Journal of Engineering Science and Technology
Vol. 17, No. 2 (2022) 1173 - 1187

THE INFLUENCE OF NANOPARTICLES ON THE DIELECTRIC DISSIPATION FACTOR AND LIGHTNING PROPERTIES IN PALM OIL-BASED NANOFLUIDS

NORASAGE PATTANADECH[1], PICHAI MUANGPRATOOM[2,*]

[1]High Voltage Engineering Laboratory, Department of Electrical Engineering, School of Engineering, King Mongkut's Institute of Technology Ladkrabang (KMITL), 10520, Bangkok, Thailand
[2]High Voltage Research Laboratory, Department of Electrical Engineering, Faculty of Engineering, Rajamangala University of Technology Isan Khon Kaen Campus (RMUTI KKC), 40000, Khon Kaen, Thailand
*Corresponding Author: pichai.mu@rmuti.ac.th

Abstract

In this study, the influence of nanoparticles when mixed with insulating palm oil is investigated in terms of tan δ or the dielectric dissipation factor and lightning properties. Three different nanofluid sample types are derived from the dispersion of zinc oxide (ZnO), titanium dioxide (TiO_2) and barium titanate ($BaTiO_3$). The nanoparticle concentrations tested were 0.01% and 0.03% while the base fluid was unmodified palm oil. Evaluation of tan δ was performed in accordance with the IEC 60247 standard via the use of the tan δ meter (model SOKEN: DAC-IM-D6) and the lightning impulse breakdown voltage were based on the IEC 60897 standard. In order to test the electrical insulation qualities of the palm oil over a range of temperatures from 35-90°C for each of the tan δ values revealed the dielectric loss tangent, and the findings lightning properties was performed at the room temperature. Significant increases of the palm oil with nanoparticles in comparison to unmodified palm oil. These results suggested that further investigation would be worthwhile to better understand the effects of the nanoparticles in palm oil upon tan δ and the lightning impulse breakdown voltage characteristics in order to make additional improvements.

Keywords: Dielectric dissipation factor, Lightning impulse voltage, Nanofluids, Palm oil, Temperature.

1. Introduction

Mineral oils are the most important of the various liquid dielectrics which are applied in power equipment. These oils are typically refined mixtures of various hydrocarbons which can be produced via the fractional distillation of petroleum. They have properties which vary according to the chemical composition. One type of liquid insulating oil based on petroleum is transformer oil, which is refined precisely to address the need for both dielectric and the transfer of heat when used in transformers. Reliability and efficiency are vital for electrical transmission and distribution systems and the transformers used must have a working lifespan exceeding forty years. The type of oil used will be critical in determining the ability of a transformer to work effectively throughout that period of time. Over the past hundred years, the most frequently employed electrical insulating liquids have been petroleum-based transformer oils. The oil quantity required by transformers lies within quite a wide range, related primarily to the transformer power rating [1].

As a consequence of environmental concerns, recent studies have sought to find alternatives to liquid insulating materials, with insulating oils offering certain more environmentally friendly qualities. Among the most common is natural oil, which is both biodegradable and suitable for use in transformers. It is an oil based on seeds and contains fatty acid natural oil triglycerides [2]. The natural oil has been used as the dielectric materials in transformers on a small or medium scale where the voltage does not exceed 66 kV. In recent years have been conducted the studies to investigate the properties of natural oil [3], examining the ageing, safety, and environmental effects of its use, as well as the electrical performance of vegetable oil. It has been reported that transformers filled with vegetable oil can be successfully used at various voltage levels [4]. Ageing in cellulose insulation can potentially be mitigated by the use of vegetable oil, as the natural oil will provide water scavenging activity and hydrolytic protection. In addition to natural ester, it is suggested that palm oil is another form of vegetable oil which could be used in transformers as the insulating materials.

Palm oil has chemical attributes which are similar to those of natural ester. It is readily biodegradable, offers flash points and high fire and non-toxic. These qualities can be attributed to the fact that palm-based oils are of a food grade type [4]. Many research studies have been performed lately to examine the use of nanotechnology to enhance the properties of dielectric insulating fluids used in transformers. Oils have been combined with various kinds of nanoparticles in order to enhance the heat transfer capabilities, as well as the dielectric and thermophysical properties [5].

In this study, experiments were carried out to examine the dielectric dissipation factor, known as tan δ and lightning properties, for widely used palm oil containing three different kinds of nanoparticles: zinc oxide (ZnO), titanium dioxide (TiO_2), and barium titanate ($BaTiO_3$). The tan δ and the lightning impulse characteristics for the palm oil samples with nanoparticles added were tested and measured at a range of temperatures from 35 °C to 90 °C for tan δ and the lightning experiments was performed at the room temperature. The study sought to test the notion that certain quantities of certain nanoparticles might increase the dielectric qualities of palm oil.

2. Methods and Materials

2.1. Tan δ (dielectric dissipation factor)

Tan δ, also known as the dielectric dissipation factor or the loss factor, is the parameter which describes the dielectric qualities of the oil. The level of them of the palm oil dissipation factor at its power frequency matches that of palm oil resistivity, and the same factors and testing conditions influence these two measures [6]. Furthermore, the tan δ is indicative of total dielectric power loss, and thus it serves as a useful estimator of capacitor power losses. Tan δ also acts as a function of the temperature of a dielectric, as well as the magnitude and frequency of the applied voltage since there is an effect on both conductivity (κ) and processes of polarization in dielectrics [1].

