J. Eng. Technol. Sci., Vol. 53, No. 3, 2021, 210312

The Effect of Temperature on the Electrical Characteristics of Nanofluids Based on Palm Oil

Pichai Muangpratoom

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
E-mail: pichai.mu@rmuti.ac.th

Highlights:

- Adding ZnO, TiO_2 and $BaTiO_3$ to palm oil caused a slight decrease in the moisture content.
- The dielectric properties of the palm oil increased, while increased concentrations of nanoparticles led to greater breakdown strength.
- The best nanofluid mixture in terms of increased breakdown strength was produced by addition of ZnO nanoparticles to palm oil.

Abstract. This study sought to apply nanotechnology to develop the electrical characteristics of palm oil. Experiments were conducted using three types of nanoparticles: zinc oxide (ZnO), titanium dioxide (TiO_2), and barium titanate ($BaTiO_3$). The nanofluid samples were prepared by mixing the nanoparticles with palm oil using various processes. In the first scenario, a combination of palm oil with nanoparticles at 0.01 vol% was created, while the next sample had 0.03 vol% of nanoparticles. The samples were then fully dispersed using a magnetic stirrer, followed by ultrasonic dispersal in order to ensure homogeneity of the nanofluid. The electrodes were set 2.5 mm apart and the test was performed six times on each test sample in compliance with the IEC 60156 standard. The voltage breakdown characteristics were recorded for each of the liquids at temperatures varying from 35 °C to 90 °C. The results showed that for the palm oil samples containing nanoparticles, the voltage breakdown was greater than for the samples containing unmodified palm oil.

Keywords: *electrical characteristics; moisture content; nanofluids; palm oil; temperature; voltage breakdown.*

1 Introduction

Power transformers rely significantly on mineral oil. The role of a transformer is to convey electrical power from a power generator to the users. Transformers typically contain two different types of insulation: mineral oil and cellulose. The

Received June 19th, 2020, 1st Revision December 7th, 2020, 2nd Revision February 15th, 2021, Accepted for publication April 1st, 2021.
 ISSN: 2337-5779,
DOI: 10.5614/j.eng.technol.sci.2021.53.3.12

cellulose plays a mechanical role in addition to that of an insulator, while the mineral oil provides electrical insulation as well as acting as a cooling medium [1-3]. Mineral oil has a long history, having been used since the production of the first commercially available oil-filled transformers. Other dielectric fluids have been tried as dielectric material in transformers, but the principal issue with mineral oil as transformer oil is its unsustainable nature, since it is a fossil fuel and is also non-biodegradable. As a result, vegetable oil appears to be a superior alternative [4], although mineral oil remains the most popular oil type used in transformers on account of its outstanding dielectric properties.

A large number of studies have been conducted to make improvements to the electrical, chemical and physical properties of mineral oil [5-8]. Its excellent performance ensures its popularity, but the problem of non-biodegradability remains. It is also feared that mineral oil may become increasingly scarce in the future and as a result there is growing interest in natural alternatives that offer better biodegradability [9]. Studies have recently been performed to examine natural esters, while palm oil has also drawn increasing interest since its qualities may be suitable for use in transformers [10]. Across Europe, palm oil is also rapidly becoming a more widespread source of energy, especially in producer countries.

The possibility of enhancing a liquid's properties by adding nanoparticles was first proposed by Choi in 1993 [11-12]. The implementation of such an approach would permit the alteration of the fluid to conduct heat. For this reason, since 1995 there has been a 30% annual increase in the number of scientific publications reporting on nanofluids in this particular field of interest [13].

Significant advances are underway in the field of nanotechnology and it is believed that certain nanoparticles may be successfully combined with palm oil to improve the properties of palm oil, thus allowing more compact transformers to be designed at lower cost. Today, the field of nanodielectrics has growing scientific importance and offers researchers a potential opportunity to create new insulation fluids that can help to optimize the functionality of transformers.

