

Article

An Experimental Study and Statistical Analysis on the Electrical Properties of Synthetic Ester-Based Nanofluids

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Abstract: The rise in power demand today necessitates its generation and transmission at high voltages. The efficient transmission of electric power requires transformers with an insulation system that exhibits excellent dielectric properties. In this paper ZnO and CuO nanomaterials are utilized to investigate the dielectric characteristics of pure synthetic ester oil and its related nanofluids (NFs) from room temperature up to 60 °C at increments of 20 °C, including AC breakdown voltage, Dielectric Dissipation factor, and DC resistivity. The breakdown testing is carried out in accordance with experimental IEC-60156 requirements. The DC resistivity and dissipation factor of oils are measured using the Dissipation Factor meter, resistivity meter, and a heating chamber with an oil cell that follows IEC 60247 standard. The statistical analysis is performed on the breakdown voltages test values using the Weibull probability distribution model for better accuracy. From the results, it has been found that ZnO nanofluid possesses a higher breakdown voltage among all the tested liquids. Furthermore CuO nanofluid gives a minimum value of dissipation factor even at higher temperatures.



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Keywords: enhanced insulation; synthetic esters-based nanofluids; AC breakdown voltage; dielectric dissipation factor; DC resistivity; effect of nanoparticle's; Weibull distribution

1. Introduction

To meet the demand of the power consumption of the growing population, transmission of high voltage has become a necessity. Safe operation of power transformers is highly desirable in order to uphold the stability of the power system network [1]. For high-capacity transformers to operate reliably it is necessary to ensure their heat transfer and insulation properties. Power transformer efficiency and reliability are significantly influenced by dielectric oils [2]. The low fire point, poor moisture tolerance, non-biodegradable, and caustic Sulphur content are the drawbacks possessed by conventional mineral oil used as insulation in transformers [3,4]. To enhance the transformer oil's dielectric properties, numerous experiments must have been carried out [5–8]. Since ester oil has a greater level of biodegradability, is non-flammable, has a high moisture tolerance, and has a greater electrical permittivity, it has therefore proven to be a superior choice. Esters oil primarily comes in two varieties: natural ester (NE) and synthetic ester (SE). Natural esters are produced during the refining process of a variety of oils, including soybean, mustard, sunflowers, and others. However, synthetic esters are compounds obtained from the reaction of carboxylic acids and alcohols called esterification. In a largely homogeneous electric field, synthetic ester's AC breakdown voltage was found to be between NE and mineral oils [9]. The synthetic ester is recognized as quite viscous, i.e., two to three times more viscous than mineral oil, and to transport heat from the windings to the outside, despite having the desirable qualities. As a result, a new category of liquid insulants known as nanofluids has been developed. TiO₂ nanoparticles were used to increase the

AC breakdown voltage of transformer oil, according to Y. DU et al. [10]. Fast-moving electrons are transformed into low-mobility particles by conductive nanoparticles, according to M. Zahn et al. findings [11,12]. Segal et al. [13] reported 50% enhancement in the nanofluids compared to base oil. The electron scavenging and shallow trap theory is the two-modification mechanism that leads to improved dielectric performance that has been analyzed by many researchers. If the charge relaxation time of the nanoparticle is extremely small, quasi free electrons in the liquid attach to the nanoparticles. This process is called “electron scavenging”. Added nanoparticles also create shallow traps for the free moving electrons, trapping and de-trapping them and hindering the movement of streamer propagation.

It is required to ascertain specific parameters, such as the dielectric dissipation factor, DC resistivity, and AC breakdown voltage (bdv) of both pure SE oil and nanofluids, in order to examine the capability of the nanofluids. In this study, the performance of ZnO and CuO-based nanofluids prepared by dispersing three distinct nanoparticle concentrations in the pure SE oil are evaluated. The concentrations are 0.01 weight percent, 0.02 weight percent, and 0.04 weight percent, respectively. The Tan-delta and DC resistivity are measured throughout a range of temperatures, from 23 °C to 60 °C, with 20 °C increments. The test apparatus includes an oil cell (containing test fluid)-equipped heating chamber, an oil dissipation factor meter, an insulation resistance meter, and a breakdown voltage tester. IEC60156 and IEC 60247 are the testing standards that were employed. Parameters of nanoparticles and SE oil properties are shown in Tables 1 and 2 respectively. Figure 1 displays a flowchart with different types of insulating oils. The nomenclature for the symbols and abbreviations used in the study is shown in Table 3.

Table 1. Nanoparticle’s specifications.

Parameters	ZnO	CuO
Particle size	20–25 nm (TEM)	20 nm (TEM)
Density (gm/cc)	5.6 gm/cc	6.3 gm/cc
Appearance	Fine powder	Fine Powder

Table 2. Characteristics of Synthetic Ester fluid.

Properties	Typical Values (MIDEL 7131)
Density at 20 °C (Kg/dm ³)	0.97
Flash point (°C)	260
Appearance	Clear free from water
Fire point (°C)	316
Breakdown voltage (kV)	Greater than 75
DC resistivity at 90 °C (GΩ·m)	Greater than 20
Moisture content (ppm)	50
Biodegradability	Readily Biodegradable

Figure 1 presents the flowchart for the classification of insulating liquids used for insulation and cooling purpose in high voltage equipment. Liquid insulants are broadly classified as organic and inorganic. Organic insulants are further classified into two types, natural and synthetic, that include petroleum-based products i.e., mineral insulating oil, vegetable oils, resins, wax, agro-products, etc. The synthetic insulants include synthetic hydrocarbons such as alcohols and hydrocarbons, and halogen-free synthetic liquids (silicon oils) that offer better insulation properties similar to mineral oils with better thermal stability and less flammability. Liquid nitrogen and SF₆ are categorized as inorganic insulants that are used as electric insulating material in circuit breakers, cables, capacitors, and transformers.

