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Experimental Analysis and Physical Mechanism Investigation of Al_2O_3 Effect on New and Aged Transformer Oil Properties

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ABSTRACT

Al_2O_3 nanoparticles were used to improve the performance of the vital properties of transformer oil (TO) under normal operating conditions and when subjected to thermal aging. Different weight percentages of Al_2O_3 in the TO were considered to maximize the breakdown voltage (BDV). Al_2O_3 nanofluid (NF) increases the BDV by 116% (31.1 kV to 67.4 kV) and the heat transfer by 33.4%, and also minimizes partial discharge (PD) by 66%. The reduction of PD is also related to the ability of Al_2O_3 to adsorb hydrogen and acetylene, two oil-soluble gases that are effective in PD. Even Al_2O_3NF was more resistant to water content in TO. BDV for TO and Al_2O_3NF, when water content increased to more than 30 ppm, were reduced by 57% and 19%, respectively. According to Arrhenius equation, both samples were placed at 120°C for 29 days to age samples (equivalent to about 30 years). Aged Al_2O_3NF has continued its exceptional performance and improved BDV by 121% compared to aged TO, and also Al_2O_3NF showed its capacity well and improved PD compared to aged TO by 71%. All the favorable properties of Al_2O_3NF are conditional on the stability of Al_2O_3. FESEM confirms the stability of Al_2O_3.

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1. INTRODUCTION

Transformers, which account for almost 60% [1] of the network cost, provide the connection between production and consumption due to changes in voltage level [2]. Transformer oil acts as a very important insulating part of the transformer. It plays a decisive role in its life [3].

The oil that is inside the transformers and is moving between the various internal components. It is like blood ins human body [4]. Examination of oil-soluble gases, such as a blood test or a scan of the human body, can warn about the internal failers of the transformer and an increase in the probability of its proper function [5].

During normal and electrical faults (breakdowns, partial discharges (PDs)) operation, the oil in power transformer ages and decompositions, breaking specific C-C and C-H bonds in the oil molecules. These conditions lead to the release of gases in the oil [6, 7]. Acetylene, carbon dioxide, methane, ethylene, carbon monoxide and hydrogen are the six main defective gases that dissolve in transformer oil (TO) [8]. Soluble gases in the oil cause a PD, which should not be underestimated. Among the mentioned gases, hydrogen and acetylene have the most severe damages and are also the most critical factors in the formation of PD [9, 10].

In general, oil performs two basic functions, cooling and insulation. It has been used for more than a century to insulate the electrical components of transformers and to transfer the heat generated in the transformer winding [11]. The two inhibiting factors for maximum power transfer and reducing the size of the transformer are the thermal and insulating properties of the oil [12]. The thermal conductivity of the oil in the transformer is usually not high, which weakens its cooling performance and ultimately reduces the life of the transformer [13, 14]. In addition, transformer operation and the aging of the

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oil, the breakdown voltage (BDV) is significantly reduced. One of the ways to improve the properties of oil is to use nanoparticles (NPs) and make a nanofluids (NFs) based on oil. NPs generally have a higher thermal conductivity. NPs help to increase the thermal conductivity of pure oil and even increase the BDV in some cases [15].

The experimental investigation has showed that the thermal conductivity of nanofluids is characterized by several dynamics such as volume or mass fraction of NPs, NPs type, NPs shape and size. Thermal conductivity mineral oil-based nanofluids with various volume concentrations suspended with Al_2O_3 (with 20 nm diameter) NPs has been examined by Timofeeva et al. [16]. About 4% of Nps was noted for the maximum improvement in thermal conductivity. Also, the investigation of the thermal conductivity of NFs with a rise in NPs concentrations has been reported by Jin [17] and Ilyas et al. [18]. In this study, a maximum enhancement about 16% in thermal conductivity at three wt% NPs concentrations has been achived. The thermal conductivity of MWCNT NPs based NFs has been investigaion for NPs effects on TO by Aberoumand and Jafarimoghaddam [19]. The results embodied an improvement of 160%. The author revealed that attributes of NPs cause this vast increase. They experimentally performed Ag/WO_3 hybrid NF in TO in three different weight fractions of 1, 2, and 4%. According to obtained results, the hybrid NFs used at a higher weight fraction and a temperature at100 ° C have increased the thermal conductivity by 41% [19]. Bhunia et al. [20] improve that TiO_2 (50–70 nm) with weight fractions (0.005 wt%) provide almost 13–23% thermal conductivity enhancement. Mansour et al. [21] showed barium titanate (BTO) NPs were inserted into the base TO by a concentration of 0.005 g/L. This insertion enhances the heat transfer coefficient by 33%. Parvar et al. [22] showed that the thermal conductivity of ZnO nanoparticles is higher than pure TO at 25°C. By adding this NPs to TO, it has shown that the thermal conductivity of NF increased by increasing NPs concentration in TO. Under these conditions, at volume fractions of 0.05% and 1% NPs in TO, the thermal conductivity increased approximately by 4.61% and 11.53%, respectively.

