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Enhancement of the Characteristics of Natural Ester in Transformer Oil Insulation using Nanofluids

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Abstract

Oil is utilized in large transformers for its insulation properties and cooling. Mineral oil (MO) is not recyclable and it poses environment risks as it serves as insulation in transformer. It can be avoided by using a liquid coolant that has all the key qualities of transformer oil and seems to be biodegradable. Natural ester, made from plants as a substitute for mineral oil, has several profits. More investigations were conducted to improve the insulating liquid properties after the advent of nanofluids. In this study, a new hybrid method is employed to explore the properties by mixing different volume-percentage of hybrid nanomaterials with various natural esters. Evaluation of breakdown voltage and various transformer oil characteristics and results achieved showed that the hybrid nanofluid was essential in identifying a feasible alternative for mineral oil.

Key words: Breakdown, nanofluids, natural ester, liquid coolant

1. Introduction

Insulation fluids are used in transformers to insulate the gap between the transformer's winding and structure but also act as coolant to disperse heat in the transformer core. MO is exclusively used throughout the transformer industry as a cooling and insulating fluid [1]. In usage, the transformer insulation is subject to a variety of stresses from the reactions of electrical, physical, and chemical agents, including oxidation, and the creation of acids. Excessive heat and thermal tension are two possible reasons in breakdowns. 32% of transformers failures are caused by excessive heat and thermal tension. These stresses cause a

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breakdown that results in a diametric change in the oil's fundamental characteristics and shortens the transformer's service life [2]-[3].

Unless a transformer malfunctions, it will be extremely expensive to acquire a replacement, even if it is expected that a sole transformer will require such a lot of investment to function as planned. Transformers that malfunction as a result of mineral oil breakdown are a dangerous and should be avoided [6]. MO limited biodegradability is a problem for the environment. Whenever there is a leakage or trip following a coincidence, this contaminates the groundwater as well as the soil and poses a serious hazard both for people and the ecology [8].

Vegetable oil are becoming more common as mineral oil replacements because of the harm they do the environment and the scarcity of their resources. Vegetable oil also has an extreme fire safety rating and causes less corrosion in transformers, extending their lifespan [10]. Due to their dielectric characteristics and environmental qualities, natural esters-extracted from crops and seeds like palm, sunflower, coconut, etc.-are becoming popular insulating oils [12].

In an additional development, research is currently attempted to improve the characteristics of these esters, with the synthesis of natural ester nanofluids being one such strategy. The findings showed that solid polymer's insulating lifespan can be effectively extended by suspending nanofillers. In order to improve the thermal and insulating properties of liquid insulation, a similar method was used. Nanomaterials are added to transformer oil with the intention of improving its thermal and insulating properties. The results of nanofluids experiments indicated that they had better thermal and insulating properties. To improve heat conductivity, however, typical micron-sized particles were predominantly utilized [19].

Nanofluids are subject of extensive theoretical and experimental research for many years. As a result, this review concentrates on how researchers might prepare, use, and overcome the limits of nanofluids to locate a future better nano insulating oil substitute [22].

2. Related Work

Ahmed et.al [1] studied the properties of the biodegradable edible oil substituting the conventional insulating oil in transformer. Excitation Emission Matrix analysis revealed the testing characteristics of aged ester oil [2]. Amin et.al [3] investigated the most recent methods and difficulties in developing transformer's insulation. Flash point and fire point tester were determined based on international standards [4]. Standard test procedure and viscosity calculation [5]. According to analysis, by Baharuddin et. al [6]. nano-based mineral oil has a better improvement in breakdown voltage than pure mineral oil Chandrasekar et.al [7] in his study suggests an innovative way to enhance performance by including the carbon nanotubes. Duzkaya et. al [8] examined natural ester based nanofluid with diffused ZnO and determined that nanofiller with ester provided better performance than absence of nanofiller. This paper assessed the impact of nanoparticles on the ageing of a vegetable oil based insulating system by Fernandez et. al [9]. Dielectric spectroscopy analysis for characteristics of nanofiller based transformer insulation was carried out by Huang et. al [10]. International standards for breakdown voltage is determined [11]. Jacob et. al [12] investigated the characteristics and stability analysis in power transformers. This investigation by khaled et.al examined and showed an improvement in breakdown voltage of mineral oil based nanofluids and natural ester based nanofluids [13] and Koutras et. al [14]. Olmo et.al [18] examined the characteristics of nanofiller based vegetable oil. An examination of oil based nanofluid as the new insulation technology for transformer application was done by suhaimi et. al [22].

