ANALYSIS OF BREAKDOWN VOLTAGE MEASUREMENT UNCERTAINTIES FOR DIFFERENT STANDARDS

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DECLARATION

I declare that this thesis entitled "ANALYSIS OF BREAKDOWN VOLTAGE MEASUREMENT UNCERTAINTIES FOR DIFFERENT STANDARDS" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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APPROVAL

I hereby declare that I have checked this report entitled "Analysis of Breakdown Voltage Measurement Uncertainties for Different Standards" and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Electrical Engineering with Honours

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DEDICATIONS

Specially dedicated to my beloved parents and families who always give me strength, encouraged, and guided throughout my journey.

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In the name of Allah, the most Merciful and Beneficent

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ABSTRACT

Transformer oil plays an important role in reducing the temperature of the transformer where it reacts as a cooling agent and insulator to the transformer. For a long time, the oil will degrade thus the transformer will have a potential for faults and costly repairs. Dielectric strength is one of the characteristics of the transformer that is used to measure the maximum voltage that the material can withstand without having a failure. Breakdown voltage test of a transformer is known as dielectric strength test. This test will indicate the quality of the oil transformer. Uncertainty of measurement is the doubt that exist about the results of any measurement. The aim of this project is to measure the breakdown voltage of different transformer oil by using different standards. Next, to measure the uncertainty of the breakdown voltage readings. Lastly, to evaluate the breakdown voltage reading from three different standards based on uncertainty measures. The project focuses on two types of transformer oil which are mineral oil and vegetable oil. Three standards are applied in this project which are IEC 60156, ASTM D877 and ASTM D1816. The initial phase of the project study the standards that are related in this project, the methods on how to calculate the measurement uncertainty and the theoretical about the breakdown voltage. The uncertainties factors in breakdown voltage include voltage rise, resolution, repeatability of data and calibration of the instruments. The more factor of measurement uncertainty included in the data, the higher the accuracy of breakdown voltage. This will give effects in the calculation of measurement uncertainty. These standards are slightly dissimilar in terms of test voltage rise, measurement gaps, and electrode shape. These differences are the source of uncertainties in breakdown strength measurement. This project use Megger OTS60PB as a main apparatus in order to measure the breakdown voltage. Prior to the breakdown voltage measurement, moisture content of the transformer oil must meet the requirement of the standard which are 200ppm for vegetable oil and 35ppm for mineral oil. The results of the breakdown voltage analysed using measurement uncertainty for each standards and transformer oil. The result of measurement uncertainty in the range of 95% as in theoretical readings. The result show the data is within the range of measurement uncertainties in every samples. All of the objectives were achieve based on the calculation in this report.

ABSTRAK

Minyak pengubah memainkan peranan penting untuk mengurangkan suhu pengubah dimana ia akan memberi reaksi sebagai agen penyejuk dan penebat didalam pengubah. Untuk masa yang lama keadaan minyak akan berkurang seterusnya pengubah akan mempunyai potensi untuk rosak dan akan memberikan kos untuk pembaikan mahal. Kekuatan dielektrik merupakan salah satu ciri pengubah yang digunakan untuk mengukur tahap maksimum bahan tanpa mengalami kegagalan. Ujian pecah tebat pengubah juga dikenali sebagai ujian kekuatan dielektrik. Ujian ini akan menunjukkan kualiti pengubah minyak. Ketidakpastian pengukuran adalah keraguan yang wujud untuk membuat keputusan didalam apa-apa pengukuran. Tujuan projek ini adalah untuk mengukur pecah tebat minyak pengubah yang berlainan dengan menggunakan piawaian yang berbeza. Seterusnya untuk mengukur ketidakpastian bacaan pecah tebat. Akhir sekali, untuk menilai bacaan pecah tebat minyak dari tiga piawaian yang berbeza dengan menggunakan cara ketidakpastian pengukuran. Projek ini memberi tumpuan kepada dua jenis minyak pengubah iaitu minyak mineral dan minyak sayuran. Tiga piawaian digunakan didalam projek ini iaitu IEC 60156, ASTM D877 dan ASTM D1816. Fasa awal projek akan mengkaji piawaian yang berkaitan dengan projek ini adalah kaedah bagaimana menghitung ketidakpastian pengukuran dan teori tentang pecah tebat. Semakin banyak faktor ketidakpastiaan pengukuran yang dimasukkan didalam data, semakin tinggi nilai pecah tebat. Disebabkan hal ini boleh memeberikan kesan didalam pengiraan ketidakpastiaan pengukuran. Standard yang digunakan memberi sedikit perbezaan dari segi peningkatan voltan, perbezaan pengukuran dan bentuk elektrod. Projek ini menggunakan Megger OTS60PB sebagai alat utama untuk mengukur pecah tebat. Untuk mengukur pecah tebat, kelembapan minyak pengubah mesti memenuhi keperluan piawaian yang ditetapkan iaitu 200ppm untuk minyak masak dan 35ppm ntuk minyak mineral. Keputusan pecah tebat dianalisis menggunakan ketidakpastian pengukuran untuk setiap piawaian dan minyak.Keputusan ketidakpastian pengkuran akan berada di dalam jangka 95% sepertimana yang dinyatakan didalam bacaan teori. Setiap sampel voltan menunjukkan hasil data berada didalam lingkungan yang ditetapkan dengan menggunakan ketidakpastian pengukuran. Semua objektif berdasarkan ketidakpastian data berjaya dihasilkan.

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LIST OF SYMBOLS AND ABBREVIATIONS

BdV	-	Breakdown Voltage
kV	-	kilovolt
ppm	-	Part Per Million
mm	-	millimetre
IEC	-	International Electrotechnical Comission
ASTM	-	American Standard Society for Testing and Materials
MU	-	Measurement Uncertainty
k_p	-	Coverage Factor
U_c	-	Meeasurement Uncertainty
c_i	-	Sensititivity Coefficient
s	-	Standard Deviation
℃	-	Degree Celcius
JCGM	-	Joint Committee for Guides in Metrology
ISO	-	International Organisation for Standardisation
σ	-	Standard Deviation
V_{eff}	-	Effectiveness Degrees of Freedom
DOF	-	Degree of Freedom

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Power transformer is one of the valuable assets in delivering power throughout the nation. There are two types of transformer in this industry which are dry-type transformer and oil-type transformer. Dry-type transformers are particularly useful for indoor locations and areas that are highly prone to fire-related risks. Oil transformers on the other hand mostly used for outdoor which can handle higher rating than the dry type because oil is a very good coolant [1].

Quality of the transformer oil plays a vital role in the performances of transformer in electrical appliances. There are two types of insulating oil that commonly used which are mineral oil and vegetable oils. The advantages of mineral oils are good resistance in oxidation, good viscosity index, easily to use and less cost while vegetable oils are good in biodegradable, high flash point and it is more environmentally fluids. The quality of the transformer can be analysed using several analysis. One of the analysis to analyse the quality of the transformer oil is by using measurement uncertainty.

1.2 Project Motivation

The motivation to contribute and conduct into this project is to measure the measurement uncertainty in breakdown voltage by using different standards. Measurement uncertainty is needed to evaluate the precision and accuracy of the data based on several factors. The project compares the readings between different standards and by using different transformer oil. In this project, it will measure each sample and evaluate on which sample is preferable in terms of standards and transformer oils.

1.3 Problem Statement

There is more than one standard for analysing breakdown voltage of insulating liquid, for example, ASTM D1816, ASTM D877 and IEC 60156. These standards are slightly dissimilar in terms of test voltage rise, measurement gaps, and electrode shape. These differences are the source of uncertainties in breakdown strength measurement. Measurement uncertainty represents the quality of measurement by characterizing the dispersion of the breakdown voltage values that could reasonably be attributed to those different terms of different standards. The role of measurement uncertainty is important in conforming these tolerances in the industrial production which has become more demanding. In addition, measurement uncertainties play a main role in order to meet the accreditation requirement outlined in the ISO 17025. This project therefore aims to evaluate the uncertainties of breakdown voltage readings from the three different standards due to the different setup parameters.

1.4 Objectives

The objectives of this project are as follows:

1. To measure the breakdown voltage of different transformer oil by using different standards
2. To measure the uncertainty of the breakdown voltage readings
3. To evaluate the breakdown voltage readings from three different standards based on uncertainty measures

1.5 Project Scopes

The scopes of this project necessitated as followed:

1) Two types of transformer oil are used in this project to measure the breakdown strength which are mineral oil (Gemini X) and vegetable oil (MIDEL 1204).
2) Three standards of breakdown strength test are applied which are *International Electrotechnical Commission* (IEC) 60156, *American Society for Testing and Materials* (ASTM) D877 and *American Society for Testing and Materials* ASTM D1816
3) The equipment that is used to analyse the breakdown voltage for each standard is Megger OTS60PB.

1.6 Project Structure

This report consists of five chapters. Chapter 1, it explains the importance of this study as well as the objectives and the scopes. Chapter 2 highlights, the background theory of breakdown mechanism in liquids and the equations related to measuring the uncertainties. Next, Chapter 3 explains the methodology of this study mostly on the experimental procedure. The results and discussion in this research written in Chapter 4. Finally, Chapter 5 concludes the finding from the literature review as well as the experimental results and discussion.

CHAPTER 2

LITERATURE REVIEW

2.1 Definition of transformer

Transformer is one of the most important elements in power system. The function of the transformer is to step up voltage from generation to transmission and step-down voltage from the transmission to the consumers. The main component of the transformer is core, winding and insulation material. The main component of the insulation system is either gas or liquid (oil) depending on the type of transformer. Transformer oil not only protect the transformer from failure but also acts as a cooler and heat transfer.

2.2 Transformer Oil

Oil transformer is widely used in power plant, industrial plant and traditional electric utility companies [14]. The transformer is filled with the liquid insulating oil which is also called as transformer oil. Transformer functions as insulator, heat transfer and agent of information as well as isolate the transformer [1].

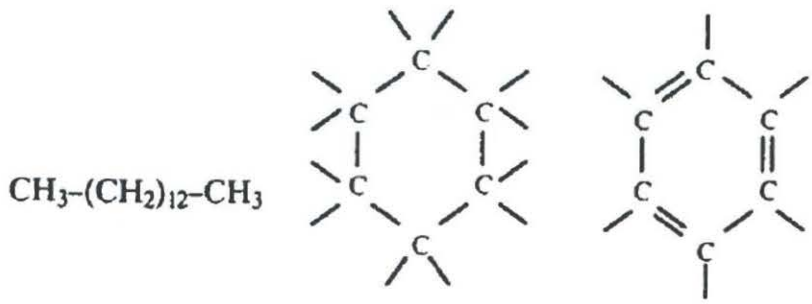
There are many types of transformer oil in the industry such as mineral oils, vegetable oil, cable oil, capacitor oil, askarels oil and silicone oil [1]. However, due to the limitation sources of the mineral oil, sustainable production of transformer oil is being hotly debated. Also, mineral oil can cause serious environmental disaster since primarily produced from non-biodegradable products [5,16]. Through research, vegetable oil found to be a suitable alternative of mineral oil that used for transformer oil [5].

2.2.1 Mineral Oil

Mineral oil is commonly used in power transformers. Mineral oils are attracted from crude oil which is formed from buried and decayed vegetable matter [2]. The function of transformer oil is as thermal fluid or coolant of electrical component which mineral oil is widely used in industry. Crude petroleum is extracted from the earth and it is a complex mixture of molecules that made up of carbon and hydrogen and a small portion of sulphur and nitrogen [2]. There are three main groups of hydrocarbon molecules which are paraffinic, naphthenic and aromatics [2,3]. Figure 2.1 shows the structure of the molecule. In that figure, paraffinic have a single-bonded atom whilst naphthenic have a single double bond but in ring-like structures. The aromatics contain more ring-like structure of carbon atom, but it is in carbon-carbon double bond. These structures can determine the physical properties in the insulating oils such as low viscosity, low pour point, high flash point, high specific heat, high electrical strength, high thermal conductivity and low density [3]. It is mentioned in [17], that the advantages of mineral oil are good resistance to oxidation, good viscosity index, relatively low fire point. Nevertheless, mineral oil is low moisture tolerance and possible to sulphur corrosion. Mineral oil is used in large power transformers, railway transformers, power capacitors and paper insulated high cables while the other transformer oil is used as insulant and coolant [3]. Table 2.1 shows the detail properties of the insulating oil in the transformer.

Table 2.1: The Properties of the Insulating Oil

Category	Type of Liquid	Applications	Properties of Insulating Oil
Mineral Oil	Naphtenic, Paraffinic	Liquid in Power Equipment (Transformers, Circuit Breakers and Others)	• Good resistance to oxidation • Good Viscosity Index • Relatively low fire point • Possible sulphur corrosion
	Paraffinic (High molecular weight of hydrocarbons)	Transformer, Load tap changer	• High flash point
Vegetable oils	Castor, soybean, cotton, palm and others	Capacitors, Transformers	• Low dielectric losses at frequency higher than 1kHz • Readily biodegradable • Low oxidation stability



Linear Paraffin **Naphthenic ring** **Aromatic ring**

Figure 2.1: Structure of molecules mineral oil [2]

2.2.2 Vegetable Oil

Vegetable oil is also known as one of the new liquid insulating oil of the transformer to replace the mineral oil. The vegetable oils belong to a group of organic compounds. Ester is the elimination of water which are generated by the reaction of acid with alcohol. The collective term for monocarboxylic acids, which consist of a carboxyl group (-COOH) and of a variable long, but nearly exclusively unbranched hydrocarbon chain is name as "fatty acid". Ester oil is known as triglycerides which are the combination of three chemical linkage of three fatty acids to one glycerol molecule. Hydrolysis is the elimination of ester and presence of strong water to form glycerol and fatty acids. Figure 2.2 shows the structure of the vegetable oils in the process of inverse reaction and esterification which is called as the hydrolysis [4]. Figure 2.2 shows that the presence of three fatty acids have a low viscosity but higher in oxidation. The presence of oxidation in transformer oil will decrease the amount of electrical strength [5]. Many researches and industries have performing investigations on vegetable oils for providing them as insulating oils in transformers and pollution free environment. The vegetable oils have the properties like high biodegradable (>95%), low toxicity, high flash point (>300C), fire points(>300C), provide lower flammability and it is considered more environmentally friendly fluids [5].

Table 2.2 shows the difference between mineral oil and vegetable oil in terms of viscosity, flash point, specific heat, thermal conductivity, density, environmental properties and oxidation. This table show mineral oil has higher oxidation stability meanwhile vegetable oil has higher biodegradable in the transformer oil. Based on

Table 2.2, some researches [30] found that vegetable oils are the other alternative method to replace the mineral oil due to it viscosity, flash point, specific heat, thermal conductivity and environmental properties. The oxidation is one of the weakness properties in vegetable oil, but it can control by controlling the exposure of moisture and oxidation to maintain it optimum performance.

Table 2.2: Difference between mineral oil and vegetable oil

Criteria	Mineral Oil	Vegetable Oil
Viscosity	Low viscosity	Twice higher than mineral oil
Flash Point	High flash point	Higher flash point
Specific Heat	High specific heat	Lower flammability
Thermal Conductivity	High thermal conductivity	Higher thermal conductivity
Environmental Properties	Not degradable due it contains compound that can hazards to the environment	High biodegradable
Oxidation	Oxidation stability	Low oxidation

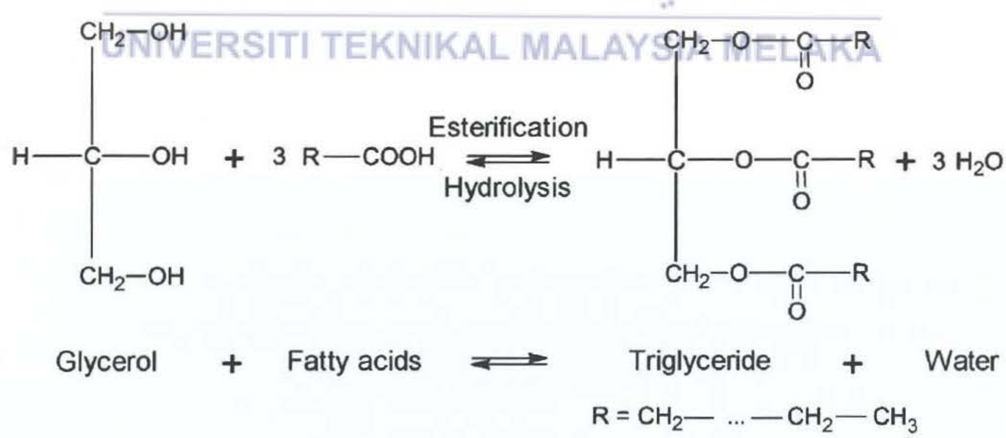


Figure 2.2: Structure of molecules of vegetable oil in esterification and hydrolysis [4]

2.3 Chemical properties of the transformer oil

2.3.1 Water Content

One of the factors that will reduce the good properties of transformer oil as an insulator is moisture or known as water content. It is extremely hazardous to transformer insulation in the presence of oxygen. Generally, the live of the insulation is divided by one and half each time the moisture is doubled in the transformer [8]. This moisture will affect the paper insulation of the core and winding of the transformer where paper is hygroscopic behavior. Hygroscopic behavior is defined as the ability of the substance to absorb water.

The presence amount of water in transformer will affect the paper insulation and reduce its life. It also can become worse in quality or condition of the transformer insulation by diminishing both mechanical and electrical strength. According to the Y. Zhou [5], the presence of 0.02% water in transformer oil will decrease the amount of electrical strength up to 20% of the dry value. To test the water content in the transformer oil, the Karl Fischer method is introduced [3]. The water content in the transformer oil is measured in parts per million or ppm. The accepted value of moisture content is varied for different type of transformer oil; 35 ppm for mineral oil and 200 ppm for natural ester as outlined in ASTM D387 and ASTM D6871.