The current study involved experimentation to consider the dielectric properties of nanofluids based on palm oil that contain particular nanoparticle types in combination with a commonly used palm oil. Once the nanoparticles had been mixed with pure palm oil, the voltage breakdown characteristics were tested and recorded. It was hypothesized that the introduction of a particular quantity of nanoparticles would serve to increase the voltage breakdown of the palm oil. The chosen nanoparticles were zinc oxide (ZnO), titanium dioxide (TiO_2) and barium titanate ($BaTiO_3$).

2 Experimental Procedure

2.1 Characteristics of Palm Oil and Preparation of the Experiment

The experiments in this research employed palm oil under the name of Morakot Palm Olein, which underwent preparation involving refinement, bleaching, and deodorizing (RBD). It was obtained via fractionation of refined palm oil, which separates it into two parts. The liquid component is olein, while the solid part is stearin. RBD palm olein is commonly used as a cooking oil in Thailand, both within the food industry and in the home. Its exact properties and characteristics have been described in other sources [14].

Nanofluids based on palm oil were produced by mixing semi-conductive nanoparticles of ZnO and TiO_2 with palm oil or by using dielectric nanoparticles of $BaTiO_3$ with palm oil. Moreover, the characteristics and technical details of ZnO, TiO_2 and $BaTiO_3$ nanopowder were: purity 99.70%, 99.90% and 99.95%; average particle sizes 30 nm, 40 nm and 50 nm, ascertained by scanning electron microscopy (SEM) and Brunauer, Emmett and Teller (BET) techniques; BET multi-point specific surface area 35 m^2/g, 40 m^2/g and 20 m^2/g; nanopowder density 5.60 g/cm^3, 3.89 g/cm^3 and 5.85 g/cm^3; melting point (m.p.) of the nanopowders were 1,980 °C, 1,850 °C and 1,600 °C respectively [15]. The general properties are summarized in Table 1.

Table 1 General properties of ZnO, TiO_2 and $BaTiO_3$ nanomaterials.

Parameters	ZnO	TiO_2	$BaTiO_3$
Average size	30 nm	40 nm	50 nm
Purity	99.70%	99.90%	99.95%
Surface area	35 m^2/g	40 m^2/g	20 m^2/g
Density	5.6 g/cm^3	3.89 g/cm^3	5.85 g/cm^3
Melting point	1,980 °C	1,850 °C	1,600 °C

2.2 Qualities of Nanoparticles and Their Preparation

Three processes were required to prepare the samples. First the palm oil was combined with the selected nanoparticles at 0.01 vol%. Further samples were then created in the same manner using 0.03 vol%. In the next step, dispersal of the nanofluids was performed with a stirrer for 30 minutes before an ultrasonic method for dispersal was employed for two hours to ensure homogeneity of the samples. The use of magnetic stirring served to achieve an even spread of the nanopowder in the base fluid without providing sufficient energy to cause breakdown of any nanoparticle agglomerations. In order to break these agglomerations, an ultrasonic device has to be employed [13,16]. The process of nanofluid preparation is illustrated in Figure 1.

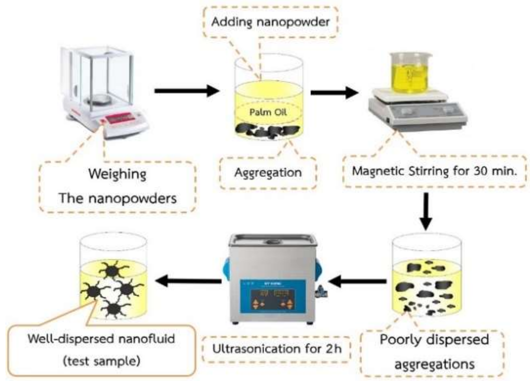


Figure 1 Diagrammatic presentation of nanofluid preparation process.

2.3 Testing of the Moisture Content

The purpose of this test was to control the moisture content value in the samples. The Karl Fischer Titrators apparatus applied for the measurements is depicted in Figure 2. The methods used to quantify the moisture or water content in both the pure palm oil and the nanofluid samples followed ASTM D 1533 and the Karl Fischer reaction method [17].

