VOL. 24, NO. 2, 2025, 149-156
elektrika.utm.my
ISSN 0128-4428

ELEKTRIKA
Journal of Electrical Engineering

Dielectric Performance of Vegetable Oil Based Silicone Dioxide and Copper Oxide Under High Temperature Ageing

Norkhairunnisa Zullizawati Mohd Zulkarnain[1], **Nur Aqilah Mohamad**[2], **Zulkarnain Ahmad Noorden**[2] and **Noor Syazwani Mansor**[2]

[1]PGEO Edible Oils Sdn Bhd, Lorong Pukal Dua, Kawasan Lembaga Pelabuhan Johor,81700 Pasir Gudang, Johor.
[2]Institute of High Voltage and High Current (IVAT), Universiti Teknologi Malaysia, 81310, Skudai, Johor.

*Corresponding author: nuraqilah.m@utm.my

Abstract: This experimental study aims to ascertain the characterization of Vegetable Oil (VO) based nanofluid with SiO_2 and CuO nanoparticles, the AC breakdown voltages and the partial discharge (PD) activities of mineral oil (MO) and VO based SiO_2 and CuO nanofluids under high-temperature ageing. Various concentrations range of SiO_2 and CuO dispersed in oil samples varied from base to 0.05%. In total, one sample of refined, bleached and deodorized palm oil (PO) and one sample of MO were measured for PD. The AC breakdown voltages measurement for all samples were carried out. Maximum PD amplitude measurements were conducted with a gap distance of 25 mm and by using needle-sphere electrode configuration for this study. The formation of SiO_2 and CuO in Refined Bleached and Deodorized Palm Oil (RBDPO) is proven through the characterization using the FTIR. Then, the SiO_2 and CuO nanoparticles are confirmed by using the X-ray Diffraction (XRD) and by comparing the experimental data with the Material Project software. SiO_2 and CuO could improve the performance of AC breakdown voltage of MO and RBDPO for 14 and 28 days of ageing. The most significant improvements in PD activities are observed at 28 days of ageing where the maximum PD amplitude shows the highest decrement for MO based SiO_2 and CuO nanofluids with 71.7% and 80.1% respectively. For RBDPO based SiO_2 and CuO nanofluids provide the highest decrement at 14 days with 34.2% and 28 days with 49.5% respectively.

Keywords: Partial Discharge, AC breakdown, silicon oxide, copper oxide, nanofluids

Article History: received 27 November 2024; accepted 13 June 2025; published 31 August 2025

1. INTRODUCTION

Insulating oil is essential in transformers to ensure thermal stability, electrical insulation, and prevent arcing during failure. It must be compatible with other components and have physiochemical, thermal, and dielectric qualities [1]. Transformers typically have an estimated lifespan of 35-40 years, necessitating that oil ageing occurs gradually and does not negatively impact other materials [2]. Thermal ageing, accelerated by factors such as heat, loading, and environmental factors like moisture, and oxygen [3]. As transformers age, by-products like gases, acids, moisture, and furanic compounds may be produced, potentially shortening the lifespan of insulating oil and papers. The industry is now shifting from petroleum-based Mineral Oil (MO) to renewable, safe, and non-hazardous natural esters like Vegetable Oil (VO).

Partial Discharge (PD) is a common issue in solid insulations and dielectric fluids, often caused by improper design, manufacturing flaws, and contaminations. It is primarily observed in conductor-dielectric contacts, bubbles, and particle contamination within the fluid. Materials flaws can strengthen the local electric field, triggering the onset of PD [4]. Discharge can accelerate insulating material deterioration, spreading from localized places into bulk oils and causing failures [5]. The location of the local field and transformer operating status also influence how discharge- induced insulation failures evolve from discharge inception to breakdown [4].

In dielectric insulating oil, discharge may take a long time to manifest, and high electrical stress should not cause PD activities. The Partial Discharge Inception Voltage (PDIV) test is a crucial measurement for assessing the state and inherent properties of dielectric insulating fluids. Choosing nanoparticles to improve dielectric characteristics of transformer oil is challenging, with fundamental characteristics like conductivity and permittivity being considered. This study investigates the PD performance of VO under high temperature ageing, considering the presence of nanoparticles under high temperature ageing.

In contrast, relatively few research study the use of nanoparticles in vegetable oils [5-7]. Some researchers have recently introduced nanoparticle addition to mineral oil to explore the influence on the oil's characteristics. Nanoparticles come in a variety of sizes and shapes. One of the nanoparticles is silicon dioxide, sometimes known as silica, which has the chemical formula SiO_2. H. Jin et al.

investigated the alternating current breakdown voltage and viscosity of mineral oil-based SiO_2 nanofluids [8]. The findings show an 38% improvement in mineral oil's AC breakdown voltage. The breakdown voltage rises as particle concentration rises. Instead of utilising mineral oil, as advised in the preceding paper, vegetable oil is proposed.