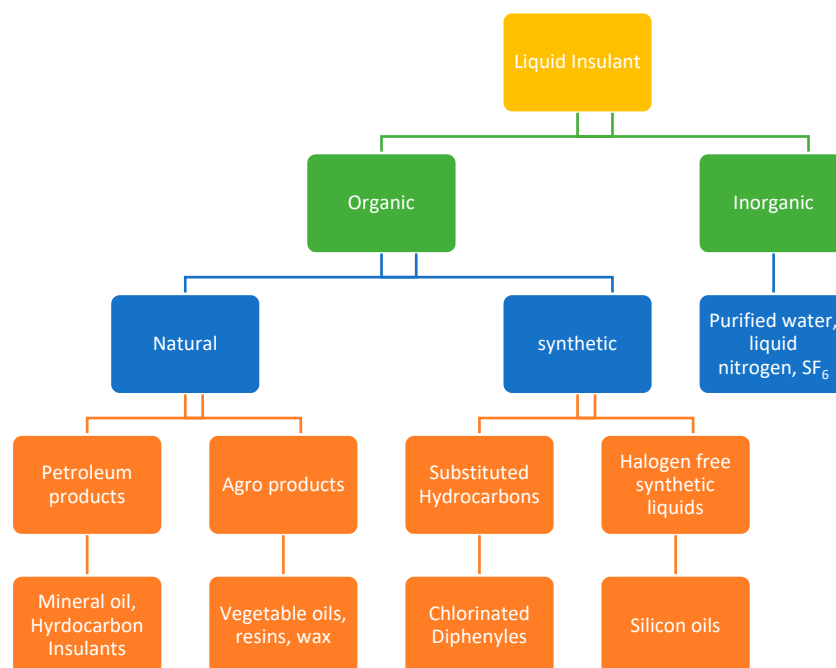


Figure 1. Flowchart showing classification of liquid insulants.

Table 3. Nomenclature Table.

Symbols and Abbreviations	Actual Meaning
NFs	Nanofluids
MO	Mineral oil
SE	Synthetic Ester
NE	Natural Ester
δ	Loss angle
bdv	Breakdown voltage
TEM	Transmission electron microscopy
nm	Nanometer
M Ω -m	Mega ohm-meter
wt%	Weight percent

The key contributions of this paper are developing nano-based synthetic ester insulating liquids that exhibit excellent dielectric characteristics. This paper presents the effect of conducting (ZnO) and semi-conducting (CuO) nanoparticles on the electrical properties such as AC breakdown voltage, dielectric dissipation factor, and DC resistivity of synthetic ester oil and its corresponding nanofluids under temperature variation. The model for dielectric modification due to nanoparticle addition in oil is presented in the paper. Moreover, the breakdown test results are analyzed using the Weibull probability distribution technique for better results estimation. The dielectric performance of both the nanofluids is compared to present the best possible alternative for insulation and cooling purpose in transformers.

The remainder of the article is organized as follows. Section 2 describes the experimental method and includes material preparation techniques, measurement of dielectric properties, and the process of dielectric change due to the addition of nanoparticles. In Section 3 experimental results for electrical properties of nanofluids and pure synthetic ester oil with temperature variation are presented and discussed. Section 4 presents the analysis of AC breakdown test values using the Weibull probability distribution function. The conclusion along with the future work is presented in Section 5.

2. Experimental Work Arrangements, Steps, and Setup Description

2.1. Materials Used and Preparation of Nanofluids

Two different types of nanoparticles, i.e., ZnO (conductive) and CuO (semi-conductive) are utilized to analyze their effect on pure SE fluid. Figure 2 shows the TEM images of ZnO and CuO nanoparticles. Six individual nanofluid samples were prepared by including ZnO and CuO nanomaterials, i.e., with three different concentrations of each nanoparticle, i.e., 0.01 wt%, 0.02 wt%, and 0.04 wt% in pure SE oil. The two steps method is used in the present work to prepare nanofluids as it is a commercial and widely accepted method [14,15]. The nanofluid preparation method involves various physical and thermal processes that consist of stirring and ultrasonication of prepared samples to homogeneously mix nanoparticles in the pure SE oil as shown in Figure 3. The time period of stirring for nanofluid samples is 25 min. Moreover, the time period for ultra-sonication of nanofluid samples is about one hour, and the operating temperature is 40 °C. The two above-mentioned processes make the sample ready for testing. The nanoparticles were carefully weighed using a Nano weight scale. The materials were procured from sigma Aldrich and were further reduced in size using a top-down nanotechnology technique. The sonication process produces high frequency waves (40 kHz), which homogeneously disperse nanoparticles in pure oil, and completes the nanofluid preparation process.

