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Suitability of Palm Based Oil as Dielectric Insulating Fluid in Transformers

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Abstract – Mineral oil has been widely used as dielectric insulating fluid in transformers due to its excellent performance in-service. However, there are few issues with mineral oil such as it has poor biodegradability and could contaminate the environment if a spillage occurs. With the increasing tight regulation on safety and environment, alternative fluids for mineral oil are currently being investigated and among the suitable candidate is the vegetable oil. There are different types of vegetable oils and one of them is the palm based oil. At the moment, extensive research works are carried out to examine its feasibility to be applied in transformers. This paper will review the previous research works that were carried out to examine the suitability of palm based oil as dielectric insulating fluid in transformers. The physical and chemical properties of palm based oil are studied based on viscosity, acidity, oxidation stability and flash point. Next, the electrical characteristics of palm based oil are examined based on AC breakdown voltage, relative permittivity, dissipation factor and partial discharge.

Keywords: Dielectric insulating fluid, Palm based oil, Transformers

1. Introduction

Most of transformers in the power system network are oil filled type. Oil is known as a crucial part of the insulation system in transformers apart from cellulose. The main function of the oil is to dissipate the heat generated by the transformer winding and core, to insulate between components at different potentials which include being able to withstand system transients due to switching or lightning surges and information carrier for condition monitoring [1].

Mineral oil is the common dielectric insulating fluid used in transformers. It is derived from the crude petroleum formed from buried and decayed vegetable matters or by the action of water on metal carbides. It is a complex mixture of carbon and hydrogen with a small proportion of sulphur and nitrogen [1]. For centuries, mineral oil has been successfully applied in transformers. However, it is known that petroleum product such as mineral oil will be eventually depleted in the future since it is a non-renewable source. With the concern on the fire safety and environmental issues, alternative fluids are currently being considered. Vegetable oil such as natural ester or synthetic ester is among the alternative fluids being considered. For years, various research works were carried out on different aspects such as on the safety / environmental, ageing and electrical performances of the vegetable oil [2-12]. Vegetable oil such as natural ester was also successfully applied in-service where it was used from small to medium transformers up to a voltage level of 66 kV [11]. Among the attractive factors of vegetable oil is the non-toxicity and highly biodegradable which ensure low risk to the environment if there is a spillage. The high flash and fire points of vegetable oil ensure more in-service operation safety than mineral oil [5]. Moreover, vegetable oil such as natural ester could also slow down the ageing rate of cellulose insulation through water scavenging and hydrolytic protection mechanisms [2-4, 12].

Apart from natural ester, palm based oil is another type of vegetable oil that can be used as dielectric insulating fluid in transformers. The chemical characteristics of palm based oil are almost close to natural ester such as it is biodegradable, has high flash/fire point and it is non-toxic since most of the palm based oil is from the food grade type [13]. Palm based oil has also a wide composition of fatty acids that include a wide range of carbon which account to the good oxidation stability as compared to other types of vegetable oils [14, 15].

In this paper, a review on the suitability of palm based oil as dielectric insulating fluid in transformers is carried out. The physical, chemical and electrical characteristics of palm based oil are reviewed thoroughly based on viscosity, acidity, oxidation stability, flash point, AC breakdown voltage, dielectric properties and partial discharge. The future works on palm based oil for transformers application are also discussed.

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2. Types of Palm Based Oils for Transformers Application

Palm based oil can be obtained by processing the palm nut which is extracted from the palm bunch. The palm nut consists of hard seed known as kernel. It is covered by a shell known as endocarp which is surrounded by flush husk known as mesocarp as shown in Fig. 1 [16]. In general, there are 2 types of oils that can be obtained from the palm nut which are Crude Palm Oil (CPO) and Palm Kernel Oil (PKO). CPO can be obtained from the mesocarp while PKO from the kernel of the palm nut [16]. Both CPO and PKO are derived from a wide composition of fatty acids which include carbon number from 8 to 18. The composition of fatty acids with their respective carbon numbers in both CPO and PKO can be seen in Table 1. PKO has much wider range of carbon number ranging from 8 to 18 while for CPO, the range of carbon number is between 14 and 18. Fatty acids with a carbon number from 8 to 16 are saturated acids while fatty acids such as Stearic acid, Oleic acid and Linoleic acid are known as unsaturated acids [14, 15].

