ENHANCING THE BREAKDOWN VOLTAGE OF NATURAL ESTER INSULATING OIL BY OPTIMIZING MIXED ANTIOXIDANTS FOR POWER TRANSFORMER APPLICATIONS

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"I hereby declare that I have read this report and in my opinion this project is sufficient in terms of scope and quality for the award of the degree of Bachelor of Electrical Engineering (Industrial Power) with Honors".

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"I declare that this report entitled *"Enhancing the Breakdown Voltage of Natural Ester Insulating Oil by Optimizing Mixed Antioxidants for Power Transformer Applications"* is the results of my own research except cited in references. The report has not been accepted for any degree and is not currently submitted in candidature of any other degree".

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Date :

Dedicated to my beloved parents and whole of family who always give me support, strength and encouragement.

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ABSTRACT

In power transformer applications, an attempt has been made to replace mineral oil with natural ester insulating (NEI) oil due to environmental issues becomes more concern. However, NEI oil is prone to oxidation due to its poor oxidative stability which can be improved by adding the antioxidants to the oil. Besides, recent studies also showed that the use of selected antioxidants also improves the breakdown voltage (BDV) of the oil. Meanwhile, previous researchers were design their experiments using the conventional one-factor-at-a-time (OFAT) method which requires more tested samples in determining the optimum response studied. Thus, a two-level (2^2) factorial design experiment is introduced in this study to replace conventional OFAT method. This method is capable on determining the optimum concentrations of propyl gallate (PG) and citric acid (CA) which resulting a high BDV of NEI oil. Throughout this study, the breakdown voltage test is conducted according to ASTM D1816 with 1mm gap using Megger OTS60PB. The experimental results indicate that by adding PG and CA antioxidants have increases BDV of NEI oils. The optimum concentration of PG and CA antioxidants which gives the highest BDV of NEI oils was 0.05 and 0.25 wt.% respectively. Finally, the regression model is developed by analysis of variance (ANOVA) to estimate the BDV of NEI oils as a function of PG and CA antioxidants.

ABSTRAK

Dalam aplikasi pengubah kuasa, suatu percubaan telah dibuat untuk menggantikan minyak mineral dengan minyak ester (NEI) disebabkan oleh isu-isu alam sekitar yang kian membimbangkan. Walau bagaimanapun, minyak NEI mempunyai kestabilan oksidatif yang lemah yang boleh diperbaiki dengan menambah antioksidan ke dalam minyak. Selain itu, kajian terkini menunjukkan bahawa penggunaan campuran antioksidan terpilih juga meningkatkan voltan kerosakan (BDV) minyak. Sementara itu, penyelidik terdahulu menggunakan kaedah konvensional satu faktor pada satu masa (OFAT) yang memerlukan sampel ujian yang lebih banyak dalam menentukan nilai optimum bagi sebarang tidak balas yang dikaji. Dalam kajian ini, dua tahap (2^2) faktorial eksperimen reka bentuk diperkenalkan untuk menggantikan kaedah konvensional OFAT. Kaedah ini digunakan untuk menentukan kepekatan optimum antioksidan terpilih; propyl gallate (PG) dan asid sitrik (CA) untuk mencapai BDV minyak NEI yang tinggi. Dalam kajian ini, ujian voltan kerosakan dijalankan mengikut ASTM D1816 dengan jarak 1mm menggunakan Megger OTS60PB. Keputusan kajian ini menunjukkan bahawa penambahan antioksidan PG dan CA meningkatkan BDV minyak NEI. Kepekatan optimum antioksidan PG dan CA yang memberikan BDV minyak NEI yang tertinggi masing-masing adalah 0.05 dan 0.25 wt.%. Akhir sekali, model regresi dibangunkan oleh analisis varians (ANOVA) untuk menganggarkan BDV minyak NEI sebagai fungsi antioksidan PG dan CA.