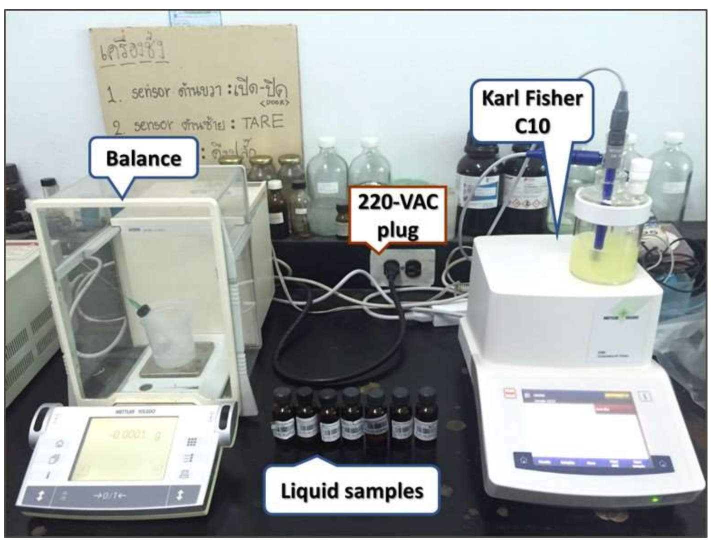
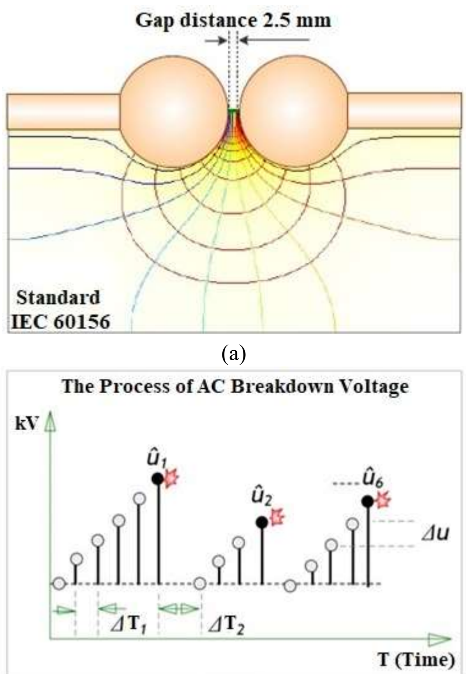


Figure 2 Moisture or water meter (Karl Fischer Titrators) used to measure the water content of the samples.

2.4 Identification of the Voltage Breakdown Characteristics

Measurement of the voltage breakdown provides an indication of the palm oil's quality and was applied to both the pure and the nanofluid samples. In the process of testing to determine the voltage breakdown strengths of the pure palm oil and the six different samples of nanofluids based on palm oil, the configuration of the sphere-sphere electrodes was as illustrated in Figure 3(a), while Figure 3(b) shows the test procedure, where $\hat{u}_{1\text{-}6}$ is defined as the breakdown voltage, Δu is voltage difference at rate 2 kV ± 0.2 kV, ΔT_1 represents the time rate of voltage 2-kV application per second until breakdown occurs, and ΔT_2 represents the time rate of a pause of at least 2 minutes after each breakdown before re-application of the voltage. This process was performed in accordance with the IEC 60156 standard to assess AC breakdown [18].



(b)

Figure 3 The method applied to all samples at different temperatures (35-90 °C). (a) The configuration of the sphere-sphere electrode, and (b) the testing techniques in accordance with the IEC 60156 standard.

The electrodes were set to have a gap of 2.5 mm between them. Tests were performed six times, once for each of the different samples, in accordance with the IEC 60156 standard, and using an oil tester for voltage breakdown (model: IIJ-II-80). For each of the nanofluids, three samples were evaluated and for all samples the average values were calculated. The testing apparatus comprised a temperature controller, a heater, a PID controller and contractor, and a sensor attached to the vessel for oil testing. The equipment is shown in Figure 4.