There are different types of palm based oils that are currently being considered for transformers application. Among them are as follow:

a) CPO

CPO is extracted from the mesocarp of the palm nut through sterilization, stripping, extraction and purification processes [17].

b) PKO

PKO is mined from the kernel of the palm nut through separation and drying processes [17].

c) Redefined, Bleached and Deodorized Palm Oil (RBDPO)

Under degumming, bleaching and deodorization, CPO can be further refined to become RBDPO [17]. The RBDPO can be separated through fractionation process to produce the RBDPO Olein [18].

d) PKO Alkyl Ester

PKO can be further synthesized by different techniques such as transesterification, epoxidation and acid catalyzed ring opening reaction to produce PKO Alkyl ester [19-22].

e) Palm Fatty Acid Ester (PFAE)

Palm Fatty Acid Ester (PFAE) is mainly derived from the unsaturated fatty acids of palm oil. PFAE is developed through laboratory synthesis which involved with molecular design and transesterification of fatty acid methyl ester and alkyl alcohol [14, 15].

Fig. 1. Cross section of the palm nut [16].

Table 1. Composition of fatty acids in CPO and PKO [14, 15].

Types of fatty acids	CPO (%)	PKO (%)
C8: Caprylic	-	3.3
C10: Capric	-	3.1
C12: Lauric	-	45.7
C14: Myristic	1.1	16.4
C16: Palmitic	44.4	8.9
C18: Stearic	4.3	2.3
C18: Oleic	39.9	17.1
C18: Linoleic	9.4	2.7
Others	0.9	0.5

3. Physical and Chemical Characteristics

3.1 Viscosity

One of the important aspects for dielectric insulating fluid is viscosity where it is a measure of fluid friction. It is important to ensure the viscosity of the oil to be as low as possible in order to avoid affecting the cooling efficiency of transformers.

According to previous works, palm based oil has a wide range of viscosity [14, 15, 20-24, 27-30]. The viscosity of CPO is 25 mm^2/s and the range of viscosity for RBDPO is between 37 mm^2/s and 50 mm^2/s [23, 24, 27] which is slightly higher than natural ester with a value of 33 mm^2/s and synthetic ester with a value of 28 mm^2/s as shown in Table 2 [25, 26]. The viscosity of RBDPO could be further reduced by reducing the amount of fat content [24, 27]. The viscosity of synthesized RBDPO, RBDPO Olein is 21 mm^2/s. The value is lower than the RBDPO and even lower than natural ester and synthetic ester [28, 29]. PKO Alkyl ester and PFAE have much lower viscosity than natural ester and synthetic ester where the range of viscosity is between 3.2 mm^2/s and 6.99 mm^2/s [14, 15, 20-22].

The viscosity performance of palm based oil is quite good compared to natural ester and synthetic ester. Apart from RBDPO, other types of palm based oils such as CPO,

Table 2. Viscosity of different types of vegetable oils.

Types of palm based oil	Viscosity (mm^2/s) at 40°C
CPO [30]	25 at 50°C
RBDPO [23, 24, 27]	Between 37 and 50
RBDPO Olein [28, 29]	21
PKO Alkyl ester [20, 22]	3.2 to 6.99 at 20°C
PFAE [14, 15]	5.06
Natural ester [25]	33
Synthetic ester [26]	28

RBDPO Olein, PKO Alkyl Ester and PFAE have much lower viscosity than natural ester and synthetic ester. The viscosity of CPO and RBDPO Olein are much better than RBDPO possibly due to the fatty acids composition. Oil with high content of unsaturated fatty acids has an excellent viscosity performance and both of CPO and RBDPO Olein have high percentage of these acids [31, 32]. On the other hand, by utilizing only most of the unsaturated fatty acids with carbon 18 as in PFAE case, the viscosity can be further improved. However, the high percentage of unsaturated fatty acids could affect the oxidation performance of the oil. Therefore, it is essential to balance the fatty acids composition in order to optimize its application in transformers.