A major causes of transformer failures are by the moisture is bubble formation, dielectric breakdown, deterioration of insulating liquid and paper and partial discharge. A presence of the moisture will lead the failure of transformer which is oil level drop, exposing the winding and moisture contamination [12]. The maximum amount of moisture in mineral is 35ppm while the vegetable oil is 200ppm [11,15].

2.3.2 Acidity of Transformer Oil

Acidity is a harmful property where the water content in the oil will becomes more soluble hence worsen. The insulating quality of paper insulation acid in transformer oil will quicken the oxidation process in the oil. With the presence of moisture, the insulating material it will be rust due to effect of the acidity. Acidity is a measure of the acid constituents of contaminant. The acidity will quicken the oxidation process in the oil. If there is acid at the material and it have a moisture on it, the material will be rust due to effect of the acidity. Neutralization number express the acidity of oil in mg of KOH required to neutralize the acid present in gram of oil. In addition, measure of acidic constituent of contaminants defines the acidity of the transformer oil [8].

2.4 Physical Properties of transformer oil

2.4.1 Flash point

The flash point and fire point refer to the flammability characteristic of the liquid that being tested. Under specific test the lowest temperature at which water vapor formed above a pool of the liquid can be ignited in air and at pressure of 1 atmosphere; this is the flash point [8]. The flash point is used to access the hazardous nature of a material and the risk of materials ability to support combustion [8].

2.4.2 Pour Point

Pour point of transformer is characterized as an important property where it happens mainly at the places where the atmosphere is frigid. Obstruction of cooling and convection flow of the transformer oil stops when the oil temperature drops below pour point. Wax content in the transformer oil influence the pour point of the transformer oil and the more wax content, the higher the pour point. In mineral oil, paraffin-based oil is one of the higher pour point content [8].

2.4.3 Viscosity

By a definition, viscosity is the resistance of flow in the transformer oil. This term can be defined as the obstruction of convection circulation oil inside the transformer. To not affect the cooling of the transformer, low viscosity is needed so it will be less resistance to the conventional flow of oil. The lower the viscosity of the oil, the lesser resistance in transformer oil flow, and the better insulation oil will have [12]. If the viscosity is low, the temperature of the oil should be low. Every oil becomes more viscous if the temperature reduced [8].

2.5 Electrical Properties of Transformer

2.5.1 Breakdown strength

In a high voltage equipment, the most important material used are conductors and insulators. The conductors will carry the current while the insulators used to prevent the flow of currents in desired paths. Breakdown voltage test for the transformer oil also known as dielectric strength test [13]. The maximum dielectric strength which the material can withstand without having a failure is well known as the dielectric strength of the insulating material. Breakdown occurs when the applied voltage is large, the current flowing through the insulation increases very sharply, thus an electrical breakdown occurs.

Breakdown in liquids is one of the breakdown in the transformer. Liquid are commonly used in the high voltage equipment to serve the deal purpose of insulation and heat conduction. The structure path of the liquid is self-healing where it is one of the advantages in the liquid [1]. Temporary failures due to over voltages are reinsulated quickly by liquid flow to the attacked area. Whereas, the products of the discharges may deposit on solid insulation supports and may lead to surface breakdown over these solid supports. The maximum of purified liquid has the maximum dielectric strength where it can support up to 1 MV/cm. The breakdown mechanism in the pure liquids is the same mechanism as in the gas breakdown but for the commercial liquids the mechanism different by the presence of solid impurities and dissolves gasses. In the previous research, it found that natural ester insulating oil has better dielectric properties compared to mineral oil [6].

2.6 Standards

Standard is applicable for dielectric test with direct voltage, alternating voltages, impulse voltage, test with impulse currents, test with combinations of the above and lastly capacitance and dielectric loss measurements. The purpose of these standards is to defined terms of general applicability, present general requirements regarding test equipment and procedures and describe methods for evaluation of test results.

2.6.1 Types of standard

In breakdown voltage, there are three types of standard that used to measure the voltage such as IEC 60156, ASTM D1816 and ASTM D877. Table 2.3 shows the parameters of standard for breakdown voltage for three standards.

Table 2.3: Parameter of standard for Breakdown Voltage [26,27,28]

	IEC 60156	ASTM 877	ASTM 1816
Voltage Rise	2kV/s$\pm$0.2	3kV/s$\pm$0.05	0.5kV/s$\pm$0.05
Electrode Shape	Mushroom, Spherical	Cylindrical	Mushroom
Intermediate Stir Time	2 in	None	Continuous
No of Test	6	5	5
Maximum Test Time	18min	8min	17min
Diameter of Electrode	2.5mm$\pm$0.05	2.54mm$\pm$0.02	2.0mm$\pm$0.03

A research paper from H.Akca, O.Arikan, C.Kocatepe discussed about breakdown strength analysis of the transformer oil due to different standards. In this research, for breakdown characteristic of non-aged and aged transformer oil was investigated under different voltage and electrode type conditions. The result show that the value of the breakdown strength measurement data obtained from spherical electrode are greater than the values obtained from the cylindrical electrode [19]. The research found that different electrode type has different electric field.

2.7 Measurement Uncertainty

According to [31], uncertainty is defined as a limit of range of values within which the true value of measurement is expected to lie in relation to the recorded results and the probability to lies within the range. It also can be defined as the experimenter should declare how much the two quantities between true value and estimator can affect each other. The amount of differences between two value is called as measurement uncertainty. If the measurement uncertainty expressed in numerical is as follows:

$$estimator \pm measurement\ uncertainty$$

There are three important of uncertainty in measurement which are for calibration, test and tolerance. The calibration is defined where the uncertainty of measurement is reported on the certificate of calibration while test is needed to determine pass or fail. Moreover, tolerance is defined as where the uncertainty is pre-determined before it can be decided whether the tolerance of a measurement is met the requirement or not.

2.7.1 Pool Method

Pool method is applied for non-repeated measurement like single data, destructive test or measurement data and chemical test data. The history or data experiment that characterizes the test/measurement is used to establish the representative standard deviation and standard uncertainty. Further test or measurement that is non-repeated type shall use the representative standard uncertainty of type A.

Type A is evaluated through statistical analysis of a series of observations/repeated measurement while type B is evaluated by other mean than type A evaluation [23]. It is based on scientific judgement which include the earlier acquired knowledge about the measurement, manufacture specification, result from calibration certificate and result from handbook and standard tables [23].

There are several steps to obtain standard uncertainty, U_i where it needs to compile history data of n number or carry out experiment to establish pool data of n number. Then, the data is tabulated while for average value and standard deviation, S is calculated. The Standard Uncertainty, U_i is calculate from the equation: $U_i = S$. The value of Standard Uncertainty, U_i for type A is used for next measurement for non-repeated value. In the pool method there are three main factors that should be considerate which are:

1. The test method or procedure shall be consistent
2. The equipment used shall be the same.
3. The environmental condition shall comply to the specification

2.7.2 Non-repeated measurement

In practice, it is possible to derive most probable value and the uncertainty foremost of the observable quantities by means of doing repeated measurement. Therefore ISO-GUM recommends determining the shape and range of probability density function of such observable quantities based on assumption, experience, knowledge or other things. This is due to when the analysed person know the shape of probability density function, the quantity can be treated as a statistical variable and can derive the standard uncertainty and the degree of freedom[23].

2.7.3 Distribution

In distribution measurement uncertainties, there are two types of measurement uncertainties which are rectangular and normal distribution.

a) Rectangular Distribution

By referring Figure 2.3, rectangular distribution is distribution of data in example chances for the value of the input quantity lies in the interval. a = semi-range or half interval.

For example, in rectangular distribution it has lower and upper limits. In the first case were if it has complete confidence that 'a' represents the absolute limits which where the probability x lies within the interval is 1 and probability x lies outside the interval is 0. The value of measurand(x) could lie anywhere in this range with equal probability (100% within limit). Thus, the degree of freedom is infinity[23].

For the second case where we have some doubt about the reliability of 'a' then the no of degree of freedom is, v where it is finite. Relative uncertainty is defined as absolute error divided by the measured value. For a relative uncertainty of R% the DOF will be estimated by:

$$v = \frac{(100/R)^2}{2} \tag{2.1}$$

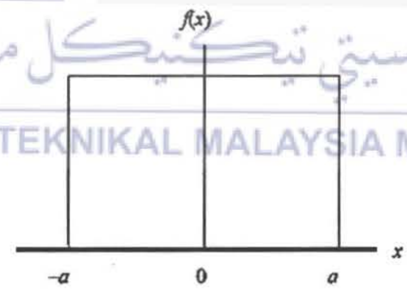


Figure 2.3: Rectangular Distribution

Standard Uncertainty

$$u(x_i) = \frac{Expanded\ Uncertainty}{\sqrt{3}} \tag{2.2}$$

From a rectangular distribution

In u(x) from a rectangular distribution if a range ($\pm a$) is given without confidence level and no further information is available it will assume a rectangular distribution.

b) Normal Distribution

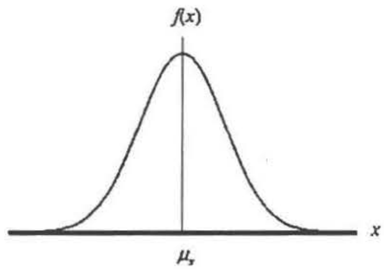


Figure 2.4: Normal Distribution

The distribution usually characterised by its mean value and a measure of width, usually the standard deviation or its square, the variance as in Figure 2.4. A normal probability distribution when plotted gives a bell-shaped curve such that

a) The total area under the curve is 1.0

b) The curve is symmetric about the mean

c) The two tail of the curve extend indefinitely.

Standard Uncertainty

$$u(x_i) = \frac{Expanded\ Uncertainty}{Coverage\ Factor} \quad (2.3)$$

2.7.4 Measurement Model

a) Input Quantities, x_i

Model is represented by the function:

$$y = f(x_1, x_2, x_3..x_n) \quad (2.4)$$

Where $x_1, x_2, x_3 .. x_n$ are the various input quantities.

The input quantities are real world data. They are the variables which are measured such as temperature and pressure or the variables which looked up in the table, handbook or previous calibration certificates or otherwise obtained as the primary level of raw data. The value of the measurand y is simply obtained by using the basic function to calculate the value of y when all the input values are known.

$$Y = y \pm U, \quad \therefore y = best\ estimate\ of\ Y \tag{2.5}$$

Standard uncertainty is uncertainty of the result of a measurement expressed as a standard deviation. There are two types of the standard uncertainty which are type A and type B.

Type A evaluation is evaluated through statistical analysis of a series of observations and repeated measurement. It is the component of uncertainty is due to the random effect. The gaussian or normal law of error forms the basis of the analytical study of random effects.

$$Standard\ Uncertainty\ = ESDM = \frac{s}{\sqrt{n}} \tag{2.6}$$

Type B evaluation is evaluated by the other mean than type A evaluation. It is based on scientific judgement using all the relevant information available, which may include the:

1. Earlier acquired knowledge about the measurement
2. Past experience
3. Manufacture specification
4. Result from handbook and standard tables
5. Result from Calibration Certificate

b) Sensitivity Coefficient, C_i

The sensitivity coefficient is the guide uncertainty measurement term for conversion factors that convert from input quantity units into units of the measurand. The conversion is defined as a quite simple conversion. For instance, multiplying micro-inch values by the sensitivity coefficient 1,000,000 converts them into inches.

However, determining sensitivity coefficient vales is sometimes a difficult process. In mathematically it can be defined as:

$$c_i = \frac{\partial f}{\partial x_1} = \frac{y}{x_i} \tag{2.7}$$

The sensitivity coefficient describes of the output estimate y varies with changes in the value of input estimates $x_1, x_2, x_3..x_n$. The sensitivity coefficients convert the input standard uncertainties to their equivalent values as output standard uncertainties.

c) Combined Standard Uncertainty

The combined standard uncertainty has an implied confidence of 67%. To meet engineering needs, a higher confidence level is required, and the ISO Guide recommends the calculation of an expanded uncertainty. The use of effective degrees of freedom to allow the combined uncertainty of the measurement to have a defined confidence level which is sufficiently high for practical used use is 95%. The world is harmonising to 95% confidence level.

$$U_c(y) = \sqrt{\sum_{i=1}^{i=N} {c_i}^2 u^2(x_i)} \tag{2.8}$$

where

$U_c(y) = Combined\ standard\ Uncertainty$

$\sum_{i=1}^{i=N} = Sum\ between\ i = 1\ and\ j = N$

${c_i}^2 =$ *Sensitivity coefficient*

$u^2(x_i) = Input\ Standard\ Uncertainties$

d) Effective degrees of measurand y

The effective degrees of measurand y is a function of the degrees of seldom of the input variables. It is obtained from Welch-Satterthwaite formula as follows:

$$V_{eff} = \frac{U_c{}^4(y)}{\frac{U_1{}^4(y)}{v_{1.}} + \frac{U_2{}^4(y)}{v_2} + \cdots . \frac{U_n{}^4(y)}{v_n}} \tag{2.9}$$

All the input quantities on the right-hand side are basically known and by putt all the parameters into the equation and calculating, the effective degrees of freedom is obtained.

In mathematically,

$$V_{eff} = \frac{U_c{}^4(y)}{\sum_{i=1}^{N} \frac{C_i{}^4 u^4(x_i)}{v_i}} \tag{2.10}$$

$V_{eff} = Effectivenes\ degrees\ of\ freedom$

$U_c(y) = Combined\ uncertainty\ (Uncertainty\ components\ u(x)\ for\ i = 1\ to\ N)$

$u(x_i) = Standard\ uncertainty\ for\ jth\ uncertainty\ component$

$c_i = Sensitivity\ coefficient\ for\ x_i$

$v_i = Degrees\ of\ freedom\ for\ jth\ uncertainty\ component$

e) Expanded Uncertainty

Expanded uncertainty is defined as the quantity of the interval about the result of a measurement within which the values that could reasonably be attributed to the measurand may be expected to lie with a high level of confidence.

The expanded measurement uncertainty for a laboratory test shall be stated in the test report and calculated as:

$$U_{lab} = k_p U_c(y) = t_p(V_{eff}) U_c(y) \quad (2.11)$$

Where the coverage factor k=2 yields approximately a 95% level of confidence for the near normal distribution typical of most measurement results where k is typically in the range from 2 to 3 [23].

f) Coverage factor k_p

Coverage factor k_p is also known as "Student's t" or "t factor". It is a numerical factor used as a multiplier of the combined uncertainty in order to obtain an expanded uncertainty. The value of coverage factor k is chosen on the basis of the level of confidence required in the interval y-U to y+U. In general, k mostly will be in the range from 2 for (95%) to 3(99%).

The detailed knowledge of the probability distribution characterized by the measurement result is required to obtain the value of the coverage factor k_p which it will produces an interval corresponding to a specified level of confidence p. For instances, the level of confidence p can be calculated when a quantity z described by a normal distribution with expectation μ_z and standard deviation σ,the value of k_p that produces an interval $\mu_z \pm k_p\sigma$ that encompasses the fraction p of the distribution. This described in Table 2.4 below.

Furthermore, if value of z is described in rectangular probability distribution with expectation μ_z and standard deviation $\sigma = \alpha/\sqrt{3}$, where α is defined as the half width of the distribution, the value of coverage factor k_p and level of confidence p (percent) is described in the Table 2.5 below.

Table 2.4: The value of coverage factor $\mathbf{k_p}$ correspond to the level of confidence p (percent) in normal distribution

$Level\ of\ Confidence, p$	Coverage factor k_p
68.27	1
90	1.645
95	1.960
95.45	2
99	2.576
99.73	3

Table 2.5: The value of coverage factor k_p correspond to the level of confidence p (percent) in rectangular distribution

Level of Confidence, p	Coverage factor k_p
57.74	1
95	1.65
99	1.71
100	1.732

Other than that, the distribution of the variable $t = (\bar{z} - \mu_z)/s(\bar{z})$ is the t distribution with $v = n - 1$ degrees of freedom, v if z is normally distributed random variable with expectation μ_z and standard deviation σ, and $\bar{z}$ is the arithmetic mean of n independent observations z_k of z with $s(\bar{z})$ the experimental standard deviation of $\bar{z}$.

g) Degree of Freedom, v

The degree of freedom,v is defined as for a single quantity estimated by arithmetic mean of n independent observation and it usually used for Type A evaluation where it based on n repeated measurement [21,22].

$$v = n - 1 \quad (2.12)$$

While if n independent observation is used to determine both the slope and intercept of a straight line by the method of least squares, V is defined as

$$v = n - 2 \quad (2.13)$$

The degrees of freedom of the standard uncertainty of each parameter, for a least-squares fit of m parameters to n data points is [21,22]

$$v = n - m \quad (2.14)$$

A research conduct by N.K Mandavgade [20], studied about measurement uncertainty evaluation of automatic tan delta and resistivity test set for transformer oil. In this research, it conducts an experiment of transformer oil to study the effects of the performance in electrical appliances. The result shows that in the arising from test voltage will be affecting the Tan Delta so the calibration of instrument and setting of tests should have a proper care so the uncertainty value will be reduced. Other than that, in the determined the uncertainty of measurement in case of resistivity is the variation attributed to the measurand that is the repeatability obtained in the measurements of the studied properties. In the case of resistivity, it found that the operator error which affects repeatability should be minimizing by following the proper procedure of the test. This study involves the development of a procedure for determining the result of measurement concerning electrical properties and their respective uncertainties [20].

