Study the Electrical Stress Withstand Properties of Heated Refined Bleached and Deodorized Palm Oil Dielectrics

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A thesis submitted in fulfillment of the requirement for the award of the Master's Degree of Electrical Engineering

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June 2015

ABSTRACT

The world's energy requirement has been dominated by petroleum oil for centuries in many application fields, including transportation, household, and electricity. Mineral oil as an important insulating material in transformers has been used more than 150 years. Mineral oil application in power system equipment can be potentially hazardous to the environment especially when there are any incidents during operational time like transformer explosion which may cause a spill of oil to the soil or water stream. Due to the concerns about the deducing petroleum resources and the environmental issues, the alternative insulating oil with biodegradable characteristics has been attracted lots of attentions for a couple of decades. In this thesis, the dielectric properties of a type of mineral oil (Transformer Oil) and a type of vegetable oil (RBDPO) were investigated, and the effect of heating on their dielectric properties were studied as well. Since the heating effects on the dielectric properties of insulating oil, such as breakdown voltage, kinetic viscosity, pH Value, In addition to the partial discharge performance under the heating condition was studied. All the experiments in this project were conducted at a heating condition for the temperatures of 25^{0}C, 50^{0}C, 70^{0}C, and 90^{0}C. RBDPO was compared with petroleum based mineral oil. The results of experiments incorporated showed the potential of oil as a substitute RBDPO to the petroleum-based mineral oil. The BDV tests incorporated showed that the high BDV for RBDPO enables it to avoid a breakdown when the electric stressed. The average value of the BDV increases slightly as the increase of the temperature. The potential of RBDPO, as an electrical insulating liquid, to replace the petroleum-based mineral oil also can be concluded from the viscosity and acidity tests. From the experiments and analysis, it has been proven that the RBDPO is a good insulation because the kinetic viscosity for RBDPO is low and very near from the viscosity of the petroleum-based mineral oil after heating the oil to 50^{0}C and above.

ABSTRAK

Keperluan tenaga dunia telah didominasi oleh minyak petroleum selama beberapa dekad dalam pelbagai bidang aplikasi, termasuk pengangkutan, perumahan dan tenaga elektrik. Minyak mineral telah digunakan lebih dari 150 tahun kerana ianya bertindak sebagai bahan penebat yang penting dalam pengubah voltan (transformer). Aplikasi minyak mineral ini dalam perkakas sistem kuasa mempunyai potensi risiko berbahaya kepada persekitaran terutamanya apabila berlakunya insiden yang tidak diingini sewaktu waktu operasi seperti letupan pengubah voltan yang akan mengakibatkan penumpahan minyak kepada tanah atau sungai. Isu berkaitan kekurangan sumber petroleum dan persekitaran telah menarik perhatian kepada penggunaan minyak penebat alternatif yang mempunyai ciri-ciri penguraian bakteria selama beberapa dekad. Dalam tesis ini, sifat-sifat dielektrik juga telah dikaji. Pemanasan terhadap sifat-sifat dielektrik bagi minyak penebat memberi kesan seperti kerosakan voltan, kelikatan kinetik dan nilai pH. Tambahan lagi, hasil kerja discaj separa (partial discharge) dalam keadaan pemanasan juga telah dikaji. Semua eksperimen dalam projek ini telah dijalankan pada suhu pemanasan setinggi 25 °C, 50 °C, 70 °C dan 90 °C. Hasil kajian eksperimen RBDPO telah dibandingkan dengan hasil kajian eksperimen menggunakan minyak mineral berasaskan petroleum. Dapatan daripada eksperimen yang terkumpul membuktikan bahawa minyak berpotensi sebagai pengganti RBDPO kepada minyak mineral berasaskan petroleum. Ujian BDV terkumpul menunjukkan bahawa nilai BDV yang tinggi untuk RBDPO membolehkan ia untuk menahan kerosakan bawah tegasan elektrik. Potensi RBDPO sebagai cecair penebat elektrik untuk menggantikan minyak mineral berasaskan petroleum juga boleh disimpulkan daripada ujian kelikatan dan keasidan. Hasil eksperimen dan analisa membuktikan bahawa RBDPO asalah penebat yang baik kerana kelikatan kinetik bagi RBDPO adalah rendah dan menghampiri kelikatan minyak mineral berasaskan petroleum selepas pemanasan minyak tersebut sehingga 50^{0}C dan keatas.

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RBDPO	- Refined Bleached and Deodorized Palm Oil
CPO	- Crude Palm Oil
PD	- Partial Discharge
BDV	- Breakdown Voltage
AE	- Acoustic Emission
RIV	- Radio Influence Voltage
IEC	- International Electrotechnical Commission
FSTPI	- Faculty of Science, Technology and Human Development
FKEE	- Faculty of Electrical and Electronics Engineering
FKMP	- Faculty of Mechanical and Manufacturing Engineering

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CHAPTER 1

INTRODUCTION

1.1 Study Background

Dielectric play important roles in electrical system to separating the electrical potential object with the earthed object (including human), use as a medium in insulating the electrodes (e.g. papers insulating winding transformer, PVC in cable). Failure in dielectric could cause electrical breakdown or short circuit in which may introduced the risk of faulty/damage to the equipment as well as causing potential danger to the human. In general, dielectric can be classified to solid (e.g. glass, porcelain, or composite polymer materials and etc.), gases (i.e. nitrogen and sulphur hexafluoride) and liquid such as mineral oils (e.g. naphthenic oil and paraffinic oil). These dielectric materials mainly used in the power transformer and the power system application such as in the AC capacitor, circuit breaker, switch gear, high voltage bushings and etc. [1].

The insulating oil provides electrical insulation and cooling in power transformers. The enough knowledge of the dielectric behavior of these insulating materials when in service in an electrical network could enhance network reliability and minimize the probability of failure. This makes the field of electrical insulation and dielectrics important in the electrical generation, transmission and distribution system.