3.2 Acidity

Another important parameter for dielectric insulating fluid is acidity. Proper monitoring of acidity is crucial to ensure the safe operation of transformers. At the moment, there is still less acidity studies were conducted on palm based oil. One of the studies reported that the acidity of RBDPO Olein is 0.074 mg KOH/g [28] which is slightly high compared to natural ester with a value of 0.022 mg KOH/g and synthetic ester with a value of 0.03 mg KOH/g [25, 26]. The acidity of PFAE is much lower than natural ester and synthetic ester where the value is 0.01 mg KOH/g [14, 15].

The difference on the acidity value between RBDPO Olein and PFAE is quite apparent which indicates that acidity could be also affected by the composition of fatty acids. It is because that RBDPO Olein consists of high percentage of both saturated and unsaturated fatty acids while PFAE only consist mainly of unsaturated fatty acids. However, further investigations on the acidity of different types of palm based oil are required in order to obtain more acidity information and verify the finding.

3.3 Oxidation stability

Oxidation is a chemical reaction that is promoted by free radicals produced through interaction between the oil and oxygen. The process could be accelerated by catalysts such as copper, water and acids. Oxidation of the oil could generate water and acids which in turn increase the rate of oil and paper ageing. In addition, the insoluble compounds such as sludge could accumulate and might block the oil duct. Under extreme condition, the flow of the oil could be interrupted and affect the cooling efficiency of transformers.

There is yet extensive studies were conducted to examine the oxidation stability of palm based oil. One of the studies investigates the performance of PFAE after subjected to oxidation stability test [14, 15]. Based on the finding, it was found that the acidity and moisture of PFAE remain almost unchanged after the test. On the other hand, for mineral oil and other types of vegetable oils, the acidity and moisture increased significantly after the test [14, 15]. The AC breakdown voltage of PFAE also remain unchanged since the acidity and moisture levels were low [14, 15]. It is a promising finding, however since only 1 type of palm based oil was tested; it is difficult to draw any conclusion on the oxidation stability performance of palm based oil. A study on other types of palm based oil is essential in order to help with understanding the oxidation stability behaviour.

Table 3. Flash point of different types of vegetable oils.

Types of palm based oil	Flash point (°C)
CPO [30]	> 250
RBDPO [23]	Between 220 and 330
PKO Alkyl ester [33]	Between 120 and 148
PFAE [14, 15]	Between 176 and 186
Natural ester [25]	316
Synthetic ester [26]	260

3.4 Flash point

High flash point is very important to ensure high safety during in-service operation. The risk of fire hazard in transformers could also be reduced if the dielectric insulating fluid has a high flash point.

The range of flash point for RBDPO is between 220 °C and 330 °C where the it is slightly lower than the flash point of natural ester with a value of 316 °C and synthetic ester with a value of 260 °C as shown in Table 3 [23, 25, 26]. The flash point of PKO Alkyl ester is quite low with a value ranging between 120 °C and 148 °C. The same pattern is observed for PFAE where the range of flash point is between 176 °C and 186 °C [14, 15].

The flash point performance of palm based oil is not as good as natural ester and synthetic ester. The highest flash point is CPO and RBDPO followed by PFAE and PKO Alkyl ester. Further studies on the flash point of palm based oil are required for improvement of its performance.

4. Electrical Characteristics

4.1 AC Breakdown voltage

AC breakdown voltage is the most common parameter used to evaluate the electrical performance of dielectric insulating fluid. In is important to ensure the AC breakdown voltage for the new oil is high since after ageing, the value could be reduced due to the presence of contaminants such as ageing by-products [6].