3. Proposed Work

In this investigation, the vegetable oil is used as a replacement for mineral oil and its

Experimental characteristics are analyzed.

3.1 Palm Oil as Sample 1

The crushing of the palm nuts is the first step in the traditional manufacturing of palm oil. Each nut was cracked with two stones, and the kernel and shell were instantaneously separated, in the process of shelling. The usage of nut-cracking stations has essentially replaced this human process. The mixture of kernels and shells supplied by the mechanical nut-crackers has to be separated. The clay-bath, a concentrated viscous clay and water mixture, is typically used to separate the kernel from the shell. The lighter kernels float to the top of the mixture while the heavier shells sink due to the clay bath's bulk.

The floating kernels are picked up, placed in baskets, thoroughly cleaned, and then dried. The shells are periodically removed from the bath and thrown away. The conventional process for extracting oil involves either heating dry nuts or frying palm kernels in old oil. In a motorized grinder, the cooked kernels are next crushed or ground to a paste. To liberate the palm kernel oil, the paste is heated while being combined with a tiny amount of water. Periodically, the top is skimmed to remove the leaked oil.

3.2 Soya Bean Oil as Sample 2

A magnetic separator that eliminates contaminants like nails, wires, and iron is a part of the seed cleaning. Bean stems and pods are also taken out of the cleaner beans. The beans are brought to the crusher after being cleaned, where they are crushed and separated from the skin and the kernels. The beans are divided into valves ranging from four to eight. Oil seed surface area is increased by crushing. The method ensures a softening effect by facilitating the transfer of warmth, temperature, and moisture during the softening of oil seed. The oil seed is softened in the following stage to optimize the temperature and moisture levels and increase its flexibility for the ideal rolling conditions. The amount of moisture in the soybean determines the softening temperature. If the moisture content is between 13% and 15%, the temperature needs to be between $70°C$ and $80°C$, which takes 15 to 30 minutes. The horizontal softening pot is a regularly used softener that helps prevent scraper and heating layer abrasion for long life. Power level and the sticky roller phenomenon are decreased by softening.

The crushed and rolled soybeans are then inserted into an enlarged, porous granular material during the extruding process. It needs to be processed at a high temperature between $110°C$ to $200°C$ for one to three minutes. The oil seed is progressed while rolling from a granular level to flake. This aids in the oil seed's cell structure being destroyed. Moreover, it broadens the seed's surface area and reduces the distance over which the oil escapes. Controlling the material's temperature and moisture is important. When the flake is squeezed and pressed, oil seeps out of the press cage gaps and collects in oil reservoirs. The flake is then taken for pressing. The extracted oil is next filtered to get rid of the solids.

3.3 Nanofluids Preparation

For the investigation, it must have been chosen to use commonly available Titanium Dioxide (TiO2), Aluminium Oxide (Al2O3), and Molybdenum disulfide (MoS2) with average grain dimensions of 50 to 70 µm and purity levels of 97.6 to 98.7%. To enhance collision energy, each particle was crushed individually in a ball mill with a 100 mm diameter using balls of various diameters. Flow chart of nanofluid preparation are shown in figure 1.

