UNIVERSITI PUTRA MALAYSIA

LIGHTNING IMPULSE BREAKDOWN PERFORMANCES OF PALM OIL AND COCONUT OIL UNDER NON-UNIFORM FIELD

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Nowadays transformers have become essential for the electricity transmission and distribution network since the invention of transformers in late 1800s. The oil filled types transformer is commonly used and petroleum based MO has been widely used as transformer dielectric insulation fluid for decades. However, the usage of MO has several drawbacks such as non-biodegradable, low flash and fire points and could contaminate the soil and waterways if serious spill occurs. Recently, vegetable oil is introduced as the potential candidate, since it is biodegradable, non-toxic and has better environmental performance with high flash and fire points. The seed based natural ester has been applied successfully as dielectric insulation fluid in small and medium transformers. In Malaysia, due to the huge plantation of PO, the types of vegetable oils considered for transformer applications are PO and CO. Before these oils can be applied in transformers, extensive assessment on its performance need to be carried out since the in-service failure could be costly. Among the common assessment is the lightning impulse strength, which is one of the important parameter for insulation design of a transformer.

This work presents the experimental studies on the lightning impulse breakdown voltages of PO and CO under various gap distances. Three different variations of PO and one sample of CO were considered in all tests. The lightning breakdown voltage test was carried out under non-uniform electric field configuration where the gap distances were set in the range of 2-25 mm. Three testing methods which are rising-voltage, up-and-down and multiple-level were used to determine the breakdown voltage results. The lightning breakdown voltages performances of PO and CO compared with MO were analysed. All lightning breakdown voltages were analysed and the withstand voltages were evaluated through Weibull distribution.

It was revealed that there is a bright future possibility of using PO as alternative insulation fluids in transformers where the breakdown voltages performances of PO and CO are comparable with MO under positive lightning impulse. However, the negative lightning impulse breakdown voltage of MO is found to be higher than both PO and CO, which might due to their different chemical structural. Based on this study,

the lightning breakdown strengths of PO and CO at 1% and 50% breakdown probability can be acquired through the empirical formulas produced where the breakdown voltage at large gap distances can be predicted which are important for transformer's insulation design. The knowledge of the lightning impulse characteristics of PO and CO are obtained and can be used for further improvement in future works.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains

PRESTASI KILAT UNTUK MINYAK SAWIT DAN MINYAK KELAPA DI BAWAH MEDAN TIDAK SERAGAM

Oleh

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Sejak ciptaan transformer pada zaman 1800, ia telah menjadi sangat penting dalam penghantaran dan rangkaian pengedaran elektrik. Transformer jenis isi minyak biasa digunakan dan MO telah digunakan sebagai cecair dielektrik penebat dalam transformer selama beberapa dekad. Walau bagaimanapun, penggunaan MO mempunyai beberapa kelemahan seperti tidak mesra alam, takat kilat dan kebakaran yang rendah dan boleh mencemarkan tanah dan jalan air jika tumpahan serius berlaku. Minyak sayuran telah diperkenalkan sebagai calon yang berpotensi kerana ia mesra alam, bukan toksik, dan mempunyai takat kilat dan kebakaran yang tinggi. Ester, minyak sayur berasaskan benih telah berjaya digunakan sebagai cecair penebat dielektrik dalam transformer kecil dan sederhana. Oleh sebab pengeluaran PO yang besar di Malaysia, jenis minyak sayuran yang boleh digunakan sebagai cecair dielektrik penebat adalah PO dan CO. Sebelum minyak ini boleh digunakan dalam transformer, penilaian menyeluruh prestasi minyak perlu dilaksanakan kerana kos kegagalan dalam industri tinggi. Kekuatan dorongan kilat adalah antara penilaian yang biasa dilaksanakan serta salah satu parameter yang penting dalam reka bentuk transformer.