The range of AC breakdown voltage for RBDPO is between 52 kV and 86 kV. These values are much higher than CPO with a value ranging between 17 kV and 23 kV [13, 23, 24, 27, 34] as shown in Table 4.

The AC breakdown voltage of RBDPO can be improved by reducing the amount of fat content [27]. Another

Table 4. AC breakdown voltage of different types of vegetable oils.

Types of palm based oil	AC breakdown voltage (kV) at 2.5 mm gap distance
CPO [13, 23]	Between 17 and 23
RBDPO [13, 23, 24, 27, 34]	Between 52 and 86
RBDPO Olein [28, 29, 35]	Between 44.78 and 60
PKO alkyl ester [20-22]	Between 42.1 and 42.6 at 1 mm gap distance
PFAE [14, 15]	Between 81 and 84
Natural ester [25]	56 at 2 mm gap distance
Synthetic ester [26]	75

Table 5. Dissipation factor and relative permittivity of different types of vegetable oils.

Types of palm based oil	Dissipation factor (%)	Relative permittivity
CPO [23]	0.006 at 90 °C	2.1 at 90 °C
RBDPO [23, 27]	Between 0.0035 and 0.014 at 90 °C	3.5 at 90 °C
RBDPO Olein [28]	0.03 at 25 °C	3.1 at 25 °C
PFAE [14, 15]	Between 0.31 and 0.8 at 80 °C	2.95 at 80 °C
Natural ester [25]	0.05 at 25 °C	3.2 at 25 °C
Synthetic ester [26]	<0.008 at 90 °C	-

technique to improve the AC breakdown voltage of RBDPO is by mixing it with mineral oil [34]. However, not all mixture produced a positive result where it was found that the mixture between RBDPO and Soybean Oil (SO) resulted in a low AC breakdown voltage [24]. On the other hand, the AC breakdown voltage of RBDPO Olein is slightly lower than the RBDPO with a value ranging between 44.78 kV and 60 kV [28, 29, 35]. The AC breakdown voltage of both PKO Alkyl ester and PFAE is higher than natural ester and synthetic ester [14, 15, 19, 20].

It is observed that without any thorough treatment such as CPO, the AC breakdown voltage of palm based oil is very low. The treatment such as degumming, bleaching and deodorization could significantly improve the AC breakdown voltage as in RBDPO, RBDPO Olein and PKO alkyl ester cases. Through further synthesis process, the AC breakdown voltage of palm based oil such as PFAE could be improved significantly which could make it suitable for application in transformers.

4.2 Dissipation factor and relative permittivity

Dissipation factor is a good indicator for determining any contaminations and evaluating dielectric losses of the oil. On the other hand, relative permittivity could be used to identify the type of dielectric insulating fluid.

One of the studies reported that the range of dissipation factor at 90 °C for CPO and RBDPO is between 0.0035 and 0.014 as shown in Table 5 [23, 27]. The dissipation factor for RBDPO Olein is slightly high with a value of 0.03 at 25 °C [28]. The dissipation factor of PFAE is much larger than RBDPO and RBDPO Olein where the range of value at 80 °C is between 0.31 and 0.8.

Since relative permittivity is not significantly affected by the temperature, it can be summarized that RBDPO, RBDPO Olein and PFAE have almost the same relative permittivity with a value ranging between 2.95 and 3.5. The relative permittivity of CPO is quite low compared to natural ester and due to this reason; it is possibly not suitable to be used for transformers application.

In general, CPO, RBDPO and RBDPO Olein have a good performance of dissipation factor compared to natural ester. However, the dissipation factor of PFAE is quite high as compared to other types of palm based oils. Since there is a difference on the tested temperature, it is difficult to determine which oil has the best dissipation factor. It is suggested that further tests are required in order to confirm the findings by testing these oils at the same temperature. On the other hand, it is expected that palm based oil should have high relative permittivity compared to mineral oil except for CPO. Palm based oil molecule has high unbalance level of geometrical structure which could lead to high degree of polarity. As a result, more dipoles will be form which in turn leads to high relative permittivity [29].