To test the effect of temperature on voltage breakdown for both the pure palm oil and the nanofluids based on palm oil, a range of different temperatures was chosen at which the measurements were taken. These temperatures were in the range of 35 to 90 °C, with seven points selected at 35, 40, 50, 60, 70, 80, and 90 °C. These temperatures were chosen because they are within the range of normal operating temperatures for oil-immersed transformers, which should never be greater than 90 °C [19,20]. When each of the temperature levels was reached, a special control system was used to hold the temperature at a stable level. The temperature of the liquids was measured using a sensor in the PID controller, which then managed the contractor to manage the power system of the heater by turning it on and off to control the temperature.

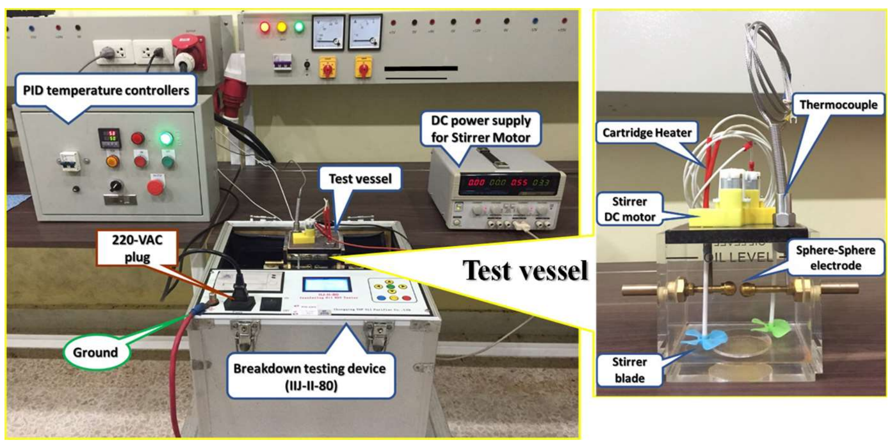


Figure 4 The liquid dielectric tester, model IIJ-II-80, used to measure the voltage breakdown.

3 Test Results and Analysis

3.1 Test Results of Moisture or Water Content

The moisture levels were clearly shown to be influenced by the presence of nanoparticles. The results of the testing of moisture content can be seen in Figure 5 and Table 2, showing the outcomes for the palm oil nanofluid samples as well as for the pure palm oil sample before the experiments were conducted. The testing of the moisture content provided confirmation that the moisture content of the pure palm oil was much greater than that of the nanofluids based on palm oil.

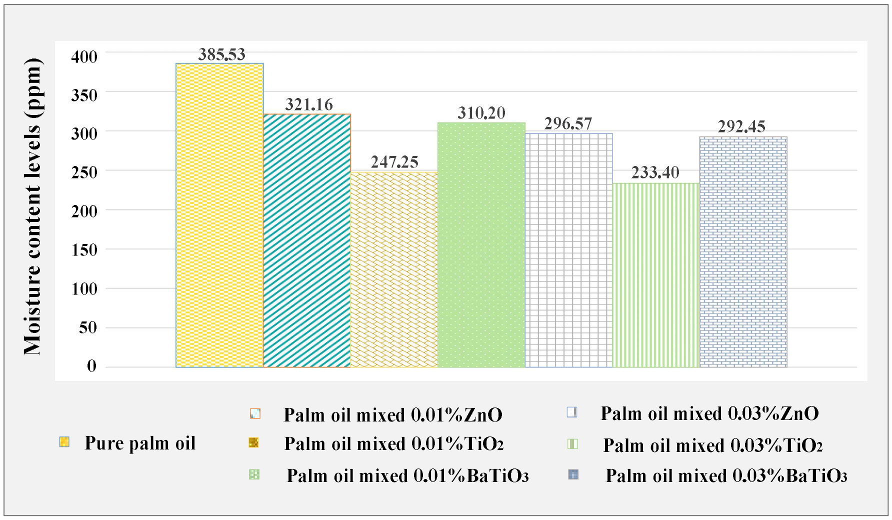


Figure 5 Results of moisture content for pure palm oil and nanofluids based on palm oil.

Table 2 Levels of moisture content of pure palm oil and nanofluids based on palm oil.