The main purposes of using oil in transformers are to increase the dielectric strength between conductors by replacing air with a high dielectric strength fluid, and filling the pores of the cellulose paper and pressboard, to prevent discharges. The oil should also have enough thermal and viscosity properties to be able to dissipate, by convection, heat generated due to losses in the transformer and it must flow freely under all operating temperatures.

For more than 100 years, mineral oils which are derived from crude petroleum have been widely used in power transformers as the most commonly liquid insulating for the purpose of cooling and insulation. However, concerns from the environmental effect of mineral oils such as soil and water contamination in the event of a spillage can cause serious environmental disaster as they are non-biodegradable [2]. This may disturb the plantation and other lives.

The demand for environmentally friendly dielectric fluids in distribution and power transformers is rising as the environmental impact of conventional fluids becomes increasingly more apparent. Vegetable based insulating oils are now commercially available as substitutes for mineral-based oils in transformer applications. Some advantages offered by these oils, which are chemically classified as Natural Esters, are the faster biodegradability, no water hazard, higher flash/fire points and low thermal expansion coefficient. Thus the application of these liquids in power transformers promises strong benefits, compared to conventional mineral oil[3].

Vegetable oils that have been proposed as a potential transformer have fatty acid triglyceride. Palm oil, as well as vegetable oils has fatty acid triglyceride. Oils with a high percentage of unsaturated fatty acid resulting low viscosity but have greater susceptibility to oxidation. Based on experiments on palm oil, the researchers found that the refined, bleached and deodorized palm oil (RBDPO) monounsaturated fatty acid content is high. Thus, RBDPO considered as an alternative to replace the latest petroleum-based mineral oil [4].

High voltage equipment is considered as one of the essential elements in electrical network. Any failure in this equipment directly reduces network reliability and increases maintenance costs[5]. Under the high voltage stress micro level electrical sparks appears in an insulator medium which is known as partial discharge phenomenon. These micro discharges ultimately lead to electrical breakdown of the insulator[6]. In any fabricated material some micro void spaces exist which is filled by the gas e.g. e air. This gas is ionized due to highly non-uniform electric field and ultimately ruptures the void space in the weakest direction. The sudden release of energy due to the partial discharge phenomenon (PD) would produce a number of effects such as chemical and structural changes in the materials[7]. The measurement level indicates the quantity and magnitude of partial discharge.

PDs are small events which occur in insulation in the presence of high electric fields; in PD phenomenon energy is emitted in the form of electromagnetic emission, radio waves, light and heat and also as acoustic emissions (AE) in the audible and ultrasonic ranges. PD is an electrical discharge or sparks that bridge small part of insulating between two conducting electrodes. PD can occur when electric field strength exceeds the breakdown strength of insulation, and can lead to flashover [7]. A good understanding of PD mechanisms, characteristics and its development processes is essential for power systems designer and power systems installation maintenance engineer. PD detection is necessary as precautionary measures to ensure that high voltage equipment insulation is not exposed to any unnecessary hazards.

The electrical manifestation of PDs is a pulse of current on the line. Typical values for the pulse area are in the Pico-coulomb range and for the duration– a few to a few hundred nanoseconds. The major difficulty with the electrical detection of PDs is the small magnitude of the current pulse as compared to the ambient current and noise on the line, which may be orders of magnitude larger. However, most of the noise energy is in the low frequency range (e.g. 50 Hz), whereas their energy is primarily in the higher frequencies, since PDs are short events. This distinction makes it possible to extract the useful information. In addition to the low-frequency rejection required of the system in order to accomplish this, filtering of specific dominant frequencies (such as 50 Hz) may further reduce the background noise.[8] There are other methods of measuring PDs, which do not provide on-line real time results. An example is the volumetric measurement of gas produced by PDs in transformer oil. However, they typically require interruptions of the operation and time delays. This makes the availability of an on-line electrical method very valuable[9].

For a reliable power system, improved functioning of power transformers are significant as they play a key role in the power transfer process. It can be observed that the failure of a transformer leads to an unhealthy power system hence to a high maintenance cost. The most possible reason for a failure of a transformer is insulation breakdown. Oil-impregnated pressboard and paper are commonly used as an insulation system in power transformers [10].

1.2 Problem Statements

In the electric power equipment, insulation oil plays the roles of the electrical insulation, heat dissipation and extinguishing voltaic arc by dipping and filling the air in the inner insulation of electric power equipment. Mineral oil has been widely used in oil-impregnated electric equipment for many years. However, its flash point is low, which cannot meet the requirements of insulation materials' fire prevention. In the fact, the mineral oil might run out in the future because it is extracted from petroleum that is non-renewable energy source. Therefore, this petroleum-based oil needs to be replaced with a new type of oil that is friendlier to the environment. Based on the previous studies that had been done, various types of vegetable-based oil would be suitable to replace the petroleum-based oil due to its positive impacts.

RBDPO is vegetable-based oil that has been modified in order to overcome its high viscosity and poor oxidation problems. As for the time being, the properties of the RBDPO are best accepted to be a good insulating medium for transformers as compared to mineral oils [4]. Since very few studies that had been done on RBDPO, it was reviewed that only dielectric properties of RBDPO has been studied. Furthermore, study for heating effect on the RBDPO has not yet been done since it is a new type of commercialized transformer oil. So it can be said that the heating performance on the dielectric properties of RBDPO and the partial discharge effects on the properties of RBDPO are not yet well studied significantly in order to achieve environmental friendly dielectric fluids in distribution and power transformers with the functional operation impact of conventional fluids with wide used in distribution level transformers influencing factors on electrical properties.

1.3 Objectives

This study would focus on the following objectives:

a) To investigate the dielectric properties of RBDPO as electrical insulating material.
b) To execute experimental study of the heating effect on the dielectric properties of RBDPO.
c) To make a comparison between RBDPO with the petroleum based mineral oil based on their electrical, physical, and chemical properties under heating condition.