This study was conducted to determine the characterization of VO based SiO_2 and CuO nanofluids, the AC breakdown voltages and the PD activities of MO and VO based SiO_2 and CuO nanofluids under high temperature ageing at 110 °C.

2. METHODOLOGY

2.1 Materials

In this study, Refined, Bleached and Deodorized Palm Oil (RBDPO) was compared to MO. The MO was used as the reference for this study. Both RBDPO and MO used in this study were obtained from readily available market products. The fats composition and vitamin E for RBDPO are outlined in Table 1.

The types of nanoparticles used in this study are insulative nanoparticle, SiO_2 and semi-conductive nanoparticle, CuO. These nanoparticles were selected due to SiO_2 can traps free electrons, delaying streamer propagation due to charge scattering. While, CuO nanoparticles can homogenize field stress, reducing arcing risks. The properties of SiO_2 and CuO nanoparticles used can be obtained in Table 2. The process of synthesis nanofluids of RBDPO and MO is under one-step method.

Table 1. Fat, Vitamin E Contents and Fatty Acid Composition of RBDPO Sample

Type of Fats	RBDPO MD (g)
Saturated	43.0
Mono-saturated	43.1
Poly-saturated	11.7
Vitamin E	94m

[a] MD = Manufacturer's datasheet

Table 2. Properties of SiO_2 and CuO Nanoparticles

Properties	SiO_2	CuO
Appearance colour	White	Black
Purity (%)	98+	99
Density (g/cm^3)	2.4	6.4
Average particle size (nm)	60-70	80
Specific surface area (m^2/g)	160-600	>18

[b] Adapted from US Research Nanomaterials, Inc

2.2 Preparation of Nanofluids

The RBDPO and MO were subjected to filtration via a membrane filter before the synthesis procedure. The synthesis process of RBDPO and MO based SiO_2 and CuO will be carried out, where this is the common method use for synthesis process of nanofluids. The SiO_2 and CuO will be first dispersed individually into either RBDPO or MO through hotplate stirrer at speed of 900 rpm for 30 minutes. All samples will be rest at ambient temperature for 30 minutes before subjected to drying process in an oven at 85 °C for 48 hours to remove the moisture.

The second part of synthesis involved thermal ageing where in this study the nanofluids were subjected to age at temperature of 110 °C for 0, 14 and 28 days. All samples were further rested at ambient temperature 24 hours before testing its PD activities. This study is conducted in an open condition. In total, without and 0.05% of SiO_2 and CuO were used as the volume concentration in this study.

2.3 Characterization of Nanofluids

Fourier Transform Infrared spectroscopy (FTIR) and X-ray Diffraction (XRD) were used to characterise the nanoparticles. FTIR is a quick, non-destructive, time-saving approach for detecting functional groups and is sensitive to changes in molecular structure. FTIR has been widely employed to determine nanomaterial functional group alteration and bonding characteristics. The instruments used (Bruker Alpha II FTIR Spectrometer). Five samples of pure RBDPO and nanofluids were tested. The samples were scanned with infrared radiation over a frequency range of 500- 4000 cm-1 to obtain the spectrum. The samples were scanned in an inert atmosphere whereby Attenuated Total Reflection (ATR) was chosen as the sampling approach. The absorbance and transmittance were plotted against the wavenumber.

The XRD of SiO_2 and CuO nanoparticles were carried out to analyse the phase and estimate the crystallite size of the samples using X-ray diffractometer (XRD, Rigaku SmartLab) with the 2θ range from 5 to 80 (40 kV, 50 mA, step size 0.01, scan rate 4 min^{-1}). The XRD patterns with diffraction intensity versus 2θ were recorded. 2θ is the diffraction angle between the incident X-ray beam and the detector's measured scattered X-ray beam. It is the primary variable plotted on the horizontal axis of an XRD pattern.

2.4 Partial Discharge Measurement

This section describes the standard used to measure PD which will further discussed in the analysis and discussion. IEC 60270 will be applied when performing the PD measurement (IEC60270, 2000). To examine sample PD behaviour, a test cell was used according to the IEC 61294. According to standard, the copper spherical electrodes have a diameter of 12.5 mm and a 3 μm radius at the needle tip. The spacing between the needle and the sphere was fixed at 50 mm ± 1 mm. In this experiment, an AC transformer with a 100 kV maximum voltage is utilised. In this inquiry, the test cell will fill with the oil samples first, and then it is permitted to stand without applying voltage for at least 15 minutes. After that, a voltage will be given to the cell raise from 11 kV at a continuous rate of 11 kV/s plus 0.5 kV/s until a PD occurred. Following that, the PD activities will be recorded using Partial Discharge Meter.

