Improving the Insulating Properties of Transformer Oil Using Nanomaterials with Regard to Thermal Aging

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Abstract – Incorporation of nanoparticles into transformer oils improves their electrical and insulating properties. However, thermal aging may undesirably decrease the performance of nanomaterials in transformer oils. Herein, pure oil together with TiO2, ZnO, and CNTs incorporated oil (nanofluids) can underwent thermal aging by simulating this phenomenon at 110, 120, and 130 ° C for 30, 30, and 15 days (equivalent of 10, 30, and more than 40 years of normal oil operation, respectively). During the accelerated thermal aging process, the total acid number (TAN), breakdown voltage, and lightning impulse breakdown voltage of all samples were measured periodically. The TAN increased with increasing temperature and time, but never exceeded the allowable level of 1.2 mg KOH/g. As the oil ages, its corrosion rate increases, which is undesirable for the transformer. The results of the breakdown voltage test suggest that the TiO2 was the best candidate, such that the breakdown voltage increased with respect to the pure oil by 17, 27, and 48% at 110, 120, and 130 °C, respectively. The outcome of the lightning breakdown test also indicated that TiO2 still performed better than the other samples.TiO2 was able to improve the lightning voltage at 110, 120, and 130 °C by 33, 8, and 5%, respectively. Therefore, as it was observed, TiO2 has been able to perform the best performance in thermal aging.

Keywords: Transformer oil; Thermal aging; Breakdown voltage; Lightning breakdown; Nanoparticle

1. Introduction

The transformer is one of the most important devices used in energy networks, which play a key role in all three sectors of production, distribution, and transmission. Moreover, they are the most valuable assets of substations. Transformers typically cover more than 60% of the total cost of a substation[1]. Buying transformers to invest in electrical power systems can cost millions of dollars. To ensure that the costs incurred for the transformers are worth buying, the life of the transformers should be extended as much as possible to reduce the cost of replacing them over the years. One of the most important factors in improving and extending the life of transformers is oil lifetime. Inside transformers, mineral oil has the most important role due to its insulating and cooling properties. This role is so important that the oil inside the transformer looks like the life-giving blood inside the human body[2]. One of the best ways to improve the insulation and thermal properties of transformer oil is to use nanotechnology and nanofluids(NF).

Nanofluids are used in transformer oil to achieve various purposes. One of the purposes of using nanofluids is to improve the insulation properties and increase the breakdown voltage[3, 4]. Nanofluids have been used to absorb soluble gases or water inside transformer oils, which also improves the electrical properties of the oil[5, 6].Nanoparticles can also be used as a sensor to detect a specific gas inside the oil[7, 8].The effect of nanofluid on partial discharge has been studied by some authors[9-11]. Usually adding nanoparticles to mineral oil improves the thermal properties of nanofluids (due to the higher thermal coefficient of nanoparticles), increases efficiency, and

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reduces costs and energy consumption.[12-14]. But the point that should never be overlooked is that over time, the insulating properties of transformer oil deteriorate. The degree of degradation is affected by the operating temperature of the oil[15].

Tsuboi et al. examined the aging effect on insulating reliability evaluation. They were able to age the oil by 30 years by heating the oil at 120° C for 29 days[15]. Segal et al. introduced an accelerated thermal aging method to study the aging stabilities of their Fe304 nanofluids. After 12 weeks of accelerated aging at 185° C, the Fe304 nanofluids fully retain its insulating advantages over the pure oil[16]. Liang et al. considering the effect of nano Al2O3 doping on thermal aging properties of oil-paper insulation. The composite and normal papers were treated with an accelerated thermal aging experiment at a temperature of 130 °C for 56 days. Nano-Al2O3 can effectively adsorb copper compounds and keep part of the acid products and water away from the thermal aging process[17].However, previous research on nanofluids has focused mainly on the properties before and after short-time high temperatures, and changes in the insulating properties of nanofluids during aging have rarely been investigated.

