

**ANALYSIS OF DIELECTRIC PROPERTIES
COMPARISON BETWEEN MINERAL OIL AND
SYNTHETIC ESTER OIL**

Thesis,
submitted in partial fulfillment of the requirements for
the degree of Master of Science in Electrical Engineering

ENDAH YULIASTUTI
1388436

Thesis Committee

Prof. Dr. J.J. Smit

Dr. P.H.F. Morshuis

Dr. X. Chen

Dr. P. Bauer

High Voltage Technology and Management Group
Department of Electrical Sustainable Energy
Faculty of Electrical Engineering, Mathematics, and Computer Science
Delft University of Technology

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PREFACE

I present my master thesis “Analysis of Dielectric Properties Comparison between Mineral Oil and Synthetic Ester Oil” as a part of my compulsory task to achieve a degree of Master of Science at Department of Electrical Sustainable Energy, TU Delft.

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My deepest gratitude goes to my husband and son, for their loves, supports and patience during my study here. And also to my beloved parents for their unending love and support. Finally, this thesis would never have been completed without the guidance from creator and sustainer of the universe, Allah SWT.

Delft, June 2010

Endah Yuliasuti

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 and a type of vegetable oil were investigated, and the effect of accelerated thermal aging on their dielectric properties were studied as well. Since it affects its dielectric properties, such as breakdown voltage, dielectric dissipation, and relative permittivity, the humidity of oil was measured along the aging process. The experimental results were compared with those from the previous research, showing that most of the test results obtained in this work was comparable with the previous work.

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Chapter 1

INTRODUCTION

1.1. Transformer insulating oil

The fast growth of the use of electricity asks for an improvement of the power system equipment with a high level of reliability and safety. The power system grid connects the power plants through transmission lines and distribution lines to the end users (Figure 1-1). The main goal is providing electrical power to the consumers in ready-to-use form.

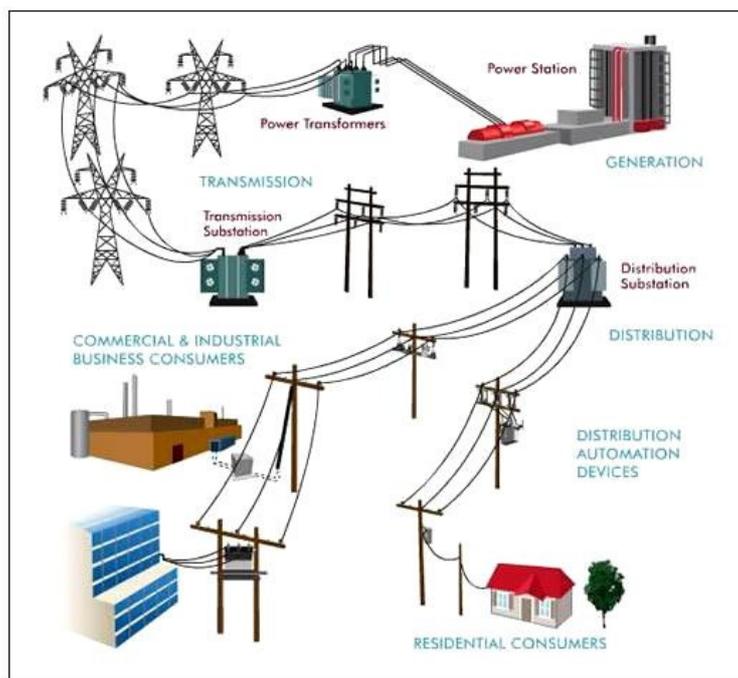


Figure 1-1. The power system grid [1]

Transformers are essential parts in the power system for voltage level conversion and maintaining the power flow. They are applied at four major regions [2]:

- At power plants, where power is generated and raised to transmission;
- At switching stations, where the transmission voltage is changed;
- At distribution substations, where the incoming transmission-level voltage is reduced to distribution voltage;
- At service transformers, where the voltage is reduced to utilization level for routing into consumers' homes and businesses.

Transformers may suffer from several conditions such as overload condition, which might lead to transformer failures. Among all of the transformer components, the insulation system plays a significant role in the transformer life, because most of transformer failures were caused by insulation problems according to the statistics of transformer failures in USA from 1997 to 2001 [3], as we can see from the transformer failure classification in Figure 1-2.

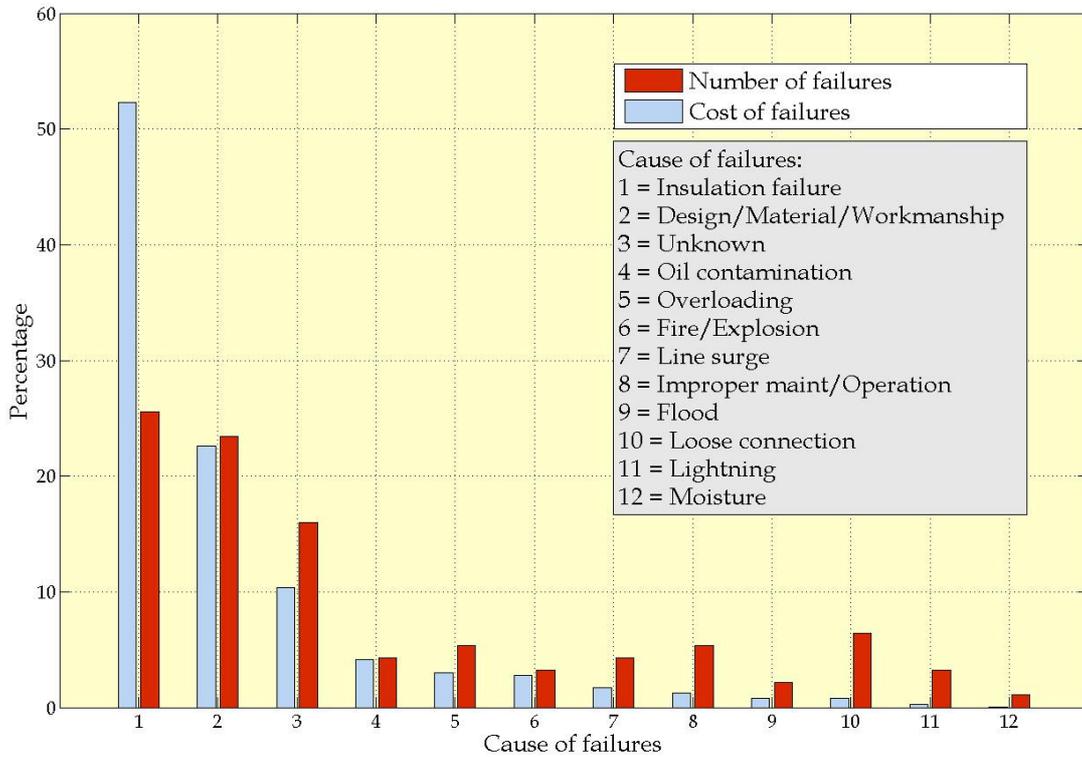


Figure 1-2. Number and cost of 25 kV transformer failures in USA (1997-2001)

There are two basic transformer insulation types, solid and liquid. Solid insulation can be made of paper, pressboard, epoxy, and wood. Among them, kraft paper is widely used as solid insulation in the transformer, which is made from unbleached softwood pulp and constructed through a sulphate process.

Oil insulation provides two main purposes in the transformer operation, as the insulation material and the cooling medium. There are several requirements for transformer insulating oil:

- a. To act as a coolant with the main task of absorbing the heat from the core and winding, then transmitting it to the outer surface of the transformer. At higher temperatures the viscosity of the oil decreases, thus facilitating the circulation of the oil. It is important to keep the pour point low so the oil is capable at any observable flow;

- b. To insulate different parts at different electrical potential. Oil makes a good contribution to transformer insulation by penetrating into and filling the spaces between wound insulation layers;
- c. In order to minimize the evaporation losses, the oil volatility should remain low. Oil temperature in service should be maintained below its flash point;

There are three factors that influence the chemical stability of oil: temperature, oxygen availability, and catalyst presence. The oil degradation process might be caused by decomposition of the hydrocarbon molecules in oil at high temperature. The oxygen contents in insulating oil might lead to a rise of the acidity number and to sludge formation [4]. Catalysts such as copper and iron are dissolved in oil during aging and might accelerate the aging process.

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. Insulating oils should fulfill the following minimum health and environmental requirements:

- a. non-toxic;
- b. biodegradable;
- c. thermostable;
- d. recyclable, reconditionable, and readily disposable;
- e. not listed as a hazardous material.

Mineral oil was first introduced in 1892 by General Electric as a dielectric coolant. The main reason for using mineral oil was the high flash point characteristic and the widespread production around the world. As of today, mineral oil has been used as the main source of insulation material for several equipments, especially power transformers. But due to the poor biodegradability characteristics of mineral oil there is still environmental concern in case of leakages during operation or due to an incident. In the beginning of 1930 until mid 1970, many transformers were insulated by Askarel, a mixture of PCB (polychlorinated biphenyl) and chlorobenzenes. This material was chosen because of its non-flammable characteristics [5]. Later, Askarel was no longer recommended as an insulation material anymore due to the environmental issues of this hazardous material. In order to settle down the environmental and sustainable issues, people started to look for alternative sources for insulating oil. The latest insulating oil implementation is vegetable oil-based fluid which is known as the most potential source to replace the mineral oil because of its biodegradability characteristic. The first vegetable oil was used for capacitor

insulation in 1962 and gave a good match with cellulose due to its higher dielectric constants [6]. One of the vegetable oil variants is known as ester oil since the extraction process of ester oil uses the vegetable source. We apply the term ester oil instead of vegetable oil in this thesis.

1.1.1. Mineral oil

Petroleum oil has been used for transformer oil since Sebastian de Ferranti discovered its useful function in 1891. The source and production process of petroleum oil are described as follows:

a. Crude petroleum

Petroleum oil comes from the extraction source which is called crude petroleum. It contains hydrocarbons and also a small portion of sulphur and nitrogen [7]. Basically, hydrocarbon molecules can be divided into three main groups as shown in Figure 1-3:

- Paraffins:

Methane (CH₄) is a gas, normal buthane (C₄H₁₀), and isobutene;

- Naphthenes

It has ring structures with six carbon atoms (within six-membered rings) or fourteen carbon atoms (within three-membered rings);

- Aromatics

It has six-membered ring structures, fall into two groups: monoaromatics (single rings) and polyaromatics (two or more rings).

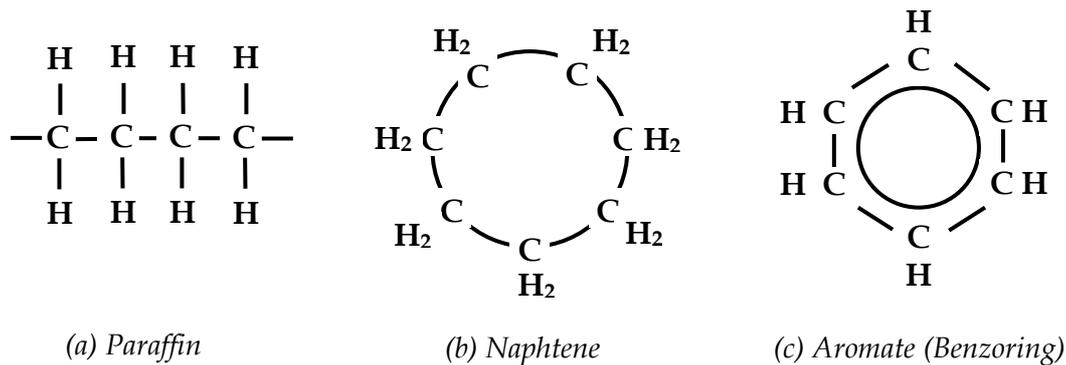


Figure 1-3. Hydrocarbon compounds in mineral oil

b. Refining petroleum

Crude petroleum needs to be refined into more useful petroleum products such as gasoline, kerosene, liquid petroleum gas (LPG), lubricating oils, and so on. The basic refining process comprises a vacuum distillation unit where several steps are followed

such as selective solvent extraction, sulphuric acid extraction, earth filtration, hydrogenation, re-distillation, filtration, and dehydration [7].

Mineral oil refined from petroleum is known as a good insulating material because of its good electrical properties, aging behavior, and low viscosity. Other characteristics such as the low relative permittivity also give a positive point for transformer operation. The most important thing is that mineral oil is already produced world wide and offered at a low cost. But, the biggest problem will occur when there is a transformer leakage and the mineral oil will endanger the environment because of its poor biodegradability.

1.1.2. Ester oil

Esters are the synthesized organic compound of acids and alcohols [8, 9]. Generally, there are two main types of esters:

a. Natural ester

It is derived from single, double or triple unsaturated fatty acids. The optimal condition is reached by using a fluid with a high single unsaturated fatty acids concentration. Natural esters can be produced from edible seed-based oil such as alcohol glycerol (triglycerides). Figure 1-4 shows the chemical structure of a natural ester oil.

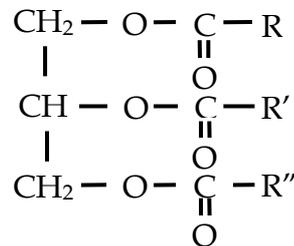


Figure 1-4. Natural triglyceride structure

b. Synthetic ester

The synthetic ester is created from an acid and an alcohol, commonly known as polyol (pentaerythritol). The most recent products used in transformer insulation are MIDEL 7131 (M&I Company) and Elantas BecFluid 9902. Figure 1-5 shows the chemical structure of a synthetic ester fluid.

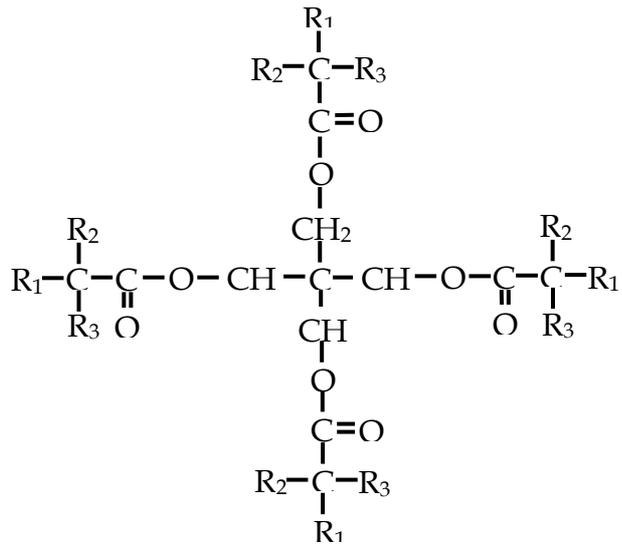


Figure 1-5. Synthetic polyol ester structure

The basic process of ester fluid production consists of three stages [10] :

a. Extraction

Ester oil can be extracted from animal fats, fish oil, palm fruits or seeds with different processes. Several typical oil seeds which are extracted and processed before they are ready to be used as the transformer insulation are represented in Figure 1-6 [6].

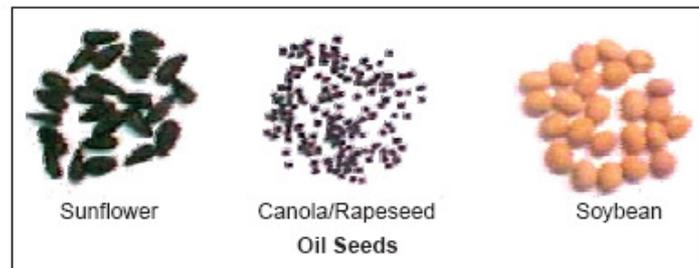


Figure 1-6. Oil seeds

Description of the extraction process of ester oil is summarized in Table 1-1 [10].

Table 1-1. Extraction process of ester oil

Type of source	Process
Animal fats	<ul style="list-style-type: none"> - Hashing and steaming; - The cells burst as fat expands through heating; - Wet steam treatment; - Oil layer decanted and centrifuged; - Alternatively, after heating the product is put through a screw process.
Fish oil	<ul style="list-style-type: none"> - Dry rendering, removes oil from fish; - Deactivated the enzymes at these temperatures.
Palm fruits	<ul style="list-style-type: none"> - Sterilized at 130°C, release the individual fruit and deactivate hydrolytic enzymes; - Broken up fruits in digester, produce liquid (oil & water) and wet solid through screw process; - Free the oil from water through centrifugation and vacuum drying.
Seeds	<ul style="list-style-type: none"> - Pretreated process: cleaning, decorticating, size reduction, cooking at 90-115°C, flaking to 0.3-0.4 mm thickness; - Resulting material: put on expeller at 3.5 kg/mm², squeeze out the oil & leave protein meal still containing 3-6% of oil; - Residual cake: contains 18-29% oil from percolation/immersion in solvent, finally contains only 0.7-1.5% of oil.
Olive oils	<ul style="list-style-type: none"> - Cold pressing: material being extracted is not heated by external means & it is favored for niche product; - Oil recovery: less efficient & possible to get further (lower grade) oil by solvent extraction.

b. Refining

The refining process converts the crude oil or fat into a suitable product, with description on Table 1-2 [10].

Table 1-2. Refining process of ester oil

Process	Material/Procedure	Impurities removed/reduced
Degumming	H ₃ PO ₄ , H ₂ O, 70-80°C	Phospholipids, trace metals, protein, CO ₂
Neutralization	NaOH/other alkali	Fatty acids, phospholipids, pigments, trace metals, sulfur compounds
Washing	Water	Soap
Drying	-	Water
Bleaching	Bentonite	Pigments, oxidation products, trace metals, sulfur compounds, phospholipids, traces of soap
Filtration	-	Spent bleaching earth
Deodoration/ physical refining	Steam at reduced pressure	Fatty acids, mono and diacylglycerols, oxidation products, pigment decomposition products, pesticides
Polishing	-	Traces of oil insoluble

c. Processing

The final product of ester oil needs enhancement of some physical properties. Some techniques have already been applied in this process which includes blending, fractionation, hydrogenation, and inesterification. Tabel 1-3 describes more details about the enhancement process [10].

Tabel 1-3. Final process of ester oil

Process	Description
Blending	Mixing process between two or more oils or between oils and fats, in order to achieve the required nutritional and physical properties
Fractionation	Liquid separation process into two or more fraction of fatty acids and triacylglycerol composition. For dry fractionation, the less soluble tryacylglycerol is being crystallized from the liquid oil.
Hydrogenation	Conversion process from liquid oil (fish or vegetable) into semi solid fat for spread component. The melting behavior will change due to the increase of solid component.
Interesterification with chemical catalysts	Fat production with required melting behavior which will have more saturated acids than the partial hydrogenated product. The inesterification process needs a catalyst such as alkali metal, sodium alkoxide or diacyl glyceroxide anion.
Interesterification with an enzymic catalysts	The inesterification uses the lipases as a catalyst. This catalyst will give an effect of acyl exchange at the sn-1 and 3 positions while leaving acyl groups at the sn-2 position unchanged.

The advantages of ester fluid can be acknowledged from its performance criteria [11]:

- a. Low vapor pressure, low volatilities, high flash point
- b. Lubricity
- c. High solvency

The high polarity of ester molecules causes a high solvency inside the fluid.

- d. Hygroscopic

Ester fluids are hygroscopic because water molecules easily attach to the polar ester bond.

- e. Thermal stability

The higher bond energy of ester linkage makes it stable to heat [12].

- f. Hydrolytic stability

Hydrolysis is the reverse action of esterification, so if the process in creating the ester fluid runs well then it also maintains the stability of the hydrolytic aspect.