3. RESULTS & DISCUSSION

3.1 Characterization of Nanofluids using FTIR

The IR spectrum is in the mid-IR range, with wavenumbers ranging from 400 to 4000 cm^{-1}. The mid-IR spectrum is separated into four regions: the single bond area between 2500 and 4000 cm^{-1}, the triple bond region between 2000 and 2500 cm^{-1}, the double bond region between 1500 and 2000 cm^{-1}, and the fingerprint region between 600 and 1500 cm^{-1}. Figure 1 illustrates the transmittance unit against wavenumber of 100% Oil, 0.05% SiO_2 nanofluid and 0.05% CuO nanofluid. There are more than five peaks seen, indicating that the studied molecule is not a simple compound. The broad peak appearing at wavelength 721.12 cm^{-1}, 1157.69 cm^{-1} and 1459.01 cm^{-1} revealed the formation of SiO_2 and CuO therefore confirming the dispersion of SiO_2 and CuO. Furthermore, the existence of stretching vibration bands of the O-H bond at 2921.27 cm^{-1} and 2853.69 cm^{-1}, as well as C=0 at 1743.32 cm^{-1}, is indicated by a few extra peaks showing in the spectra of the examined samples.

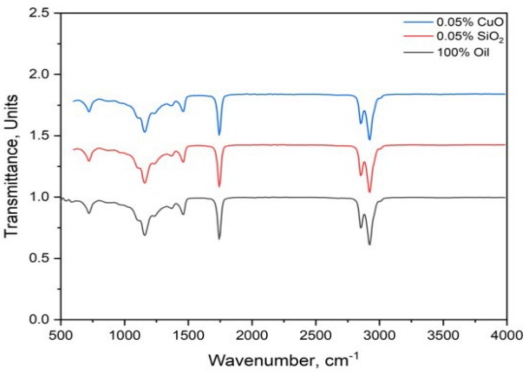


Figure 1. Transmittance spectrum of all samples

3.2 Characterization of Nanofluids using XRD

Identification of phases was carried out by comparing the diffraction pattern obtained from tested XRD with other profile. Figure 2 shows the tested XRD pattern of SiO_2nanoparticles, where it shows a broad peak centered at 2θ =22.43° is observed and no other diffraction peaks can be detected. The XRD in Figure 3 confirmed the amorphous phase and structure of the SiO_2 as sharp peaks is absence which shows that there is no crystalline structure of the SiO_2. Also, the wide peaks display the amorphous structure. The average atomic weight, crystallize size and lattice volume of CuO are 39.773, 0.21407 nm and 81.614 Å3. The collected data from the tested SiO_2 was insert to The Material Project software to check the composition of the nanoparticles along with the crystal structure as illustrated in Figure 4. From the data of the ideal SiO_2, the band gap is high around 5.74 eV, which confirms SiO_2 is an insulative nanoparticle.