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LIST OF ABBREVIATIONS

AA	-	Ascorbic Acid
AC	-	Alternating Current
AF	-	Advance Feature
ANOVA	-	Analysis of Variance
ASTM	-	American Society for Testing and Materials
BDV	-	Breakdown Voltage
BHA		Butylated Hydroxy Anisole
BHT	-	Butylated Hydroxy Toluene
CA	-	Citric Acid
DBPC	-	2, 6-di-tert-butyl-pcresol
DoE	-	Design of Experiment
FT-IR	-	Fourier Transform Infra-Red
IEC	-	International Electrotechnical Commission
NEI	-	Natural Ester Insulating
OFAT	-	One-factor-at-a-time
OTS	-	Oil Test Set
PB	-	Portable
PDSC	-	Pressure Differential Scanning Calorimetry
PG	-	Propyl Gallate
RH	-	Relative Humidity

SOP	-	Standard of Procedures
SS	-	Sum of Squares
TBHQ	-	Tert Butyl Hydro Quinone
TFD	-	Two-level Factorial Designs
VDE	-	Verband Deutscher Elektrotechniker
α-T	-	Alpha-Tocopherol

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter will preview about research background, problem statement, objectives and scopes of works, contribution of research, and end with thesis outline. Research background will briefly explain the general overview of this study. Then, the problem statement will brief the issues that need to be solved during this study. Objectives and scopes of works will review the purpose and target that need to be achieved in order to solve the problems that have been identified. Lastly, the report outline will shows the summary of chapter provided in this thesis.

1.2 Research Background

A transformer is one of the key components in a power network which converts voltage and transfers energy. The reliability of a power transformer is largely determined by its insulation condition [1]. In liquid-filled transformers, the insulating liquid plays two important functions; providing the electrical insulation and serve as a coolant by absorbing the temperature occurring in transformer winding and core [2, 3]. For more than hundred years, liquid-immersed transformers have been mainly filled with mineral oil due to its wide availability, its good properties, and its low cost. Due to environmental issues becoming more concerns, it is important to use a product with a high biodegradability and more environmental friendly. Thus, the recent availability of natural ester fluids based on vegetable oils has provided a new insulating liquid for use with transformers [2].

Nowadays, researches on the viability of using natural ester-based insulating (NEI) oils as one of the alternatives to replace the mineral oils in power transformers are gaining much attention due to the excellent biodegradability, higher fire point and good dielectric properties they possess such as breakdown voltage. Besides, NEI oil could increase the life span of a transformer because of its better hydrophilic property compared to the conventional mineral oils [4]. However, NEI oil has low pour point which makes it less suitable in cold climate temperatures and also seems to be prone to oxidation due to its low oxidation stability. Thus, the researchers soon recognized that NEI oils needed further improvement to be used as a transformer insulating oil.

1.3 Problem Statement

The ester oil has the disadvantage of poor oxidative stability which can be improved by adding the antioxidants to the oil. In general, antioxidants are compounds that delays or slow down oxidation process of transformer oil [5]. However, recent studies showed that by applying selected antioxidants mixtures in NEI oil also improves its breakdown voltage (BDV). Therefore, in this study, the effect of the antioxidants to the oxidation stability of the NEI oil is assessed through its breakdown voltage. Meanwhile, previous researchers have only implemented the one-factor-at-a-time (OFAT) method as their experimental design approach to determine the optimum ratios of antioxidant mixtures that yield better results on the performance of insulation oil. But, this conventional OFAT method requires a large number of test runs or experiments for the estimation of effect that possibly produce a better output. Since more experiments are needed, it will consume a lot of time and cost to execute all the experiments. Hence, in this study, Design of Experiment (DoE) approach with two-level factorial designs (TFD) is introduced to replace conventional OFAT method which can improves in term of its number of test runs or experiments, time consuming as well as reduce overall experimental cost. TFD is also can be used to determine the optimum concentration antioxidants mixtures which will maximize the BDV of the NEI oils.

1.4 Objectives

The objectives of this study are formulated as follows:

1. To select the type of natural ester-based insulating oil and mixed antioxidants.
2. To design series of experiments of mixed antioxidants in NEI oil using Design of Experiment (DoE) approach.
3. To identify the optimum concentration of mixed antioxidants in NEI oil by assessing breakdown voltage.

