DIELECTRIC PROPERTIES OF MIXING PALM OIL WITH SOYBEAN OIL AS A POTENTIAL INSULATING FLUID IN TRANSFORMER

by

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LIST OF ABBREVIATIONS

AC	Alternating current
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
BDV	Breakdown voltage
BHA	Butylated hydroxyl anisole
BHT	Butylated hydoxy toluene
BOD	Biochemical Oxygen Demand
CEC	Coordinating European Council
CPO	Crude Palm Oil
DBPC	2,6-ditertiary-butyl paracresol
EDS	Estimated Dielectric Strength
FAME	Fatty Acid Methyl Ester
FR3	Envirotemp FR3
GC-MS	Gas Chromatograph-Mass Spectrometers
HMWH	High Molecular Weight Hydrocarbon
HTT	High temperature transformer
HV	High voltage
IEC	International Electrotechnical Commission
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
JIS	Japanese Industrial Standard
LC50	Median lethal concentration
LED	Light-emitting diode

NEC	National Electrical Code
NIST	National Institute of Standards and Technology
OECD	Organization for Economic Co-operation and Development
PC	Personal computer
PCB	Polychlorinated biphenyls
PFAE	Palm Fatty Acid Ester
RBDPO	Refined, Bleached and Deodorized Palm Oil
RBDP Olein	Refined, Bleached and Deodorized Palm Olein
RBDSO	Refined, Bleached and Deodorized Soybean Oil
THBP	Tetra hydro butro phenone
TBHQ	Mono-tertiary butyl hydroquinone
TCU	Transformer control unit
VDE	Verband Deutscher Electrotechniker

CIRI-CIRI DIELEKTRIK BAGI CAMPURAN MINYAK SAWIT DENGAN MINYAK KACANG SOYA SEBAGAI SATU BENDALIR PENEBAT BERPOTENSI DI DALAM TRANSFORMER

ABSTRAK

Transformer adalah salah satu peralatan yang paling penting di dalam sistem kuasa elektrik. Hampir semua transformer voltan tinggi diisi dengan minyak untuk bertindak sebagai medium penyejukan dan penebat. Secara umumnya, minyak mineral berasaskan petroleum digunakan sebagai minyak transformer. Walaubagaimanapun, oleh kerana kebimbangan terhadap alam sekitar dan kitar hayat minyak mineral, sumber yang boleh diperbaharui seperti minyak sayuran telah dipilih sebagai pilihan yang terbaik untuk menggantikan minyak mineral ini. Kajian yang lepas telah menunjukkan bahawa minyak sawit mempunyai sifat dielektrik yang setara bagi menggantikan minyak mineral sebagai cecair dielektrik di dalam transformer elektrik kuasa. Walaubagaimanapun kelikatan kinematiknya tidak memenuhi keperluan piawaian IEC 60296 dan ianya perlu diperbaiki. Salah satu cara ialah dengan mencampurkan minyak sawit dengan minyak kacang soya. Setakat ini, tidak ada kajian yang dilaporkan tentang ciri-ciri dielektrik campuran minyak sawit dan minyak kacang soya. Oleh itu, di dalam projek ini, siasatan ke atas ciri-ciri dielektrik campuran RBDPO/RBDSO dan RBDP Olein/FR3 telah dijalankan. Nisbah produk berasaskan minyak kacang soya (RBDSO dan FR3) di dalam campuran minyak sawit (RBDPO dan RBDP Olein) telah dihadkan kepada 50%. Ciri-ciri dielektrik bagi campuran minyak seperti kekuatan dielektrik, factor pelesapan (δ tan), ketelusan relatif (dielektrik malar), kelikatan kinematik, kandungan air dan analisis komposisi kimia telah ditentukan. Kesan nisbah pencampuran dan perbezaan suhu minyak campuran terhadap ciri-ciri dielektriknya

telah disiasat. Ciri-ciri dielektrik RBDPO/RBDSO dan RBDP Olein/FR3 juga telah dibandingkan dengan minyak mineral. Kekuatan dielektrik dan ketelusan relatif kedua-dua RBDPO/RBDSO dan RBDP Olein/FR3 menunjukkan keputusan yang lebih tinggi berbanding minyak mineral iaitu satu tanda positif bagi menggunakannya sebagai cecair penebat di dalam transformer. Faktor pelesapan bagi semua nisbah kedua-dua campuran minyak juga menunjukkan lebih rendah berbanding dengan minyak mineral. Sementara itu, kandungan air dan kelikatan kinematik bagi kedua-dua minyak campuran menunjukkan telah melebihi piawaian IEC 60296 serta minyak mineral. Daripada keputusan dan perbincangan, nisbah 30% minyak berasaskan produk kacang soya di dalam campuran RBDPO/RBDSO dan RBDP Olein/FR3 menunjukkan peratusan pencampuran terbaik selepas dibandingkan dengan minyak mineral dan piawaian IEC 60296. Secara kesimpulannya, perbandingan antara campuran RBDPO/RBDSO dan RBDP Olein/FR3 menunjukkan bahawa RBDP Olein/FR3 mempunyai lebih potensi untuk digunakan sebagai cecair penebat di mana 70%RBDP Olein/30%FR3 telah menghimpunkan ciri-ciri dielektrik yang paling memuaskan sebagai calon minyak transformer berasaskan campuran minyak kelapa sawit dan minyak kacang soya.