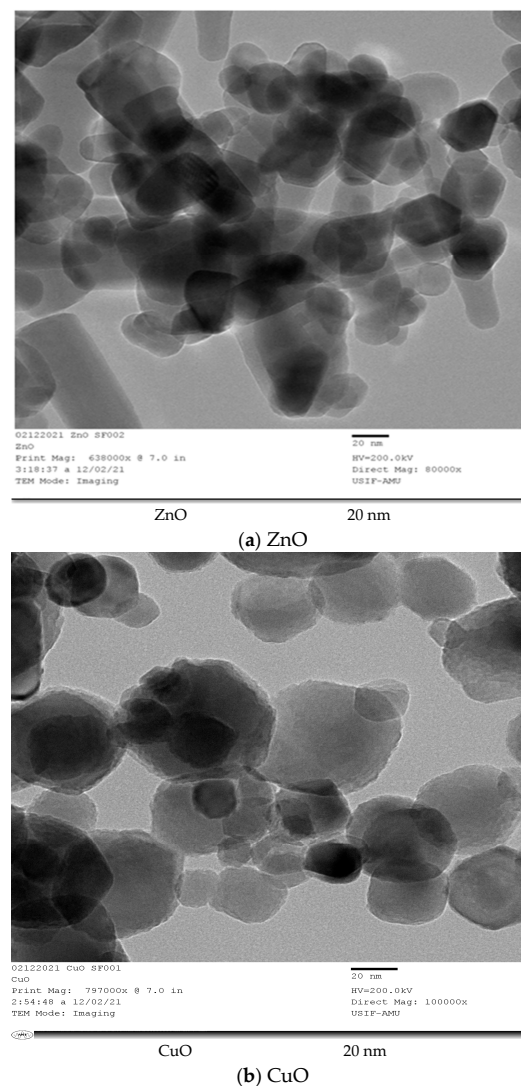


Figure 2. TEM images of (a) ZnO and (b) CuO nanoparticles.

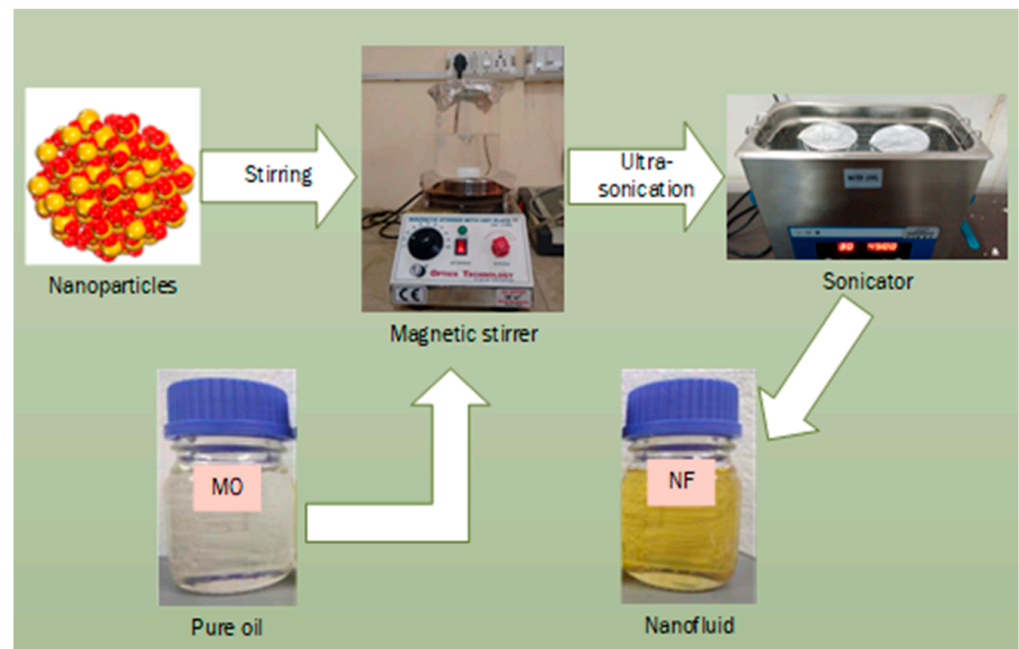


Figure 3. Process for the preparation of nanofluids.

2.2. Stability of Nanofluids

The evaluation of stability of nanofluids is an important aspect to test its applicability as a transformer dielectric for insulation and cooling purposes. The dispersion is stable if the nanoparticles are uniformly distributed in the base liquid. However, if the nanoparticles do not mix uniformly they may form aggregate matter in the oil and then lose their functional property. The concept of stability is well explained by DVLO theory, which says that the particles are subjected to various forces such as van der Waals attractive forces and electrical repulsive forces, etc., in the oil. If the repulsive forces acting are higher than the attractive forces, then the dispersion is stable. In this study, the stability of the nanofluid samples was determined using the simple bottle test, which shows no sedimentation even after 72 h of its preparation.

2.3. Measurement of Electrical Properties

DC resistivity and dissipation factor of oils are determined using the PE-ORDF-2 model as shown in Figure 4. The equipment comprises a Dielectric dissipation factor and a DC resistivity meter. The AC bdv is measured by means of an oil breakdown tester, which is shown in Figure 4a. The heating chamber comprises of an oil cell that has a three-electrode system (high voltage electrode, low voltage electrode, and guard electrode). The nanofluid samples were heated at 23 °C, 40 °C, and 60 °C, respectively. The voltage level of 250 V is selected for measurement. A fully automatic oil breakdown tester is utilized to measure the AC breakdown voltage of the nanofluids. The sphere–sphere electrodes configuration is used with a separation of 2.5 mm between them. The repetitive breakdown measurement is performed on each prepared nanofluid sample. The time period between the two consecutive breakdown measurements is at least 2 min so that no gas bubbles exist between the electrodes before each breakdown measurement. The oil temperature is suitably changed within a heating chamber, as shown in Figure 4b.

