Dielectric Properties of Eco-friendly Nanofluids

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Abstract. Power and energy sector is adopting the modern technology in all science streams for improving the efficiency after the inclusion of distributed generation and smart grids. The key component in power transmission and distribution is a Transformer. Oil filled transformers are used in High Voltage Transmission and Low Voltage Distribution. To improve the operational efficiency of these huge machines, researches are carried out to prepare insulating oils with high dielectric strength. The present work focuses on the enhancement of dielectric properties of natural oil based insulating fluid by modifying with suitable nanoparticles. The available edible oils such as coconut oil, rice bran oil, sesame oil and sunflower oil are chosen for this purpose. Nanoparticles of TiO₂, Fe₃O₄, SiO₂, h-BN and Al₂O₃ are selected as additives. The properties such as Break Down Voltage, Tan delta and Viscosity are compared for different samples. The values obtained has proved the opportunity to develop natural vegetable base oil with nanomaterial like white graphene having superior qualities compared to the mineral based transformer oil.

1. Introduction
Power transformers are integral part of AC power transmission. Without them the concept of power transfer is almost meaningless. Transformer oil serves the dual purpose of acting as an insulation and coolant for which mineral oil was used. But it has adverse impacts on the environment. With the extent of ultra-high voltage ac power transmission, it is desirable to develop a new kind of oil insulation system, with higher dielectric strength compared to conventional insulation systems, in order to improve the long term operational reliability of power transformers and thus power systems. According to the technical specifications of transformer oils and IEC standards, the important properties to classify transformer oils are the physical properties, chemical properties, and most importantly, the electrical properties. These are examined in several publications [1-6]. Certain processes are implemented in the [4-6] to improve the electrical properties as well as other properties of base oils.

Researches regarding nanofluid were always active. But the concept of nanofluid was developed very recently to replace transformer oil. Vegetable oils are environmental friendly, but they lack properties to compete with the existing standards needed for insulating oil in transformers. Each geographical zone has its own typical and abundant vegetable oil. In crude form it is not suitable for use in transformers. So an extensive study is conducted in various samples obtained by incorporating the base oil with various nano particles and analyze the variations in their properties.
2. Preparation Of Insulating Oil

Solid nanoparticles are dispersed in the host oil using ultrasonic treatment. There are several important properties such as dielectric strength, flash point, viscosity, specific gravity and pour point and all of them have to be considered when qualifying certain oil as transformer oil. Nano particles are selected which remain electrically neutral with increase in voltage level. When the voltage level across the oil is increased, these nanoparticles become polarized and will be able to trap the moving electrons. Thus the net electron flow decreases which results in the increase of Breakdown Voltage (BDV). Also, the nanofluid should have high pour point and stability to be used as transformer oil.

An electronic weigh balance was calibrated and accurately measured the amount of nano particles. About 550 ml of base oil is taken and the amount of nano particle was chosen satisfying the weight to volume ratio 0.1g/100ml. The ultrasonic agitator was filled with water till the prescribed level and the tightly sealed container was immersed in it. The agitation process was carried out for 20 minutes. After 20 minutes the agitator automatically stops and a delay of 10 minutes was given to allow the base oil to cool. Then the process was repeated till a 3 hour agitation was completed. By this the nanofluid is prepared from the base oil and it was stored in an airtight container.

3. Tests Conducted On The Insulating Oil

3.1 Breakdown Voltage Test

The breakdown voltage of oil is the minimum voltage that causes a portion of oil to lose its dielectric strength and transform it from an insulator to conductor. Breakdown voltage is a characteristic of an insulator that defines the maximum voltage difference that can be applied across the material before the insulator collapses and conducts. Oil test kits are used to find out the breakdown strength of transformer oil. The equipment are complete in themselves and supplied with oil cell as per IS: 335 and IS 6792. Its application however is restricted to oils having a kinematic viscosity of less than 50 centistokes at 27°C. The oil test kit consists of shell fitted with two standard-compliant test electrodes. The distance between these electrodes can be adjusted by using feeler gauge. The shell is properly cleaned and distance between them is adjusted to 2.5mm. The base oil is filled in the vessel of the testing device. A test voltage is applied to the electrodes and is continuously increased up to the breakdown voltage with a constant, standard-compliant slew rate of e.g. 2 kV/s. At a certain voltage level breakdown occurs in an electric arc, leading to a collapse of the test voltage. An instant after ignition of the arc, the test voltage is switched off automatically by the testing device. Ultra-fast switch off is highly desirable, as the carbonization due to the electric arc must be limited to keep the additional pollution as low as possible. The transformer oil testing device measures and reports the root mean square value of the breakdown voltage. After the transformer oil test is completed, the insulation oil is stirred automatically and the test sequence is performed repeatedly. As a result the breakdown voltage is calculated as mean value of the individual measurements.