1.4 Scope of Research

The area covered by an activity or topic are quiet wide. The scopes of the project are limited as follows:

a) Literature review that covers all study of insulating oil, the development in, the future problem facing, the characteristics needed and etc.
b) The Samples used for this project are transformer oil and pure RBDPO as insulating materials.
c) The experimental of the PD test on transformer oil and RBDPO will be conduct at High Voltage Laboratory in UTHM using TERCO PD METER.
d) The Fourier Transform Infrared Spectroscopy (FTIR) device used to identify the chemical compounds of the RBDPO and the mineral oil, and this test will be conduct at Polymer and Manufacturing Laboratory in UTHM.
e) The viscosity test will be conduct at Polymer and Manufacturing Laboratory in UTHM using viscometer device.
f) The pH value test will be conduct at chemistry laboratory in UTHM using pH meter.
g) Analyse the data base from the experimental result by comparing with the data for the mineral oil and other conclusion may come out from this work.

1.5 Thesis Outline

This project's thesis is basically to document the concept, implementation and outcome of the project which is relevant to the project's progress. This project thesis consists of five chapters.

Chapter one: discusses the basic background of the ideas to find the alternative insulating oils and the problem that faced with existing insulating oils now days. The objectives and scopes of this project are explained in details.

Chapter two: discusses the basic theoretical and the types of existing liquid insulation and more discusses on the effects of partial discharge phenomenon on the vegetable oils, and listing of previous work.

Chapter three: discussion on the experimental procedures or methodology including electrical characteristic on the test.

Chapter four: presents the result and analysis of the project.

Chapter five: discusses the conclusion of this project and recommendation for the future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter includes the study about insulation and characteristics of liquid insulation for the mineral oil (Transformer Oil) and RBDPO. The literature reviews discussed more about electrical, physical, and chemical properties for the insulating oil under heating condition such as breakdown voltage, colour, kinetic viscosity and PH value. It was also discussed about PD characteristic which will be used as parameter to investigate whether RBDPO is a good insulator or not.

2.2 Oil as Insulator

Insulating material is the materials in which electrostatic field can remain almost indefinitely, the material thus offer a very high resistance to the passage of direct current between two conductors. Dielectrics can be as formed of gaseous, solid, and liquid. Insulating oil has a good electrical properties such as to insulate and to prevent the corona and the arcing, thus it is mainly used as a dielectric material for the purpose of electrical insulation in power transformer applications. In addition to use the insulating oil as a coolant in power transformer [11].

The first idea of using oil as dielectric fluid in the power transformer was patented by Elihu Thomson in 1882. Till date, mineral oils which are extractinfrom crude petroleum have been widely used for the purpose of insulation, besides being an insulating material; it also has functions as a cooling media in electrical power apparatus such as power transformers, capacitors, etc. [2]. But concerns from the environmental effect of mineral oils such as soil and water contamination in the event of a spillage can cause serious environmental disasters as they are non-biodegradable [11].

In the past two decades, extensive studies were carried out for to find suitable alternate natural esters. The latest insulating oil implementation is (vegetable oils) which are known as the most potential source to replace the mineral oil for using in electrical applications [12]. Vegetable oils have the advantages such as the high biodegradability, fire safety; low thermal expansion coefficient, low moisture contents, and is readily available [3]. Transformer that was filled with vegetable oil has already been successfully tested at different levels of voltage [11]. In general, the insulating oils of transformer can be classified into two main types as in figure 2.1:

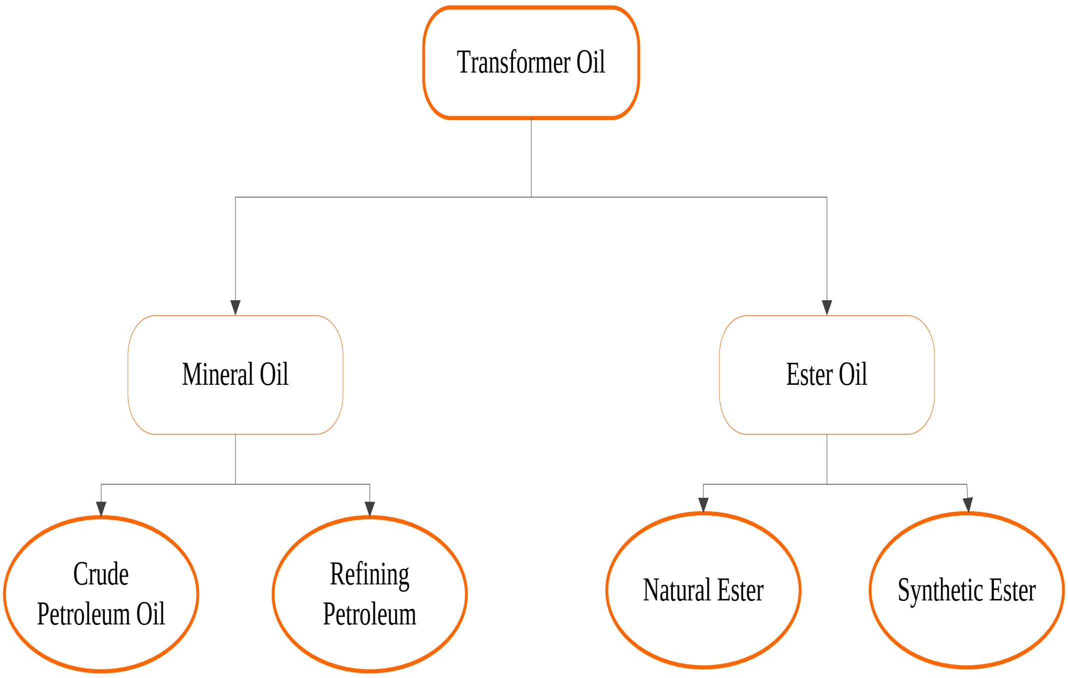
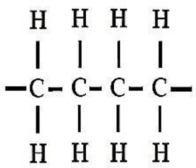
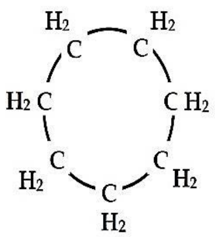
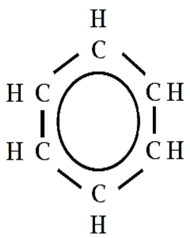