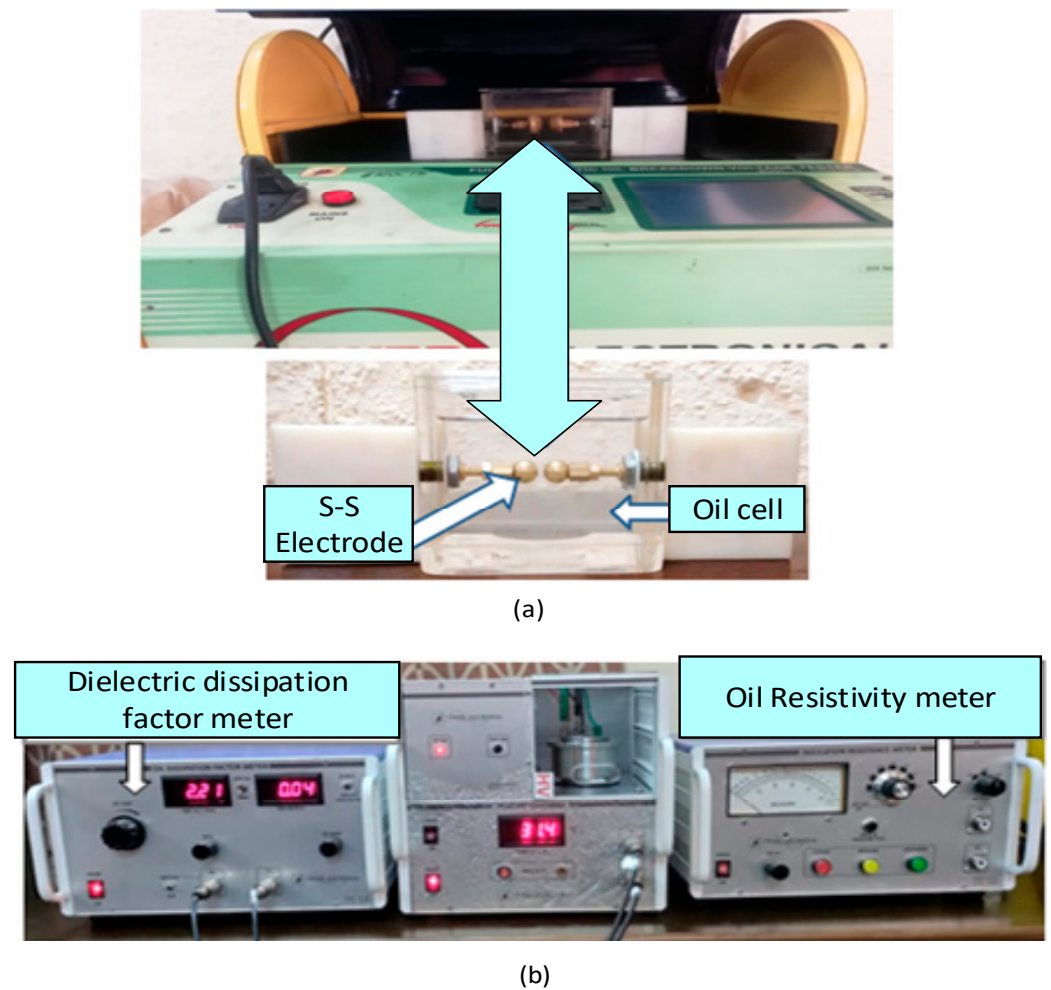


Figure 4. Experimental set-up to measure (a) AC Breakdown voltage of oils and (b) DC Resistivity and dielectric dissipation factor.

2.4. Dielectric Modification Mechanism

M Zahn et al. studied Segal's experimental results. They introduced an electron capture model, which improved the dielectric capability of nanofluids [16,17]. Free electrons shift to the surface when the electric field is applied, and the nanoparticle will become polarized. This process is known as "charge relaxation" as shown in Figure 5. According to this model, the charge relaxation time constant described in Equation (1) plays an important part in the modification mechanism:

$$\tau = (2\epsilon_1 + \epsilon_2) / (2\sigma_1 + \sigma_2) \quad (1)$$

where ϵ_1 and ϵ_2 are the permittivities of the oil and nanoparticles, respectively. σ_1 and σ_2 are the conductivities of oil and nanoparticles respectively. The concept of improvement in dielectric characteristics of nanofluids is well explained with the help of the charge relaxation model, which states that if the relaxation time is appropriately short, the electric field lines congregate near the nanoparticles, and thus electrons get attached to the surface of the nanoparticle. This process is known as "electron scavenging". The nanoparticles change into sluggish, negatively charged particles and streamer propagation is reduced. Thus, better insulation properties are achieved.

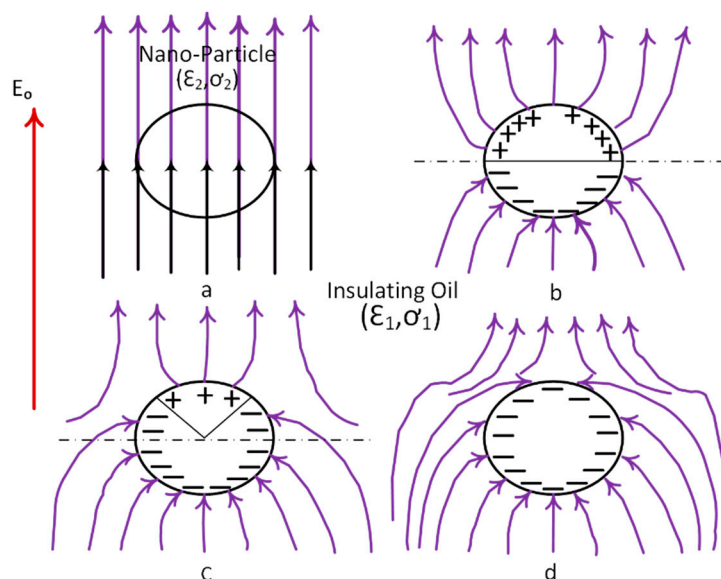


Figure 5. Charge relaxation model for improved breakdown voltage in NFs. The nanoparticles get rapidly polarized upon the application of electric field as seen from (a) to (b), the fast-moving electrons are captured by the nanoparticles as a result converting them into slow moving negative charge carriers as seen in (c). Due to low mobility of these charge carriers the net space charge is hindered and suppresses the streamer propagation in the oil as shown in (d). Hence, results in improved breakdown strength.

