UNIVERSITI PUTRA MALAYSIA

PRE-BREAKDOWN STREAMER PROPAGATION AND LIGHTNING PERFORMANCE OF PALM OIL WITH CONSIDERATION OF PRESSBOARD AND ALUMINIUM OXIDE

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By

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In recent years, various types of vegetable oils have been introduced as alternatives for Mineral Oil (MO) due to its biodegradability, environmentally friendly, and high flash/fire safety. Palm Oil (PO) has been found as a viable option to be considered as dielectric insulating fluids in transformers. Currently, only some information can be obtained related to the pre-breakdown streamer propagation and lightning performances of vegetable oils such as natural ester i.e. rape seed based. However, there is no information on pre-breakdown streamer propagation for PO either under positive or negative polarities. In addition, the knowledge on the impact of the pressboard on the streamer propagation of the PO is still not available. Furthermore, the effect of the insulative nanoparticles on the lightning properties of the PO has not been examined in previous studies.

The aim of this study is to investigate the pre-breakdown and breakdown performances of 2 types of refined, bleached, and deodorized palm oil olein. The streamer propagation and breakdown event in PO either with or without pressboard interface were investigated under both positive and negative lightning voltages. The influence of nanoparticle namely Aluminium Oxide, Al_2O_3 on the lightning performance of the PO was also considered with and without surfactant. The type of surfactant used in the study was Cetyl Trimethyl Ammonium Bromide (CTAB). MO was also examined for comparison purposes. The lightning impulse voltage tests for all studies were carried out under the needle-plane electrodes configuration at a gap distance of 25 mm based on the rising voltage method. A high-speed camera was used to obtain the streamer propagation with and without pressboard interface while the photomultiplier tube was used to detect the weak emitting light signal in the presence of Al_2O_3 and CTAB.

It is found that the positive lightning performances i.e. streamer propagation and breakdown of both PO are comparable with MO. However, due to different chemical

structures, the negative streamers of the PO have more branches and propagate faster than MO. These phenomena lead to the lower negative lightning breakdown voltage of the PO as compared to MO. The positive and negative lightning breakdown voltages for both PO impregnated pressboards are slightly higher than open oil gaps. At the same voltage level, streamers on PO impregnated pressboards propagate further and have lower lightning breakdown voltage than MO impregnated pressboard. After subjected to ageing, the lightning breakdown voltage for both PO and MO impregnated pressboard decrease under both positive and negative polarities. The introduction of Al_2O_3 can improve the positive lightning breakdown voltages of PO and MO at certain volume concentrations. In addition, the effects of Al_2O_3 and CTAB on the positive streamer propagation of PO and MO are quite small based on light signal analyses. CTAB can provide a slight further improvement in the positive lightning breakdown voltage at 0.001% concentration Al_2O_3 for both PO. However, it is apparent that the light signals of all samples increase as the applied voltage increases for both PO and MO.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

PROPAGASI PENJURUS DAN PRESTASI KILAT TERHADAP MINYAK KELAPA SAWIT DENGAN PERTIMBANGAN PAPAN DAN ALUMINIUM OKSIDA

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Sejak kebelakangan ini, pelbagai jenis minyak sayuran telah diperkenalkan sebagai alternatif untuk minyak galian (MO) kerana biodegradasinya, mesra alam, dan keselamatan kilat / kebakaran yang tinggi. Minyak Sawit (PO) telah dijumpai sebagai pilihan yang layak untuk dianggap sebagai cecair penebat dielektrik dalam pengubah. Pada masa ini, hanya beberapa maklumat yang dapat diperoleh berkaitan dengan penyebaran penjurus pra-pemecahan dan persembahan kilat minyak sayuran seperti ester semula jadi iaitu berasaskan biji rogol. Walau bagaimanapun, tidak ada maklumat mengenai penyebaran penjurus pra-pemecahan untuk PO sama ada di bawah kutub positif atau negatif. Di samping itu, pengetahuan mengenai kesan penjurus pada papan penekan daripada PO masih tidak boleh didapati. Tambahan pula, kesan nanopartikel insulative kepada sifat-sifat kilat PO belum diperiksa dalam kajian sebelum ini.

Tujuan kajian ini adalah untuk mengkaji prestasi pra-pemecahan dan voltan kegagalan kilat bagi 2 jenis minyak sawit olein yang diperhalusi, diputihkan, dan dihilangkan bau. Peristiwa penyebaran dan kerosakan penjurus dalam PO dengan dan tanpa kehadiran papan penekan disiasat di bawah voltan impuls kilat positif dan negatif. Pengaruh nanopartikel Aluminium Oksida, Al_2O_3 terhadap prestasi kilat PO juga dipertimbangkan dengan dan tanpa surfaktan. Jenis surfaktan yang digunakan dalam kajian ini adalah Cetil trimetil amonium bromida (CTAB). MO juga diperiksa untuk tujuan perbandingan. Ujian voltan impuls kilat untuk semua kajian dilakukan di bawah konfigurasi elektrod satah jarum pada jarak jurang 25 mm berdasarkan kaedah voltan meningkat. Kamera berkelajuan tinggi digunakan untuk mendapatkan penyebaran penjurus dengan dan tanpa kehadiran papan penekan sementara tiub fotopendarab digunakan untuk mengesan isyarat cahaya pemancar yang lemah semasa ujian dengan kehadiran Al_2O_3 dan CTAB.

Didapati bahawa prestasi kilat positif dalam penyebaran penjurus dan voltan kegagalan kilat untuk kedua-dua PO setanding dengan MO. Walau bagaimanapun, kerana struktur

kimia yang berbeza, penjurus negatif PO mempunyai lebih banyak cabang dan menyebar dengan lebih cepat berbanding dengan MO. Fenomena ini membawa kepada voltan kegagalan kilat negatif PO yang lebih rendah berbanding dengan MO. Voltan kegagalan kilat positif dan negatif untuk kedua-dua PO yang diserapi papan penekan lebih tinggi daripada minyak terbuka. Pada tahap voltan yang sama, penjurus pada PO yang diserapi papan penekan menyebar dengan lebih jauh dan mempunyai voltan kegagalan kilat yang lebih rendah daripada MO yang diserapi papan penekan. Setelah mengalami penuaan, voltan kegagalan kilat untuk kedua-dua PO dan MO yang diserapi papan penekan menurun di bawah kutub positif dan negatif. Pengenalan Al_2O_3 dapat meningkatkan voltan kegagalan kilat positif PO dan MO pada kepekatan isipadu tertentu. Di samping itu, kesan Al_2O_3 dan CTAB pada penyebaran positif PO dan MO agak kecil berdasarkan analisis isyarat cahaya. CTAB dapat memberikan sedikit lagi peningkatan selanjutnya dalam voltan kegagalan kilat positif pada kepekatan 0.001% Al_2O_3 untuk kedua-dua PO. Walau bagaimanapun, jelas menunjukkan isyarat cahaya dari semua sampel meningkat apabila voltan yang dikenakan meningkat untuk kedua-dua PO dan MO.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