Babu and Babu [23] used nanocrystal nickel-manganese ferrite at different concentrations. In their article, the effect of increasing concentrations on the increase of dielectric strength was investigated. As a result, the concentration of 0.04 g/L showed a great increase in breakdown of voltage, about 42.3% [23]. Electrical strength and stability of SiO_2, Al_2O_3 and TiO_2 based NFs at different concentrations were investigated by Paul et al. [24] for TO. The reported data showed the highest breakdown of voltage for Al_2O_3 at a concentration of 0.06 g/L [23]. Oparanti et al. [25] utilized TiO_2, Al_2O_3, and MoS_2 NPs in TO and showed that the dielectric strength of TiO_2 was higher than the other samples. Electrical BDV in TO NFs with NPs such as ZnO, MgO, Al_2O_3, TiO_2, SiO_2, graphite, $LiTaO_3$ and Fe_3O_4 was investigated by Moghadassi et al. [26]. Electrical breakdown was studied for NFs based on ester oil at 0.2 to 1 weight percentage of Al_2O_3 nanoparticles. They observed that Al_2O_3 (at 0.6wt%) NPs improve the BDV of ester oil to 29kV [25]. As you can see, various valuable studies have been done on the effect of NPs on the improvement of BDV and thermal properties. However, as far as the author's knowledge, less research has been done on reducing the PD (as one of the essential properties of TO) in oil using NPs as well as improving the BDV and heat transfer simultaneously. Failure to consider PD in applying NPs in TO is a vast and severe gap in research on this subject. Also, one of the other issues is the stability of nanomaterials in the oil, which can be said that almost less attention has been paid. This lack of awareness and research has been done while all the properties of NPs in oil (and their function) have a natural and extraordinary relationship to stability. On the other hand, in normal operating conditions of the transformer, it is often subjected to different stress conditions and causes the oil to move towards aging. So, the function and stability of NPs inside the oil should not be neglected when aging occurs.

In this paper, Al_2O_3 was used to reduce the partial discharge, improving the BDV and TO heat transfer under normal and thermal aging conditions. Another fundamental goal that has been studied in this research is to provide an obvious and accurate sight of the relationship between PD and gas-soluble bubbles, as well as the physical mechanism of Al_2O_3NPs in oil. Al_2O_3 and a two-stage method have been used to make the NF. Several samples of NF were prepared by considering different amounts of NPs. NF was regarded as the primary sample whose BDV was maximized. Stability is the fundamental problem in using NPs in oil, which were photographed FESEM to prove the stability of Al_2O_3NPs. In the next step, laboratory tests (BDV, gas Chromatography, moister effect on BVD, heat transfer, total acid number (TAN), PD) were performed on the samples. In the last stage of the laboratory test, to comprehensively evaluate the performance and stability of Al_2O_3 in the TO, the oil is thermally aged using the Arrhenius equation and examined (BDV, TAN, PD). Finally, the physical mechanism of Al_2O_3NP function was investigated.

2. MATERIALS AND METHODS

2. 1. Materials Table 1 summarizes the specifications of NP that was purchased from US Research Nanomaterials, Inc. (USA). As can be seen, Al_2O_3 has a purity of more than 99% and a heat transfer

TABLE 1. NP specifications

Nano particle	Purity	Color	Specific heat capacity	Density
Al_2O_3 (20 nm)	99+%	White	880 J/(kg-K)	3890 kg/m^3

coefficient of 880 J/(kg-K), which indicates a relatively high power to improve the thermal transfer coefficient of the final nano oil. The average particle size (APS) is 20 nm.

2. 2. NF Prepration Methods Single-step and two-step designs are usually used for preparation of NF. The single-phase method involves the simultaneous development and dispersion of particles in the fluid. Drying, storage, transfer, and dispersion of NPs are avoided in single-phase process. Therefore, the accumulation of NPs is limited and fluid stability has increased [26]. Single-phase systems have the ability to produce nanoparticles with homogeneous distribution. Based on this, particles can be placed in a liquid at stable condition. This process has advantages due to the control of NP size, reduction of NP aggregation, and development of NFs including metal NPs. In addition to being expensive, this method is not able to produce NFs on a large scale. Another major drawback associated with the single-phase process is that the development of NFs with high volume loadings of NPs is very challenging.

The two step process is commonly used to synthesize NFs by stirring NPs in the base fluids. Typically, two steps are involved in this technique. NPs are commercially available and are produced using physical, chemical and mechanical methods at the first step. The most important physical, chemical and mechanical methods are crushing, grinding, sol-gel. Then, in the second phase the dry NPs are dispersed in the base liquids using ultrasound, magnetic mixing, and high shear agitation. During this phase, some activities, for example, the incorporation of scattered materials or ultrasound, are usualy performed to improve the stability of the derived NFs [27].

The two-step process is usually used to prepare Al_2O_3NF [28]. By using this method, it has been shown that Al_2O_3 has excellent stability [23]. As shown in Figure 1, Al_2O_3 and mineral oil are first throughly mixed in a magnetic stirrer for 30 minutes. In the next step, the sample is placed in a sonic device for 30 minutes to obtain a homogeneous mixture. In the last stage, to achieve high accuracy in the test results and complete removal of oil-soluble gases (which occurs in the previous steps), the solution is kept at a pressure of less than 1 kPa for 48 hours. It is very important to mention two points. First, the initial moisture content of the NPs has been tried to be very low so as not to aberration the test results (for 10 h at 160 °C), and second, all the above steps have been performed at environment temperature.