The permittivity and conductivity values of both nanoparticles and oil are used to determine their time constants. The permittivity and conductivity of ZnO nanoparticles are 7.5 and 10^2 S/m respectively. The permittivity and conductivity of CuO nanoparticles are 18.4 and 10^5 S/m respectively. The permittivity of the oil is 3.2, and its conductivity is less than 0.05 S/m. The time constants of the nanomaterials have been identified in determining the influence on the electron scavenging mechanism and streamer propagation and its effect on the improved breakdown strength. The time constants of both ZnO nanoparticles are 1.05×10^{-11} s, and for the CuO nanoparticle are 3.12×10^{-11} s, which is lesser than the time required for the streamer to propagate in oil and is of the order of a few microseconds. If the time constant of nanoparticles is lesser than the streamer propagation time in the oil, then the nanoparticle will scavenge the electrons present in the oil. Therefore, the nanoparticles will get polarized rapidly due to the applied electric field and nanoparticles will capture the fast electrons present in the oil, which suppresses the streamer propagation and hence improves the breakdown strength of ZnO and CuO-based nanofluids. The shallow trap theory was considered for various nano oils prepared using Al_2O_3 , TiO_2 , and Fe_3O_4 [18].

It is demonstrated that nanofluids have a substantially higher shallow trap density than mineral oil. High-density traps are thought to grab fast electrons in nanofluids and convert them to slow electrons, creating a local negative space charge.

As a result, the space charge density was lowered, resulting in a more even distribution of electric fields. Because nanoparticles increase the trap density of the nanofluids, free electrons are caught and released during movement, which can obstruct electron migration. As a result, the rate of streaming in the oil is reduced, and the oil's breakdown strength is improved. Some more publications on this hypothesis can be found in [10,19–21].

3. Experimental Results and Discussion

3.1. AC Breakdown Voltage

AC breakdown test is essential to determine the dielectric functionality of insulating oil used in electric transformers [14]. The electric strength of insulating material is a measure of its ability to withstand electrical stress. This strongly depends upon the chemical and physical properties like acidity in oil, viscosity, and gases dissolved in oil

like oxygen and carbon dioxide, and dust fibers. The breakdown strength is influenced by moisture, nanoparticle type, nanoparticle volume percentage, and surface modification of nanoparticles. A median of more than ten BDV iterations was taken, and Table 4 shows the breakdown voltage and corresponding enhanced value for all the samples. When ZnO and CuO are introduced to the base liquid, they improve the AC breakdown voltage, as can be seen from the comparison. This increase in breakdown strength can really be related to the above-discussed electron scavenging mechanism and the shallow trap concept, according to which speedy electrons are transformed into slow electrons.

Table 4. Enhancement in AC Breakdown Voltage for Pure SE oil and Nanofluids.

Pure Synthetic Ester Oil BDV (kV)	Concentration	ZnO		CuO	
		BDV (kV)	% Enhancement	BDV (kV)	% Enhancement
60.40	0.01 wt%	76.20	26.20	70.40	16.50
60.40	0.02 wt%	83.80	38.70	84.80	40.40
60.40	0.04 wt%	78.60	30.13	74.70	23.67

The findings demonstrate that, as shown in Figure 6, there is a particular ideal nanofluid concentration that produces the highest breakdown strength after which the AC breakdown voltage starts to decline.

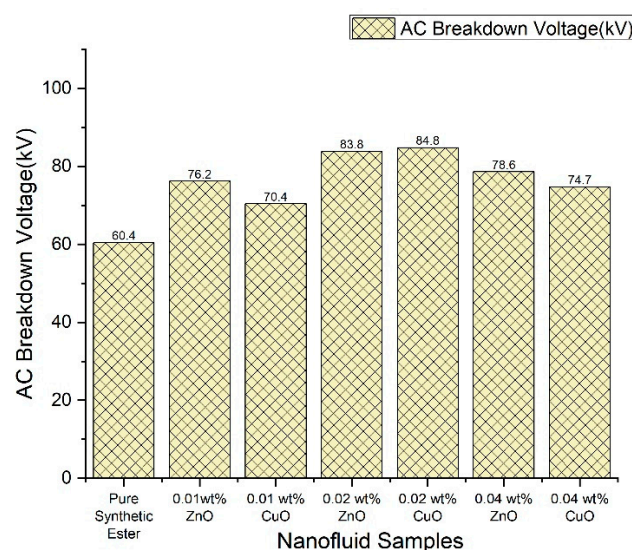


Figure 6. Variation of AC breakdown voltage for changed concentrations of nanofluids.

In this work, for both ZnO and CuO nanofluids, 0.02 wt% concentration yields the greatest AC BDV. When the concentration is raised, the nanoparticles tend to aggregate, which causes saturation and eventually a decrease in breakdown strength. As can be shown, ZnO nanofluid performs better than CuO nanofluid at all nanoparticle concentrations because of its superior dielectric characteristics and lower ZnO nanoparticle relaxation time constant.

3.2. DC Resistivity

The ability to forecast the capability and condition of insulating material relies heavily on resistivity [22]. Temperature and the concentration of nanoparticles cause nonlinear variations in resistivity. The resistivity reduces when the temperature of the synthetic ester oil rises, and it likewise does so as the concentration of nanoparticles in the nanofluid rises.