A research conduct by Rahul Raj Choudhary studied about role and significance of uncertainty in high voltage measurement of porcelain insulators. In this research it conducts an uncertainty calculation for high voltage power frequency transformer as the standard used IS 731:1971. In this report it shows that the measurement result cannot be complete until uncertainties in the measurement as well as traceability to the standards are expressed [21].

CHAPTER 3

METHODOLOGY

3.1 Experimental Apparatus

This project will be fully utilised by using hardware component where it will used megger OTS 60B to measure the breakdown voltage for three standards which are ASTM D1816, IEC 60156 and ASTM D877. This project will record 90 readings of data for IEC 60156 while 75 readings for ASTM D1816 and ASTM D877.

3.2 List of Apparatus

3.2.1 Megger OTS60PB

Figure 3.1: Megger OTS60PB Oil Test Measurement

Figure 3.1 is designed to measure the breakdown strength of liquid insulants such as insulating oils that commonly used in transformers, switchgear, cables and other electrical apparatus. Besides, this equipment is suitable for testing on site such as in the laboratory. This equipment can withstand up to 60kV. This equipment has followed all the standards that specify and described in many national which are ASTM 877, ASTM D1816, IEC 158, IEC 60156 and others.

3.2.2 OHAUS PA214C

Figure 3.2: OHAUS PA214C Weighing Measurement

Figure 3.2 is an analytical balances is designed to measure the small masses that can measure in sub-milligram range that usually used in the lab. It is a very sensitive equipment that can detect and weight the smallest sample. In this equipment it can measure the particles up to 0.0001g.

3.2.3 Fluke 971

Figure 3.3: Fluke 971

Figure 3.3 is an equipment that used to predict the amount of the humidity and temperature to maintain the good quality of the air and optimal comfort levels.

3.2.4 DPP400W Pen Style Digital Picket Test

Figure 3.4: D400W Pen Style Digital Pocket Test

Figure 3.4 is an equipment that used to measure the amount of temperature in the insulating oil with 0.1 resolution. This equipment can measure the temperature between $-40°C\ to\ 200°C$.

3.2.5 899 Coulometer

Figure 3.5: 899 Coulometer

Figure 3.5 is an equipment that used to measure the amount of moisture or water content of the transformer oil using Karl Fischer Method (KFC).

3.2.6 Type of Electrodes

Figure 3.6: Disk Electrode

Figure 3.7: Spherical Electrode

Figure 3.6 and Figure 3.7 are used in the setting up the high voltage apparatus to determine the breakdown voltage based on different standards. The procedures to setup the electrodes gap follow based on type of the standard used.

3.3 Flowchart of the project

This section details the flow of the project that will consist of sample preparation, test moisture, procedure for moisture content, procedure for treatment, preparation on breakdown voltage and preparation on measurement uncertainties.

3.3.1 Transformer Oil

The transformer oil that is used in the project are mineral oil (Gemini X) and vegetable oil (Midel 1204). By using different types of oil, there will analysis the performance of two different oils as mentioned in the objectives by using measurement uncertainties.

3.3.2 Preparing oil sample

There are two different type of transformer oils that selected in the project such as for mineral oil, the transformer used is Gemini X manufactured by Nynas while for vegetable oil, the transformer used is MIDEL EN 1204 (Rapeseed Oil) that manufactured by M&I Materials, UK.

In preparing oil sample, for each standard there will be three sample size to record the data. The container that is preferred to store the oil is the amber glass where it is most advisable rather than a clear bottle where it can get a direct light and it shall be shielded until it ready to be tested. Screw caps with polyolefin or polytetrafluoroethylene insert are preferred for sealing.

All of containers and caps should be cleaned by washing with suitable solvent to remove all the remaining part of an earlier sample. Then, these containers must be rinsed with acetone and blew by warm air. Moreover, the container must be put in the vacuum oven to make sure there will be no water particles left in the container. The container shall be filled with oil sample but leaving about 3% of the container volume when sampling is conducted.

3.3.3 Test Moisture Content

In the third step of this project is by testing the moisture content. The moisture content is tested by using 899 Coulometer. It is a titrator used for coulometric water content determination according to Karl Fischer. Karl Fischer (KF) is a technique to determination of water content. It is a process that will based on the reaction of iodine with water. The advantages of this method are it capable to accurately measure small amount of moisture [24].

3.3.4 Procedure for moisture content

In this step, the moisture of the water content is analysed and recorded by using five sample of data which each of the sample consist of 1 ml of the transformer oil.

Figure 3.8: Karl Fischer Coulorimeter

In this step, there will be several procedures on how to measure the data of the moisture. This step will show in below:

1. The gloves are put along this process.
2. The STOP button is pressed to turn on the KFC as shown in the Figure 3.9

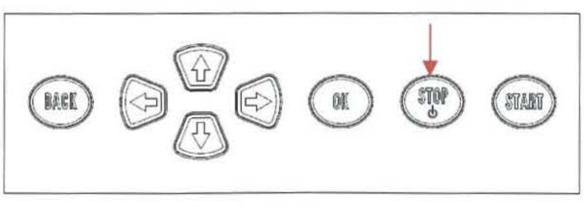


Figure 3.9: Keypad off the KFC

3. The water content in the bottle must be below 20 μg (micrograms) before it will be tested.
4. The KFC METHOD is selected as in the Figure 3.11 below
5. 5 ml of oil is taken from the amber glass to test the moisture content by referring ASTM D5133 mineral oil standard on KFC.

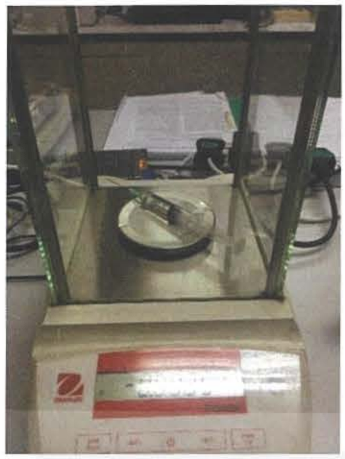


Figure 3.10: OHAUS Analytical balances with syringe

6. The bubble inside the syringe is removed by pressing the syringe until the bubble is disappeared to make sure there is no contamination in testing the moisture.
7. The syringe is put inside the OHAUS weighing to measure the amount of the mineral oil.
8. The START button is pressed once the CONDITION OK is displayed.
9. The sample is added when the monitor of the KFC is displayed "Add sample".
10. After adding the sample, the size sample is inserted on the KFC.
11. The START button is selected to continue the process.
12. The data of the sample is displayed as shown in the Figure 3.11 below.

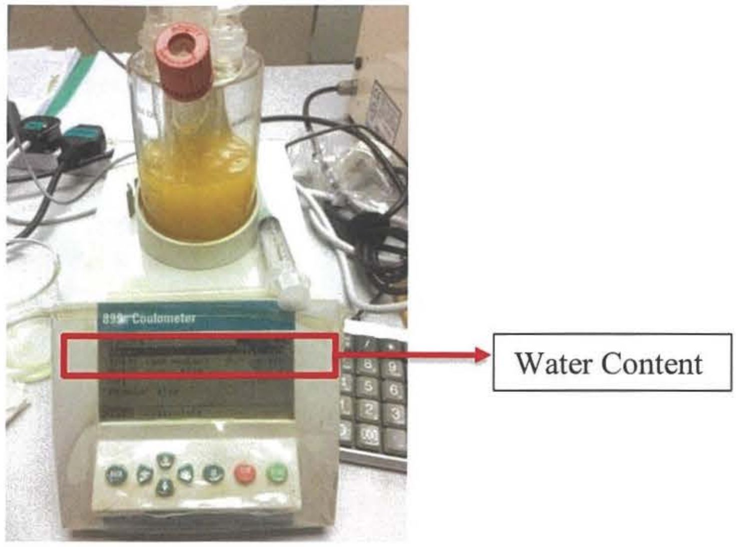


Figure 3.11: The Karl Fischer

13. The data of the moisture content of the mineral oil is recorded to be analysed.

3.3.5 Procedure for treatment process

For the data that is not meet the water content based on the standard of ASTM D3487(Mineral Oil) and D6871(Vegetable Oil), where the water content for mineral oil exceed 35 part per million (ppm) while for the Vegetable Oil exceed 200ppm, the oil must be treatment using the filtration, nitrogen or vacuum oven process. This method will reduce the amount of water content in the transformer oil.

3.3.6 Filtration Process

This process is referred from a paper "Insulation Oil Treatment and its' Necessity in Power Transformer" written by Gerards Gavriloves. In this paper it introduced three types of oil treatment which are filtering, purification with drying process, and regeneration (reclamation) with degassing. In this project, it will used only filtration process to reduce the moisture content.

Procedure of filtration process.

1. The filtration is setup as in the Figure 3.12 below.

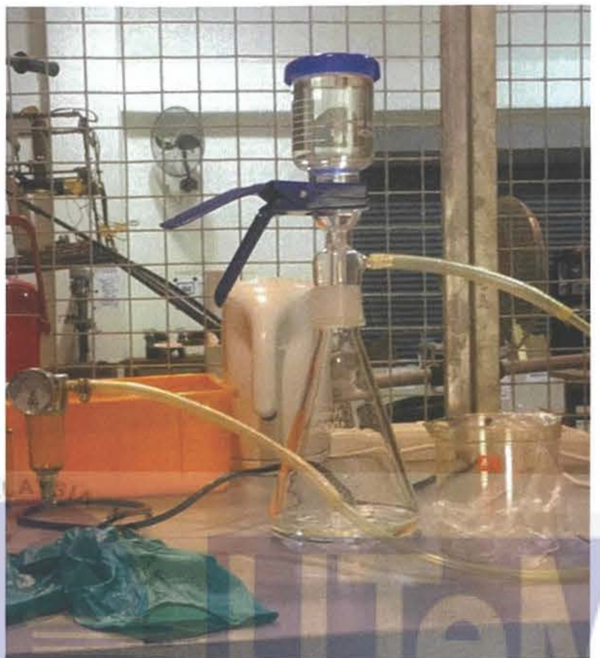


Figure 3.12: Filtration Setup

2. The filtration process used 0.2 microns filter as in figure 3.13.

Figure 3.13: Microporous membrane filter for $0.22\mu m$

3. A 450ml volume of the transformer oil is poured into the filtration beaker.

4. After 1 hour, the transformer oil is filled into the beaker to be test for moisture and breakdown voltage.
5. The data is recorded.

3.3.7 Nitrogen Saturated Process.

A paper of "*An Environmentally Friendly Dissolved Oxygen and Moisture Removal System for Freely Breathing Transformer*" written by J. Sabau et al is referred to do this method [25]. According to this paper, blanketing the nitrogen into the transformer oil is used to reduce the moisture in the transformer oil. There are three improvement done to the parameters of the blanketing nitrogen method such as:

1. From a flow rate nitrogen gas on oil to saturated nitrogen gas
2. From 24 hours rate on oil to 20 minutes into ester oil.
3. From heat oil at 70°C to without heat due to when the temperature increase, the amount of water that can be dissolve in insulating oil also increases.

Procedure of nitrogen gas.

1. The nitrogen saturated is set up as shown in the Figure 3.14 below.
2. A 450 ml weight of transformer oil is filled into a 500 ml beaker and placed inside the flask.
3. The moisture is tested and record every 5 minutes to validate the data
4. In 20 minutes, the data is recorded, and the transformer oil is ready to use.
5. The transformer oil is used for breakdown voltage after 20 minutes
6. The data is recorded for a nitrogen saturated process sample.

Figure 3.14: Process of Nitrogen Gas

3.4 Preparation on Breakdown Voltage

3.4.1 Preparation for IEC60156

1. Megger OTS60PM is setup for 2.5mm gap following the IEC 60156 standard.
2. 450ml pure mineral oil is taken from amber glass that have tested by moisture in the earlier procedure into a 450ml beaker to test the breakdown voltage by using OTS60PB.
3. The temperature of the oil is initially checked to ensure in room temperature as mention in the parameter of the standard.
4. Mineral oil is inserted into Megger OTS60B and the chamber cover is closed.
5. Megger OTS60PB is switched on and IEC 60156 standard is selected as provided in the Megger.
6. Megger OTS60PB will display the measurement of the gap to get the confirmation before the experiment start.
7. The button start is selected to proceed the breakdown voltage
8. Megger OTS60PB will stirrer around five minutes.
9. The data will have a finished data once the data is finished, it will be displayed average, and standard deviation of the breakdown voltage
10. This testing for this standard will be conducted six time.
11. The value of the six-time testing, and the average is recorded.
12. Steps 3 to 12 is repeated for 5 times due to the data will record in 5 times.
13. After the 5 testing is finished, two sample is tested using the same step as mention in step 1 to step 12.
14. This step is repeated for the other standards and the value of breakdown is recorded and analysed.

3.4.2 Diagram Flowchart of the project

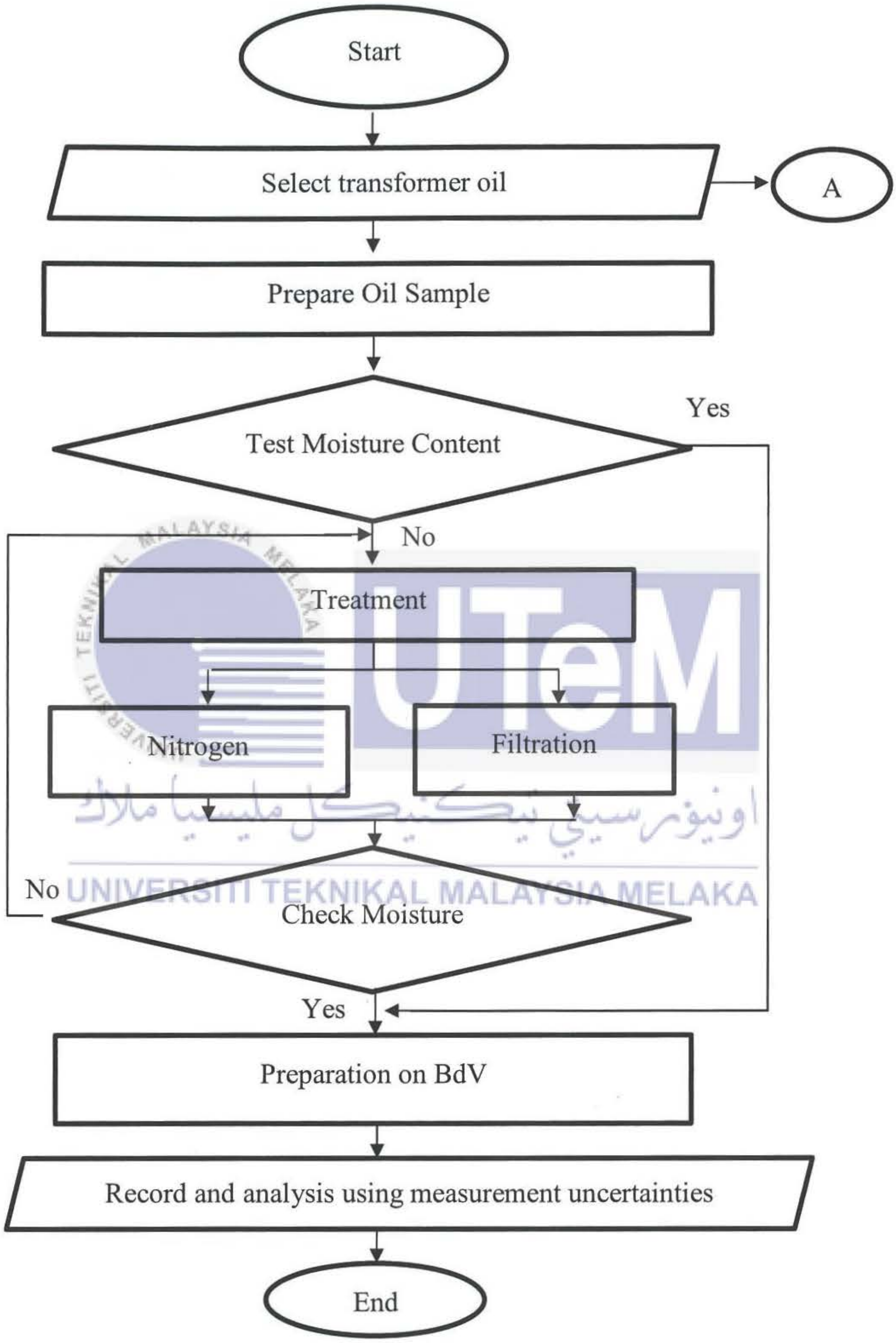


Figure 3.15: Flowchart of the project

3.5 Flowchart of the sampling

As in Figure 3.16, it shows the flowchart of the sampling for the breakdown voltage for three standards. In this breakdown voltage, for each standard it will determine three samples. In each sample it will consist of five tests where it will take 18 minutes for ASTM D816 and IEC 60156 while 8 minutes for ASTM D877. The total readings for the one sample will gives 30 readings. For all total of the three sample will gives 90 readings for each standard. These readings will be evaluating and analysis with the measurement of uncertainty.