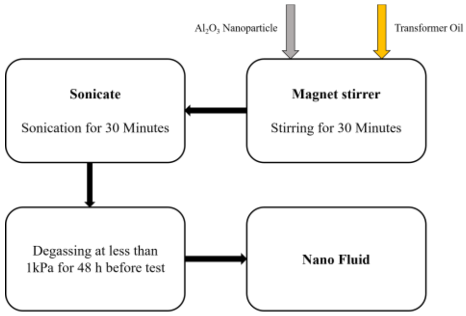


Figure 1. Two steps method for Al_2O_3NF preparation

One way to prove the uniform distribution of NPs in oil is to use field emission scanning electron microscopy (FESEM). FESEM is used to visualize tiny topographic details on the surface. This technique is used to observe structures with several nanometers in size. FESEM is consequential in two ways: 1) Evidence of homogeneous dispersion of NPs in the oil 2) Displacement of APS. FESEM photo of NF can be seen in Figure 2. As it turns out, 1) NPs are well dispersed and stabled; 2) APS of Al_2O_3 is 20 nm. The importance of NP stability is analayzed in section 5.

3. EXPERIMENTAL TEST

As mentioned above, TO as a liquid insulator is a type of insulating oil with suitable electrical and thermal insulating properties. Two functions of TO that are related to the life of the transformer are cooling and electrical insulation. The TO deteriorates over time due to operating conditions. These conditions affect the performance of the transformer. Therefore, checking the status of the TO during the operation period is vital. For this purpose, testing sequences and procedures are defined by different international standards. In this section, some critical electrical tests on oil insulation are evaluated.

3. 1. Breakdown Voltage The insulating strength of TO is considered one of its electrical properties in oil testing. The BDV test is introduced in this regard. BDV

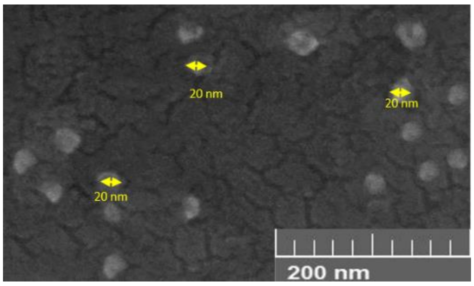


Figure 2. FESEM micrographs provided from Al_2O_3 NP

is determined based on the voltage level that flashover occurs between two electrodes at a certain distance. BAUR PGO S-3 device was used for this test and the procedure is described in Standard Method ASTM D1816. According to the standard, two electrodes are fixed with a gap of 2.5 mm, and voltage is applied to them. The rate of rising of the applied voltage is controlled at 2 kV/s. As the voltage increases, the amount of voltage is recorded when the first discharge occurs between electrodes. After pouring the oil into the test vessel, it is rested for 10 minutes, and then the voltage is applied. This test is performed six times with an interval of 1 minute, and at the end, the average of the obtained results is considered BDV. All experiments were conducted at room temperature and power frequency (50 Hz).

3. 2. Gas Chromatography To obtain the number of dissolved gases in TO, gas chromatography method has been used. Acetylene, carbon dioxide, methane, ethylene, carbon monoxide and hydrogen are the six main defective gases that dissolved in TO. Determining the amount of H_2 and C_2H_2 in base oil and NF is crucial to investigate and prove the performance of Al_2O_3NF in the PD process.

3. 3. Water Content Water, as a destructive factor, reduces the boiling point of TO, premature aging of TO, and degrades the insulating properties of paper insulation. The moisture in the paper insulation has the ability to transfer to the oil, which increases the oxidation level, which will increase the water and acid content in the oil. Therefore, it is necessary to always control the water content of TO, which has been carried out using the necessary tests by the METHROM 831 device under ASTM D877 standard.

3. 4. Heat Transfer Test The use of nanoparticles in TO has been investigated as a new method to improve heat transfer. In general, the goal is to increase the thermal conductivity and reduce the heat produced. One of the most practical ways to measure heat transfer is to use the immerse heating method [29]. The selected sample must first be placed in a particular container to use this method. Then, to increase the temperature inside the oil, an element must be placed inside it. To monitor the temperature inside the sample, place a thermometer at a fixed distance from the element. The element must be connected to a constant voltage source in the next step. In order to ensure equal conditions of the element in experimental samples, its voltage and current are monitored. In the final stage, to check the temperature transfer, temperature changes are recorded in seconds.

3. 5. Total Acid Number The acid concentration in TO is defined as the oil's TAN. The standard unit for measuring TAN is mg KOH/g. Generally, it refers to the milligrams of potassium hydroxide (KOH) necessary to countract free acids in 1 gram of oil. Based on ASTM D974 standard, transformer oil TAN has been measured. The main source of acid production in TO is oil decay/oxidation. The TAN in the oil detriment the structure of insulation and can raise the corrosion intensity of inside parts of transformer in the existence of moisture.