Liquid samples	Levels of moisture content
Pure palm oil	385.53 ppm
Palm oil mixed with ZnO on percentage by volume, 0.01%	321.16 ppm
Palm oil mixed with TiO_2 on percentage by volume, 0.01%	247.25 ppm
Palm oil mixed with $BaTiO_3$ on percentage by volume, 0.01%	310.20 ppm
Palm oil mixed with ZnO on percentage by volume, 0.03%	296.57 ppm
Palm oil mixed with TiO_2 on percentage by volume, 0.03%	233.40 ppm
Palm oil mixed with $BaTiO_3$ on percentage by volume, 0.03%	292.45 ppm

These differences may eventually result in different values of breakdown strength being observed for the palm oils, with changes dependent on the presence or absence of nanoparticles. The breakdown strength would be affected by electron traps that may arise during the course of electron transfer. Furthermore, the water content may also have an influence on the breakdown strength, which will vary in line with the gap distance.

3.2 Test Results of Voltage Breakdown

The voltage breakdown strength results for pure palm oil and nanofluids based on palm oil at different concentrations and temperatures are presented in summary in Tables 3 and 4, allowing comparisons to be drawn.

Table 3 Voltage breakdown for pure palm oil and 0.01% nanofluids based on palm oil.

Voltage breakdown, AC (kV)				
°C	Pure palm oil	Palm oil mixed with nanoparticles on percentage by volume, 0.01%		
		ZnO	TiO_2	$BaTiO_3$
35	42.5	44.6	49.3	43.4
40	44.7	49.1	54.9	46.3
50	49.8	58.7	61.5	52.7
60	54.6	64.2	66.2	57.4
70	59.3	68.5	69.7	61.2
80	66.8	73.4	74.9	71.6
90	69.5	75.2	76.1	73.4

Table 4 Voltage breakdown for pure palm oil and 0.03% nanofluids based on palm oil.

Voltage breakdown, AC (kV)				
°C	Pure palm oil	Palm oil mixed with nanoparticles on percentage by volume, 0.03%		
		ZnO	TiO_2	$BaTiO_3$
35	42.5	54.7	52.4	49.3
40	44.7	58.9	56.4	53.8
50	49.8	68.3	67.5	63.6
60	54.6	71.8	69.1	67.5
70	59.3	76.5	73.8	72.2
80	66.8	77.3	75.3	73.6
90	69.5	79.2	77.2	75.8

It is obvious that with increasing temperature (35°C to 90 °C) there was an increase in voltage breakdown for the pure palm oil as well as for the nanofluids based on palm oil containing ZnO, TiO_2, and $BaTiO_3$. With the nanoparticle concentration at 0.01%, the voltage breakdown of the palm oil and TiO_2 nanofluid mixtures rose in all cases. However, a greater increase was seen in the voltage breakdown of the palm oil with ZnO nanofluid mixture, where the concentration was 0.03%.

For all scenarios, due to the increased voltage breakdown with rising temperature, both the pure palm oil and the nanofluids based on palm oil were expected to act as heat transfer medium and electric insulator. Thermal conductivity is considered a vital parameter in improving the heat transfer of palm oil [21]. The specific effects of the different nanoparticles on voltage breakdown can be seen in Figure 6 and Table 5, in which the percentage increments in the data for the tested nanofluids are shown.

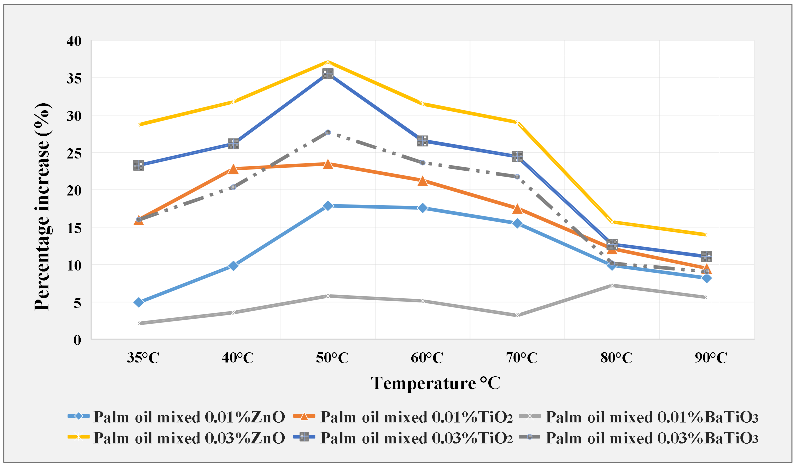


Figure 6 Comparison of the percentage increase in the mean voltage breakdown of the nanofluids based on palm oil.