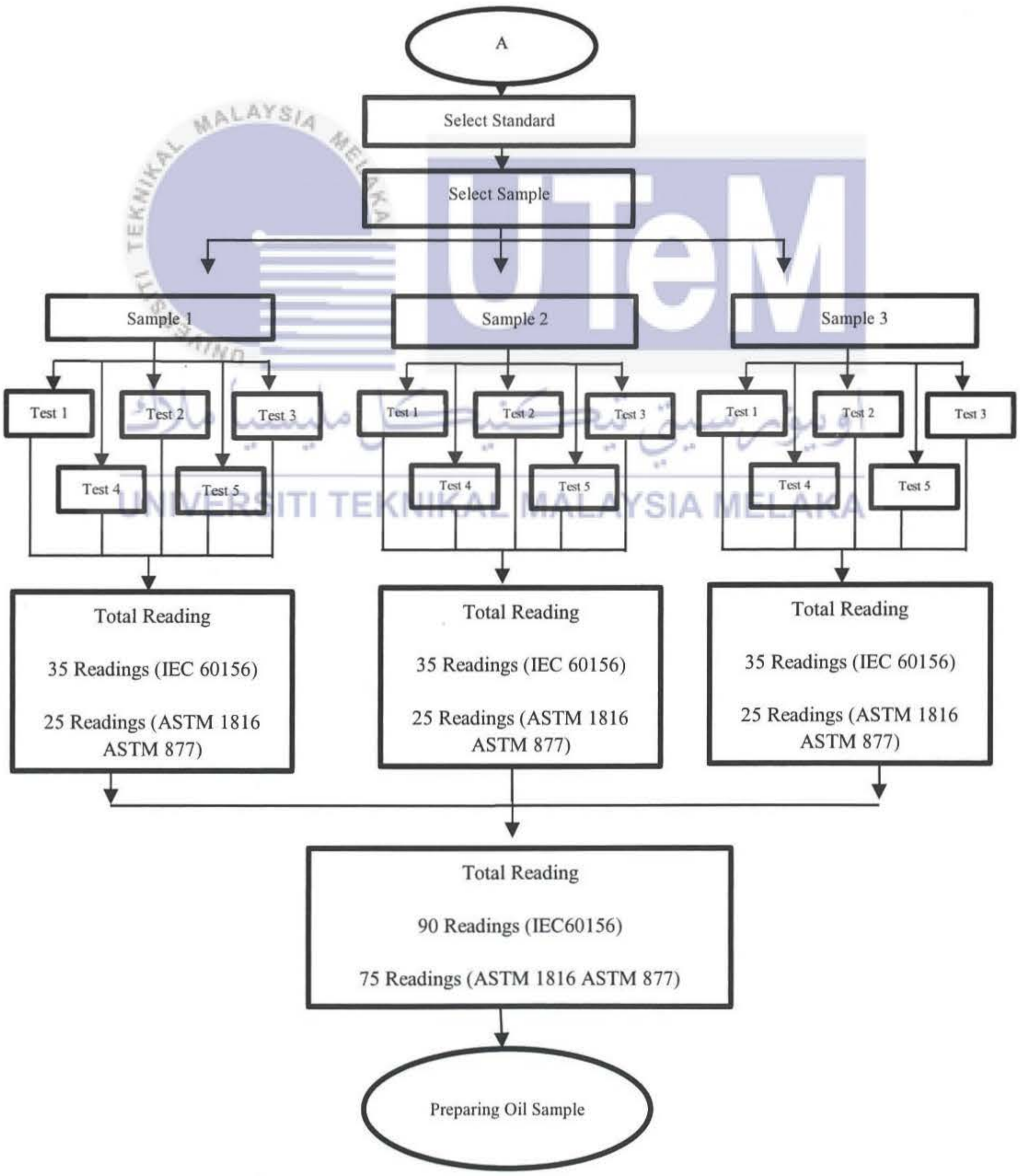


Figure 3.16: Flowchart of the sampling

3.6 Measurement Uncertainty

Procedure of Measurement Uncertainty

1. All of the value of the breakdown voltage is tabulated in excel worksheet
2. The model of measuring system is listed out, y=f(x)
3. All sources of the uncertainty are identified based on type A or type B
4. The value is calculated based on the formula of Standard Uncertainty, U_i and the degree of freedom V_i for each component of type A and type B uncertainty
5. The value of sensitivity coefficient of each component, C_i is calculated
6. The value of combined standard uncertainty, U_c is calculated
7. The value of the effective degrees of freedom, V_{eff}
8. The student's t coverage factor, k is determined corresponding to V_{eff} and the required confidence level, which it 95%
9. The value of expanded uncertainty, $U_{95\%} = k \times U_c$ is calculated
10. All of the value that calculated is expressed in uncertainty measurement.

Average mean, $\bar{x}$

The value of three sample for each standard is calculated using this formula

$$\bar{x} = \frac{\sum x_i}{n} \tag{3.1}$$

$$x_i = Sum\ of\ all\ the\ values\ of\ the\ variable$$

$$n = Number\ of observations$$

Standard Deviation, $s(\bar{x})$

$$s(\bar{x}) = \sqrt{\frac{\sum_{x_i=1}^{n}(x_i - \bar{x})^2}{n-1}} \tag{3.2}$$

$$x_i = Sum\ of\ all\ the\ values\ of\ the\ variable$$

$$n = Number\ of\ observations$$

$$\bar{x} = Average\ mean\ of\ the\ data$$

Experimental Standard Deviation, ESDM

$$ESDM = \frac{s(\bar{x})}{\sqrt{n}} \tag{3.3}$$

$$Standard\ deviation = s(\bar{x})$$

$$n = Number\ of\ observations$$

Standard Uncertainties

(i) Normal Distribution

$$u(x_i) = \frac{Expanded\ Uncertainty}{Coverage\ Factor} \tag{3.4}$$

(ii) Rectangular Distribution

$$u(x_i) = \frac{Expanded\ Uncertainty}{\sqrt{3}} \tag{3.5}$$

Degree of Freedom

$$V_i : V_i = n - 1 \tag{3.6}$$

Combined Uncertainty

$$U_c(y) = \sqrt{\sum_{i=1}^{i=N} {c_i}^2 u^2(x_i)} \tag{3.7}$$

Effective Degree of Freedom

$$V_{eff} = \frac{{U_c}^4(y)}{\sum_{i=1}^{N} \frac{{C_i}^4 u^4(x_i)}{v_i}} \tag{3.8}$$

T-Distribution

The t-factor $t_p(v_{eff})$ for the desired level of confidence p is obtain from Figure 4.4 which is table t-distribution. For n=90, in 95% confidence interval from the t-distribution is 1.984 equivalent to sample 100

Coverage Factor, k_p

$$k_p = t_p(v_{eff}) \tag{3.9}$$

Expanded Uncertainty

$$U_{95\%} = kU_c(y) = t_p(v_{eff})\, U_c(y) \tag{3.10}$$

Express in the expression

$$U = \bar{x} \pm U_{95\%} \tag{3.11}$$

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

Measurement of uncertainty was used to analyse the data for the breakdown voltages. Different transformer oils and standards such as IEC 60156, ASTM D1816, ASTM D877 were used on all samples. Results taken were then sort out by using tables and charts corresponding to the measurement uncertainty.

4.2 Breakdown Voltage

4.2.1 Data of Breakdown Voltage of Transformer Oil

The breakdown voltage for eighteen samples is recorded as in the tables below. Table 4.1 to table 4.3 show the breakdown voltage of mineral oil while table 4.4 to table 4.6 show the breakdown voltage of vegetable oil for three standards which are IEC 60156, ASTM D1816 and ASTM D877.

Table 4.1: Breakdown Voltage of Mineral Oil using IEC 60156

Sample 1		Sample 2		Sample 3	
Test Run	**BdV(kV)**	**Test Run**	**BdV(kV)**	**Test Run**	**BdV(kV)**
1	25	**1**	32	**1**	18
2	34	**2**	32	**2**	23
3	51	**3**	26	**3**	39
4	37	**4**	26	**4**	23
5	30	**5**	22	**5**	16
6	39	**6**	42	**6**	24
7	35	**7**	25	**7**	22
8	49	**8**	43	**8**	51
9	33	**9**	27	**9**	53
10	39	**10**	51	**10**	60
11	52	**11**	34	**11**	29
12	41	**12**	24	**12**	54
13	40	**13**	28	**13**	35
14	47	**14**	27	**14**	60
15	32	**15**	26	**15**	35
16	34	**16**	24	**16**	54
17	47	**17**	33	**17**	42
18	36	**18**	37	**18**	19
19	21	**19**	26	**19**	29
20	30	**20**	32	**20**	23
21	39	**21**	27	**21**	52
22	40	**22**	36	**22**	46
23	37	**23**	23	**23**	34
24	23	**24**	25	**24**	60
25	34	**25**	26	**25**	51
26	28	**26**	24	**26**	52
27	37	**27**	25	**27**	22
28	25	**28**	22	**28**	57
29	26	**29**	23	**29**	30
30	35	**30**	23	**30**	35
Average Voltage, kV	25.6	**Average Voltage, kV**	29.0333	**Average Voltage, kV**	38.2667
Average Voltage, kV	30.9656				

Table 4.2: Breakdown Voltage of Mineral Oil ASTM D1816

Sample 1		Sample 2		Sample 3	
Test Run	**BdV(kV)**	**Test Run**	**BdV(kV)**	**Test Run**	**BdV(kV)**
1	25	**1**	42	**1**	31
2	27	**2**	42	**2**	25
3	30	**3**	36	**3**	29
4	26	**4**	34	**4**	30
5	28	**5**	30	**5**	26
6	25	**6**	35	**6**	21
7	28	**7**	38	**7**	26
8	11	**8**	24	**8**	36
9	17	**9**	30	**9**	31
10	24	**10**	32	**10**	21
11	24	**11**	29	**11**	20
12	27	**12**	36	**12**	32
13	24	**13**	36	**13**	39
14	24	**14**	26	**14**	33
15	26	**15**	28	**15**	24
16	22	**16**	30	**16**	29
17	18	**17**	29	**17**	32
18	12	**18**	29	**18**	33
19	15	**19**	22	**19**	16
20	14	**20**	30	**20**	22
21	25	**21**	34	**21**	29
22	26	**22**	29	**22**	13
23	22	**23**	33	**23**	19
24	26	**24**	29	**24**	19
25	21	**25**	29	**25**	24
Average Voltage, kV	22.68	**Average Voltage, kV**	31.680	**Average Voltage, kV**	26.40
Average Voltage, kV	26.92				

Table 4.3: Breakdown Voltage of Mineral Oil ASTM D877

Sample 1		Sample 2		Sample 3	
Test Run	**BdV(kV)**	**Test Run**	**BdV(kV)**	**Test Run**	**BdV(kV)**
1	35	**1**	44	**1**	30
2	29	**2**	39	**2**	32
3	28	**3**	37	**3**	31
4	23	**4**	34	**4**	29
5	25	**5**	23	**5**	28
6	29	**6**	37	**6**	34
7	29	**7**	25	**7**	33
8	30	**8**	43	**8**	34
9	32	**9**	41	**9**	25
10	33	**10**	30	**10**	26
11	38	**11**	43	**11**	23
12	33	**12**	42	**12**	31
13	34	**13**	34	**13**	30
14	32	**14**	34	**14**	25
15	26	**15**	43	**15**	30
16	22	**16**	42	**16**	30
17	29	**17**	48	**17**	30
18	22	**18**	41	**18**	34
19	27	**19**	36	**19**	34
20	30	**20**	34	**20**	27
21	30	**21**	34	**21**	30
22	31	**22**	35	**22**	27
23	30	**23**	34	**23**	29
24	29	**24**	37	**24**	32
25	28	**25**	40	**25**	32
Average Voltage, kV	29.36	**Average Voltage, kV**	37.20	**Average Voltage, kV**	29.84
Average Voltage, kV	32.1333				

Table 4.4: Breakdown Voltage of Vegetable Oil IEC 60156

Sample 1		Sample 2		Sample 3	
Test Run	**BdV(kV)**	**Test Run**	**BdV(kV)**	**Test Run**	**BdV(kV)**
1	40	**1**	26	**1**	56
2	36	**2**	39	**2**	47
3	31	**3**	33	**3**	26
4	38	**4**	25	**4**	47
5	46	**5**	39	**5**	29
6	40	**6**	19	**6**	48
7	42	**7**	30	**7**	41
8	41	**8**	42	**8**	42
9	57	**9**	36	**9**	48
10	53	**10**	20	**10**	55
11	45	**11**	37	**11**	41
12	40	**12**	37	**12**	54
13	52	**13**	33	**13**	46
14	42	**14**	35	**14**	36
15	50	**15**	31	**15**	47
16	39	**16**	24	**16**	51
17	46	**17**	38	**17**	50
18	47	**18**	29	**18**	46
19	37	**19**	23	**19**	50
20	36	**20**	39	**20**	51
21	45	**21**	39	**21**	49
22	45	**22**	19	**22**	54
23	59	**23**	28	**23**	39
24	44	**24**	31	**24**	52
25	49	**25**	31	**25**	55
26	52	**26**	26	**26**	45
27	53	**27**	30	**27**	51
28	58	**28**	23	**28**	52
29	55	**29**	24	**29**	42
30	46	**30**	23	**30**	57
Average Voltage, kV	45.4667	**Average Voltage, kV**	30.30	**Average Voltage, kV**	45.4667
Average Voltage, kV	40.411kV				

Table 4.5: Breakdown Voltage of Vegetable Oil ASTM D1816

Sample 1		Sample 2		Sample 3	
Test Run	**BdV(kV)**	**Test Run**	**BdV(kV)**	**Test Run**	**BdV(kV)**
1	33	**1**	33	**1**	39
2	32	**2**	39	**2**	46
3	31	**3**	32	**3**	48
4	22	**4**	31	**4**	43
5	28	**5**	35	**5**	37
6	28	**6**	41	**6**	49
7	22	**7**	32	**7**	36
8	29	**8**	30	**8**	28
9	31	**9**	42	**9**	33
10	36	**10**	23	**10**	23
11	36	**11**	41	**11**	42
12	30	**12**	33	**12**	39
13	37	**13**	32	**13**	39
14	29	**14**	43	**14**	33
15	33	**15**	22	**15**	40
16	33	**16**	37	**16**	43
17	33	**17**	36	**17**	42
18	35	**18**	38	**18**	40
19	29	**19**	40	**19**	43
20	36	**20**	44	**20**	44
21	25	**21**	36	**21**	34
22	34	**22**	45	**22**	39
23	26	**23**	40	**23**	28
24	31	**24**	40	**24**	36
25	41	**25**	36	**25**	29
Average Voltage, kV	31.2	**Average Voltage, kV**	36.04	**Average Voltage, kV**	38.12
Average Voltage, kV	35.12				

Table 4.6: Breakdown Voltage of Vegetable Oil ASTM D877

Sample 1		Sample 2		Sample 3	
Test Run	**BdV(kV)**	**Test Run**	**BdV(kV)**	**Test Run**	**BdV(kV)**
1	47	**1**	58	**1**	43
2	53	**2**	47	**2**	42
3	47	**3**	48	**3**	44
4	43	**4**	40	**4**	46
5	51	**5**	35	**5**	41
6	50	**6**	38	**6**	47
7	49	**7**	46	**7**	51
8	39	**8**	45	**8**	51
9	25	**9**	44	**9**	53
10	41	**10**	34	**10**	29
11	43	**11**	36	**11**	51
12	49	**12**	38	**12**	49
13	40	**13**	38	**13**	53
14	29	**14**	30	**14**	44
15	27	**15**	31	**15**	48
16	34	**16**	40	**16**	53
17	35	**17**	37	**17**	57
18	39	**18**	33	**18**	51
19	34	**19**	40	**19**	47
20	41	**20**	28	**20**	48
21	38	**21**	30	**21**	55
22	30	**22**	24	**22**	55
23	29	**23**	33	**23**	52
24	36	**24**	33	**24**	43
25	37	**25**	38	**25**	48
Average Voltage, kV	39.4	**Average Voltage, kV**	37.76	**Average Voltage, kV**	48.04
Average Voltage, kV	41.733				

4.2.2 Comparison of Breakdown Voltage between Mineral Oil and Vegetable Oil

Graph in Figure 4.1 and Figure 4.2 show the breakdown voltage for mineral oil and vegetable oil. Meanwhile, Figure 4.3 shows the comparison of breakdown voltage of transformer oil by using different standards. Based on Figure 4.1 , 2 out of 3 sample of IEC 60156 shows the higher number of breakdown voltage that pass the standards value compared to ASTM D1816 and ASTM D877. Meanwhile, based on Figure 4.2 , 3 out of 3 sample of ASTM D1816 shows the higher number of breakdown voltage compared to IEC 60156 and ASTM D1816. Moreover, based on Figure 4.3, the average of breakdown voltage of mineral oil for IEC 60156 is higher than vegetable oil with the values of 40.889 and 34.3889.

In IEC 60156 and ASTM D1816 the minimum breakdown voltage of insulating liquids should reached is 35kV. Some of the samples are discarded due to breakdown voltage lower than 35kV. This is probably due to the high moisture in the liquid. The presence of moisture in the insulating liquids may decrease the breakdown voltage. Thus, new samples are developed using additional treatments such as nitrogen saturated process and filtration process.

In standard ASTM D1816 shows the lowest value of average breakdown voltage for vegetable oil which is 26.92 kV compared to IEC 60156, 34.3889 kV and ASTM D877,32.1333kV There are several factors that affect this value such as the moisture of the oil, the preparation of the electrodes, the measurement gap of the electrode, the humidity of the surrounding and the temperature of the oil sample. According to Y. Zhou [5], the presence of 0.02% water in transformer oil will reduced the amount of electric strength up to 20% of the dry value. Moreover, the breakdown voltage is well known sensitive to impurities such as the presence of moisture, surroundings, temperature and gas bubbles [2]. This is one of the reasons why some of the value of breakdown voltage of transformer oil does not meet the standards even the experiment is repeated a few times.

