UNIVERSITI PUTRA MALAYSIA

DIELECTRIC PERFORMANCES OF PALM OIL AND COCONUT OIL-BASED NANOFLUIDS WITH SURFACTANTS

NUR AQILAH BINTI MOHAMAD

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By

NUR AQILAH BINTI MOHAMAD

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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With the current interest of green technology application in transformers, PO and CO have been introduced as viable alternatives for MO. Previous studies have shown that the dielectric performances of these oils are comparable with MO. These properties however could be further improved through introduction of conductive, semi-conductive and insulative nanoparticles. Currently, there are only few studies that have been conducted in this area for these oils, which prompt for in-depth investigation. In addition, the roles of ionic and non-ionic surfactants for vegetable based nanofluids are quite limited which warrants for further investigation for its feasibility to enhance the effectiveness of the nanoparticles.

This study aims to examine the dielectric performances of RBDPO and CO in the presence of Fe_3O_4, CuO and Al_2O_3 nanoparticles with surfactant. The types of surfactants used in this study were CTAB, SDS and OA. Fourier transform infrared and particle size distribution were used to characterize the nanoparticles in the oils. MO was also examined for comparison purpose. The AC breakdown voltage was carried out and the data was analysed for the AC withstand voltage at 1% probability. The Al_2O_3 was chosen for the lightning breakdown voltages and PD since it could provide the highest improvement of AC breakdown voltage. The lightning breakdown test was carried out based on needle-sphere electrodes configuration at the gap distance of 25 mm under positive and negative polarities. The PD were measured based on needle-sphere electrode configuration at the gap distance of 50 mm. Rising voltage method was applied for the lightning breakdown voltage and PDIV measurements. A photo multiplier tube was also used to detect faint optical signals from weakly emitting sources during the PD test.

It is found that only Al_2O_3 can improve the average AC breakdown voltage of RBDPO and CO. The AC withstand voltages at 1% probability for RBDPO, CO and MO could be improved through introduction of Fe_3O_4, CuO and Al_2O_3 at certain volume concentrations. OA could provide the highest improvement of the AC withstand voltages at 1% probability for RBDPO, CO and MO based Al_2O_3 nanofluids. Al_2O_3 could improve both positive and negative lightning breakdown voltages of RBDPO and CO. Under both polarities, CTAB provide the highest improvements on the lightning breakdown voltages of RBDPO, CO and MO based Al_2O_3 nanofluids. CTAB further increases the times to breakdown and decrease the average streamer velocities of RBDPO based Al_2O_3 nanofluid under both polarities. The same finding is observed for CO under positive polarity with CTAB and SDS as well as under negative polarity with all surfactants. It is found that, RBDPO, CO and MO based Al_2O_3 nanofluids have second mode of streamer whereby the streamer velocities are from 1 km/s to 3.4 km/s regardless with or without surfactants. The presence of Al_2O_3 does improve the PDIV of RBDPO and CO without and with either CTAB or SDS. The maximum PD amplitudes of RBDPO, CO and MO could further be enhanced in the presence of Al_2O_3 with either SDS or OA. On the other hands, the PD repetition rates for RBDPO, CO and MO improve in the presence of Al_2O_3 regardless with and without surfactants. Al_2O_3 leads to the increment of light signal emissions for RBDPO and CO and it is further enhanced in the presence of surfactants.

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

PRESTASI DIELEKTRIK TERHADAP MINYAK KELAPA SAWIT DAN MINYAK KELAPA-BERASASKAN CECAIR NANO DENGAN SUFKATAN

Oleh

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Dengan faedah terkini aplikasi teknologi hijau terhadap alat ubah atau "transformer", PO dan CO telah diperkenalkan sebagai alternatif yang sesuai untuk MO. Kajian sebelum ini menunjukkan bahawa prestasi dielektrik minyak ini setanding dengan MO. Walau bagaimanapun, ciri-ciri ini dapat diperbaiki dengan memperkenalkan nanopartikel. Pada masa ini, hanya beberapa kajian sahaja yang dilakukan ke atas minyak tersebut, di mana ianya memerlukan penyelidikan yang lebih mendalam. Di samping itu, peranan surfaktan untuk cecair nano berasaskan minyak sayuran adalah agak terhad dan kajian lebih lanjut diperlukan untuk meningkatkan keberkesanannya ke atas nanopartikel.