Natural ester fluid needs some additives such as antioxidant or metal deactivators, to improve the performance and oxidation stability. They ensure that the combination between the natural ester fluid and additive material is in the range of minimum environmental and health safety target.

The general side-to-side characteristic comparison between mineral oil and ester oil is described in Table 1-4 [13].

Table 1-4. Characteristic comparison between mineral oil and ester oil

Criteria	Mineral oil characteristic	Ester oil characteristic
Key properties	Produced from increasingly scarce and non-renewable special petroleum crude	Produced from domestically grown, renewable sources, such as soybeans and corn
Environmental Properties	Contains compounds that do not readily biodegrade. May contain traces of a confirmed carcinogen (especially the hydrotreated light naphthenic petroleum distillate as the primary component)	Highly biodegradable; non-toxic; does not contain petroleum, silicone, or halogens
Leaks and Spills	Spill clean-ups are required by regulation and typically necessitate special equipment and material to help capture contaminated runoff	Relatively rapid biodegradation may eliminate the need for environmentally related clean-up operations
Fire Risk	Catches fire more easily, leading to higher probability of transformer fires	Higher fire point reduces the frequency and impact of transformer fires; virtually eliminates sustained fires
Transformer Performance	Does not slow down the standard insulation aging rate; requires special and expensive processing to dry out the paper insulation	Proven to slow down the aging rate of the insulation system, resulting in an increase in the expected life of a transformer by decades; also promotes automatic dry-out of paper insulation
Utility Cost	Smaller investment leads to shortened life of transformer and diminished economic returns; increases liability	Upfront investment promotes transformer life and leads to longer-term economic benefits

1.2. Problem definition

Almost 85% of the energy used in the world comes from fossil fuel [14, 15] which is known as the main resource of mineral oil (Figure 1-7). Now, the existence of mineral oil in the world has been reduced as the time goes by and probably it will not occupy our needs for the next millennium.

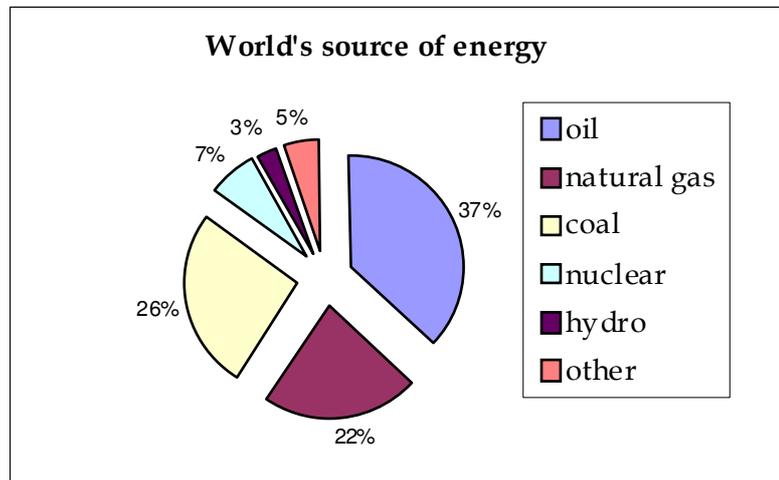


Figure 1-7. World's sources of energy

A scenario for world oil and gas liquids has been proposed by Colin Campbell [16] as in Figure 1-8. The peak of world oil production happened at around 2007-2008 and the production will be depleted afterward. It is important to find alternative oil sources that have similar dielectric characteristics with the existing one and probably can increase the performance of related equipment.

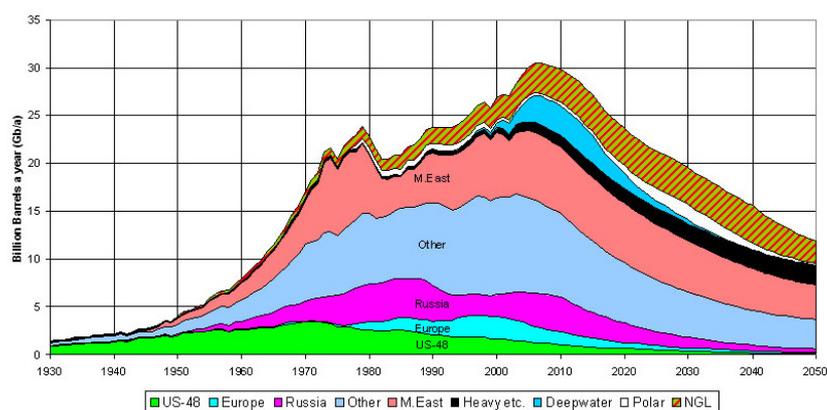


Figure 1-8. Colin Campbell's 2004 scenario for world oil and gas liquids

Transformer insulation gets weaker with the transformer age. Any failures such as an internal arcing could happen to the oil-filled transformer due to intrusion of animals, lightning hits, or seal leakage. This may lead to transformer explosion and cause a leakage

of oil. The spilled oil will harm the environment such as trees, soil, water, and other living things. Figure 1-9 shows an example of mineral oil leakage from a 19 kV transformer explosion in Fairfax County, Virginia in 2006 [17]. This incident was ignited by a mechanical failure inside the transformer.



Figure 1-9. Mineral oil leakage after a 19 kV transformer explosion

Ester oil has a capability as the alternative source for transformer insulation. The biggest advantage of ester oil is the non-toxic material characteristic which will not produce any dioxin or toxic product during fire. Carbon dioxide and water are the only products that are formed during the biodegradation process. They are also less flammable liquids with a minimum flash point above 300°C. They resist oxidation and adsorb more moisture than mineral oil. On the other side, their high viscosity might cause a problem to the heat transfer system in the transformer [5].

A research by Stockton et al has revealed the fact that natural ester oil has a higher solubility for water than mineral oil [18]. This property is very helpful to eliminate any moisture from the insulating paper. A comparison of water content in mineral oil and natural ester oil is shown in Figure 1-10.

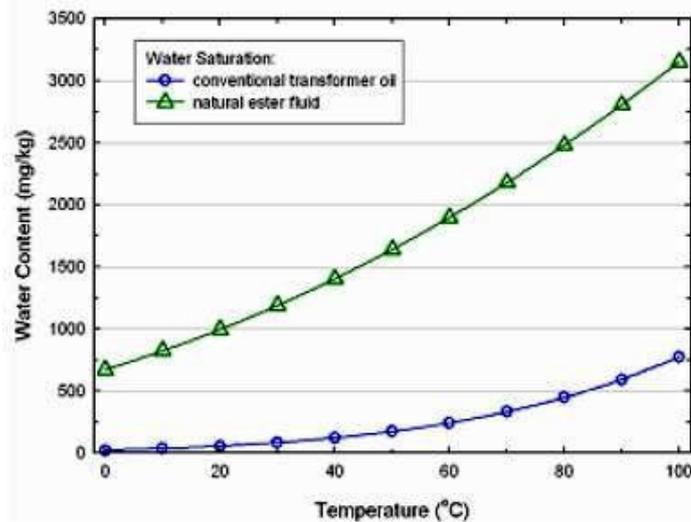


Figure 1-10. Solubility of water comparison

Another chemical parameter which is known as the degree of polymerization (DoP) of paper aged in transformer oil was also measured by C.P. McShane et al [19]. Paper samples were aged at different temperatures (130°C, 150°C, and 170°C). The results show a better performance of the natural ester oil compared to the mineral oil as shown in Figure 1-11.

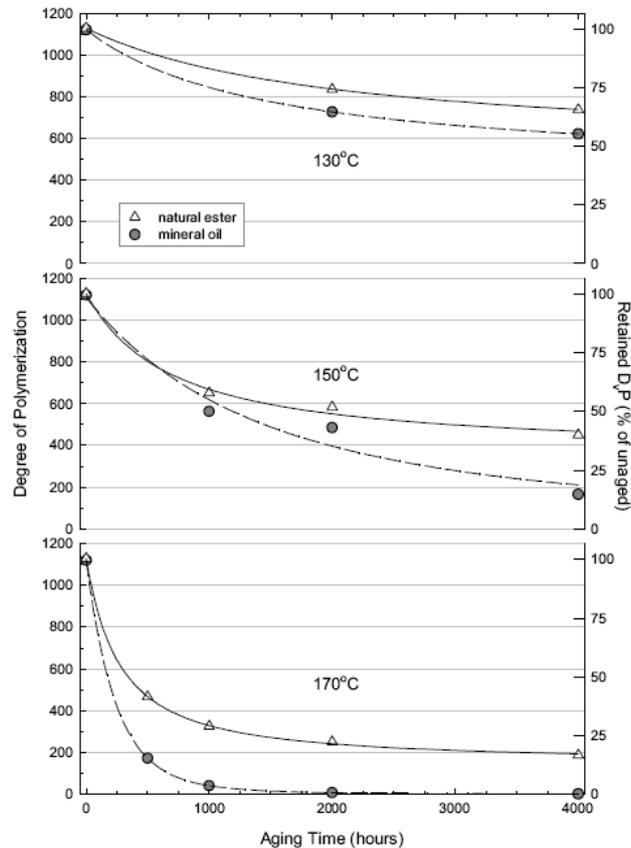


Figure 1-11. DoP comparison between mineral oil and natural ester oil

The result of ester oil characteristics gives a good impression as the biodegradability material, compared to mineral oil. But the problem for wide application of ester oil is due to the high price, not yet widely available and also the long-term stability since some of vegetable oil component are degraded in relatively short time [6].

Several researches have been carried out in this field. Perrier and Beroual experimentally investigated three different insulating liquids: mineral, ester, and silicon oils [20]. They added copper as a catalyst and measured the acidity and dielectric dissipation factor ($\tan \delta$) to analyze the oxidation stability. The result showed that some natural ester oil had a better oxidation stability than the non-inhibited mineral oil. But ester oils are also characterized by a relatively high viscosity which would give less efficiency of heat transfer in transformers. The investigation conducted by Oommen [6] and Lewand [21] gave unsatisfactory results of application of ester oils because some natural ester oils tended to become a gel during the aging process. Another research by Borsi [22] performed an aging process on synthetic ester oil in open vessels with additional catalyst such as copper, steels, and aluminium chips. The breakdown strength measurement on ester oil gave a similar result to silicone oil, but it showed higher values of $\tan \delta$ and moisture contents. The investigation still continues to find out the optimal dielectric characteristic of ester oil.

1.3. Objective of the study

In this master thesis, a comparative study will be conducted between mineral oil and synthetic ester oil during an accelerated thermal aging process. The objective of this master thesis project is to analyze the dielectric properties of synthetic ester oil (Midel 7131) and mineral oil, such as the breakdown voltage, dielectric losses ($\tan \delta$), and relative permittivity during an accelerated thermal aging process. The dielectric properties are measured along the accelerated aging process. All oil samples underwent thermal aging which influenced their chemical reaction rate at high temperature. The humidity value during the aging or moisture instability of the oil samples was measured to see its influence on the dielectric characteristics. In order to compare with mineral oil, the same aging process and dielectric tests are carried out on mineral oil (Shell Diala B). Later, the final result will acknowledge the difference of dielectric characteristics of each insulated oil types.

Generally, the measurements in this thesis project follow the international standards (IEC). In this project a new tool for $\tan \delta$ in oil measurement has been developed by the high voltage laboratory.

1.4. Experimental approach

The experimental research was carried out in the high voltage laboratory and several measuring equipments were used. The experiments followed the following methods:

- a. Material samples (mineral oil and ester oil) for the accelerated aging process were kept in the oven for approximately 2 months (1440 hours) at 100°C based on IEC 61125.
- b. Breakdown voltage measurement based on IEC 60156;
- c. Dielectric losses measurement based on IEC 60247;
- d. Relative permittivity measurement based on IEC 60247;
- e. Humidity measurement;
- f. Collection and evaluation of the results comparison of the dielectric properties between mineral oil and synthetic ester oil.

1.5. Thesis overview

This thesis is divided into five chapters which include all aspects of investigating the two types of insulating oil. Chapter 1 introduces the important background of vegetable-based insulating oil as an alternative for transformer oil. Then, the basic knowledge for several experimental activities in this thesis project will be discussed in Chapter 2. The experimental procedures to measure the dielectric properties of both types of oil will be described in Chapter 3; the accelerated aging process, the breakdown voltage measurement, the dielectric losses measurement, and the relative permittivity measurement. In Chapter 4 the measurement results are analyzed. The dielectric properties of the mineral oil and the synthetic ester oil are compared. In Chapter 5 conclusions are presented based on this work.

Chapter 2

DIELECTRIC MEASUREMENT THEORY

In this chapter, the basic theory behind the experimental work of this thesis project will be introduced and discussed. The theoretical background consists of several definitions and formulas, which will be used to analyze the experimental data. The experimental work will investigate the effect of accelerated thermal aging on the dielectric properties of two series of oil samples (mineral oil and synthetic ester oil), such as the humidity influence, the breakdown voltage, the dielectric dissipation factor ($\tan \delta$), and the relative permittivity.

2.1. Aging of oil

In general, insulating materials will deteriorate under normal operating conditions. The aging rate of any material is influenced by several external aging stresses: thermal, electrical, mechanical, and ambient stresses [23]. Thermal stress can be recognized by the temperature gradient of insulation during the long-term operation and especially the presence of hotspots. Electrical stress may lead to partial discharge, treeing, and dielectric heating due to a lossy insulation or highly conductive contaminants. For mechanical stress, the aging process relies on the torsion, compression, tension or bending factors. Ambient stress is closely related to the environmental factors such as corrosive chemicals, petroleum fluids, high humidity, and ultraviolet radiation from the sun. The composition and molecular structure of insulating materials can be decomposed by all of the stresses, leading to a situation in which the material eventually can no longer fulfill its insulation functions.

2.1.1. *The bathtub curve relationship*

The transformer reliability depends largely on the properties of the electric insulation system (EIS) due to the fact that the highest percentage of transformer failures result from the insulation degradation. Thus, aging of the insulation has been recognized as one of the main cause of transformer failures. Insulating oil plays an important role in the transformer insulation. The degradation of the insulating oil can result in an increase of humidity, an enhancement of the possibility of partial discharges in the insulation system, and a decrease of the breakdown strength of the oil-paper insulation system. The aging process of the insulating oil can be illustrated by Figure 2-1, which is determined by the thermal and

electrical stresses on it [24]. In Figure 2-1, the oxygen comes from solved air and the thermal stress can decompose the oil and form sludge or mud. Finally, the aged oil affects the solid insulation ultimately leading to a transformer failure.

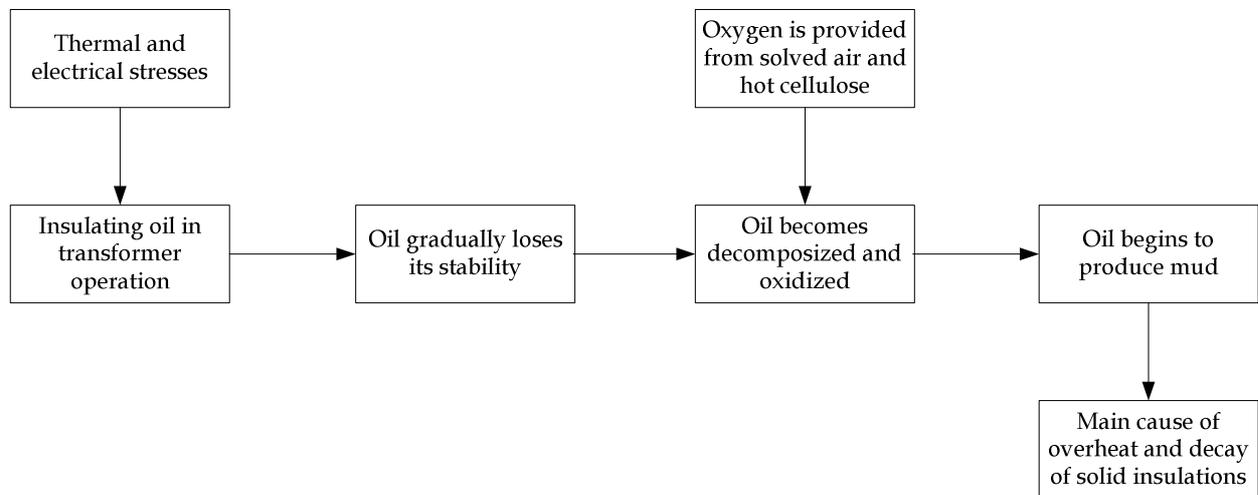


Figure 2-1. Degradation mechanism in oil

Several transformer life assessment methods have already been established to find out an optimal life time prediction. The transformer's predicted life time is determined by the failure rates of its insulation. The relation of transformer's failure rate and the predicted life time is represented in the bathtub curve in Figure 2-2 [25].

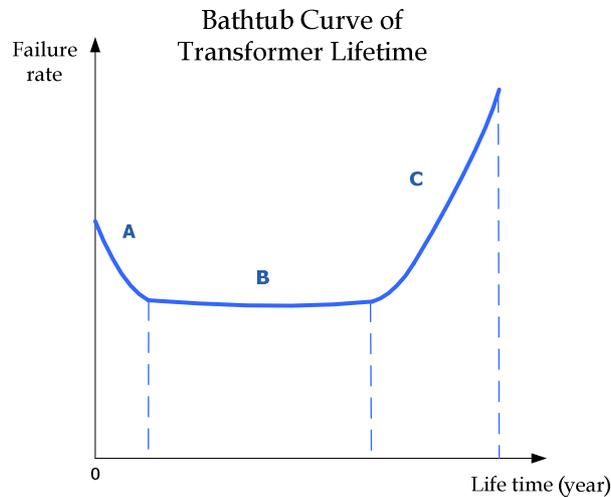


Figure 2-2. Bathtub curve of transformer lifetime

Generally, the operating life of a transformer is divided into three phases [24, 25]:

- Phase A
This is the phase of a new transformer, which consists of the first 1-3 years after commissioning. Most failures are caused by the production side due to poor materials, design or imperfect installation.

- Phase B
During this phase, a transformer works in normal operation between 20-30 years. Any random failures can happen such as switching surges, lightning, or operator's faults which are not related to the early failures.
- Phase C
The failure rate significantly increases due to the degradation of insulation system and it may start after 20 years of operation time.

2.1.2. *The accelerated thermal aging process*

Insulating oils in the transformer deteriorate during its service life. The aging rate of the insulating oils depends on the magnitude of the electrical, thermal, and mechanical stresses. It is also determined by the composition and molecular structure of the oils. The thermal aging principle is derived from the thermal condition of the insulating oil itself. Long term elevated temperatures cause internal chemical effects on the insulating oil. It is mostly related to oxidative degradation due to the interaction between hydrocarbon in the oils and the dissolved oxygen from air, which generates oxidation by-products such as acids and sludge.

Many researchers have tried to calculate the loss of transformer functional life to predict how long the transformer would optimally operate. Transformer insulation life defines the total time between the initial state for which the insulation is considered new and the final state for which dielectric stress, short circuit stress, or mechanical movement, which could occur in normal service and would cause an electrical failure [26]. The loss of transformer functional life was actually the same as the loss of transformer insulation life.

Montsinger [27] in 1930 conducted a research on aging and life time of a kind of varnished cambric, placing the varnished cambric tape insulation into a series of oil-filled test tubes, getting them heated up, then measuring the insulation's tensile strength. He concluded that every 8°C increase in continuous temperature will reduce the life of the varnished cambric by fifty percent. In 1944, Montsinger revised his research by stating that the 8°C rule can not be properly applied at lower temperatures.