3. 6. Partial Discharges According to Standard IEC 60343, PD in TO is localized insulating discharge in a limited volume of liquid insulation when subjected to high voltage electrical stress. According to mentioned standard, the distance between the needle and plane electrode was set to 1 mm. PD is one of the sources of deterioration of TO, which can even lead to electrical discharge in the oil. The PD apparent charge quantity is measured and recorded to measure PD. In this regard, the base charge is significant in measuring PD and must be present in minimal amounts. PD pulses created in the oil were conditioned in the electronic coupling device, connected to a coupling capacitor, and processed in the measuring instrument. Due to the very high sensitivity of PD measurements to noise, it is necessary to calibrate the measuring device to achieve high accuracy. A JDEVS-PDMA 300 was utilized for PD test. PD signals were sense by the PD detector device at a voltage of approximately 32% of each sample's BDV. This voltage was considered as the PD initial voltage. This experiment aimed to decrease the quantity of PD in the TO by NPs; the applied voltage was approximately 40% of that of the BDV of each sample to ensure the conditions of PD [30].

3. 7. Thermal Aging Destruction of electrical insulation plays an important role in the aging of the transformer and reducing its life. Increasing heat in the insulation can lead to its decomposition, which can intensify this process. The losses of Core and coil in operating transformers cause considerable internal heat. If it does not transfer out quickly, it can increase the insulation system's aging rate and shorten the unit's life. In addition to what was said about aging, humidity is another important factor. In fact, the creation of oxygen in the transformer oil along with other gases in it leads to the production of water [31]. Figure 3 represents a superficial schematic of the decomposition mechanism of transformer insulation. Aluminum and iron are the main components of the body and winding of transformers, and nothing can be done to remove them. Still, moisture and O_2 play a significant role in transformer oil degradation. Therefore, in examining the aging process of oil, moisture and O_2 must be monitored.

Arrhenius equation has been used for the thermal aging of oil. Pure oil and Al_2O_3NF were placed at 120°C for 29 days for accelerating aging. By increasing the

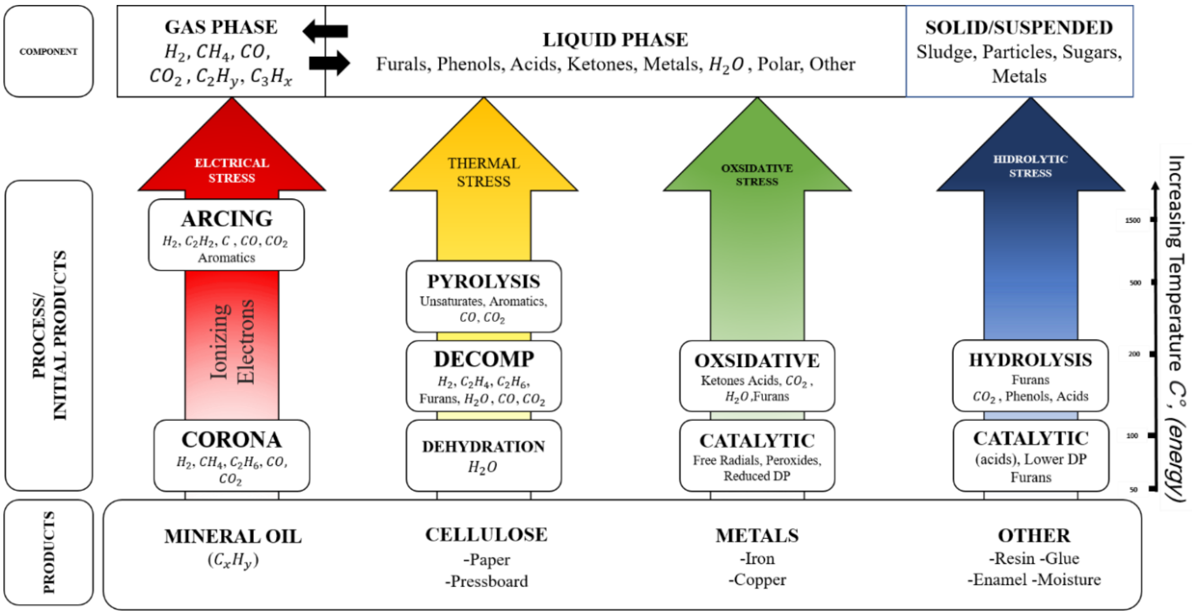


Figure 3. schematic of the decomposition mechanism of transformer insulation

temperature by 7°C from the reference temperature (60°C), it is possible to halve the lifetime of the insulating material. Hence, accelerated thermal aging for 29 days at 120°C approximates 30 years [32]. Both aged samples were taken out periodically for BDV and TAN tests during this process.

4. RESULTS AND DISCUSSION

4. 1. Pure Oil and Al_2O_3 NF Test Results

The amount of BDV is one of the essential factors in TO. To improve the properties of the oil using NPs, the BDV should be increased as much as possible. For this purpose and to achieve the maximum BDV, five samples of NFs with values of 0.01, 0.05, 0.1, 0.02, and 0.3 g/L of Al_2O_3 NPs were considered. The point to pay special attention is that the water content is less than 10 ppm in all samples, and all tests are performed at room temperature.