AIN	Aluminium Nitride
Al_2O_3	Aluminium Oxide
ASTM	American Society for Testing and Materials
BDV	Breakdown voltage
BN	Boron
C	Carbon
CI	Confidence Interval
CPC	Cetylpyridinium chloride
CPO	Crude Palm Oil
CTAB	Cetyltrimethylammonium Bromide
CTAC	Cetyltrimethylammonium chloride
Cu_2O	Copper Oxide
CuO	Copper (II) Oxide
DBP	2,6-Ditertiary-Butyl Phenol
DBPC	2,6-Ditertiarybutyl Para-Cresol
Fe_2O_3	Iron (III) Oxide
Fe_3O_4	Iron (II,III) Oxide
GC	Gas Chromatography
HCTAB	Hexadecyl Trimethyl Ammonium Bremide
HV	High Voltage
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Standards Organization
Max	Maximum
Min	Minimum
MO	Mineral Oil
NE	Natural Ester
OA	Oleic Acid
Pd	Diameter of plane
pC	Pico Columb
PFAE	Palm Fatty Acid Ester
PKO	Palm Kernel Oil
PMT	Photo Multiplier Tube
PO	Palm Oil
PVP	Polyvinylpyrolidone
RBDPO	Refined, Bleached and Deodorized Palm Oil
r	tip radius of needle
SDBS	Sodium Dodecyl Benzene Sulfonate
SDS	Sodium Dodecyl Sulfate
SEM	Scanning Electron Microscope
SiO_2	Silicon Dioxide
TEM	Transmission Electron Microscopy
TiO_2	Titanium Dioxide
VO	Vegetable Oil
ZnO	Zinc Oxide
Zr_2O	Zirconium Oxide

CHAPTER 1

INTRODUCTION

1.1 Research background

Various types of vegetable oils have been considered for application as a dielectric insulating fluid in transformers. The main function of the dielectric insulating fluid used in transformers is to act as electrical insulation, cooling medium, an information carrier. The advantage vegetable oils are biodegradable, non-toxic, eco-friendly, and have higher flash and fire points compared with the conventional Mineral Oil (MO). Over the past few years, there are significant interests in the application of vegetable oils as alternative dielectric insulating fluids [1-5]. Palm Oil (PO) is among one of the vegetable oils that have been examined extensively in recent years. PO is low cost to produce and it is readily available in South East Asian especially in Malaysia and Indonesia [6].

A number of studies have been carried out on PO covering on several aspects such as the dielectric, chemical/physical, and ageing properties [6-16]. Parameters such as the AC breakdown strength, lightning breakdown strength, dielectric dissipation factor, relative permittivity, and resistivity of PO have been examined under dielectric properties [17-20]. Currently, only a few studies have been carried out to investigate the lightning breakdown performances under different electrode geometries and nanoparticle effects of PO [19-27]. However, there is still no investigation on the pre-breakdown lightning impulse streamer propagation of PO either in the presence of pressboard or insulative nanoparticle.

Generally, a non-uniform field lightning breakdown study is carried out to represent an event where discharge is initiated by an apparent defect in a transformer. Such a non-uniform field can be created by needle-plane or needle-sphere configurations which can simulate the imperfections that could occur in transformers [28]. One of the most important factors that can affect the lightning breakdown voltages under a non-uniform field is the polarity of the lightning impulse voltage [29, 30]. The mechanism of the breakdown in the fluid is different under positive and negative polarities. Under a negative polarity, electrons are injected into the fluid if there is a high electrical field to initiate the streamer [31]. The interaction between the electrons and the molecules in the fluid will cause Joule heating and create gas bubbles. If these gas bubbles are long-lived, electrons traveling through this channel will acquire more energy to eject more electrons and if the process continues, it will cause an avalanche [32]. Due to the presence of positive space charge, a higher voltage is required to cause the breakdown under negative polarity [32]. On the other hand, under positive polarity, the source of the electrons is obtained from the ionisation of the fluid molecules themselves [32]. These electrons will accelerate toward the positive electrode and the further ionisation of the induced positive charge in the gas channel will cause an electron avalanche and streamer propagation [31, 32].

A number of studies have reported that the lightning breakdown voltages of dielectric insulating fluids under negative polarity tend to be higher than under positive polarity [33-38]. In one of the studies, the breakdown voltages of MO under negative polarity can be 60% higher than under positive polarity at a gap distance of 5 mm [37]. Previous study also found that in a hydrocarbon fluid such as MO, electrons exhibited greater mobility than positive ions [39]. Under negative polarity, the high mobility electrons produced a smaller space charge, whereas higher negative applied voltages were needed for an event breakdown to occur [39]. The polarity effect is also apparent for esters where the breakdown voltages under negative polarity can be 63% higher than for positive polarity [40]. Similar findings were observed for esters at a gap distance from 2 mm to 200 mm [41-43]. In another study, it was observed that the differences between breakdown voltages of MO and esters between negative and positive polarities increased as the gap distance increased [38]. In addition, it was found that the increment of the breakdown voltage for MO was much steeper under negative polarity as compared to positive polarity as the gap distance increased [38, 40]. There are still several characteristics of PO that need to be investigated such as the streamer propagations and breakdown performances under lightning impulse voltage.

In this study, refined, bleached, and deodorized palm oil was used and MO was used as a benchmark. Both PO and MO have different chemical compositions that could behave differently under lightning impulse voltage. Furthermore, the presence of pressboards and nanoparticles could also influence its streamer and breakdown characteristics.

1.2 Problem statement

Vegetable based insulating liquids, an eco-friendly product, have been introduced as an interesting alternative for MO in transformers due to its high fire safety, biodegradable, and environmentally friendly. There are different types of vegetable oils that have been examined not only at the laboratory level but also tested in-service. Natural esters have been used as alternative to MO and applied in low or medium voltage transformers [44, 45]. Most of the natural esters that have been examined are soya, rapeseed and sunflower based. However, natural ester has poor oxidation stability as compared to other types of insulation fluids, which could create thermal issues in transformers [46-48]. Previous studies on PO reveals that it has better oxidation stability whereby the acidity maintain low even after subjected to high temperature and open air ageing conditions [46-48]. Considering this factor, PO offers promising alternative especially to be used for either for free breathing or sealed transformers. Several works have been carried out to examine PO viability as a possible candidate for application in transformers.

Lightning could significantly impact the electrical power networks and equipment either through a direct strike or induced effects. Therefore, it is important to devise approaches that could protect these components. It is well acknowledged that insulation is one of the protection barriers that could provide safe operation of the transformers. MO is known could provide the required protection against lightning impulses. With the introduction of vegetable oil such as PO, this aspect needs to be re-examined due to the differences in molecular structures and chemical compositions as compared to MO. Previous studies with MO have shown that these properties could affect the streamer propagations and

breakdown characteristics which in turn influence the lightning breakdown voltages. To date, there is knowledge of lightning impulse breakdown performances of PO and still no available knowledge on its streamer propagation aspects for PO which could be useful to identify the underlying mechanisms for breakdowns [19-21, 26, 49].