A single capacitor can represent the transformer insulation, whereby for dielectrics at AC voltage, the current (*I*) of the voltage (*V*) will lead by an angle of around $\varphi \approx 90^{\circ}$. As a consequence of conductivity losses and polarization losses, there can be a deviation in the phase angle φ from 90° by the loss angle (δ). Accordingly, the application of alternating voltage to the insulation of a distribution transformer involving insulating palm oil leads to the appearance of a current, comprising resistive (I_δ) and capacitive (I_C) elements, as can be observed in Fig. 1 [7, 8].

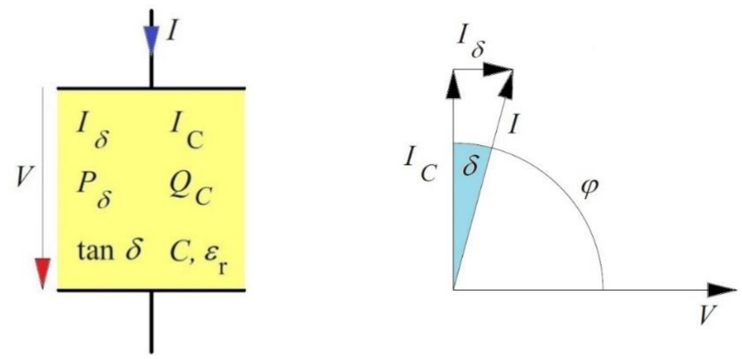


Fig. 1. Dissipation factor phasor diagrams, employing complex AC calculation techniques.

The loss factor or dissipation factor can serve to define the loss angle δ, as indicated by Eqs. (1) to (4).

$$\tan \delta = \frac{I_\delta}{I_C} \quad (1)$$

Using power quantities

$$P_\delta = V I_\delta \quad (2)$$

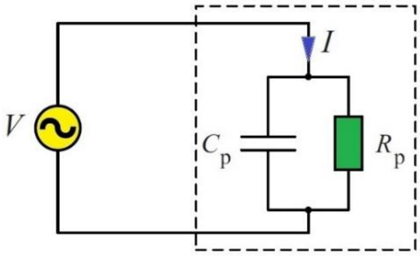
and

$$Q_C = V I_C \quad (3)$$

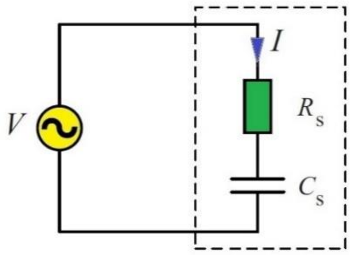
While the loss or dissipation factor can be expressed as

$$tan\,\delta = \frac{P_\delta}{Q_C} \quad (4)$$

Furthermore, to establish the dissipation factor for the transformer insulation, the resistance and capacitance must be taken into consideration, and can be represented as parallel or series equivalent circuits, where *V* is applied alternating voltage and *I* is a current that will flow in circuits, as presented in Fig. 2 [7, 8].



(a) Parallel equivalent circuit.



(b) Series equivalent circuit.

Fig. 2. Single equivalent capacitance and resistance.

From Eq. (1), the dissipation factors are derived from the ratio of power converted to resistance to reactive power allocated to capacitance [8]. In the case of the parallel equivalent circuit, the calculation considers the small tan δ values such that the resulting tan δ will be approximately equal, as shown in Eq. (5).

From Eq. (4),

$$tan\,\delta = \frac{P_\delta}{Q_C} = \frac{\frac{V^2}{R_p}}{\omega C_p V^2} = \frac{1}{\omega C_p R_p} \quad (5)$$

The series equivalent circuit produces small tan δ values, which are approximately equal, as can be seen in Eq. (6).

From Eq. (4),

$$tan\,\delta = \frac{P_\delta}{Q_C} = \frac{R_s I^2}{\frac{I^2}{\omega C_s}} = \omega C_s R_s \quad (6)$$

2.2. Lightning impulse voltage

High voltage testing is necessary in order to evaluate the ability to withstand the effects of lighting impulses resulting in internal or external over voltages. Furthermore, the tests allow the breakdown mechanisms to be assessed. Generation of these high voltage impulses occurs through the rapid discharge of the charged capacitors via switching gaps and into the network comprising resistors and capacitors. In such scenarios, voltage multiplier circuits can frequently be employed [9, 10]. It is possible to measure the peak lightning values through the use of electronic circuits in combination with voltage dividers. The lightning property measurements are obtained through the use of an oscilloscope, so that the voltage time characteristics can be evaluated via voltage dividers or sometimes through analog digital converters [10].

This research study of lightning properties in the context of palm oil nanofluids indicates that voltage shapes are governed by the time parameters related to the front and tail. For the tests, the lightning impulse voltage used was in the form of a standard where the time of the wave front was 1.2 μs ± 30% and the time of the wave tail was 50 μs ± 20% on the basis of IEC 60897 [11].

2.3. Water content in palm oil

It is possible for water to dissolve in palm oil on a molecular level, although the solubility is minimal and dependent upon the temperature and the exact molecular composition. The solubility of water is greater in silicon oils and even more so in esters, especially phosphate esters, in which the level of solubility can be greater than 600 ppm. Absorption of the water by the palm oil may take place, or the process can result from the oxidation occurring in the palm oil [6]. This tendency of phosphate esters to absorb water is a challenge for users, since handling must be carried out with great care to avoid increasing the moisture content, which can rise to 0.1%, which will have adverse consequences in terms of the properties. This can be a problem for the dielectric strength and dissipation factor or tan δ.