The BDV diagram for the base oil and the other five NFs is shown in Figure 4. As can be seen, for TO and NFs with concentration of 0.01, 0.05, 0.1, 0.02, and 0.3 g/L, the BDVs are 31.1, 60.9, 67.4, 62.6, 56.7 and 50.1 kV, respectively. The BDV is maximized for 0.05 g / l. NF, in this case, has been able to improve the BDV by about 116%, which is very impressive. For all NFs, the BDV is greater than pure oil. Because the BDV is one of the essential properties of TO, to maximize the BDV, 0.05 g/L of Al_2O_3 is used to achieve the desired Al_2O_3NF. The results obtained up to 0.05 g/L can be justified: By increasing NP concentration up to 0.05 g/L, the amount of charge traps and as a result BDV increases. Meanwhile, for concentrations higher than 0.05 g/L,

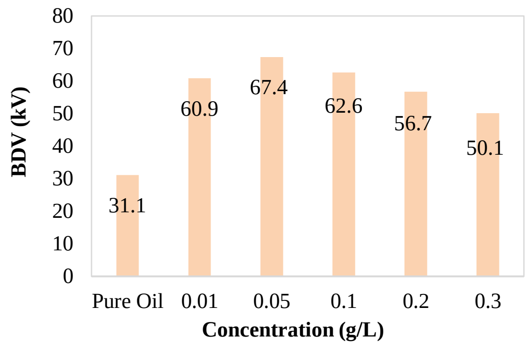


Figure 4. The BDV of TO/Al_2O_3 NFs

BDV decreases due to the accumulation of nanoparticles. However, the reversible NP aggregation caused by the electric field improves the BDV due to the catch of free electrons.

The presence of acid content in transformer oil is unavoidable due to its operating conditions. The TO and NF TAN values are 0.03 and 0.01, respectively. These values indicate that the TAN value was within the allowable range for both samples, and the NF (albeit a small one) was even able to reduce it. Table 2 shows the amount of H_2 and C_2H_2 gases in the TO and Al_2O_3NF samples. As can be seen, Al_2O_3NF reduced the amount of H_2 from 67 to 9 ppm (86% reduction) and the amount of C_2H_2 from 198 to 53ppm (73% reduction).

The water content must be low and equal in range to perform a BDV test. Otherwise, the values obtained for the BDV will not be valid. The water content test results prove that water content is less than 10 ppm for both

TABLE 2. Amount of H_2 and C_2H_2 after GC test, TAN for samples

H_2 (ppm)	**TO**	**Al_2O_3NF**
	67	**9**
C_2H_2 (ppm)	198	53
TAN (mg KOH/g)	0.03	0.01

samples. An experiment was designed to demonstrate the destructive effect of moisture inside TO. Thus, four samples of TO and four Al_2O_3NF with different water content were provided. The moisture effect on the BDV of TO and Al_2O_3NF is shown in Figure 5. It is pretty evident that the BDV decreases from 31.1 kV to 13.2 kV by increasing the amount of moisture in the oil from less than 10 to more than 30 ppm, which indicates a 57% decrease in the BDV. For the same moisture inside the Al_2O_3NF, the BDV decreases from 67.4 to 54.5 kV, representing a 19.1% reduction. As can be seen, as the water content increases, the Al_2O_3NF experiences a smaller percentage reduction in the amount of BDV than the MO. One of the reasons for this is the ability of Al_2O_3 to absorb H_2 as one of the constituents of water in MO.

Figure 6 illustrates the results obtained from the immerse heating method. Both samples' temperature changes were recorded from ambient temperature (25 °C) to 80 °C. As can be seen, the oil has risen from 25 to 80 °C in 560 seconds. On the other hand, Nano oil only needs 373 seconds to cross the same path. This result shows that the temperature in nano oil is transferred to the base oil 33.4% faster, and in the transformer operation, it can transfer heat from the warmer part of the transformer to the lower temperature parts in less time. There are many cases of transformer explosions. Increasing the thermal conductivity of TO reduces the flammability of TO and expands the safety point of view.

One of the tests that show the effect of NPs on oil performance is the PD test. Parameters such as the number of charges and the phase angle can be achieved using this test. The number of charges of TO is equal to 1373. The phase angle variations of PD based on

