Low Concentration Vegetable Oil Based Nanofluid: Dielectric properties, AC Breakdown Voltage and Kinematic Viscosity

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Abstract. The transformers oil acts as an insulation as well as cooling liquid of a transformer. It is very important that the transformer oil is maintained so that the oil properties are preserved with time. Petroleum-based mineral oil is widely used as insulation oil in transformer due to its excellent insulating qualities and low cost despite its non-biodegradable and hazardous property. This paper seeks to find an alternative of mineral oil by using palm oil based nanofluids at lower concentration values that match the IEC standards for ester oil. The nanoparticles used in this project are zinc oxide (ZnO) and zirconium dioxide (ZrO2). ZnO has conductive nature while ZrO2 on the other hand shows insulative behavior. Three different concentration value were used which were 0.0015 g/L, 0.0025 g/L and 0.005 g/L which had never been reported before. Tests performed on the samples includes AC breakdown, dielectric properties and kinematic viscosity. Research outcome shows an outstanding result at optimum value in improving the measured properties at these low nanofluid concentrations. Reducing the amount of nanoparticles use also means saving cost and providing a more eco-friendly solution.

Keywords: Nanofluids, Insulation oil, Dielectric, Oil Breakdown, Viscosity

1. Introduction
Liquid filled transformer uses an insulation and cooling system that mainly consisting of transformer oil. The oil helps transformer to cool down from the heat produced during operation through heat conduction and convection process [1-2]. Since transformer oil is also part of the electrical insulation of internal live parts, it must remain stable for a long period of time at high temperatures [3]. Impurity is the key factor which reduces the efficiency of insulation, hence maintaining the insulation system will largely determine the life span of the transformer. There will certainly be increased capacity and size in future transformer and new materials may be required in their design. Transformers can operate at higher temperatures and in turn require more stable transformer oils.

Mineral oil has good cooling power, high dielectric efficiency, low dielectric losses, inexpensive, good long-term performance and easily available. These factors have led to the extensive
use of mineral oil to date. Nevertheless, it has poor effects on the environment regardless of the size of the insulating material, as it is non-biodegradable. Serious spills occurred periodically, causing pollution of the rivers and groundwater. Leakage from a transformer can also result in fire and explosion. In addition, mineral oil comes from fossil fuel that will run out one day. Sustainable, environmentally friendly commodities such as vegetable oils are therefore the best alternative to replace them due to environmental problems [4].

No sulphur, aromatic hydrocarbons, metals or crude oil remains are present in vegetable oil [5]. The lack of sulphur means that sulphur emissions, which can generate sulphuric acid in our atmosphere, can be reduced and lessen the formation of acid rain. Crude oils from oilseeds are dark and contain solid components, like protein, fibre, and liquid (fat and oil). Fats and oil are fatty acid triglyceride esters, but fats are relatively high in saturated triglyceride and freezes at room temperature and contain relatively high incidences. Palm oil consist approximately 49.3 % saturated fatty acid together with 37% monounsaturated and 9.3% polyunsaturated fatty acid, which made it saturated/unsaturated fat ratio close to 1. This factor made it oxidatively stable oil compared to other vegetable oils [6]. The potential use of palm oil as insulating oil has been widely reported and the number of work has continue to grow as the scope has widen to the use of antioxidant [7-9] as well as nanoparticles for properties enhancement [10-12].

In the extend of nanoparticle usage in vegetable oil, many works have been published covering the effect of the materials in improving the electrical and physicochemical properties of the oils. The experiments include the use of a wide range of nanoparticles from conductive to insulative nanoparticles, with varying concentration from 0.002-0.2% of weight fraction or 0.1%-1% volume fraction. Research on low concentration nanofluids has never been investigated and reported properly and hence became the objective of this work. Palm oil were in the research used as the base fluid due to its good insulating properties and one of the main products of Malaysia. The properties of these low nanofluids were then compared to higher concentration nanofluids to see if small amount of nanoparticle is adequate to enhance the palm oil performance as an insulating liquid.

2. Experiment details

2.1. Preparation Samples

The preparation of nanofluids used the two-step method, which requires mixing and ultrasonic dispersion. In the two-step method, solid nanoparticles were prepared and then suspended in the base via oil ultrasonic dispersion and magnetic stirring [13]. The specified volume fraction of nanoparticles was mixed into the palm oil sample. A magnetic stirrer was used for 30 minutes to disperse the nanoparticles [14]. The sonication process took place until full dispersion is achieved. This two-step method is broadly employed to produce nanofluids on a large scale because of its lower cost. There were two types of nanoparticles used with similar concentrations which were 0.0015 g/L, 0.0025 g/L, and 0.005 g/L, on top of the pure palm oil without any additive. Table 1 shows the list of samples with different concentration to be tested and sonication period. Zinc Oxide (ZnO) and Zirconium Dioxide (ZrO2) have conductive and non-conductive property respectively with both having average grain diameter of 100 nm in size. The main concentration unit used in this paper is g/L which is also converted in approximation to weight (wt%) and volume (v%) fraction for easy reference. In this research, 400 ml of each nanofluid was prepared and as expected, sonication period increases as the concentration increases.
Table 1: The list of nanoparticles with different concentrations to be tested.