Later, Dakin modified the Arrhenius law to calculate the transformer insulation deterioration [28]. The Dakin-Arrhenius law is formulated as

$$\text{The remaining life} = A \cdot \exp^{\frac{B}{T}} \quad (2-1)$$

where A is the initial life, B is a constant, depending on the properties of the material studied, and T is absolute temperature in K. The simple insulation life curve was developed to relate the insulation's life and its operating temperature.

According to life test protocol for distribution transformers which is mentioned in ANSI/IEEE C57.100-1986 [6, 29], the life expectancy of oil-immersed distribution transformers is formulated as:

$$\log_{10} \text{life}(h) = \frac{6328.8}{273 + \theta} - 11.269 \quad (2-2)$$

where h is the life time and θ is the hot spot temperature of the winding. The formula is valid for accelerated hot spot temperature, which has higher temperature rising than the conductor at the top of the winding [30] as shown in Figure 2-3.

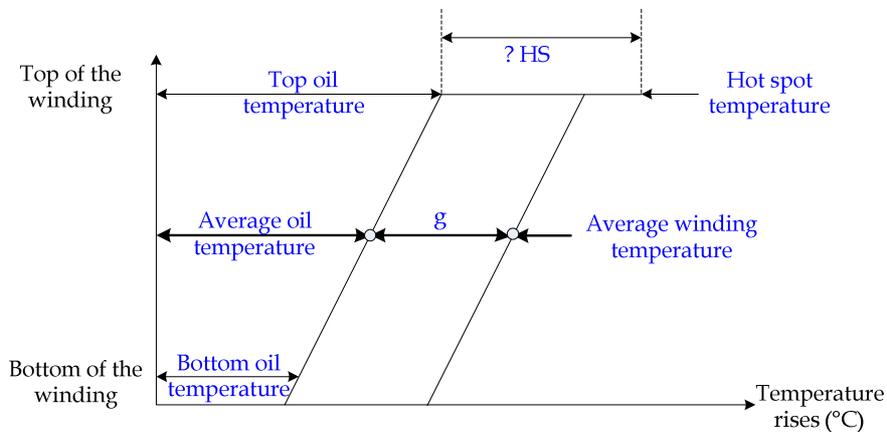


Figure 2-3. Basic thermal model in transformer winding

The example of minimum aging periods at accelerated hot spot temperatures [6] are shown in the following table:

Table 2-1. The minimum periods at accelerated hot spot temperatures

Temperature	Life time
160°C	2224 h
180°C	503 h
200°C	129 h

To compensate for the statistical uncertainty, it is specified that the life testing be conducted five times the minimum period shown above. It is customary to round off the final numbers to 10,000, 2500, and 720 h, and this interval is divided into ten equal periods for the ten end-point tests. A test period is a series of aging temperature cycles which consist of a specified time at a specified hottest-spot temperature followed by a return to approximately ambient temperature [29]. The end-point test is considered as the particular

test on specimen when the thermal degradation has progressed to a point such that the specimen cannot withstand any one of a series of tests (tensile strength, degree of polymerization).

A theory by Moses [31] about accelerated aging processes in oil is known as the ten (10) degree rule which states “a 10 degree decrease in temperature cuts the reaction in a half, while the 10 degree increase doubles the reaction rate” [32]. The situation can be explained through Figure 2-4, where the time for the oil to oxidize versus a neutralization number is compared at three temperatures: 70°C, 60°C, and (60-X)°C.

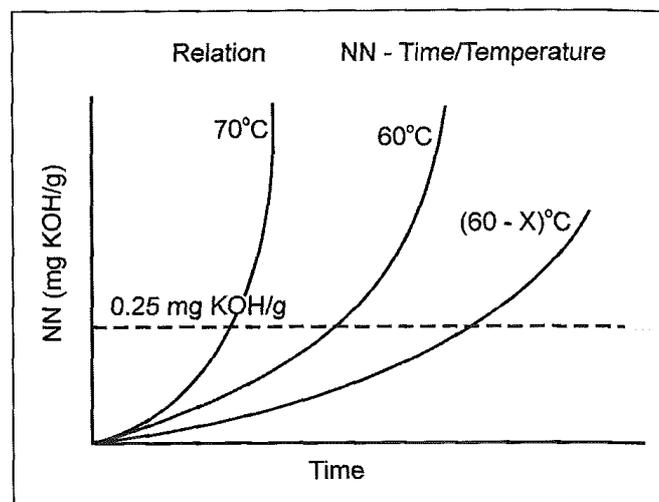


Figure 2-4. The 10 degree rule application on oil's neutralization number

According to standard IEC 61125 [33], the oxidation stability in insulating liquids is measured by accelerated thermal aging of the liquid sample and injecting bubbled oxygen or air, and maintaining the sample for a given period at a given temperature, 100°C or 120°C, in the presence of solid copper. There are three different methods that can be selected:

a. Method A

This method is applied at a temperature of $100^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ for 164 h aging duration and using a piece of copper wire as a catalyst.

b. Method B

This method is applied at a temperature of $120^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ without specific aging duration and using a piece of copper wire as a catalyst.

c. Method C

This method is applied at a temperature of $120^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ for 164 h aging duration and using a piece of copper wire as a catalyst. For the insulating liquids with improved oxidation stability, it requires longer test periods.

An experimental research by Liu et al. [34] mentioned about an accelerated thermal aging process on mineral oil at 120°C for 675 h. The oil samples were tested in the mini-static tester for the electrostatic charging tendency (ECT). Other parameters such as dissipation factor, volume resistivity, and acid number were also measured with different standard methods. Dissipation factor and volume resistivity have been measured according to IEC standard 60247-2004, whereas measurement of acid number followed the Chinese standard GB/T264-1983. The experiments discovered an increasing tendency of ECT along the aging time as shown in Figure 2-5.

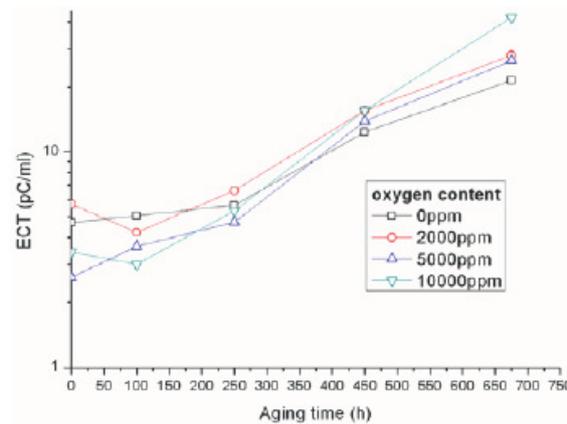


Figure 2-5. ECT vs. aging time in mineral oil (by Liu et al.)

Perrier and Beroual [35] performed a similar experiment as Liu et al. on different types of oils. The accelerated aging process was performed at 120°C for several samples of mineral oil, vegetable oil, silicone oil, and synthetic ester oil for a duration of 14 days. They determined the influence of accelerated thermal aging on the insulating oil properties. Figure 2-6 shows that the acidity level of all insulating oil samples increased due to the aging process. A similar behavior was found for the viscosity of vegetable oil, but the viscosity of mineral oil remained constant (shown in Figure 2-7).

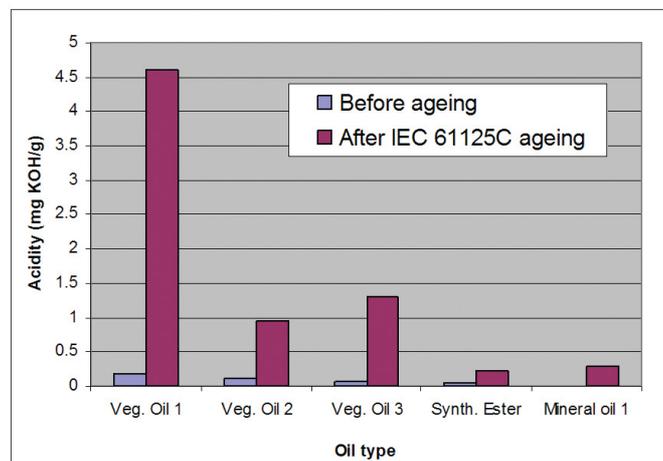


Figure 2-6. Acidity before and after ageing (by Perrier and Beroual)

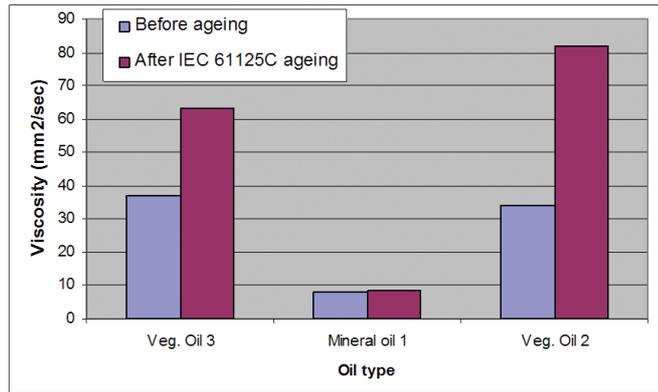


Figure 2-7. Viscosity before and after aging (by Perrier and Beroual)

Based on the result of these two researches, in this thesis project a similar accelerated thermal aging procedure is performed on two types of insulating oil, i.e. the mineral oil and synthetic ester oil. The oil samples will be put into an oven to carry out the thermal aging process at 100°C. According to the 10 degree rule and 675 hours aging duration at 120°C, the aging duration carried out in this thesis project is determined to be 1440 hours.

2.2. Breakdown in oil

The definition of the breakdown voltage according to IEC standard 60243 is:

- a. For continuously rising voltage test

The breakdown voltage is the voltage at which the specimen suffers breakdown under the test condition.

- b. For step-by-step test

The breakdown voltage is the highest voltage which a specimen withstands without breakdown for the duration of the time at the voltage level.

2.2.1. Breakdown phenomena

Breakdown phenomena in oil can be analyzed by electro-optical means [36]. First, a conduction process occurs through charge injection at a point of field enhancement at the cathode. In figure 2-8 (a) and (b), it is shown that an avalanche process is started in the low density region created by the energy dissipated in the former conduction process. Electrons leave the cathode and their number increases due to the collision process under high electric field on their way to the anode. They create a narrow filamentary channel as they leave the cathode plane. Negative streamers which look like a branch part of a tree propagate from the discharge region to the anode.

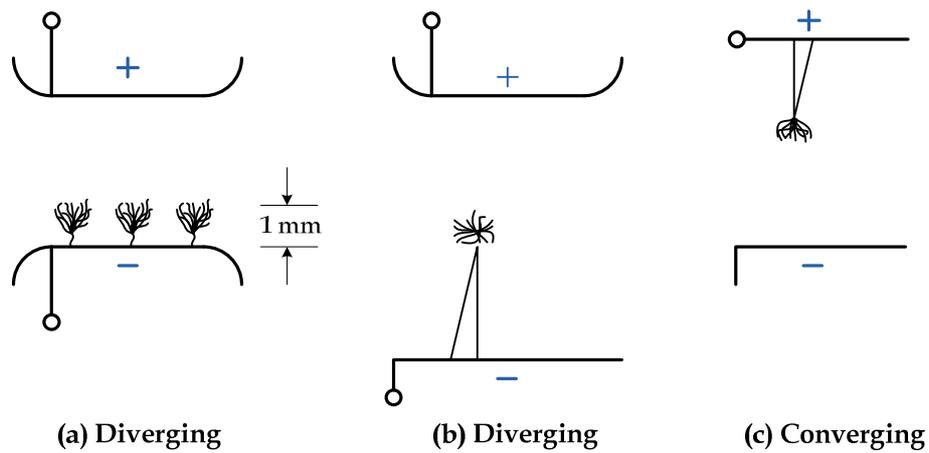


Figure 2-8. Discharge development in n-hexane

Alternatively, a converging process moves towards a positive point or plane, see Figure 2-8 (c). Electrons from the liquid or plane cathode or their descendents from a charge multiplication process converge on the point anode. After the negative charge carriers reach the point anode, they suddenly generate a very high voltage gradient and cause prolific ionization. This condition initiates positive streamers striking back to the cathode.

Thermal breakdown in oil may take place under ac field condition at localized hot spots [37]. If the temperature at such hot spots continues to increase when the heat generation rate exceeds the dissipation ability of the surrounding medium, the oil may be vaporized. This condition can ignite a channel development between the opposite electrodes to generate a breakdown. Thermally induced breakdown depends on the time of ac voltage application and may apply to breakdown under long-term operating conditions. However, a thermal breakdown may occur over a very short time condition if the oil is subjected to very short repetitive pulses.

2.2.2. The influence of bubbles

Gas bubbles can be produced during a heating process in insulating oil as the product of gas and water contamination. In this case, the bubbles may be a source of discharges in oil with uniform electric field E . The electric field in a gas-filled cavity in oil with a relative permittivity ϵ_R equals

$$\frac{3 \epsilon_R E}{2 \epsilon_R + 1} \quad (2-3)$$

The maximum field in the cavity is $1.5E$ assuming $\epsilon_R \rightarrow \infty$. For mineral oil with $\epsilon_R = 2.2$, the maximum value is $1.22E$. For silicone oil with $\epsilon_R = 2.8$, the maximum value is $1.27E$. And for ester oil (Midel 7131) with $\epsilon_R = 3.3$, the maximum value is $1.30E$.

Spherical bubbles often occur in low density areas in oils. The discharge process may initiate from the bubbles due to the higher electric field and lower electric strength of the enclosed gases in the bubbles. Effective spherical bubbles can be developed within a space where a sphere is highly conducting compared to the surrounding liquid. The gap g between point cathode and plane anode will be reduced to $g-d$ after the discharge region has formed a conducting sphere with diameter d . The gap reduction can accelerate the speed of travel of the streamer away from point cathode and develop a breakdown. The illustration of spherical discharge region is shown in Figure 2-9.

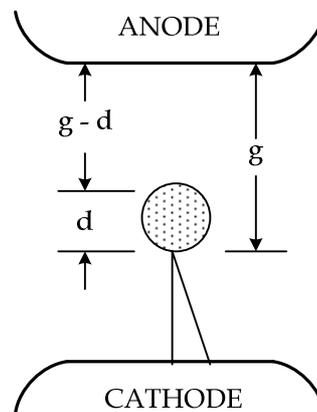


Figure 2-9. Spherical discharge region

Several impacts can be derived from BDV process in oil [38]. Moisture in the oil delivers charge carriers and decreases the withstand strength. Acids as the aging byproduct also deliver charge carriers through dissociation processes. They are surface active and decreasing the surface tension. This will also lead to the development of bubbles and weaken the dielectric strength.

2.2.3. The effect of contaminations

Particle contamination in insulating oil may lead to a decrease of the breakdown strength. A breakdown at relatively low voltage can happen if the oil is heavily contaminated with fibres which can form a bridge of fibres between the electrodes along the highest field intensity. Moreover, in the case that a wet fibre exists in electrically stressed oil, it will cause a stream of water or vapor along with a breakdown channel, further decreasing the electric strength of the oil.

Liquid movement may also lead to a breakdown. For example, if oil is pumped through an electrode gap or the electrodes are rotated, then it will initiate the breaking of fibre chains or movement of gas accumulation. This will result in a lowering of the alternating and direct breakdown voltage, but it will not affect the lightning impulse breakdown strength.

2.3. Dielectric Dissipation Factor ($\tan \delta$) and Relative Permittivity (ϵ_R)

There are two fundamental parameters characterizing a dielectric material, the conductivity σ and the real part of the permittivity or dielectric constant ϵ' (or ϵ_R).

The conductivity σ of a dielectric material is defined as the ratio of the leakage current density J_l (in A cm⁻²) to the applied electric field density E (in V cm⁻¹),

$$\sigma = \frac{J_l}{E} \quad (2-4)$$

It is also determined in terms of the measured insulation resistance R (in Ω) as

$$\sigma = \frac{d}{RA} \quad (2-5)$$

where d is the insulation thickness (in cm) and A is the surface area (in cm²).

The dielectric constant ϵ' is defined as the amount of electrostatic energy which can be stored per unit volume per unit potential gradient. But it is also known as the real part of permittivity which is determined as the ratio of

$$\epsilon' = \frac{C}{C_0} \quad (2-6)$$

where C is the measured capacitance (in F) and C_0 is the equivalent capacitance *in vacuo*. C_0 can be obtained from the same specimen geometry of

$$C_0 = \epsilon_0 \frac{A}{d} \quad (2-7)$$

while ϵ_0 represents the permittivity *in vacuo* with the value of 8.854×10^{-14} F cm⁻¹. The value of ϵ_0 in free space is essentially equal to that in a gas (ϵ_R' of air = 1.000536).

The relative permittivity definition from IEC 60247 is the ratio of capacitance C_x of a capacitor in which the space between and around the electrodes is entirely and exclusively filled with the insulating material, to the capacitance C_0 of the same configuration of electrodes in vacuum,

$$\epsilon_R' = \frac{C_x}{C_0} \quad (2-8)$$

Dielectric losses may initially be caused by the movement of free charge carriers (electrons and ions), space charge polarization or dipole orientation. Most causes are influenced by the temperature, electric field strength, and are frequency dependent. A complex permittivity ϵ is defined as

$$\epsilon = \epsilon' - j\epsilon'' \quad (2-9)$$

where ϵ'' is the imaginary value of permittivity and means the dielectric loss contributed by the leakage current and the polarizations, ϵ is the complex permittivity and equal to the ratio of dielectric displacement vector \bar{D} to the electric field vector \bar{E} . The losses determine the phase angle δ between vector \bar{D} and \bar{E} . Based on the position in the vector, \bar{D} and \bar{E} should have the complex notation $D_0 \exp[j(\omega t - \delta)]$ and $E_0 \exp[j\omega t]$ with D_0 and E_0 as the vector magnitudes respectively. Thus, the following relations result

$$\epsilon' = \frac{D_0}{E_0} \cos \delta \quad (2-10)$$

$$\epsilon'' = \frac{D_0}{E_0} \sin \delta \quad (2-11)$$

The dielectric dissipation factor ($\tan \delta$) can be expressed as:

$$\tan \delta = \frac{\epsilon''}{\epsilon'} = \frac{\epsilon''_{pol} + \frac{\sigma}{\omega}}{\epsilon'} \quad (2-12)$$

The behavior of the losses of a dielectric can be determined from an equivalent electrical circuit. The parallel circuit is commonly used for analysis as seen in Figure 2-10 (a).