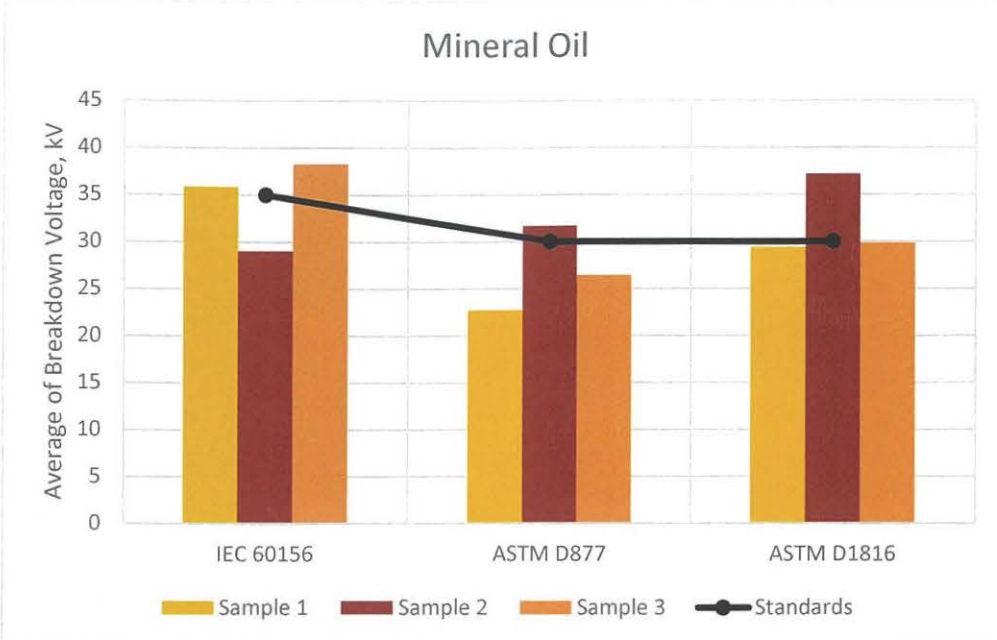


Figure 4.1: Breakdown Voltage of Mineral Oil for IEC 60156

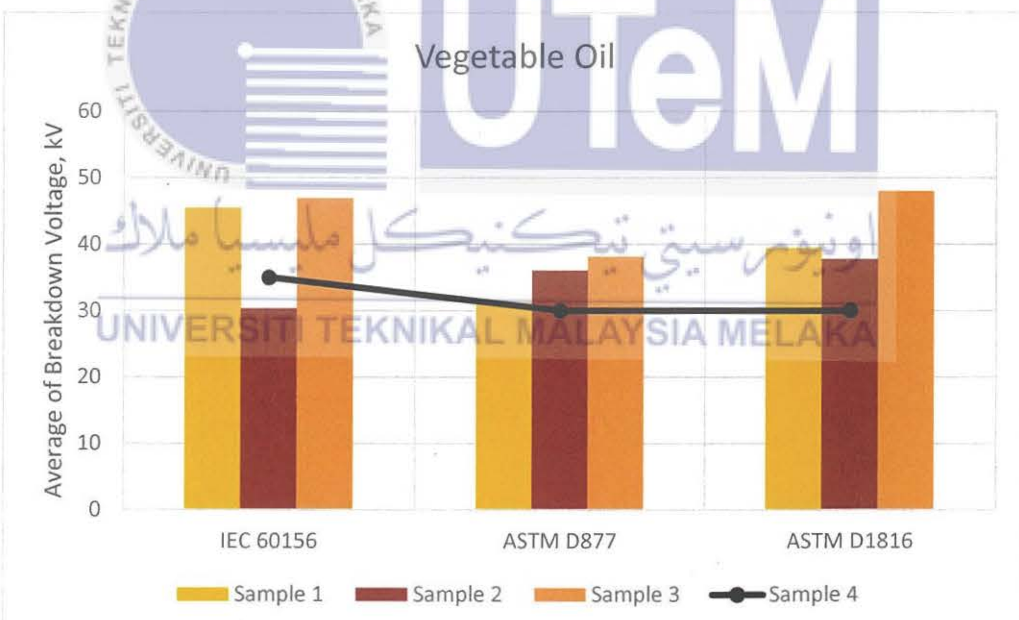
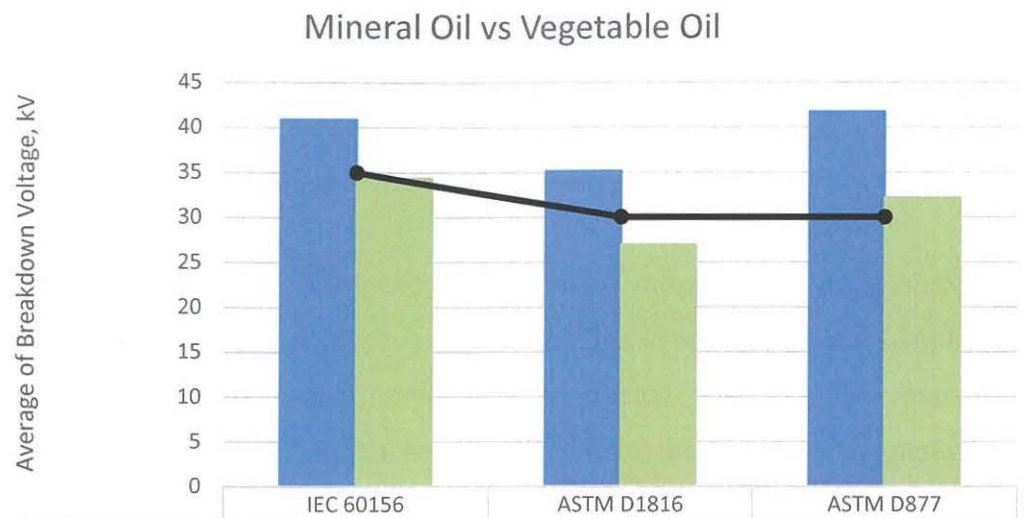


Figure 4.2: Breakdown Voltage of Vegetable Oil for IEC 60156



	IEC 60156	ASTM D1816	ASTM D877
Mineral Oil	40.889	35.12	41.747
Vegetable Oil	34.3889	26.92	32.1333
Standards	35	30	30

Figure 4.3:Breakdown Voltage of Mineral Oil and Vegetable Oil for each standards

4.3 Measurement Uncertainty

4.3.1 Calculation of Measurement Uncertainty

In section 4.3.1 shows the calculation of measurement uncertainty for all samples in this experiment. Type A is evaluated based on the repeated samples in the experiment. Other than that, type B is evaluated based on the manufacture specification, result from handbooks and earlier knowledge about the experiment.

In type A the calculation to evaluate the uncertainty measures involved is average mean and standard deviation. This result is significant to measures the estimation of standard deviation (ESDM).

As in type B, the calculation to evaluate the uncertainty measures involved is the repeatability, calibration, resolution and voltage rise. The variables that used to calculate for this repeatability, calibration, resolution and voltage rise are evaluation type, distribution type, semi range, divisor, standard uncertainty, sensitivity coefficient and degree of freedom. The degree of freedom for calibration and resolution are estimated in a larger value as the number is 999,999,999 or 888,888,888 by indicated it is an infinity value. While the other variables are calculated by referring to Joint Committee for Guides in Metrology [23].

Type of Transformer Oil: Mineral Oil

Type of Standard: IEC 60156

a) Average Mean, $\bar{x}$

$$\bar{x} = \frac{\sum x_i}{n} = \frac{Summation\ of\ x_i\ data}{size\ of\ the\ data}$$

$$= \frac{(Sum\ of\ bdv1) + (sum\ of\ bdv2) + (sum\ of\ bdv3) \ldots + (sum\ of\ bdv4)}{(30)}$$

$$= \frac{\begin{matrix}25 + 34 + 51 + 37 + 30 + 39 + 35 + 49 + 33 + 39 + 52 + 41 + 40 + +47 + 32 \\ +34 + 47 + 36 + 21 + 30 + 39 + 40 + 37 + 23 + 34 + 28 + 37 + 25 + 26 + 35\end{matrix}}{30}$$

$= 25.6\text{kV}$

b) Standard Deviation, $s(\bar{x})$

$$s(\bar{x}) = \sqrt{\frac{\sum_{x_i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

$$= \sqrt{\frac{(x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + (x_3 - \bar{x})^2 \ldots. + (x_{90} - \bar{x})^2}{30 - 1}}$$

$$= \sqrt{\frac{283.20}{29}}$$

$= 3.124983\text{kV}$

c) Estimation Standard Deviation, ESDM

$$ESDM = \frac{s(\bar{x})}{\sqrt{n}}$$

$$= \frac{3.124983\text{kV}}{\sqrt{30}}$$

$= 0.570541$

d) Degree of Freedom, DoF

$$V_i = n - 1$$

$$V_i = 30 - 1$$

$$V_i = 29$$

Measurement Info:

Resolution : 1kV

Bias : None

Voltage Rise : 2kV $\pm$ 0.2%

From Calibration Certificate:

U_{calb} : 0.045

K : 2

Vi (From Table) : 888,888,888

Error : 1kV

Sensitivity Coefficient, c_i : 1

Table 4.7: Measurement Uncertainty of Type B

Sources of Uncertainty, x	Evaluation Type, A and B	Distribution Type	Semi Range, a	Divisor	Standard Uncertainty u_i	Sensitivity Coefficient c_i	Degrees of Freedom υ	Uncertainty Contribution $c_i u_i$
Repeatability	A	Student-T	NA	NA	4.753800657	1	29	4.7538007
Calibration	B	Student-T	NA	NA	0.00225	1	888,888,888	0.0022500
Resolution	B	Rectangular	0.5	1.732050808	0.288675135	1	999,999,999	0.2886751
Accuracy (Drift)	B	Rectangular	NA	NA	NA	1	NA	0
Method (Precision)	B	Rectangular	NA	NA	NA	1	NA	NA

Repeatability

Evaluation Type : A

Distribution Type : Student T

Semi Range : Not Available, NA

Divisor : Not Available, NA

Standard Uncertainty, u_i : $\frac{Dof}{Mean,\bar{x}} = \frac{29}{\sqrt{25.6}} = 4.753801$

Sensitivity Coefficient, u_i :1

Degree of Freedom, v_i :29

Uncertainty Contribution, $c_i u_i$: $1 * 4.7538007 = 4.7538007$

Calibration

Evaluation Type : B

Distribution Type : Student T

Semi Range : Not Available, NA

Divisor : Not Available, NA

Standard Uncertainty,u_i : $\frac{Ucalb}{k} = \frac{0.045}{2} = 0.00225$

Sensitivity Coefficient, u_i : 1

Degree of Freedom, v_i :888,888,888

Uncertainty Contribution, $c_i u_i$: $1 * \ 0.00225 = 0.0022500$

Resolution

Evaluation Type : B

Distribution Type : Rectangular

Semi Range, a : $\frac{1}{2} = 0.5$

Divisor : $\sqrt{3} \approx 1.73205$

Standard Uncertainty, u_i : $\frac{Semi\ Range}{Divisor} = \frac{0.5}{\sqrt{3}} = 0.288675135$

Sensitivity Coefficient, u_i : 1

Degree of Freedom, v_i : 999,999,999

Uncertainty Contribution, $c_i u_i$: $1 * 0.288675135 = 0.288675135$

Voltage Rise

Evaluation Type : B

Distribution Type : Rectangular

Semi Range, a : $\frac{(1.02*2-0.98*2)}{2} = 0.04$

Divisor : $\sqrt{3} \approx 1.73205$

Standard Uncertainty, u_i : $\frac{Semi\ Range}{Divisor} = \frac{0.04}{\sqrt{3}} = 0.023094011$

Sensitivity Coefficient, u_i : 1

Degree of Freedom, v_i : 999,999,999

Uncertainty Contribution, $c_i u_i$: $1 * 0.023094011 = 0.023094011$

e) Combined Uncertainty, (U_c)

$$U_c(y) = \sqrt{(C_1 \times Ux_1)^2 + (C_2 \times Ux_2)^2} = \sqrt{(C_1 \times Ux_1)^2 + ..(C_n \times Ux_n)^2}$$

$$U_c(y) = \sqrt{\begin{matrix}(1 \times 4.7538007\,)^2 + (1 \times 0.0022500)^2 + (1 \times 0.288675135)^2 + \\ (1 \times 0.519615242)^2 + (1 \times\ 0.023094011)^2\end{matrix}}$$

$$= 4.790875955$$

f) Effectiveness Degree of Freedom, V_{eff}

$$V_{eff} = \frac{U_c{}^4(y)}{\frac{U_1{}^4(y)}{v_1} + \frac{U_2{}^4(y)}{v_2} + \ldots\frac{U_n{}^4(y)}{v_n}}$$

$$V_{eff} = \frac{4.790875955^4(y)}{\left(\begin{matrix}\frac{4.75380074^4(y)}{29} + \frac{0.0022500^4(y)}{888{,}888{,}888} + \frac{0.288675135^4(y)}{999{,}999{,}999} + \\ \frac{0.5196152420^4(y)}{999{,}999{,}999} + \frac{0.023094011^4(y)}{999{,}999{,}999}\end{matrix}\right)}$$

$$= 29.35183 \approx 30$$

e) Coverage Factor from Student-t distribution, k

The student of t-distribution is selected from table t-distribution in 95% Confidence Interval

k=T-Distribution-95% (30) = 2.04

Figure 4.4: Table of T-Distribution

Degree of Freedom	Fraction p in percent (%)					
v	68.27	90	95	95.45	99	99.73
1	1.84	6.31	12.71	13.97	63.66	235.8
2	1.32	2.92	4.3	4.53	9.92	19.21
3	1.2	2.35	3.18	3.31	5.84	9.22
4`	1.14	2.13	2.78	2.87	4.6	6.62
`5	1.11	2.02	2.57	2.65	4.03	5.51
6	1.09	1.94	2.45	2.52	3.71	4.90
7	1.08	1.89	2.36	2.43	3.50	4.53
8	1.07	1.86	2.31	2.37	3.36	4.28
9	1.06	1.83	2.26	2.32	3.25	4.09
10	1.05	1.81	2.23	2.28	3.17	3.96
11	1.05	1.80	2.20	2.25	3.11	3.85
12	1.04	1.78	2.18	2.23	3.05	3.76
13	1.04	1.77	2.16	2.21	3.01	3.69
14	1.04	1.76	2.14	2.20	2.98	3.64
15	1.03	1.75	2.13	2.18	2.95	3.59
16	1.03	1.75	2.12	2.17	2.92	3.54
17	1.03	1.74	2.11	2.16	2.90	3.51
18	1.03	1.73	2.10	2.15	2.88	3.48
19	1.03	1.73	2.09	2.14	2.86	3.45
20	1.03	1.72	2.09	2.13	2.85	3.42
25	1.02	1.71	2.06	2.11	2.79	3.33
30	1.02	1.70	2.04	2.09	2.75	3.27
35	1.01	1.70	2.03	2.07	2.72	3.23
40	1.01	1.68	2.02	2.06	2.70	3.20
45	1.01	1.68	2.01	2.06	2.69	3.18
50	1.01	1.68	2.01	2.05	2.68	3.16
100	1.005	1.660	1.984	2.025	2.626	3.077
∞	1.000	1.645	1.960	2.000	2.576	3.000

a) For a quantity z described by a normal distribution with expectation μ_z and standard deviation σ, the interval $\mu_z \pm k\sigma$ encompasses p = 68,27 percent, 95,45 percent and 99,73 percent of the distribution for k = 1, 2 and 3, respectively.

f) Expanded Uncertainty

$$U_{lab} = k_p U_c(y) \; = \; t_p(v)\, U_c(y)$$

$$U_{lab} = 2.04 \; \times 1.621554$$

$$= 9.773386959$$

g) Expression of the Uncertainty, BdV

$$25.6 \pm 9.727034 \; kV$$

h) Expression of the Uncertainty in percentage

$$\text{BdV (\%)} = \frac{Uncertainty\ BdV}{Mean}$$

$$\text{BdV (\%)} = \frac{9.773386959\ kV}{25.6\ kV}$$

$$\text{BdV (\%)} = \; 37.996227\ \%$$

Thus,

$$25.6 \pm 37.996227\ \%\ kV$$

4.3.2 Graph of measurement uncertainty between mineral oil
4.3.3 and vegetable oil

Figure 4.5 shows the value of mineral oil for each standard for nine samples of transformer oil. The value of uncertainty measurement is converted into percentage in order to get the smallest number of uncertainties. Based on the calculation IEC 60156 for mineral oil in sample 3, the number of measurement uncertainties shows the smallest number which is 37.9330812% compared to sample 1 and sample 2.

Figure 4.7 shows the comparison of uncertainty measurement between different transformer oil by using different standards. Generally, the lowest number of measurement uncertainty is affected by the calculation as in section 4.3.1.

The calculation of measurement uncertainty in section 4.3.1 is calculated based on case study by Rahul Raj Chaudhary and Evaluation of Measurement data. According to the bar graph, IEC 60156 shows the lowest value of uncertainty measurement for both transformer oil compared to ASTM D1816 and ASTM D877.