DIELECTRIC PROPERTIES OF MIXING PALM OIL WITH SOYBEAN OIL AS A POTENTIAL INSULATING FLUID IN TRANSFORMER

ABSTRACT

Transformer is one of the most important equipments in electrical power system. Nearly all high voltage transformers are filled with oil to act as cooling medium and insulator. Generally, petroleum-based mineral oil is used as transformer oil. However, due to environmental concern and life-cycle of mineral oil, renewable resource such as vegetable oil is chosen as the best option to replace this mineral oil. Past researches have shown that palm oil has equivalent dielectric properties to substitute the mineral oil as liquid dielectric in electrical power transformer. However the kinematic viscosity does not fulfill the IEC 60296 standard requirements and need to be improved. One of the ways is by mixing the palm oil with soybean oil. So far, there are no reported studies on dielectric properties of palm oil and soybean oil mixture. Thus, in this project, the investigation on dielectric properties of RBDPO/RBDSO and RBDP Olein/FR3 mixtures was carried out. The ratios of soybean oil based products (RBDSO and FR3) in the palm oil (RBDPO and RBDP Olein) mixtures were limited to 50%. The dielectric properties of the oil mixture which are dielectric strength, dissipation factor (tan δ), relative permittivity (dielectric constant), kinematic viscosity, water content and chemical composition analysis have been determined. The effect of mixing ratio and temperature variances of the oil mixtures to its dielectric properties has been investigated. The dielectric properties of RBDPO/RBDSO and RBDP Olein/FR3 also have been compared with mineral oil. The dielectric strength and relative permittivity of both RBDPO/RBDSO and RBDP Olein/FR3 shows higher compared

to mineral oil which a positive sign in using as insulating liquid in transformer. The dissipation factor for all ratios of both oil mixtures also shows lower compared to the mineral oil. Meanwhile, the water content and kinematic viscosity for both of the oil mixtures show exceeded the IEC 60296 as well as the mineral oil results. From the results and discussions, 30% ratio of soybean oil based product in RBDPO/RBDSO and RBDP Olein/FR3 mixtures was found to be the best mixing percentage after comparing with the mineral oil and IEC 60296 standard. In conclusion, comparison between RBDPO/RBDSO and RBDP Olein/FR3 mixture shows that RBDP Olein/FR3 possesses more potential in using as insulating liquid where 70%RBDP Olein/30%FR3 shows to accumulate the most satisfactory of dielectric properties as the candidate of palm oil and soybean oil mixture based transformer oil.

CHAPTER 1

INTRODUCTION

1.1 Overview

High voltage (HV) transformers convert voltages from one level or phase configuration to another, usually from lower to higher voltages. They can include particular features for electrical isolation, power distribution, and instrumentation applications. High voltage transformers can be configured as either a single-phase primary configuration or a three-phase configuration (The Electricity Forum, 2011).

There are two types of high voltage transformers which are dry type transformer and liquid filled type transformer. Nearly all high voltage transformers are filled with an oil to act as an insulator. Generally, the main function of the oil is to cool the transformer by being circulated through the core and coil structure of the transformer. If the cooling is insufficient, when high temperatures occur, the oil could become oxidized with the possible formation of peroxides, water, organic acids and sludge. These products lead to the chemical deterioration of the paper insulation and metal parts of the transformer. Sludge sediments can greatly reduce the heat transfer capabilities of the oil, and also forms a heat insulating layer on the coil structure, the core and the tank wall (Naidu and Kamaraju, 2008).

In some situation, the drop in dielectric properties performance of the insulating oil causing low impedance faults that result in the appearance of arcing in transformer tanks. The oil will become vapor and the generated gas will pressurize because the liquid inertia prevents its expansion. The difference of pressure between the gas and the surrounding liquid oil generates pressure waves, which propagate and interact with the tank. The average pressure can rise and lead to the explosion of the tank. Any resulting fire can lead to great damage to the transformer and other electricity facilities (Perigaud et al., 2008). Based on these facts, it is clear that insulation oil forms a very significant part in the transformer. Thus, the choice of suitable oil as an insulating material for a transformer to meet the standard requirements is very important.

Generally worldwide, petroleum-based mineral oils are used as transformer insulating oils. The popularity of mineral oil is due to its easy availability and low cost, as well as being an excellent dielectric and cooling medium. However, the extensively utilization of this oil in transformer has contributes to the seriously shortage of this product in the future. Moreover, the unfriendly environmental aspect of this oil contributes to the contamination of soil and waterways if the oil is seriously spilled out of the transformer tank. These environmental concern have become an issue to seek another green replacement among researchers (Oommen, 2002; Abdullahi et al., 2004). Thus, suitable replacements are being sought for petroleum based oils which are more environmental friendly. Materials such as vegetable oils are the strong candidates for this replacement.

In Europe, vegetable oils such as soybean oil, sunflower oil, and coconut oil have been used as insulating fluid in transformer either independently or by combination. Names such as BIOTEMP, BIOTRANS, and Envirotemp FR3 have already known as vegetable based transformer oil. BIOTEMP which manufactured by ABB Group is comprised mostly of mono unsaturated high oleic acid triglyceride vegetable oil. Examples of high oleic acid are sunflower oil, and rapeseed oil. BIOTRANS which manufactured by Cargill is a mixture of partially hydrogenated soybean oil high in oleic acid content (Biermann and Metzger, 2007). Envirotemp FR3 which manufactured by Cooper Power System is soybean based transformer oil. Thus, the used of vegetable oil as transformer oil has already developed in outside range of Malaysia.

One abundant, biodegradable vegetable oil available in Malaysia is palm oil (Basiron, 2004; Lam et al., 2009). There has been extensive research into the use of palm oil as alternative transformer oil (Suwarno et al., 2003; Abdullahi et al., 2004; Aditama, 2005; Kanoh et al., 2008; Suwarno and Darma, 2008; Rajab et al., 2009; Al-Ammar and Qureshi, 2009; Al-Ammar, 2010; Abdelmalik et al., 2011). The extensive research has shown that some of its dielectric properties have shown a good agreement with the existing standard. Compared to mineral oil, palm oil also has more elevated breakdown voltage (BDV), flash point and fire point (Abdullahi et al., 2004). However, it is also found that one of palm oil properties does not comply with the standard which is its kinematic viscosity (Suwarno et al., 2003). Elimination of this weakness should be considered for realization of utilization of palm oil as insulating fluid in transformer. One of the suggestions is by the mixture of palm oil with soybean oil, since soybean oil has been known of its ability as vegetable grade insulating fluid in transformer (Cannon and Honary, 2001).

However, the dielectric properties of the palm oil and soybean oil mixture have not been reported. Therefore, the aim of this research is to investigate the dielectric properties of the palm oil and soybean oil mixture at various ratios and different temperatures. Then, the dielectric properties of the oil mixture are compared with the conventional mineral oil. The optimum mixing ratio of oil mixture which shows the most compatible in using as transformer oil is then selected. Two types of palm oil and soybean oil mixtures with different ratios have been used which are RBDPO/RBDSO and RBDP Olein/FR3. Some of their dielectric properties such as breakdown voltage, dissipation factor (tan δ), relative permittivity (dielectric constant), kinematic viscosity, water content, and chemical composition have been analyzed and compared with the IEC 60296 standard.