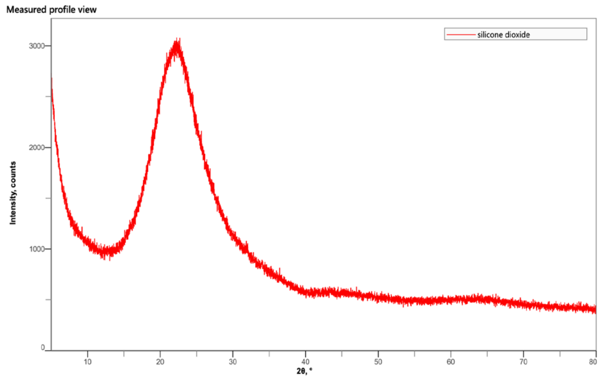


Figure 2. XRD pattern of SiO_2 nanoparticle

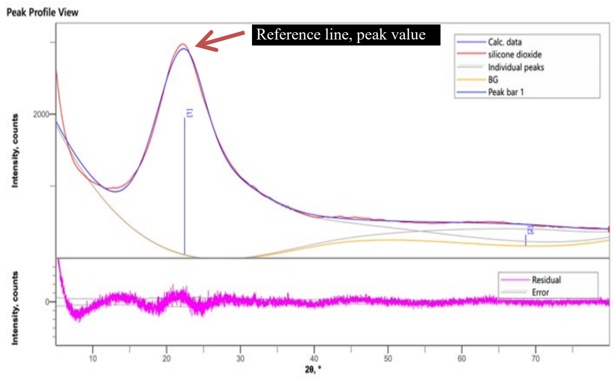


Figure 3. XRD amorphous phase and structure of SiO_2

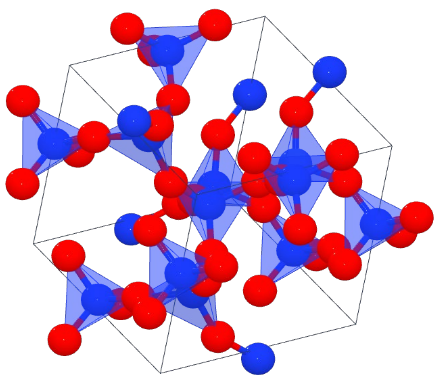


Figure 4. Crystal structure of SiO_2

Figure 5 reflects the XRD pattern of CuO nanoparticles, where it shows a sharp peak which indicates the CuO is crystalline. Next, Figure 6 shows the phase data between observed XRD and other profiles. A good match of peaks absorbed of the tested data with CuO can be observed. The highest peaks at (35.45, 38.70, 48.69 and 66.16)° it is found that monoclinic crystal system. The average atomic weight, crystallize size and lattice volume of CuO are 39.773, 0.21407 nm and 81.614 Å3. From the tested data, the crystal structure of the ideal CuO can be seen as imported from the Material Project software in Figure 7. The structure of the ideal CuO clearly shows it is a monoclinic crystal system same as the tested CuO as all the three axes are unequal in length and two axes are perpendicular to each other. From the data of the ideal CuO, the band gap is very low, which confirms CuO is a conductive nanoparticle.

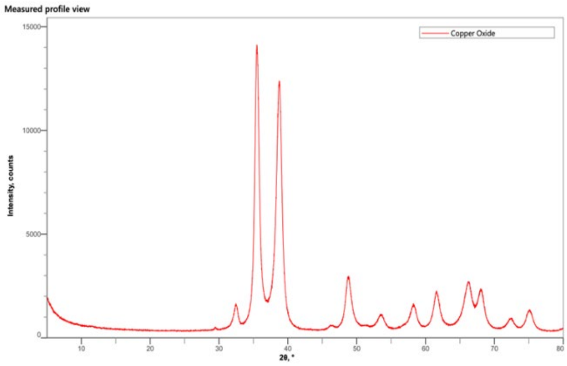


Figure 5. XRD of CuO Nanoparticles

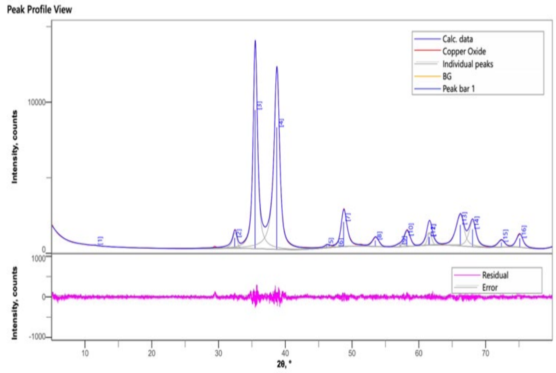


Figure 6. XRD amorphous phase and structure of CuO

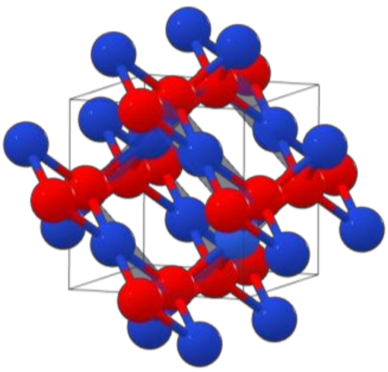
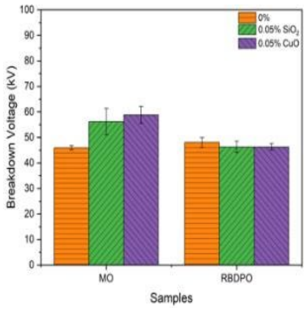


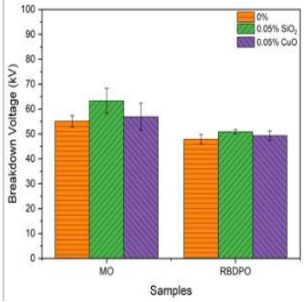
Figure 7. Crystal structure of ideal CuO

3.3 AC Breakdown Voltage

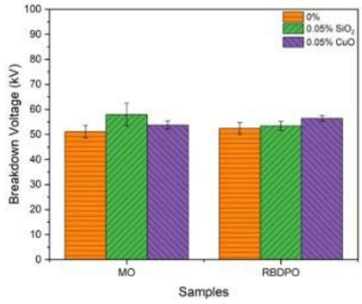
The effect of SiO_2 and CuO nanoparticles on MO and RBDPO with consideration of thermal ageing are discussed in this section. Generally, the introduction of SiO_2 and CuO on MO and RBDPO shows significant increment of AC breakdown voltage after 28 days of ageing. It is also observed that the AC breakdown voltage of all MO are quite close to RBDPO. The AC breakdown voltages of MO provide clear increment after the addition of SiO_2 and CuO nanoparticles as shown in Figure 8 (a). The AC breakdown voltages for MO shows a steady increment after 14 days of ageing and a slight decrement after 28 days of ageing. MO with the addition of 0.05% SiO_2 for both 14 and 28 days of ageing, shows steady increment for the AC breakdown voltages. However, the AC breakdown for MO based CuO shows slight decrement at 14 days of ageing as shown in Figure 8 (b). Meanwhile, with the addition of 0.05% CuO provides slight improvements of MO after 28 days of ageing for the AC breakdown voltages as illustrated in Figure 8 (c). There was a slight reduction for RBDPO after 14 days of ageing and slight improvement after 28 days of ageing for the AC breakdown voltages. There is a clear improvement trend for RBDPO based SiO_2 and CuO nanofluids after 14 and 28 days of ageing. The improvement of AC breakdown in all samples after 28 days ageing agrees with Kumar et al [9], who reported enhancement under similar conditions. For instance, the observed improvement in MO and RBDPO with CuO/SiO_2 nanoparticles aligns closely with findings from Xiao Peng who reported 12.23% enhancement under similar conditions AC breakdown and PD [10].