4.3 Partial discharge

Partial discharge (PD) is a symptom that could cause insulation deterioration in transformers. PD occurs once the electric field exceeds the threshold value which leads to the partial breakdown on the surrounding medium [36]. Once the discharge is initiated, the surrounding insulation will be degraded which lead to the propagation from the local area to the bulk fluid and lead to the complete breakdown [37]. Therefore, it is crucial to monitor the PD in order to maintain the integrity of the insulation of transformers.

At the moment, there is yet extensive studies were conducted to examine the PD of palm based oil. One of the studies reported that RBDPO Olein had almost the same characteristics as mineral oil [38]. The PD test was carried out based on needle-plane electrodes configuration with a 20 mm gap distance and an acrylic with a thickness of 15 mm was placed in between electrodes to prevent breakdown [35]. High voltage was supplied to the needle and the PD pulses were observed through the RC detector [35]. Among the findings were as follow:

a) Both RBDPO Olein and mineral oil had PD occurs on both half cycle of applied voltage.
b) Both oils had PD initiated at the negative half cycle of applied voltage and high PD number was observed at this cycle.
c) The PD magnitudes are independent of instantaneous value of applied voltage for both oils.
d) There is an existence of the phase shift for PD

occurrence for both oils.

There are only a few differences of PD characteristic between RBDPO Olein and mineral oil. One of them is the PD pulses of RBDPO Olein spread in a much wider area than mineral oil. Secondly, the phase shift of PD occurrence for RBDPO Olein is bigger than mineral oil [38]. It was suggested that the phenomenon is due to the viscosity where the space charges in RBDPO Olein diffused into electrodes much slower than in mineral oil [38].

5. Future of Palm Based Oil as Dielectric Insulating Fluid in Transformers

The test results from the previous works on palm based oil comply with the international standards and some of the parameters are almost close to mineral oil and other types of vegetable oils. In term of sustainability, palm based oil is the most efficient among other types of oil-seed crop. One hectare of palm oil plantation is able to generate 10 times more than other types of oil-seed crop. Among 10 major oil-seeds in the world, palm based oil account for 32% of the total production and it is priced competitively compared to other types of oilseed crops [16]. However, there are few areas that required further investigation before it can be practically applied in-service.

One of the important areas is the ageing and oxidation stability performances. For example, the viscosity of vegetable oils such as natural ester could increase significantly after subjected to ageing [39]. Oil with a high viscosity could affect the cooling efficiency of transformers. Therefore, a simple quick change from mineral oil to palm based oil in transformers is not always feasible and require a lot of studies especially on ageing and oxidation stability at laboratory level. A study was conducted previously to examine the viscosity performance of palm Olein after subjected to ageing for 120 hours at 150°C [40]. The viscosity of palm Olein reduced by 5% from the initial value after ageing while for mineral oil, the viscosity increased by 3.6%. The finding is promising but it is suggested that in order to further understand the ageing performance and mechanism of palm based oil; extensive studies need to be carried out which cover different aspects such as the effect of different ageing conditions and under the presence of cellulose insulation such as paper and pressboard. In addition, further study need to be carried out to examine the oxidation stability performance of different types of palm based oils.

Gassing characteristic is also one of the important aspects that need to be considered. Dissolved Gas Analysis (DGA) is usually the most common method used to detect any incipient faults in transformers. DGA assessment provides early warnings of which corrective action can be carried out. Currently, vegetable oils are using a slightly different DGA assessment scheme from mineral oil since the key fault gases are different [7, 41]. Key fault gases are important for fault interpretation and misinterpretation could be costly especially during in-service operation. Therefore, it is essential to identify the key gases of palm based oil under different types of fault so that correct interpretation and corrective action could be carried out once it is applied in-service.