Figure 2.1: Classification of Transformer Oil

2.2.1 Mineral Oil

More than a century ago, mineral oils which are extracted from non-renewable source (Crude Petroleum) have been widely used in power transformers as the most commonly liquid insulating for the purpose of cooling and insulation. Mineral oils used widely in electrical applications as a commercial product early in the year 1899 [1]. The mineral oil allows that the internal isolations of transformer remain preserved during transformer operations, , causing that the mineral oil dielectric and cooling properties are more efficient; because it transfers the internal heat generated in transformer coils towards the outside [13]. The main reason for using mineral oil was the high flash point characteristic and the widespread production around the world. In general, mineral oil consists of 14% hydrogen, 84% carbon in various structures and 1-3% sulphur-oxygen-nitrogen [14]. There are has two types of mineral oil which are crude mineral oil and refining mineral oil. For refining mineral oil, the refining process is the process which used to remove or reduce waxes, sulphur, nitrogen and oxygen-compound and the aromatic hydrocarbon. The mineral oil after refining process has good insulation properties [14]. Table 2.1 shows the main types of mineral oil.

Table 2.1: Main Types of Mineral Oil [15]

Paraffin	**Naphthenic**	**Aromatic**
		
Methane (CH4) is a gas, normal butane (C4H10), and isobutene.	It has ring structures with six carbon atoms or fourteen Carbon atoms.	It has ring structures with six carbon atoms or fourteen Carbon atoms.

2.2.2 Ester Oil

Esters are the synthesized organic compound of acids and alcohols [14]. In general there are two main types of esters which are synthetic ester and natural ester. The synthetic ester is created from an organic acid and an alcohol. Complex ester is mostly used in field high temperature lubricant and hydraulic. Model type 7131 transformer fluid has developed in United Kingdom by Micanite and Insulator Limited is a synthetic ester product with higher viscosity point. In 1984 synthetic ester has been as insulating for railroad traction transformer as well in scientific apparatus such as klystron modulators [1, 14]. Figure 2.2 shows the Synthetic Polyol Ester which is the most common structure used in synthetic ester. This structure derived from pentaerythritol and a branched organic acid.

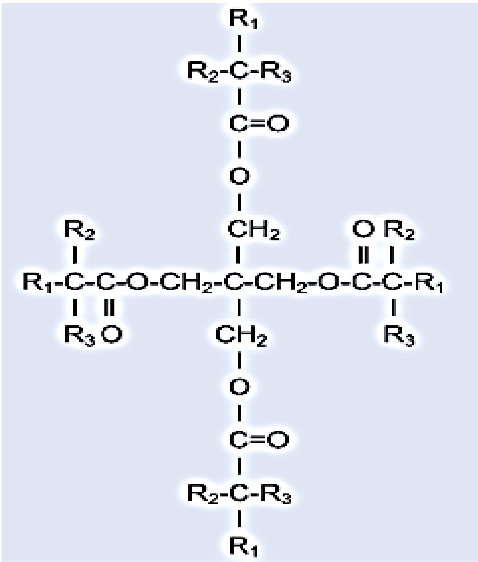


Figure 2.2: Synthetic Polyol Ester Structure [16]

The first commercialized ester was a synthetic polyol ester introduced in the year 1984, developed primarily as an environmentally acceptable substitute. And its technical performance was very good, but the cost is prohibitive for most applications. The desired characteristics of the polyol ester stimulate searching into other, more cost-effective, ester chemistries. This led to the evaluation of a natural (vegetable oil) ester dielectric coolant having many of the same performance advantages of synthetic esters, but much more economical. The main disadvantages of the natural esters are their natural capability to oxidation and higher pour point [17]. Vegetable oils (natural esters) which be considered for potential transformer application are fatty acid ester triglyceride. The fatty acid components are linier chains 14-22 carbons long containing zero to three double bonds. Figure 2.3 shows the triglyceride structure of vegetable oil, where the R, R' and R" are fatty acid chains [1, 13]. The optimal condition is reached by using a fluid with a high single unsaturated fatty acids concentration.

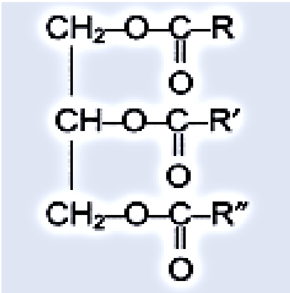


Figure 2.3: Structure of Vegetable Oil (Triglyceride) [1, 13]

Table 2.2 shows the advantages and disadvantages between natural ester and the synthetic ester oil.

Table 2.2: Advantages and Disadvantages for Natural and Synthetic Ester

	Advantages	**Disadvantages**
Natural ester	Higher fire point Readily biodegradable Moisture tolerant	Higher viscosity Sensitive of oxidation High pour point
Synthetic ester	Higher fire point Readily biodegradable Moisture tolerant Oxidation stable Low pour point	Expensive

Table 2.3 shows the comparison characteristics between the mineral oil and ester based oil.

Table 2.3: Comparison Characteristics between Mineral Oil and Ester [18]

Characteristics	Mineral oil	Ester oil
Raw material	Produced from petroleum sources which are non-renewable source.	Produced from the plant, which are renewable source such as corn and sunflower oil.
Environmental safety	Contain non-biodegradable compound.	Highly biodegradable
Fire risk	Catch more easily fire, leading to higher probability of transformer fired	Higher fire point, reduced the impact of transformer fires
Performances	Does not slow down the standard insulation aging rate	Proven to slow down the aging rate of insulation system

2.3 Oil Application Inside Transformer

High voltage transformer is a static device that transfer electrical energy from one circuit to another by electromagnetic without change in frequency. The transformers can be divided to two types (either step up or step down transformer). The transformers are manufactured in difference size, shape and types. For all transformer components, the insulation system plays one of the major important roles in the transformer life and performance, because most of transformer failures were caused by insulation problems [19]. The main purposes of application for transformer oil are shown in figure 2.4.