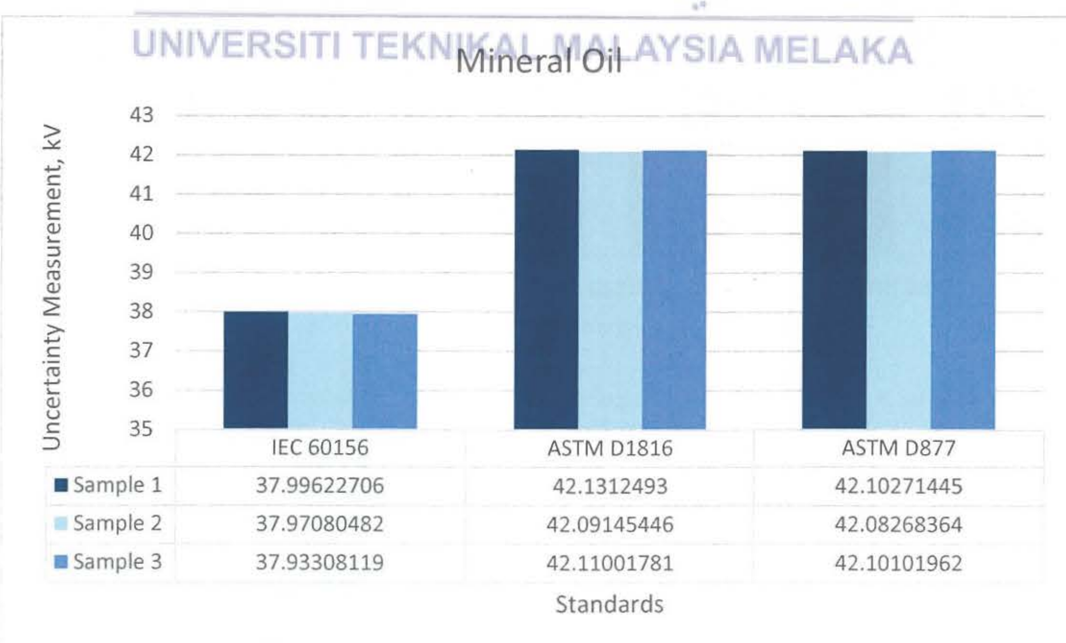
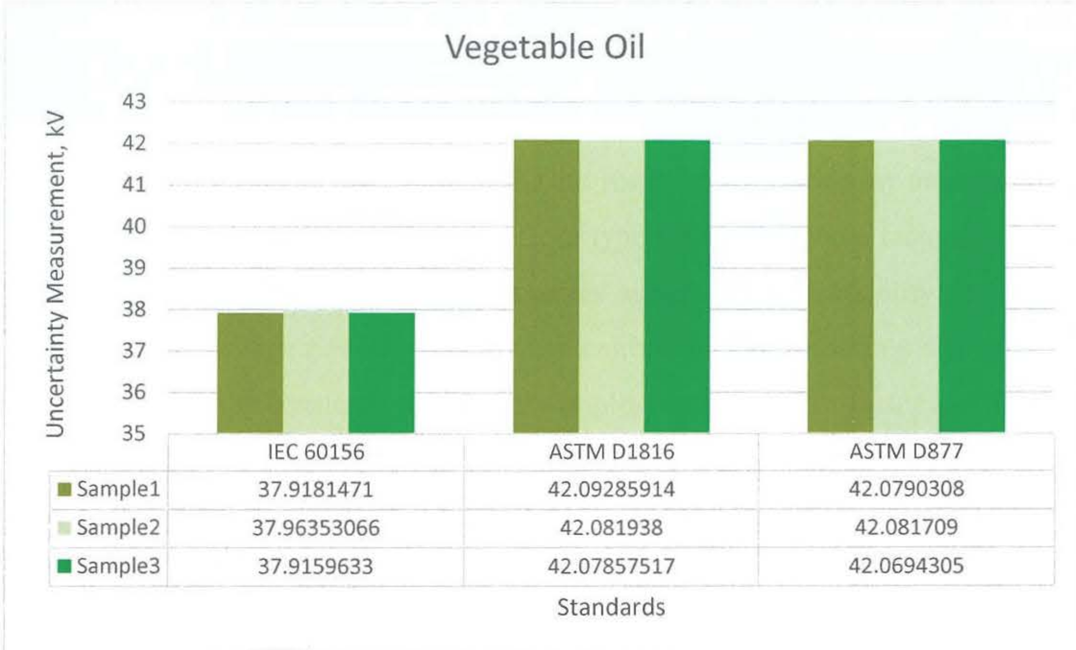


Figure 4.5: Measurement Uncertainty of Mineral Oil



	IEC 60156	ASTM D1816	ASTM D877
Sample1	37.9181471	42.09285914	42.0790308
Sample2	37.96353066	42.081938	42.081709
Sample3	37.9159633	42.07857517	42.0694305

Figure 4.6: Measurement Uncertainty of Vegetable Oil

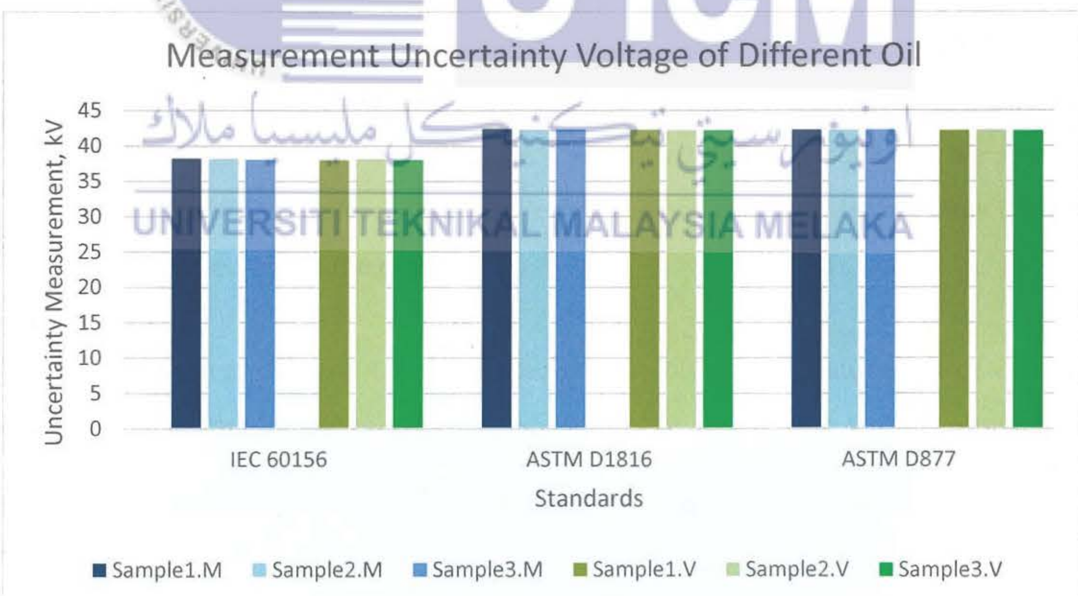


Figure 4.7: Measurement Uncertainty of Different Oil

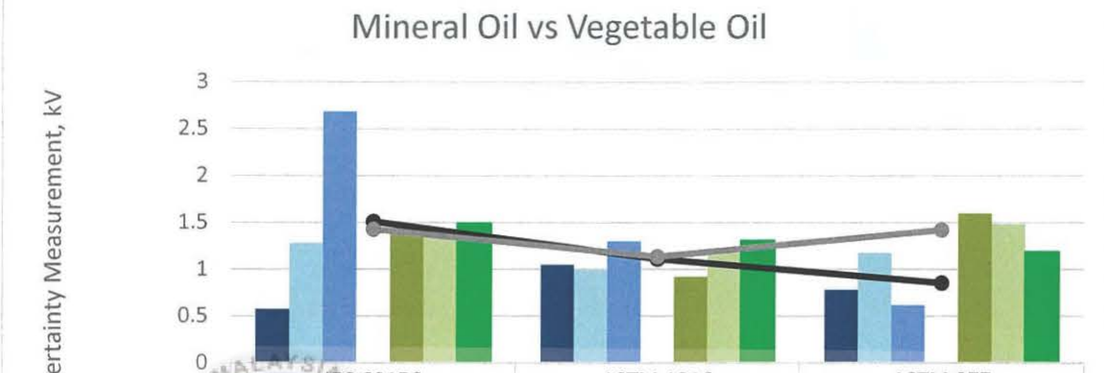
4.3.4 Factors that influence the result of measurement uncertainty

The figures show the factors that influenced the result of measurement uncertainties. The factor that influenced the result of measurement uncertainties is affected by type A and B. As in table 4.7, in type B there are three factors that affect the result of the measurement uncertainties which are repeatability, calibration, resolution and voltage rise. However, since calibration and resolution are one of the factors that give the constant value for all samples, thus the major factor that affect the uncertainties measurement for type B is repeatability and voltage rise. Other than that, type A also give the effect to the result of the measurement uncertainties which is standard deviation.

Next, in Figure 4.8, sample 3 for mineral oil in IEC 60156 show the highest standard deviation with 1.4887 while sample 1 for vegetable oil in ASTM D877 show the lowest standard deviation with 1.5969. The data of mineral oil in IEC 60156 recorded the highest number of average standard deviation with 1.5094 while ASTM D877 recorded the lowest number of average deviations in mineral oil with 0.8528. In IEC 60156, both transformer oil shows the highest number of uncertainty measures where it can influence the data in Figure 4.10. Based on the observation for standard deviation, ASTM D877 shows the smaller number of standard deviation as it shows the value is closed to the mean value.

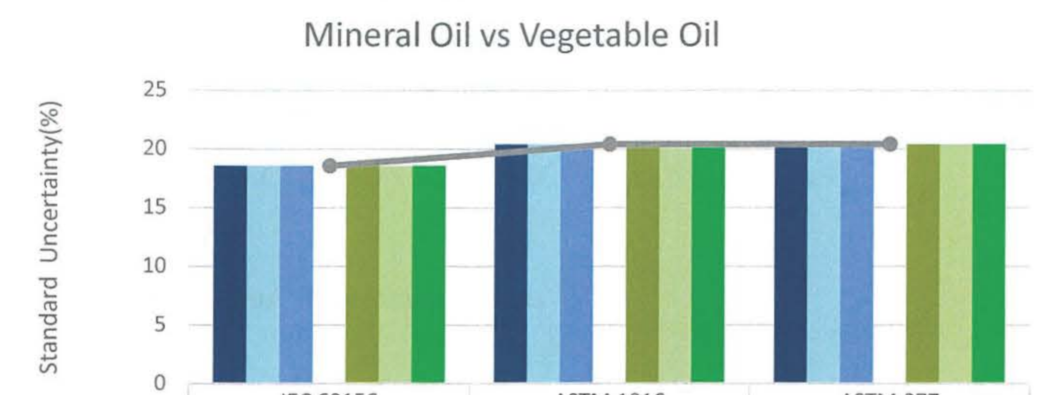
Moreover, Figure 4.9 shows the repeatability of measurement of different standards and transformer oil. IEC 60156 shows the dependable variable depends on the average data. The repeatability of measurement uncertainties for type B is influenced on the experiment conducted. IEC 60156 shows the major effect of measurement uncertainty compared to the other standards. There is significant value that affect every sample. This is due to the precision setup of the experiment, type of electrode used, the number of repeatability data in every standard, the percentage of the impurities of the transformer oil, the humidity of the surrounding, the temperature of the oil and temperature of the oil.

Lastly, the factor that influenced the measurement uncertainties is voltage rise. IEC 60156 has the highest value of uncertainty voltage rise with 0.7670 and 0.5875 compared to ASTM D1816 and ASTMD877. Differences in voltage rise does not affect calculation for measurement of uncertainty due to only four decimal points in the calculation.



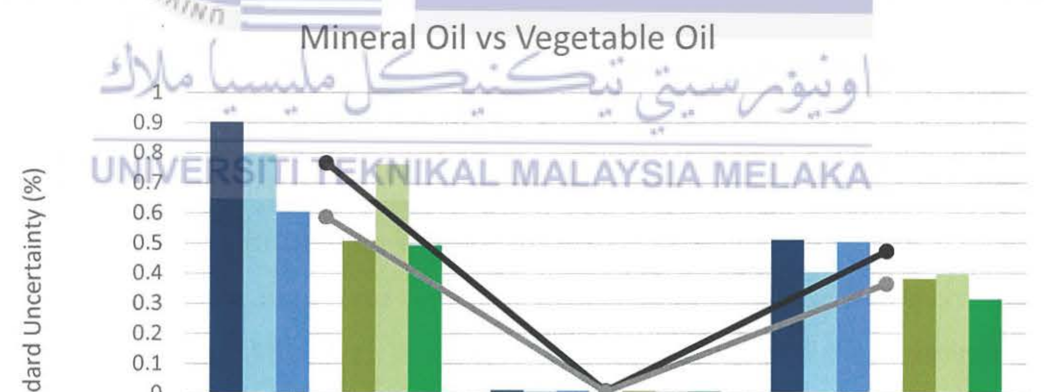
	IEC 60156	ASTM 1816	ASTM 877
Sample1.M	0.570541	1.0468	0.7765
Sample2.M	1.276204	0.9878	1.169
Sample3.M	2.681539	1.2949	0.6129
3	0	0	0
Sample1.V	1.4353	0.9183	1.5949
Sample2.V	1.3556	1.1797	1.4824
Sample3.V	1.4887	1.3042	1.1839
Average.M	1.509428	1.109833333	0.8528
Average.V	1.426533333	1.134066667	1.4204

Figure 4.8: Standard Deviation of Measurement Uncertainty Type A



	IEC 60156	ASTM 1816	ASTM 877
Sample1.M	18.56953516	20.41241623	20.41241485
Sample2.M	18.57166724	20.41241477	20.41241398
Sample3.M	18.56951867	20.41241288	20.41241287
Column1	0	0	0
Sample1.V	18.56952011	20.41241346	20.41241379
Sample2.V	18.56953465	20.41241451	20.41241446
Sample3.V	18.5695339	20.41241453	20.41241445
Average.M	18.57024035	20.41241463	20.4124139
Average.V	18.56952956	20.41241417	20.41241423

Figure 4.9: Repeatability of Measurement Uncertainty Type B



	IEC 60156	ASTM 1816	ASTM 877
Sample1.M	0.902109375	0.011022928	0.510899183
Sample2.M	0.795521874	0.007891414	0.403225806
Sample3.M	0.6036069	0.009469697	0.502680965
3	0	0	0
Sample1.V	0.507932179	0.008012821	0.380324544
Sample2.V	0.762178218	0.006936737	0.397245763
Sample3.V	0.492409382	0.006558237	0.3122398
Average.M	0.767079383	0.009461346	0.472268651
Average.V	0.587506593	0.007169265	0.363270035

Figure 4.10: Voltage Rise of Measurement Uncertainty Type B

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions and Recommendations

The experimental work presented in this thesis contributes to a further understanding on breakdown strength analysis of transformer oil due to different standards. The analysis that used in the projects important to measure the breakdown voltage of different transformer oil, measure the uncertainty of the breakdown voltage readings and evaluate the breakdown voltage readings from three different standards based on uncertainty measures. All the factors that contributed to the result of measurement uncertainties is analysed and calculated. Based on the findings, IEC 60156 shows the smallest uncertainties readings compared to ASTM D1816 and ASTM D877. Although IEC 60156 shows the smallest uncertainties readings, however there are some samples that not met the requirement of standard breakdown voltage.

Measure of repeatability is important in order to get consistent data. The factors that affect the lowest breakdown voltage can be either moisture in the transformer oil, temperature of the transformer oil and the experimental setup. Hence, the experiment was performed in confined room with the lowest value of the temperature and better humidity to reduce the impurities content in the transformer oil thus will increase the value of experiment. Moreover, accuracy (drift) and method of the experiment is needed in the specification of the instrument as it will affect the value of the measurement uncertainties. By having more several factors of measurement uncertainties of type B will makes the data more accurate.

5.2 Future Works

For future improvements, accuracy of the breakdown strength analysis of the transformer oil could be enhanced as follows:

1. Consider more factors for analysis in example measurement gap, method rise and accuracy.

2. Repeat the filtration and nitrogen saturated process several times to remove the contaminants in the oil.

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APPENDICES

APPENDIX A MINERAL INSULATING OIL SPECIFICATION

Designation: D3487 – 09

Standard Specification for Mineral Insulating Oil Used in Electrical Apparatus[1]

This standard is issued under the fixed designation D3487; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 This specification covers new mineral insulating oil of petroleum origin for use as an insulating and cooling medium in new and existing power and distribution electrical apparatus, such as transformers, regulators, reactors, circuit breakers, switchgear, and attendant equipment.

1.2 This specification is intended to define a mineral insulating oil that is functionally interchangeable and miscible with existing oils, is compatible with existing apparatus and with appropriate field maintenance,[2] and will satisfactorily maintain its functional characteristics in its application in electrical equipment. This specification applies only to new insulating oil as received prior to any processing.