Table 5 Percentage increase resulting from palm oil mixed with nanoparticles.

°C	% Increase of voltage breakdown compare with pure palm oil					
	0.01% nanofluids based on palm oil			0.03% nanofluids based on palm oil		
	ZnO	TiO_2	$BaTiO_3$	ZnO	TiO_2	$BaTiO_3$
35	4.94	16.00	2.12	28.71	23.29	16.00
40	9.84	22.82	3.58	31.77	26.17	20.36
50	17.87	23.49	5.82	37.15	35.54	27.71
60	17.58	21.25	5.13	31.50	26.56	23.63
70	15.51	17.54	3.20	29.01	24.45	21.75
80	9.88	12.13	7.19	15.72	12.72	10.18
90	8.20	9.50	5.61	13.96	11.08	9.06

The results make it clear that the nanofluid samples provided greater voltage breakdown strength than the pure palm oil sample. Besides, the nanofluid concentration also affected the breakdown strength. At higher temperatures, the breakdown strength was greater, and when the nanoparticle concentration was increased this also led to a higher voltage breakdown strength. According to [16,21], the increase in breakdown strength is the result of the suspension of different concentrations of nanomaterials in palm oil as a result of the greater chance of electrons becoming trapped in the oil gap due to the smaller spacing between nanoparticles. Each nanoparticle has a polarization effect in the presence of an external electric field, which can start the trapping process. Moreover, its thermal conductivity properties and suspended nanomaterials are expected to enhance their heat transfer and thermal conductivity performance.

4 Conclusions

This research investigated the effects of temperature on the electrical properties of nanofluids based on palm oil. The findings revealed that the voltage breakdown properties of the nanofluids were significantly affected by the particular type of nanoparticle added. Adding nanoparticles served to raise the voltage breakdown slightly due to the nanoparticles obstructing the streamer increase and decreasing streamer propagation. The test results therefore confirmed that the nanoparticles selected for use in this study are strong candidates for application in developing palm oil for dielectric purposes. Especially palm oil mixed with ZnO at 0.03 vol% manifested good dielectric characteristics. Therefore, it may be a good substitute for insulating fluids for power transformers.

Acknowledgements

This paper and the research behind it would not have been possible without the exceptional support of Assoc. Prof. Dr. Norasage Pattanadech, Department of Electrical Engineering, and Assoc. Prof. Dr. Wanwilai Vittayakorn, College of Nanotechnology, King Mongkut's Institute of Technology Ladkrabang (KMITL). Furthermore, a special thanks to the Faculty of Engineering, RMUTI KKC, for providing the facilities used in this research work.

References

[1] Lee, J.C., Seo, H.S. & Kim, Y.J., *The Increased Dielectric Breakdown Voltage of Transformer Oil-based Nanofluids by an External Magnetic Field*, Journal of Thermal Sciences, **62**(2012), pp. 29-33, June. 2012.

[2] Liu, R.S., *Fundamental Research on the Application of Nano Dielectrics to Transformers*, Proceedings of IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Cancun, Mexico, pp. 423-427, 2011.

[3] Rafiq, M., *Insulating and Aging Properties of Transformer Oil-based TiO_2 Nanofluids*, Proceedings of IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Des Moines, IA, USA, pp. 457-461, 2014.

[4] Katim, N.I.A., *Investigation on AC Breakdown of Vegetable Oils with Insulated Electrodes*, Proceedings of International Conference on High Voltage Engineering and Power Systems (ICHVEPS), Sanur, Indonesia, pp. 312-316, 2017.