This study therefore sought to manage the moisture levels in the samples. The measurements were taken using apparatus from Karl Fischer Titrators. The Karl Fischer reaction and ASTM D 1533 test were used to measure the water content in all of the different samples [12].

2.4. Palm oil and nanoparticles

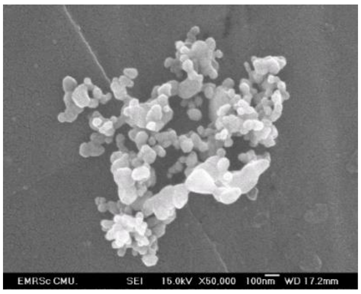
This study conducted experiments using palm oil which had the brand name Morakot Palm Olein. Prior to use, this palm oil was prepared through the processes of RBD (refinement, bleaching, and deodorizing). It can be produced as a result of the fractionation of refined palm oil. In this process, two components are derived; the liquid part is known as olein, and the solid component is the stearin. In Thailand, RBD palm olein is widely employed for cooking purposes, both domestically and commercially. Other sources clearly list its various properties [13].

To produce palm oil-based nanofluids, the semi-conductive nanoparticles of ZnO and TiO_2. Alternatively, palm oil could be mixed with the dielectric nanoparticles of $BaTiO_3$. These particular ZnO, TiO_2, and $BaTiO_3$ nanoparticles had respective diameters of 30 nm, 40 nm, and 50 nm respectively [14]. SEM was employed to determine the structure and exact size of the dry nanopowder particles, and the results are presented in Fig. 3. It was clearly apparent that no particles had diameters greater than 50 nm.

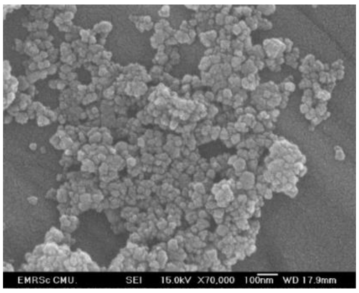
3. Experimental Setup

3.1. Preparation of nanofluids

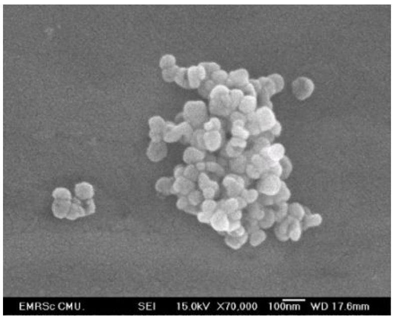
The nanofluid samples were produced via three different processes. First of all, the palm oil and the selected nanoparticles were combined using a 0.01% nanoparticle volume fraction. Additional samples were then produced using a 0.03% nanoparticle volume fraction. Next, the magnetic stirrer was dispersed nanofluids using for 30 minutes prior to a further two hours of ultrasonic dispersal to ensure nanofluid homogeneity. Magnetic stirring is particularly effective in ensuring that the nanoparticles are evenly distributed in the base oil, while energy levels are maintained below the point which could cause the nanoparticle agglomerations to loss. To achieve such nanofluids samples, ultrasonic dispersal is necessary [15, 16]. Figure 4 shows the process of preparing nanofluids.



(a) ZnO nanoparticles.



(b) TiO_2 nanoparticles.



(c) $BaTiO_3$ nanoparticles.

Fig. 3. SEM analysis of the sample of the nanoparticle surface.

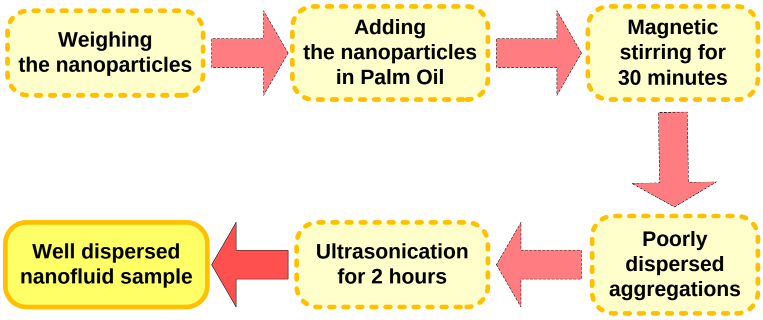


Fig. 4. Combining palm oil with nanoparticles.

3.2. Instrumentation used to measure the properties of tan δ

Measuring bridges are specifically designed to draw magnitude and phase comparisons between currents which flow through the test object and then through an almost totally lossless standard capacitor. Around 100 years ago, a high-voltage bridge designed to measure the dielectric dissipation factor was created by

Schering. This original design remains in use, with certain modifications [17]. There will be a measurable response in the tan δ values in terms of insulation capabilities and palm oil ageing when using SOKEN DAC-IM-D6 as the tan δ tester model. The value is therefore a critical guide to transformer operation. This research assessed tan δ in pure or unmodified palm oil and nanofluids based on palm oil at each of the following temperatures: 35 °C to 90 °C. Measurement processes followed the IEC 60247 standards [18]. Figures 5 and 6 presents the set-up of the testing system.