Kajian ini bertujuan untuk mengkaji prestasi dielektrik RBDPO dan CO dengan kehadiran Fe_3O_4, CuO and Al_2O_3 nanopartikel dengan kehadiran surfaktan. Jenis surfaktan yang digunakan di dalam kajian ini CTAB, SDS dan OA. Penyebaran inframerah transformasi Fourier dan ukuran zarah digunakan untuk menggambarkan sifat nanopartikel dalam minyak. MO juga digunakan untuk tujuan perbandingan. Voltan kerosakan AC diuji dan data dianalisis pada kebarangkalian 1%. Nanopartikel, Al_2O_3 dipilih untuk voltan kerosakan kilat dan PD kerana ianya dapat meningkatkan voltan kerosakan AC yang paling tinggi. Ujian kerosakan kilat dilakukan berdasarkan konfigurasi elektrod sfera-jarum pada jarak jurang 25 mm di bawah kutub positif dan negatif. PD diukur berdasarkan konfigurasi elektrod sfera-jarum pada jarak jurang 50 mm. Kaedah peningkatan voltan digunakan untuk mengukur voltan kerosakan kilat dan PDIV. Tiub pengganda foto juga digunakan untuk mengesan isyarat optik samar daripada sumber yang lemah semasa ujian PD.

Al_2O_3 adalah satu-satunya komponen yang dapat meningkatkan voltan kerosakan AC pada RBDPO dan CO. OA dapat memberikan peningkatan

voltan AC yang paling tinggi pada kebarangkalian 1% untuk cecair nano Al_2O_3 berasaskan RBDPO, CO dan MO. Al_2O_3 juga dapat meningkatkan voltan kerosakan kilat positif dan negatif RBDPO dan CO. Di bawah pengaruh kutub positif dan negatif, CTAB memberikan peningkatan tertinggi pada voltan kerosakan kilat dari nanofluid Al_2O_3 berdasarkan RBDPO, CO dan MO. CTAB meningkatkan lagi masa untuk pemecahan dan mengurangkan kelajuan aliran rata nanofluid Al_2O_3 berasaskan RBDPO di bawah kedua-dua kutub. Penemuan yang sama diperhatikan pada CO di bawah kutub positif dengan CTAB berserta SDS di bawah kutub negatif dengan semua surfaktan. Pemerhatian mendapati bahawa nanofluid Al_2O_3 berasaskan RBDPO, CO dan MO mempunyai mod aliran kedua di mana had laju aliran adalah dari 1 km/s hingga 3.4 km/s tanpa atau degan kehadiran surfaktan. Kehadiran Al_2O_3 meningkatkan PDIV bagi RBDPO dan CO tanpa dan bersama CTAB atau SDS. Amplitud PD maksimum RBDPO, CO dan MO dapat ditingkatkan lagi dengan adanya Al_2O_3 berserta SDS atau OA. Sebaliknya, kadar pengulangan PD untuk RBDPO, CO dan MO bertambah baik dengan kehadiran Al_2O_3 tanpa mengira kadar surfaktan. Al_2O_3 membawa kepada peningkatan pelepasan isyarat cahaya untuk RBDPO dan CO dan ia ditingkatkan lagi dengan adanya surfaktan.

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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

°C	Degree Celsius
%	Percentage
-	Negative
+	Positive
Ω	Ohm
α	Alpha
β	Beta
μ	Micro
μm	Micrometer
cm	Centimeter
cSt	Centistokes
C	Carbon
dm	Decimeter
d	Distance
e	Electron
F	Farad
g	Gram
g/ml	Gram per milliliter
J	Joule
K	Kelvin
kg	Kilogram
km	Kilometer
kV	Kilo volt
lm	Lumen
mg	Milli gram
min	Minute
ml	Milliliter
mm	Millimeter
mN/m	Millinewton per meter
MVA	Mega volt ampere
nm	Nanometer
p	Pico
pC	Pico Columb
ppm	Parts per million
s	Second
S	Siemens
t	Time
v	Velocity
V	Volt
W/m.k	Watts per meter Kelvin
AC	Alternating Current
AIN	Aluminium Nitride
Al_2O_3	Aluminium Oxide
ASTM	American Society for Testing and Materials
ATR	Attenuated Total Reflection
BAC	Benzethonium Chloride
BN	Boron