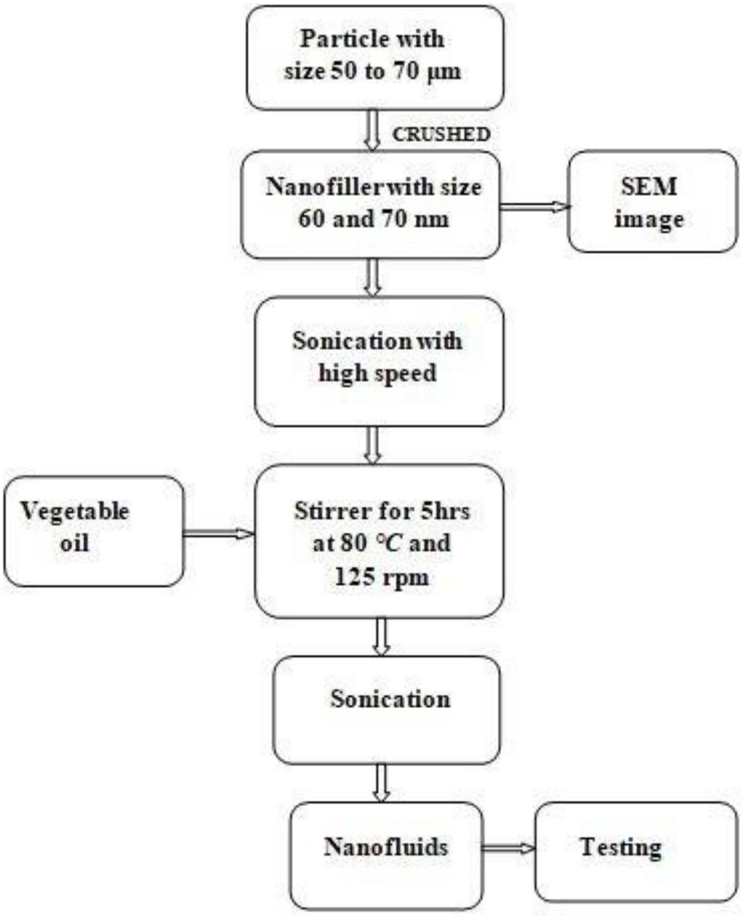
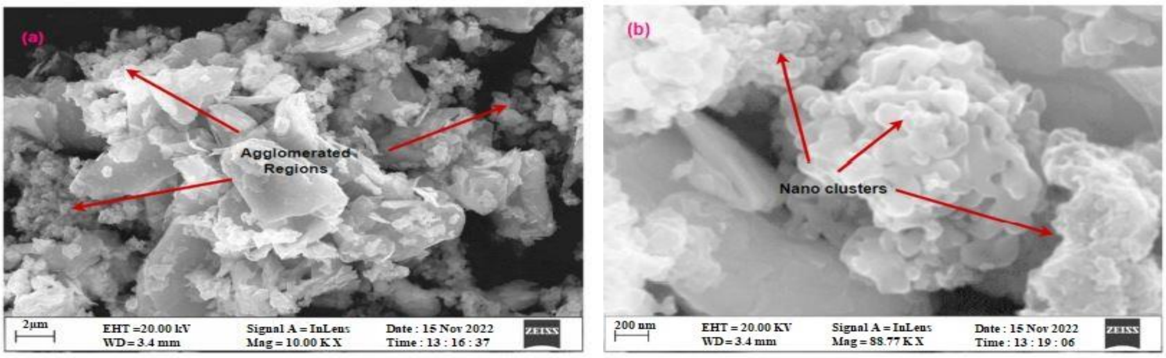


Figure 1. Flow chart of nanofluid preparation

Images of nanofillers obtained with a scanning electron microscope (SEM) at various magnifications are shown in Figures 2 a–2 c [23]. In hybrid nanofillers, the particles can agglomerate together.



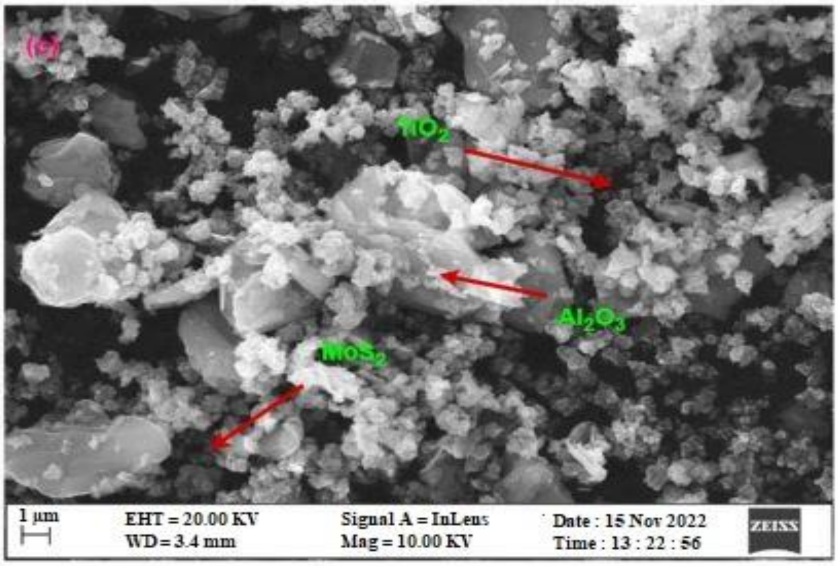


Figure 2. SEM image of TiO_2, Al_2O_3, MoS_2 hybrid nanofillers [23]

According to Table 1, the particles were mixed with 500 ml of oil samples using a magnetic stirrer with various weight ratios of 0.01, and 0.05. To obtain homogeneous particle distribution in the oil, all the samples were stirred for 5 hours in the magnetic stirrer at a temperature of 80°C and 125 rpm.