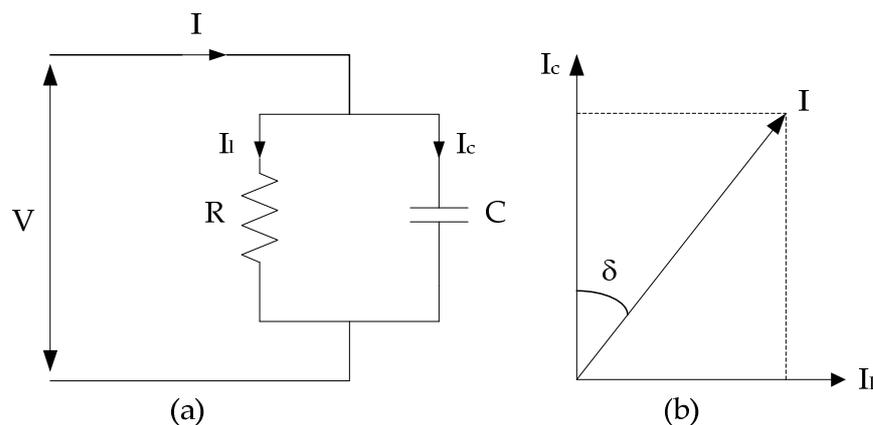


Figure 2-10. (a) Parallel circuit and (b) Phasor diagram

The behavior of equation (2-7) is commonly described in parallel circuit representation, with dielectric components such a capacitance C parallel with resistance R . When an applied voltage V passes through a dielectric material, it generates a leakage

current $I_l = \frac{V}{R}$ and displacement current $I_c = j\omega CV$. From the phasor diagram in Figure

2-10 (b), it represents the value of $\tan \delta = \frac{I_l}{I_c}$. Then by applying the substitution on I_l and I_c

, it will give a final expression of

$$\tan \delta = \frac{1}{\omega RC} \quad (2-13)$$

The definition of dielectric dissipation factor ($\tan \delta$) according to IEC 60247 is the tangent of the loss angle and the loss angle here is described as the angle difference between applied voltage and the resulting current deviating from $\pi/2$ rad.

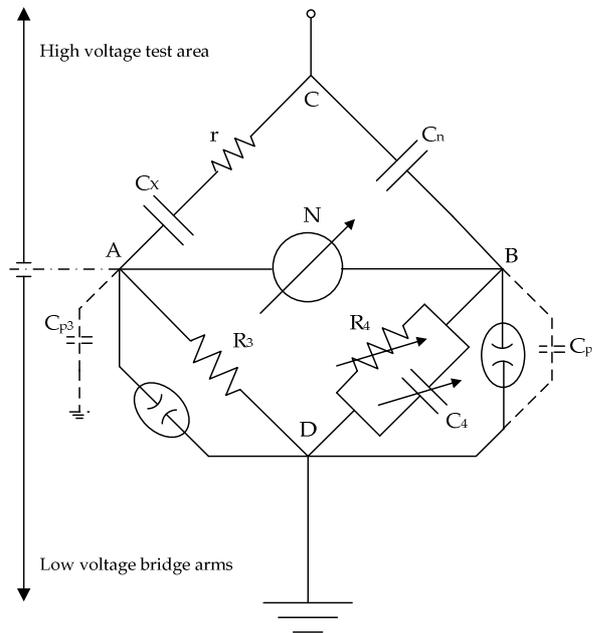


Figure 2-11 . Principle of Schering bridge

The Schering bridge is an equipment for measuring $\tan \delta$ and capacitances (shown Figure 2-11). This equipment is divided into two test areas, i.e. the high-voltage area and the low-voltage area. The standard lossless capacitor C_n has an accurately known capacitance (typically 92.926 pF) and connects the earth side at low-voltage bridge arms (node A and B) together with test object capacitance C_x . In the high-voltage area, the applied voltage is energized here and passes through C_n and C_x . Standard resistor R_3 , calibrated impedances R_4 and C_4 are placed in low voltage test area for adjusting the balance of the bridge. At the balance condition, the value of C_x is obtained from

$$C_x = \frac{R_4}{R_3} C_n \quad (2-14)$$

and $\tan \delta$ will be determined by

$$\tan \delta = \omega R_4 C_4 \quad (2-15)$$

The loss mechanism in insulating oil might have several causes:

a. Conductive losses

The low value of insulation resistance R may increase the leakage current (I_l) and tend to add losses in dielectric insulation. According to equation (2-12), $\tan \delta$ value will decrease as the frequency rises.

b. Dipole orientation losses

It is only applied for material with permanent molecular or side-link dipoles when a considerable overlap occurs between the permanent dipole and ionic relaxation regions.

c. Ionic relaxation losses

These losses occur due to a short range jump of ions between two or more equilibrium position.

d. Interfacial or space charge losses

It only happens in the multilayered structures, the components of which have different conductivity and permittivity. Space-charge losses are initiated by limited movement of charge carriers in the electrodes.

Chapter 3

EXPERIMENTAL PROCEDURES

This chapter will discuss the experimental procedures used in this thesis project, including the accelerated aging process on both types of oil, the measurement procedure of breakdown voltage, dielectric dissipation factor ($\tan \delta$), relative permittivity, and humidity content.

3.1. Pre-conditioning of the oil samples

Before starting the accelerated thermal aging process, the oil samples are pre-conditioned. First, the sample bottles or jars are cleaned before they are filled with oil. After taking some samples from the oil container, then the samples are vacuumized. This procedure is intended to reduce the humidity of the oil that may have increased during the oil storage in the container. New transformer oils are stored in containers. The imperfect bung closures and seals will allow the oil in the container to breathe air. Another reason is when we take the oil using the pump, it may introduce moisture to the oil too.

The humidity content of the oil affects its dielectric properties, such as dielectric loss and breakdown stress. In order to study the aging effect on the dielectric properties, the humidity of the oil should be reduced as much as possible. For mineral oils, humidity tests show that it is necessary to reduce the humidity through the vacuum process before starting the aging process in the oven, because the humidity value of new mineral oil is around 18 ppm before the vacuum process, while it is reduced to 12 ppm after the vacuum process. For the ester oil which is used in this study, the vacuum process is not necessary as the humidity level is as low as 3 ppm even without the vacuum process and the oil does not show a measurable change of humidity after a vacuum process.

The vacuum oven (see Figure 3-1) is equipped with a heating apparatus to accelerate the evaporation process. Lower temperature setting (e.g. 60°C instead of 100°C) is more reliable to remove the moisture because it can reduce problems of degradation of heat labile substances. In order to avoid the accumulation of moisture within the oven, there is an air inlet and outlet to take the moisture of the sample out from the vacuum oven. The oil samples were kept in the vacuum oven for up to 2 hours.

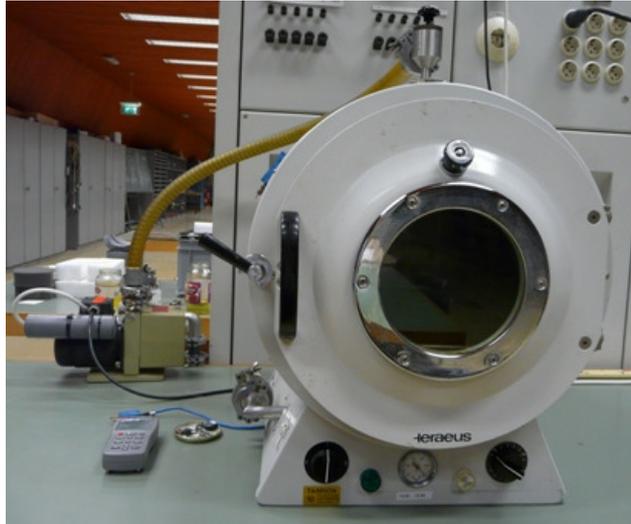


Figure 3-1. Photo of the vacuum oven

3.2. Accelerated aging in oil

After the vacuum process, the oil samples are ready to put inside the oven for the accelerated thermal aging process. The samples are directly exposed to the air inside the oven in order to represent the free breathing transformer and allow an oxidation process. The samples arrangement inside the oven is shown in Figure 3-2.



Figure 3-2. Photo of oil samples in the oven for accelerated aging process

The accelerated thermal aging process is arranged for approximately 1440 hours or 2 months at an aging temperature of 100°C. The schedule for each dielectric measurement is described in Table 3-1.

Table 3-1. Schedule of measurement

Test	Breakdown voltage measurement									
Aging time	new	44 h	92 h	164 h	284 h	428 h	596 h	740 h	1196 h	1436 h
Test	Tan δ and relative permittivity measurement									
Aging time	new	46 h	94 h	190 h	286 h	430 h	598 h	766 h	1102 h	1438 h

3.3. Breakdown voltage measurement in oil

According to standard IEC 60156 insulating liquid - determination of the breakdown voltage at power frequency, there are several procedures that should be followed:

a. Sample preparations

The breakdown test set up for oils is illustrated in Figure 3-3 and the description of the set up is explained below:

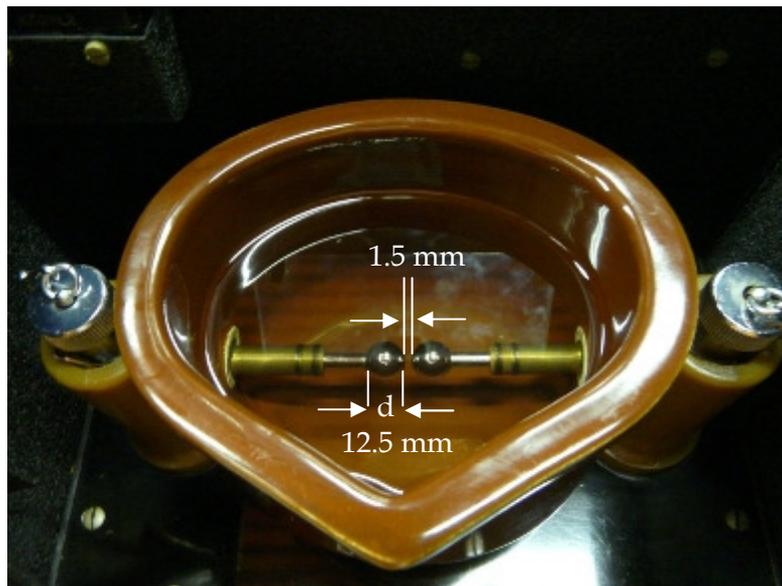


Figure 3-3. Photo of breakdown test set up for oils

- The electrodes shall be polished and either spherical (12.5 mm – 13 mm diameter) or partially spherical. The axis of the electrode system shall be horizontal and at least 40 mm below the surface of the test liquid in the cell. No part of the electrode should be closer than 12 mm to the cell wall. According to IEC standard 60156, the gap between the electrodes is originally set to $2.5 \text{ mm} \pm 0.05 \text{ mm}$. But

due to limitation of output voltage of the test set up, the gap is adjusted to 1.5 mm \pm 0.05 mm.

- When filling oil sample in, containers should be almost filled with sample, leaving about 3% of the container volume as free air space. At the time of test, temperature of the oil sample should be equal to ambient temperature. The test cell should be drained and rinsed the walls, electrodes and other component parts, with the oil sample.

If the electrodes are put in a vertical position then the gas bubbles which can be produced after the breakdown process will try to go up and be released to the air. Several gas bubbles might still trap in the oil since their way to the open air is blocked by the upper electrode. A horizontal position of the electrodes allows to remove the air bubbles since there is no upper blocking and the gas bubbles are easier released to the air. The comparison of vertical and horizontal electrodes is illustrated in Figure 3-4.

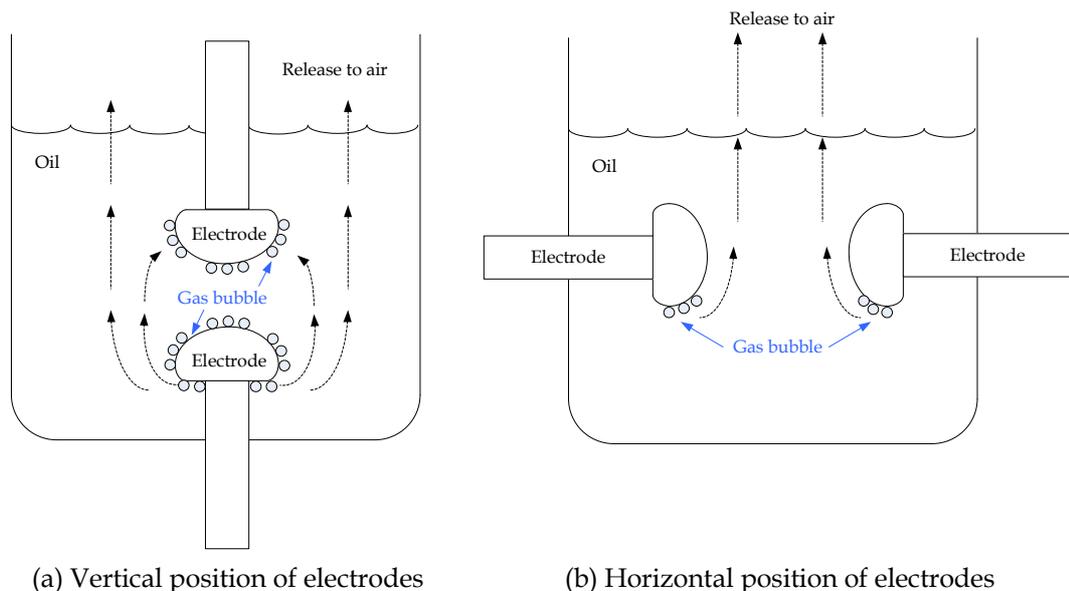


Figure 3-4. Comparison of vertical (a) and horizontal (b) electrodes

b. Measurement procedures

- First voltage application is started approximately 5 min after completion of the filling and there should be no air bubbles which are visible in the electrode gap.
- The applied voltages uniformly increase from zero at the rate of 2 kV/s \pm 0.2 kV/s until breakdown occurs.

- The measurements are carried out until 6 breakdowns on the same cell filling have occurred, allowing a pause of at least 2 min after each breakdown before reapplication of voltage or until there is no gas bubbles present within the electrode gap.
- The final result is calculated from the mean value of the 6 breakdowns in kV.
- In order to get an accurate result, ASTM D 3300 gives the additional requirement for the final result that the range of the measurement results must not exceed 10% of the mean value.

3.4. Dielectric losses ($\tan \delta$) measurement in oil

The dielectric dissipation factor ($\tan \delta$) measurement in this project follows the standard IEC 60247 including preparation of measurement tool. The design of the test cell has been slightly modified to reduce the complexity. Figure 3-5 and Figure 3-6 show the design of the test cell.

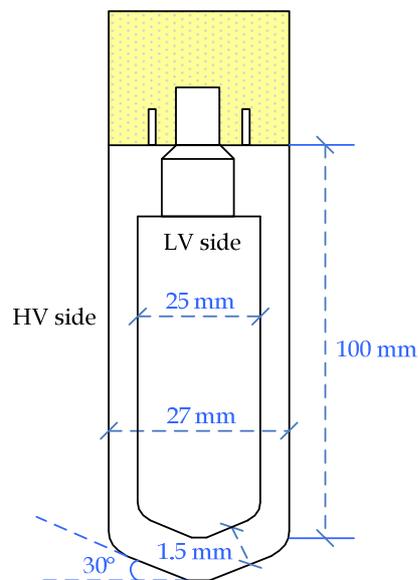


Figure 3-5. $\tan \delta$ test cell dimension

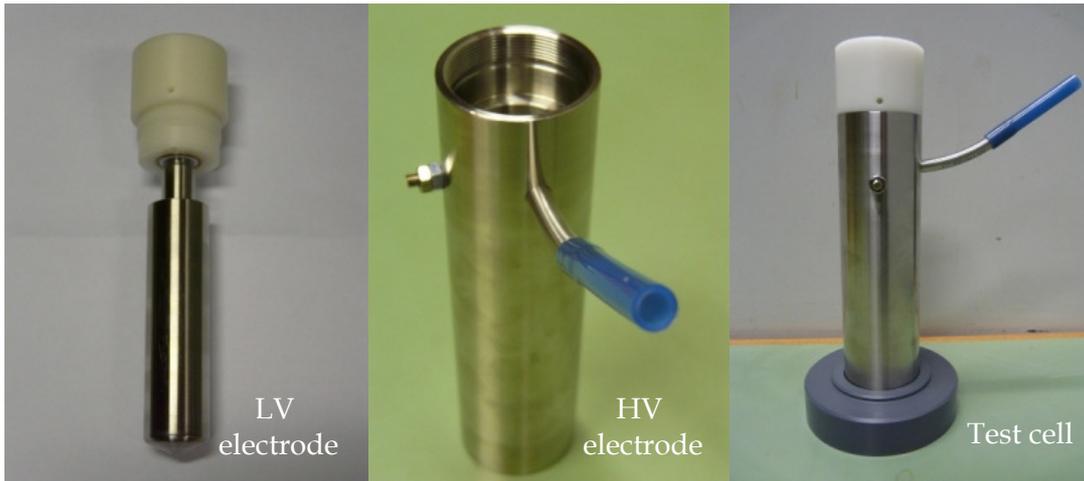


Figure 3-6. $\tan \delta$ and relative permittivity test cell

This test cell consists of two main parts, high voltage (HV) and low voltage (LV) electrodes. All electrodes are made of stainless steel that qualifies for its high heat resistance. The cover on the top of LV electrode is made of epoxy as an insulator and equipped with a potential guard which is put inside it. The potential guard has a function to minimize the effect of any leakage current on the measurement. Two additional parts, the small hole in the cover of LV electrode and a long air junction pipe connected on the side of HV electrode, are intentionally designed in order to assure that no air is trapped inside the test cell after it is filled with the oil sample. The test cell has been measured with empty condition and a capacitance value of 133.58 pF and 3.60E-4 of $\tan \delta$ value at 600 V applied voltage were measured.

The $\tan \delta$ in insulating oil can be measured using the Schering bridge and other related equipments as described in a circuit diagram (Figure 3-7). The balance condition and the capacitance value are observed by the Tettex C_ $\tan \delta$ bridge.

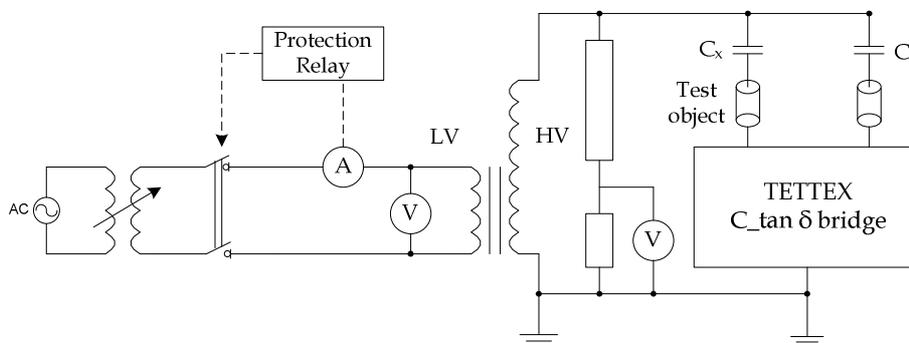


Figure 3-7. Circuit diagram for $\tan \delta$ measurement

The test cell is parallel connected to a standard capacitor C_n at the HV side which has a nominal value of 100 pF. It also connects to balanced detector Tettex at LV side. This test arrangement is shown in Figure 3-8.



Figure 3-8. Test cell connection to HV-LV side

The arrangement of balance detector Tettex and voltage regulator which is equipped with the step-up transformer is shown in Figure 3-9.



Figure 3-9. Balance detector (Tettex) and voltage regulator

There are several preparations and measurement procedures on the test cell and the samples:

a. Cleaning the test cell

First step is cleaning the test cell by demi (demineralized) water with an ultrasound cleaning machine. The test cell after (or before) a measurement is first washed by demi water and then put into the ultrasound cleaning bath filled by demi water for further

cleaning. The test cell is put into the ultrasound cleaning bath for about half an hour in order to remove the embedded oil particles or contaminant from the test cell. The principle of ultrasound cleaning bath refers to the usage of high frequency sound waves to agitate in aqueous or organic compound.

Second step is cleaning the test cell by benzene (C_6H_6) and the same procedure is followed as the first step. In this step, the benzene is only filled in the test cell, not in the cleaning bath. After 30 minutes in the cleaning bath, the cell should be washed using the demi water again and then placed in the ultrasound cleaning bath for another 30 minutes. An air pump is used to remove water drops on the surface of the cell and then it is ready to finally dry in the oven. The test cell is put in the oven for up to 2 hours at $60^\circ C$.