In this work and in the first step, all nanofluids prepare by the two-step method. In the second step for accelerating aging, pure oil and TiO2, ZnO, and CNTs nanofluids were placed in 110,120 and 130°C for 30,30 and 15 days. During this process, all samples were taken out periodically for insulating properties tests including total acid number(TAN), break down voltage, and lightning breakdown tests.

2. Experimental Test

2.1 Materials, methods, and nano fluids preparations

Nanofluid preparation is not a simple process of combining nanoparticles in a base oil. The uniform and stable suspension of nanoparticles in the base liquid is very difficult due to the attractive Wonder Walls attractive forces between them that lead to the aggregation effect. In order to achieve a nanofluid with a homogeneous composition, nanoparticles must be added to the base liquid under specific environmental conditions and by special methods. Based on the number of nanofluid preparation steps, there are several methods for preparing nanofluids that are divided into two basic methods: One-step and Two-step techniques. The two-step method is the most widely and economically method to produce nanofluids on a large scale[18].

For the preparation of nanofluids (based on The two-step method) and in the first step, nanoparticles used in this method are produced as dry powders by chemical or physical methods. Nanoparticles including TiO2 (99.9% purity, density: 3.9 g.cm-3), CNTs (99.95% purity, density: 5.6 g.cm-3) and ZnO (95% purity, density: 2.1 g.cm-3) were purchased from US Research Nanomaterials, Inc., USA. TiO2, CNTs and ZnO respectively having the average sizes of 18nm, 30nm and 18nm. In the second step, the Nano-sized powder will be dispersed into a fluid with the help of intensive magnetic force and ultrasonic agitation. In this work and for nanofluids preparation, the nanoparticles were weighed by a high accuracy scale with the precision of 1 mg. Then all nanoparticles dried in a drying oven for 8 h at 200 °C to erase their moisture. After the nanoparticles have cooled down slowly, they are combined with transformer oil. To make a homogenous dispersion of nanoparticles in the oil, the mixtures were stirred for 30 min using a magnetic stirrer. Finally, in the final stage, the nanofluids were sonicated for 2 h to ensure that the nanoparticles were well dispersed in the oil phase and all the prepared samples were degassed at less than 1kPa for 48 h before test. In order to maximize the breakdown voltage for each nanofluids, optimum contents for CNTs, ZnO and TiO2 nanofluids were 0.01, 0.01, and 0.075 wt.%, respectively.

2.2 Accelerated thermal aging

For accelerating aging, pure oil and TiO2, ZnO, and CNTs nanofluids were placed in 110,120 and 130°C for 30,30, and 15 days. The aged status of all samples was evaluated based on the Arrhenius equation in which the lifespan of insulating materials decreases by half as its temperature exceeds the reference temperature (60°C) by 7°C. Hence, accelerated thermal aging for 30days at 110 and 120°C approximates 10 and 30 years, and thermal aging for 15 days at 130°C is 40years' service condition[15]. During this process, all samples were taken out periodically for insulating properties tests.

2.3 TAN test:

METROHM 848 device in base on ASTM D664 standard, were used to perform the TAN test. The allowable TAN level according to ASTM D664 in the transformer oil is 1.2 mg KOH/g.

2.4 Breakdown voltage test

The breakdown voltage test was generated by the BAUR PGO S-3 device according to standard IEC 60156. The test device consists of two spherical electrodes with a distance of 2.5 mm and a voltage of 2kV/s. The time interval with stirring action after each breakdown was set to 1 min. All the experiments were done at room temperature and ambient pressure. It is important to note that, in order to obtain highly accurate results from the breakdown voltage test, the moister content value of all samples were kept in the normal range.

2.5 Lightning breakdown tests

According to IEC 60897, 25 mm gap of needle with a 50μm radius of curvature to sphere electrodes was chosen in the tests. The needle was replaced by a new one after each breakdown to ensure all experiments were under the same conditions. The initial standing time was fixed at 5 minutes and the time between two successive lightning breakdown was 1 minute. To ensure the repeatability, every sample gained six repetitive experiments and the average value was recognized as the lightning impulse voltage.