It is crucial to carry out proper PD monitoring in order to avoid significant deterioration of insulation in transformers. The monitoring can be carried out by looking into the PD parameter such as Partial Discharge Inception Voltage (PDIV), magnitude, repetition rate, phase shift and etc. Due to the chemical and physical nature of palm based oil, the PD parameter could be different from the mineral oil. The initial study on PD of RBDPO Olein indicated that there is a difference with mineral oil in term of PD pulses and phase shift occurrence [35]. However, since the study was carried out only for 1 type of palm based oil, it is difficult to draw any conclusion yet. Further studies on PD of different types of palm based oils are required in order to further confirm the finding.

6. Conclusion

Palm based oil is a good candidate as an alternative fluid for mineral oil in transformers. In term of viscosity, the performance of most of the palm based oil is comparable to other types of vegetable oils such as natural ester and synthetic ester. The acidity of palm based oil is slightly high compared to natural ester but for PFAE, the acidity is comparable to mineral oil. The oxidation stability for some of the palm based oil such as PFAE is good compared to other types of vegetable oils. However, further studies on the oxidation stability of other types of palm based oil are required in order to verify the performance. The flash point performance of palm based is not as good as natural ester and synthetic ester and requires extensive studies for further improvement.

In term of electrical performance, the AC breakdown voltage of palm based oil is comparable to natural ester and synthetic ester except for CPO. The AC breakdown voltage of PFAE is the highest followed by PKO Alkyl ester, RBDPO Olein, RBDPO and CPO. The AC breakdown voltages of RBDPO and RBDPO Olein are comparable to natural ester and synthetic ester while for PFAE and PKO Alkyl ester, the AC breakdown voltage is higher than these oils. For all types of palm based oils, the relative permittivity is much higher than mineral oil. On the other hand, the dissipation factor for palm based oil except for PFAE is comparable to natural ester and synthetic ester. The PD pattern of some of the palm based oil such as RBDPO Olein is almost the same as mineral oil.

The application of palm based oil as dielectric insulating fluid is still new and required more studies for further improvement. Based on the works carried out previously, it can be summarized that PFAE is promising fluid that can be used in transformers. With further research and development, palm based oil can be applied commercially and widely in the future as dielectric insulating fluid not only in transformers but also to other power system apparatus such as cables, circuit breakers and switchgears.

References

[1] M. Heathcote, "J & P Transformer Book," 2011.

[2] R. Liao, S. Liang, C. Sun, L. Yang, and H. Sun, "A comparative study of thermal aging of transformer insulation paper impregnated in natural ester and in mineral oil," European Transactions on Electrical Power, vol. 20, pp. 518-533, 2010.

[3] C. P. McShane, K. J. Rapp, J. L. Corkran, G. A. Gauger, and J. Luksich, "Aging of paper insulation in natural ester dielectric fluid," IEEE/PES Transmission and Distribution Conference and Exposition, vol. 2, pp. 675-679, vol.2, 2001.

[4] C. P. McShane, K. J. Rapp, J. L. Corkran, G. A. Gauger, and J. Luksich, "Aging of Kraft paper in natural ester dielectric fluid," IEEE International Conference on Dielectric Liquids (ICDL), pp. 173-177, 2002.

[5] D. P. Stockton, J. R. Bland, T. McClanahan, J. Wilson, D. L. Harris, and P. McShane, "Natural Ester Transformer Fluids: Safety, Reliability & Environmental Performance," IEEE Petroleum and Chemical Industry Technical Conference (PCIC), pp. 1-7, 17-19 September 2007.

[6] X. Wang and Z.D. Wang, "Study of dielectric behavior of ester transformer liquids under ac voltage," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 19, pp. 1916-1925, 2012.

[7] W. Zhongdong, Y. Xiao, H. Jinping, J. V. Hinshaw, and J. Noakhes, "Fault gas generation in natural-ester fluid under localized thermal faults," IEEE Electrical Insulation Magazine, vol. 28, pp. 45-56, 2012.