Kerja ini membentangkan kajian eksperimen voltan kegagalan kilat untuk PO dan CO di bawah pelbagai jurang jarak. Tiga jenis PO yang berlainan dan satu sampel CO telah dipertimbangkan dalam semua ujian di bawah medan tak seragam dengan jarak jurang yang ditetapkan dalam lingkungan 2 hingga 25 mm. Tiga kaedah ujian, naik-voltan, naik-dan-turun dan pelbagai-voltage telah digunakan untuk menentukan voltan kegagalan kilat. Prestasi voltan kegagalan kilat PO dan CO berbanding dengan MO telah dianalisiskan. Semua voltan kegagalan kilat kemudiannya dianalisis untuk mendapatkan voltan penahanan kilat dengan menggunakan statistik taburan Weibull.

Ia telah mendedahkan bahawa penggunaan PO sebagai cecair penebat alternatif mempunyai kemungkinan masa depan yang cerah di mana voltan kegagalan kilat PO dan CO adalah setanding dengan MO di bawah voltan positif. Voltan kegagalan kilat MO lebih tinggi daripada PO dan CO di bawah voltan negatif mungkin disebabkan struktur kimia yang berbeza. Berdasarkan kajian ini, kekuatan kegagalan kilat PO dan CO pada 1% dan 50% kegagalan kebarangkalian boleh diperolehi melalui formula

empirik yang dihasilkan di mana voltan kegagalan pada jarak jurang besar boleh diramalkan dan penting untuk reka bentuk penebat pengubah transformer. Pengetahuan tentang ciri-ciri kilat kegagalan PO dan CO boleh diperolehi dan boleh digunakan bagi mempertingkatkan lagi taraf kerja-kerja masa depan.

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LIST OF ABBREVIATIONS

ΔT	Time Interval
ΔU	Step Voltage Increment
ΔV	Different Voltage
α	Scale Parameter
β	Shape Parameter
+	Positive
–	Negative
ø	Diameter
σ	Standard Deviation
μ	Mean Value
°C	Celsius
µs	Micro Second
a	Constant
AC	Alternating Current
Agip ITE360	Commercial Transformer Oil
ASTM	American Society for Testing and Materials
b	Constant
B.P	Breakdown Probability
C	Carbon
CO	Coconut Oil
CPO	Crude Palm Oil
cSt	CentiStokes
Cu	Cumulative Probability
d	Gap Distance
DBP	2,6-Ditertiary-Butyl Phenol
DBPC	2,6-Ditertiarybutyl Para-Cresol
DC	Direct Current
DINP	Diisononyl Phthalate
DTE	Ditolyl Ether
dynes/cm	Dynes per Centimetre
e	Exponential
$E_{average}$	Average Field
E_{max}	Maximum Field
f	Electric Field Enhancement Factor
Fluorinert FC77	Perfluorinated Hydrocarbons Fluorinert FC6001
FR3	Fire Resistant Natural Ester
g/ml	Gram per Millilitre
GC	Gas Chromatography
IEC	International Electrotechnical Commission
ISO	International Standards Organization
k	Number of Breakdown
kV	Kilo Voltage
kVA	Kilo (Voltage x Ampere)
kΩ	Kilo Ohm
M&DBT	Mono & Dibenzyl Toluene
Max	Maximum
mgKOH/g	Milligram Potassium Hydroxide per Gram
Min	Minimum

Min. oil	Mineral Oil
mm	Millimetre
MO	Mineral Oil
MO3	Mineral Oil
MPOB	Malaysia Palm Oil Berhad
M-U.S. fat	Monounsaturated Fat
MV/cm	Mega Voltage per Centimetre
MΩ	Mega Ohm
N	Total Sample Size
Nat. ester	Natural Ester
ns	Nano Second
pF	Piko Farad
PFPE	Perfluoro Polyether
PKO	Palm Kernel Oil
PO	Palm Oil
PPM	Part per Million
PPMS	Poly Phenyl Methyl Siloxane
P-U.S. fat	Polyunsaturated Fat
PXE	Phenyl Xylene Ethane
q	Number of Non-Breakdown
r	Curvature Radius Of Needle Tip
RBDCO	Refined, Bleached and Deodorized Coconut Oil
RBDPO	Refined, Bleached and Deodorized Palm Oil
RS oil	Rape Seed Oil
S. fat	Saturated Fat
Synt. ester	Synthetic Ester
U-mean	Mean Value
V	Voltage
V.A	Vitamin A
V.E	Vitamin E
V_0	First Breakdown Voltage Value
$V_{50\%}$	50% Breakdown Voltage
Va	Voltage Acceleration
Vb	Breakdown Voltage
VBO	Vegetable Based Oil
VO4	Natural Ester
W	Weight
x	Measured Breakdown Data