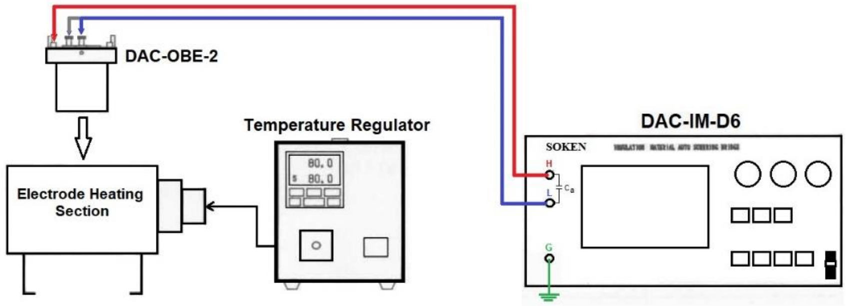


Fig. 5. The test circuit connections for tan *δ* measurement.

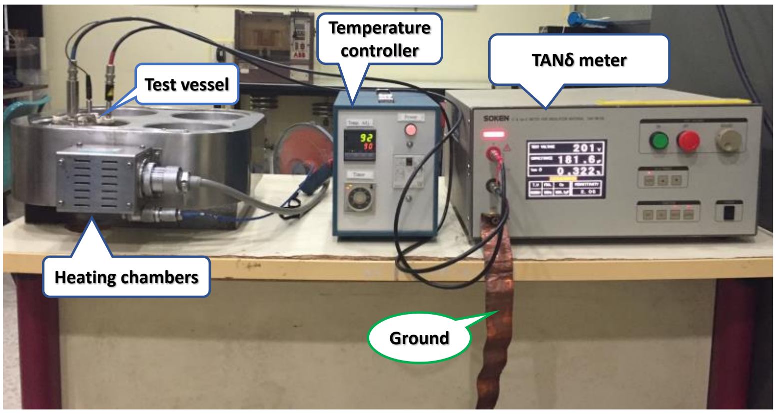


Fig. 6. The test circuit set-up used for the measurement of tan *δ* characteristics.

3.3. Evaluation of lightning properties

Testing of the lightning properties was conducted using a needle-sphere electrode system in line with the guidelines of IEC 60897 [11]. The test circuit diagram is shown in Fig. 7, and the experimental testing set up can be seen in Fig. 8. Gap spacing for the experimental configuration was set to be 15 mm for the needle-sphere electrodes: a tungsten needle whose tip radius was 40 μm served as the high voltage electrode while a brass sphere of 13 mm in diameter served as the grounded electrode. On the basis of IEC 60897, a rising voltage technique was used. In each test, the voltage level at the start was gradually and constantly increased until the eventual breakdown took place. The voltage increases were performed in incremental steps of 5 kV. A time interval of 60 seconds was established between each breakdown. With no changes made to the fluid samples or the electrodes, it was possible to complete six breakdowns for each of the samples and for the results to be recorded.

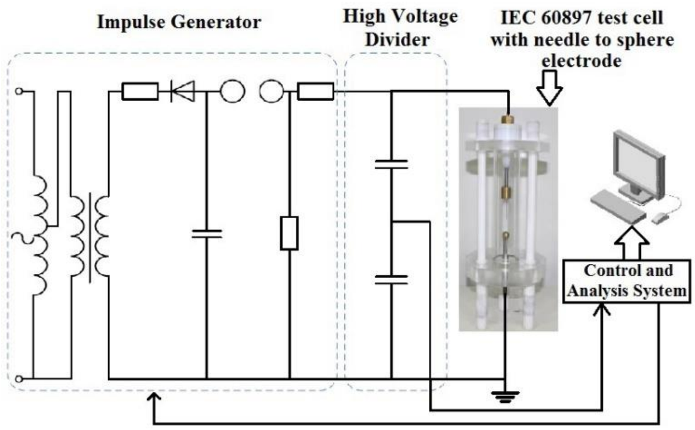


Fig. 7. The test circuit connections for lightning properties.

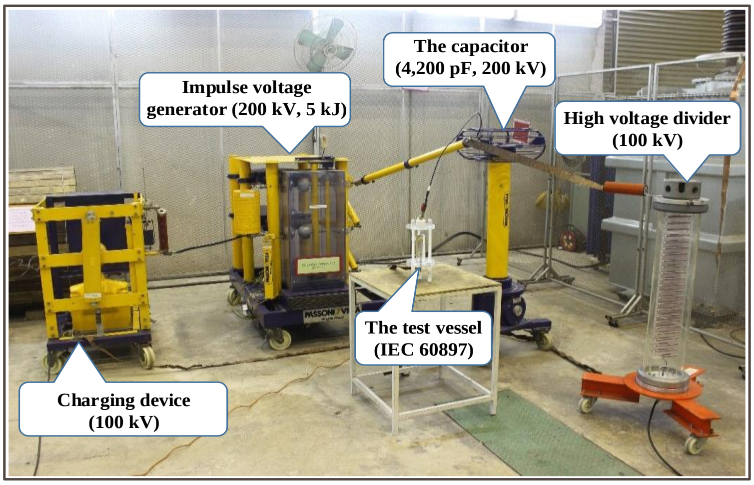


Fig. 8. The test circuit set-up used for the measurement of lightning properties.