CI	Confidence Interval
CO	Coconut Oil
CPC	Cetylpyridinium chloride
CPO	Crude Palm Oil
CTAB	Cetyltrimethylammonium Bromide
CTAC	Cetyltrimethylammonium chloride
Cu_2O	Copper Oxide
CuO	Copper (II) Oxide
FAT	Factory Acceptance Test
Fe_2O_3	Iron (III) Oxide
Fe_3O_4	Iron (II,III) Oxide
FTIR	Fourier Transform Infrared
GC	Gas Chromatography
GO	Graphine Oxide
HV	High Voltage
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Standards Organization
LV	Low Voltage
MLS	Magnesium Laurel Sulfate
MO	Mineral Oil
MWCNT	Multi-wall Carbon Nanotubes
NE	Natural Ester
OA	Oleic Acid
PD	Partial Discharge
PDIV	Partial Discharge Inception Voltage
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
RCO	Refined Coconut Oil
SDBS	Sodium Dodecyl Benzene Sulfonate
SDS	Sodium Dodecyl Sulfate
SiO_2	Silicon Dioxide
SLS	Sodium Lauryl Sulfate
TiO_2	Titanium Dioxide
VCO	Virgin Coconut Oil
VDE	Verband der Elektrotechnik
VO	Vegetable Oil
ZnO	Zinc Oxide
Zr_2O	Zirconium Oxide

CHAPTER 1

INTRODUCTION

1.1 Background

For more than a century, Mineral Oil (MO) have been widely used in high voltage transformers. Among the main functions of the MO are to insulate between components, dissipate heat generated from the core/winding and act as information carriers for condition monitoring purposes [1-4]. However, there are several issues associated with MO such as its non-biodegradable nature, low flash/fire points and toxicity which could lead to serious environmental issues if there is a spillage [5]. Due to the increasing regulations on environment and safety, alternative dielectric insulating fluids for MO are currently been sought. Among the possible oils considered for transformers application is Vegetable Oil (VO). VOs are highly biodegradable, non-toxic, high in flash/fire points and low in term flammability [6-8]. There are a significant number of studies on different types of VOs that have been carried out to investigate the performances of the VOs. Natural ester (NE), rapeseed, palm, soybean and corn oils are among the VOs that have been examined focusing into the basic characteristics, ageing properties and breakdown mechanisms [7, 9-12]. Palm Oil (PO) and Coconut Oil (CO) are among the types of VOs that are considered as insulation oils. PO and CO have also been identified as among the sustainable VOs in the market [13]. At present, a number of studies have been carried out on PO and CO that covers different basic electrical, physiochemical properties such as AC breakdown voltage, lightning breakdown strength, Partial Discharge (PD), dielectric properties, acidity, viscosity, moisture and colour [9, 10, 14, 15].

Nowadays, nanotechnology provides exciting new possibilities to enhance the performances of dielectric insulating fluids especially on the electrical properties, PD, thermal conductivity, thermal diffusivity, cooling properties, viscosity and convective heat transfer coefficients [16-19]. The effects of nanoparticles on dielectric insulating fluids are known to be dependent upon the intrinsic properties, volume concentrations, solid-liquid contact areas, suspension by surfactants and synthesis methods [20, 21].

Various studies have been carried out on MO and VO based nanofluids based on conductive, semi-conductive and insulative nanoparticles. Electrical properties such as AC breakdown voltage, lightning breakdown voltage, PD, streamer, thermal ageing and dielectric properties have been examined through various setups [3, 21-36]. Different types of nanoparticles such as Iron (II,III) Oxide (Fe_3O_4), Iron (III) Oxide (Fe_2O_3), Titanium Dioxide (TiO_2), Zinc Oxide (ZnO), Silicon Dioxide (SiO_2), Copper (II) Oxide (CuO), Aluminium Oxide (Al_2O_3), Zirconium Oxide (Zr_2O), Multi-wall Carbon Nanotubes (MWCNT) and Aluminium Nitride (AIN) have been examined through different types of synthesis procedures [3, 19, 22-39]. Both mineral and vegetable-based nanofluids have been examined for AC breakdown voltage and the performance improvements up to 256% and 63% have been recorded [35, 36]. It was also found that the highest improvement on the lightning breakdown voltage of MO and VO based nanofluids can be up to 83% and 37%, respectively, [26, 39]. While the AC/lightning breakdown voltages and PD studies on MO based nanofluids are quite extensive, the knowledge on the AC/lightning breakdown voltages and PD of VO especially on Refined, Bleached and Deodorized Palm Oil (RBDPO) and CO based nanofluids are still lacking.