CHAPTER 1

INTRODUCTION

1.1 Research background

The invention of transformers has led to an efficient utilisation of the power system network since the late 1800s [1]. Transformers are used to transfer energy between two circuits through electromagnetic induction and have become a reliable electricity supply of power to industrial, commercial and domestic consumers [2].

The majority of transformers in the power system network are oil filled types. The main function of the oil in transformers is as an electrical insulation in order to withstand the system transients and lightning surges, cooling medium by dissipating heat generated from the loss of transformer windings and cores and information carrier [3]. Conventionally, the main type of dielectric insulation fluid used in transformers is MO, since it has been proven to be successfully applied in-service for decades. It is well known that the popularity of MO is attributable to its excellent dielectric characteristics and wide availability [4]. However, it is non-biodegradable and can potentially contaminate soil and waterways if there is a serious spill occur [4-6].

Due to the increasing concern on the environmental consideration in recent years, biodegradable oil was introduced as an alternative to the conventional MO. Biodegradable oil such as vegetable oils possesses high flash/fire points, non-toxic, environmentally friendly and natural product that is abundant in the environment [7, 8]. Various research works were carried out to investigate the suitability of vegetable oils as dielectric insulation fluid in transformers by looking into different aspects such as electrical, physical and chemical performances under different parameter and conditions [4-10].

PO and CO are among vegetable oils that are considered for application in transformers. To date, a number of studies were carried out on PO and CO which had covered on different basic electrical, physical and chemical aspects [11-21]. In terms of electrical properties, parameters such as AC and lightning breakdown strength, dielectric properties and partial discharge characteristics of PO and CO were examined [22-25]. A number of studies were also carried out to investigate the chemical and physical properties of PO and CO such as moisture, acidity, and viscosity [26-28]. There are still several characteristics of PO and CO that are needed to be further investigated and one of the important parameters for the new dielectric insulation fluid is the lightning impulse performance.

Lightning impulse study on dielectric insulation fluid is normally carried out to test its breakdown and withstand ability since the failure in-service could be costly to the utilities. Lightning studies can be carried out under uniform, quasi-uniform or non-uniform fields. The uniform and quasi-uniform fields are normally represented by plane-plane and sphere-sphere electrodes configurations, while either point-plane or point-sphere configurations can represent the non-uniform field. Currently, a limited number of studies have been carried out on lightning breakdown performance of PO and CO, especially under non-uniform field, and its behaviour under variation of gap distances, polarities and types of electrodes.

1.2 Problem statement

MO has been an important insulation material in transformers for decades. However, there are several drawbacks associated with the usage of MO, including low flash points, non-biodegradability and non-renewable resources. Moreover, the usage of MO could cause damage to the environment if there is a spillage [29, 30]. Therefore, biodegradable vegetable oil, possesses high flash and fire points, non-toxic and complies with environmental regulation has been introduced. Malaysia is known as one of the large palm and coconut plantation and producers in the world. Therefore, among the vegetable oils that have been proposed for application in transformers are PO and CO. Although PO and CO are quite attractive for transformers application due to its environmentally friendliness advantages, there are several underlying issues especially on its lightning breakdown performances that need to be addressed before these oils can be applied to in-service, which are [15, 31-34];