1.5 Scope of Works

The scopes of this study are:

1. Type of NEI oil used is Midel eN (rapeseed based) while mixed antioxidants used are propyl gallate (PG) and citric acid (CA).
2. Design of Experiment (DoE) approach with two-level factorial designs (TFD) statistical technique is implemented using Design Expert Software (Statistics Made Easy, version 6.0.10, Stat-Ease, Inc., Minneapolis, MN).
3. The concentration of mixed antioxidants in NEI oil is optimized using TFD while the breakdown voltage test is complies with ASTM D1816 standard using Megger OTS60PB.

1.6 Contribution of Research

This research can contribute to liquid-filled transformer applications which use NEI oil as a replace of mineral oil. The antioxidants mixtures are added to the NEI oil which could slowing the ageing rate and improve oxidation stability while enhance the breakdown voltage of the NEI oil. Hence, this improvement could increase the life span of the transformer. Besides, the optimum concentration of the applied antioxidants is determined from DoE approach using TFD. At the same time, by using TFD, the tested samples could be reduced by half rather than using conventional OFAT method.

1.7 Thesis Outline

In general, this thesis is divided into five chapters, where it consists of:

Chapter 1: Introduction

Chapter 2: Literature Review

Chapter 3: Research Methodology

Chapter 4: Results and Discussion

Chapter 5: Conclusion and Recommendation

Chapter 1 is an overview of the research project. In this chapter, the problem statement, objectives, and scopes of the research are defined. The research of works will be done according to the objectives and scopes stated earlier.

Chapter 2 presents the literature review. This chapter explained and discussed all theory related to this research such as the insulation system of the transformer, types of insulating oil in transformer, property requirement of insulating oil of transformer and types of antioxidants. It also consists of statistical analysis theory of two-level factorial designs (TFD). Besides, the review of previous related works regarding to this research also discussed.

Chapter 3 presents the research methodology adopted for this research work. This chapter consists of all process involves throughout the project implementation. It is includes the selection process of NEI oil and antioxidants, the pre-processing of the fresh NEI oil, the procedure of two-level factorial designs (TFD) method, sample preparation of the NEI oil with antioxidants mixtures and the procedures of breakdown voltage testing conducted to the NEI oil.

Chapter 4 presents the results and discussion of this study. It is include present the breakdown voltage of the oil before and after mixed with antioxidant and the analysis of results using two-level factorial designs (TFD) statistical method.

Chapter 5 concludes all the works that had been presented in previous chapters and followed by suggesting some recommendation for future study work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter contains a literature review that related to this study. All relevant information and related theory such as the insulation system of the transformer, types of liquid insulation in transformer, importance of transformer insulating oil testing and types of antioxidants are studied and discussed in this chapter. Besides, this chapter also consists of the Design of Experiment (DoE) method with two-level factorial designs (TFD) and the paper review of previous related works that have been conducted by some researchers.

2.2 Insulation System of the Transformer

In electrical power system network, transformer is one of the most important equipment. The main function of transformer is to step up or step down AC voltages without changing the frequency [6]. As electrical energy is transformed from one level of voltage to another level, high electrical stress and amount of heat developed inside the transformer. Thus, it is important to having a transformer with a good insulation system since it will determine the transformer‟s life span. The main functions of insulation are providing mechanical support between windings and act as a coolant by dissipating the heat. In general, there are three different states of insulations used in transformer; gas, solid and liquid [7, 8].

a. Gas Insulation

The simplest and the most commonly found insulation are gases. One of the examples of gas is air. Air is commonly used as the insulating medium in the most of the electrical apparatus. Besides, there are other gases such as nitrogen (N_2), carbon dioxide (CO_2), freon ($CC1_2F_2$) and sulphur hexafluoride (SF_6) are also used as the insulating medium. In high voltage applications, there are several preferred properties of a gaseous insulation for practical use. The properties includes high dielectric strength, thermal and chemical stability inactivity towards materials of construction, non-flammability, low temperature of condensation, and good heat transfer. In recent years, it is found that SF_6 seem to possess most of these requirements. From all these requirements, dielectric strength contributes the most important property in gaseous insulation for practical use [9].