| Nanoparticles | Types of Nanoparticles | Nanofluid Concentration | Sample Name | Sonication Period (Minutes) |
|---------------|------------------------|--------------------------|-------------|-----------------------------|
| **ZnO**      | Conductive             | 0.0015 1.7 2.7 10^{-4} (wt%) 10^{-3} (v%) | ZNO15       | 36                          |
|               |                        | 0.0025 2.8 4.5           | ZNO25       | 39                          |
|               |                        | 0.0050 5.7 8.9           | ZNO50       | 44                          |
| **ZrO_2**    | Insulative             | 0.0015 1.7 2.6 10^{-4} (wt%) 10^{-3} (v%) | ZR_{O_2}15  | 35                          |
|               |                        | 0.0025 2.8 4.2           | ZR_{O_2}25  | 38                          |
|               |                        | 0.0050 5.7 8.5           | ZR_{O_2}50  | 41                          |
| **None**     | -                      | -                        | -           | PO                          |

2.2. AC Breakdown Voltage Test
The AC breakdown voltage test was carried out following the IEC 60156 standard using the 2.5 mm gap spacing electrodes at room temperature. This experiment was conducted at 50 Hz power frequency and the voltage was kept increasing at the rate of 2 kV/s ± 0.2 kV/s. This voltage rate was maintained until the tested liquid sample reaches the voltage breakdown. The final result is calculated from the mean value of the 55 breakdowns in kV. To get an accurate result, ASTM D 877 gives the additional requirement for the final result that the range of the measurement results must not exceed 10% of the mean value. The samples were degassed at 100°C in the oven for one hour before the AC breakdown voltage test was performed to reduce the moisture content of the oil.

2.3. The Conductivity Test, Relative Permittivity Test, and Dissipation Factor Test
The conductivity, relative permittivity and dissipation factor were measured according to IEC 60247 standards [15]. The dielectric constant or relative permittivity is defined as the amount of electrostatic energy which can be stored as electrical energy. The relative permittivity also measures the resistance produced in the electrical field of a dielectric material. The dissipation factor is also known as tan δ or dielectric loss tangent. The dielectric losses may initially be caused by the movement of free charge carriers (electrons and ions), space charge polarization or dipole orientation. Most causes are influenced by the temperature, electric field strength, and are frequency dependent. For a good insulation property of transformer oil, the value of the dissipation factor needs to be as low as possible. A low dissipation factor value will result to a higher resistive property in an insulator. On the other hand conductivity is the ability of a dielectric material to conduct electricity and a good insulator must have low conductivity value. In this project, the conductivity, relative permittivity, and dissipation factor test were measured by using the HIOKI IM 3570 Impedance Analyzer.

2.4. Kinematic Viscosity Test
The kinematic viscosity test was conducted at a 40-degree Celsius temperature, following the ASTM D445 standards. The viscometer was placed in the water bath that was set constant at 40°C. The flow of fluids was recorded by the time taken for the liquid tested to flow from A to B point. The higher the viscosity, the slower the liquids flow in the viscometer tube which is not good for insulating oil. This value will affect the ability of the liquid to act as colling material in an electrical equipment. As the liquid become more viscose, convection becomes much harder and leads to increase in temperature.

3. Results and Discussion

3.1. AC Breakdown Voltage
The scatter graph shows in figure 1 show AC breakdown voltage for all samples at every instance. The result shows for pure palm oil, palm oil-based zinc oxide nanofluids, and palm oil-based zirconium dioxide nanofluids. The breakdown values of these samples only vary in small range and shows the stability of the oils. The average breakdown value is presented in figure 2. The value of AC breakdown voltage pure palm oil is lower than the anticipated vegetable oil which is 38.09 kV which may due to the excess moisture in the oil. Zirconium dioxide nanofluids-based palm oil at a concentration of 0.005 g/L has the highest breakdown voltage value, which is 69.57 kV. The second highest is zinc oxide nanofluids at the same concentration of 0.005 g/L which is at 69.28 kV. Nevertheless, all nanofluids samples has breakdown voltage that falls in the same range and almost similar. This shows that the adding nanoparticle is better at improving the dielectric breakdown strength of the palm oil compared to the pure palm oil. And in addition, this is the first time reported the breakdown strength value for small concentration nanofluid which is almost similar to breakdown voltage of higher concentration nanofluids [16]. This finding is significant as by adding a small amount of nanoparticle will result to high breakdown strength that is achieved by higher concentration nanofluid.

3.2. Conductivity

Conductivity is the ability of a dielectric material to conduct electricity. A good insulator is a material that has a low conductivity value. Figure 4 shows the conductivity versus frequency for all samples in a frequency range of 48 to 60 Hz. The line graph shows zinc oxide has increased the conductivity of palm oil for about 25-75%. This increment is expected since zinc oxide has conductive property [17-18] which is in opposite of zirconium dioxide. As seen in figure 4, zirconium dioxide reduces the conductivity value of palm oil which is perfect for an insulator. Nevertheless, the reduction is not directly proportional to the concentration which may due to moisture effect from the oil. Precaution has been made to use a fully closed liquid electrode during measurement. However, some moisture may be absorbed into the oil during the handling process.