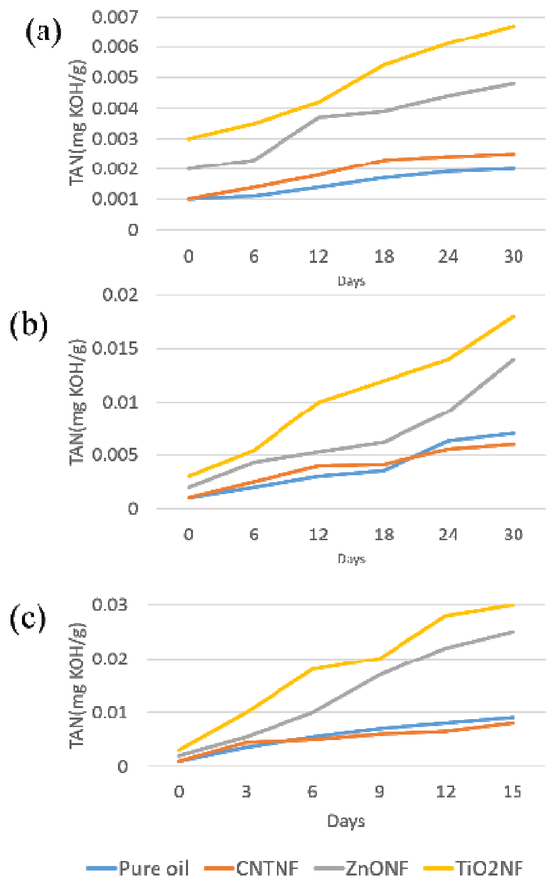

Figure 1: The results of TAN test for (a)110°C; (b)120°C; and (c) 130°C

3. Results and discussion

After preparing the samples, the TAN was measured for all of them. The TAN for pure oil, CNTNF, ZnONF, and TiO2NT were 0.001, 0.001, 0.002, and 0.003 mg KOH/g, respectively. The results of TAN test are shown in Fig.1.As can be seen in the figure, the TAN for all samples increases over the days. On the other hand, as the temperature rises, this amount increases, which indicates the degradation of oil in high temperatures. In normal oil operation, the higher the operating temperature of the oil, the greater the degree of damage, and one of the reasons for the destruction is the increase in the amount of acid. This figure shows a very good correlation between the TAN and the actual age of the oil. In Fig1. (a), which deals with the aging of the oil in 10 years, as you can see, the TAN for all samples has increased very low, which is very low in the normal operation of the oil in 10 years. In Fig1. (b), which is related to oil performance in 30 years, the number of TAN has increased a lot, and in Fig1. (c), which is related to operation over 40 years, the amount of total acid has increased significantly, which indicates the degradation of oil properties. The TAN for all samples is within the allowable limit and below 1.2 mgKOH/g.

After preparing the samples and before performing the test, the breakdown voltage for pure oil, CNTNF, ZnONF, and TiO2NT were 59, 18, 44, and 68 KV, respectively. Fig.2 shows the breakdown voltages for both pure oil and nanofluids along the aging process. To perform this test, all samples were subjected to equal conditions. Fig2. (a) shows the breakdown voltage results after 30 days at temperature 110 ° C, which simulates the performance of the oil in 10 years. As can be seen, the breakdown voltage did not change significantly due to the lower operating temperature of the samples. In the real operation of the oil in 10 years, if the transformer works in its optimal condition, the amount of breakdown voltage will not change much. After performing the test, the breakdown voltage for pure oil, CNTNF, ZnONF, and TiO2NT were 56, 43, 17, and 66 KV, respectively. As can be seen, TiO2NF has the best results and has been able to improve the breakdown voltage compared to oil by 17%. Meanwhile, CNTNF and ZnONF reduced the breakdown voltage by 70 and 23% after the test.