b. Solid Insulation

Solid insulation materials are mainly used to insulate conductors from one another and also to provide mechanical support for conducting parts. Generally, there are two types of materials used in transformer which is kraft paper and pressboard. Kraft paper is used as winding insulation while pressboard is used as spacing between the conductors. Both of these materials are manufactured using cellulose fiber and they are commonly used in oil-filled transformer application due to their low cost, ability to absorb the dielectric oil, and their ease of fabrication. In transformers, the degradation solid insulation (cellulose based products) is affected by the temperature, moisture content, oxygen and acid exists in the insulation system. The degradation of solid insulation produces chemical products such as furanic derivatives, carbon monoxide (CO) and carbon dioxide (CO_2) which dissolved in the transformer oil. These chemical products are produced due to the chains of cellulose molecular are getting shorter after the degradation process occurs. As the degradation process occurs, the paper will becomes very brittle and the life span of the transformer will become shorter [10].

c. Liquid Insulation

Liquid insulation or transformer oil is mainly used as heat transfer agent in transformer. Consequently, oil-filled transformer technology has been used for more than four decades. With proper maintenance, the life of transformer can be extended more than the prescribed life [7, 10]. There are several factors that affecting the quality of insulating oil such as oxidation, contamination, and excessively high temperature. From all these factors, oxidation is the most common cause of oil deterioration. Many transformer manufactures overcome this problem by sealing the transformer from the atmosphere. Besides, moisture is the main contaminants in the oil where its presence can reduce the dielectric properties of the insulating oil. Apart from that, excessively high temperature in transformer will cause decomposition of the oil and will increase the rate of oxidation. The best way to avoid excessive heat is by preventing the transformer from overloading [11].

2.3 Types of Liquid Insulation in Transformer

There are three basic types of insulating liquid that are used in liquid-filled transformer which are mineral oils, synthetic ester oils and natural ester oils. The use of each type of the insulating liquid is depends on its application.

a. Mineral Insulating Oil

Mineral oil is a mixture of different kinds of hydrocarbon compounds. There are three types of hydrocarbon compounds that can be found in mineral oil which are naphthenic C_nH_{2n}, paraffinic C_nH_{2n+2}, and aromatic C_nH_n. The composition of carbons in naphthenic and paraffinic structures defines the type of mineral oil [12]. Besides, mineral oil is the insulating fluid that commonly used in the transformer industry because of its wide availability, good properties and low cost [2]. However, mineral oils have relatively low flash point resulting a high combustibility. Combustion products of mineral oil which occurred due to transformer failure are considered to be dangerous and cause air pollution [13]. Therefore, one of the solution in reducing the negative impact of the transformer to the environment is by replacing it by a new environmentally friendly insulating liquids produced on the basis of natural and synthetic esters [14].

b. Synthetic Esters Insulating Oil

The combination of alcohol and acid will form a synthetic ester. The structure of the synthetic ester is very stable since several acid and alcohol groups is bonded together. This structure makes the synthetic esters have excellent oxidation stability. Besides, synthetic ester has high performance and significantly more biodegradable than mineral oil. However, synthetic ester is less used in power transformers due to its high cost [15].

c. Natural Esters Insulating (NEI) Oil

Natural esters oil is also known as vegetable oils which are directly derived from renewable plant sources. In the last decades, researchers have been studied the viability in using natural ester as insulating oils in power transformers. Results from their studies have shown that NEI oils are suitable for use as insulating oils in power transformers because of its good dielectric properties, high flash points, and good dissipation factor (tan δ). However, NEI oils have low oxidation stability compared the required standard value for insulating oils [16]. Low oxidation stability makes the oil is tends to oxidation and only recommended for use in sealed transformer. So, the oxidation stability of NEI oil is identified and discussed further in Chapter 2.4.

2.4 Chemistry of NEI Oil Oxidation

Oxidation stability of insulating liquids is an important parameter, which is describing the quality of the liquid in terms of suggested long term use.

2.4.1 Oxidation Stability

The chemical composition of NEI oils is primarily consists of triglycerides and minimal amounts of diglycerides, monoglycerides and organic fatty acids [4]. Triglyceride is an ester derived from glycerol and three fatty acids. Glycerol is a trihydric