(a)



(b)



(c)

Figure 8. Comparison of AC breakdown voltage between MO and RBDPO for (a) 0 day, (b) 14 days and (c) 28 days

In this study, Weibull distribution was used to predict the AC withstand voltages at 50% probability from the breakdown voltage distribution of MO and RBDPO as shown in Figure 9. At 50% probability, the AC withstand voltages of MO and RBDPO are 46.1 kV and 48.3 kV respectively.

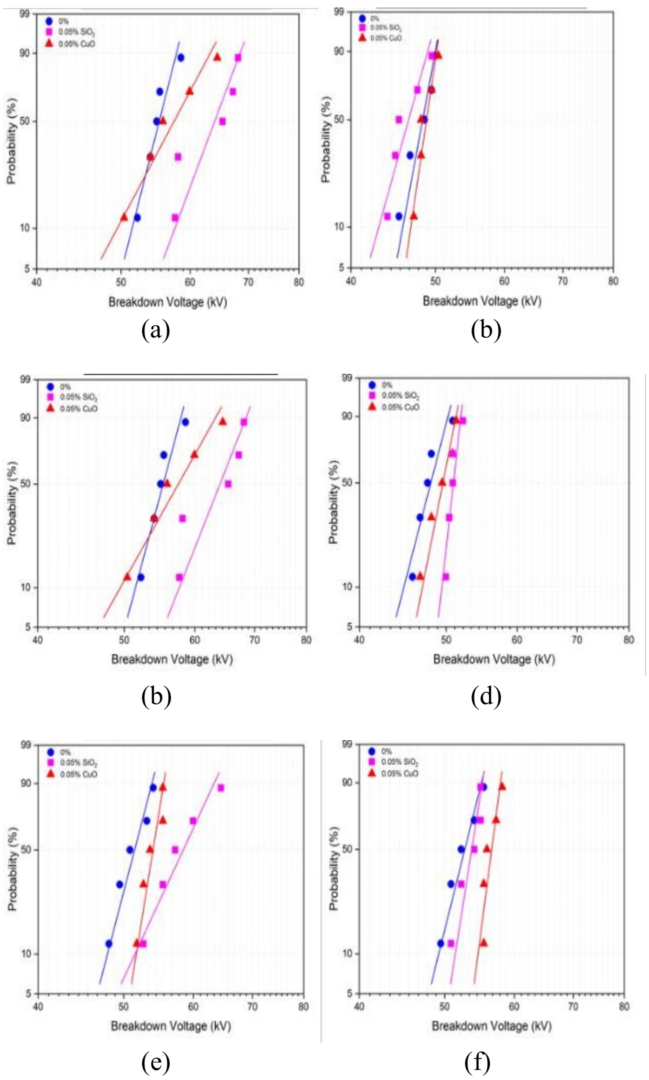


Figure 9. Weibull distribution of (a) 0 day MO, (b) 0 day RBDPO, (c) 14 days MO, (d) 14 days RBDPO, (e) 28 days MO and (f) 28 days RBDPO

According to the present investigation, adding SiO_2 and CuO nanoparticles might increase the average AC breakdown voltages of MO and RBDPO. CuO nanoparticles have been demonstrated to improve the average AC breakdown voltage of MO and RBDPO. Previous research has shown that adding SiO_2 nanoparticles to MO and RBDPO increases their dielectric strength under impulse voltages [6]. The inclusion of semi-conductive nanoparticles, ZnO into MO and sunflower oil produces the greatest breakdown voltage among all [7]. The dispersion of nanoparticles inside insulating oils may conditionally boost matrix oil's breakdown voltage and thermal conductivity. The thermal conductivity of the nanofluid is also affected by temperature This effect is seen in water-based Al_2O_3, CuO, ethylene glycol-based ZnO, and carbon nanotube nanofluids [11].