1.3 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D88 Test Method for Saybolt Viscosity
D92 Test Method for Flash and Fire Points by Cleveland Open Cup Tester
D97 Test Method for Pour Point of Petroleum Products
D445 Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)
D611 Test Methods for Aniline Point and Mixed Aniline Point of Petroleum Products and Hydrocarbon Solvents
D877 Test Method for Dielectric Breakdown Voltage of Insulating Liquids Using Disk Electrodes
D923 Practices for Sampling Electrical Insulating Liquids
D924 Test Method for Dissipation Factor (or Power Factor) and Relative Permittivity (Dielectric Constant) of Electrical Insulating Liquids
D971 Test Method for Interfacial Tension of Oil Against Water by the Ring Method
D974 Test Method for Acid and Base Number by Color-Indicator Titration
D1275 Test Method for Corrosive Sulfur in Electrical Insulating Oils
D1298 Test Method for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method
D1500 Test Method for ASTM Color of Petroleum Products (ASTM Color Scale)
D1524 Test Method for Visual Examination of Used Electrical Insulating Oils of Petroleum Origin in the Field
D1533 Test Method for Water in Insulating Liquids by Coulometric Karl Fischer Titration
D1816 Test Method for Dielectric Breakdown Voltage of Insulating Oils of Petroleum Origin Using VDE Electrodes
D1903 Practice for Determining the Coefficient of Thermal Expansion of Electrical Insulating Liquids of Petroleum Origin, and Askarels
D2112 Test Method for Oxidation Stability of Inhibited Mineral Insulating Oil by Pressure Vessel
D2300 Test Method for Gassing of Electrical Insulating Liquids Under Electrical Stress and Ionization (Modified Pirelli Method)
D2440 Test Method for Oxidation Stability of Mineral Insulating Oil
D2668 Test Method for 2,6-*di-tert*-Butyl-*p*-Cresol and 2,6-*di-tert*-Butyl Phenol in Electrical Insulating Oil by Infrared Absorption
D2717 Test Method for Thermal Conductivity of Liquids
D2766 Test Method for Specific Heat of Liquids and Solids
D3300 Test Method for Dielectric Breakdown Voltage of Insulating Oils of Petroleum Origin Under Impulse Conditions
D4059 Test Method for Analysis of Polychlorinated Biphenyls in Insulating Liquids by Gas Chromatography

[1] This specification is under the jurisdiction of ASTM Committee D27 on Electrical Insulating Liquids and Gases and is the direct responsibility of Subcommittee D27.01 on Mineral.

Current edition approved Dec. 1, 2009. Published December 2009. Originally approved in 1976. Last previous edition approved in 2008 as D3487 – 08. DOI:10.1520/D3487-09.

[2] Refer to American National Standard C 57.106, Guide for Acceptance and Maintenance of Insulating Oil in Equipment (IEEE Standard 64). Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

TABLE 1 Property Requirements

Property	Limit: Type I	Limit: Type II	ASTM Test Method
Physical:			
Aniline point, °C, min	63[A]	63[A]	D611
Color, max	0.5	0.5	D1500
Flash point, min, °C	145	145	D92
Interfacial tension at 25°C, min, dynes/cm	40	40	D971
Pour point, max, °C	−40[B]	−40[B]	D97
Relative Density (Specific gravity), 15°C/15°C max	0.91	0.91	D1298
Viscosity, max, cSt (SUS) at:			
100°C	3.0 (36)	3.0 (36)	D445 or D88
40°C	12.0 (66)	12.0 (66)	
0°C	76.0 (350)	76.0 (350)	
Visual examination	clear and bright	clear and bright	D1524
Electrical:			
Dielectric breakdown voltage at 60 Hz:			
Disk electrodes, min, kV	30	30	D877
VDE electrodes, min, kV 0.040-in. (1.02-mm) gap	20[C]	20[C]	D1816
0.080-in. (2.03-mm) gap	35[C]	35[C]	
Dielectric breakdown voltage, impulse conditions			D3300
25°C, min, kV, needle negative to sphere grounded, 1-in. (25.4-mm) gap	145[D]	145[D]	
Gassing tendency, max, µL/min	+30	+30	D2300
Dissipation factor (or power factor), at 60 Hz max, %:			D924
25°C	0.05	0.05	
100°C	0.30	0.30	
Chemical[E]			
Oxidation stability (acid-sludge test)			D2440
72 h:			
% sludge, max, by mass	0.15	0.1	
Total acid number, max, mg KOH/g	0.5	0.3	
164 h:			
% sludge, max, by mass	0.3	0.2	
Total acid number, max, mg KOH/g	0.6	0.4	
Oxidation stability (rotating bomb test), min, minutes	—	195	D2112
Oxidation inhibitor content, max, % by mass	0.08[F]	0.3	D4768 or D2668[G]
Corrosive sulfur	noncorrosive	noncorrosive	D1275
Water, max, ppm	35	35	D1533
Neutralization number, total acid number, max, mg KOH/g	0.03	0.03	D974
PCB content, ppm	not detectable	not detectable	D4059

[A] The value shown represents current knowledge.

[B] It is common practice to specify a lower or higher pour point, depending upon climatic conditions.

[C] These limits by Test Method D1816 are applicable only to as received new oil (see Appendix X2.2.1.2). A new processed oil should have minimum breakdown strengths of 28 kV and 56 kV for a 0.04 in. (1.02 mm) or 0.08 in. (2.03 mm) gap respectively.

[D] Currently available oils vary in impulse strength. Some users prefer oil of a 145 kV minimum for certain applications, while others accept oil with impulse strength as low as 130 kV for other applications.

[E] Furanic compounds, as determined by Test Method D5837, are useful for assessing the level of cellulose degradation that has occurred in oil impregnated paper systems. Specifying maximum allowable furan levels in new oils for this purpose should be by agreement between user and supplier.

[F] Provisions to purchase totally uninhibited oil shall be negotiated between producer and user.

[G] Both 2,6-ditertiary-butyl para-cresol (DBPC/BHT) and 2,6-ditertiary butylphenol (DBP) have been found to be suitable oxidation inhibitors for use in oils meeting this specification.

Preliminary studies indicate both Test Methods D2668 and D4768 are suitable for determining concentration of either inhibitor or their mixture.

APPENDIX B VEGETABLE INSULATING OIL SPECIFICATION

Designation: D6871 – 03 (Reapproved 2008)

Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus[1]

This standard is issued under the fixed designation D6871; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification covers a high fire point natural vegetable oil ester insulating fluid for use as a dielectric and cooling medium in new and existing power and distribution electrical apparatus such as transformers and attendant equipment.

1.2 Natural vegetable oil ester insulating fluid differs from conventional mineral oil and other high fire point (or "less-flammable") fluids in that it is an agricultural product derived from vegetable oils rather than refined from petroleum base stocks or synthesized from organic precursors.

1.3 This specification is intended to define a natural vegetable oil ester electrical insulating fluid that is compatible with typical materials of construction of existing apparatus and will satisfactorily maintain its functional characteristic in this application. The material described in this specification may not be miscible with some synthetic electrical insulating liquids. The user should contact the manufacturer of the natural ester insulating fluid for guidance in this respect.

1.4 This specification applies only to new insulating fluid as received prior to any processing. The user should contact the manufacturer of the equipment or fluid if questions of recommended characteristics or maintenance procedures arise.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory requirements prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D88 Test Method for Saybolt Viscosity

D92 Test Method for Flash and Fire Points by Cleveland Open Cup Tester

D97 Test Method for Pour Point of Petroleum Products

D117 Guide for Sampling, Test Methods, and Specifications for Electrical Insulating Oils of Petroleum Origin

D445 Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)

D877 Test Method for Dielectric Breakdown Voltage of Insulating Liquids Using Disk Electrodes

D923 Practices for Sampling Electrical Insulating Liquids

D924 Test Method for Dissipation Factor (or Power Factor) and Relative Permittivity (Dielectric Constant) of Electrical Insulating Liquids

D974 Test Method for Acid and Base Number by Color-Indicator Titration

D1275 Test Method for Corrosive Sulfur in Electrical Insulating Oils

D1298 Test Method for Density, Relative Density, or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method

D1500 Test Method for ASTM Color of Petroleum Products (ASTM Color Scale)

D1524 Test Method for Visual Examination of Used Electrical Insulating Oils of Petroleum Origin in the Field

D1533 Test Method for Water in Insulating Liquids by Coulometric Karl Fischer Titration

D1816 Test Method for Dielectric Breakdown Voltage of Insulating Liquids Using VDE Electrodes

D1903 Practice for Determining the Coefficient of Thermal Expansion of Electrical Insulating Liquids of Petroleum Origin, and Askarels

D2300 Test Method for Gassing of Electrical Insulating Liquids Under Electrical Stress and Ionization (Modified Pirelli Method)

D2717 Test Method for Thermal Conductivity of Liquids

D2766 Test Method for Specific Heat of Liquids and Solids

D2864 Terminology Relating to Electrical Insulating Liquids and Gases

D3300 Test Method for Dielectric Breakdown Voltage of Insulating Oils of Petroleum Origin Under Impulse Conditions

[1] This specification is under the jurisdiction of ASTM Committee D27 on Electrical Insulating Liquids and Gases and is the direct responsibility of Subcommittee D27.02 on Gases and Non-Mineral Oil Liquids.

Current edition approved Oct. 1, 2008. Published December 2008. Originally approved in 2003. Last previous edition approved in 2003 as D6871-03. DOI: 10.1520/D6871-03R08.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

TABLE 1 As-Received New Fluid Property Requirements

Property	Limit	ASTM Test Method
Physical:		
Color, max	1.0	D1500
Fire point, min, °C	300	D92
Flash point, min, °C	275	D92
Pour point, max, °C	−10	D97
Relative density (specific gravity) 15°C/15°C, max	0.96	D1298
Viscosity, max, cSt at:		D445 or D88
100°C (212°F)	15	
40°C (104°F)	50	
0°C (32°F)	500	
Visual Examination	Bright and Clear	D1524
Electrical:		
Dielectric breakdown voltage at 60 Hz		
Disk electrodes, min, kV	30	D877
VDE electrodes, min, kV at:		D1816
1 mm (0.04 in.) gap	20	
2 mm (0.08 in.) gap	35	
Dielectric breakdown voltage, impulse conditions 25°C, min, kV, needle negative to sphere grounded, 1 in. (25.4 mm) gap	130	D3300
Dissipation factor (or power factor) at 60 Hz, max, %		D924
25°C	0.20	
100°C	4.0	
Gassing tendency, max, μl/min	0	D2300
Chemical:		
Corrosive sulfur	not corrosive	D1275
Neutralization number, total acid number, max, mg KOH/g	0.06	D974
PCB content, ppm	not detectable	D4059
Water, max, mg/kg	200	D1533[A]

[A] As stated in Test Methods D1533 Annex A1 "Alternative Solvent Systems," alternate reagents may be needed for certain natural ester formulations. Consult the manufacturer for recommendations. Reagents for aldehydes and ketones (such as Coulomat AK and CG-K) should be used if the additives are unknown. When alternate reagents are needed, using the Test Methods D1533 reagents may yield elevated and erratic water content results.

D4059 Test Method for Analysis of Polychlorinated Biphenyls in Insulating Liquids by Gas Chromatography

2.2 *National Fire Protection Association Standard:*

National Electrical Code Article 450-23[3]

3. Terminology

3.1 *Definitions*—Definitions of terms related to this specification are given in Terminology D2864. Vegetable oil natural ester: vegetable oil containing ester linkages, typically triglycerides. Most often obtained from seed crops (a "natural" source of esters, as opposed to synthesized esters).

4. Sampling and Testing

4.1 Take all fluid samples in accordance with Test Methods D923.

4.2 Perform each test in accordance with the ASTM test method specified in Table 1.

5. Property Requirements

5.1 Natural ester insulating fluid, as received, shall conform to the requirements of Table 1. The significance of these properties is covered in Guide D117 and Appendixes X2.1-X2.3.

6. Keywords

6.1 electrical insulating fluid; fire point; flammability; insulating fluid; natural ester

[3] *National Electrical Code*, NFPA 70, National Fire Protection Association Inc.

APPENDIX C CALIBRATION OF MEGGER OTS60PB

CALIBRATION CERTIFICATE

STANDARDS MALAYSIA
ACCREDITED LABORATORY
MS ISO/IEC 17025
CALIBRATION
SAMM NO. 285

DATE OF ISSUE : 16 April 2017 **CERTIFICATE NUMBER : IVAT2017/04/CAL029**

ISSUED BY : Institut Voltan dan Arus Tinggi
Universiti Teknologi Malaysia
81310 UTM Johor Bahru, Johor.
Tel: 07-5535615/93 Fax: 07-5578150

PAGE 1 OF 2 PAGES

Name of customer : **MAKMAL PENYELIDIKAN KEJURUTERAAN VOLTAN TINGGI**
Fakulti Kejuruteraan Elektrik,
Universiti Teknikal Malaysia Melaka
76100, Durian Tunggal, Melaka.

Details of the Calibrated Item :-

Instrument : 60 kV HVAC Oil Test Set **Model Number** : OTS-60-PB

Manufacture : MEGGER **Serial Number** : 611-204/090209/4067

Instrument Condition When Received : 1. Good Physical Condition

Instrument Condition When Returned : 1. Calibrated and tested serviceable as per customer request
2. No adjustment done

Date Received : 5 April 2017

Date Calibrated : 10 April 2017

Location of Calibration : IVAT Laboratory

Environmental Conditions :-

Dry Bulb Temperature : 30.0 °C **Barometer Pressure :** 1015 mbar

Measurement Uncertainty : See page 2

Calibration Method :

This instrument was calibrated according to In-House Procedures (LWI-UTM-IVAT (2) 2013)

Calibration Standard(s) used :

Instrument Type	Serial Number	Traceability	Due Date
HV Probe (Working AC-C)	E 0104	SAMM No. 285	22/07/2017
Digital Measuring Instrument 551	081624-05	SAMM No. 176	21/06/2017

Approved Signatory : Prof. Dr. Zulkurnain Abdul Malek

Signature of Approved Signatory :

The uncertainties are for a confidence probability of approximately 95% and have a coverage factor of k = 2 unless specified otherwise.

CALIBRATION CERTIFICATE

MS ISO/IEC 17025
CALIBRATION
SAMM NO. 285

DATE OF ISSUE : 16 April 2017

CERTIFICATE NUMBER : IVAT2017/04/CAL029

Instrument : 60 kV HVAC Oil Test Set

Serial Number : 611-204/090209/4067

RESULTS OF CALIBRATION

The result shown in this certificate is based on a comparative calibration method.

Set Voltage at Customer's Voltmeter (kV)	Voltage Indicated by Reference Meter (kV)	Absolute Correction (kV)	Uncertainty (%)
15.0	15.04	0.04	1.0
30.0	29.83	-0.17	0.90
45.0	44.44	-0.56	0.89
60.0	59.38	-0.62	0.88

The largest contributor to the uncertainty estimation of the 15 kV measurement is the standard uncertainty of reference divider as much as 0.45%.

Calibrated by:

Dr. Zuraimy Adzis
Calibration Manager

The uncertainties are for a confidence probability of approximately 95% and have a coverage factor of k = 2 unless specified otherwise.

APPENDIX D SPECIFICATIONS OF MEGGER OTS60PB

Specification

Output Voltage (max.)
60 kV r.m.s. (30 kV – 0–30 kV) at 61,8 Hz

Parameters of Standard Test Specifications

Test Specifications Parameters							
Test Spec.	Initial Stand Time	Rate of rise of Test Voltage	Intermediate Stir Time	Intermediate Stand Time	Number of Tests	Maximum Test Time	Results
5 min test	1 min.	2 kV/s	30 s	30 s	3	4 min. 30 s	Mean
BS 148 etc.	3 min	2 kV/s	1 min	1 min	6	18 min	Mean
ASTM	3 min.	2 kV/s	Continuous/None	2 min	6	18 min.	Mean
EN 60156	5 min	2 kV/s	Continuous/None	2 min	6	19 min	Mean
ASTM D877	3 min. 20 s	3 kV/s	-	1 min.	5	8 min.	Mean
ASTM D1816	3 min.	0.5 kV/s	Continuous	1 min.	5	17 min.	Mean
UNE21	10 min	2 kV/s	1 min.	4 min.	6	38 min.	Mean of last 5 tests
Withstand 'A'		2 kV/s	Ramps to preselected value for 1 minute or breakdown				
Withstand 'B'		2 kV/s	As above and continues to breakdown or maximum value of test set				
BS5730a	-	2 kV/s	1 min.	1 min.	Withstand test at 22 kV, 30 kV or 40 kV (depending on equipment category and electrode gap) for 1 min. If breakdown occurs another two tests are carried out, both must pass for sample to be accepted.		
BS5730a LEPLC	1 min stir + 1 min stand	2 kV/s	1 min.	1 min.	As per BS5730a but ramps to Breakdown after test is passed.		
BS148 etc. includes BS 5874, VDE 0370, NFC 27, CEI 344, GOST 6581, SABS 555, AS 1767, STAS 286 and IP 295. NFC 27, STAS 286 and UNE 21 omit the first breakdown value from the average calculation.							

Display	Dot-matrix liquid crystal display giving alpha-numeric information and kV test voltage to two digits.
Temperature Range	
Operation	0 °C to + 40 °C
Storage	–20 °C to +65 °C
Humidity Range	
Operating	90% RH at 40 °C (non-condensing)
Storage	93% RH at 40 °C, 95% RH at 25 °C cyclic (in accordance with BS 2011 Part 2–1)
Input Socket	Battery charger or 12 volt vehicle supply inlet socket.
Safety	The test set meets the requirements for safety to IEC 1010-1 (1995), EN61010 (1995). The safety interlock is to BS 5304 (1988) 'Guarding of Machinery' standard.
E.M.C.	In accordance with IEC 61326 including amendment No. 1
Power Supply	Internal rechargeable 12 V, 12 Ah, battery (typically 12 hours continuous testing). Charger supply 90 V to 264 V, 50/60 Hz. 12 volt, negative to chassis, vehicle lead set (does not recharge internal battery)
Fuses	2 x F6, 3 A, IEC 127/1, 20 mm x 5 mm, HBC fuses.
Dimensions	373 mm x 259 mm x 247 mm (14¾ in x 10⅛ in x 9¾ in) basic without accessories.
Weight	19 kg (42 lb) basic without accessories.
Cleaning	The exterior case can be wiped with a clean cloth dampened with an alcohol based cleaning fluid.