4. Results and Analysis

4.1 Test results for water content

The presence of nanoparticles has a clear effect upon the water levels. Water content test results are presented in Fig. 9 and show findings for both pure or unmodified palm oil and nanofluids based on palm oil. These tests were carried out prior to commencing experimentation. These results confirmed the unmodified palm oil contained higher levels of moisture than the samples of palm oil with nanoparticles.

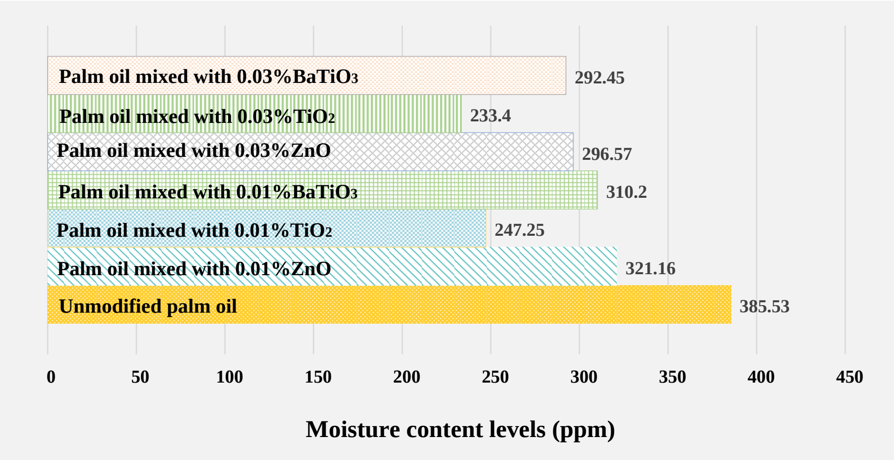


Fig. 9. Results for water content measurements.

The initial differences may contribute to the later tan δ values and lightning properties recorded in palm oils, as any subsequent changes may depend on whether or not the palm oil contains nanoparticles. One particular effect is that tan δ and the lightning properties are influenced by electron traps which can occur when electron transfer takes place. It is also possible that water content itself can affect tan δ, which is also governed by temperature changes inside the electrode (DAC-OBE-2) and the lightning properties by the needle to sphere electrode within test cell.

4.2 Test results for properties of tan δ

Figure 10 shows the outcomes for tan δ in unmodified palm oil and in palm oil-based nanofluids which use different temperatures and different nanoparticle concentrations. From these results, it is possible to make comparisons. As the temperature rises incrementally from 35 °C to 90 °C, the tan δ also rises for all samples. In all cases, there was an increase in tan δ as temperatures increased. Moreover, the exact influence of the various nanofluids upon tan δ in terms of the notion that certain quantities of certain nanoparticles might increase the dielectric qualities of palm oil. It is clear that for all nanofluids, the tan δ values are higher than those of unmodified palm oil. Furthermore, the tan δ values are also affected by nanofluid concentrations. As temperature rises, the tan δ values increase, and when the concentrations are higher, this also leads to increased tan δ values, especially when the concentration of added ZnO were 0.01% and 0.03%.

Besides, the dissipation factor tan δ is a material parameter that is determined by the polarization and conductivity losses, according to Eq. (4), Fig. 1. Furthermore, moisture causes a significant rise in losses due to quickly polarized water molecules as well as an increase in conductivity. This is particularly important for moisture-sensitive materials like palm oil and filled synthetics [8]. The addition of ZnO, TiO_2, and $BaTiO_3$ to palm oil resulted in a decrease in moisture content in this study.

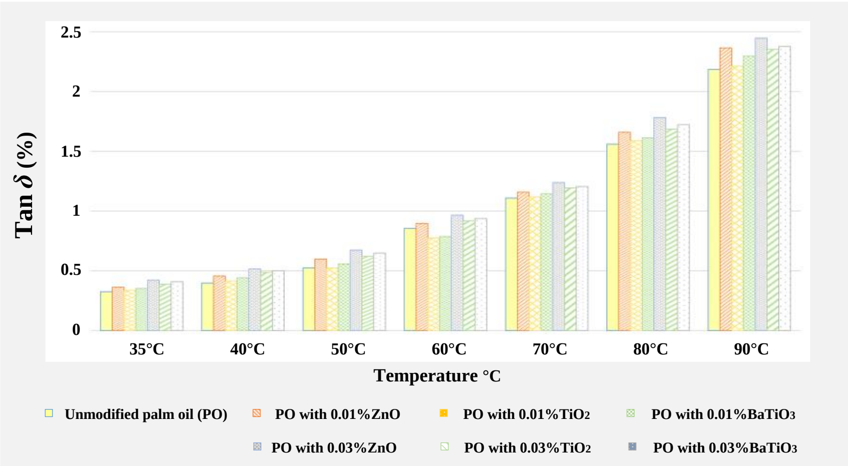


Fig. 10. Comparison of tan δ results for unmodified palm oil and palm oil based nanofluids.

The palm oil-based nanofluids can serve as a heat transfer medium while still being electrically insulating. In enhancing the heat transfer of transformers, thermal conductivity properties are considered a critical parameter [19]. Moreover, its thermal conductivity properties and suspended nanomaterials are expected to improve heat transfer and thermal conductivity efficiency by reducing power loss and evaporation losses. The thermal conductivity of palm oil is affected by the suspension of ZnO, TiO_2, and $BaTiO_3$ nanoparticles, and suspended nanoparticles are supposed to improve thermal conductivity and heat transfer efficiency.