Apart from dielectric insulating fluids, pressboards are one of the common insulations in transformers. Pressboards are mainly used to provide an additional barrier to prevent flashover in the oil gaps of transformers. However, the introduction of pressboards could initiate creepage discharges whereby the streamers propagate along the surface. While this behavior is well examined in MO, the knowledge for PO is still limited and it requires further examination. In addition, it is known that pressboards can be subjected to in-service ageing. Based on the study of MO, it is found that aged pressboards could affect the overall electrical and physiochemical performances of the insulation in transformers. To date, there was previous research on the streamer and breakdown characteristics in synthetic and natural ester with pressboard interface but for the knowledge on the impact of PO impregnated aged pressboards on lightning breakdown performances is still unknown [50]. Furthermore, there is still no available knowledge on the nature of streamers along the surface of the PO impregnated aged pressboards.

MO is known to have superior electrical performances as compared to vegetable oils. Based on previous studies, MO based Al_2O_3 nanofluid show the most optimum improvement of the positive lightning impulse breakdown voltage as compared to MO based Fe3O4 and MO based TiO2 nanofluid [51, 52]. Significant efforts have been undertaken to improve the electrical performances of vegetable oils through the introduction of nanoparticles. Similar exercises have been carried out on PO especially on examining the properties of AC breakdown voltages [27, 53, 54]. However, the knowledge of the lightning breakdown characteristics for the PO in the presence of nanoparticles is still unclear. In addition, the roles of surfactants especially to aid the nanoparticles on the improvement of the lightning breakdown performances of the PO need to be further examined in order to improve the understanding of the overall mechanisms of breakdowns.

1.3 Research objectives

The aim of this project is to examine the lightning breakdown performances and characteristics of the PO with consideration on the pressboard and nanoparticle. To achieve the aim of the project, several objectives have been devised as follows;

a. To evaluate the lightning breakdown voltages and pre-breakdown streamers characteristics such as shape, length and velocity of PO under non-uniform field configuration.
b. To explore the effect of new and aged pressboards on the pre-breakdown streamers shape, length and velocity as well as breakdown voltages of PO through high-speed imaging.
c. To assess the impact of nanoparticle, Al_2O_3 and surfactant, CTAB on the breakdown voltage and its characteristics such as velocity and light intensity of PO based on the light signal analysis.

1.4 Hypothesis of work

The hypothesis of work are;

a. The pre-breakdown streamer shape for PO has more branches, the propagation rate for PO is 2nd mode, and the breakdown voltage of PO is expected to be almost the same as the performance of natural ester which is in the range from 80 kV to 100 kV under positive polarity and 140 kV to 160 kV under negative polarity [33].
b. The introduction of new pressboard is expected has no influence on the PO streamer stopping length and does not affect the lightning breakdown voltage. As the aged pressboard duration increased, the PO streamer will propagate faster and reduce the lightning breakdown performances.
c. The adding of nanoparticle, Al_2O_3 and surfactant, CTAB can enhance the lightning impulse breakdown performances of PO.

1.5 Scope of work

The scope and limitations of this research work are;

a. The type of PO used in the research is the Refined Bleached and Deodorized Palm Oil (RBDPO), which are the cooking oil that is readily available in the market.
b. This research considers the lightning impulse streamer propagation and breakdown voltages of the PO under the strong non-uniform field in order to consider the worst-case senario.
c. This research considers only an insulative nanoparticle, Al_2O_3 and cationic surfactant, CTAB which shown greatest enhancement in previous study.
d. The volume concentration of Al_2O_3 under this study are from 0.001% to 0.050%, in order to result uniform dispersion and stable suspension of nanoparticles in fluids.
e. Only positive applied lightning impulse voltage is considered to evaluate the performance of PO based Al_2O_3 nanofluid with and without CTAB, which can represent the worst-case senario.

1.6 Contribution of the research

Among the main contributions of this research are as follow;

a. The knowledge on the streamer shapes, branches, lengths, and velocities of PO can be used to further understand the mechanisms of lightning discharge propagations in vegetable based oils. In addition, the statistical analysis of lightning breakdown voltage can be used for the design purpose of transformers filled with PO in the future.
b. Further understanding of the surface discharge of vegetable oils can be obtained through PO impregnated new pressboard lightning impulse study. Additional

knowledge can be obtained on the in-service streamer propagations through PO impregnated aged pressboard which can be beneficial to evaluate the condition of the insulation in transformers filled with PO in the future

c. The knowledge obtained from the positive lightning impulse of PO based nanofluids without and in the presence of surfactants can be used to understand the breakdown characteristics, which is important for justification of nanoparticle application in transformers in the future.

1.7 Thesis layout

This thesis consists of five chapters, namely, the introduction, literature review, methodology, result and discussion which comprised of pre-breakdown streamer and breakdown characteristics, in the presence of pressboard and aged pressboard, in the presence of nanoparticle and surfactant, conclusion and recommendations for future work.

Chapter 1 Introduction

This chapter describes the general background of this research, the overview of the thesis, as well as the problem statement and objectives.

Chapter 2 Literature review

This chapter presents a comprehensive review of related studies in the existing body of literature, which comprises insulation paper and fluids in transformers and the types of nanoparticles, the streamer, and breakdown studies along with the influence of several parameters that affect the breakdown strength of oils.

Chapter 3 Methodology

Chapter three elaborates on the types of fluids to be tested and on the preparation procedures for the sample fluids. The test setup and test cell configuration are described and consists of several testing configurations for the streamer propagation and breakdown voltages. The result of data processing and methods of the statistical analysis used in the study are also discussed.

Chapter 4 Result and discussion

Chapter four investigates the propagation of streamer and the lightning impulse breakdown voltage of the PO. The streamer propagations of PO are investigated for both positive and negative polarities. Based on the high-speed camera results, streamer lengths and streamer velocities are obtained. The breakdown performances of the PO are also discussed. Secondly, experiments the propagation of streamer and the lightning impulse breakdown voltage of PO in the presence of pressboard and aged pressboard. The streamer propagations of PO with different ageing duration aged pressboards are

investigated under both positive and negative polarities. Based on the high-speed camera results, streamer lengths and streamer velocities are obtained. The breakdown performances of PO with and without pressboard and aged pressboard are investigated. Lastly, experiments only the positive lightning breakdown voltage of PO in the presence of nanoparticle and surfactant. This effect of nanoparticle at variation of concentration and the presence of surfactant on the lightning breakdown voltages of PO are investigated. Based on the emission of light signals, the patterns of light signals for PO based nanofluids are obtained.

Chapter 5 Conclusion and recommendations

The final chapter summaries the conclusions on the findings and objectives of this research and the recommendations are provided for future work on investigating the behaviour of PO under lightning impulse voltage.

REFERENCES

[1] I. K. D. Martin, J. Dai & Z.D. Wang, "An Overview of the Suitability of Vegetable Oil Dielectrics for Use in Large Power Transformers," *Euro TechCon*, 2006.

[2] H. B. H. Sitorus, A. Beroual, R. Setiabudy, and S. Bismo, "Pre-breakdown phenomena in new vegetable oil - based jatropha curcas seeds as substitute of mineral oil in high voltage equipment," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 22, no. 5, pp. 2442-2448, 2015.

[3] M. Rycroft and E. Publishers, "Vegetable oil as insulating fluid for transformers," in *Energize*, ed. South Africa, 2014, pp. 37-40.