Cleaning the test cell becomes an important process because if there is any contaminant left after a previous measurement, it will affect the $\tan \delta$ value and might lead to an early breakdown in oil.

b. Storage of the test cell

If the cell is being used regularly, it is recommended to be filled with either a clean sample of the insulating liquid normally used or with a solvent which has no detrimental effect on the cell if different liquids are tested. If the cell is not in regular use, it shall be cleaned, dried, assembled and stored in a dry and dust free cabinet.

c. Sample preparations

A new oil sample (especially mineral oil) should be put into the vacuum oven in order to remove the water content in the oil. After finishing the vacuum process, the oil sample is ready to be stored in the oven for the accelerated aging process.

d. Measurement procedures are described as follows:

- The test cell and oil samples are measured at ambient temperature. The test cell should be rinsed at least three times with a portion of oil sample. The filling process of oil samples is carefully done to minimize the entrapment of air bubbles.
- The test ac voltage should be applied to the liquid within the electric stress between 0.03 kV/mm - 1 kV/mm . The applied voltages are slowly increased to the test voltage, and then $\tan \delta$ value can be determined from an adjustment of the Schering bridge variable (capacitance, resistance).
- The final result is calculated as the mean of two consecutives values for $\tan \delta$, and agrees to within 0.0001 plus 25% of the higher value of two values being compared.

3.5. Relative permittivity measurement of oil

According to IEC 60247 for insulating liquids – measurement of relative permittivity, dielectric dissipation factor ($\tan \delta$) and d.c. resistivity, there are several procedures to be conducted during the test:

- a. Cleaning the test cell – the same as the $\tan \delta$ procedure
- b. Storage of the test cell – the same as the $\tan \delta$ procedure
- c. Sample preparations – the same as the $\tan \delta$ procedure
- d. Measurement procedures are described as follows:
 - Measurement of the capacitance of the empty test cell or capacitance of the cell with air as the dielectric C_a .
 - Measurement of the capacitance C_x of the cell filled with the liquid under test. The relative permittivity ϵ_x can be determined from

$$\epsilon_x = \frac{C_x}{C_a} \quad (3-1)$$

- The measurement shall have two consecutive results that differ by no more than 5% of the higher value. The final result is calculated from the mean of the valid measurements.

3.6. The humidity in oil measurement

The humidity value in the oil sample is tested after the dielectric measurement to avoid contamination of the oil. The humidity tester Vaisala MM70 (see Figure 3-10) should be turned on before placing the humidity probe inside the oil. The result is shown after several minutes, until it reaches a steady value in ppm. This humidity tester has an operating temperature range of -40°C to 60°C and sensitivity of 1 ppm.



Figure 3-10. Humidity tester Vaisala MM70

To clean the probe after a measurement, two types of cleaning solvent (n-Heptaan) are used. The humidity tester can be used again at least 30 minutes after cleaning to get rid of any traces of the cleaning solvent.

Chapter 4

RESULT DATA AND ANALYSIS

All observed data from the dielectric property measurements which include the breakdown voltage, dielectric dissipation factor ($\tan \delta$), relative permittivity, and humidity content are collected and the data is presented in trend plots to be used for comparing the dielectric characteristics between mineral oil and synthetic ester oil.

4.1. Accelerated aging process

The oil samples were taken out of the test set up for accelerated thermal aging to perform the dielectric property measurements according to the measurement schedule listed in Table 3-1. The accelerated thermal aging has an effect on the color of the oil sample. The change of color was observed intuitively. Figure 4-1 shows the color comparison of mineral oil during the aging process, while Figure 4-2 gives the color comparison of ester oil.

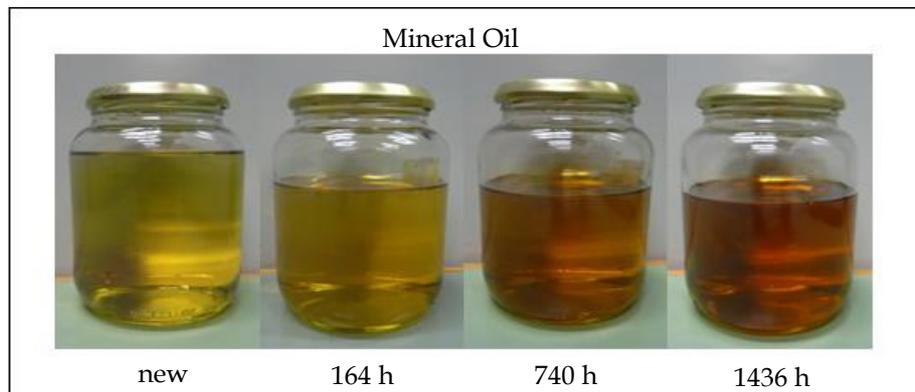


Figure 4-1. Color comparison of new mineral oil, after aged 164 h, 740 h and 1436 h

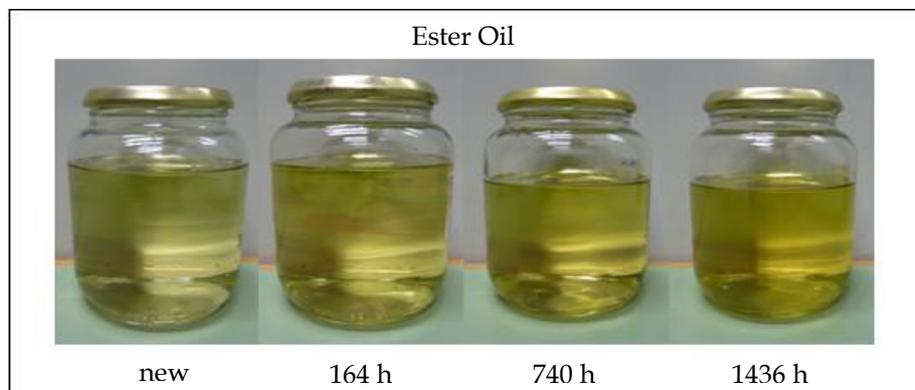


Figure 4-2. Color comparison of new ester oil, after aged 164 h, 740 h and 1436 h

Figure 4-2 shows a significant change of color during the aging period. New mineral oil has a light yellow brown color, but at the end of the aging period the color got darker and some sludge formed in the oil (shown in Figure 4-3). For the ester oil sample, the color did not assertively change or form any sludge tracery.



Figure 4-3. Sludge in mineral oil

4.2. Breakdown voltage (BDV)

The results of breakdown voltage (BDV) measurements for mineral and ester oils are listed in Table 4-1. BDV measurement was performed in such a way that two samples were used for each aging stage and six breakdown tests were conducted on each sample. Thus, there were 12 breakdown voltages obtained for each aging stage. The results of each aging time listed in Table 4-1 are the mean values of the 12 two measurements values.

Table 4-1. Breakdown voltage results of mineral and ester oils

Aging time (hours)	Breakdown voltage (kV)	
	Mineral oil	Ester oil
0	38.63	39.08
44	37.58	38.08
92	34.50	34.33
164	35.92	38.08
284	33.58	36.58
428	38.92	35.33
596	37.42	35.75
908	37.17	33.33
1196	37.42	36.25
1436	36.83	36.67

A graphic presentation of the breakdown voltage comparison between mineral oil and ester oil along the aging time is described in Figure 4-4.

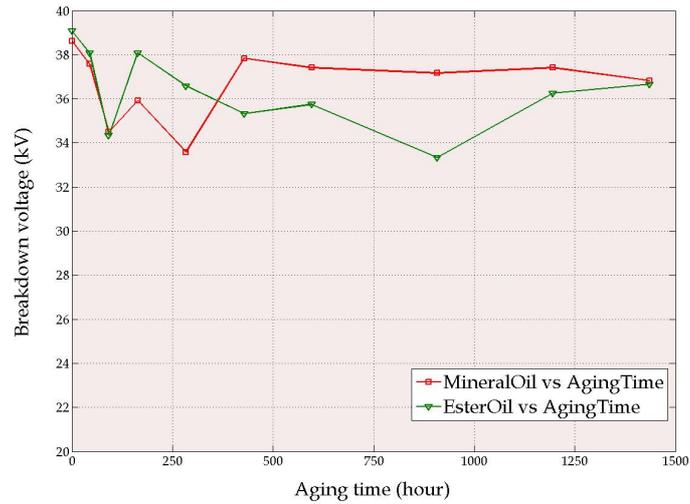


Figure 4-4. BDV vs Aging time

At the beginning of the aging period, the BDV of mineral oil decreased slightly between 0-92 h, then the BDV slightly went up at 164 h before going down again at 284 h. Between 284-428 h, BDV value increased to the highest value which was still lower than the BDV at the beginning of test, before slightly decreasing and becoming more stable until the end of aging time.

The initial BDV value for new synthetic ester oil was higher than mineral oil, but after 92 h it jumped down to similar value as mineral oil. At 164 h, the BDV value increased to the same value as 44 h but then showed a tendency of declining until 428 h before started to increase again. At 908 h, the BDV value reached the lowest part and slightly increased until the end of aging time. Both types of oil show a lower BDV value at the end of aging if compared to the initial BDV value. For mineral oil, the BDV value was reduced from 39.0 kV (new oil) to 36.7 kV (end of aging). The BDV value of synthetic ester oil also was reduced from 38.6 kV (new oil) to 36.8 kV (end of aging). A similar result in Figure 4-5 was found in previous research by Perrier and Beroual [1] for an accelerated aging process at 120°C for 14 days. The BDV of mineral oil (MO) and synthetic ester oil at the end of aging were lower than the initial BDV.

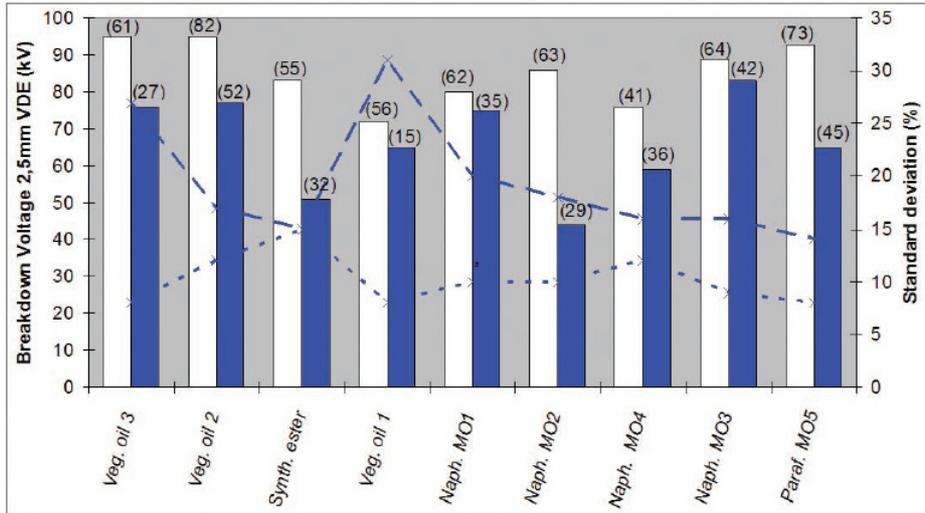


Figure 4-5. Evolution of average BDV after aging (by Perrier and Beroual)

The dispersion data of BDV measurements are described in the scatter diagram of mineral oil (see Figure 4-6) and synthetic ester oil (see Figure 4-7). Each set of data consists of 12 measurement values at each aging time. From those diagrams we can see how the BDV scatters in every set of data. These results comply with the theory of breakdown in oil by Naidu [2] who assumes that each breakdown is an independent event due to the self healing ability of insulating oil, and a consideration that there is sufficient time between measurements to expel the breakdown products or gas bubbles.

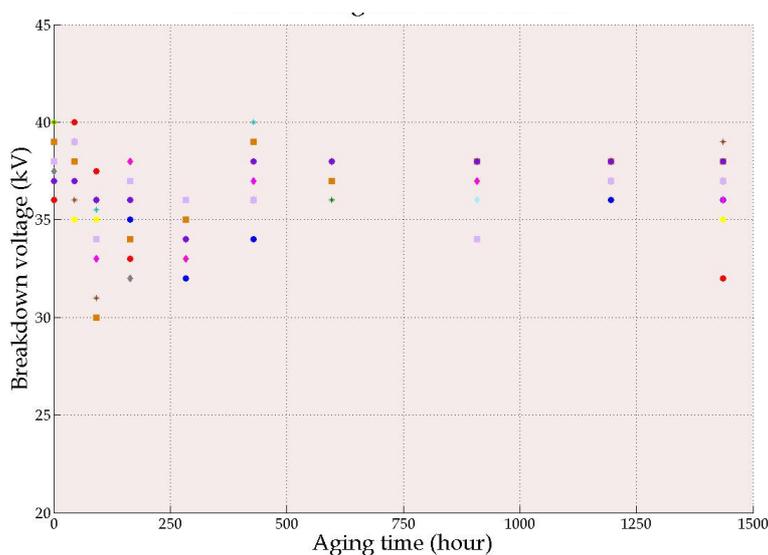


Figure 4-6. Scatter of BDV vs. aging time for mineral oil

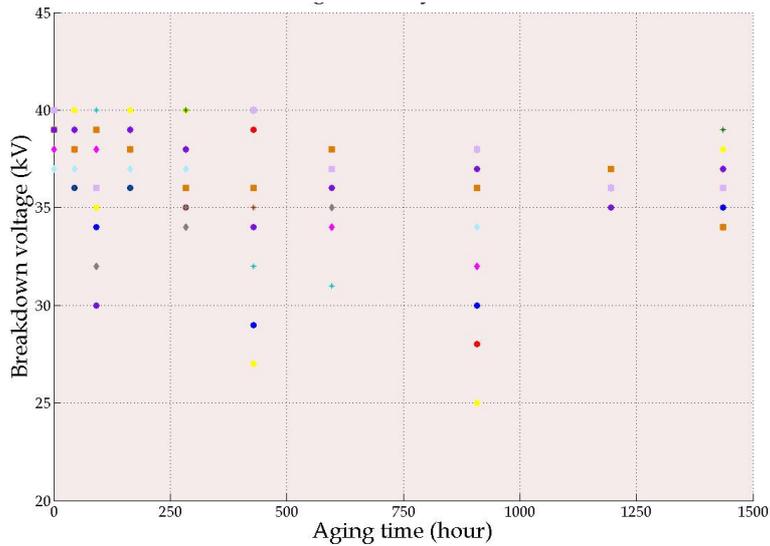


Figure 4-7. Scatter of BDV vs. aging time for synthetic ester oil

Similar results were found by Perrier and Beroual [20]. They observed that the BDV results were dynamic and the BDV values of ester oil were relatively close to those of mineral oil after 18 measurement times (shown in Figure 4-8). This condition is comparable to the scatter of the BDV results on 12 measurements of each set of data in this project.

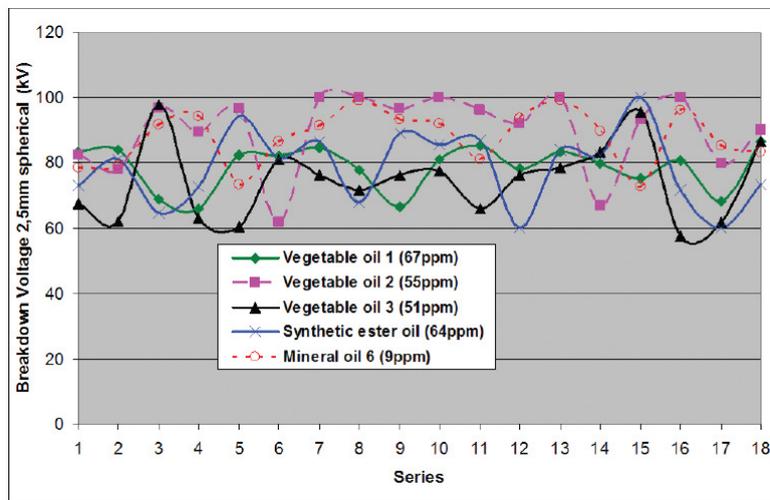


Figure 4-8. BDV of fresh treated oils by Perrier and Beroual [1]

4.3. Dielectric dissipation factor (Tan δ)

The $\tan \delta$ results of both types of oil along the aging time are calculated from the mean of two consecutive measurements for each applied voltage. The following data show $\tan \delta$ results for mineral oil (Table 4-2) and synthetic ester oil (Table 4-3) for each applied voltage from 100 V to 600 V.

Table 4-2. Tan δ results for mineral oil

Aging time (hour)	Tan δ results ($\times 10^{-4}$)					
	100 V	200 V	300 V	400 V	500 V	600 V
0	1.67	0.36	0.33	0.36	0.33	0.32
46	1.35	2.00	2.00	1.51	1.50	1.58
94	1.80	3.00	2.75	2.46	2.45	2.44
190	4.00	3.00	2.46	2.43	2.74	2.41
286	3.70	3.44	3.35	3.25	3.28	3.28
430	3.31	3.19	3.09	3.00	2.99	3.06
598	1.77	1.00	0.65	0.99	1.10	1.09
766	0.41	0.43	0.67	0.40	0.41	0.40
1102	0.98	0.98	0.88	0.89	1.03	0.89
1438	1.56	1.21	0.95	0.84	0.69	0.81

Table 4-3. Tan δ results for synthetic ester oil

Aging time (hour)	Tan δ results ($\times 10^{-4}$)					
	100 V	200 V	300 V	400 V	500 V	600 V
0	1.57	2.63	2.95	3.30	3.55	3.62
46	1.52	2.58	3.13	3.39	3.56	3.58
94	0.65	1.73	2.53	2.62	2.86	3.30
190	1.44	3.38	3.46	3.41	4.54	4.72
286	1.44	2.60	2.80	3.10	3.40	3.58
430	1.98	3.16	3.53	3.68	4.21	4.44
598	4.57	5.71	5.97	6.52	6.79	7.31
766	5.44	6.85	7.61	7.76	8.17	8.31
1102	9.53	10.71	11.09	11.69	11.80	12.26
1438	15.11	16.53	17.07	17.50	17.71	18.15

Graphical presentations of tan δ results for mineral oil and synthetic ester oil along the aging time at 100 V applied voltage and 600 V applied voltage are illustrated in Figure 4-9 and Figure 4-10 respectively. The maximum applied voltage for mineral oil was 600 V after several trial measurements on new oil indicated a breakdown in oil when we tried to increase the voltage up to 650 V. Meanwhile, the maximum applied voltage for synthetic ester oil actually was higher than mineral oil. It could stand the voltage up to 900 V before breakdown occurred. But for comparison, we use the maximum applied voltage of mineral oil. The electrical stress for this measurement can be calculated from the ratio of maximum applied voltage and the critical distance between two electrodes,

$$E = \frac{0.6 \text{ kV}}{1.5 \text{ mm}} = 0.4 \text{ kV/mm} \quad (4-1)$$

It is still within the normal range of the standard electrical stress for $\tan \delta$ measurement in oil (0.03 – 1 kV/mm) according to IEC 60247.