1.2 Problem Statement

Oil filled power transformer is one of the most crucial equipment in electrical power system. Generally, petroleum-based mineral oil is filled inside the transformer for cooling and insulating purposes. However, petroleum-based mineral oil which originates from fossil fuel reserved is depleted from time to time. Moreover, mineral oil is also non-environmental friendly where it takes a long time to biodegrade. As a result, renewable and environmental friendly product such as vegetable oil has been chosen as alternative of the mineral oil. Concerning of this issue, palm oil which abundance and indigenous resource product of Malaysia has been paid attention as the replacement. However, the kinematic viscosity of palm oil is higher compared to IEC 60296 standard. One of the suggestions to improve the kinematic viscosity is by mixing the palm oil with soybean oil. Nevertheless, the dielectric properties of the oil mixture have not been investigated. Therefore, the aims of this research are to investigate and to compare the dielectric properties of palm oil and soybean oil mixture with mineral oil dependence on various ratios and temperatures. The mixing formulation of oil mixture, which has dielectric properties compatible to utilize as insulating liquid in transformer is then selected.

1.3 Objectives

The objectives of this research are:

1. To investigate the dielectric properties (electrical, physical and chemical properties) of RBDPO/RBDSO and RBDP Olein/FR3 oil mixtures at various ratios.
2. To investigate the electrical properties of RBDPO/RBDSO and RBDP Olein/FR3 oil mixtures at different temperatures.
3. To compare the dielectric properties of RBDPO/RBDSO and RBDP Olein/FR3 oil mixtures with mineral oil.
4. To find the optimum mixing ratio of RBDPO/RBDSO and RBDP Olein/FR3 which its dielectric properties are the most compatible in using as transformer oil.

1.3 Contributions of the Research

This research work contributes knowledge on dielectric properties of palm oil and soybean oil mixtures. In addition, it gives valuable information on the kinematic viscosity properties of the palm oil and soybean oil mixtures for the utilization of liquid dielectric in electrical power transformer. The results revealed from the experiments are very useful for clarifying the potential of using palm oil and soybean oil mixture as dielectric fluid in transformer and as a guidance in designing the liquid type HV transformer utilizing vegetable oil.

1.4 Scope of the Research

The scopes of this research work cover two parts of analysis; major and minor. In this research work, two types of oil mixtures; RBDPO/RBDSO and RBDP Olein/FR3 with various ratios were used as the specimens. The ratio of soybean oil based products into palm oil products were limited until 50% since the main liquid dielectric of utilized in this study is palm oil.

The major analysis was started by conducting six experiments testing. The six experiments were conducted by testing the dielectric properties; divided into electrical, physical and chemical properties of palm oil and soybean oil mixtures. Three of the experiments were tested on the electrical properties while the other three were tested on the physical and chemical properties of the oil mixtures. The electrical properties such as breakdown voltage, dissipation factor (tan δ), and relative permittivity (dielectric constant) were measured at different temperatures and ratios. The breakdown voltage of the oil mixture was measured at 40˚C to 100˚C from 0% to 50% ratio of soybean oil based products. Meanwhile, the dissipation factor and relative permittivity of the oil mixture were measured at 40˚C, 70˚C and 90˚C for 10%, 30% and 50% of soybean oil based products content. The kinematic viscosity was measured at 40˚C from 0% to 50% of soybean oil based products in the oil mixtures. The water content and chemical composition were measured at room temperature also from 0% to 50% of soybean oil based products.

The minor analysis was done by evaluating the calculation and simulation of dielectric strength (electric field strength) of the oil mixtures. The calculation and simulation of the dielectric strength were evaluated by using the obtained experimental result of breakdown voltage. In addition, Weibull analysis on determining the breakdown probability of the oil mixtures has also been carried out.

1.5 Outline of the Thesis

This thesis is classified into five chapters which are introduction, literature review, methodology, results and discussions, and conclusions. The outline of the thesis can be composed as follows;

Chapter 2 presented the literature review obtained from books, thesis, conference papers, reports and journals. This chapter briefly explains the role of liquid dielectric in transformer, the depletion of mineral oil as liquid dielectric in transformer, the vegetable oil as replacement of mineral oil as liquid dielectric in transformer and palm oil as liquid dielectric in transformer. In addition, this chapter also includes the research trend on the dielectric properties of palm oil as insulating liquid in transformer.

Chapter 3 presented the research methodology. This chapter explained the samples preparation of palm oil and soybean oil mixtures, the experimental test setup and procedures of breakdown voltage, dissipation factor (tan δ), relative permittivity (dielectric constant), kinematic viscosity, water content, and chemical composition. This chapter also includes the calculation and simulation procedures of dielectric strength of the oil mixtures. All the research process on investigating the dielectric properties of oil mixtures is briefly summarized in a flow chart.

Chapter 4 presented the results obtained from the experimental work. The results obtained were breakdown voltage, dissipation factor (tan δ), relative permittivity (dielectric constant), kinematic viscosity, water content, and chemical composition of the oil mixtures. This chapter also presented the results of dielectric strength of the oil mixtures obtained from the calculation and simulation. Furthermore, the analysis and discussion of each result obtained by comparison with other journals and conference papers was also included. Moreover, the comparison between the oil mixtures and mineral oil were also included. The comparison between the two types of palm oil and soybean oil mixtures to find the optimum ratio which its dielectric properties was the most compatible in using as transformer liquid was also presented.

Chapter 5 presented the summarization of this thesis. The thesis was concluded and the future work was also recommended.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the role of transformer oil is described. The innovation of vegetable oils used as liquid dielectric in power transformer is also presented. Recent research trend of palm oil as a liquid insulator in power transformer are also reviewed. Several research papers related to this topic are included and discussed in this chapter as well.