[4] T. V. Oommen, "Vegetable oils for liquid-filled transformers," *IEEE Electrical Insulation Magazine*, vol. 18, no. 1, pp. 6-11, 2002.

[5] M. A. G. Martins, "Vegetable oils, an alternative to mineral oil for power transformers- experimental study of paper aging in vegetable oil versus mineral oil," *IEEE Electrical Insulation Magazine*, vol. 26, no. 6, pp. 7-13, 2010.

[6] Norhafiz Azis, Jasronita Jasni, Mohd Zainal Abidin Ab Kadir, and M. N. Mohtar, "Suitability of Palm Based Oil as Dielectric Insulating Fluid in Transformers," *Journal of Electrical Engineering & Technology*, vol. 1, 2013.

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

[8] S. Banumathi, S. Chandrasekar, and G. C. Montanari, "Investigations on PD characteristics of vegetable oils for high voltage applications," in *IEEE 1st International Conference on Condition Assessment Techniques in Electrical Systems (CATCON)*, 2013, pp. 191-195.

[9] D.C. Abeysundara, C. Weerakoon, J R Lucas, and K. A. I. G. a. K. C. Obadage, "Coconut Oil As An Alternative To Transformer Oil," presented at the ERU Symposium 2001.

[10] 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," in *Conference Record of the IEEE International Symposium on Electrical Insulation (ISEI)*, 2012, pp. 22-25.

[11] 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.

[12] Y. Z. Arief *et al.*, "A comparative study on the effect of electrical ageing on electrical properties of palm fatty acid ester (PFAE) and FR3 as dielectric materials," in *IEEE International Conference onPower and Energy (PECon)*, 2014, pp. 128-133.

[13] A. Johari, A. A. Suleiman, N. Bashir, N. A. Muhamad, M. H. Ahmad, and I. M. Inuwa, "Performance of biodegradable insulating oil under accelerated thermal ageing," in *IEEE International Conference on Power and Energy (PECon)*, 2014, pp. 9-12.

[14] A. A. Suleiman, N. A. Muhamad, N. Bashir, N. S. Murad, Y. Z. Arief, and B. T. Phung, "Effect of moisture on breakdown voltage and structure of palm based

insulation oils," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 21, no. 5, pp. 2119-2126, 2014.

[15] S. Aditama, "Dielectric properties of palm oils as liquid insulating materials: effects of fat content," in *International Symposium on Electrical Insulating Materials, (ISEIM),* 2005, vol. 1, pp. 91-94

[16] R. Kurnianto, M. Taufan, Z. Nawawi, M. Nagao, and N. Hozumi, "Breakdown strength of biodegradable dielectric liquid: The effect of temperature and viscosity," in *22nd Australasian Universities Power Engineering Conference (AUPEC)*, 2012, pp. 1-4.

[17] N. A. Mohamad *et al.*, "A study on the dielectric properties of Palm Oil and Coconut Oil," in *IEEE International Conference on Power and Energy (PECon)*, 2014, pp. 109-112.

[18] S. S. Sinan, S. N. Shawaludin, J. Jasni, N. Azis, M. Z. A. A. Kadir, and M. N. Mohtar, "Investigation on the AC breakdown voltage of RBDPO Olein," in *IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)*, 2014, pp. 760-763.

[19] Y. V. Thien *et al.*, "Investigation on the lightning breakdown voltage of Palm Oil and Coconut Oil under non-uniform field," in *IEEE International Conference on Power and Energy (PECon)*, 2014, pp. 1-4.

[20] N. I. A. Katim *et al.*, "Examination on the lightning breakdown strength of biodegradable oil under quasi-uniform field," in *IEEE International Conference on Power and Energy (PECon)*, 2014, pp. 17-20.

[21] Y. V. Thien *et al.*, "The effect of polarity on the lightning breakdown voltages of palm oil and coconut oil under a non-uniform field for transformers application," *Industrial Crops and Products*, vol. 89, pp. 250-256, 10/30/ 2016.

[22] Y. V. Thien *et al.*, "Evaluation on the Lightning Breakdown Voltages of Palm Oil and Coconut oil under Non-uniform Field at Small Gap Distances," *Journal of Electrical Engineering & Technology*, vol. 11, no. 1, pp. 184-191, 2016.

[23] N. A. Yee Von Thien, Jasronita Jasni, Mohd Zainal Abidin Ab Kadir, Robiah Yunus, Zaini Yaakub, "Investigation on The Positive and Negative Lightning Breakdown Voltages of Refined Bleached and Deodorized Palm Oil Olein under The Presence of Copper (II) Oxide Nanoparticle," *Solid State Science and Technology*, vol. 26, no. 2, pp. 70-75, 2019.

[24] Y. V. T. Norhafiz Azis, Robiah Yunus, Zaini Yaakub, "Lightning Breakdown Voltages of Refined Bleached and Deodorised Palm Oil under Needle-plane Configuration," *Pertanika Journal of Science and Technology*, vol. 25, pp. 69-78, 2017.

[25] Y. V. Thien *et al.*, "Pre-breakdown streamer propagation and breakdown characteristics of refined bleached and deodorized palm oil under lightning impulse voltage," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 25, no. 5, pp. 1614-1620, 2018.

[26] Y. V. Thien *et al.*, "A Study on the Lightning Impulse Breakdown Voltages of Palm Oil and Coconut Oil by Different Methods," *Applied Mechanics and Materials*, vol. 793, pp. 9-13, 2015.

[27] S. F. M. Nor, N. Azis, J. Jasni, M. Z. A. A. Kadir, R. Yunus, and Z. Yaakub, "Investigation on the electrical properties of palm oil and coconut oil based TiO2 nanofluids," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 24, no. 6, pp. 3432-3442, 2017.

[28] R. Bartnikas, *Engineering Dielectrics - Electrical Insulating Liquids*. Varennes, Canada: ASTM 1916 Race Street Philadelphia, 1994.

[29] C. Hosticka, "Dependence of Uniform/Nonuniform Field Transformer Oil Breakdown on Oil Composition," *IEEE Transactions on Electrical Insulation,* vol. EI-14, no. 1, pp. 43-50, 1979.

[30] V. Y. Ushakov, V. F. Klimkin, and S. M. Korobeynikov, *Impulse Breakdown of Liquids*. India: Springer, 2007.

[31] P. Wedin, "Electrical breakdown in dielectric liquids-a short overview," *IEEE Electrical Insulation Magazine,* vol. 30, no. 6, pp. 20-25, 2014.

[32] D. J. P. Holtzhausen and D. W. L. Vosloo, *High Voltage Engineering Practice and Theory*. Stellenbosch 2011.

[33] Q. Liu and 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.

[34] R. Liu, C. Tornkvist, V. Chandramouli, O. Girlanda, and L. A. A. Pettersson, "Geometry impact on streamer propagation in transformer insulation liquids," presented at the Annual Report Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), 17-20 Oct. 2010, 2010.

[35] I. V. Timoshkin, M. J. Given, M. P. Wilson, and S. J. MacGregor, "Review of dielectric behaviour of insulating liquids," in *Proceedings of the 44th International Universities Power Engineering Conference (UPEC)*, 2009, pp. 1-4.