According to recent research, the AC breakdown voltage of base oil and nanofluids was higher at 90°C than at 25°C [12]. At changing temperatures, the moisture content in the oil remains constant. However, when the temperature rose, VO's saturated water absorption capacity increased, lowering the relative moisture concentration [13]. Because of the polarity sorting that happens under an electric field, electrons quickly move through a neatly organised bridge to the discharge channel, relative wetness had a substantial effect on the breakdown voltage. As a result, the breakdown voltage was raised. The SiO_2 nanoparticles had strong insulation and a broad band gap of roughly 5.74 eV, which increased the RBDPO's breakdown voltage. High band gap can prevent electron excitation, reducing leakage current and increasing breakdown voltage in RBDPO. Furthermore, due to the polarisation caused by the electric field, an electric charge was created on the surface of the nanoparticles. The electric field was formed by these polarised charges, which changed the initial electric field. The formation of a trapping around the nanoparticles increased the AC breakdown voltage [13,14].

Typically, when electrical stress exceeds its threshold voltage level [15], dielectric insulating fluid breakdown might begin. When an electron leaves the negative electrode and moves slowly and unhindered towards the positive electrode, a process known as streamer propagation [15], the basic breakdown in AC uniform field of dielectric insulating fluids begins. Figure 10 depicts the motion of an electron in an insulating fluid under AC. Since the dielectric breakdown is closely related to the electron transport process, the presence of nanoparticles in insulating fluids modifies the breakdown process, which could impact electron movement. As illustrated in Figure 11, the presence of nanoparticles aids in the delayed conversion of the quickly travelling electron into negatively charged particles.

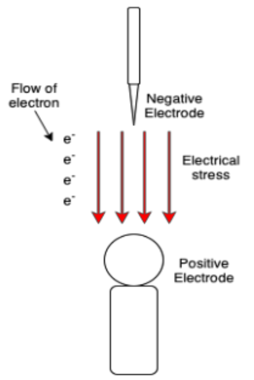


Figure 10. Schematic movement of electrons in based oil under AC voltage

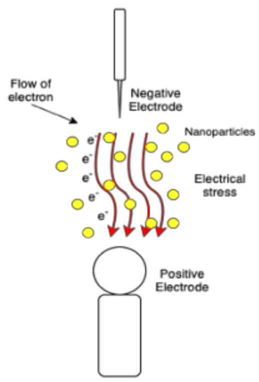
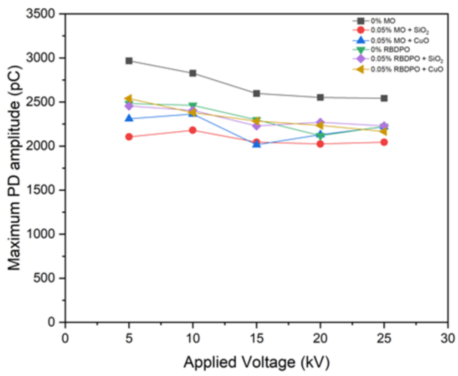


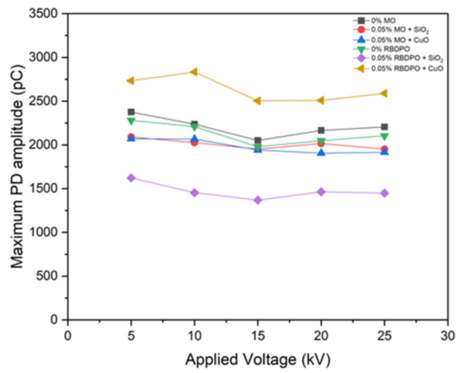
Figure 11. Schematic of electron movement nanofluids based oil under AC voltage

3.4 Partial Discharge Activites

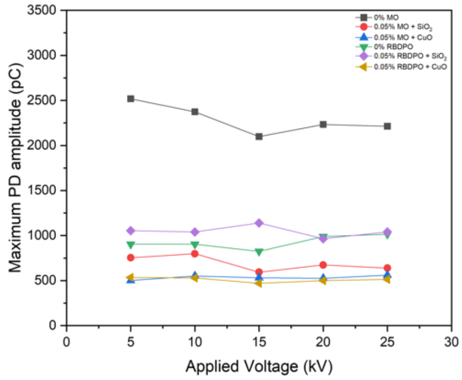
PD test is one of the most important tests to determine the intrinsic dielectric characteristics of insulation fluid for transformers. This part discusses the discharge activities such as PD amplitude of RBDPO and MO based SiO_2 and CuO nanofluids under high temperature ageing. Figure 12 illustrates the relationship between the maximum PD amplitude and the applied voltage for MO and RBDPO based SiO_2 and CuO nanofluids. The patterns of the PD amplitude for MO and RBDPO based nanofluids shows two distinctive features. The first pattern appears at region more than 1500 pC whereby the PD amplitude decrease slowly as the voltage increases. The PD amplitude of all types of oil reduce significantly as the applied voltage increased as shown in Figure 12 (a). The same pattern was observed in Figure 12 (b) as the applied voltage increase, the PD amplitude is reduced except for the introduction of 0.05% CuO for RBDPO could improve the PD amplitude at 14 days of ageing. Meanwhile, the addition of 0.05% SiO_2 on RBDPO does not provide clear improvements of PD amplitudes. As the applied voltage increase to 25 kV, the PD amplitudes for all nanofluids is lower than the base MO as shown in Figure 12 (c).