2.2 Role of Transformer Oil in Oil-Filled Power Transformer

Transformer plays an important role in providing a reliable and efficient electricity supply and is one of the most crucial equipments in electric power transmission and distribution systems (Liao et al., 2011). Power transformer is used to convert the voltage from high level to low level or vice versa at each point of transmission lines and distribution lines when the power is needed to be transmitted from power station to consumers as shown in Figure 2.1 (Kiameh, 2003a). Two types of power transformers exist in electrical power system. They are classified based on cooling medium which are dry type (air-cooled) and liquid-filled (oil-cooled) transformers (Kiameh, 2003b). Historically, oil-filled power transformer is the primary option used in electrical power system after mineral oil is used as the transformer oil in 1892 (Sierota and Rungis 1995; Nunn, 2000). Figure 2.2 shows the cut view of general oil-filled power transformer (Kiameh, 2003a). The main part of the transformer are: (a) iron core, magnetic circuit comprising limbs, yokes and clamping structures, (b) electrical circuit comprising primary, secondary winding, insulation and bracing devices and (c) main tank which housing all the equipment. In a core-type transformer, the normal design is a three phase which composed by three-leg core where the core is surrounded by the winding coils. In oil-filled power transformer, the core and winding coils are immersed inside the oil for cooling and insulation purposes. In large power transformer, the oil-filled tank often has radiators through which helps the circulation of oil by natural convection. High power transformer (with capacities of thousands kVA) may have cooling fans, oil pumps and oil-to-water heat exchangers for improvement of cooling performance (Khan et al., 2007).

Apart from being the cooling medium, a high dielectric strength owned by transformer oil gives it the ability to become an excellent insulator for high voltage power transformers (Naidu and Kamaraju, 2008). Its excellent insulation becomes superior by the combination with cellulose material known as oil-paper insulating system. This cellulose material is mostly known as Kraft paper, act as the solid insulation for core and winding of the transformers (Prevost and Oommen, 2006). Transformer oil can perform both of cooling and insulating function in expectancy life of about 25 to 30 years (Parkash, 2010). However, under influence of thermal and chemical stress, deterioration of the transformer oil can occur rapidly which could short the life span of the transformer. Figure 2.3 shows the statistical of oil-filled power transformer failures in United States from 1997 to 2001 (Bartley, 2003). The insulation failure is the most contribute to the transformer failure with transformers' average life is only 18 years. Overload temperature is one of the factor leads to this failure. In prevention of this type overload condition, ANSI/IEEE and IEC standards have developed a standard temperature limit for oil-filled power transformer as shown in Table 2.1 (Sim, 1998; Sim and Digby, 2007; IEEE, 2010; Sim et al., 2011). This standard is the guideline for operating limit of the transformer oil inside the transformer. Thus, in brief, transformer oil has a significant role in order to reduce or to prevent the transformers failure in electrical power system.

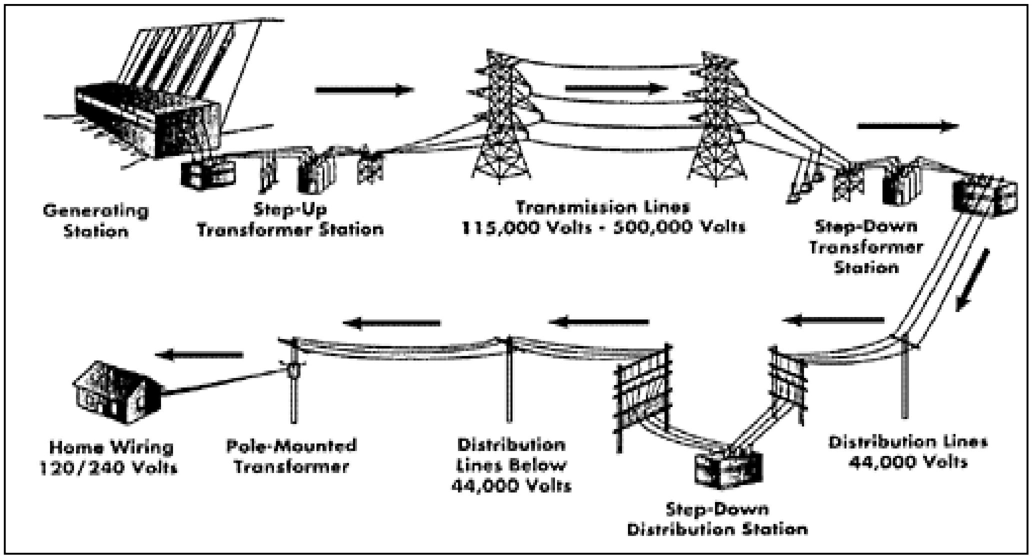

Figure 2.1: Power transformers in electrical power system (Kiameh, 2003a)

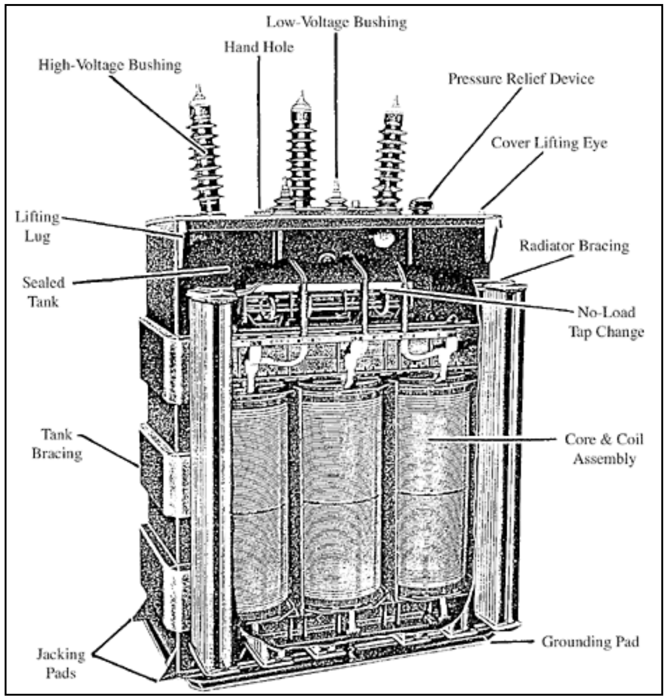

Figure 2.2: Cut view of oil-filled power transformer (Kiameh, 2003a)

