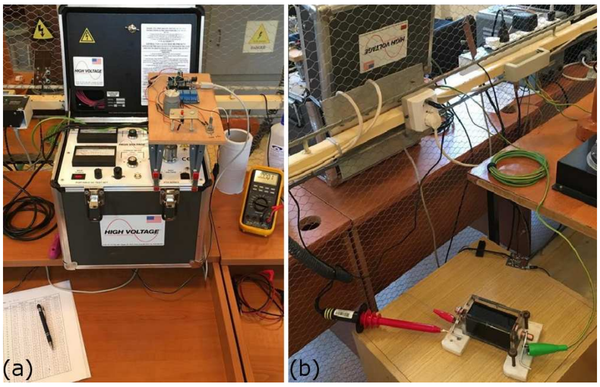

Fig. 1. The experimental setup employed in the breakdown voltage measurements. (a) High voltage power supply with the output voltage rise rate control system. (b) BDV test vessel filled with the ferrofluid.

distance of 0.5 mm. Thus, the measuring configuration consists of high voltage power supply PTS-37.5 (High Voltage, USA) and an external regulator of DC voltage ramp rate, which can be seen in Fig. 1a. The digital multimeter Hexagon 720 (Beha Electronics, CN) and high voltage probe HV40 (Elma Instruments, DK) were used to detect the BDV (Fig. 1b). In the tests, the high potential was applied to both the needle and the sphere. After pouring the investigated liquids into the vessel, the created bubbles were removed by using a vacuum pump and a desiccator. Three negative voltage ramp rates were chosen, with values of 470, 750, and 1100 V/s. The values of BDV were measured 30 times to obtain reproducible average BDV with an eliminated statistical error. Between each measurement, we kept an off set of 2 min. After each detected BDV we gently stirred the sample by using a small non-conducting rod. The tests were carried out at ambient conditions.

3. Results and discussion

The values of the BDV were statistically treated and the results are presented in Fig. 2. First of all, the results confirm the enhanced BDV of the ferrofluid samples as compared to the oil. With the increasing nanoparticle concentration, the increasing BDV trend is observed. Then, it is clear that the mean increases with the increasing voltage ramp rise for each of the tested samples and for both electrode arrangements with the high negative potential on the needle (-N) and on the sphere (-S). This implies that the time during which the voltage increases to BDV plays an important role in creating favorable conditions for the breakdown. During that time the nanoparticles or impurities in the oil undergo polarization and ionization. Even though these particles may be polarized and ionized at fields far below the breakdown, the time may not be sufficient to draw more particles into the high-field region where a streamer could be formed. That is a possible reason due to which higher BDV are measured for higher voltage rise rates.

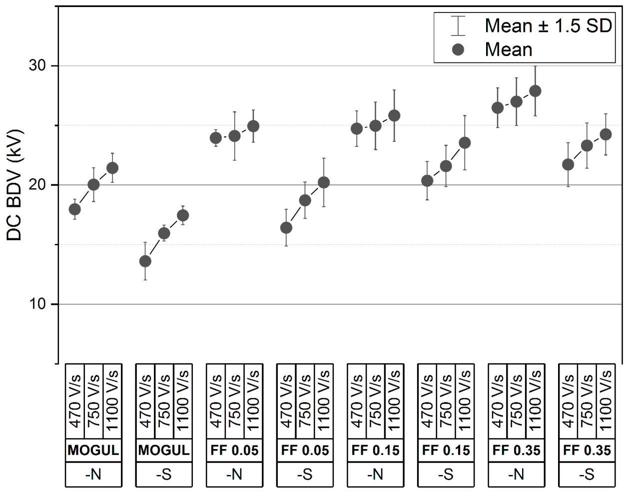

Fig. 2. BDV of MOGUL TRAFO CZ-A oil and ferrofluid samples with the magnetic particle volume concentrations of 0.05, 0.15, and 0.35 vol.%. The BDV are presented for the three voltage ramp rates with the high negative potential needle (-N) and sphere (-S) electrode. FF abbreviation stands for ferrofluid.

To consider the effect of various voltage ramp rates on the BDV in the transformer oil and the ferrofluids, one can take into account the possible formation of bubbles in the pre-breakdown state. When electrons are emitted from the cathode, they undergo acceleration in the electric field and may transfer their energy to molecules or particles or are absorbed by the particles to form negative ions. Approaching the BDV, the negative space charge may significantly increase in density. In that case, the ions repel each other and give rise to the formation of microbubbles. In the bubbles, the longer free paths allow the electrons to gain enough energy to ionize the oil molecules. These processes are obviously dependent on the duration of the applied voltage [10].

For each sample, the BDV values are higher when the needle is the cathode and the sphere electrode is grounded. In this case, one can assume that a negative streamer initiated from the needle is formed and propagates opposite to the direction of the electric field. According to earlier studies [11], the higher BDV at the needle as a cathode can be attributed to the different propagation velocities of positive and negative streamers. The positive streamers grow at faster rates than the negative ones. However, there is a remarkably different effect of the voltage ramp rate on the BDV tested with the high potential needle and sphere. For the transformer oil, the difference of 3.5 kV in the mean BDV was found when the results obtained at 470 and 1100 V/s were compared. With this electrode arrangement, the ferrofluid samples exhibited the difference in the mean BDV measured for the two voltage ramp rates as follows: 1 kV for the ferrofluid with concentration of 0.05 respectively 0.15 vol.% and 0.6 kV for the sample with concentration of 0.35 vol.%. More significant difference in the mean

BDV for the two voltage ramp rates was observed for the high potential sphere — grounded needle electrode arrangement. In this case, the difference of 3.9 kV and 3.15 kV was found for the samples with 0.05, 0.15, and 0.35 vol.%, respectively.

Interestingly, from Fig. 2 one can see that the measured BDV increases remarkably with increasing nanoparticle concentration, especially in the case of negative sphere. This is true for each voltage rise rate applied and therefore this effect is in accordance with the nanoparticle charging and the related velocity of the streamer propagation model [7]. However, it is shown that the BDV measured with the negative needle for the ferrofluid with 0.05% of nanoparticles does not differ from the BDV values measured on the ferrofluid with 0.15% of nanoparticles. On the contrary, the BDV values obtained for the two samples spread practically over the same range. This may imply that the negative streamer propagation velocity is less affected by the nanoparticle number than the positive streamer propagation velocity. However, deeper theoretical analysis and comprehensive understanding of the reported result require further rigorous experimentation which is beyond the scope of this paper. The application of suitable complementary methods, like electronic and optical measurements of the streamer propagation velocity has a potential to shed light on the peculiar BDV behavior, and the nanoparticle concentration and polarity effects.

4. Conclusions

In this article we tested the influence of negative DC voltage ramp rates on BDV of alternative insulation liquids. The tested samples were the transformer oil and the magnetic fluid with different concentrations of magnetic nanoparticles. Comparing the results of each sample we came to a conclusion that the higher negative DC voltage ramp rate results in higher breakdown voltage. It is necessary to point out that geometry of electrodes plays the important role in the BDV. With electrode geometry negative needle — grounded sphere, we measured a higher BDV than in the opposite case. On the one hand, these results may be useful for improvement of the existing theoretical models of the breakdown mechanism in ferrofluids. On the other hand, the presented results may open a new avenue for deeper experimental and theoretical investigation of the dielectric breakdown in ferrofluids.

Acknowledgments

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