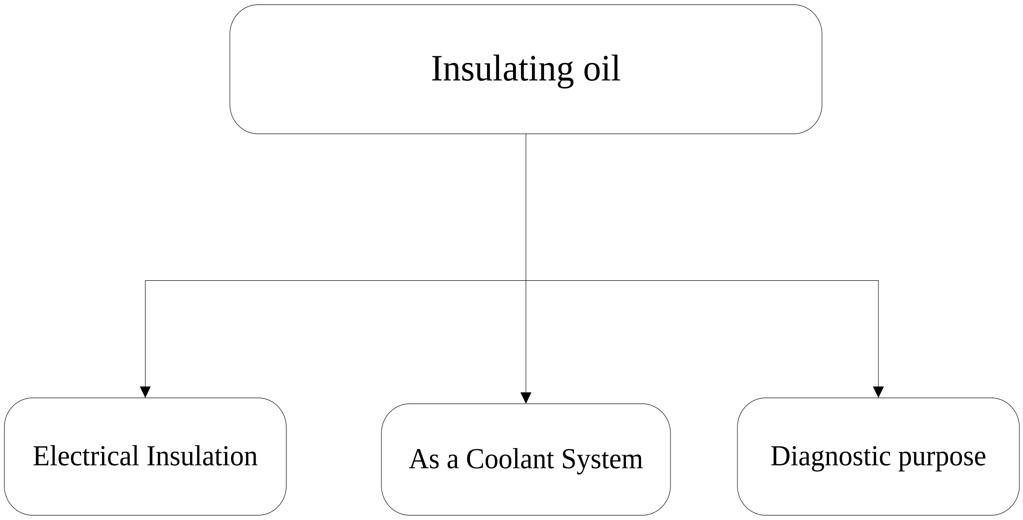


Figure 2.4: Transformer Oil Applications

2.3.1 Electrical Insulation

Liquid insulation in the transformer function is used to provide dielectric medium that acts as insulation surrounding various energized conductor. Oil makes a good contribution to transformer insulation by penetrating into and filling the spaces between wound insulation layers. Besides that, the liquid insulation acts as a protective coating to the metal surface against chemical reaching such as oxidation [19].

2.3.2 Cooling System

A secondary function of the insulating liquid is to absorbs heat from the areas and distribute equally the thermal energy over a generally large mass of oil and tank of the devices. It is transferred by means of conduction, convection and radiation to the surrounding environment [19].

2.3.3 Diagnostic Purpose

The insulating oil also can be used to determine the condition (both chemical and electrical) of operational of the liquid filled transformer. When fault is happen in the transformer, the caused energy from the fault is wasted through the liquid by chemical degradation. The analysis of these degradation products can provide information about the type of fault that is present.

2.4 Vegetable Oil for Insulation

The development of biodegradable insulating oil in transformer obtained from high oleic vegetable sources. However, to improve electrical properties of the oil, further purified and special additives were added to improve the oxidation stability. Rape seed oil were found to be an alternative to mineral oil, however modification should be done to improve the oil as insulating oil which studied by R. Badent, et al in [20]. A number of qualifying tests were performed including the usual acceptance tests for the transformer oils. Oxidation stability tests and other relevant test methods were done on the oils. Biodegradability, life testing and decomposition studies were also done as a more advanced testing. The stability of the oil is determined by the fatty acid content since vegetable oils are mixtures of triglycerides of fatty acids. So, fatty acid compositions were examined [21].

The interest of substituting vegetable-based insulating oil as an alternative to replace mineral oil for transformer insulation had started since early 1990's. Many researches were started during the year in order to obtain fully biodegradable insulating oil. Vegetable oil is obtained from natural resources and easily available. Vegetable oil consists of triglycerides esters from fatty acids with 8 to 22 carbon atoms [11].

Vegetable oil is high in biodegradability, hence safe to environment. Due to its higher fire point, so its resistance against fire is high and hence being much safer from the risk of transformer explosion. However, vegetable-based oil disadvantages are regarding oxidation stability and higher viscosity. The higher viscosity is due to the presence of saturated fatty acids. Existence of multiple double bonds causes vegetable oil suffer oxidation problem [15]. Based on result in [22], investigation against standards for the properties of palm oil showed that the oil has high potential to be used as insulating oil. The breakdown voltage which is the main issue of insulating properties was found to be good in palm oil.

Example of current, commercially-known, natural ester dielectrics are shown in Table 2.4

Table 2.4: Commercially Known Vegetable Transformer Oil [14]

Name	Type	Manufacturer
BIOTEMP®	Comprised mostly of mono-unsaturated high oleic acid triglyceride vegetable oils. Examples of high oleic oils are sunflower, safflower, and rapeseed (canola).	ABB Inc.
BIOTRANS	A mixture of partially hydrogenated soybean oil high in oleic acid content, methyl esters produced from soybeans, palm or coconut oils used to thin the dielectric liquid.	Cargill
Envirotemp® FR3	Edible-seed oil based dielectric liquid. It is a natural ester (triglyceride - fatty acid ester). Suitable vegetable oils, which may be used independently or combined, include: soya, sunflower, and rapeseed (canola).	Cooper Power Systems
Coconut Oil	Coconut oil	University of Moratuwa

2.5 Palm Oil

Palm oil is a type of edible vegetable oil obtained from oil palm fruits and seeds. Palm oil is usually coloured red because they contain beta-carotene content is very high. Palm oil is oil that has high saturated fat. Therefore, it would be in a semi-solid at room temperature. It is used as cooking oil, margarine and as a basic component to process the food. Boiling in a few minutes to destroy carotenoids and red palm oil will be changed to white. Figure 2.5 shows the palm oil bunch and figure 2.6 shows the palm oil structure.