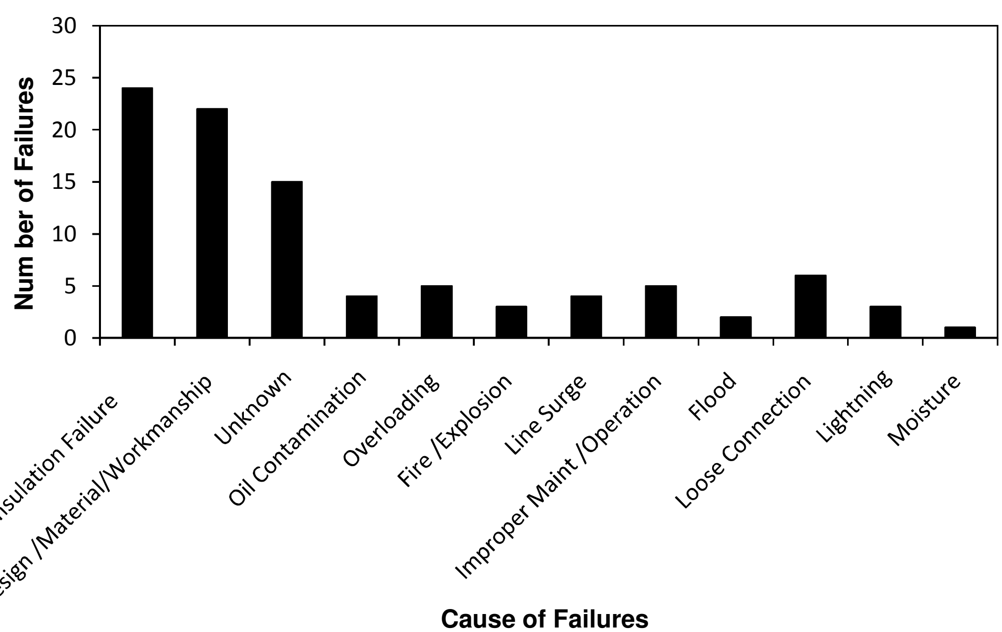

Figure 2.3: The number of 25MVA and above power transformer failures from 1997 to 2001 (Bartley, 2003)

Table 2.1: Standard limits for temperature rises above ambient for oil-filled power transformer (Sim, 1998; Sim and Digby, 2007; IEEE, 2010; Sim et al., 2011)

Temperature Limit	**Standard**	
	ANSI/IEEE	**IEC**
Max. ambient temperature	40˚C	40˚C
Average winding temperature rise	65˚Ca	70˚C
Hot spot temperature rise	80˚C	78˚C
Top liquid temperature rise	65˚C	60˚C

aThe base rating is frequently specified and tested as 55˚C

2.3 Depletion of Non-Environmental Mineral Oil as Insulating Liquid in Oil-Filled Power Transformer

Nowadays, insulating fluids have been reevaluate based on their total life-cycle cost of economics, fire safety, and environmental aspects. The industry has focused on sustain insulating liquid with improved environmental and health properties while maintaining the fire-resistant properties of less-flammable fluids. The insulating fluids now is suggested to fulfill the minimum health and environmental requirements such as non-toxic, biodegradable, thermal-stable, recyclable, reconditionable, readily disposable, and not listed as hazardous material (McShane, 2001b)

Mineral oil was first used as transformer oil after it is introduce by General Electric Company in 1892. The extensively used of mineral oil until this day was due to availability, low cost and also excellent dielectric and cooling medium. Less quantity of alternative insulating liquids also has been used to retrofill the transformer. The used of these alternative fluids is depended on the transformer special application such as high temperature transformer (HTT) (McShane, 2001a).

The concern on environmental issue started as early as 1970's after non-flammable fluids, Askarel, which was the mixture of polychlorinated biphenyls (PCB) and trichlorobenzene has been banned to be used as insulating liquid in transformer due to the hazardous issues to the environment (McShane, 2002). As replacement, Perchloroethylene (C_2C_{l4}) or Perc has been introduced to substitute the PCB (Fofana et al., 2002). However, besides of compatibility with transformer material and non-flammability, the decomposition of fires from Perc will produce toxic materials and could cause the hazardous to the health. Consideration was then given to use less environmental risks fluid with almost similar electrical and thermal properties.

High Molecular Weight Hydrocarbon (HMWH) (high temperature mineral oil) and silicone oil are currently ranked as the most popular choices in applications requiring less-flammable fluid. Due to highly cost, a less-flammable liquid known as synthetic polyol ester was limited to be used in traction and mobile transformers, and other specialty applications. Table 2.2 shows the comparison of the dielectric properties of mineral oil with these less-flammable fluids (Oommen et al., 1997). HMWH, silicone oil and synthetic polyol ester shows a high flash and fire point, an adequate characteristic as less-flammable fluid in transformer. However, as shown in Figure 2.4, the HMWH has low biodegradability which is almost the same with the conventional mineral oil. In other paper, silicone oil shows 0% biodegradability in 21 days period (Cooper Power System, 2005). Synthetic polyol ester biodegrade much quicker than mineral oil and silicone oil but its highly in cost was the main issue which hinders it to be used widely.

Table 2.2: Comparison of transformer fluids (Oommen et al., 1997)

Dielectric Properties	**Regular Transformer Oil**	**HMW* Mineral Oil**	**Silicone Fluid**	**Polyol Ester**
Dielectric Strength, kV/mm	40-45	40-45	43	45
Dissipation Factor %, 25˚C	0.01	0.01	0.01	0.1
Dielectric Constant	2.2	2.2	2.7	3.2
Acidity	0.01	0.01	0.002	0.03
Viscosity at 40˚C	8-10	120	40	34
Pour Point, ˚C	-50	-24	-55	-50
Flash Point, ˚C	150	275	305	280
Fire Point, ˚C	170	300	350	310
Water solubility at 20˚C, ppm	55	55	180-200	1000
Specific Gravity	0.89	0.89	0.96	0.97

* High Molecular Weight (high temperature)