Equations (2) and (3) provide the formulas for calculating DC Resistivity and Insulation Resistance (IR).

$$\text{Total resistance (M}\Omega) = \frac{\text{meter reading} * \text{range multiplier} * \text{test voltage}}{500} \quad (2)$$

$$\text{Resistivity (M}\Omega - \text{m)} = \frac{\text{total resistance in ohm} * \text{cell constant}}{100} \quad (3)$$

The addition of nanoparticles significantly increases DC resistivity [23], as can be seen from the graph of DC Resistivity with temperature in Figure 7. As given in Table 5 Up to 40 °C, the resistivity of pure synthetic esters rapidly decreases and remains constant after that point. This effect occurs because, as the temperature of the insulating liquid rises, the firmly bound electrons to the nuclei gather enough energy to be thrown out of their source atoms and become current carriers, lowering the liquid's resistivity. However, for temperatures below 40 °C for both ZnO and CuO, the DC resistivity is greatly increased due to nanoparticles addition. The conclusion that the nanoparticles are capturing the free electrons and inhibiting streamer development, reducing conductivity and improving resistivity, is therefore clear from the results. The reason for improved resistivity of nanofluids can be attributed to the electron scavenging by the nanoparticles, since the nanoparticles are rapidly polarized due the applied electric field and attach themselves with the negatively charged carriers and reduce the flow of electrons in the oil. As a result, this reduces the conductivity, and hence the resistivity of oil is improved. For temperatures beyond 40 °C, the results shown by 0.03 wt% concentration ZnO NF is superior to 0.01 wt% and 0.02 wt% concentrations as opposed to 0.01 wt% concentration for CuO nanofluids. Thus, CuO nanofluid is less stable at higher concentrations of nanoparticles and at higher temperatures as the resistivity drops due to various factors such as heat dissipation, impurities, undesired moisture content or solid particles in the oil and aggregation, etc., whereas for ZnO nanofluids, the concentration below 0.04 wt% does not yield a sufficient number of nanoparticles, and the rate of generation of free electrons exceeds the rate of electrons getting trapped by the nanoparticles resulting in a decrease of resistivity.

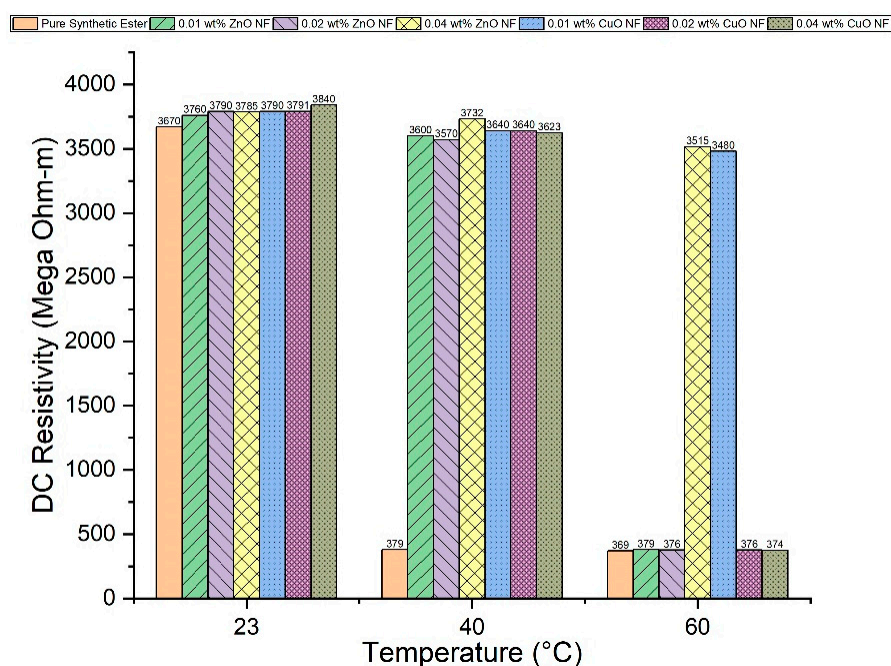


Figure 7. The DC Resistivity Vs. Temperature plot for nanofluids and pure oil.

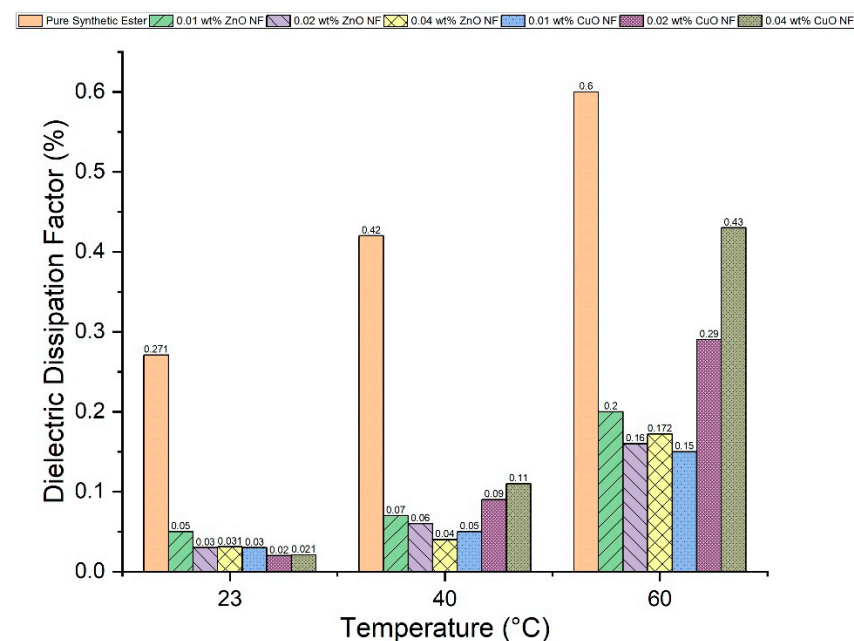
Table 5. DC Resistivity variation for different nanofluid samples with temperature.