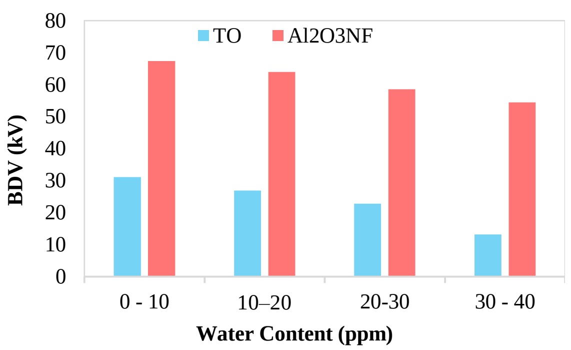


Figure 5. Effect of moisture on the BDV

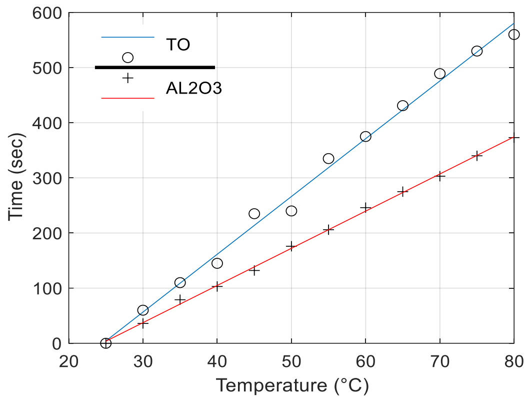
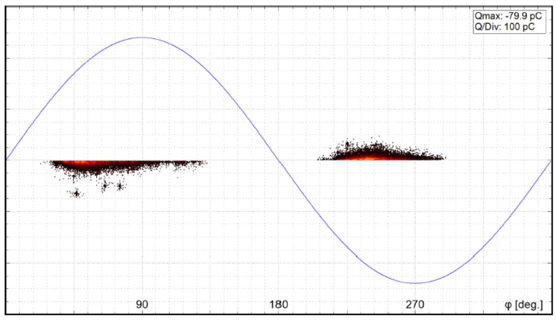


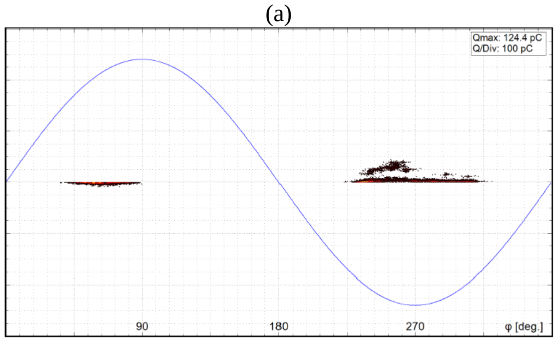
Figure 6. The time required to increase the temperatures

reference sinusoidal voltage waveform is shown in Figure 7(a). Based on the presented result for TO, the PD has occurred between $45 < \varphi < 135$ at positive or negative cycle of the reference waveform. However, most PD with larger amplitudes are seen at angles less than 90 degrees.

Using the Al_2O_3, the number of charges in Al_2O_3NF sample has reduced by 66%. The number of charges in Al_2O_3NF is equal to 461. As shown in Figure 7(b), the trend of phase angle variation of Al_2O_3NF is similar to TO. The comparison of TO and Al_2O_3NF at the same phase angles shows a decrease in the PD number and amplitude. The change of phase angle in the positive



(a)



(b)

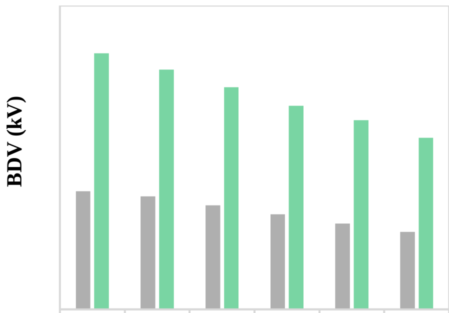
Figure7. The phase angle variations of PD based on reference sinusoidal voltage waveform (a) for TO; (b) for Al_2O_3NF

cycle to less than 90 degrees indicates the proper performance of the Al_2O_3 to control the PD in the oil. The oil insulation performance against PD activity is improved via the NPs proposed in this paper.

4. 2. Aged Oil and Al_2O_3 NF Test Results Three essential properties of the TO, which are very important and decisive in its performance in aging, are BDV, PD and TAN. Figure 8 shows the average value of TO and Al_2O_3NF BDV in the aging state. As you can see, the BDV for TO starts at 31.1 kV and decreases to 20.4 kV after 29 days, which is a 34% reduction. The decreasing trend of oil BDV is due to oil aging. This reduction for NF also remains strong. The BDV for the Al_2O_3NF starts at 67.4 kV and decreases after 29 days to 45.2 kV (33% reduction).

Figure 9 shows the TAN for aged TO (ATO) and NF samples. The point to note is that according to ASTM D974, the maximum number of acids is 1.2 mg KOH/g. As the aging process begins and MO's ages increases, the amount of TAN also increases so that the TAN of the ATO at the end of 29 days is more than the allowable limit and has a value of 1.4 mg KOH/g. This result indicates a very unsatisfactory condition of the ATO load after the aging process. The situation does not change much for Al_2O_3NF, and the TAN for Al_2O_3NF increases with an increase in thermal aging of the NF. But the exciting point is that the Al_2O_3NF has been able to comply with the permissible limit and maintain the oil condition better.

PD is one of the things that changes due to the aging of the oil. Based on the aging process used in this paper, the parameters used for PD were investigated. The number of charges in ATO has increased to 2781. This amount has increased by 102% compared to TO. Under these conditions, the angle of occurrence of PD has increased and, according to Figure 10, the angle is approximately between $45 < \varphi < 135$. These conditions are different from the performance of TO and indicate variations in the oil's PD.