(a)



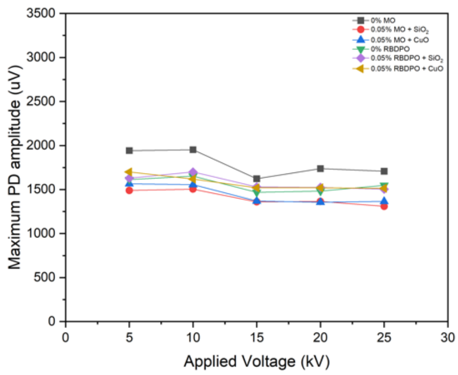
(b)



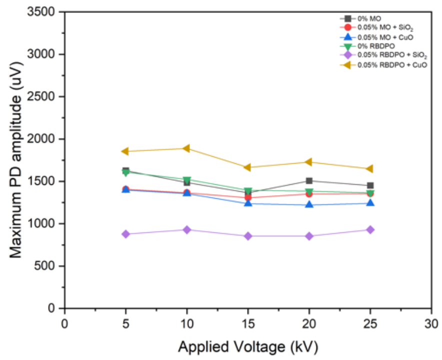
(c)

Figure 12. Maximum PD amplitude with applied voltage in MO and RBDPO for (a) 0 day, (b) 14 days, (c) 28 days in pC

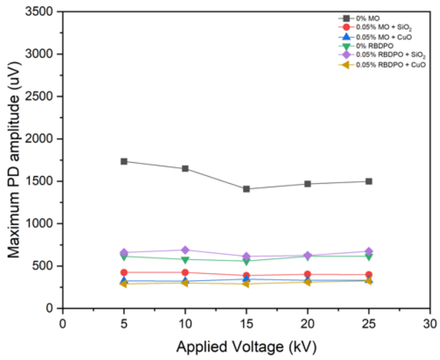
In Figure 13 (a) the PD amplitudes for MO and RBDPO based SiO_2 and CuO are quite close but at lower levels than base MO. With 0.05% of CuO, the PD amplitude of RBDPO maintains at higher level than the other samples throughout the application of the voltage as seen in Figure 13 (b). Meanwhile, the introduction of 0.05% SiO_2 could cause the PD amplitude of RBDPO to be lower than the other samples as the applied voltage increased. The PD amplitude of all samples does not show any clear apparent improvements compared to base MO which shows improvements of PD amplitude throughout the application of the voltage as shown in Figure 13 (c).



(a)



(b)



(c)

Figure 13. Maximum PD amplitude with applied voltage in MO and RBDPO for (a) 0 day, (b) 14 days, (c) 28 days in μV

The PD amplitude is an essential criterion for detecting insulating fluid deterioration and assessing the quality of produced products. The inclusion of nanoparticles and thermal ageing are thought to contribute to the variations in the pattern of maximum PD amplitude decrement between MO and RBDPO based SiO_2 and CuO nanofluids. Changes in the space and electric field distribution in the oils with nanoparticles alter the mobility of electrons and ionization happens in the oils from which electrons are created, hence improving insulation performance [16].

4. CONCLUSION

The experimental results demonstrate that SiO_2 and CuO nanoparticles significantly enhance the dielectric properties of both MO and RBDPO based nanofluids. The FTIR spectroscopy confirmed successful nanoparticle integration through characteristic functional group modifications, while XRD analysis verified the diffraction pattern is similar to a fingerprint of the crystal structure. It is a strong and quick approach for identifying unfamiliar materials. XRD analyses have confirmed that the nanoparticles are amorphous phase and monoclinic phase for SiO_2 and CuO respectively. The AC breakdown voltage of MO and RBDPO based SiO_2 and CuO nanofluids provide clear increment trend with thermal ageing. The AC breakdown voltage improved most MO based CuO nanofluids based 28.0% due to charge trapping at the semiconductor interface, while aged RBDPO based SiO_2 samples showed more stable performance by 13.3% after 28 days. Partial discharge (PD) suppression reached 80.1% in aged MO based CuO nanofluids, attributed to CuO's higher electron affinity $\chi = 1.8$ eV compared to SiO_2 by 71.7% reduction. The superior performance of CuO in MO suggests its potential for high-voltage applications, whereas RBDPO based SiO_2 nanofluid may serve as a sustainable alternative with moderate enhancements. However, long-term stability studies beyond 28 days are recommended to evaluate nanoparticle agglomeration and oxidative degradation effects under extended operational conditions. These findings provide critical insights for developing advanced nanofluid-based insulation systems with tailored dielectric properties.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support from Ministry of Higher Education and Universiti Teknologi Malaysia under Potential Academic Staff (PAS) Research Grants (Q.J130000.2723.04K25). Special thanks to High Voltage Power and Energy Research (HiPER) and Penulaju Sdn. Bhd. for the technical support.