4.3 Lightning properties testing results

The breakdown voltage strength for the lightning impulses was measured in order to establish the related properties of the palm oil. The mean values for the breakdown records were used as a means of estimating the unmodified palm oil quality, and hence the quality of the nanofluids derived from the palm oil. However, the design of the actual transformers is not based on mean values; instead, the minimum voltage which can be withstood is the value which is considered to be more important. Experimental studies have shown that variables such as nanoparticle types and nanoparticle volume concentration influence impulse breakdown strength. The mechanism by which nanoparticles influence oil breakdown properties is yet to be thoroughly elucidated. The traditional theory of liquid dielectric dissolution fails to account for the improved insulating properties of palm oil-based nanofluids [20]. The scattered conductive nanoparticles absorb the electrons and reduce their mobility and energy transfer, according to Hwang et al. [21]. This was the primary cause of improved dielectric efficiency and lower positive streamer velocity in the prepared nanofluids. Suspended nanoparticles capture high mobility electrons created by electric field ionization, which are then converted to slow negative charge carriers. The charge relaxation time constant (τ_r) theory was used to further explain the main electrodynamic mechanism for palm oil and nanoparticle materials. Equation (7) gives the relaxing time constant [21, 22].

$$\tau_r = \frac{2\varepsilon_1+\varepsilon_2}{2\kappa_1+\kappa_2} \qquad (7)$$

where ε_1 and ε_2 represent the permittivity of palm oil and nanoparticle materials respectively; κ_1 and κ_2 represent the electrical conductivities of palm oil and nanoparticle materials respectively. Furthermore, a low relaxation time constant indicates rapid electron absorption on the nanoparticles' surface.

A summary of the mean lightning impulse breakdown voltage strengths can be seen in Fig. 11, while Tables 1 and 2, include presents the percentage increments for the nanofluid lightning strengths. In all cases, the addition of nanoparticles leads to increases in both positive and negative lightning properties when compared to the results for unmodified palm oil. Further analysis is necessary to determine the exact types and volume fractions of nanoparticles which will deliver optimal results for lightning properties. To analyse the effect of nanoparticles added in the palm oil on the dielectric strength's property. The breakdown strength of the palm oil-based nanofluid increased as a result of the nanoparticles ZnO, TiO_2, and $BaTiO_3$ obstructing streamer growth and decreasing streamer propagation [16]. The effect of the concentrations of ZnO, TiO_2, and $BaTiO_3$ nanoparticles can be explained as follows. The spacing between nanoparticles in palm oil decreased, as the concentration of nanoparticles mixed in palm oil increased. Therefore, there was a possibility that electrons could be accelerated and ionized, allowing them to ionize oil molecules. This explains why, at a concentration of 0.01%, the breakdown intensity improved marginally. The spacing between particles grew smaller as the concentration of ZnO, TiO_2, and $BaTiO_3$ nanoparticles increased, and electrons were caught quickly in the oil gap. Meanwhile, at 0.03% ZnO, TiO_2, and $BaTiO_3$ concentrations, this resulted in a significant increase in breakdown strength.

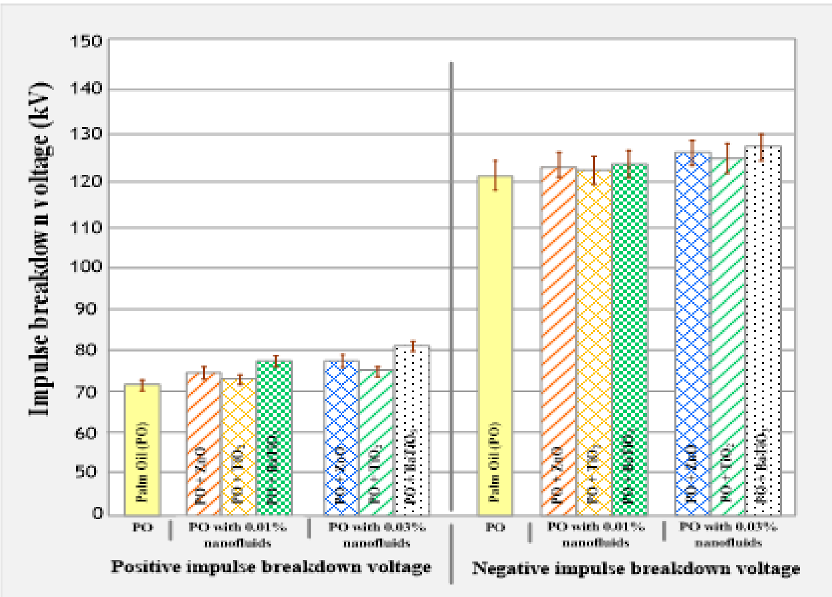


Fig. 11. Comparison of the average lightning breakdown voltages of unmodified palm oil and palm oil based nanofluids.

Table 1. Results of positive lightning strength of unmodified palm oil and palm oil mixed with 0.01% and 0.03% ZnO, TiO_2, and $BaTiO_3$.