[8] Q. Liu, Z.D. Wang, "Streamer characteristic and breakdown in synthetic and natural ester transformer liquids under standard lightning impulse voltage," IEEE Transactions on Dielectrics and Electrical Insulation, vol.18, no.1, pp.285-294, 2011.

[9] S. Tenbohlen and M. Koch, "Aging Performance and Moisture Solubility of Vegetable Oils for Power Transformers," IEEE Transactions on Power Delivery, vol.25, no.2, pp. 825-830, 2010.

[10] N. Azis, "Ageing assessment of insulation paper with consideration of in-service ageing and natural ester application," PhD dissertation, School of Electrical and Electronic Engineering, The University of Manchester, 2012.

[11] P. Hopkinson, L. Dix, C. P. McShane, H. R. Moore, S. Moore, J. Murphy, T. Prevost, and B. Beaster, "Progress report on natural esters for distribution and power transformers," IEEE Power & Energy Society General Meeting (PES), pp. 1-3, 26-30 July 2009.

[12] K. J. Rapp, C. P. McShane, and J. Luksich, "Interaction mechanisms of natural ester dielectric fluid and Kraft paper," IEEE International Conference on Dielectric Liquids (ICDL), pp. 393-396, 26 June-1 July 2005.

[13] U. U. Abdullahi, S. M. Bashi, R. Yunus, Mohibullah, and H. A. Nurdin, "The potentials of palm oil as a dielectric fluid," in National Proceedings of Power and Energy Conference(PECon), pp. 224-228, 2004.

[14] T. Kanoh, H. Iwabuchi, Y. Hoshida, J. Yamada, T. Hikosaka, A. Yamazaki, Y. Hatta, and H. Koide, "Analyses of electro-chemical characteristics of Palm Fatty Acid Esters as insulating oil," IEEE International Conference on Dielectric Liquids (ICDL), pp. 1-4, June 30-July 3 2008.

[15] T. Kano, T. Suzuki, R. Oba, A. Kanetani, and H. Koide, "Study on the oxidative stability of palm fatty acid ester (PFAE) as an insulating oil for transformers," IEEE International Symposium on Electrical Insulation (ISEI), pp. 22-25, 10-13 June 2012.

[16] "Sime Darby Plantation-Palm oil facts and figures," 2013.

[17] F. D. Gunstone, "Palm oil-Critical reports on applied chemistry," Society of Chemical Industry, Wiley, 1987.

[18] "http://www.mpob.gov.my/."

[19] A. A. Abdelmalik, J. C. Fothergill, and S. J. Dodd, "Electrical breakdown strength characteristics of palm kernel oil ester-based dielectric fluids," Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), pp. 183-186, 16-19 October 2011.

[20] A. A. Abdelmalik, J. C. Fothergill, and S. J. Dodd, "Electrical properties of ester dielectric fluids from palm kernel oil," Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), pp. 415-418, 16-19 October 2011.

[21] A. A. Abdelmalik, J. C. Fothergill, S. J. Dodd, A. P. Abbott, and R. C. Harris, "Effect of side chains on the dielectric properties of alkyl esters derived from palm kernel oil," International Conference on Dielectric Liquids (ICDL), pp. 1-4, 26-30 June 2011.

[22] A. A. Abdelmalik, J. C. Fothergill, and S. J. Dodd, "Electrical conduction and dielectric breakdown characteristics of alkyl ester dielectric fluids obtained from palm kernel oil," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 19, pp. 1623-1632, 2012.

[23] Suwarno, F. Sitinjak, I. Suhariadi, and L. Imsak, "Study on the characteristics of palm oil and it's derivatives as liquid insulating materials," International Conference on Properties and Applications of Dielectric Materials (ICPADM), vol. 2, pp. 495-498, vol.2, 1-5 June 2003.

[24] K. Kiasatina, M. Kamarol, M. Zulhilmey, and Y. A.