Figure 2.5: Palm Oil Bunch [23]

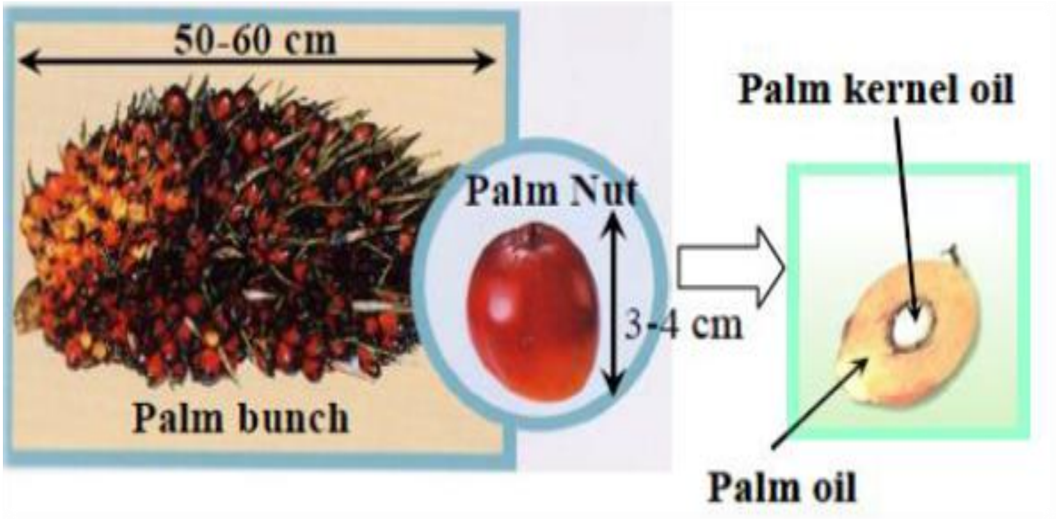


Figure 2.6: Palm Oil Structure [23]

Palm Kernel Oil is “tropical" oil derived from the seeds of palm tree fruit. Because this is mainly a saturated oil (80% - 85% saturated) and low in essential fatty acids, palm kernel oil may be heated without the risk of creating harmful breakdown products. Although palm kernel oil is saturated oil, some research conducted in areas ripe with live palm trees indicates that a diet high in tropical oils may decrease cholesterol levels. However, other research contradicts these findings. As with other saturated oils, palm kernel oil (especially refined palm kernel oil) should be used in moderation or avoided in one’s diet [23].

Refined is defined as a process of purification of a substances to obtain edible oils from crude oils through processing steps such as degumming, neutralisation, bleaching and deodorization. Bleached is defined as Removal of colour and oxidizing bodies, residual gums, soap and trace metals by mixing oil with special adsorbents (silica and/ or bleaching earth). The adsorbents containing the mentioned impurities are then removed by filtration. While deodorized is a process of removing the fatty acids, odour, flavour and destabilizing impurities by subjecting the oil to high vacuum and temperature, under conditions so that the impurities are vaporized and removed while the oil remains liquid [4].

2.6 Insulating Oil Properties

Vegetable oil can be used as dielectrics. Physical and electrical properties such as breakdown voltage, viscosity, and pH value can be varied in the wide range. The appropriate application of a liquid dielectric in an apparatus is determined by its physical, chemical and electrical properties. In addition, applications also depend upon the requirements of the functions to be performed.

2.6.1 Breakdown Voltage

Breakdown voltage is the most common parameter used to evaluate the electrical performance of dielectric insulating fluid. It is important to ensure that the breakdown voltage for the new oil is high since after ageing. Breakdown voltage defines as a maximum voltage applied to the insulation at the moment of breakdown. It also can be defined as maximum voltage difference that can be applied across the material before insulator collapse and conducts. Breakdown voltage also knows as striking voltage [24].

Some insulators will become electrically conduc~~tive when the dielectr~~ic strength of insulators is less than the breakdown voltage. The breakdown voltage can be defined as the maximum electric stress. The dielectric material can withstand without breakdown as shown as equation 2.1.

$$\mathbf{V_b = Ed} \tag{2.1}$$

Where V_b is a breakdown voltage, E is the electric field strength, and d is a sphere gap length of test cell. Important factor for high voltage system is electric field stress and dielectric strength of the insulating materials. Due to the space charge density caused by the application of high voltage stress across the insulating materials, electric field distribution was developing. The factor which effects on the dielectric strength is temperature, humidity, frequency and thickness of the specimen. When the temperature, humidity and frequency increase, the value also will increase. It is also same to thickness of the specimen. The values of the dielectric strength increase if the thickness of the specimen was increase in gases, two mechanism of breakdown voltage are avalanche and streamer mechanism. Avalanche mechanism also called Townsend Breakdown Process. This mechanism based on the generation of successive secondary avalanche to produce breakdown. Where an electric field exist in gas, free electron suppose exist. Free electron likely to ionize a gas molecule by simple collision resulting in two electrons and a positive ion during the field strength is sufficiently high. This process will continue and cumulative cause the number of free electron will increase. The producers of electron and free electron in this way called electron avalanche. This process is shown in Figure 2.7.

Streamer breakdown because of add effect of the space charge field of an avalanche and photo-electric ionization in the gas volume. The development of a spark discharge directly from a single avalanche predict in the streamer theory causes sufficient distortion of the electric field.

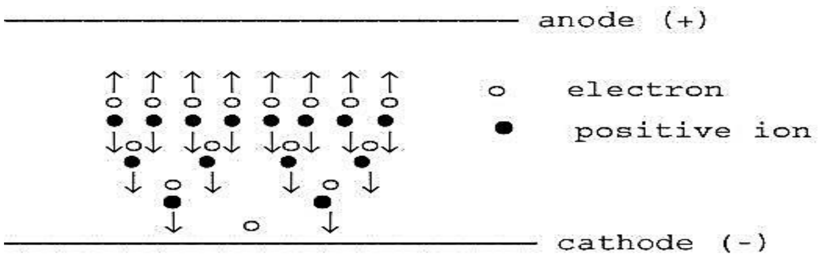


Figure 2.7: Electron Avalanche [25].