[36] S. Yanchao, Z. Yuanxiang, N. Dexin, W. Zhirong, and D. Jiangang, "A study on electric conduction of transformer oil," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 21, no. 3, pp. 1061-1069, 2014.

[37] C. Mazzetti, M. Pompili, R. Cecere, and E. O. Forster, "The effect of molecular structure of dielectric fluids on their conduction breakdown," in *10th International Conference on Conduction and Breakdown in Dielectric Liquids, ICDL*, 1990, pp. 557-563.

[38] E. O. Forster, H. Yamashita, C. Mazzetti, M. Pompili, L. Caroli, and S. Patrissi, "The effect of the electrode gap on breakdown in liquid dielectrics," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 1, no. 3, pp. 440-446, 1994.

[39] W. F. Schmidt and D. R. Pugh, "On the polarity effect of the breakdown voltage for dielectric liquids in an inhomogeneous field," *Journal of Applied Physics,* vol. 10, p. 1139, 1977.

[40] Z. D. Wang, Q. Liu, X. Wang, P. Jarman, and G. Wilson, "Discussion on possible additions to IEC 60897 and IEC 61294 for insulating liquid tests," *IET Electric Power Applications,* vol. 5, no. 6, pp. 486-493, 2011.

[41] L. Rongsheng, C. Tornkvist, V. Chandramouli, O. Girlanda, and L. A. Pettersson, "Ester fluids as alternative for mineral oil: The difference in streamer velocity and LI breakdown voltage," in *IEEE Conference on Electrical Insulation and Dielectric Phenomena, CEIDP*, 2009, pp. 543-548.

[42] D. Vukovic, S. Tenbohlen, J. Harthun, C. Perrier, and H. Fink, "Breakdown strength of vegetable-based oils under AC and lightning impulse voltages," in *IEEE International Conference on Dielectric Liquids (ICDL)*, 2011, pp. 1-4.

[43] C. T. Duy, O. Lesaint, A. Denat, N. Bonifaci, and Y. Bertrand, "Streamer propagation and breakdown in rape-seed oil at high voltage," in *IEEE International Conference on Dielectric Liquids, ICDL*, 2008, pp. 1-4.

[44] R. Fritsche and G. J. Pukel, "Large Power Transformers using Alternative Liquids Experience in the range of 420 kV transmission level," presented at the CIGRE, Paris, 2016.

[45] P. Hopkinson *et al.*, "Progress Report on Natural Esters for Distribution and Power Transformers," presented at the IEEE PES Transmission and Distribution Conference and Exhibition, 21-24 May 2006, 2006.

[46] C. Perrier and A. Beroual, "Experimental Investigations on Mineral and Ester Oils for Power Transformers," presented at the Conference Record of IEEE International Symposium on Electrical Insulation, ISEI 9-12 June 2008, 2008.

[47] N. A. Mohamad *et al.*, "Investigation on the Dielectric, Physical and Chemical Properties of Palm Oil and Coconut Oil under Accelerated Thermal Ageing," *Journal of Electrical Engineering & Technology*, vol. 11, pp. 709-718, 2016.

[48] N. Azis, "Ageing Assessment of Insualtion Paper with Consideration of In-services Ageing and Natural Ester Application," PhD, Faculty of Engineering and Physical Sciences, University of Manchester, 2012.

[49] M. T. I. Nurul Izzatul Akma Katim, Nur Aqilah Mohamad Amin, Mardhiah Hayati Abdul Hamid, Khairol Amali Ahmad and Norhafiz Azis "Lightning Breakdown Voltage Evaluation of Palm Oil and Coconut Oil as Transformer Oil under Quasi-Uniform Field Conditions," *Energies*, vol. 11, p. 2676, 2018.

[50] Q. Liu and Z. D. Wang, "Streamer characteristic and breakdown in synthetic and natural ester transformer liquids with pressboard interface under lightning impulse voltage," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 18, no. 6, pp. 1908-1917, 2011.

[51] M. Rafiq, Y. Lv, and C. Li, "A Review on Properties, Opportunities, and Challenges of Transformer Oil-Based Nanofluids," *Journal of Nanomaterials*, vol. 2016, p. 8371560, 2016/07/14 2016.

[52] Q. Wang, M. Rafiq, Y. Lv, C. Li, and K. Yi, "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*, vol. 2016, p. 5802753, 2016/01/18 2016.

[53] N. A. Nur Aqilah Mohamad, Jasronita Jasni, Mohd Zainal Abidin Ab Kadir, Robiah Yunus and Zaini Yaakub, "Impact of Fe3O4, CuO and Al_2O_3 on the AC Breakdown Voltage of Palm Oil and Coconut Oil in the Presence of CTAB," *Energies* vol. 12, no. 9, 2019.

[54] S. F. M. Nor *et al.*, "A study on the AC breakdown voltages of as-received palm oil and coconut oil under presence of TiO2," in *IEEE Conference on Energy Conversion (CENCON)*, 2015, pp. 354-357.

[55] J. Dai, Z. D. Wang, and P. Jarman, "Moisture and Aging Effect on the Creepage Discharge Characteristics at the Oil/Transformer-board Interface under Divergent Field," in *Electrical Insulation and Dielectric Phenomena, 2008. CEIDP 2008. Annual Report Conference on*, 2008, pp. 662-665.

[56] "Transformer oil handbook," ed. Sweden: Nynas Naphthenics AB, 2004.

[57] (24 August 2020). *Electrical Insulation Crepe Paper*.

[58] (24 August 2020). *Electrical Insulation Transformer Pressboard*.

[59] Hyrax, "Product Information - Hyrax Hypertrans Transformer Oil."

[60] C. A2-35, "Experiences in Service with New Insulating Liquids," United Kingdom2010.

[61] C. P. McShane, "Vegetable-oil-based dielectric coolants," *Industry Applications Magazine, IEEE,* vol. 8, no. 3, pp. 34-41, 2002.

[62] "Oilseeds: World Markets and Trade," United States Department of Agriculture (USDA FAS), United States 2015.

[63] 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," presented at the 2011 IEEE International Conference on Dielectric Liquids (ICDL), 26-30 June 2011, 2011.

[64] 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, no. 5, pp. 1623-1632, 2012.

[65] K. Azmi, A. Ahmad, and M. Kamarol, "Study of Dielectric Properties of a Potential RBD Palm Oil and RBD Soybean Oil Mixture as Insulating Liquid in Transformer," *Journal of Electrical Engineering and Technology,* vol. 10, pp. 709-723, 2015.

[66] T. V. Oommen, C. C. Claiborne, and J. T. Mullen, "Biodegradable electrical insulation fluids," in *Electrical Manufacturing & Coil Winding and Electrical Insulation Conference*, 1997, pp. 465-468.

[67] L. Jian, L. Ruijin, and Y. Lijun, "Investigation of natural ester based liquid dielectrics and nanofluids," presented at the International Conference on High Voltage Engineering and Application (ICHVE), 17-20 Sept. 2012, 2012.