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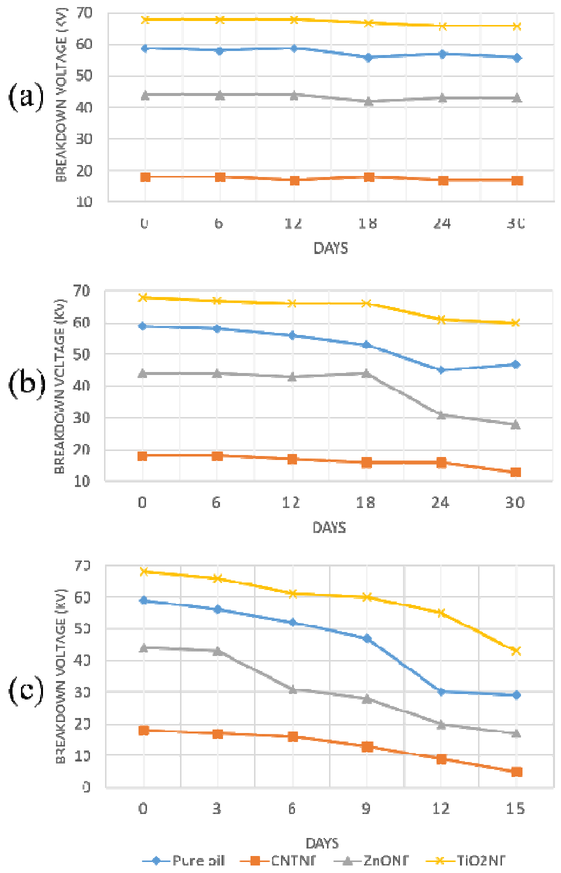

Figure2: The results of breakdown voltage tests for (a)110°C; (b)120°C; and (c) 130°C

Fig2. (b) shows the breakdown voltage results after 30 days at temperature 120 ° C. The results show that the breakdown voltage has been significantly reduced due to exposure to high temperatures, which is equivalent to 30 years of oil aging. After performing the test, the breakdown voltage for pure oil, CNTNF, ZnONF, and TiO2NT were 47, 28, 13, and 60 KV, respectively. TiO2NF has the best results and has been able to improve the breakdown voltage compared to oil by 27%.However, CNTNF and ZnONF have a detrimental effect on oil aging and reduced the breakdown voltage by 70 and 51%.

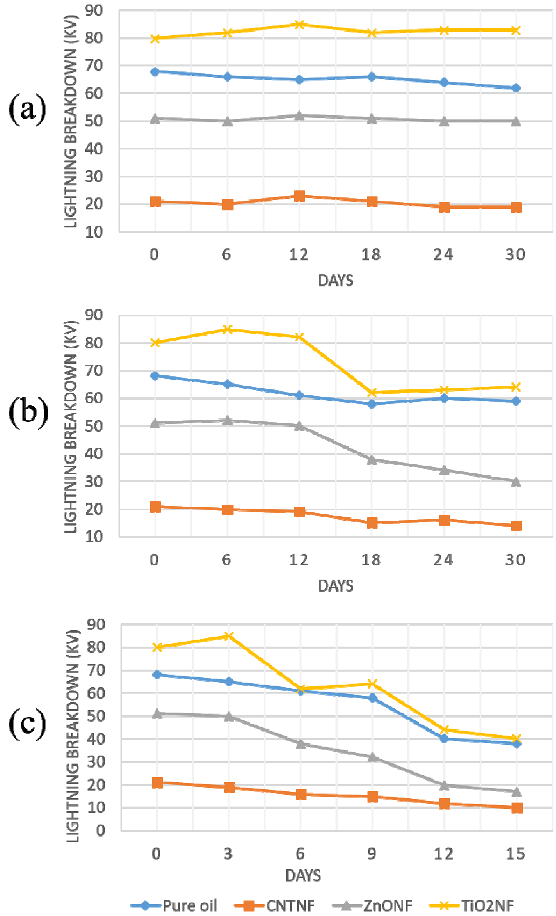

Figure3: The results of lightning breakdown voltage tests for (a)110°C; (b)120°C; and (c) 130°C