The free electron move towards the avalanche head, and in so doing generate further avalanches in a process that rapidly becomes cumulative. This process leads to very rapid development of breakdown. This process shown in figure 2.8

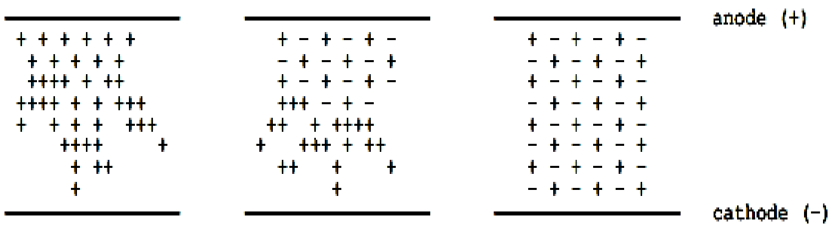


Figure 2.8: Streamer Breakdown Voltage [25].

In liquid condition, breakdown control by phenomena similarly with gas. The electric strength for the liquid condition also high (estimates 100 KV/mm). Unfortunately, liquids are easily contaminated, and may contain solids, other liquids in suspension and dissolved gasses.

The effect of these impurities is relatively small for short duration pulses (10µs). Due to the liquid globules and the presence of solid particles causes breakdown. Breakdown voltage for liquids can be determined by experimental investigations only and it is not a simple phenomenon. Breakdown also depends on applied voltage mode, time application and voltage nature. Breakdown of liquid can be determined using equation 2.2

$$\mathbf{V_b = Ad^n} \qquad (2.2)$$

Where V_b is a breakdown voltage, A is a constant, d is a sphere gap length, and n also is a constant that always below than 1.

In solid condition, the breakdown strength is high compared to liquids and gases. Solid is good dielectric that has a low dielectric loss, high mechanical strength, free from gaseous inclusion and moisture, resistant to thermal and chemical deterioration. Unfortunately, when breakdown occur, solid get totally damaged. The breakdown mechanism is intrinsic breakdown, electromechanical breakdown, thermal breakdown, surface breakdown and internal discharge breakdown.

2.6.2 Viscosity

Viscosity of oil is its resistance to flow and it can be expressed in two ways; they are Dynamic viscosity and Kinematic viscosity. The definition of dynamic viscosity is given as the ratio between the applied shear stress and rate of shear of the oil. Kinematic viscosity can be defined as the resistance of flow under gravity. Dynamic viscosity of oil can also be computed by multiplying kinematic viscosity by its density. Unit of dynamic viscosity of the oil is poise and that of kinematic viscosity is Stokes. The kinematic viscosity of oil is generally expressed in centistokes. Kinematic viscosity is measured by determining the time required to flow for a fixed volume of oil under gravity through standard capillary tubes. Viscosity of oil is very sensitive to its temperature. Viscometer is the device that use to viscosity test for the oil. The standard that used to measuring the viscosity for insulating oil is BS EN ISO 3104:1996. [26]

Viscosity is one of the important chemical properties of transformer oil. The viscosity of insulating oil will effect on the amount of heat transfer. Heat is transferred from the winding that exist in transformer [27]. The higher viscosity means that the poorer the ability of the oil to cool the transformer or poor heat transfer. When the heat transfer inside the oil is poor, the oil will get hot and hence cause problem to transformer insulating and cooling functions [28]. Low viscosity of transformer oil is essential, but it is equally important that, the viscosity of oil should increase as less as possible with decrease in temperature. Every liquid becomes more viscous if temperature decreases.

2.6.3 Viscometer

There are numerous methods by which viscosity can be measured, and these have been reviewed in detail in ref [29] where they are grouped into 4 types: capillary, falling body, oscillating body, and vibrating viscometers. Most viscometers of the first two types, capillary and falling body viscometers, are considered 'absolute' viscometers, which mean they rely on rigorous working equations. However, they still require calibration with a fluid with known viscosity at a specified temperature and pressure in order to determine correction factors included in the equations. These factors correct for effects that could contribute systematic errors to the measurements. These include the kinetic energy effect and the end effect in the capillary viscometers, and also wall effects in falling body viscometers. This limits their accuracy in absolute viscosity measurements (if no calibration made) to ±3 %; however, they can provide considerably more accurate measurements when suitably calibrated. Capillary viscometers are the most used type due to their simple design and operation. On the other hand, oscillating body and vibrating object viscometers do not require correction factors because under specific restraints the working equations are complete. A measurement in vacuum is used to determine the 'self' damping of these viscometers. Figure 2.9 shows the scheme of typical vibrating viscometer device.

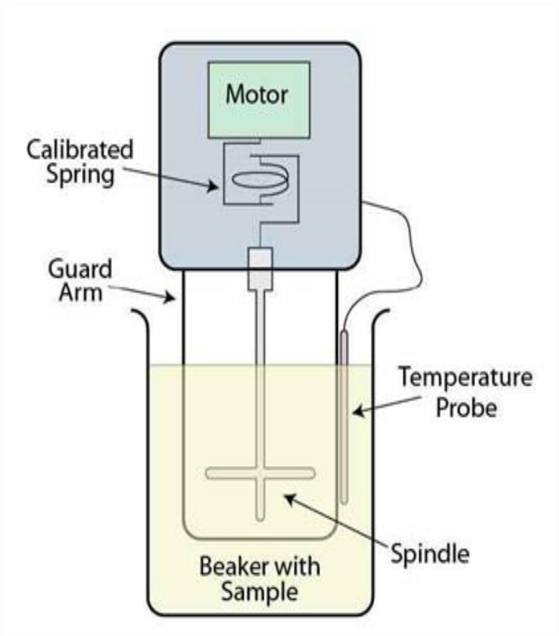


Figure 2.9: Scheme of Typical Vibrating Viscometer Device

2.6.4 Measurement of pH Value

A pH can be defined as the negative logarithm of the hydrogen ion concentration $[H^+]$. This value ranges from pH 0 to 14 pH. For acidic, the values is below 7pH meanwhile the value that is above 7pH is determine as base or alkaline. Since 7pH is the center of the measurement scale, it is neither acidic nor basic; therefore it is called as neutral. The term "pH" was first described by Danish biochemist Soren Peter in 1909 in Germany. PH is an abbreviation for "power of hydrogen". [30]