Positive lightning strength (kV)				% Increase		
Palm oil pure	**Palm oil mixed with 0.01% nanofluids**					
	ZnO	**TiO_2**	**$BaTiO_3$**	**ZnO**	**TiO_2**	**$BaTiO_3$**
71.03	75.73	74.53	78.55	6.61	4.92	10.58
Palm oil pure	**Palm oil mixed with 0.03% nanofluids**					
	ZnO	**TiO_2**	**$BaTiO_3$**	**ZnO**	**TiO_2**	**$BaTiO_3$**
71.03	78.51	76.86	80.48	10.53	8.20	13.30

Table 2. Results of negative lightning strength of unmodified palm oil and palm oil mixed with 0.01% and 0.03% ZnO, TiO_2, and $BaTiO_3$.

Negative lightning strength (kV)				% Increase		
Palm oil pure	**Palm oil mixed with 0.01% nanofluids**					
	ZnO	**TiO_2**	**$BaTiO_3$**	**ZnO**	**TiO_2**	**$BaTiO_3$**
121.50	122.90	122.35	123.53	1.15	0.70	1.67
Palm oil pure	**Palm oil mixed with 0.03% nanofluids**					
	ZnO	**TiO_2**	**$BaTiO_3$**	**ZnO**	**TiO_2**	**$BaTiO_3$**
121.50	126.01	124.70	127.79	3.71	2.63	5.17

In addition, the evident in Tables 3 and 4 that the nanofluids based on palm oil has higher the lightning strength in comparison with pure palm oil in all samples. The nanofluids based on palm oil indicated overall the best performance of the lightning properties results, demonstrating higher mean the lightning strength and lower standard deviation. A high standard deviation indicates that the values on average, in Table 3 (group 0.01%), are further from the mean, especially in the case of palm oil mixed with 0.01% $BaTiO_3$. Besides, a small standard deviation in Table 4 (group 0.03%) indicates that the values in a statistical data set on test results, on average, similar to the data set's mean.

Table 3. Results of mean, standard deviation, lowest and maximum of positive the lightning strength (LS) values.

Dielectric liquid		Lowest LS, kV	Maximum LS, kV	Mean LS, kV	Std. deviation, kV
Palm oil (PO)		68.40	73.63	71.03	2.01
Group 0.01%	**PO+ZnO**	72.02	79.26	75.73	2.43
	PO+TiO_2	72.58	78.72	74.53	2.31
	PO+$BaTiO_3$	75.46	83.18	78.55	3.45
Group 0.03%	**PO+ZnO**	76.76	80.28	78.51	1.23
	PO+TiO_2	74.81	78.72	76.86	1.44
	PO+$BaTiO_3$	79.28	82.63	80.48	1.19

Table 4. Results of mean, standard deviation, lowest and maximum of negative the lightning strength (LS) values.

Dielectric liquid		Lowest LS, kV	Maximum LS, kV	Mean LS, kV	Std. deviation, kV
Palm oil (PO)		121.16	122.05	121.50	0.29
Group 0.01%	**PO+ZnO**	121.44	124.22	122.90	1.18
	PO+TiO_2	121.44	123.50	122.35	0.78
	PO+$BaTiO_3$	122.61	125.63	123.53	1.17
Group 0.03%	**PO+ZnO**	125.63	126.74	126.06	0.50
	PO+TiO_2	123.70	125.68	124.70	0.79
	PO+$BaTiO_3$	126.85	128.91	127.79	0.79

5. Conclusions

This study provided an evaluation of the effects of nanoparticles in the context of tan δ, or the dielectric dissipation factor at a range of different temperatures and the lightning properties was performed at the room temperature, for nanofluids based on palm oil. The results showed that nanofluid tan δ properties were significantly influenced in the case of all of the different nanoparticle types: ZnO, TiO_2, and $BaTiO_3$. The dielectric loss tangent is shown by the sample tan δ values, and the increases were significant for nanofluids based on palm oil when compared to unmodified palm oil. Besides, data analysis revealed that the lightning properties of palm oil nanofluids depend significantly upon the specific type of nanoparticles introduced to the palm oil. There were three nanoparticle types used: $BaTiO_3$, ZnO, and TiO_2. When $BaTiO_3$ is added to the palm oil, the result is enhanced lightning strength with both positive and negative polarity. In the case of ZnO or TiO_2 nanoparticles, there is only a small change recorded in the lightning strength. This confirmed that the nanoparticles do indeed have an influence upon tan δ and lightning properties in palm oil-based nanofluids. Therefore, the nanofluids based on palm oil should undergo further investigation to assess the potential for further enhancements. Moreover, these results suggested that further investigation would be worthwhile to better understand the effects of the nanoparticles in palm oil upon tan δ and the lightning strength in order to make additional improvements.

Acknowledgements

This work is supported by King Mongkut's Institute of Technology Ladkrabang (grant number KREF 046107). The authors gratefully acknowledge the support of techniques involved in nanomaterials from Assoc. Prof. Dr. Wanwilai Vittayakorn, college of nanotechnology, KMITL, Bangkok, Thailand.

Besides, a special thanks to Faculty of Engineering, Rajamangala University of Technology Isan Khon Kaen Campus, Khon Kaen, Thailand, for the research support facility.