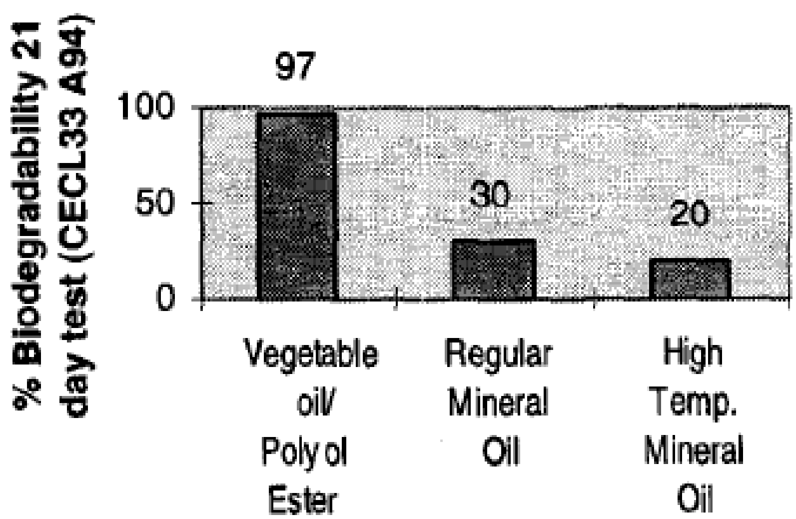

Figure 2.4: Comparison of biodegradability of insulating fluids (Oommen et al., 1997)

Until today, million gallons of mineral oil including high temperature mineral oil and less quantity of other insulating liquid such as silicone oil are used in oil-filled power transformer. The poor biodegrade of mineral oil can cause contamination to the waterways and soil if a serious spills occur as shown in Figure 2.5. This condition also cause a highly maintanence to clean up the spills as shown in Figure 2.6. This situation indicates that the non-environmental issue of mineral oil should be taken seriously.

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Figure 2.5: Oil from the spill at the Pepco substation in Alexandria, U.S covers the water, shoreline, and road around the plant in 2011 (Branch, 2011)

Figure 2.6: Cleanup workers removing the oil from transformer below the damaged power house in Southwest Washington, U.S in 2002 (Washington State Department of Ecology, 2002)

The shortage issue of mineral oil also not new anymore. Statistic in 2010 shows around 88% of global energy consumption come from non-renewable resource of fossil fuel as shown in Figure 2.7 (BP, 2011). Fossil fuel is classified as non-renewable resource because it takes million of years to form, and reserves are being depleted much faster than the new product to be made. Mineral oil is one of the products of this non-renewable fossil fuel and the highest consumption product in every year. In 2004, Colin Campbell, has proposed that the maximum production of world oil and liquid gas will happened at around 2007 to 2008 before the declination occur as shown in Figure 2.8 (Aleklett, 2010). This proposal has been confirmed by International Energy Agency (IEA) in 2011 World Energy Outlook (IEA, 2011). Thus, this situation indicates that the existence of mineral oil in the world has been reduced as the time goes by and probably it will not occupy population needs in the next millennium.

Even though only a small percentage of mineral oil is used in the transformer and other oil-filled electrical equipments, yet, this small amount is almost irreplaceable. Thus, in concern of environmental aspect and life-cycle of mineral oil, a new renewable resource such as vegetable oil is the best option to replace this mineral oil. Vegetable oil is the abundance product and natural resource available in plenty. Its dielectric properties are also almost compatible in using as transformer fluids. Therefore, it is the best candidates to replace the deficiency of this mineral oil in using as insulating liquid in transformer.

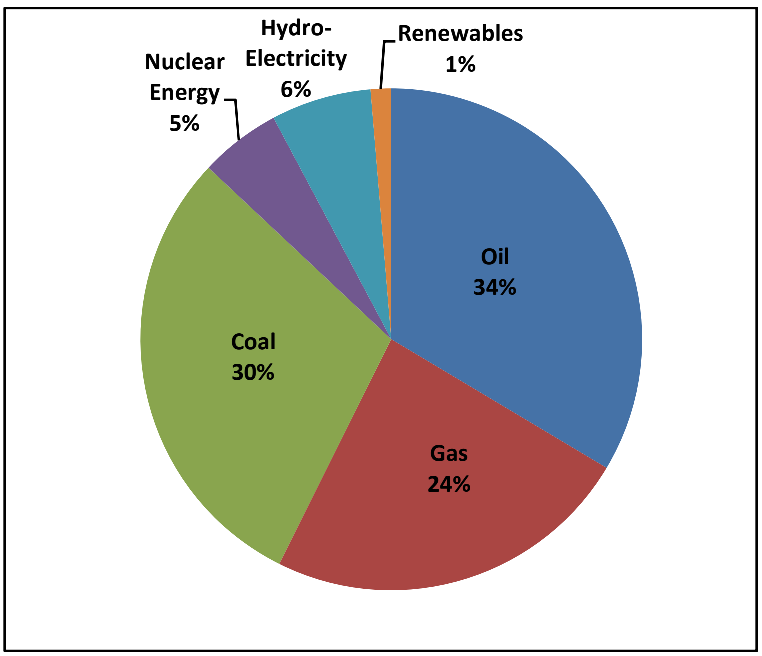

Figure 2.7: The global energy consumption in 2010 (BP, 2011)

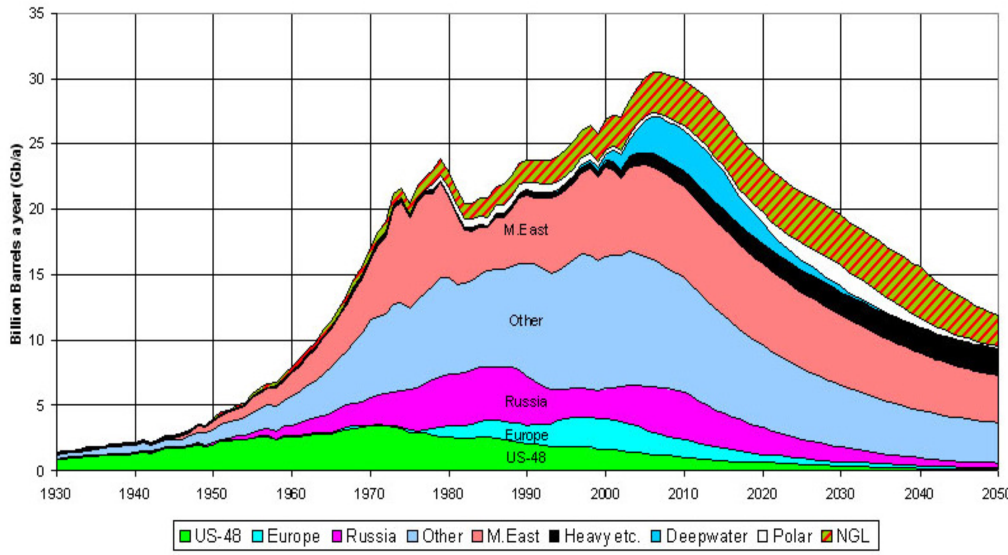

Figure 2.8: The oil and gas liquid scenario in 2004 (Aleklett, 2010)