3.2 Tan-delta Test

A very low frequency test voltage is applied across the equipment whose insulation to be tested. First the normal voltage is applied. If the value of tan delta appears good enough, the applied voltage is raised to 1.5 to 2 times of normal voltage, of the equipment. The tan delta controller unit takes measurement of tan delta values. A loss angle analyzer is connected with tan delta measuring unit to compare the tan delta values at normal voltage and higher voltages, and analyze the results. During test it is essential to apply test voltage at very low frequency. If frequency of applied voltage is high, then capacitive reactance of the insulator becomes low, hence capacitive component of electric current is high. The resistive component is nearly fixed; as the carbonization due to the electric arc must be limited to keep the additional pollution as low as possible. The transformer oil testing device measures and reports the root mean square value of the breakdown voltage. After the transformer oil test is completed, the insulation oil is stirred automatically and the test sequence is performed repeatedly. As a result the breakdown voltage is calculated as mean value of the individual measurements.
3.3 Viscosity Test

Viscosity is a property arising from collisions between neighbouring particles in a fluid that are moving at different velocities. When the fluid is forced through a tube, the particles which compose the fluid generally move more quickly near the tube's axis and more slowly near its walls: therefore some stress, (such as a pressure difference between the two ends of the tube), is needed to overcome the friction between particle layers to keep the fluid moving. For the same velocity pattern, the stress required is proportional to the fluid's viscosity. [3]. A good oil should have low viscosity so that it offers less resistance to the convectional flow of oil thereby not affecting the cooling of transformer. Low viscosity of transformer oil is essential, but it is equally important that, the viscosity of oil should increase as less as possible with decrease in temperature. The most common method of determining kinematic viscosity in the lab is the capillary tube viscometer. In this method, the oil sample is placed into a glass capillary U-tube and the sample is drawn through the tube using suction until it reaches the start position indicated on the tube's side. The suction is then released, allowing the sample to flow back through the tube under gravity. The narrow capillary section of the tube controls the oil’s flow rate; more viscous grades of oil take longer to flow than thinner grades of oil. This procedure is described in ASTM D445 and IS 3104.

4. Test Results And Analysis

This Section gives the details of all the test results as described in the previous Section.

4.1 BDV Results

The results of BDV test done on plain base oils are given in Table 1.

| Sample Oil         | BDV (kV/cm) |
|--------------------|-------------|
| 1 Mineral Oil      | 88          |
| 2 Coconut Oil      | 70          |
| 3 Sunflower Oil    | 60          |
| 4 Rice Bran Oil    | 104         |
| 5 Sesame Oil       | 62          |

It can be noted that the value of BDV is much high for a pure Rice Bran oil compared to all other samples.

The base oils are then mixed with the nanoparticles in the ratio of 0.1g/100ml. The samples were then tested at a span of several days as the particles were settling with time. The testing frequency is 1 day, 5 days, 15 days and 30 days. The complete results are given in Figure 1.
As per IS 335, the minimum value of BDV for any transformer insulating oil is 65 KV/cm. Oils like rice bran oil and coconut oil satisfied this condition in its untreated form itself. Oils like sunflower as well as sesame oil satisfied the condition after it was agitated with nanoparticles.

The values of BDV given in Table 1 show that pure rice bran oil has the greatest BDV. The results given in Figure 1 indicates an increase in BDV of Coconut Oil for about 5.7% to 22.8% with increase in number of settling days from 1 to 30 with the addition of nanoparticles of TiO$_2$ whereas an increase in BDV of about 35.7% to 80% is noted with increase in number of settling days from 1 to 30 with the addition of nanoparticles of Fe$_3$O$_4$.