1.2 Problem Statement

The current trend in electrical power system network is moving towards the application of green technologies. The limitations of MO do not fit with the initiatives whereby alternatives such as VO are currently considered. In order to provide alternative to VO (rapeseed based), several effort have been carried out to examine other types of VO such as PO and CO. These oils have been identified as possible options for application as dielectric insulating fluids in transformers. The basic dielectric properties of these oils are comparable with other types of VO. There are however several element that can be improved in electrical properties of PO and CO through chemical modification or introduction of nanoparticles. Nanoparticles could provide the simplest solution to improve the performances of PO and CO. At the moment, the detailed knowledge especially on the AC breakdown voltage, lightning breakdown voltages of PO and CO based nanofluids are still unclear. AC breakdown voltage is the key parameter for insulation design and condition monitoring purposes of transformers. Even though it has been shown that different types of nanoparticles such as Fe_3O_4, Al_2O_3, TiO_2 and SiO_2 could improve the AC breakdown voltages of different types of oils, limited studies have been carried out on PO and CO. It is critical to identify which nanoparticles can give the highest improvement of AC breakdown voltages of PO and CO. Furthermore, the effects and roles of different types of surfactants such as Cetyltrimethylammonium Chloride (CTAB), Sodium Dodecyl Sulfate (SDS) and Oleic Acid (OA) especially to aid the nanoparticles on the improvement of the AC breakdown voltages of PO and CO have not been discussed in much detail in previous studies. Other important parameter for dielectric insulating fluids is lightning breakdown voltage. The test is normally carried out once the oils have passed the AC breakdown voltage requirement. Most of the studies on lightning breakdown voltage of nanofluids such as Fe_3O_4, TiO_2 and SiO_2 are without the presence of surfactants. Since surfactants are one of the crucial components to maintain the suspension of nanoparticles in oils, it is important to examine its effect especially on the streamer velocities and times to breakdown under different polarities. Furthermore, limited information can be obtained on these parameters especially for PO and CO under non-uniform field. PD is considered one of the advanced measurements to identify any possible deformations in transformers. Considering nanoparticles would affect the PD properties of nanoparticles, it is important that the acceptance levels are adequate for practical in-service applications. To date, there is no study has been carried out to identify the acceptance levels and discharge characteristics for Fe_3O_4, CuO and Al_2O_3 based nanofluids with and without CTAB, SDS and OA surfactants especially for PO and CO.

1.3 Research Aim and Objectives

The aim of this research is to examine the dielectric performances of RBDPO and CO based nanofluids with and without CTAB, SDS and OA. In order to achieve the aim of this research, several objectives identified are as follows:

1. To examine the AC and withstand breakdown voltages of RBDPO and CO based nanofluids with and without CTAB, SDS and OA, and identification the suitable nanoparticles that provide optimum improvement.
2. To investigate the lightning breakdown voltage and streamer properties of RBDPO and CO based nanofluids with and without CTAB, SDS and OA under non-uniform field configuration.
3. To examine the Partial Discharge Inception Voltage (PDIV) and discharge activities of RBDPO and CO based nanofluids with and without CTAB, SDS and OA with consideration on the light analysis.

1.4 Scope of Work

The scope and limitations of this research work are as follows:

1. This research only considers a conductive nanoparticle, Fe_3O_4, semi-conductive nanoparticle, CuO and insulative nanoparticle, Al_2O_3, which are shown the greatest enhancement in MO and previous studies.
2. The volume concentrations of Fe_3O_4, CuO and Al_2O_3 used in this study are 0.001%, 0.025%, 0.035% and 0.05%, in order to result uniform dispersion and stable suspension of nanoparticles in the oils.
3. This research only considers cationic surfactant, CTAB, anionic surfactant, SDS and non-ionic surfactant, OA which shown the greatest improvement of the stability the suspension nanoparticles in dielectric insulating in the previous study.
4. This research focuses on the AC breakdown voltages, lightning breakdown voltages, PDIV and discharge activities of RBDPO and CO based nanofluids with and without CTAB, SDS and OA.