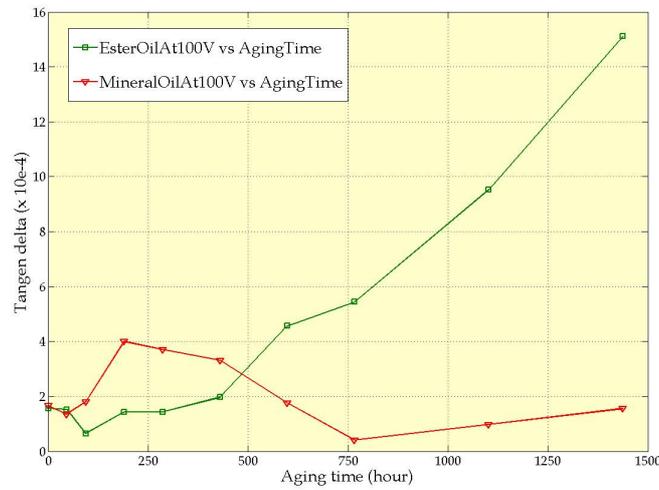


Figure 4-9. $\tan \delta$ vs. aging time at 100 V applied voltage

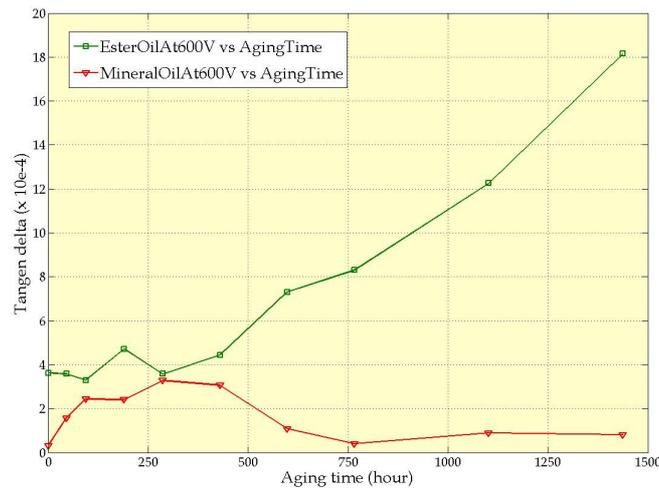


Figure 4-10. $\tan \delta$ vs. aging time at 600 V applied voltage

From a comparison of the two graphics we can infer different trends for both types of oil. Synthetic ester oil exhibited a significant increase of $\tan \delta$ along the aging time. The value of $\tan \delta$ increased approximately 82.9% from the initial value until the end of aging, as the average $\tan \delta$ percentage calculation of all applied voltages. This result is similar to what was found by Perrier and Beroual [20] who also discovered a significant increase of $\tan \delta$ of synthetic ester oil (see Figure 4-11).

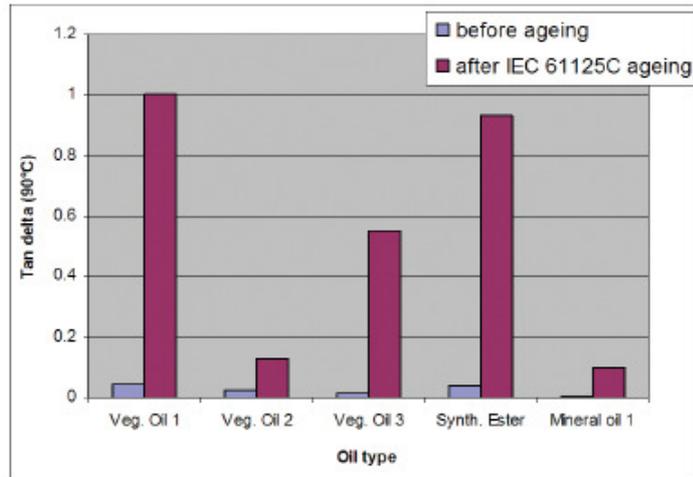


Figure 4-11. Tan δ before and after IEC 61125 ageing (164 h at 120°C) by Perrier and Beroual [20]

The tan δ trend of synthetic ester oil is illustrated more specifically in Figure 4-12 to show that the tan δ values increased along the aging time and at elevated applied voltages.

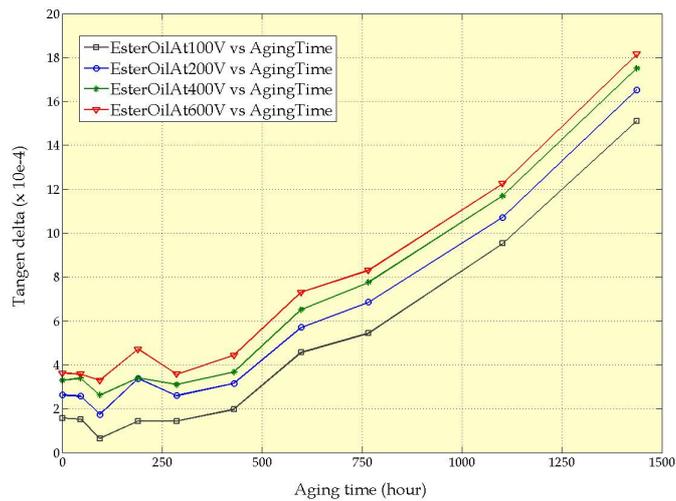


Figure 4-12. Tan δ vs. aging time for synthetic ester oil at different applied voltages

Figure 4-13 shows the influence of applied voltage on the tan δ results of synthetic ester oil along the aging time. The increase of tan δ value is relevant to the increase of the applied voltages and each of graphic lines has similar pattern.

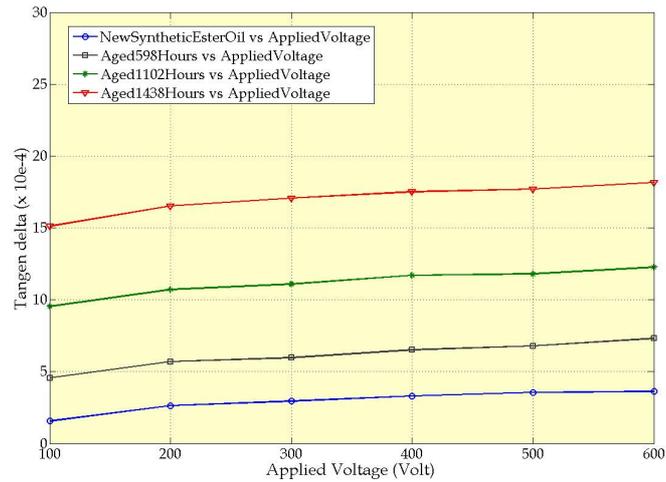


Figure 4-13. Tan δ vs. applied voltage for synthetic ester oil

Figure 4-14 shows the tan δ results for mineral oil versus the aging time at different applied voltages. It can be seen that the tan δ tended to increase at the beginning of accelerated aging process till 286 hours then decreased along the aging time till 766 hours, and then tended to be stable up to the end of aging.

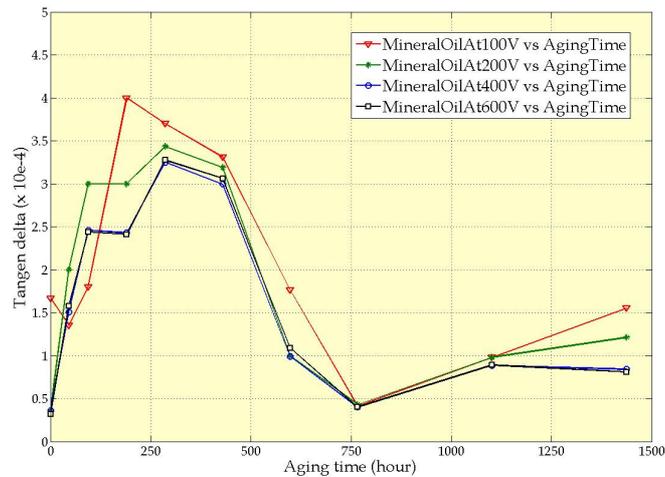


Figure 4-14. Tan δ vs. aging time for mineral oil at different applied voltages

If we plot the graph of tan δ in mineral oil as a function of applied voltage, we get two types of graphs. First, a graph with a peak tan δ value at the early stage of aging before it continues to decrease and becomes constant (see Figure 4-15). Second, a graph with a tendency of tan δ values which slightly decrease at the early aging and continue with a steady position (see Figure 4-16). This phenomenon rarely happened for tan δ measurements in oil. It does not mean that the dielectric strength of mineral oil increased during the accelerated aging process. More investigation on chemical content will be

needed to determine the thermal reaction product in mineral oil during the accelerated aging.

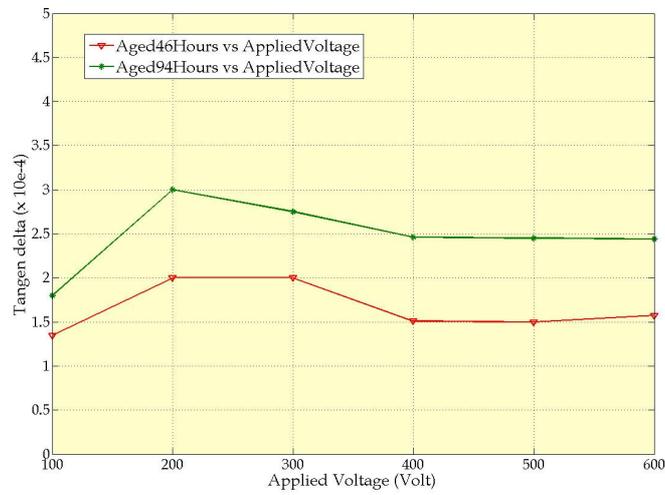


Figure 4-15. Tan δ vs. applied voltage for mineral oil at 46 h and 94 h

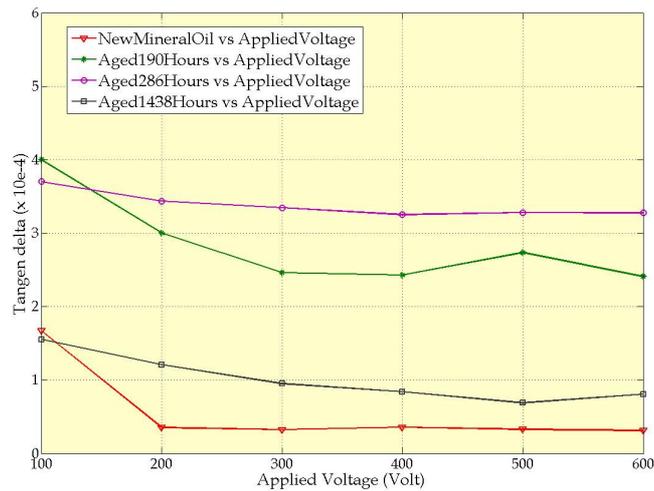


Figure 4-16. Tan δ vs. applied voltage for new mineral oil, at 190 h, 286 h, and 94 h

4.4. Relative permittivity

The relative permittivities of both types of oil along the aging time are calculated from the mean of two consecutives measurements for each applied voltage. Actually the measurement itself only determined the capacitance of the test object, the relative permittivity (ϵ_x) was calculated as the ratio of capacitance of the cell filled with the oil (C_x) and capacitance of the cell with air as the dielectric (C_a). Data of C_a is shown in Table 4-4, while Table 4-5 and Table 4-6 correspond to the relative permittivity results for mineral oil

and synthetic ester oil respectively. All data are measured at different applied voltage from 100 V to 600 V.

Table 4-4. Capacitance of the cell filled with air (C_a)

Applied voltage (Volt)	Capacitance of the cell with air (C_a) in pF
100	133.68
200	133.65
300	133.58
400	133.58
500	133.58
600	133.58

Table 4-5. Relative permittivity results for mineral oil

Aging time (hour)	Relative permittivity for mineral oil					
	100 V	200 V	300 V	400 V	500 V	600 V
0	2.19	2.19	2.19	2.19	2.19	2.19
46	2.18	2.18	2.18	2.18	2.18	2.18
94	2.19	2.19	2.19	2.19	2.19	2.19
190	2.21	2.21	2.21	2.21	2.21	2.21
286	2.22	2.22	2.22	2.22	2.22	2.22
430	2.20	2.20	2.20	2.20	2.20	2.20
598	2.20	2.21	2.21	2.21	2.21	2.21
766	2.20	2.20	2.20	2.20	2.20	2.20
1102	2.20	2.20	2.20	2.20	2.20	2.20
1438	2.20	2.20	2.20	2.20	2.20	2.20

Table 4-6. Relative permittivity for synthetic ester oil

Aging time (hour)	Relative permittivity results for synthetic ester oil					
	100 V	200 V	300 V	400 V	500 V	600 V
0	3.19	3.19	3.19	3.19	3.19	3.19
46	3.18	3.18	3.18	3.18	3.18	3.18
94	3.19	3.19	3.19	3.19	3.19	3.19
190	3.19	3.19	3.19	3.19	3.19	3.19
286	3.18	3.18	3.18	3.18	3.18	3.18
430	3.18	3.18	3.18	3.18	3.18	3.18
598	3.18	3.18	3.18	3.18	3.18	3.18
766	3.18	3.18	3.18	3.18	3.18	3.18
1102	3.17	3.17	3.17	3.17	3.17	3.17
1438	3.17	3.17	3.17	3.17	3.17	3.17

Graphical presentations of relative permittivity results for mineral oil and synthetic ester oil along the aging time at 600 V applied voltages (shown in Figure 4-17).

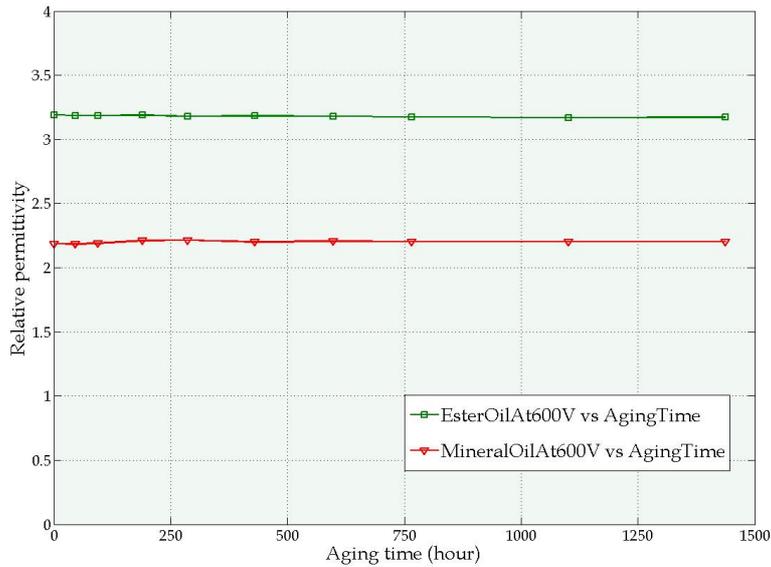


Figure 4-17. Relative permittivity vs. aging time at 600 V applied voltage

The relative permittivity results for both types of insulating oil are apparently stable during the accelerated aging process at different applied voltages. Based on the graphic illustration, it is clearly seen that ϵ_x values for mineral oil is lower than synthetic ester oil. It can be concluded that the relative permittivity in insulating oil is not affected by the accelerated aging process.

4.5. Humidity content

The humidity values of mineral oil and synthetic ester oil along the aging time are presented in Table 4-7. The humidity test was not conducted until the oil reached the room temperature.

Table 4-7. Humidity values of mineral oil and synthetic ester oil

Aging time (hour)	Humidity measurement (ppm)	
	Mineral oil	Synthetic ester oil
0	11	4
46	11	5
94	11	5
190	15	5
286	13	4
430	13	4
598	15	6
766	17	6
1102	19	6
1438	16	5

The graphical result of humidity measurement between mineral oil and synthetic ester oil is illustrated in Figure 4-18.

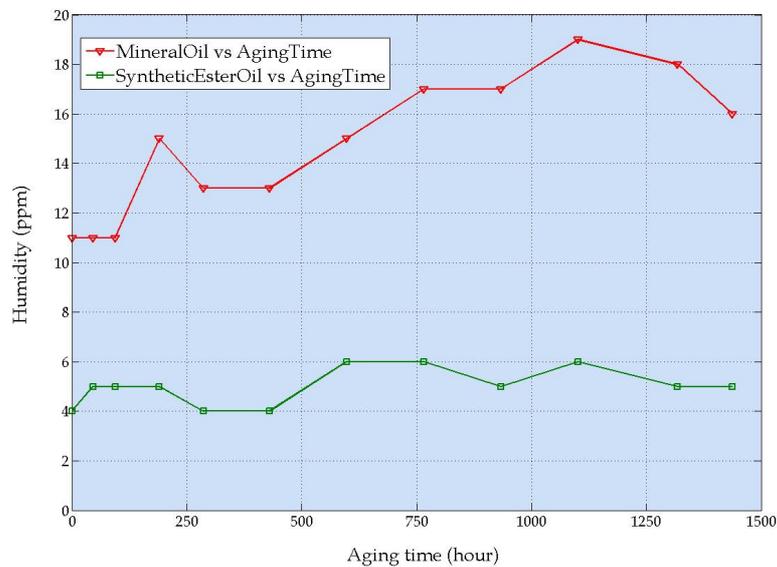


Figure 4-18. Humidity vs. aging time

From the graphic above, we can see that the initial humidity value of mineral oil was relatively high synthetic ester oil. Along the accelerated aging process, the humidity value of mineral oil was slightly increased until the maximum at 766 h aged and reduced a little bit at the end of aging process. The condition was almost similar to synthetic ester oil, but the humidity value did not significantly increase and intended to be stable until the end of accelerated aging process. The stable condition of humidity in synthetic ester oil can be explained due to its high water solubility characteristic.

4.6. Correlation analysis

The graphical analysis of measurements can be enhanced by the correlation analysis, in order to determine the apparent connection between the different values. The most popular approach for correlation analysis is the Pearson's correlation. It considers a series of n measurements of X and Y written as x_i and y_i with $i = 1, 2, \dots, n$, so that the sample correlation coefficient r_{xy} can be calculated as

$$r_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{(n - 1) s_x s_y} \quad (4.2)$$

where \bar{x} and \bar{y} are the sample means of X and Y , then s_x and s_y are the sample standard deviations of X and Y .

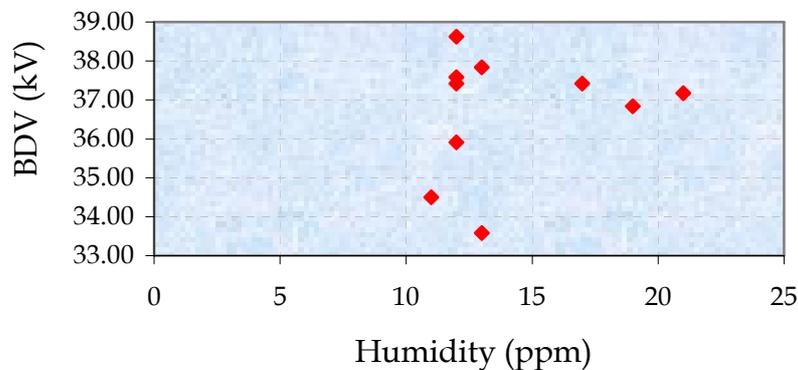
There are three types of correlation characteristic: positive correlation, negative correlation, and no correlation. Positive correlation has the strongest point at 1.0. Negative correlation has the strongest point at -1.0. The weakest point for a correlation is zero. The closer the coefficient is to either -1.0 or 1.0, the stronger the correlation between the variables. A general classification for interpreting the r value is shown in Table 4-8.