Days	0	6	12	18	24	29
TO	31.1	29.8	27.4	25	22.6	20.4
Al2O3NF	67.4	63.1	58.5	53.6	49.8	45.2

Figure 8. Mean BDV for aged TO and NF

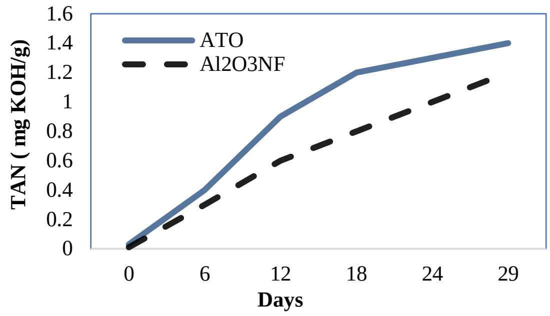


Figure 9. TAN values for ATO and Al_2O_3NF

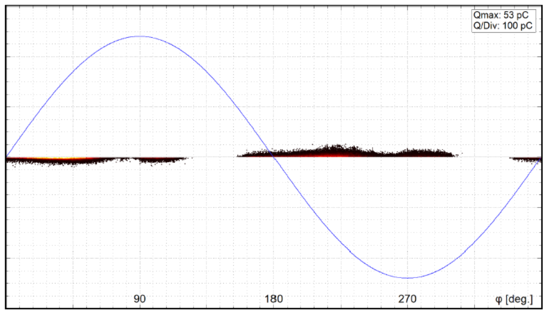


Figure 10. The phase angle variations of PD based on reference sinusoidal voltage waveform for ATO

The result presented in Figure 11 shows that the repetition of the oil aging process with the Al_2O_3NF has caused variations in the PD parameters. Based on this, it is possible to improve the oil properties of TO and aged ones. The reduction in the number of charges is significant. PD reduced to 801, which shows the addition of Al_2O_3 prevents the occurrence of PD in the aged oil by about 71%. A significant result of the suitable performance of the NP is the change in PD's angle, which is between 45 and 135 degrees. These situations, along with reducing the number of charges, indicate the improved ATO performance in combination with the Al_2O_3.

Figure 12 presents the immerse heating method for both samples after thermal aging. Both samples' temperature changes were recorded from ambient temperature (25 °C) to 80 °C. As can be seen, the ATO temperature has risen from 25 to 80 °C in 631 seconds. Aged-NF needs 398 seconds to reach 80°C. This result shows that the temperature in Aged NF transferred 36.9% faster than ATO. Also, transformer oil is about 13% less capable of moving heat in the aging state than before.This is about 7% for nanofluids.

5. PHYSICAL MECHANISM

The performance of NPs in this work can be split into two general aims: improving electrical and thermal

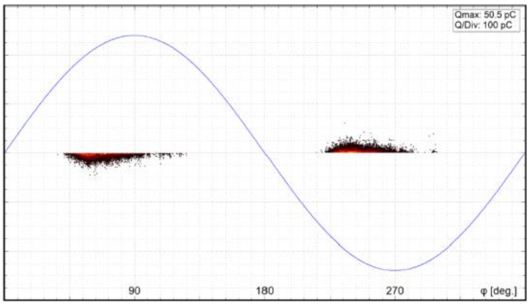


Figure 11. The phase angle variations of PD based on reference sinusoidal voltage waveform for aged Al_2O_3NF

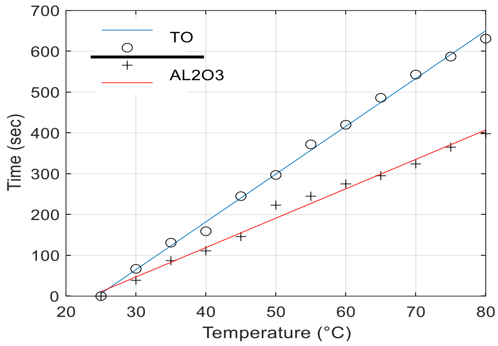


Figure 12. The time required to increase the temperatures for both samples in aging mode

properties. The mechanism of NPs action in improving the BDV is that the NPs trap and absorb electrons. In other words, this NP acts as an electron absorber in NFs, which reduces the streamer propagation and increases the BDV compared to TO. On the other hand, another critical reason for NPs to help improve the BDV is the low conductivity of NPs.

The same factors used to improve the BDV also apply to PDs. PD inside the oil is a localized dielectric breakdown (DB) in such a way that it does not entirely bridge the space between the two conductors (electrical breakdown does not occur). When free electrons are absorbed and trapped, the conditions for PD become much more difficult. This factor causes a PD to happen later. On the other hand, the PD is due to the presence of soluble gas bubbles inside the oil and the difference between its dielectric coefficient and the oil. As observed, when the NPs were added to the base oil, the number of soluble gases inside the oil dramatically decreased. These two factors can be mentioned as the main reasons for reducing PD for Al_2O_3NF.

One of the important factors in heat transfer, which plays a decisive role in determining the insulation system, is thermal conductivity, which must be high for TO. Transformer oil must have good heat transfer and low viscosity. However, the thermal conductivity of TO is usually low, which causes damage to the transformer in overload conditions. Therefore, it is important to increase the thermal conductivity of the transformer in order to increase its lifespan. Ideally, transformer oil should have good heat transfer and low viscosity in addition to proper insulating properties. Various methods have been used to increase TO thermal conductivity and heat transfer.

The method used to improve heat transfer is a suspension of convenient NPs into the TO. Nano-materials have a significant and, at the same time, unique property: improved surface-to-volume ratio or aspect ratio. This feature increases the effect of cooling in the transformer. The heat produced in the transformer is absorbed by nano materials. In this regard, the strength and melting point of these materials can be improved by changing their dimensions. The heat generated in the transformer is transferred due to the structure and molecular motion of the oil and is transferred from the hot point to the cold point according to the principle of thermodynamics. By adding NPs to the oil, its performance in heat transfer can be increased.