Arief, "Breakdown characteristics of RBDPO and soybean oil mixture for transformer application," International Conference on Electrical, Control and Computer Engineering (INECCE), pp. 219-222, 21-22 June 2011.
[25] "Envirotemp FR3 fluid product datasheet."
[26] "MIDEL 7131 fluid product datasheet."
[27] Suwarno and S. Aditama, "Dielectric properties of palm oils as liquid insulating materials: effects of fat content," International Symposium on Electrical Insulating Materials (ISEIM), vol. 1, pp. 91-94, Vol. 1, 5-9 June 2005.
[28] A. Rajab, Suwarno, and S. Aminuddin, "Properties of RBDPO Oleum as a candidate of palm based-transformer insulating liquid," International Conference on Electrical Engineering and Informatics (ICEEI), vol. 02, pp. 548-552, 5-7 August 2009.
[29] A. Rajab, A. S. S. Sudirham, and Suwarno, "A Comparison of Dielectric Properties of Palm Oil with Mineral and Synthetic Types Insulating Liquid under Temperature Variation," Inst. Technology Bandung J. Eng. Sci., vol. 43, pp. 191-208, 2011.
[30] "GUSTAV HEESS crude palm oil product datasheet."
[31] P. Boss and T. V. Oommen, "New Insulating Fluid for Transformers Based on Biodegradable High Oleic Vegetable Oil and Ester Fluid," The Institution of Electrical Engineers, London, 1999.
[32] T. V. Oommen, C. C. Claiborne, E. J. Walsh, and J. P. Baker, "A new vegetable oil based transformer fluid: development and verification," IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), vol. 1, pp. 308-312, vol.1, 2000.
[33] A. A. Abdelmalik, "The feasibility of using a vegetable oil-based as electrical insulating fluid," PhD dissertation, Department of Engineering, University of Leicester, 2012.
[34] M. Y. Yusnida, M. Kamarol, and M. A. Ahmad, "Breakdown voltage characteristic of MO and RBDPO mixture for power transformer insulation," IEEE Colloquium on Humanities, Science and Engineering (CHUSER), pp. 300-303, 3-4 December 2012.
[35] N. S. Mansor, M. Kamarol, M. Y. Yusnida, and K. Azmi, "Breakdown voltage characteristic of biodegradable oil under various gap of quasi-uniform electrode configuration," IEEE International Conference on Power and Energy (PECon), pp. 732-735, 2-5 December 2012.
[36] W. Mang-Hui and H. Chih-Yung, "Application of extension theory to PD pattern recognition in high-voltage current transformers," IEEE Transactions on Power Delivery, vol. 20, pp. 1939-1946, 2005.
[37] O. Lesaint, " "Streamers" in liquids: Relation with practical high voltage insulation and testing of liquids," IEEE International Conference on Dielectric Liquids (ICDL), pp. 1-6, June 30 -July 3 2008.
[38] A. Rajab, U. K., D. Hamdani, A. S., Suwarno, Y. A. M. Tsuchie, M. Kozako, S. Ohtsuka, and M. Hikita, "Partial Discharge Phase Distribution Of Palm Oil As Insulating Liquid," Telkomnika, vol. 9, pp. 1-8, 2011.
[39] H. M. Wilhelm, L. Tulio, R. Jasinski, and G. Almeida, "Aging markers for in-service natural ester-based insulating fluids," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 18, pp. 714-719, 2011.
[40] M. S. A. Kamal, N. Bashir, and N. A. Muhamad, "Insulating properties of vegetable oils and their blends," IEEE Power Engineering and Optimization Conference (PEOCO), pp. 455-458, 3-4 June 2013.
[41] M. Jovalekic, D. Vukovic, and S. Tenbohlen, "Dissolved gas analysis of alternative dielectric fluids under thermal and electrical stress," IEEE International Conference on Dielectric Liquids (ICDL), pp. 1-4, 26-30 June 2011.

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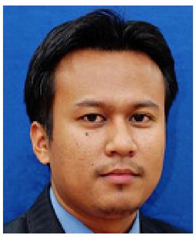

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