Table 1. Tested samples with nanofiller

Base oil sample	Type of nanofiller added	Ratio of nanofiller added
Palm Oil	TiO_2	0.05 (Vol. %)
	Al_2O_3	0.05 (Vol. %)
	MoS_2	0.05 (Vol. %)
Soya Bean Oil	TiO_2	0.05 (Vol. %)
	Al_2O_3	0.05 (Vol. %)
	MoS_2	0.05 (Vol. %)

4. Results and Discussion

To ensure the measurement accuracy on investigating the oil based nanofluids and the base oil properties, each measurement was performed five times, with the average result being given.

4.1 Breakdown Voltage

The breakdown voltage, which measures the insulation oil's capacity to tolerate electrical tension without malfunctioning, together with stress, temperature, humidity, and electrode configuration, are some significant factors determining the insulation oil's performance in transformers. Transformer oil should always have a high dielectric strength. Acidity, bubbles, solid particles, and moisture are significant elements that influence the dielectric strength of oil. This is done using IEC 156 Test. The spacing between is predetermined (2 mm). The voltage measured at the point the existing arcs through this gap represents the insulating liquid's dielectric breakdown strength. Water, conducting particles, and dirt are contaminants that reduce the insulating oil's dielectric strength. The schematic diagram of the apparatus used to measure dielectric strength [23] is shown in Figure 3.

Figure 3. Dielectric strength measuring equipment [23]

The voltage was gradually raised and kept at 30 kV for one minute. The oil sample's ability to tolerate the required voltage was next tested. The breakdown voltage was recorded if it occurred at a voltage lower than 30 kV. After that, the voltage is raised again until the breakdown occurs, and the voltage is recorded. The oil needs to be sent for refurbishment if the breakdown strength is less than 30 kV. These days, transformer oil is available with breakdown strength of above 65 kV. Comparing TiO2-based vegetable oil to Al2O3- and MoS2-based vegetable oil, Table 2 reveals that TiO2-based palm oil has greater breakdown strength.

Table 2. Breakdown voltage of oil samples

Oil Samples	Nanofillers	Breakdown Voltage (KV)
Mineral Oil	-	53.5
Palm oil	-	77.2
	TiO_2	79.3
	Al_2O_3	78.2
	MoS_2	77.6
Soyabean oil	-	76.3
	TiO_2	78.3
	Al_2O_3	77.5
	MoS_2	77.0

A comparison graph of breakdown voltage is shown in Figure 4.

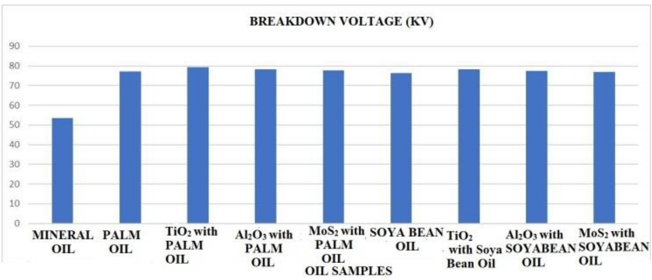


Figure 4. Comparison graph of breakdown voltage

4.2 Interfacial Tension

This determines the Mili-Newton /meter or dyne/cm attraction force among oil and the water molecules. The transformer oil is guaranteed by a high amount of interfacial tension. Table 3 reveals the Interfacial Tension of mineral oil and nanofluids based vegetable oils.

Table 3. Interfacial Tension of mineral oil and nanofluids based vegetable oils

Oil Samples	Nanofillers	Interfacial Tension (mN/m)
Mineral Oil	-	42.5
Palm oil	-	38.3
	TiO_2	35.2
	Al_2O_3	37.8
	MoS_2	36.9
Soyabean oil	-	36.2
	TiO_2	36.5
	Al_2O_3	38.7
	MoS_2	37.2

A comparison graph of interfacial tension is shown in Figure 5.