In Fig2. (c), you can see the breakdown voltage for all samples at 130 ° C for 15 days. The breakdown voltage for CNTNF, ZnONF, and TiO2NT were 29, 17, 5, and 43 KV, respectively. It is well known that with the exception of TiO2NT, the breakdown voltage of the rest of the samples has been reduced so much that it can be said that they have lost their insulating properties. Moreover, TiO2NF has the best results and has been able to improve the breakdown voltage compared to oil by 48%. Meanwhile, CNTNF and ZnONF reduced the breakdown voltage by 82 and 41%.The breakdown voltage reduction related to their initial values for pure oil, CNTNF, ZnONF, and TiO2NT were 50, 61, 72, and 36%, respectively. From the results of the breakdown voltage test it is quite clear thatTi02NF can not only improve the breakdown strength of transformer oil, but also refrain from the decline of breakdown strength caused by aging.

The initial lightning breakdown for pure oil, CNTNF, ZnONF, and TiO2NT were 68, 51, 21, and 80kV, respectively. Fig.3 shows the lightning breakdown for both pure oil and nanofluids along the aging process. In Fig.3 (a), due to the low thermal aging of the oil at 110 ° C, the lightning breakdown for CNTNF and ZnONF has not changed significantly. For pure oil, however, it has been reduced from 68 kV to 62 kV (9% reduction). In contrast to pure oil, TiO2NF has been able to increase lightning breakdown by 4%(80 to 83 kV). Also,TiO2NThas been able to improve the lightning breakdown by 33% compared to pure oil.Fig.3 (b) shows the lightning breakdown at 120 ° C for 30 days. The lightning breakdowns for pure oil, CNTNF, ZnONF, and TiO2NT were decreased by13(68kV to 59kV), 41(21kV to 14kV), 33(52kV to 30kV), and 20%(80kV to 64kV), respectively. But TiO2NThas still been able to improve impulse by 8% compared to pure oil.Fig.3 (c) shows the lightning breakdown at 130 ° C for 15 days. The lightning breakdown for pure oil, CNTNF, ZnONF, and TiO2NT were 38, 10, 17, and 40 kV, respectively. The lightning breakdowns for ZnONF, CNTNF were decreased by 66 and 52%. The lightning breakdown reduction is 50% and 40% for TiO2NTand pure oil. It is quite clear that even at a temperature of 130 ° C, TiO2NT has the best performance and was able to improve the lightning breakdown by 5% (2kV) compared to oil.

4. Conclusion

The TiO2NT manifested better insulating and anti-aging properties as compared to the base mineral oil. The dielectric strength improvement of nanofluids is due to the uniform internal electric field distribution associated with a high density of additional shallow electron traps created by the TiO2 nanoparticles, and hopping transport of electrons between these traps. The fast electrons produced by high electric field which are responsible of ionization and accumulation of space charge and hence breakdown, will be captured by these shallow traps and released from the shallow traps in the oil. These fast electrons will be converted to slower ones by repeated trapping and de-trapping process in the oil, and hence the breakdown will happen at higher voltages in nanofluids as compared to base mineral oil [19]. TAN, breakdown voltage, and lightning impulse breakdown voltage of all samples were measured periodically.

The results show that with increasing temperature and time, the TAN increased but never exceeded the allowable level of 1.2 mg KOH / g. It is emphasized that as the oil ages, its corrosion rate increases, which is undesirable for the transformer. The results of the breakdown voltage test for temperatures of 110, 120, and 130 ° C show that the TiO2NF had the best result and was able to increase the breakdown voltage relative to pure oil by 17, 27, and 48%, respectively. The outcome of the Lightning breakdown test indicates that TiO2NF still performed better than the other samples.TiO2NF has been able to improve the voltage at temperatures of 110, 120, and 130 ° C by 33, 8, and 5%, respectively, compared to the base oil.

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