Temperature (°C)	DC Resistivity (Mega Ohm-m)						
	Pure Synthetic Ester	0.01 wt% ZnO	0.02 wt% ZnO	0.04 wt% ZnO	0.01 wt% CuO	0.02 wt% CuO	0.04 wt% CuO
23.0	3670.0	3760.0	3790.0	3785.0	3790.0	3791.0	3840.0
40.0	379.0	3600.0	3570.0	3732.0	3640.0	3640.0	3623.0
60.0	369.0	379.0	376.0	3515.0	3480.0	376.0	374.0

3.3. Dielectric Dissipation Factor ($\tan\delta$)

Insulation level is assessed by the dielectric dissipation factor. The dielectric dissipation factor evaluates the losses in insulation caused by the presence of voids, contaminants, or solid particles when an AC electric field is applied to the dielectric fluid [15]. A low $\tan\delta$ suggests that the power losses associated with insulation are minimal and give better dielectric strength to the oil [22]. Its high value, on the other hand, denotes the presence of soluble impurities and contaminants.

As can be seen in Figure 8, for pure SE, the dissipation factor rises linearly with temperature. This is due to the fact that charge carriers become more effective at high temperatures, raising conduction current values, conduction loss values, and the dissipation factor.

**Figure 8.** The DDF Vs. Temperature plot of nanofluids and pure oil.

When compared to pure synthetic ester, the dissipation factor for all concentrations is significantly reduced by the introduction of nanoparticles. Nanoparticles when added to the oil act as a perfect dielectric that minimizes the dissipation factor of nanofluids. Moreover, the low electrical conductivities of CuO nanoparticles and their low relaxation time constants are responsible for the reduction in leakage current and hence minimize the dissipation factor of nanofluids. Similarly, the low relaxation time constant of ZnO nanoparticles that suppresses the leakage current and also the high thermal conductivity of ZnO nanoparticles that will absorb the heat produced and remain stable at high temperatures can be attributed to the low dissipation factor of nanofluids. This shows that the inclusion of nanoparticles reduces leakage current due to its enhanced charge-trapping process and enhanced insulating qualities.

Nanofluids' dielectric dissipation factor rises as the temperature rises. This is owing to the oil's degradation, and the nanomaterial's susceptibility to oxidation at high temperatures because of its low density, which introduces an effect of aging and ultimately leads to failure of insulation.

The performance displayed by 0.02 weight percent ZnO nanofluid at 60 °C is superior to 0.04 weight percent concentration, as shown in Table 6. This could be a result of larger quantities of nanoparticles aggregating. The dissipation factor is minimum at 0.01 wt% concentration for CuO nanofluids at 60 °C, and the value increases as the concentration rises. CuO nanofluid is obviously less stable at higher temperatures and concentrations.

Table 6. The values of Dielectric dissipation factor (DDF) of different samples of oil.

Temperature (°C)	Dielectric Dissipation Factor (%)						
	Pure Synthetic Ester	0.01 wt% ZnO	0.02 wt% ZnO	0.04 wt% ZnO	0.01 wt% CuO	0.02 wt% CuO	0.04 wt% CuO
23.0	0.2710	0.050	0.030	0.031	0.030	0.020	0.021
40.0	0.420	0.070	0.060	0.040	0.050	0.090	0.11
60.0	0.60	0.20	0.160	0.172	0.150	0.290	0.43

4. Statistical Analysis

The lengthy experimental data for breakdown voltages need correct estimation using a statistical technique like the probability distribution technique, as normal distribution gives unsatisfactory and unclear results [24]. The Weibull distribution is a well-known statistical method used to determine the probability distribution of breakdown voltage. The Weibull distribution is generally utilized in reliability and lifespan prediction studies. The equation for the Weibull probability distribution function contains two parameters, i.e., shape parameter (k) and scale parameter (c) [25,26], that decide the maximum voltage stress on the insulation. The two-parameter Weibull model, also known as the cumulative distribution function, is given as in Equation (4)

$$F(x) = 1 - e^{-\left(\frac{V}{c}\right)^k} \quad (4)$$

where, V is AC breakdown voltage (kV), k and c are the shape and scale parameters respectively. The shape parameters are important factors in Weibull distribution, and its larger value indicates smaller discreteness.

The breakdown voltages at 50% and 63.2% probability were determined using a two-parameter Weibull distribution model for the ZnO and CuO-based nanofluids and pure synthetic ester oil using Equation (4). The AC breakdown test results consist of more than 10 breakdown data values for each nanofluid and oil. The spherical electrode system is used for breakdown test. The results are shown graphically between Weibull probability distribution (%) and breakdown voltage (kV) for ZnO and CuO nanofluids at different nanoparticle concentrations along with the pure oil in Figures 9 and 10 respectively. As can be seen from the results, breakdown voltage at 63.2% probability is higher than 50% probability at all nanoparticle concentrations for both the ZnO and CuO nanofluids. Moreover, the breakdown voltage for ZnO-NF is higher than CuO-NF at all concentrations and at both the probabilities (50% and 63.2%) except at 0.04 wt% concentration. The breakdown voltage of CuO-NF at 0.04 wt% is 84.5 kV and 85.1 kV at 50% and 63.2% probability respectively, which is higher compared to breakdown voltage of ZnO-NF at 0.04 wt% i.e., 83.8 kV and 84.1 kV at 50% and 63.2% probability respectively. The results for AC Breakdown voltage at different failure probabilities of investigated nanofluids is shown graphically in Figures 9 and 10. It can be seen for synthetic esters that both the nanoparticles help to increase its breakdown voltage uniformly.