[5] Nor, S.F.M., *A Study on the Voltage Breakdowns of As-received Palm Oil and Coconut Oil under Presence of TiO_2*, Proceedings of IEEE Conference on Energy Conversion, Johor Bahru, Malaysia, pp. 354-357, 2015.

[6] Wang, X. & Wang, Z.D., *Particle Effect on Breakdown Voltage of Mineral and Ester Based Transformer Oils*, Proceedings of Annual Report Conference on Electrical Insulation and Dielectric Phenomena., Quebec, QC, Canada, pp. 598-602, 2008.

[7] Zhou, J.Q., *AC and Lightning Breakdown Strength of Transformer Oil Modified by Semiconducting Nanoparticles*, Proceedings of Annual Report Conference on Electrical Insulation and Dielectric Phenomena. Cancun, Mexico, pp. 652-654, 2011.

[8] Segal, V., *AC and Impulse Breakdown Strength of a Colloidal Fluid Based on Transformer Oil and Magnetite Nanoparticles,* Proceedings of IEEE International Symposium on Electrical Insulation, Arlington, Virginia, USA, pp. 619-622, 1998.

[9] Thirugnanam, A.R.P.R., Siluvairaj, W.I.M. & Karthik, R., *Performance Studies on Dielectric and Physical Properties of Eco-friendly Based Natural Ester Oils Using Semi-conductive Nanocomposites for Power Transformer Application*, Journal of IET Science, Measurement & Technology, **12**(3), pp. 323-327, Jan. 2018.

[10] Thien, Y.V., *Investigation on the Lightning Breakdown Voltage of Palm Oil and Coconut Oil under Non-uniform Field*, Proceedings of IEEE International Conference on Power and Energy (PECon), Kuching, Malaysia, pp. 1-4, 2014.

[11] Das, S.K., *Nanofluids: Science and Technology*, 1st ed., John Wiley & Sons Inc., 2008.

[12] Choi, S.U.S. & Eastman, J.A., *Enhancing Thermal Conductivity of Fluids with Nanoparticles*, Proceedings of International Mechanical Engineering Congress and Exhibition, San Francisco, United States, pp. 99-105, 1995.

[13] Jin, H., *Dielectric Strength and Thermal Conductivity of Mineral Oil based Nanofluids*, PhD dissertation, Department of Electrical Engineering, Delft University of Technology, Amsterdam, the Netherlands, 2015.

[14] Muangpratoom, P., *Morakot Palm Olein*, retrieved from http://www.morakot.com/morakot-industrialproducts/ (March 2, 2020)

[15] Muangpratoom, P., *Inframat Advanced Materials LLC*, retrieved from http://www.advancedmaterials.us. (March 6, 2020)

[16] Muangpratoom, P. & Pattanadech, N., *Dielectric Properties of Mineral Oil-Based Nanofluids under Temperature Variations*, Journal of IET Science, Measurement & Technology, **13**(9), pp. 1318-1325, Oct. 2019.

[17] ASTM, D1533-12 International Standard, *Standard Test Method for Water in Insulating Liquids by Coulometric Karl Fischer Titration*, 2012.

[18] IEC-156 International Standard, *Insulating Liquids-Determination of the breakdown Voltage at Power Frequency-test Method*, Second Edition, 1995.

[19] Pattanadech, N. & Muhr, M., *Partial Discharge Inception Voltage Investigation of Mineral Oil: Effect of Electrode Configurations and Oil*

Conditions, Journal of IEEE Transactions on Dielectrics and Electrical Insulation, **23**(5), pp. 2917-2924, Oct. 2016.

[20] Montsinger, V.M., *Loading Transformers by Temperature*, Journal of Transactions of the American Institute of Electrical Engineers, **49**(2), pp. 776-790, Apr. 1930.

[21] Muhammad, R., Yuzhen, Lv. & Chengrong, Li., *A Review on Properties, Opportunities, and Challenges of Transformer Oil-based Nanofluids,* Journal of Nanomaterials, Article ID 8371560, 23 pages, 2016.