1.5 Contributions of Research

The contributions of this research are as follows:

1. The information derived from the effect of various concentrations, different types of nanoparticles and surfactants on the AC breakdown voltage of RBDPO and CO based nanofluids can be utilized to identify the optimum combination that can provide the highest improvement.
2. The knowledge obtained from the lightning breakdown voltages of RBDPO and CO based nanofluids with and without surfactants can be

used to understand the streamer characteristics that can be used for design purposes in transformers.

3. The knowledge from the PDIV and discharge activities of RBDPO and CO based nanofluids with and without surfactants can be used to identify the acceptance levels for design purposes in transformers. The discharge mechanisms that are also understood from this knowledge can be used to prevent unnecessary breakdowns for in-service applications.

1.6 Chapter Outline

This thesis consists of seven chapters, which covers the introduction, literature review, methodology, result and discussion. The chapters are comprised of: AC breakdown voltages; lightning breakdown voltages and PD; and conclusion and recommendations for future work. Chapter 1 introduces the background and problem statement of this study. Also described are the research aim and objectives, together with the scope, limitations and contributions of the research. While, Chapter 2 provides a detailed overview of the insulation materials in transformers and a brief introduction of nanoparticles and surfactant in dielectric insulating fluids. The synthesis processes of nanofluids are described along with the most recent studies on MO and VO based nanofluids. Chapter 3 describes the procedure of nanofluids preparation. It describes the properties of oils and explains the characteristics of nanoparticles and surfactant. This is followed by the pre-processing of the materials and procedure to prepare all the oil samples. The detailed explanation of AC, lightning breakdown voltages and PD measurement are also presented. The result data processing and methods of the statistical analysis used in this study are also discussed. Chapter 4 presents the measurement results and data analysis of the AC breakdown voltage of RBDPO and CO based nanofluids. The effect of different types of nanoparticles, different types of surfactants, variation of nanoparticle concentration and testing method on the AC breakdown voltages of RBDPO and CO are investigated. The AC breakdown voltages results are analysed using statistical analysis to determine the withstand voltages. Chapter 5 discusses the final results of the lightning breakdown voltage of RBDPO and CO based nanofluids. This investigation includes the influence of different types of nanoparticles, different types of surfactants, variation of nanoparticle concentration and voltage polarity on lightning breakdown voltage of RBDPO and CO. The results obtained from the analysis are then used to determine the lightning withstand voltages based on statistical analysis. Chapter 6 investigates the PDIV and discharge activities of the RBDPO and CO based nanofluids with and without surfactants. This includes the partial discharge assessment of RBDPO and CO based on PDIV and discharge activities. Chapter 7 summarizes the conclusions on the findings and objectives of this research. At the end of this chapter, recommendations for future work on investigating the behaviour of RBDPO and CO based nanofluids with and without surfactants under electrical properties is given.

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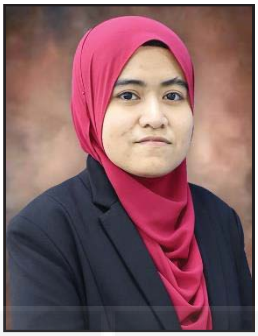

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LIST OF PUBLICATIONS

Journals

[1] **Nur Aqilah Mohamad**, Norhafiz Azis, Jasronita Jasni, Mohd Zainal Abidin Ab Kadir, Robiah Yunus and Zaini Yaakub, "Impact of Fe_3O_4, CuO and Al_2O_3 on the AC Breakdown Voltage of Palm Oil and Coconut Oil in the Presence of CTAB", Energies, vol. 12, pp. 1-14, 2019.

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[1] **N. A. Mohamad**, N. Azis, J. Jasni, M. Z. A. Ab Kadir, R. Yunus and Z. Yaakub, "AC Breakdown Voltages of Refined Bleached and Deodorized Palm Oil and Coconut Oil under the presence of Fe_3O_4 and CTAB", 2^{nd} Advanced Research in Engineering and Information Technology International Conference (AVAREIT 2018), pp. 1-5, Kuala Lumpur, 22-24 January 2018.

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