The results for Sesame oil shows a change of about 12.9% to 6.45 % with increase in number of settling days with the addition of nanoparticles of TiO$_2$. It shows a decrease in BDV from its maximum value with increase in number of settling days. The BDV of Sunflower oil shows a change of 25.% to 29.5 % with the addition of nanoparticles of TiO$_2$.

An increase in BDV of Rice bran oil of about 25% to 42.3% is observed with increase in number of settling days with the addition of nanoparticles of TiO$_2$. 19.2% to 34.6 % increase is noted with the addition of nanoparticles of Fe$_3$O$_4$. An interesting feature is noted in the rice bran oil with Al$_2$O$_3$ where the BDV swings between 14% and 19% where it rises from first day to 15th day and then decreases till 30th day. The change in BDV with the addition of SiO$_2$ is seen to go down with days.

The most promising result is observed when Rice Bran Oil is mixed with h-BN (White graphene) nanoparticles. The results show a rise in BDV from 150kV/cm to 172 kV/cm as the days increase for settling.

It was also observed that, as the agitation time increases, the stability of the nanofluid increases. The total agitation time was fixed as five hours from previous results. As the settling time increases, the BDV increases to a limit and then remains constant in most of the cases.

4.2 Tan Delta Results
The results of Tan Delta and Loss angle test done on different samples are given in Table 2.
On the basis of tests performed, it was found that the tan δ value of mineral oil was 0.054. It was found that the tan δ value of coconut oil was 2.22, which is a significantly higher value. The value of tan δ increases as the charge carriers increases. The tan δ value of the rice bran oil is around the specified value. As per IEC, the preferred value of tan δ is 0.2/mm. On addition of nanoparticles, the tan δ value increases further. Almost all combinations done except coconut oil + TiO₂ with value 0.26, had a tan δ value below the preferred value. By using suitable substances, it may be possible to reduce tan δ further.

### 4.3 Viscosity Results

The results of the tests done on the same samples for viscosity are given in Table 3.

| Sample Oil                  | Viscosity (cSt) |
|-----------------------------|-----------------|
| Transformer Oil             | 10.48           |
| Transformer Oil + TiO₂      | 21.06           |
| Transformer Oil + Fe₃O₄     | 11.335          |
| Coconut Oil Plain           | 40.388          |
| Coconut Oil + TiO₂          | 57.65           |
| Rice Bran Oil Plain         | 62.844          |
| Rice Bran + TiO₂            | 60.244          |
| Rice Bran + Fe₃O₄           | 53.43           |
| Rice Bran + h-BN            | 52.55           |

On the basis of tests performed, it was found that mineral oil has a viscosity of 10.48cSt. For samples with TiO₂ and Fe₃O₄ nanoparticles, the values are 21.06 cSt and 11.335 cSt respectively at room temperature. As per IEC, the preferred values of viscosity are 27cSt at 27degree Celsius and 12 cSt at 40degree Celsius. For rice bran oil, viscosity value is 62.844cSt. With the addition of TiO₂ and Fe₃O₄ nano particles, viscosity reduces to 60.244cSt and 53.43cSt respectively. Even with the addition of nano particles the values are quite larger than those preferred. In the case of Coconut oil, viscosity value is 40.388cSt and with the addition of TiO₂, the value increased to 57.65cSt. Combination of white graphene and rice bran oil gave a viscosity of 52.55cSt,
which is lower than the value of pure rice bran oil. From the results, it was found that none of
nanofluid made from natural oil have viscosity below 27cSt.
Generally, the natural oils are more viscous than mineral oils due to high intermolecular forces of
attraction between the large sized oil particles. The viscosity can be decreased by reducing the size of
the particles. This can be achieved by the emulsification of oil by using suitable agents. Moreover a
combination of thin oil with regular oil can also reduce viscosity.

5. Conclusion
Samples of Nanofluids are prepared from Transformer oil (mineral base) and other natural vegetable
environment friendly oils. The eligibility tests of each sample for using it as insulating medium in
transformers revealed a very high chance of manufacturing a superior quality nanofluid with Rice
Bran Oil as base and h-BN as an additive, since this sample recorded the highest BDV. The other
properties of Tan Delta and viscosity can be brought to the desirable limits only with additional
surfactants or binders. Further research on identifying suitable binding agents is under process.

Acknowledgments
The authors would like to acknowledge the support and funds provided by the TEQIP Phase II
implemented in TKM College of Engineering, Kollam, Kerala.

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