[68] P. Rozga, M. Stanek, and D. Cieslinski, "Comparison of properties of electrical discharges developing in natural and synthetic ester at inception voltage," presented at the IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), 20-23 Oct. 2013, 2013.

[69] G. HEESS, "Crude palm oil product datasheet," ed, 2010.

[70] Suwarno, F. Sitinjak, I. Suhariadi, and L. Imsak, "Study on the characteristics of palm oil and it's derivatives as liquid insulating materials," in *7th International Conference on Properties and Applications of Dielectric Materials*, 2003, vol. 2, pp. 495-498 vol.2.

[71] K. Kiasatina, M. Kamarol, M. Zulhilmey, and Y. A. Arief, "Breakdown characteristics of RBDPO and soybean oil mixture for transformer application," in *International Conference on Electrical, Control and Computer Engineering (INECCE)*, 2011, pp. 219-222.

[72] S. Aditama, "Dielectric properties of palm oils as liquid insulating materials: effects of fat content," in *International Symposium on Electrical Insulating Materials (ISEIM 2005)*, 2005, vol. 1, pp. 91-94 Vol. 1.

[73] A. Rajab, Suwarno, and S. Aminuddin, "Properties of RBDPO Oleum as a candidate of palm based-transformer insulating liquid," in *International Conference on Electrical Engineering and Informatics, ICEEI* 2009, vol. 02, pp. 548-552.

[74] Y. LvOrcId, M. Rafiq, C. Li, and B. Shan, "Study of Dielectric Breakdown Performance of Transformer Oil Based Magnetic Nanofluids," *Energies,* vol. 10, p. 1025, 07/19 2017.

[75] M. Rafiq, Y. Lv, C. Li, and Y. Kai, "Effect of different nanoparticle types on breakdown strength of transformer oil," in *2016 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, 2016, pp. 436-440.

[76] Y. Du *et al.*, "Effect of semiconductive nanoparticles on insulating performances of transformer oil," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 19, no. 3, pp. 770-776, 2012.

[77] Y. L. Yuefan Du, Chengrong Li, Mutian Chen, Jianquan Zhou, Xiaoxin Li, You Zhou, and Youping Tu, "Effect of electron shallow trap on breakdown performance of transformer oil-based nanofluids," *Journal of Applied Physics* vol. 110, no. 10, 2011.

[78] J. G. Hwang, M. Zahn, F. M. O'Sullivan, L. A. A. Petterson, O. Hjortstam, and R. Liu, "Effect of nanoparticle charging on streamer development in transformer oil-based nanofluids," *Journal of Applied Physics*, vol. 107, no. 1, pp. 1-17, 2010.

[79] Y. Hwang *et al.*, "Stability and thermal conductivity characteristics of nanofluids," *Thermochimica Acta*, vol. 455, pp. 70-74, 2007.

[80] Y. Hwang *et al.*, "Stability and thermal conductivity characteristics of nanofluids," *Thermochimica Acta*, vol. 455, no. 1, pp. 70-74, 2007/04/01/ 2007.

[81] M. Z. J. George Hwang, Francis M. O'Sullivan, Leif A. A. Pettersson, Olof Hjortstam, and Rongsheng Liu, "Effects of nanoparticle charging on streamer development in transformer oil-based nanofluids," *Journal of Applied Physics*, vol. 107, no. 1, 2010.

[82] W. Yu and H. Xie, "A Review on Nanofluids: Preparation, Stability Mechanisms, and Applications," *Journal of Nanomaterials*, vol. 2012, p. 17, 2012, Art. no. 435873.

[83] S. F. M. Nor, "Breakdown Characteristics and Dielectric Properties of Palm Oil and Coconut Oil Based TiO2 Nanofluids," Degree of Master of Science, Faculty of Engineering, Universiti Putra Malaysia, Malaysia, 2016.

[84] "Cetyltrimethylammonium Bromide (CTAB)," I. Columbus Chemical Industries, Ed., ed. Columbus: Columbus Chemical Industries, Inc, 2015.

[85] *IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines*, 2011.

[86] Q. Liu and Z. D. Wang, "Breakdown and withstand strengths of ester transformer liquids in a quasi-uniform field under impulse voltages," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 20, no. 2, pp. 571-579, 2013.

[87] Q. Liu, "Electrical Performance Of Ester Liquids Under Impulse Voltage For Application In Power Transformers," Faculty of Engineering and Physical Sciences, The University of Manchester, 2011.

[88] M. J. Heathcote, *The J & P transformer book*. Great Britain: Elsevier Ltd, 2007.

[89] D. Martin and Z. D. Wang, "Statistical analysis of the AC breakdown voltages of ester based transformer oils," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 15, no. 4, pp. 1044-1050, 2008.

[90] J. K. Nelson and C. Shaw, "The impulse design of transformer oil-cellulose structures," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 13, no. 3, pp. 477-483, 2006.

[91] W. Lick and M. Muhr, "Strength investigations on long oil gaps," in *IEEE 14th International Conference on Dielectric Liquids, ICDL*, 2002, pp. 228-230.

[92] X. Wang, "Partial Discharge Behaviours And Breakdown Mechanisms Of Ester Transformer Liquids Under Ac Stress," Faculty of Engineering and Physical Sciences, The University of Manchester, 2011.

[93] A. Sun, C. Huo, and J. Zhuang, "Formation mechanism of streamer discharges in liquids: a review," *Journals of the Institution of Engineering and Technology, IET - High Voltage*, vol. 1, no. 2, pp. 74-80, 2016.

[94] C. T. Duy, O. Lesaint, A. Denat, and N. Bonifaci, "Streamer propagation and breakdown in natural ester at high voltage," *Dielectrics and Electrical Insulation, IEEE Transactions on*, vol. 16, no. 6, pp. 1582-1594, 2009.

[95] M. Hemmer, Y. Julliard, R. Badent, and A. J. Schwab, "Streamer inception and propagation in rape-seed oils and mineral oils," presented at the Conference on Electrical Insulation and Dielectric Phenomena, 2001, 2001.

[96] M. N. Ngoc, O. Lesaint, N. Bonifaci, A. Denat, and M. Hassanzadeh, "A comparison of breakdown properties of natural and synthetic esters at high voltage," presented at the Annual Report Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), 17-20 Oct. 2010, 2010.

[97] M. I. Qureshi, A. Beroual, and E. A. Al-Ammar, "Optical observation of streamer propagation and breakdown in seed based insulating oil under impulse voltages," *International Journal of Physical Sciences*, vol. 9, no. 13, pp. 292-301, 2014.

[98] V. Dang, A. Beroual, and C. Perrier, "Comparative study of streamer phenomena in mineral, synthetic and natural ester oils under lightning impulse voltage," in *International Conference on High Voltage Engineering and Application (ICHVE)*, 2010, pp. 560-563.

[99] V. Dang, A. Beroual, and C. Perrier, "Investigations on streamers phenomena in mineral, synthetic and natural ester oils under lightning impulse voltage," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 19, no. 5, pp. 1521-1527, 2012.

[100] A. Beroual *et al.*, "Propagation and structure of streamers in liquid dielectrics," *IEEE Electrical Insulation Magazine*, vol. 14, no. 2, pp. 6-17, 1998.