The main challenge in producing a NFs is the homogeneous dispersion of NPs. In fact, NPs tend to aggregate under the influence of Van der Waal's forces. Meanwhile, long-term dispersion is considered as a primary requirement in practical applications. Also, thermal conductivity as another parameter is affected by the stability of NF, which has the ability to improve thermal conductivity if stability is provided. To solve this challenge, physical and chemical methods such as adding surfactants and using different surface modifications for nanoparticles have been used.

FESEM clearly shows that Al_2O_3 has very good stability. As long as the NPs have a uniform distribution and do not stick to each other; They have a higher surface-to-volume ratio (aspect ratio) and further improve thermal conductivity.

In aging mode, the physical mechanism performance of NPs is highly dependent on how they interact with O_2 and moisture as the two main factors in accelerating aging (aging catalysts). An effect to consider is that it is two unpaired electrons in the ground state for O_2. One or both of the two unpaired electrons of O_2 molecules can be coupled with the unpaired electron of paramagnetic free radicals. The diradical aspect of the O_2 molecule is considered as a favorable factor for creating an effective reaction with weak hydrocarbon. Under this reaction, hydroperoxide is created, which changes the color of the oil from bright yellow to amber. In this regard, The presence of copper increases redox reactions. This condition leads to an increase in oil dissipation factor due to the production of load carriers. Due to the weakness of the peroxide bond, it is possible to break it. Based on this, the absorption of the thermal energy of the chain reaction by two new free radicals leads to the strengthening of oxidation. Also, insoluble colloidal suspensions are created from the combination of free radicals. In general, increasing the concentration of free radicals increases random chemical reactions between them. Eventually, the soluble and insoluble oil-borne decomposition products are the result.

As can be seen, in the aging state, the conditions for Al_2O_3 become much more complex, and they have to deal with the more threatening factors of the oil properties. The function of O_2 in oil was discussed above. O_2 is a massive threat for two reasons: a) free electrons, b) accelerated oxidation and aging. It was seen that the NP could trap the free electrons of O_2 to some extent and reduce its movement speed. On the other hand, absorbing O_2 reduces the aging process of the oil, and oil conditions remain at an acceptable level.

6. CONCLUSION

A noteworthy point in the results is the effect of water content on the samples and the much better reaction of the NF against it compared to TO. In such a way, NF has withstood a higher voltage against moisture and has been able to have a much lower BDV reduction percentage (19.1% vs 57%) than oil. This behavior of NPs regarding water dissolved in oil can occur for two main reasons:

a) Dissolved water bound to the surface of Al_2O_3, which has the property of reducing the BDV of liquid insulation, can be the cause of this condition. The breaking of multi-molecular water clusters attached to the surface of some Al_2O_3 into single water molecules can increase the BDV in these conditions.
b) As you can see in the gas chromatography results, the amount of H_2 dissolved in the oil has decreased by about 86%. Since oil-soluble H_2 is one of the factors in the formation of water in oil, when the amount of hydrogen can be reduced, the amount of water can also be reduced. As the amount of water in the oil decreases, it can be expected that (because one of the causes of oil aging has decreased) the oil will show better properties than pure aging oil as it ages.

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Persian Abstract

چکیده

نانوذرات Al_2O_3 برای بهبود عملکرد خواص ذاتی روغن ترانسفورماتور (TO) در شرایط بهره‌برداری پایدار و در معرض پیری حرارتی استفاده شد. درصدهای وزنی مختلف Al_2O_3 در TO برای به حداکثر رساندن ولتاژ شکست (BDV) در نظر گرفته شد. نانوسیال Al_2O_3 (NF) ولتاژ شکست را ١١٦٪ (٣١.١ کیلوولت به ٦٧.٤ کیلوولت) و انتقال حرارت را تا ٣٣.٤٪ افزایش می دهد و همچنین تخلیه جزئی (PD) را تا ٦٦٪ به حداقل می‌رساند. کاهش PD همچنین به توانایی Al_2O_3 برای جذب هیدروژن و استیلن، دو گاز محلول در روغن که در PD موثر هستند، مرتبط است. حتی Al_2O_3NF نسبت به محتوای آب در TO مقاوم‌تر است. ولتاژ شکست برای TO و Al_2O_3NF، زمانی که محتوای آب به بیش از ٣٠ ppm افزایش یابد، به ترتیب ٥٧٪ و ١٩٪ کاهش یافته است. طبق معادله آرنیوس، هر دو نمونه به مدت ٢٩ روز در دمای ١٢٠ درجه سانتیگراد قرار گرفتند تا نمونه‌ها پیر شوند (معادل حدود ٣٠ سال). Al_2O_3NF پیرشده BDV را ١٢١٪ نسبت به TO پیرشده و همچنین PD را نسبت به TO پیر شده تا ٧١٪ بهبود داده است. تمام خواص مطلوب Al_2O_3NF مشروط به پایداری Al_2O_3 است. FESEM پایداری Al_2O_3 را تایید می کند.