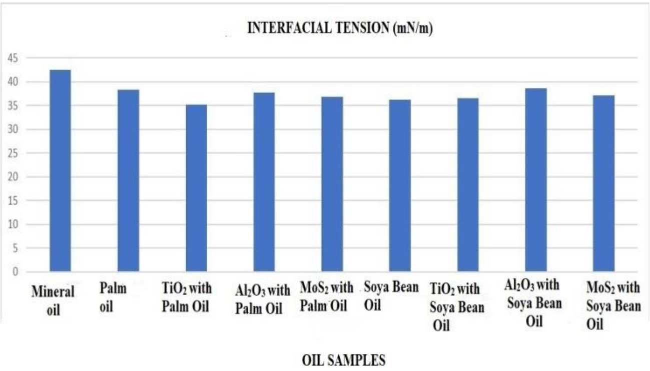


Figure 5. Comparison graph of interfacial tension

4.3 Flash Point

It specifies the temperature at which oil releases enough vapour to combine with the air around it to form a flammable mixture. Under normal conditions, a quick spark is the result of flame. Flashpoint is an important performance feature because it brings attention to the possibility of fire danger in the specific application.

The schematic diagram of the apparatus used to measure flash point is shown in Figure 6.

Figure 6. Flash point measuring equipment

A desirable characteristic for transformer oil in a given application is a high flash point. It is typically above 140°*C* (>10°*C*). A high flash point guarantees an insulating oil of superior quality. Table 4 reveals the flash point of sample oils

Table 4. Flash Point of sample oils

Oil Samples	Nanofillers	Flash Point (°C)
Mineral Oil	-	142
Palm oil	-	260
	TiO_2	330
	Al_2O_3	315
	MoS_2	310
Soyabean oil	-	320
	TiO_2	308
	Al_2O_3	300
	MoS_2	290

A comparison graph of flash point is shown in Figure 7.

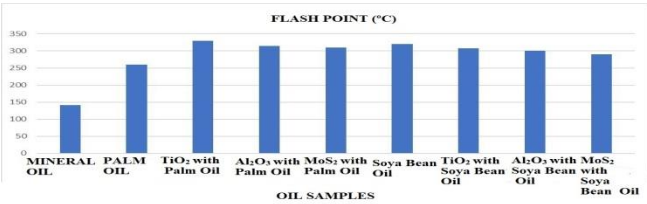


Figure 7. Comparison graph of flash point

4.4 Pour Point

It is the lowest temperature at which oil starts flowing under normal operating conditions. It is a crucial characteristic of transformer oil, particularly in frosty weather. Transformer oil stops the convectional current and inhibits cooling pour point that is above the existing temperature. Usually the pour point is high for a better quality insulating oil. In general, vegetable oils freeze at greater temperatures than mineral oils, which have a pour point of less than 40 °C. Due to differences in the components of each oil, the freezing point differs from one oil to the next. Greater oil saturation levels correspond to higher freezing points. Table 5 reveals the pour point of sample oils.

Table 5. Pour Point of Sample oils

Oil Samples	Nanofillers	Pour Point (°C)
Mineral Oil	-	150
Palm oil	-	220
	TiO_2	245
	Al_2O_3	230
	MoS_2	215
Soyabean oil	-	208
	TiO_2	205
	Al_2O_3	210
	MoS_2	202

A comparison graph of pour point is shown in Figure 8.

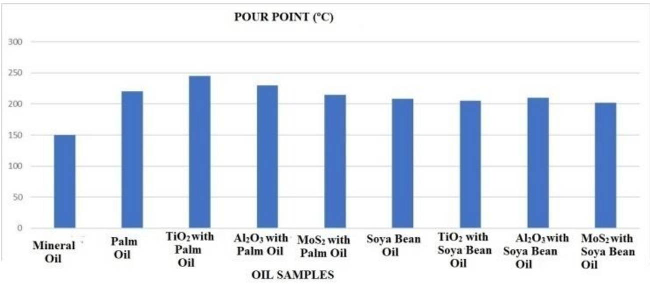


Figure 8. Comparison graph of pour point

4.5 Viscosity

It is described as the flow resistance under typical conditions. When it comes to transformer oil, flow resistance denotes a barrier to the oil's convectional current. High convection current is ensured by good quality dielectric oil's lower viscosity, that prevents a transformer's cooling rate from being compromised. The low oil viscosity is not only critical, but it is also crucial as the oil's viscosity remain constant while the temperature changes. In general, liquid tends to become less viscous as temperature rises. The dielectric liquid has a larger potential for heat transfer because of its low viscosity and high specific heat capacity. The schematic diagram of the apparatus used to measure viscosity is shown in Figure 9.