Almost all process that has been containing water has a need of pH measurement. The living things depend on a proper pH to sustain life. It is express mathematically as equation 2.3 below:

$$pH = -\log [H+] \tag{2.3}$$

Where: $[H^+]$ is hydrogen ion concentration in mol/L. A change of one pH unit represents a 10- fold change in concentration of hydrogen ion. In a neutral solution, the equation below represents pH of 7.

$$\begin{aligned} pH &= -Log\,[1 * 10^{-7}] \\ &= [-Log\,1 + Log\,10^{-7}] \\ &= -\,[0 + -7] \\ &= 7.0 \end{aligned}$$

2.6.5 pH Meter

A pH meter is an electronic instrument used to measure the pH (acidity or basicity) of a liquid (though special probes are sometimes used to measure the pH of semi-solid substances, such as cheese). A typical pH meter consists of a special measuring probe (a glass electrode) connected to an electronic meter that measures and displays the pH reading. The pH probe measures pH as the concentration of hydrogen ions surrounding a thin-walled glass bulb at its tip [30]. The probe produces a small voltage (about 0.06 volt per pH unit) that is measured and displayed as pH units by the meter. For more information about pH probes, see glass electrode. The meter circuit is fundamentally no more than a voltmeter that displays measurements in pH units instead of volts. The input impedance of the meter must be very high because of the high resistance approximately 20 to 1000 MΩ (Mega ohms) of the glass electrode probes typically used with pH meters. The circuit of a simple pH meter usually consists of operational amplifiers in an inverting configuration, with a total voltage gain of about - 9 17. The inverting amplifier converts the small voltage produced by the probe (+0.059 volt/pH in basic solutions, -0.059 volt/pH in acid solutions) into pH units, which are then offset by 7 volts to give a reading on the pH scale. The pH meters range from simple and inexpensive pen-like devices to complex and expensive laboratory instruments with computer interfaces and several inputs for indicator (ion-sensitive, red ox) [30], reference electrodes, and temperature sensors such as thermo resistors or thermocouples. Cheaper models sometimes require that 25 temperature measurements be entered to adjust for the slight variation in pH caused by temperature. Specialty meters and probes are available for use in special applications, harsh environments, etc. Pocket pH meter are readily available today for a few tens of dollars that automatically compensate for temperature. Figure 2.10 shows the Scheme of typical pH glass electrode.

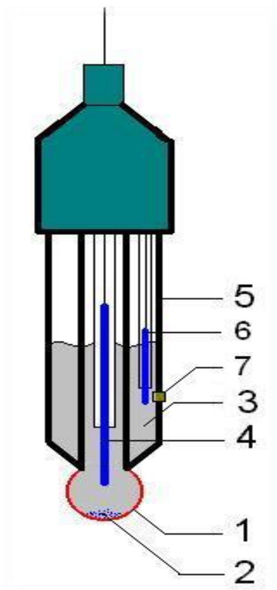


Figure 2.10: Scheme of Typical pH Glass Electrode

2.7 Fourier Transform Infrared (FTIR)

FTIR is a technique to determine the transformer oil quality. Contaminations existence in the oil could be detected by this technique. A picture of the oil's health could be identified from the infrared testing where it detects any contaminants present. An infrared spectrometer works by passing an infrared beam through a fixed thickness of oil, usually 100µm (0.1mm). Figure 2.11 shows typical infrared beam in FTIR. Some of the infrared radiation will be absorbed by the oil contaminants and additive molecules at certain frequencies [31].

The samples for doing the FTIR could be solid, liquid, or gaseous. The results of FTIR spectrum are in the range of 4000 - 400 cm-1 which are recorded by absorption of the incident monochromatic radiation. The attenuation of the transmitted IR radiation can be displayed as a function of wavelength, which is the IR spectrum. The presence or absence of functional groups is an important type of information that can be extracted from the FTIR spectrum [32].

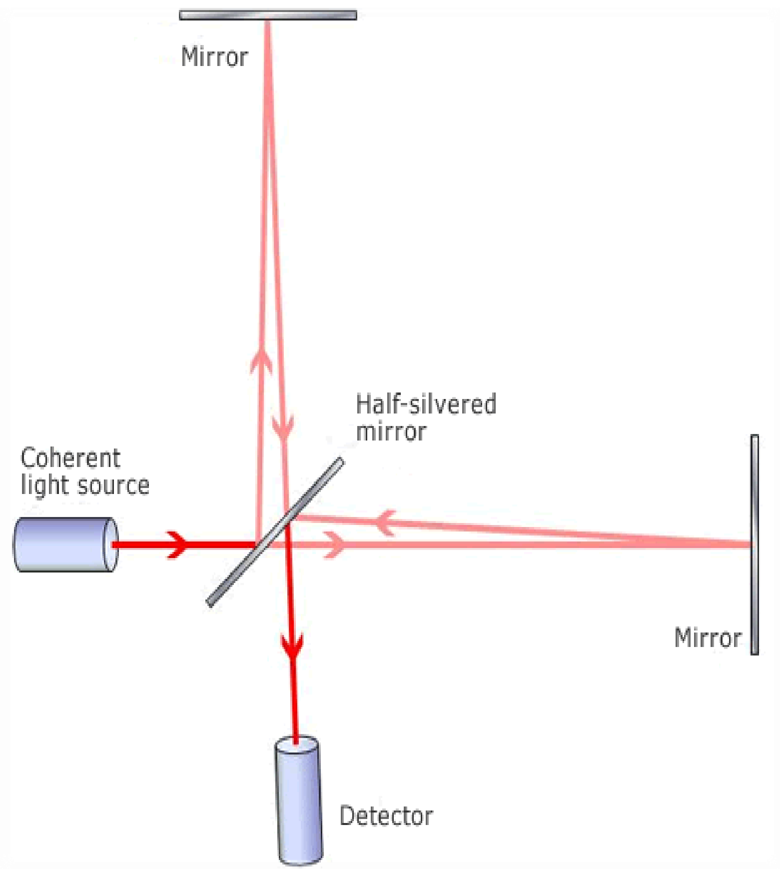


Figure 2.11: Infrared beam in FTIR [31]

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