Nomenclatures

C	Capacitance
C_p	Parallel equivalent capacitance
C_s	Series equivalent capacitance
I	Current, complex r.m.s. phasor
I_C	Current, comprising capacitive elements
I_δ	Current, comprising resistive elements
P_δ	Dielectric power loss
Q_C	Capacitive reactive power in a dielectric
R_p	Parallel equivalent resistance
R_s	Series equivalent resistance
V	Voltage, complex r.m.s. phasor
Greek Symbols	
κ	Electrical conductivity
φ	Phase angle
ω	Angular frequency

ε	Permittivity
τ_r	Charge relaxation time constant
δ	Loss angle
Abbreviations	
ASTM	American Society for Testing and Materials
IEC	International Electrotechnical Commission
SEM	Scanning Electron Microscopy

References

1. Arora, R.; and Mosch,.W. (2011). *High voltage and electrical insulation engineering* (1st ed.). New Jersey: John Wiley & Sons, Inc.
2. Suwarno.; Sitinjak, F.; Suhariadi, I.; and Imsak, L. (2003). Study on the characteristics of palm oil and its derivatives as liquid insulating materials. *Proceeding of the* 7th *International Conference on Properties and Applications of Dielectric Materials*. Nagoya, Japan, 495-498.
3. Thien, Y.V.; Azis, N.; Jasni, J.; Kadir, M.Z.A.A.; Yunus, R.; Ishak, M.T.; and Yaakub, Z. (2014). Investigation on the lightning breakdown voltage of palm oil and coconut oil under non-uniform field. *Proceeding of the IEEE International Conference on Power and Energy*. Kuching, Malaysia, 1-4.
4. Amin, N.A.M.; Ishak, M.T.; Hamid, M.H.A.; and Rahman, M.S.A. (2017). Partial discharge investigation on palm oil using needle – plane electrode configuration and electric field distribution using ANSYS Maxwell. *Proceeding of the International Conference on High Voltage Engineering and Power System*. Denpasar, Indonesia, 440-445.
5. Nor, S.F.M.; Azis, N.; Jasni, J.; Kadir, M.Z.A.A.; Yunus, R.; and Yaakub, Z. (2017). Investigation on the electrical properties of palm oil and coconut oil based TiO_2 nanofluids. *IEEE Transactions on Dielectrics and Electrical Insulation*, 24(6), 3432-3442.
6. Abdel-Salam, M.; Anis, H.; El-Morshedy, A.; Radwan, R. (2000). *High-Voltage Engineering: Theory and Practice* (2nd ed.) New York: Marcel Dekker, Inc.
7. Faria, G.; Pereira, M.; Lopes, G.; Vilibor, J.; Tavares, P.; and Faria, I. (2018). Evaluation of capacitance and dielectric dissipation factor of distribution transformers–experimental results. *Proceeding of the IEEE Electrical Insulation Conference*. San Antonio, TX, USA, 336-339.
8. Küchler, A. (2018). *High voltage engineering: fundamentals – technology – applications* (1st ed.) Germany: Springer Vieweg.
9. Rozga, P.; Stanek, M.; and Rapp, K. (2018). Lightning properties of selected insulating synthetic esters and mineral oil in point-to-sphere electrode system. *IEEE Transactions on Dielectrics and Electrical Insulation*, 25(5), 1699-1705.
10. Kind, D. (1978). *An introduction to high-voltage experimental technique* (1st ed.). Berlin: Vieweg & Sohn in Braunschweig.
11. IEC 60897. (1987). Methods for the determination of the lightning impulse breakdown voltage of insulating liquids. *International Electrotechnical Commission.*
12. ASTM D1533-12. (2012). Standard test method for water in insulating liquids by coulometric karl fischer titration. ASTM International.

13. Muangpratoom, P. (2020). Morakot vegetable oil. Retrieved February 15, 2020, from http://www.morakot.com/morakot-industrialproducts/.
14. Muangpratoom, P. (2020). Inframat advanced materials. Retrieved March 6, 2020, from http://www.advancedmaterials.us.i.
15. Jin, H. (2015). *Dielectric strength and thermal conductivity of mineral oil based nanofluids*. Ph.D. Dissertation, Delft University of Technology.
16. Muangpratoom, P.; and Pattanadech, N. (2019). Dielectric properties of mineral oil-based nanofluids under temperature variations. *Journal of IET Science*, *Measurement & Technology*, 13(9), 1318-1325.
17. Schon, K. (2019). *High voltage measurement techniques: fundamentals*, *measuring instruments*, *and measuring methods* (1st ed.). Niedersachsen: Springer Nature Switzerland AG.
18. IEC 60247. (2004). Insulating liquids: Measurement of relative permittivity, dielectric dissipation factor (tan δ) and d.c. resistivity. *International Electrotechnical Commission*.
19. Rafiq, M.; Lv, Y.; and Li, C. (2016). A review on properties, opportunities, and challenges of transformer oil-based nanofluids. *Journal of Nanomaterials*, 1-23.
20. Lv, Y.Z.; Zhou, Y.; Li, C.R.; Wang, Q.; and Qi, B. (2014). Recent progress in nanofluids based on transformer oil: preparation and electrical insulation properties. *IEEE Electrical Insulation Magazine*, 30(5), 23-32.
21. Hwang, J.G.; Zahn, M.; O’Sullivan, F.M.; Pettersson, L.A.A.; Hjortstam, O.; and Liu, R. (2010). Effects of nanoparticle charging on streamer development in transformer oil-based nanofluids. *Journal of Applied Physics*, 107(1), 1-17.
22. Lv, Y.; Rafiq, M.; Li, C.; and Shan, B. (2017). Study of dielectric breakdown performance of transformer oil based magnetic nanofluids. *Energies*, 10(7), 1-21.