Figure 9. Viscosity measuring equipment

Table 6 reveals the viscosity of mineral oil and nanofluids based vegetable oils.

Table 6. Viscosity of mineral oil and nanofluids based vegetable oils

Oil Samples	Nanofillers	Viscosity (cSt) @40°C
Mineral Oil	-	40
Palm oil	-	77
	TiO_2	70
	Al_2O_3	60
	MoS_2	55
Soyabean oil	-	50
	TiO_2	60
	Al_2O_3	78
	MoS_2	45

A comparison graph of interfacial tension is shown in Figure 10.

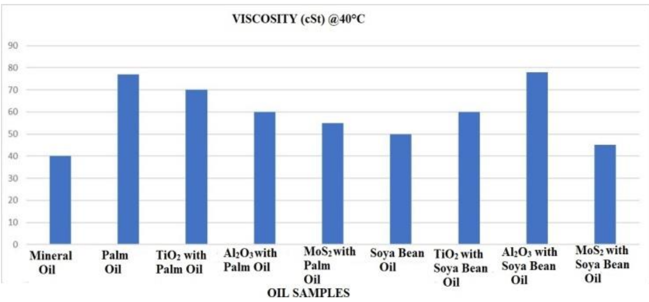


Figure 10. Comparison graph of viscosity

5. Conclusion

Employing insulators like Al_2O_3 and semiconductor materials like TiO_2 and MoS_2, vegetable oil based on nanofluids is created in the research to improve the qualities of transformer oil. Nanomaterials is created using a magnetic stirrer and vegetable oil at a concentration of 0.05%. According to the standards, measurements of breakdown voltage, interfacial tension, flash point, fire point, and viscosity are taken. As TiO_2 is stable in higher electric fields and has a relatively high dielectric strength, it has better qualities than vegetable oils based on MoS_2 and Al_2O_3. Vegetable oil use has various benefits, including a low impact on the environment, adaptation to difficult climates, high sustainability, fewer fire hazards, and customer friendliness.

References

[1] Ahmed, Md Raju, Md Shahidul Islm, and Ashish Kumar Karmaker. "Experimental investigation of electrical and thermal properties of vegetable oils for used in transformer." In *2021 International Conference on Automation, Control and Mechatronics for Industry 4.0 (ACMI)*, pp. 1-4. IEEE, 2021.

[2] Amalanathan, Arputhasamy Joseph, Ramanujam Sarathi, Swayam Prakash, Ashok Kumar Mishra, Ribhu Gautam, and Ravikrishnan Vinu. "Investigation on thermally aged natural ester oil for real-time monitoring and analysis of transformer insulation." *High Voltage* 5, no. 2 (2020): 209-217.

[3] Amin, Danial, Rashmi Walvekar, Mohammad Khalid, Mahesh Vaka, Nabisab Mujawar Mubarak, and T. C. S. M. Gupta. "Recent progress and challenges in transformer oil nanofluid development: a review on thermal and electrical properties." *IEEE Access* 7 (2019): 151422-151438.

[4] ASTM D445, "Standard Test Method for Kinematic Viscosity ofTransparent and Opaque Liquids (and Calculation of DynamicViscosity)", 2011.

[5] ASTM D93, "Standard Test Methods for Flash Point by Pensky-Martens Closed Cup Tester", 2012.

[6] Baharuddin, Muhammad Faris, Izzah Hazirah Zakaria, Mohd Hafizi Ahmad, Zainuddin Nawawi, Muhammad Abu Bakar Sidik, and Muhammad Irfan Jambak. "Effect of surfactant on breakdown strength performance of transformer oil-based nanofluids." *Journal of Electrical Engineering & Technology* 14 (2019): 395-405.

[7] Chandrasekar, Subramaniam, Palanisamy Kasi Viswanathan, Periyayya Uthirakumar, and Gian Carlo Montanari. "Investigations on novel carbon quantum dots covered nanofluid insulation for medium voltage applications." *Journal of Electrical Engineering & Technology* 15 (2020): 269-278.

[8] Duzkaya, Hidir, and Abderrahmane Beroual. "Statistical analysis of AC dielectric strength of natural ester-based ZnO nanofluids." *Energies* 14, no. 1 (2020): 99.