Figure 1 AC breakdown voltage for palm oil and ZnO nanofluids samples.
Figure 2 AC breakdown voltage for palm oil and ZrO$_2$ nanofluids samples.

Figure 3 Average AC breakdown voltage for all sample.

Figure 4 Conductivity versus frequency for all samples.
3.3. Relative Permittivity

The dielectric constant or relative permittivity is defined as the amount of electrostatic energy which can be stored as electrical energy. The relative permittivity also measures the resistance produced in the electrical field of a dielectric material. Figure 5 shows the relative permittivity value versus frequency graph for all samples. At 50 Hz power frequency, ZrO$_2$15 has the highest permittivity compared to other samples, while the lowest permittivity value is recorded for ZnO15. Nevertheless, the value of all samples lies in a similar range which indicates that adding nanoparticle at these low concentration does not affect much on the relative permittivity value. According to the ASTM D924 standard, at 25 °C the maximum value of the relative permittivity of vegetable oil is 3.1. The results fulfill the requirement for these nanofluids to be used in a transformer.

3.4. Dissipation Factor

Dissipation factor is also known as tan δ or dielectric loss tangent. For a good insulation property of transformer oil, the value of the dissipation factor needs to be as low as possible. A low dissipation factor value will cause a higher resistive property in an insulator. Figure 6 shows the dissipation factor versus frequency for all samples. The result shows that zirconium nanofluids have successfully reduced the dissipation factor of pure palm oil. Zinc oxide on the other hand has increased the dissipation factor despite all values are lower than the ASTM D924 standard upper limit which is 0.05 at 25 °C. Hence, these values are acceptable.

Figure 5 Permittivity vs power frequency for all sample.
3.5. Kinematic Viscosity

Kinematic viscosity is an important property for a cooling liquid of a transformer. The lower the viscosity of the oil, the better the flow of liquid and the better the cooling performance of the oil. One challenge of replacing mineral oil with vegetable oil is to match the viscosity value of the former. It is well known that viscosity value of mineral oil is much lower than that of vegetable oil. However, according to IEC 62770 standard, the higher limit for viscosity of natural ester is 50 cst [19]. Figure 7 shows that the viscosity values for palm oil exceeded this limit. Adding nanoparticle has successfully reduce the viscosity by 13-33 % of the original value. Zirconium dioxide nanofluid again has shown the greatest performance by recording the lowest viscosity which is 35.89 cSt at 0.0015 g/L concentration. This value is almost similar to the value reported in [20] at higher nanofluid concentration which is 0.05g/L. It was suggested that the ultrasonic waves from sonication process supplies energy to the liquid molecules to vibrate at higher rate. This vibration causes rapid compressive and stretching force within the molecular structure and break the bonds between the molecules allowing them to move away from the original position [21-22]. Hence, it produces cavitation and causes viscosity reduction. This effect depends on the amplitude, processing time and temperature in which the liquid exposed to the sonication radiation. However, the result may not solely due to the sonication process since the sonication period does not directly proportional to the viscosity reduction. Other factors like the type and amount of nanoparticles added to the base oil should also be considered as one of the reasons for viscosity reduction.

![Figure 6](image_url) Dissipation factor versus power frequency.

![Figure 7](image_url) Kinematic viscosity versus oil samples.
4. Conclusion
This paper has successfully filling the research gap in which the dielectric properties of low concentration palm oil-based nanofluids is reported. Overall, adding nanoparticle at a concentration of 0.0015-0.005 g/L has improved the base oil properties for breakdown voltage, dielectric properties as well as the kinematic viscosity. It is shown that palm oil-based zirconium dioxide with concentration 0.0015g/L, has most potential properties compared to the other samples. Although the breakdown voltage improvement is not significantly different compared to other nanofluid samples, but ZrO\textsubscript{2}15 scored high for the other measurements. Summarised in Table 2, the percentage improvement of ZrO\textsubscript{2}15 sample compared to the base oil. This result is significant in showing that at low concentration of nanofluid (in this case ZnO and ZrO\textsubscript{2} in palm oil base liquid) one could achieve almost similar result when using higher concentration nanofluid. This alternative is rather optimum, economic and promising for the future of environment friendly insulation oil.

Table 2: Properties enhancement of ZrO\textsubscript{2}15 sample compared to the base oil.

| Properties  | AC Breakdown Voltage | Conductivity at 50 Hz, $\sigma$ | Relative permittivity at 50 Hz, $\varepsilon_r$ | Dissipation factor at 50 Hz, $\tan \delta$ | Kinematic viscosity at 40 °C |
|-------------|----------------------|---------------------------------|---------------------------------------------|------------------------------------------|-----------------------------|
| Percentage Enhancement (%) | 82.65 | 37.12 | 9.22 | 32.2 | 33.09 |

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