[101] O. Lesaint and G. Massala, "Positive streamer propagation in large oil gaps: experimental characterization of propagation modes," *Dielectrics and Electrical Insulation, IEEE Transactions on*, vol. 5, no. 3, pp. 360-370, 1998.

[102] Q. Liu, Z. D. Wang, and O. Lesaint, "Comparison of streamer propagation in mineral oils under lightning and step impulse voltages," in *2014 IEEE 18th International Conference on Dielectric Liquids (ICDL)*, 2014, pp. 1-4.

[103] P. Rozga, "Streamer propagation in a non-uniform electric field under lightning impulse in short gaps insulated with natural ester and mineral oil," *Bulletin of the Polish Academy of Sciences. Technical Sciences*, vol. 64, no. 1, 2016.

[104] J. Dai, Z. D. Wang, and P. Jarman, "Creepage discharge on insulation barriers in aged power transformers," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 17, no. 4, pp. 1327-1335, 2010.

[105] V. Sokolov, Z. Berler, and V. Rashkes, "Effective methods of assessment of insulation system conditions in power transformers: a view based on practical experience," in *Proceedings: Electrical Insulation Conference and Electrical Manufacturing and Coil Winding Conference (Cat. No.99CH37035)*, 1999, pp. 659-667.

[106] O. Lesaint and G. Massala, "Transition to fast streamers in mineral oil in the presence of insulating solids," in *Conference Record of the 1996 IEEE International Symposium on Electrical Insulation*, 1996, vol. 2, pp. 737-740 vol.2.

[107] L. Lundgaard, D. Linhjell, G. Berg, and S. Sigmond, "Propagation of positive and negative streamers in oil with and without pressboard interfaces," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 5, no. 3, pp. 388-395, 1998.

[108] Q. Liu and Z. D. Wang, "Streamer characteristic and breakdown in synthetic and natural ester transformer liquids with pressboard interface under lightning impulse voltage," *Dielectrics and Electrical Insulation, IEEE Transactions on*, vol. 18, no. 6, pp. 1908-1917, 2011.

[109] A. Beroual, V. Dang, M. Coulibaly, and C. Perrier, "Investigation on creeping discharges propagating over pressboard immersed in mineral and vegetable oils under AC, DC and lightning impulse voltages," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 20, no. 5, pp. 1635-1640, 2013.

[110] P. Sun, W. Sima, M. Yang, and J. Wu, "Influence of thermal aging on the breakdown characteristics of transformer oil impregnated paper," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 23, no. 6, pp. 3373-3381, 2016.

[111] C. N. M.M. Tshivhilinge, "Effect of Surface Discharges on Lightning Impulse Breakdown Voltage of Oil-Impregnated Pressboard in Power Transformers," *South African Institute of Electical Engineers*, vol. 107, no. 1, pp. 38-45, 2016.

[112] H. Ding, Z. D. Wang, and P. N. Jarman, "Effect of ageing on the impulse breakdown strength of oil-impregnated pressboard used in power transformers," in *2006 IEEE Conference on Electrical Insulation and Dielectric Phenomena*, 2006, pp. 497-500.

[113] M. S. a. B. P. Pawel Rozga, "Characteristics of Negative Streamer Development in Ester Liquids and Mineral Oil in a Point-To-Sphere Electrode System with a Pressboard Barrier," *Energies* vol. 11, 2018.

[114] Y. Du, Y. Lv, J.-q. Zhou, X. Li, and C. Li, "Breakdown properties of transformer oil-based TiO2 nanofluid," in *2010 Annual Report Conference on Electrical Insulation and Dielectic Phenomena*, 2010, pp. 1-4.

[115] Y. Z. Ziyi Wang, Wu Lu, Neng Peng and Weijie Chen, "The Impact of TiO2 Nanoparticle Concentration Levels on Impulse Breakdown Performance of Mineral Oil-Based Nanofluids," *Nanomaterials*, vol. 9, no. 4, 2019.

[116] Y. Lv *et al.*, "Effect of TiO2 nanoparticles on streamer propagation in transformer oil under lightning impulse voltage," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 23, no. 4, pp. 2110-2115, 2016.

[117] Y. Lv *et al.*, "Nanoparticle Effect on Dielectric Breakdown Strength of Transformer Oil-Based Nanofluids," in *2013 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, 2013, pp. 680-682.

[118] U. S. R. M. Srinivasan, K. Sindhuja and A. Raymon, "Investigation and Performance Analysis of Nanoparticles and Antioxidants Based Natural Ester," *International Journal of Advanced Engineering Technology*, vol. 7, no. 2, pp. 1000-1007, 2016.

[119] J. Li, Z. Zhang, P. Zou, S. Grzybowski, and M. Zahn, "Preparation of a vegetable oil-based nanofluid and investigation of its breakdown and dielectric

properties," *IEEE Electrical Insulation Magazine*, vol. 28, no. 5, pp. 43-50, 2012.

[120] B. Du, J. Li, F. Wang, W. Yao, and S. Yao, "Influence of Monodisperse Fe₃O₄ Nanoparticle Size on Electrical Properties of Vegetable Oil-Based Nanofluids," *Journal of Nanomaterials*, vol. 2015, p. 560352, 2015/10/05 2015.

[121] N. A. Nur Aqilah Mohamad, Jasronita Jasni, Mohd Zainal Abidin Ab. Kadir, Robiah Yunus, Zaini Yaakub, "Effect of Surfactants on the Lightning Breakdown Voltage of Palm Oil and Coconut Oil based Al_2O_3 Nanofluids," *Nanotechnology*, 2020.

[122] A. H. A. Tarmizi, S. W. Lin, and A. Kuntom, "Development of Palm-Based Reference Materials for the Quantification of Fatty Acids Composition," *Journal of Oleo Science*, vol. 57, no. 5, pp. 275-285, 2008.

[123] M. Coulibaly, C. Perrier, M. Marugan, and A. Beroual, "Aging behavior of cellulosic materials in presence of mineral oil and ester liquids under various conditions," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 20, no. 6, pp. 1971-1976, 2013.

[124] M. Rafiq *et al.*, "Use of vegetable oils as transformer oils – a review," *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 308-324, 2015/12/01/ 2015.

[125] M. G. Niasar, N. Taylor, H. Edin, and R. C. Kiiza, "Impact of thermal and electrical aging on breakdown strength of oil-impregnated paper," in *2015 IEEE Eindhoven PowerTech*, 2015, pp. 1-5.

[126] L. Shuai, Z. Xuetong, R. Liao, L. Yang, and P. Guo, "Study on ageing characteristics of insulating pressboard impregnated by mineral-vegetable oil," in *2016 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, 2016, pp. 70-73.

[127] D. H. S. a. A. W. Stannett, "A review of paper aging in power transformers," *IEE Proceedings on Generation, Transmission and Distribution*, vol. 132, pp. 312-319, 1985.

[128] S. K. T. P. Das, Stephen U. S. Choi, Wenhua Yu, *Nanofluids - Science and Technology*. 2008.