Table 4-8. General correlation categories

Correlation coefficient (r)	Correlation category
0.0 - 0.2	Very weak to negligible correlation
0.2 - 0.4	Weak/low correlation (not significant)
0.4 - 0.7	Moderate correlation
0.7 - 0.9	Strong/high correlation
0.9 - 1.0	Very strong correlation

Correlation between humidity and BDV of mineral oil shows the very weak correlation (see Figure 4-19) because there is no similarity trend, BDV values have a random trend meanwhile of humidity level intends to increase.

BDV vs. humidity of mineral oil

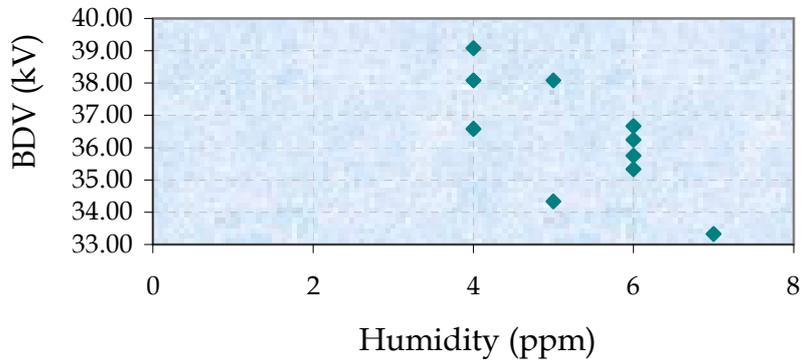


Correlation coefficient	Correlation category
0.187	very weak correlation

Figure 4-19. BDV vs. humidity of mineral oil

Correlation between humidity and BDV of synthetic oil shows a strong negative correlation (see Figure 4-20) because the BDV values have a random trend and the humidity level is slightly constant.

Humidity vs BDV of synthetic ester oil

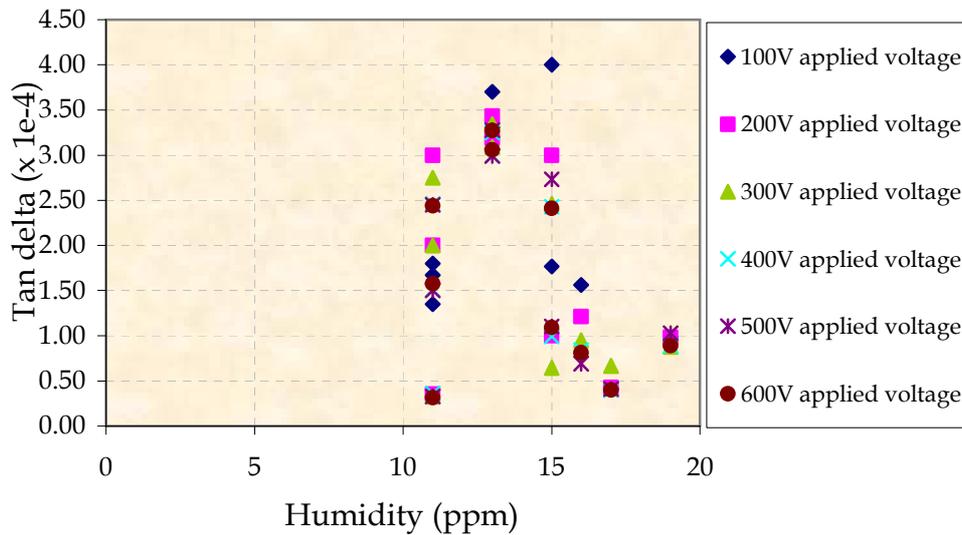


Correlation coefficient	Correlation category
-0.719	Strong/high negative correlation

Figure 4-20. BDV vs. humidity of synthetic ester oil

In Figure 4-21, we can see that $\tan \delta$ exhibits a weak negative correlation to the humidity of mineral oil. The $\tan \delta$ results have a decreasing trend while the humidity tends to increase.

Tan delta vs. humidity of mineral oil

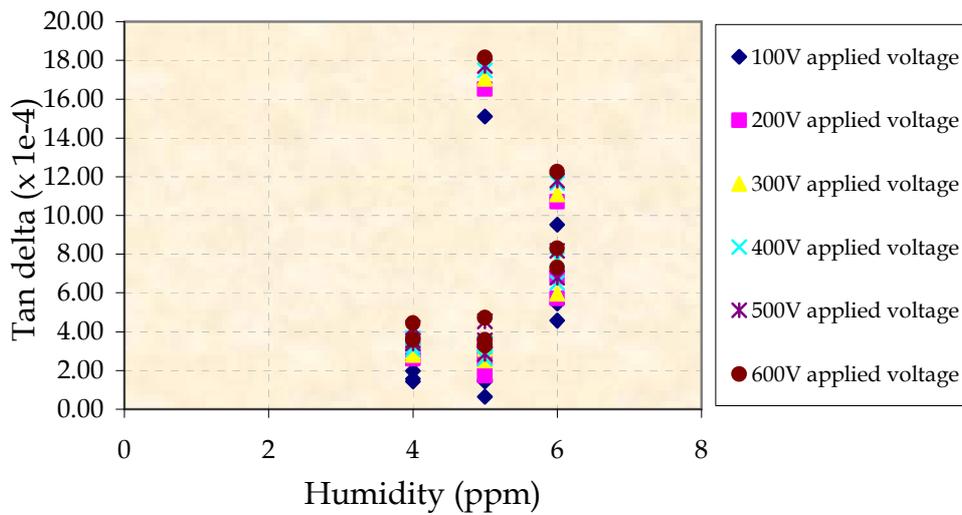


Applied voltage	Correlation coefficient	Correlation category
100V	-0.285	weak/low
200V	-0.397	weak/low
300V	-0.422	moderate
400V	-0.376	weak/low
500V	-0.331	weak/low
600V	-0.374	weak/low

Figure 4-21. Tan δ vs. humidity of mineral oil

A different condition is applied to the correlation between humidity and tan δ of synthetic ester oil (see Figure 4-22). Even though the humidity level is relatively stable while the tan δ tends to rise significantly, but there is also a tendency of the humidity value to have a small increases. Because these small increased values are included in the calculation, so the result is became a moderate correlation.

Tan delta vs. humidity of synthetic ester oil

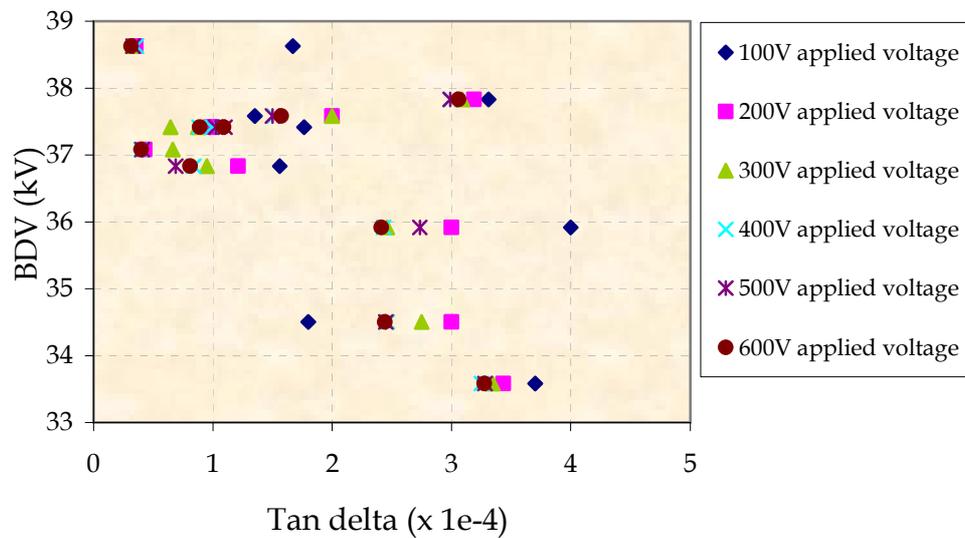


Applied voltage	Correlation coefficient	Correlation category
100V	0.424	moderate
200V	0.429	moderate
300V	0.440	moderate
400V	0.444	moderate
500V	0.444	moderate
600V	0.453	moderate

Figure 4-22. Tan δ vs. humidity of synthetic ester oil

The correlation between $\tan \delta$ and BDV is calculated to analyze how the dielectric loss characteristic of insulating oil can affect its breakdown strength. In Figure 4-23, the correlation between $\tan \delta$ and BDV shows a moderate negative correlation. This behavior resulted from the decreasing trend of $\tan \delta$ compared to the random data of BDV. The scatter data determines how random and inconsistency connection between two parameters. But there is a tendency of BDV to decrease as the $\tan \delta$ attains the higher value.

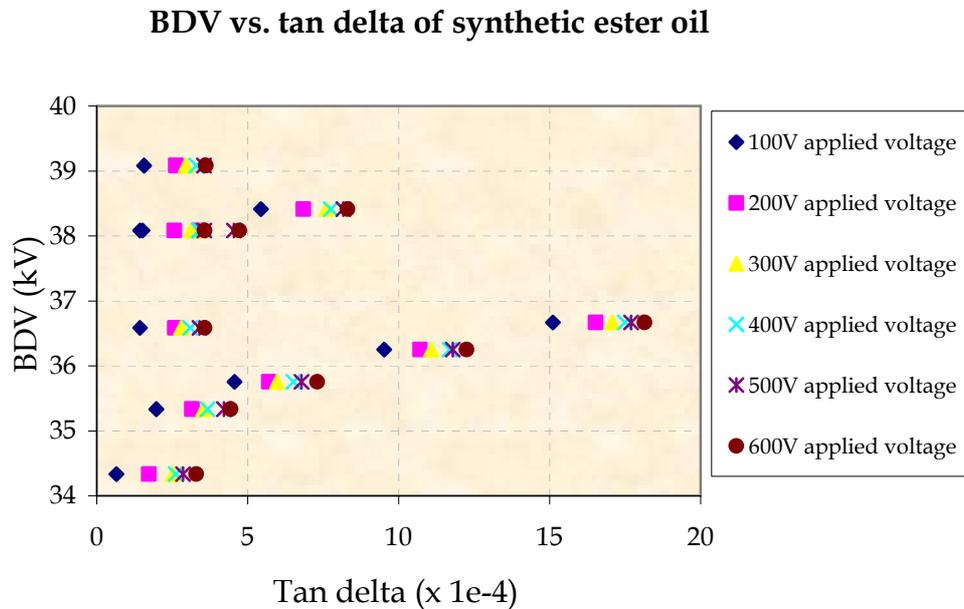
BDV vs. tan delta of mineral oil



Applied voltage	Correlation coefficient	Correlation category
100V	-0.455	moderate
200V	-0.673	moderate
300V	-0.663	moderate
400V	-0.660	moderate
500V	-0.654	moderate
600V	-0.646	moderate

Figure 4-23. BDV vs. $\tan \delta$ of mineral oil

In Figure 4-24, $\tan \delta$ and BDV of synthetic ester oil has a very weak negative correlation. The $\tan \delta$ results increased significantly while the BDV gave the random values along the aging time. Several points at low $\tan \delta$, BDV values are taken place very random. But in the middle value of $\tan \delta$, BDV has a trend to increase sequentially.



Applied voltage	Correlation coefficient	Correlation category
100V	-0.050	very weak
200V	-0.032	very weak
300V	-0.041	very weak
400V	-0.045	very weak
500V	-0.032	very weak
600V	-0.059	very weak

Figure 4-24. BDV vs. $\tan \delta$ of synthetic ester oil

4.7. Chapter conclusions

The accelerated thermal aging process showed a different effect to the color of oil samples. The color of aged mineral oil was darker than the new oil, while the color of synthetic ester did not change too much. There was also indicated sludge content in aged mineral oil, while in synthetic ester oil it was hardly observed.

The BDV of both types of oil showed a dynamic behavior along the accelerated thermal aging process, and there was a tendency of all oil samples to get lower BDV at the end of aging.

The measurements of $\tan \delta$ gave different trend between mineral oil and synthetic ester oil. Mineral oil had a peak value at the early aging process between aged 100 to 300 hours before tended to decrease and stable till the end of aging. Meanwhile, $\tan \delta$ of synthetic ester oil showed a significant increase along the aging process.

The relative permittivity values of both types of oil were quite constant since the beginning until the end of accelerated aging process. But there is a difference in humidity results. The humidity content of mineral oil increased along the aging process, while synthetic ester oil kept the humidity value more stable.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

In this thesis an experimental research is described on the dielectric properties of insulating oils and how they are affected by an accelerated thermal aging process. In order to rate the dielectric properties of alternative insulating oil, a vegetable oil used in distribution level transformers and a widely used mineral oil were investigated. The conclusions from Chapter 1 to Chapter 4 are summarized below:

1. On one side, the lack of mineral oil resources become a world issue and encourages people to find the alternative energy source. On the other side, the application of mineral oil in transformer also brings a problem when there is a leakage during operation and the oil become a pollutant to the environment due to its less biodegradable characteristic.
2. Vegetable oil has been acknowledged as good alternative material for transformer oil due to its good biodegradability characteristic, low pour point, high flash point, and high solubility.
3. Both the mineral oil and the synthetic ester oil exhibited lower breakdown voltages at the end of the aging process than at the beginning. For the mineral oil, BDV value reduced from 39.1 kV (new oil) to 36.7 kV (end of aging). For the synthetic ester oil, the BDV value reduced from 38.6 kV (new oil) to 36.8 kV (end of aging). Comparable results were also observed in the previous research by Perrier and Beroual, which the BDV of mineral oil decreased from 41 kV to 36 kV, while the BDV of synthetic ester oil also decreased from 55 kV to 32 kV. The main difference of the observed BDV between this thesis and the previous research may be caused by using different electrode distance. An electrode distance of 2.5mm was used in the previous research, whereas a 1.5-mm distance was used in this thesis due to the output limitation of the test transformer.
4. The $\tan \delta$ of the synthetic ester oil increased significantly along the aging process from 3.62×10^{-4} (new oil) to 18.15×10^{-4} (end of aging). A comparable results came from the previous research by Perrier and Beroual, which revealed the significant increased of $\tan \delta$ in synthetic ester oil. The $\tan \delta$ of the mineral oil during the aging process showed different behavior compared with that of the ester oil. The measured $\tan \delta$ of the mineral

oil showed a maximum value at 4×10^{-4} after aging between 100 to 300 hours in the aging, then decreased for some time and tended to increase again before the end of aging.

5. The humidity value for new mineral oil was around 11 ppm and it went up to maximum 19 ppm in the aging duration. For the synthetic ester oil, there was no significant change in the humidity with the range values of 4 ppm to 6 ppm during the aging process, resulting in a weak correlation between the humidity and BDV or $\tan\delta$ results.

5.2. Recommendations

Some suggestions are made to improve the research in this field, which can resort to the new measurement methods or analysis.

1. In order to achieve more information about the effect of the accelerated thermal aging process on oil, we need to perform several chemical measurements such as the oxidation stability and the acidity.
2. The addition of catalyst such like cooper in oil sample may define a new or different result since it can speed up the accelerated aging process.

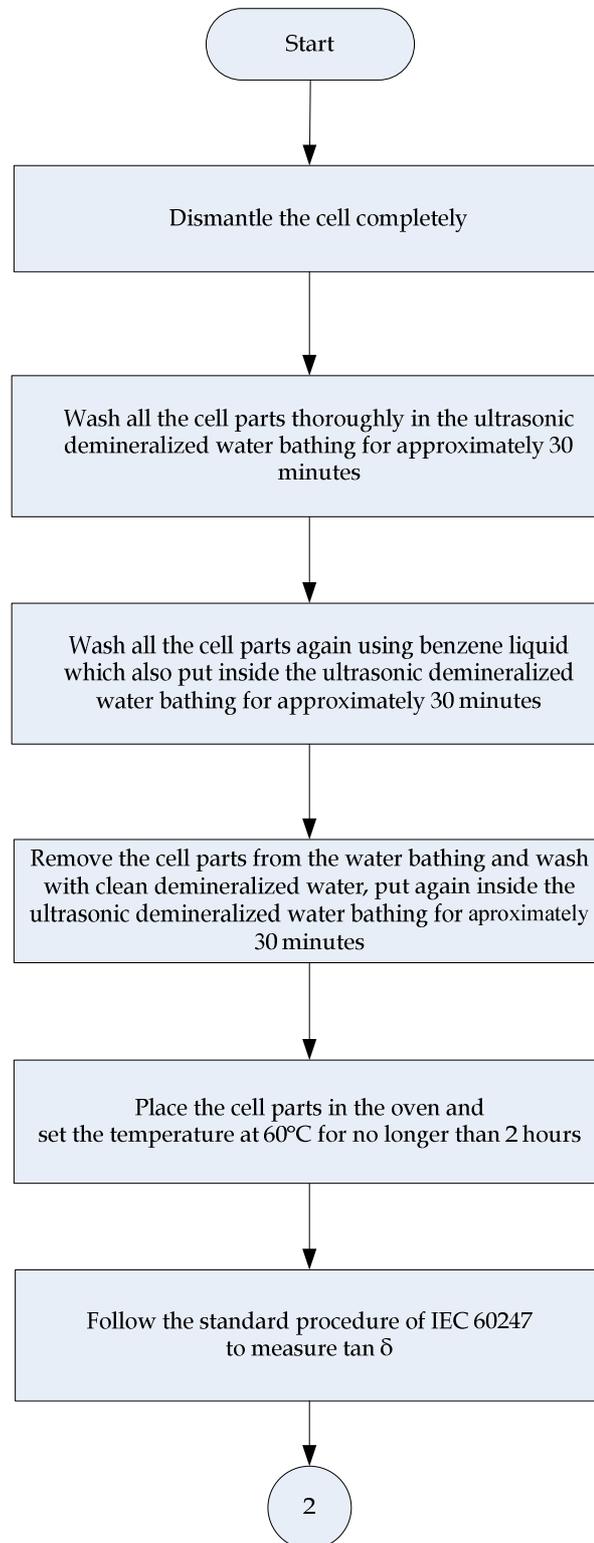
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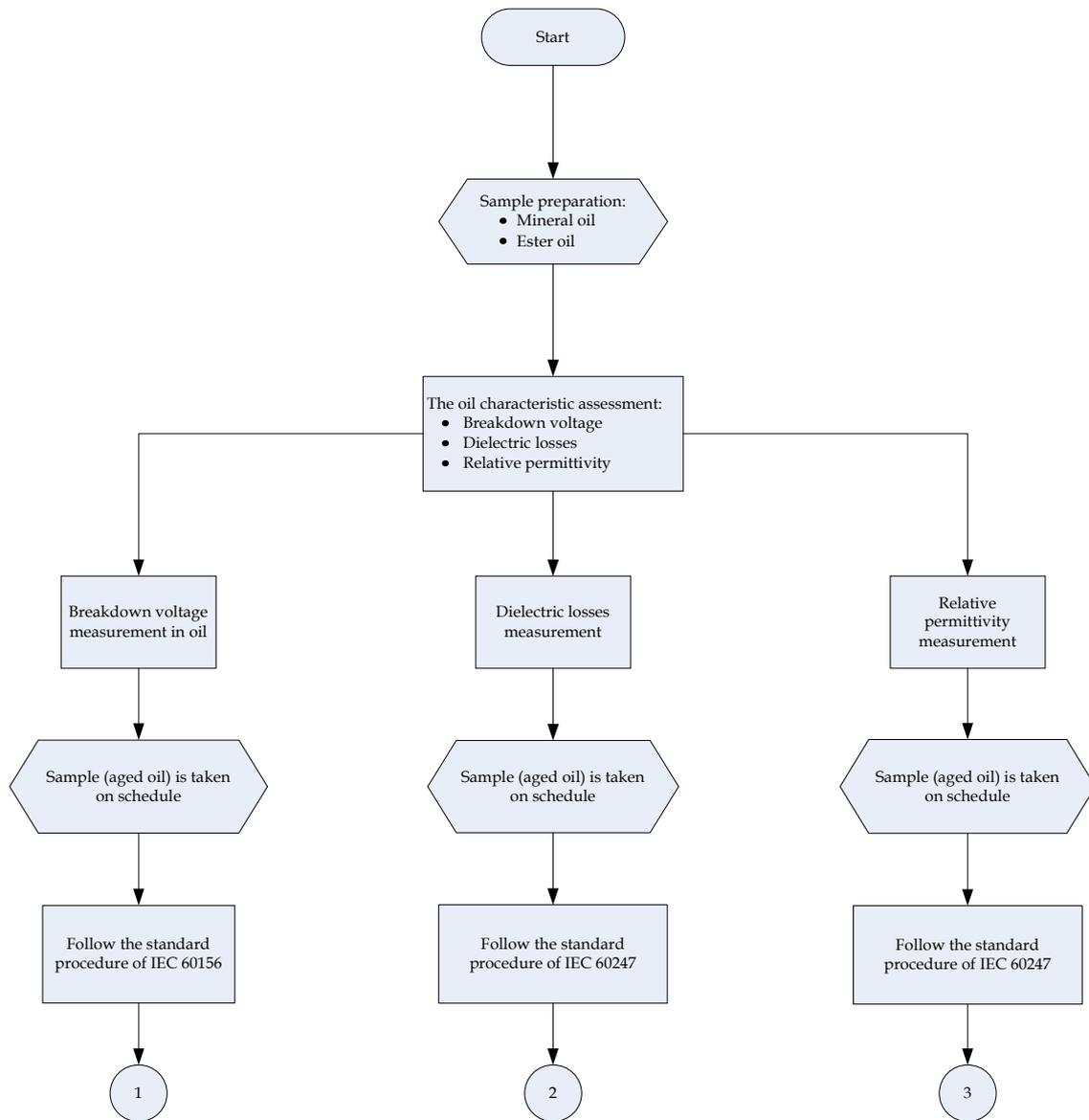
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APPENDIX A: The flowcharts of measurement methods