[9] Fernández, Inmaculada, Rafael Valiente, Félix Ortiz, Carlos J. Renedo, and Alfredo Ortiz. "Effect of TiO2 and zno nanoparticles on the performance of dielectric nanofluids based on vegetable esters during their aging." *Nanomaterials* 10, no. 4 (2020): 692.

[10] Huang, Zhengyong, Jian Li, Wei Yao, Feipeng Wang, Fu Wan, Yaxiong Tan, and Muhammad Ali Mehmood. "Electrical and thermal properties of insulating oil-based nanofluids: a comprehensive overview." *IET Nanodielectrics* 2, no. 1 (2019): 27-40.

[11] IEC 60156 Third edition, "Insulating liquids–Determination of the breakdown voltage at power frequency–Test method", 2003-11.

[12] Jacob, Joyce, P. Preetha, and T. K. Sindhu. "Stability analysis and characterization of natural ester nanofluids for transformers." *IEEE Transactions on Dielectrics and Electrical Insulation* 27, no. 5 (2020): 1715-1723.

[13] Khaled, Usama, and Abderrahmane Beroual. "AC dielectric strength of mineral oil-based Fe3O4 and Al2O3 nanofluids." *Energies* 11, no. 12 (2018): 3505.

[14] Koutras, Konstantinos N., Ioannis A. Naxakis, Aspasia E. Antonelou, Vasilios P. Charalampakos, Eleftheria C. Pyrgioti, and Spyros N. Yannopoulos. "Dielectric strength and stability of natural ester oil based TiO2 nanofluids." *Journal of Molecular Liquids* 316 (2020): 113901.

[15] Madavan, Rengaraj, Subburaj Saroja, Alagar Karthick, Srinivasan Murugesan, V. Mohanavel, P. Velmurugan, Sami Al Obaid, Saleh Alfarraj, and S. Sivakumar. "Performance analysis of mixed vegetable oil as an alternative for transformer insulation oil." *Biomass Conversion and Biorefinery* (2022): 1-6.

[16] Muangpratoom, Pichai. "The Effect of Temperature on the Electrical Characteristics of Nanofluids Based on Palm Oil." *Journal of Engineering & Technological Sciences* 53, no. 3 (2021).

[17] Olmo, Cristian, Cristina Méndez, Félix Ortiz, Fernando Delgado, and Alfredo Ortiz. "Titania nanofluids based on natural ester: Cooling and insulation properties assessment." *Nanomaterials* 10, no. 4 (2020): 603.

[18] Rafiq, Muhammad, Muhammad Shafique, Anam Azam, Muhammad Ateeq, Israr Ahmad Khan, and Abid Hussain. "Sustainable, renewable and environmental-friendly insulation systems for high voltages applications." *Molecules* 25, no. 17 (2020): 3901.

[19] Rafiq, Muhammad, Muhammad Shafique, Anam Azam, and Muhammad Ateeq. "Transformer oil-based nanofluid: The application of nanomaterials on thermal, electrical and physicochemical properties of liquid insulation-A review." *Ain Shams Engineering Journal* 12, no. 1 (2021): 555-576.

[20] Reffas, Abderrahim, Abderrahmane Beroual, and Hocine Moulai. "Comparison of breakdown voltage of vegetable olive with mineral oil, natural and synthetic ester liquids under DC voltage." *IEEE Transactions on Dielectrics and Electrical Insulation* 27, no. 5 (2020): 1691-1697.

[21] Ritonga, Alvin Daniel Sorimuda, Yulia Erina Sari, and Suwarno Suwarno. "Comparative Study of Liquid Insulating Materials for High Voltage Transformer." In *2019 2nd International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*, pp. 1-5. IEEE, 2019.

[22] Suhaimi, Sabrina N., Abdul RA Rahman, Muhamad F. Md Din, Muhammad Zahir Hassan, Mohd Taufiq Ishak, and Mohd Taufik bin Jusoh. "A review on oil-based nanofluid as next-generation insulation for transformer application." *Journal of Nanomaterials* 2020 (2020): 1-17.

[23] Sumathi, S., R. Rajesh, and P. Subburaj. "Investigation of dielectric strength of transformer oil based on hybrid TiO2/Al2O3/MoS2 Nanofluid using taguchi and response surface methodology." IETE Journal of Research 67, no. 6 (2021): 817-825.

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