[129] M. Hanai, S. Hosomi, H. Kojima, N. Hayakawa, and H. Okubo, "Dependence of TiO2 and ZnO nanoparticle concentration on electrical insulation characteristics of insulating oil," in *Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, 2013, pp. 780-783.

[130] S. Aldrich, "Sodium dodecyl sulfate," *Materials Safety Data Sheet*, pp. 1-9, 2018.

[131] S. Aldrich, "Oleic Acid," *Materials Safety Data Sheet*, pp. 1-7, 2016.

[132] S. Aldrich, "Cetyltrimethylammonium Bromide " pp. 1-5, 2008 2008.

[133] "IEC 60897 "Methods for the determination of the lightning impulse breakdown voltage of insulating liquids"," ed: International Electrotechnical Commission, 1987.

[134] A. Shrivastava, "2 - Polymerization," in *Introduction to Plastics Engineering*, A. Shrivastava, Ed.: William Andrew Publishing, 2018, pp. 17-48.

[135] D. Martin and Z. Wang, *Evaluation of the Dielectric Capabilities of Ester Based Oils for Power Transformers*. University of Manchester, 2007.

[136] J. K. Nelson and C. Shaw, "The Impulse Design of Transformer Oil-Cellulose Structures," *IEEE Transaction on Dielectric and Electrical Insulation,* vol. 13, pp. 477-483, 2006.

[137] W. Lick and M. Muhr, "Strength Investigations on Long Oil Gaps," presented at the IEEE International Conference on Dielectric Liquids, Austria, 2002.

[138] X. Wang, "Partial Discharge Behaviours and Breakdown Mechanisms of Ester Transformer Liquids Under AC Stress," Doctor of Philosophy, School of Electrical and Electronic Engineering, University of Manchester, Manchester, England, 2011.

[139] H. Z. Ding, Z. D. Wang, and P. Jarman, "Dielectric Strength of Aged Transformer Oils. Experimental Studies and Statistical Analysis of Breakdown Voltage," presented at the International Symposium on High Voltage Engineering, China, 2005.

[140] N. V. Dung, H. K. Hoidalen, D. Linhjell, L. E. Lundgaard, and M. Unge, "A study on positive streamer channels in Marcol Oil," in *Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, 2012, pp. 365-370.

[141] W. G. Chadband and T. M. Sufian, "Experimental Support for a Model of Positive Streamer Propagation in Liquid Insulation," *IEEE Transactions on Electrical Insulation,* vol. EI-20, no. 2, pp. 239-246, 1985.

[142] R. Zamiri, A. Zakaria, H. A. Ahangar, A. R. Sadrolhosseini, and M. A. Mahdi, "Fabrication of Silver Nanoparticles Dispersed in Palm Oil Using Laser Ablation," *International Journal of Molecular Sciences,* vol. 11, no. 11, pp. 4764-4770, 2010.

[143] O. Lesaint, A. Denat, and F. M. Cluskey, "Positive streamers in short and large gaps in hydrocarbons of various chemical natures," in *IEEE 18th International Conference on Dielectric Liquids (ICDL)*, 2014, pp. 1-4.

[144] I. Fofana, H. Borsi, E. Gockenbach, and M. Farzaneh, "Aging of transformer insulating materials under selective conditions", *European Transactions on Electrical Power,* vol. 17, pp. 450-470, 2006.

[145] Z. D. W. H. Z. Ding, "On the degradation evolution equations of cellulose," *Cellulose,* vol. 15, pp. 205-224, 2008.

[146] P. Rozga, M. Stanek, and B. Pasternak, "Characteristics of Negative Streamer Development in Ester Liquids and Mineral Oil in a Point-To-Sphere Electrode System with a Pressboard Barrier," *Energies*, vol. 11, no. 5, 2018.

[147] J. R. Lucas, *High Voltage Engineering*. Sri Lanka: Department of Electrical Engineering University of Moratuwa, 2001.

[148] Y. V. Torshin, "Prediction of Breakdown Voltage of Transformer Oil from Predischarge Phenomena," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 10, no. 6, pp. 933-941, 2003.

[149] Qi Wang, Muhammad Rafiq, Yuzhen Lv, Chengrong Li, and K. Yi, "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*, pp. 1-6, 2016.

[150] M. Rafiq, Y. lv, and C. Li, "Effect of Shape, Surface Modification and Concentration of Al_2O_3 Nanoparticles on Breakdown Performance of Transformer Oil," *Journal of Electrical Engineering & Technology*, vol. 15, 01/22 2019.

[151] S. Kumar, M. Gradzielski, and S. K. Mehta, "The critical role of surfactants towards CdS nanoparticles: Synthesis, stability, optical and PL emission properties," *RSC Advance*, vol. 3, no. 8, pp. 2662-2676, 2013.

[152] O. Lesaint and G. Massala, "Positive Streamer Propagation in Large Oil gaps: Experimental Characterization of Propagation Modes " *IEEE Transaction on Dielectric and Electrical Insulation*, vol. 5, no. 3, pp. 360-370, 1998.

[153] *ASTM D6871-03 Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus*, 2008.

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LIST OF PUBLICATIONS

Journals

[1] **Y. V. Thien**, N. Azis, J. Jasni, M. Z. A. Ab Kadir, R. Yunus, M. T. Ishak, Z. Yaakub, "The effect of polarity on the lightning breakdown voltages of palm oil and coconut oil under a non-uniform field for transformers application," Industrial Crops and Products, vol. 89, pp. 250-256, 2016.

[2] N. Azis, **Y. V. Thien**, R. Yunus, and Z. Yaakub, "Lightning Breakdown Voltages of Refined Bleached and Deodorised Palm Oil under Needle-plane Configuration," Pertanika Journal of Science and Technology, vol. 25, pp. 69-78, 2017.

[3] **Y. V. Thien**, N. Azis, J. Jasni, M. Z. A. A. Kadir, R. Yunus, M. K. M. Jamil, et al., "Pre-breakdown streamer propagation and breakdown characteristics of refined bleached and deodorized palm oil under lightning impulse voltage," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 25 (5), pp. 1614-1620, 2018.

[4] **Y. V. Thien**, N. Azis, J. Jasni, M. Z. A. A. Kadir, R. Yunus, and Z. Yaakub, "Investigation on The Positive and Negative Lightning Breakdown Voltages of Refined Bleached and Deodorized Palm Oil Olein under The Presence of Copper (II) Oxide Nanoparticle," Solid State Science and Technology, vol. 26 (2), pp. 70-75, 2018.

[5] **Y. V. Thien**, N. Azis, J. Jasni, M. Z. A. A. Kadir, R. Yunus, and Z. Yaakub, "Pre-Breakdown Streamer Propagation and Positive Lightning Breakdown Characteristics of Palm Oil Impregnated Aged Pressboard," IEEE Access, vol. 8, pp. 58836-58844, 2020.

Conference Proceedings

[1] **Y. V. Thien**, N. Azis, J. Jasni, R. Yunus, M. Z. A. A. Kadir and Z. Yaakub, "Influence of Electrode Geometry on the Lightning Impulse Breakdown Voltage of Palm Oil," IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), pp. 317-320, Kota Kinabalu, Sabah, October 2018.

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