2.4 Vegetable Oil as Replacement of Mineral Oil as Insulating Liquid in Oil-Filled Power Transformer

The experimentation in using the vegetable oil or natural ester as dielectric coolant in transformer has started around the same time as early as mineral oil. However, they proved less desirable than mineral oil due to oxygen instability, and higher pour point, and viscosity values (Clark, 1962). These poor characteristics of vegetable oils are due to its chemical structure as shown in Figure 2.9 known as triglyceride ester.

Triglyceride ester is composed by one glycerol and three fatty acids. These three fatty acids can be either only saturated, saturated with unsaturated or only unsaturated. The chemical and thermal reactivity in vegetable oil come from the double bond in the unsaturated fatty acid components (Hill, 2000). The degree of chemical and thermally instability of unsaturated fatty acids progresses from monounsaturated (single double bond), di-unsaturated (two double bond) and tri-unsaturated (three double bond). Nevertheless, the presence of double bond in unsaturated fatty acid gives the ability of vegetable oil to remain in liquid form at room temperature. Saturated fatty acids do not have the double bond which increases the chemical and thermal stability but gives a high value of viscosity and pour point to the vegetable oil (Boss and Oommen, 1999).

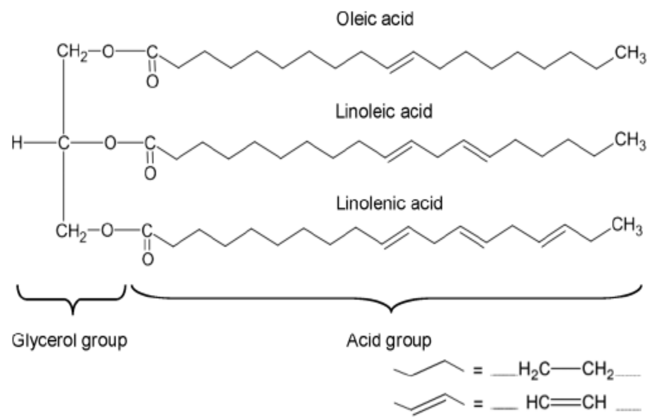

Figure 2.9: Example of triglyceride ester (rape seed oil) (Tenbohlen and Koch, 2010)

In early 1990's, an extensive research on vegetable oil conclude that the oil could be chemically enhanced to overcome the initial barriers of inferior oxidation stability, pour point, and viscosity values. The investigation conducted by Oommen et al. (2000) have shown that the addition of below than one percent of oxidation inhibitor although in the presence of copper could enhance the oxidation stability of the vegetable oil. To improve the pour point, he mentions that less than one percent of pour point depressant could depress the pour point by ten degrees without affecting the conductivity. McShane (2000) also mentions in his paper that the food grade material oxidation additives are possible to be used in the vegetable oil in order to improve the oxidation stability.

In correlation with cellulosic insulating paper, a high solubility of water featured by vegetable oil allows removing more moisture from the insulating paper. Stockton et al. (2009) and Martins (2010) revealed that the vegetable oil has higher water solubility than mineral oil which resulting in improved dielectric performance, and a reduction in paper aging rate. McShane et al. (2001) have measured the degree polymerization of aged insulating paper in mineral oil and vegetable oil at 130˚C, 150˚C and 170˚C, and the result revealed that paper degrade much slow in vegetable oil compared to mineral oil. Jian et al. (2007) also have measured the AC breakdown of oil-paper insulation composite of mineral oil and vegetable oil in accordance to IEC 60243-1 and the result shows that oil-paper insulation composite of vegetable oil gives greater breakdown strength compared to mineral oil as shown in Figure 2.10.

Vegetable oil also gives advantageous in electrical properties which possess high relative permittivity and breakdown voltage with low maximal discharge magnitude. Marci et al. (2011) revealed that vegetable oil has higher relative permittivity compared to mineral oil and silicone oil as shown in Figure 2.11. The high value of relative permittivity is desirable because it reduces the mismatch between the oil and paper in transformer. They also measured the discharge activity in vegetable oil accordance to IEC 60270. Figure 2.12 shows that the maximal discharge magnitude of vegetable oil was constantly low for all voltage levels compared to mineral oil. Viet-Hung et al. (2011) have conducted an experiment comparing the breakdown voltage between different types of mineral oils, vegetable oils and synthetic ester oil under AC voltage. The experiment was conducted according to IEC 60156 using Baur Dieltest at voltage rate of 2.0±0.2kV/s with electrode gap 2.50±0.05mm. The result shows that the dielectric strength of vegetable oils under AC voltage was slightly better compared to mineral oil and synthetic ester oil as shown in Figure 2.13.