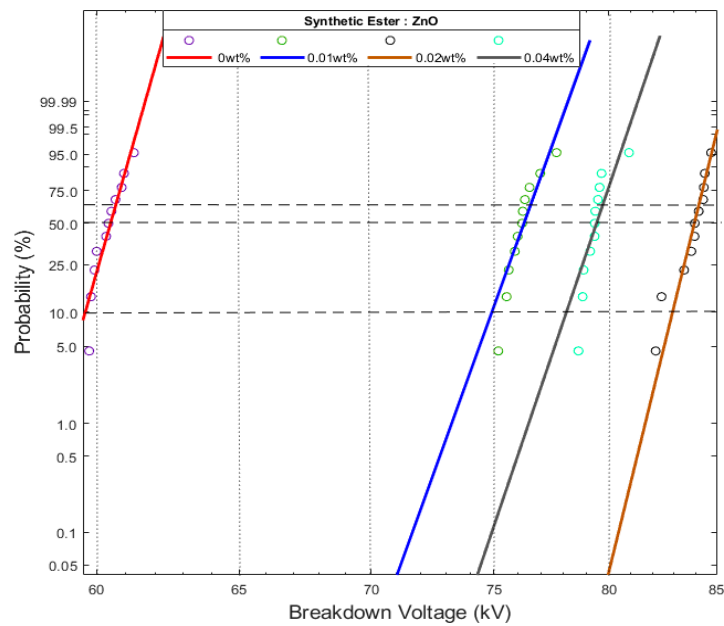


Figure 9. Plot of Probability distribution vs. Breakdown voltage for ZnO nanofluids and Pure oil.

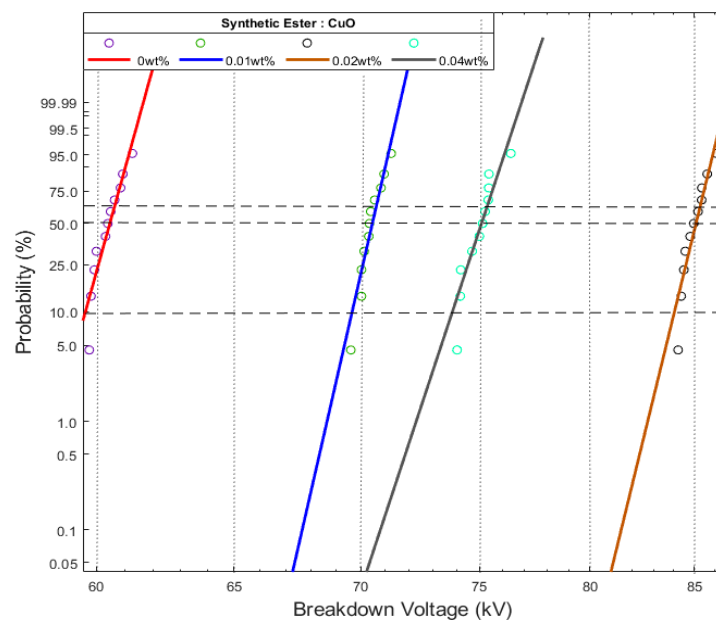


Figure 10. Plot of Probability distribution vs. Breakdown voltage for CuO nanofluids and pure oil.

5. Conclusions

With this study, the performance of liquid insulants was examined in relation to ZnO and CuO nanoparticles. The results indicate that introducing these particles had a good effect on the dielectric characteristics of pure SE.

- When ZnO and CuO were added to the pure fluid, the inclusion of nanoparticles increased the AC BDV for both materials. Up to a certain optimal concentration, the improvement is associated to the electron scavenge process and shallow trap theory, as stated before, but beyond that point, the BDV saturates because of the aggregation of nanoparticles at greater concentrations.
- Because ZnO nanofluid has better dielectric capabilities than CuO nanofluid and has a smaller relaxation time constant, it performed better than the latter.

- The inclusion of ZnO and CuO nanoparticles improved the nanofluids' resistivity. The nanoparticles suppress streamer propagation, capture flow of electrons, and reduce conductivity while increasing resistance.
- When the temperature was under 40 °C, both nanofluids responded in nearly the same manner. Beyond 40 °C, 0.04 weight percent ZnO NF outperforms other concentrations in comparison to 0.01 weight percent CuO NF.
- By preventing leakage current from flowing, the inclusion of nanoparticles lowers the dissipation factor of NFs at all concentrations as compared to an unmodified SE. The dissipation factor is least for temperatures under 60 °C when ZnO nanofluids are incorporated with 0.02 weight percent, and 0.02 weight percent ZnO nanofluid performed better at 60 °C.
- The statistical technique applied gives enhanced breakdown voltage uniformly for synthetic esters due to ZnO and CuO nanoparticles at all probabilities, specifically more pronounced at lower concentrations and higher probability.
- For CuO nanofluids, 0.01 weight percent concentration yields the minimum values of the dissipation factor compared to those other concentrations for nearly the whole temperature range.

The work done in this paper can be used for a better understanding of the dielectric characterization of transformers insulating fluids, and commercialization of nanofluids by evaluating the thermal and electrical traits of nano-insulating oils. This work proposes the synthetic ester oil as an alternative to the present mineral oil used in transformers, and also develops its corresponding nanofluids for enhancing the dielectric properties of base synthetic ester oil, although synthetic esters possess certain drawbacks like higher dissipation factor at elevated temperature, which can be improved with future research.

Future work includes more research related to stability studies of nanofluids. The long-term stability is a concern for the application of nanofluids as transformer insulating oils. Therefore, this needs to be investigated more for its industrial application. Moreover, the present nanofluids preparation methods involve higher cost. Therefore low-cost nanofluid preparation techniques should be researched more. Furthermore, the materials that exhibit excellent dielectric traits for synthetic esters with lower cost should be considered as a part of future research.

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