REFERENCES

[1] Kumar, A., Verma, H.C., Baral, A., Pradhan, A.K. and Chakravorti, S. (2018), Estimation of paper-moisture in transformer insulation employing dielectric spectroscopy data. IET Sci. Meas. Technol., 12: 536-541. https://doi.org/10.1049/iet-smt.2017.0447

[2] Jacob, J., Preetha, P. and Thiruthi Krishnan, S. (2020), Review on natural ester and nanofluids as an environmental friendly alternative to transformer mineral oil. IET Nanodielectrics, 3: 33-43. https://doi.org/10.1049/iet-nde.2019.0038

[3] S. Zervos, "Natural and Accelerated Ageing of Cellulose and Paper: A Literature Review," *Cellulose: Structure and Properties, Derivatives and Industrial Uses,* pp. 1-42, 2010.

[4] Wang, X. Partial Discharge Behaviours and Breakdown Mechanisms of Ester Transformer Liquids under AC Stress. Ph.D. Thesis, University of Manchester, Manchester, UK, 2011.

[5] Mohamad Zul Hilmey, M. (2019). Dielectric and electrical characteristics of palm oil-based nanofluid as high voltage insulation material/Mohamad Zul Hilmey Makmud. UM Students' Repository.

[6] Ainanie Azizie, N., & Hussin, N. (2020). Preparation of vegetable oil- based nanofluid and studies on its insulating property: A review. *Journal of Physics: Conference Series*, *1432*(1). https://doi.org/10.1088/1742-6596/1432/1/012025

[7] Hussin, N., Kwong Yeaw, L., Nabil Mohd Khalil, A., Kamarol Mohd Jamil, M., Nayan, N. M., Nizam Md Arshad, S., & Ainanie Azizie, N. (2020). The effect of semi-conductive and non-conductive nano particles in sunflower oil-based insulation. *Journal of Physics: Conference Series*, *1432*(1). https://doi.org/10.1088/1742-6596/1432/1/012016

[8] H. Jin, T. Andritsch, P.H.F Morhuis and J.J Smit, "AC Breakdown voltage and viscosity of mineral oil based SiO_2 nanofluids", IEEE,2012.

[9] Prabat Kumar Maiti, (2023). Behavior of Nanoparticles in Service Transformer Oils and their Perdormance on Laboratory Ageing. Power Research – A journal of CPRI, 19(1), pp. 29-34. https://doi.org/10.33686/pwj.v19i1.1116

[10] Peng, X. Q. Wang, S. Kang, C. Chen, Gang. Li, Ke. Wang, R. Liao, X. Zhao (2024). Research Progress in Modified Mineral Oil, Natural Ester and Mixed Oil in Transformers. Electrical Materials and Applications. Vol. 1(1), pp. 1-13. https://doi.org/10.1049/ema3.12005

[11] Charalampakos, V.P. & Peppas, G.D. & Pyrgioti, Eleftheria & Bakandritsos, Aristides & Polykrati, Aikaterini & Gonos, Ioannis. (2019). Dielectric Insulation Characteristics of Natural Ester Fluid Modified by Colloidal Iron Oxide Ions and Silica Nanoparticles. Energies. 12. 3259. 10.3390/en12173259.

[12] M. Jama, T. Singh, S. M. Gamaleldin et al., "Critical review on nanofluids: preparation,

characterization, and applications," Journal of Nanomaterials, vol. 2016, Article ID 6717624, 22 pages, 2016.

[13] Yao, W., Huang, Z., Li, J., Wu, L., & Xiang, C. (2018). Enhanced Electrical Insulation and Heat Transfer Performance of Vegetable Oil Based Nanofluids. *Journal of Nanomaterials*, *2018*. https://doi.org/10.1155/2018/4504208

[14] J. Li, B. Du, F. Wang, W. Yao, and S. Yao, "The effect of nanoparticle surfactant polarization on trapping depth of vegetable insulating oil- based nanofluids," Physics Letters A, vol. 380, no. 4, pp. 604–608, 2016.

[15] E. G. Atiya, D. A. Mansour, and A. M. Azmy, "Dispersion Behavior and Breakdown Strength of Transformer Oil Filled with TiO_2 Nanoparticles," IEEE Transaction on Dielectric and Electrical Insulation, vol. 22, no. 5, pp. 2463-2472, 2015.

[16] Wang, Qi & Rafiq, Muhammad & lv, Yuzhen & Li, Chengrong & Yi, Kai. (2016). Preparation of Three Types of Transformer Oil-Based Nanofluids and Comparative Study on the Effect of Nanoparticle Concentrations on Insulating Property of Transformer Oil. Journal of Nanotechnology. 2016. 1-6. 10.1155/2016/5802753.