a. According to previous data, lightning causes the highest percentage of failure (35%) in high voltage applications. Practically, lightning may stroke directly on transformers or on earth near overhead lines connected to transformers which in turn could cause overvoltages.
b. These events will eventually lead to transformer failures if the oil and design are not at the proper level. Therefore, for a new dielectric insulation fluid to be used in transformers, lightning characteristics of these oils need to be thoroughly investigated.
c. Under best case scenario, lightning breakdown study under uniform field is normally carried out which can be used to test the design capability of transformers with the presence of new dielectric insulation fluid.
d. It is also crucial to consider the worst case scenario which can present in a form of design imperfections, defects that could exist during manufacturing stage, in-service or foreign materials that could enter during the dielectric insulation fluid filling stage. In these scenarios, the non-uniform field could exist in transformers and discharge could be initiated which could led to the breakdown of dielectric insulation fluids. In this case, the breakdown would be lower than uniform field. Therefore, it is important to determine whether the non-uniform breakdown of new dielectric insulation fluid is within the acceptable level.
e. To add with to complexity, several parameters such as the voltage polarity, testing method, gap distance and needle tip radius may influence the lightning breakdown voltages performance of dielectric insulation fluid under non-uniform field.

f. Ester based oil have been used as alternative to MO and applied in low or medium voltage transformers. Natural ester is mostly produced from soya, rapeseed and sunflower oils. However, natural ester has poor oxidation stability compared to other types of insulation fluids which could create thermal issues in transformers. Based on previous studies carried out on ageing performances of PO and CO, PO and CO show more promising performances compared to natural ester. Thus, as the popularity of natural esters grows, other types of crop oils such as PO or CO might be able to be used as insulation fluids.
g. There is still lack of knowledge on the lightning breakdown voltages performances for PO and CO, which is the main interest of this study.

1.3 Research objectives

The objectives of this research have been identified;

a. To determine the lightning impulse breakdown voltages of PO and CO under non-uniform field at various gap distances.
b. To analyse the effect of different voltage polarities, testing methods and electrode needle tip radius on the lightning impulse breakdown performance of PO and CO.
c. To evaluate the relationship of PO and CO lightning impulse breakdown voltages and various gap distances thus develop its empirical formulas.

1.4 Scope of work

The scope and limitations of this research work are;

a. This research only considers the lightning impulse breakdown voltages of PO and CO under non-uniform field at various gap distances of 2.0, 3.8, 6.0, 10.0, 15.0 and 25.0 mm.
b. This investigation only focuses on the influence of both positive and negative voltage polarities on the lightning breakdown voltages of PO and CO.
c. This research only uses three independent testing methods, which are rising-voltage, up-and-down and multiple-level methods.
d. The type of PO used in this research is RBDPO Olein type which could be easily obtained from the markets.

1.5 Contribution of the research

Among the main contributions of this research are;

a. Based on this research, the lightning breakdown strengths of PO and CO under non-uniform field are obtained. For transformer's insulation design, the 1% and 50% breakdown voltages of PO and CO parameters are important.

b. The lightning breakdown voltage of all the samples at large gap distances can be predicted for transformer's insulation design purpose based on the empirical formulas determined from the relationship between lightning breakdown voltage V (kV) and gap distance d (mm) of all samples for both positive and negative polarities under non-uniform field.
c. Based on studies carried out on the lightning breakdown performances under different testing methods, voltage polarities and needle tip radius, it can be used to determine whether PO and CO suitable to be applied as dielectric insulation fluids in transformers. Besides, future consideration should be taking account in large gap distances and pressboard.

1.6 Thesis layout

This thesis consists of 5 chapters, the introduction, literature review, methodology, results and discussion, conclusion and recommendations for future work.

Chapter 1 describes the general background of this research, the overview of the thesis, as well as the problem statement and objectives.

Chapter 2 presents a comprehensive review of related studies in the existing body of literature, which comprises insulation paper and fluids in transformers and the breakdown event of insulation fluids, including the breakdown theories in AC/impulse, along with the influence of several parameters that affect the breakdown strength of oils.

Chapter 3 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 methods for the breakdown voltages, namely, rising-voltage, up-and-down and multiple-level methods. The result data processing and methods of the statistical analysis used in the study are also discussed.

Chapter 4 investigates the influence of voltage polarity, testing methods and tip radius of needle on the lightning impulse breakdown strength of PO and CO. The results obtained from the analysis are then used to determine the lightning withstand voltage at various gap distances and statistical analyses.

The final chapter 5 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 and CO under lightning impulse voltage.

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