FLOWCHART OF TEST CELL CLEANING FOR TAN δ MEASUREMENT



FLOWCHART OF INSULATING OIL CHARACTERISTIC MEASUREMENTS



1

Sample preparation:

- Test cell should be almost filled with sample, leaving about 3% of the container volume as free air space
- Temperature of the test liquid and ambient air shall not differ by more than 5°C and for referee test the liquid temperature shall be 20°C ± 5°C
- The volume of the cell shall be between 350 ml–600 ml of liquid
- The electrodes shall be polished and in shape, either spherical (12.5 mm–13 mm diameter) or partially spherical of the shape and with dimension given below
- The axis of the electrode system shall be horizontal and at least 40 mm below the surface of the test liquid in the cell
- No part of the electrode shall be closer than 12 mm to the cell wall or stirrer
- The gap between the electrodes shall be 1.5 mm ± 0.05 mm

Before filling the test cell, the sample container is gently agitated and turned over several times in such a way as to ensure as far as possible a homogeneous distribution of impurities contained in the liquid

Drain the test cell and rinse the walls, electrodes and other component parts, with the test sample

First application voltage is started approximately 5 min after completion of filling and checking that no air bubbles are visible in the electrode gap

Apply voltage to the electrodes and uniformly increase voltage from zero at the rate of 2 kV/s ± 0.2 kV/s until breakdown occurs

Carry out 6 breakdowns on the same cell filling allowing a pause of at least 2 min after each breakdown before reapplication of voltage, check that no gas bubbles are present within the electrode gap

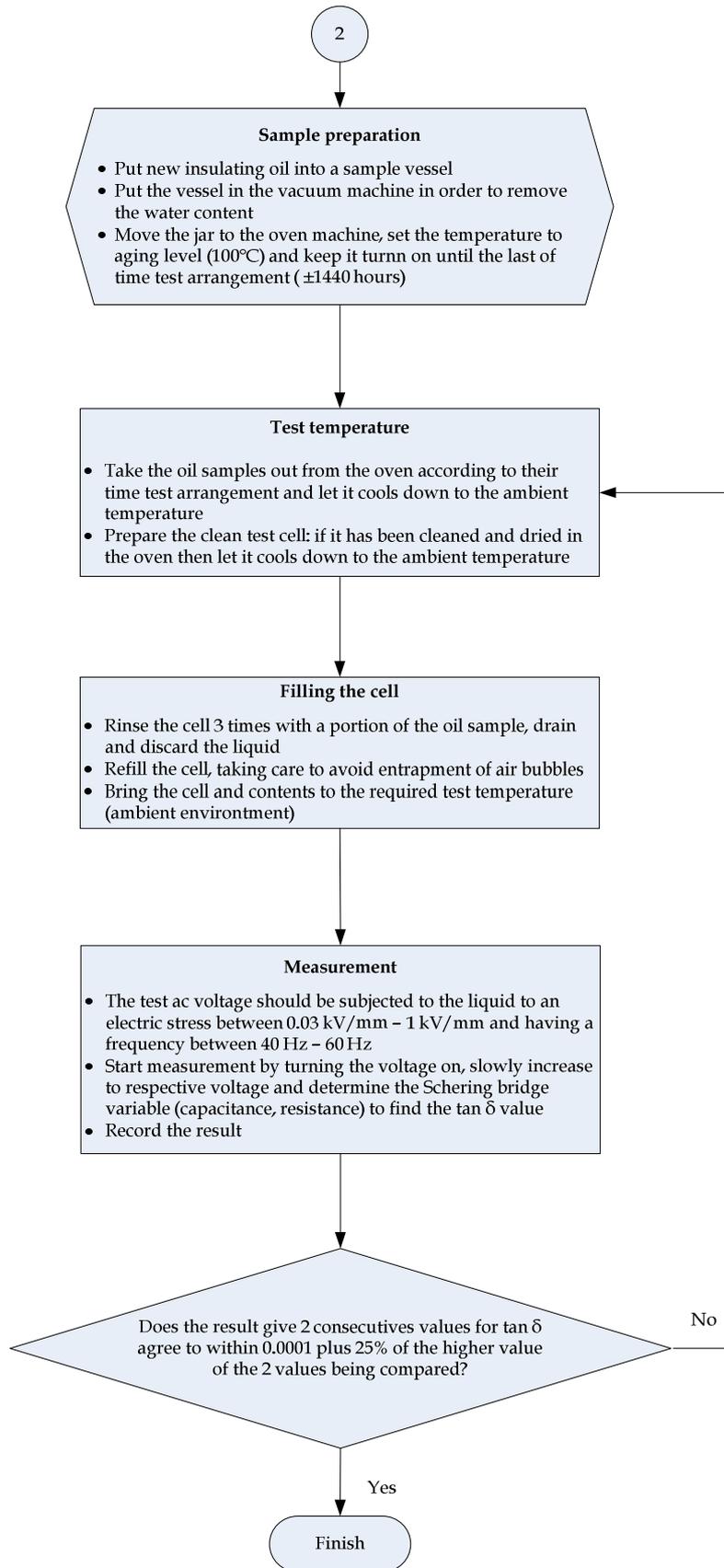
Calculate the mean value of the 6 breakdowns in kV

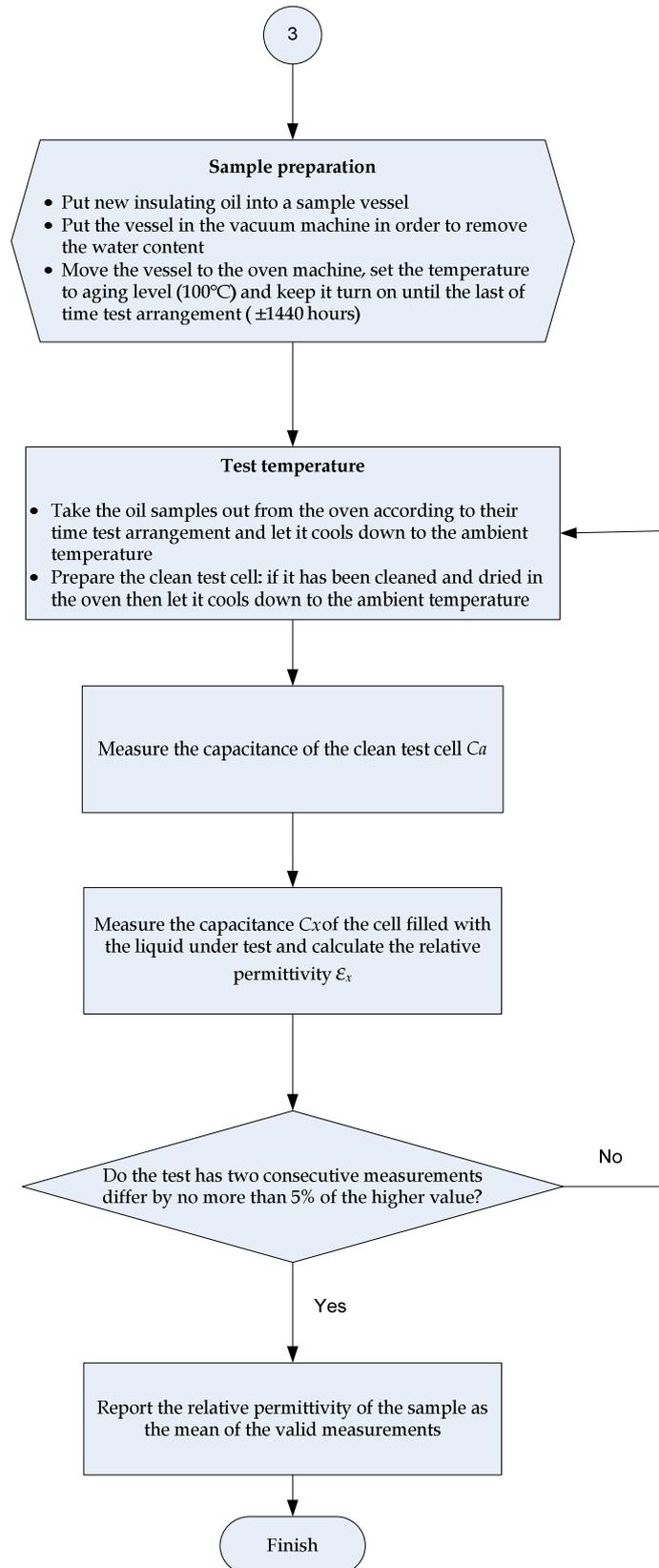
The range of the measurements must not exceed 10% of the mean value

No

Yes

Finish





APPENDIX B: Raw data and graphical results

Raw data from all measurements are described in the next tables.

No. of test	BDV of mineral oil (kV)									
	new	44 hours	92 hours	164 hours	284 hours	428 hours	596 hours	908 hours	1196 hours	1436 hours
1	36.00	40.00	37.50	33.00	34.00	39.00	38.00	38.00	38.00	32.00
2	40.00	35.00	34.00	35.00	32.00	34.00	37.00	38.00	36.00	36.00
3	40.00	35.00	35.00	38.00	33.00	39.00	38.00	37.00	37.00	35.00
4	40.00	38.00	35.50	34.00	33.00	40.00	38.00	37.00	37.00	39.00
5	40.00	36.00	31.00	38.00	33.00	39.00	37.00	37.00	37.00	39.00
6	40.00	37.00	36.00	38.00	33.00	38.00	36.00	38.00	38.00	38.00
7	38.00	38.00	36.00	38.00	33.00	39.00	37.00	36.00	38.00	37.00
8	38.00	39.00	33.00	38.00	33.00	37.00	38.00	37.00	38.00	36.00
9	37.50	39.00	36.00	32.00	34.00	36.00	38.00	38.00	37.00	37.00
10	38.00	39.00	34.00	37.00	36.00	36.00	37.00	34.00	37.00	37.00
11	39.00	38.00	30.00	34.00	35.00	39.00	37.00	38.00	38.00	38.00
12	37.00	37.00	36.00	36.00	34.00	38.00	38.00	38.00	38.00	38.00

No. of test	BDV of synthetic ester oil (kV)									
	new	44 hours	92 hours	164 hours	284 hours	428 hours	596 hours	908 hours	1196 hours	1436 hours
1	40.00	40.00	30.00	40.00	35.00	39.00	36.00	28.00	37.00	36.00
2	40.00	36.00	34.00	36.00	36.00	29.00	36.00	30.00	36.00	35.00
3	40.00	40.00	35.00	40.00	40.00	27.00	36.00	25.00	36.00	38.00
4	38.00	39.00	40.00	39.00	35.00	32.00	31.00	32.00	36.00	39.00
5	40.00	37.00	36.00	37.00	34.00	35.00	36.00	36.00	37.00	39.00
6	39.00	36.00	32.00	36.00	40.00	36.00	36.00	34.00	37.00	39.00
7	37.00	37.00	30.00	37.00	37.00	36.00	38.00	34.00	36.00	36.00
8	38.00	39.00	38.00	39.00	38.00	40.00	34.00	32.00	36.00	37.00
9	39.00	38.00	32.00	38.00	34.00	40.00	35.00	38.00	36.00	34.00
10	40.00	38.00	36.00	38.00	36.00	40.00	37.00	38.00	36.00	36.00
11	39.00	38.00	39.00	38.00	36.00	36.00	38.00	36.00	37.00	34.00
12	39.00	39.00	30.00	39.00	38.00	34.00	36.00	37.00	35.00	37.00

Applied Voltage (Volt)	Tan δ of Mineral oil ($\times 10^{-4}$)									
	new	46 hours	94 hours	190 hours	286 hours	430 hours	598 hours	766 hours	1102 hours	1438 hours
100	2.34	1.00	1.60	4.00	4.00	2.62	2.19	0.42	0.46	1.52
200	0.33	2.00	3.00	3.50	3.25	2.62	1.00	0.44	0.80	1.18
300	0.33	2.00	3.00	2.45	3.20	2.55	0.62	0.67	0.53	0.80
400	0.32	1.54	2.50	2.42	3.20	2.35	1.50	0.40	0.72	0.76
500	0.32	1.52	2.51	3.26	3.30	2.48	1.63	0.42	1.00	0.58
600	0.26	1.66	2.50	2.30	3.27	2.62	1.18	0.40	0.78	0.70
100	1.00	1.70	2.00	4.00	3.40	4.00	1.34	0.40	1.50	1.59
200	0.38	2.00	3.00	2.50	3.62	3.76	1.00	0.42	1.16	1.24
300	0.32	2.00	2.50	2.47	3.49	3.63	0.67	0.66	1.22	1.10
400	0.40	1.48	2.42	2.44	3.30	3.64	0.48	0.40	1.05	0.92
500	0.34	1.48	2.39	2.21	3.26	3.50	0.57	0.40	1.05	0.80
600	0.37	1.49	2.38	2.52	3.28	3.50	1.00	0.40	1.00	0.92

Applied Voltage (Volt)	Tan δ of Synthetic ester oil ($\times 10^{-4}$)									
	new	46 hours	94 hours	190 hours	286 hours	430 hours	598 hours	766 hours	1102 hours	1438 hours
100	1.57	3.00	4.55	1.21	1.51	1.95	4.64	5.48	9.40	15.72
200	2.63	3.45	5.45	3.45	2.62	3.46	5.94	6.90	10.80	17.58
300	2.95	4.27	6.57	3.45	2.70	3.46	6.45	7.65	11.42	17.88
400	3.30	4.48	6.54	3.45	2.98	3.41	6.54	7.96	11.74	18.38
500	3.55	4.55	7.42	4.42	3.44	4.56	6.79	8.34	11.88	18.59
600	3.62	4.90	7.72	4.80	3.65	4.55	7.52	8.42	12.38	19.08
100	1.57	3.80	5.45	1.66	1.37	2.00	4.49	5.40	9.65	14.50
200	2.63	3.81	6.46	3.30	2.58	2.86	5.47	6.80	10.62	15.48
300	2.95	4.00	7.65	3.46	2.90	3.60	5.48	7.56	10.76	16.26
400	3.30	4.34	7.84	3.37	3.22	3.94	6.50	7.56	11.64	16.62
500	3.55	4.51	7.70	4.66	3.36	3.86	6.78	8.00	11.72	16.82
600	3.62	4.68	8.30	4.64	3.50	4.32	7.09	8.19	12.13	17.22

Applied Voltage (Volt)	C _x of Mineral oil (pF)									
	new	46 hours	94 hours	190 hours	286 hours	430 hours	598 hours	766 hours	1102 hours	1438 hours
100	292.69	293.27	293.00	293.59	294.36	293.81	294.58	294.06	293.96	294.30
200	292.66	293.30	293.00	293.67	294.36	293.81	294.58	294.09	293.96	294.33
300	292.66	293.30	293.00	293.69	294.36	293.81	294.60	294.09	293.98	294.35
400	292.69	293.34	293.10	293.69	294.37	293.82	294.63	294.08	293.98	294.34
500	292.69	293.32	293.10	293.72	294.38	293.82	294.64	294.09	294.00	294.36
600	292.69	293.33	293.30	293.76	294.39	293.81	294.68	294.09	294.02	294.37
100	292.68	293.83	292.83	293.92	294.21	294.07	294.92	294.75	294.32	294.34
200	292.69	293.89	292.85	293.94	294.21	294.08	294.95	294.77	294.34	294.35
300	292.70	293.88	292.86	293.96	294.22	294.09	294.96	294.75	294.35	294.36
400	292.71	293.89	292.87	293.96	294.23	294.09	294.97	294.75	294.35	294.36
500	292.71	293.89	292.87	293.98	294.24	294.10	294.97	294.76	294.35	294.37
600	292.72	293.90	292.89	294.00	294.25	294.11	294.98	294.77	294.35	294.37

Applied Voltage (Volt)	C _x of Synthetic ester oil (pF)									
	new	46 hours	94 hours	190 hours	286 hours	430 hours	598 hours	766 hours	1102 hours	1438 hours
100	428.83	429.00	428.00	428.31	427.50	427.55	427.00	426.45	425.38	426.16
200	428.83	428.89	428.00	428.26	427.51	427.55	427.00	426.45	425.36	426.15
300	428.83	429.00	428.00	428.29	427.51	427.56	427.00	426.47	425.35	426.18
400	428.85	429.00	428.20	428.28	427.53	427.57	427.00	426.48	425.34	426.18
500	428.87	429.60	428.30	428.33	427.54	427.58	427.00	426.49	425.33	426.18
600	428.89	429.11	428.50	428.34	427.54	427.63	427.00	426.52	425.33	426.25
100	428.91	429.70	427.92	428.61	427.14	427.68	427.38	426.90	426.12	426.36
200	428.90	429.50	427.90	428.58	427.13	427.69	427.38	426.88	426.09	426.33
300	428.90	429.50	427.91	428.58	427.13	427.69	427.40	426.88	426.09	426.34
400	428.91	429.60	427.92	428.59	427.15	427.68	427.39	426.88	426.10	426.35
500	428.91	426.65	427.96	428.59	427.18	427.70	427.42	426.87	426.11	426.35
600	428.94	429.80	428.00	428.60	427.20	427.69	427.48	426.87	426.12	426.38

The complete result of measurements including the dielectric dissipation losses ($\tan \delta$) and relative permittivity at different applied voltages are illustrated in the following graphics.