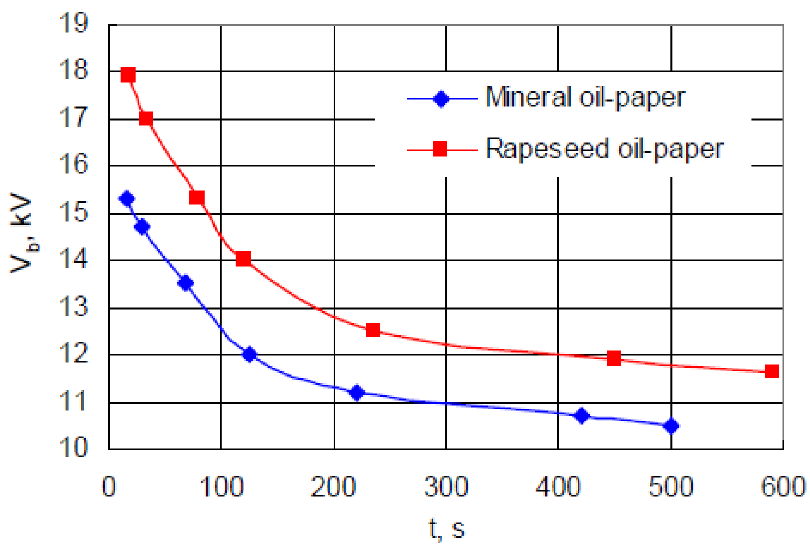

Figure 2.10: Breakdown voltage of versus time of test voltage applied for refined rapeseed oil-paper and mineral oil-paper insulation (Jian et al., 2007)

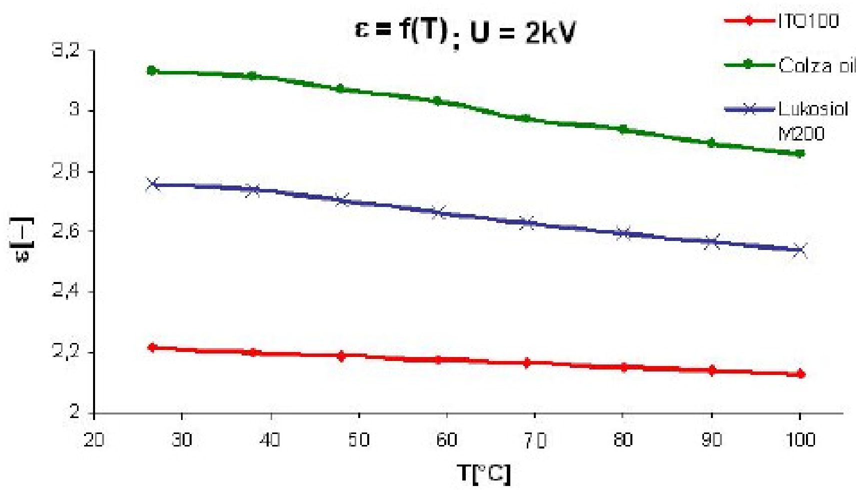

Figure 2.11: Comparison of relative permittivity of vegetable oil (Colza oil), mineral oil (ITO 100) and silicone oil (Lukosiol M200) under influence of temperature (Marci et al., 2011)

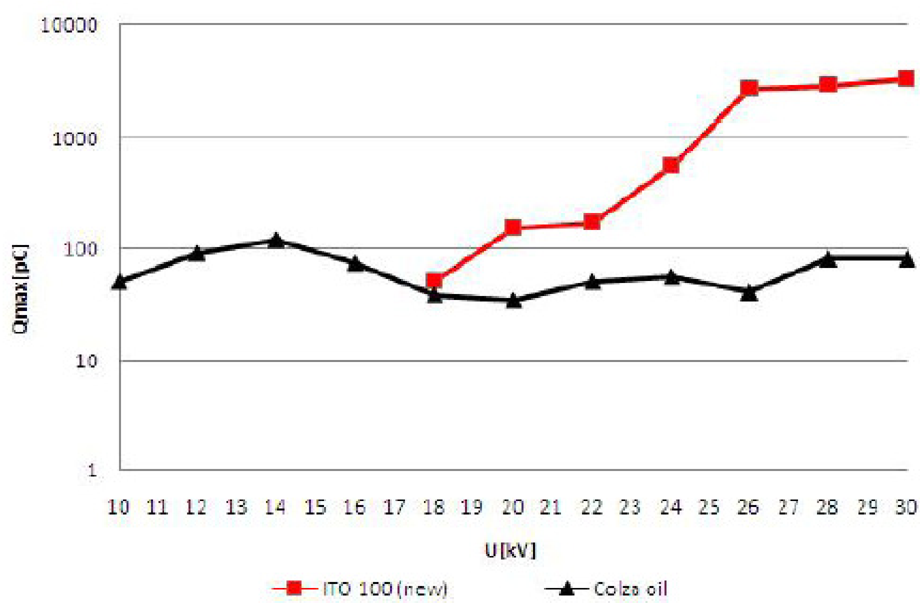

Figure 2.12: Maximal discharge magnitude of vegetable oil (Colza oil), and mineral oil (ITO 100) under influence of applied voltage (Marci et al., 2011)

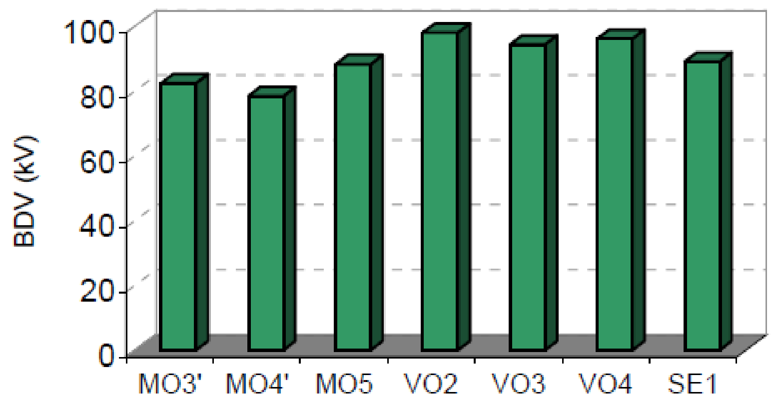

Figure 2.13: Mean breakdown voltage of mineral oils (MO3', MO4', MO5), vegetable oils (VE2, VE3, VE4) and synthetic ester oil (SE1) (Viet-Hung et al., 2011)

In addition, vegetable oil also a natural less-flammable liquid and possess fully biodegradability which distinguishes from mineral oil. Table 2.2 shows that the vegetable oil (natural ester) was qualified as less-flammable fluid due to its fire point achieved the minimum open-cup fire point of 300˚C as specified by National Electrical Code (NEC) (McShane, 2001a). In biodegradability aspect, Oommen (2002) has tested the vegetable oil using CEC-L-33 test method and the vegetable oil posses about 98% biodegradability after 21 days compared to mineral oil and silicone oil as show in Figure 2.14.