5

APPENDIX E MEASUREMENT UNCERTAINTY OF MINERAL OIL FOR IEC 60156

MU OIL BREAKDOWN VOLTAGE TEST FOR IEC 60156 OF MINERAL OIL

Measurement Info				From CC:	
Resolution=	1kV			Ucalb	0.0045
Accuracy=	3% of 60kV	Voltage Rise=	2kV±0.2%	K=	2
Bias=	NA			Vi(From Table)=	888888888
				Error=	1kV
Repeatibility Data				Ci:	1

Test Run	BDV	x1-mean	(xi-mean)^2	
1	28	2.40	5.76	
2	17	-8.60	73.96	
3	28	2.40	5.76	
4	28	2.40	5.76	
5	26	0.40	0.16	
6	18	-7.60	57.76	
7	24	-1.60	2.56	
8	24	-1.60	2.56	
9	22	-3.60	12.96	
10	28	2.40	5.76	
11	27	1.40	1.96	
12	22	-3.60	12.96	
13	26	0.40	0.16	
14	26	0.40	0.16	
15	27	1.40	1.96	
16	24	-1.60	2.56	
17	24	-1.60	2.56	
18	30	4.40	19.36	
19	26	0.40	0.16	
20	29	3.40	11.56	
21	25	-0.60	0.36	
22	30	4.40	19.36	
23	28	2.40	5.76	
24	24	-1.60	2.56	
25	26	0.40	0.16	
26	23	-2.60	6.76	
27	29	3.40	11.56	
28	27	1.40	1.96	
29	28	2.40	5.76	
30	24	-1.60	2.56	
	768			
Total	768		283.200	
Number of data,n	30			
Average,Mean(x)		25.60000		
Standard Deviation(s)		3.124983	3.072458299	3.124982759
Std Uncr,Ur,ESDM		0.570541	Z	
DoF,Vi		29		

Sources of Uncertainty	Evaluation Type A or B	Distribution Type	Semi Range a	Divisor	Standard Uncertainty	Sensitivity Coefficient	Degrees of Freedom i	Uncertainty Contribution			$(c_iu_i)^4\ \upsilon$
Repeatability	A	Student-T	NA	NA	4.753800657	1	29	4.7538007	22.59862069	510.6976571	17.61026
Calibration	B	Student-T	NA	NA	0.00225	1	888,888,888	0.0022500	5.0625E-06	2.56289E-11	2.88E-20
Resolution	B	Rectangular	0.5	1.732050808	0.288675135	1	999,999,999	0.2886751	0.083333333	0.006944444	6.94E-12
Accuracy (Drift)	B	Rectangular	NA	0	NA	1	NA	0.0000000	0	0	0
Method (Precision)	B	Rectangular	NA	NA	NA	1	NA				
Voltage Rise	B	Rectangular	0.4	1.732050808	0.230940108	1	999,999,999	0.2309401	0.053333333	0.002844444	2.84E-12
								SUM	22.73529242	510.707446	17.61026

Combined Standard Uncertainty	$u_c = \sqrt{\sum (c_i u_i)^2}$	4.768153984	
Effective Degrees of Freedom	$v_{eff} = \dfrac{(u_c)^4}{\dfrac{(c_1u_1)^4}{v_1} + \dfrac{(c_2u_2)^4}{v_2} + \dfrac{(c_3u_3)^4}{v_3} + \ldots \dfrac{(c_nu_n)^4}{v_n}}$	29.35183256	
Coverage Factor from Student-t Table	k_{95}	2.04	
Expanded Uncertainty	$U = ku_c$	Value: 9.727034128	Percentage: 37.99622706

Reporting The Result
Breakdown Voltage=(25.6±9.7)kV, k=2.04 at CL=95%
Breakdown Voltage (%) =(25.6±37.996227%)kV k=2.04 at CL=95%

Max	30	
Min	17	
Upper Bound	35.32703	
Lower Bound	15.87297	

M/S 73 k=T95(30)=2.04

K	V
2.06	25
2.04259268	29.35183
2.04	30

APPENDIX F MEASUREMENT UNCERTAINTY OF MINERAL OIL FOR ASTM D1816

MU OIL BREAKDOWN VOLTAGE TEST FOR ASTM D1816 OF MINERAL OIL

Measurement Info				From CC:	
Resolution=	1kV	Coefficient of Variant(ML)	17%	Ucalb	0.0045
Accuracy=	3% of 60kV	Voltage Rise=	0.5kV±0.05%	K=	2
Bias=	NA			Vi(From Table)=	888888888
				Error=	1kV
Repeatability Data				Ci:	1

Test Run	BDV	x1-mean	(xi-mean)^2
1	42	10.3200	106.5024
2	42	10.3200	106.5024
3	36	4.3200	18.6624
4	34	2.3200	5.3824
5	30	-1.6800	2.8224
6	35	3.3200	11.0224
7	38	6.3200	39.9424
8	24	-7.6800	58.9824
9	30	-1.6800	2.8224
10	32	0.3200	0.1024
11	29	-2.6800	7.1824
12	36	4.3200	18.6624
13	36	4.3200	18.6624
14	26	-5.6800	32.2624
15	28	-3.6800	13.5424
16	30	-1.6800	2.8224
17	29	-2.6800	7.1824
18	29	-2.6800	7.1824
19	22	-9.6800	93.7024
20	30	-1.6800	2.8224
21	34	2.3200	5.3824
22	29	-2.6800	7.1824
23	33	1.3200	1.7424
24	29	-2.6800	7.1824
25	29	-2.6800	7.1824

	792		
Total	792		585.440
Number of data	25		
Average,Mean(x)		31.6800	
Standard Deviation(s)		4.9390	
Std Uncr,Ur,ESDM		0.9878	
DoF,Vi		24	

Sources of Uncertainty	Evaluation Type A or B	Distribution Type	Semi Range a	Divisor	Standard Uncertainty u_i	Sensitivity Coefficient c_i	Degrees of Freedom υ_i	Uncertainty Contribution $c_i u_i$	$(c_i u_i)^2$	$(c_i u_i)^4$	$(c_i u_i)^4\ \upsilon$
Repeatability	A	Student-T	NA	NA	6.46665292	1	24	6.4666529	41.8176	1748.71167	72.86298624
Calibration	B	Student-T	NA	NA	0.00225	1	888,888,888	0.0022500	5.0625E-06	2.56289E-11	2.88325E-20
Resolution	B	Rectangular	0.5	1.732050808	0.28867513	1	999,999,999	0.2886751	0.083333333	0.006944444	6.94444E-12
Accuracy (Drift)	B	Rectangular	NA	0	NA	1	NA	0.0000000	0	0	0
Method (Precisi	B	Rectangular	NA	NA	NA	1	NA				
Voltage Rise	B	Rectangular	0.0025	1.732050808	0.00144338	1	999,999,999	0.0014434	2.08333E-06	4.34028E-12	4.34028E-21
								SUM	41.90094048	1748.718614	72.86298624

Combined Standard Uncertainty	$u_c = \sqrt{\sum (c_i u_i)^2}$	6.47309358	
Effective Degrees of Freedom	$v_{eff} = \dfrac{(u_c)^4}{\dfrac{(c_1u_1)^4}{v_1} + \dfrac{(c_2u_2)^4}{v_2} + \dfrac{(c_3u_3)^4}{v_3} + \ldots \dfrac{(c_nu_n)^4}{v_n}}$	24.095757	
Coverage Factor from Student-t Table	k_{95}	2.06	
Expanded Uncertainty	$U = ku_c$	Value 13.3345728	Percentage 42.09145446

M/S 73 k=T95(25)=2.06

Max	42
Min	22
Upper Bound	45.01457
Lower Bound	18.34543

Reporting The Result
Breakdown Voltage=(31.68±13.3345728)kV, k=2.06 at CL=95%
Breakdown Voltage=(31.68±42.09145446%)kV, k=2.06 at CL=95%

APPENDIX G MEASUREMENT UNCERTAINTY OF MINERAL OIL FOR ASTM D877

MU OIL BREAKDOWN VOLTAGE TEST FOR ASTM D877 OF MINERAL OIL

Measurement Info				From CC:	
Resolution=	1kV	Coefficient of Variant(ML)	17%	Ucalb	0.0045
Accuracy=	3% of 60kV	Voltage Rise=	3kV±0.05%	K=	2
Bias=	NA			Vi(From Table)=	888888888
				Error=	1kV
Repeatibility Data				Ci:	1

Test Run	BDV	x1-mean	(xi-mean)^2
1	35	5.6400	31.8096
2	29	-0.3600	0.1296
3	28	-1.3600	1.8496
4	23	-6.3600	40.4496
5	25	-4.3600	19.0096
6	29	-0.3600	0.1296
7	29	-0.3600	0.1296
8	30	0.6400	0.4096
9	32	2.6400	6.9696
10	33	3.6400	13.2496
11	38	8.6400	74.6496
12	33	3.6400	13.2496
13	34	4.6400	21.5296
14	32	2.6400	6.9696
15	26	-3.3600	11.2896
16	22	-7.3600	54.1696
17	29	-0.3600	0.1296
18	22	-7.3600	54.1696
19	27	-2.3600	5.5696
20	30	0.6400	0.4096
21	30	0.6400	0.4096
22	31	1.6400	2.6896
23	30	0.6400	0.4096
24	29	-0.3600	0.1296
25	28	-1.3600	1.8496

	734		
Total	734		361.760
Number of data,n	25		
Average,Mean(x)		29.3600	
Standard Deviation(s)		3.8824	
Std Uncr,Ur,ESDM		0.7765	
DoF,Vi		24	

Sources of Uncertainty x_i	Evaluation Type A or B	Distribution Type	Semi Range a	Divisor	Standard Uncertainty u_i	Sensitivity Coefficient c_i	Degrees of Freedom υ_i	Uncertainty Contribution c_iu_i	$(c_iu_i)^2$	$(c_iu_i)^4$	$(c_iu_i)^4/\upsilon$
Repeatability	A	Student-T	NA	NA	5.993084904	1	24	5.9930849	35.91706667	1290.035678	53.75149
Calibration	B	Student-T	NA	NA	0.00225	1	888,888,888	0.0022500	5.0625E-06	2.56289E-11	2.88E-20
Resolution	B	Rectangular	0.5	1.732050808	0.288675135	1	999,999,999	0.2886751	0.083333333	0.006944444	6.94E-12
Accuracy (Drift)	B	Rectangular	NA	0	NA	1	NA	0.0000000	0	0	0
Method (Precision)	B	Rectangular	NA	NA	NA	1	NA				
Voltage Rise	B	Rectangular	0.15	1.732050808	0.08660254	1	999,999,999	0.0866025	0.0075	5.625E-05	5.63E-14
								SUM	36.00790506	1290.042679	53.75149

Combined Standard Uncertainty	$u_c = \sqrt{\sum (c_i u_i)^2}$	6.000658719	
Effective Degrees of Freedom	$v_{eff} = \dfrac{(u_c)^4}{\dfrac{(c_1u_1)^4}{v_1} + \dfrac{(c_2u_2)^4}{v_2} + \dfrac{(c_3u_3)^4}{v_3} + \dots \dfrac{(c_nu_n)^4}{v_n}}$	24.12155104	
Coverage Factor from Student-t Table	k_{95}	2.06	
Expanded Uncertainty	$U = ku_c$	Value 12.36135696	Percentage 42.10271445

M/S 73 k=T95(25)=2.06

Max	38	
Min	22	
Upper Bound	41.72136	
Lower Bound	16.99864	

Reporting The Result

Breakdown Voltage=(29.36±12.361357kV, k=2.06 at CL=95%

Breakdown Voltage=(29.36±42.10271%)kV, k=2.06 at CL=95%

APPENDIX H MEASUREMENT UNCERTAINTY OF VEGETABLE OIL FOR IEC 60156

MU OIL BREAKDOWN VOLTAGE TEST FOR IEC 60156 OF VEGETABLE OIL

Measurement Info				From CC:	
Resolution=	1kV	Coefficient of Variant(ML)	17%	Ucalb	0.0045
Accuracy=	3% of 60kV	Voltage Rise=	2kV±0.2%	K=	2
Bias=	NA			Vi(From Table)=	888888888
				Error=	1kV
Repeatibility Data				Ci:	1

Test Run	BDV	x1-mean	(xi-mean)^2
1	40	-5.4667	29.8844
2	36	-9.4667	89.6178
3	31	-14.4667	209.2844
4	38	-7.4667	55.7511
5	46	0.5333	0.2844
6	40	-5.4667	29.8844
7	42	-3.4667	12.0178
8	41	-4.4667	19.9511
9	57	11.5333	133.0178
10	53	7.5333	56.7511
11	45	-0.4667	0.2178
12	40	-5.4667	29.8844
13	52	6.5333	42.6844
14	42	-3.4667	12.0178
15	50	4.5333	20.5511
16	39	-6.4667	41.8178
17	46	0.5333	0.2844
18	47	1.5333	2.3511
19	37	-8.4667	71.6844
20	36	-9.4667	89.6178
21	45	-0.4667	0.2178
22	45	-0.4667	0.2178
23	59	13.5333	183.1511
24	44	-1.4667	2.1511
25	49	3.5333	12.4844
26	52	6.5333	42.6844
27	53	7.5333	56.7511
28	58	12.5333	157.0844
29	55	9.5333	90.8844
30	46	0.5333	0.2844
	1364		
Total	1364		1493.467
Number of data,n	30		
Average,Mean(x)		45.4667	
Standard Deviation(s)		7.1763	
Std Uncr,Ur,ESDM		1.4353	
DoF,Vi		29	

Sources of Uncertainty x_i	Evaluation Type A or B	Distribution Type	Semi Range a	Divisor	Standard Uncertainty u_i	Sensitivity Coefficient c_i	Degrees of Freedom υ_i	Uncertainty Contribution $c_i u_i$	$(c_i u_i)^2$	$(c_i u_i)^4$	$(c_i u_i)^4/\upsilon$
Repeatability	A	Student-T	NA	NA	8.442948042	1	29	8.4429480	71.283372	5081.319073	175.2179
Calibration	B	Student-T	NA	NA	0.00225	1	888,888,888	0.0022500	5.063E-06	2.56289E-11	2.88E-20
Resolution	B	Rectangular	0.5	1.732051	0.288675135	1	999,999,999	0.2886751	0.0833333	0.006944444	6.94E-12
Accuracy (Drift)	B	Rectangular	NA	0	NA	1	NA	0.0000000	0	0	0
Method (Precision)	B	Rectangular	NA	NA	NA	1	NA				
Voltage Rise	B	Rectangular	0.4	1.732051	0.230940108	1	999,999,999	0.2309401	0.0533333	0.002844444	2.84E-12
								SUM	71.420043	5081.328862	175.2179

Combined Standard Uncertainty	$u_c = \sqrt{\sum (c_i u_i)^2}$	8.451038006	
Effective Degrees of Freedom	$\nu_{eff} = \dfrac{(u_c)^4}{\dfrac{(c_1u_1)^4}{\nu_1} + \dfrac{(c_2u_2)^4}{\nu_2} + \dfrac{(c_3u_3)^4}{\nu_3} + \ldots \dfrac{(c_nu_n)^4}{\nu_n}}$	29.1113101	
Coverage Factor from Student-t Table	k_{95}	2.04	
Expanded Uncertainty	$U = ku_c$	Value: 17.24011753	Percentage: 37.91814706

Reporting The Result
Breakdown Voltage=(45.47±17.24012)kV, k=2.04 at CL=95%
Breakdown Voltage=(45.47±37.9181471%)kV, k=2.04 at CL=95%

M/S 73 k=T95(30)=2.04

Max	59
Min	31
Upper Bound	62.70678
Lower Bound	28.22655

K	V
2.06	25
2.0435548	29.1113101
2.04	30

APPENDIX I MEASUREMENT UNCERTAINTY OF VEGETABLE OIL FOR ASTM D1816

MU OIL BREAKDOWN VOLTAGE TEST FOR ASTM D1816 OF VEGETABLE OIL

Measurement Info				From CC:	
Resolution=	1kV	Coefficient of Variant(ML)	17%	Ucalb	0.0045
Accuracy=	3% of 60kV	Voltage Rise=	0.5kV±0.05%	K=	2
Bias=	NA			Vi(From Table)=	888888888
				Error=	1kV
Repeatibility Data				Ci:	1

Test Run	BDV	x1-mean	(xi-mean)^2
1	33	1.8000	3.2400
2	32	0.8000	0.6400
3	31	-0.2000	0.0400
4	22	-9.2000	84.6400
5	28	-3.2000	10.2400
6	28	-3.2000	10.2400
7	22	-9.2000	84.6400
8	29	-2.2000	4.8400
9	31	-0.2000	0.0400
10	36	4.8000	23.0400
11	36	4.8000	23.0400
12	30	-1.2000	1.4400
13	37	5.8000	33.6400
14	29	-2.2000	4.8400
15	33	1.8000	3.2400
16	33	1.8000	3.2400
17	33	1.8000	3.2400
18	35	3.8000	14.4400
19	29	-2.2000	4.8400
20	36	4.8000	23.0400
21	25	-6.2000	38.4400
22	34	2.8000	7.8400
23	26	-5.2000	27.0400
24	31	-0.2000	0.0400
25	41	9.8000	96.0400

	780		
Total	780		506.000
Number of data,n	25		
Average,Mean(x)		31.2000	
Standard Deviation(s)		4.5917	
Std Uncr,Ur,ESDM		0.9183	
DoF,Vi		24	

Sources of Uncertainty x_i	Evaluation Type A or B	Distribution Type	Semi Range a	Divisor	Standard Uncertainty u_i	Sensitivity Coefficient c_i	Degrees of Freedom υ_i	Uncertainty Contribution $c_i u_i$	$(c_i u_i)^2$	$(c_i u_i)^4$	$(c_i u_i)^4/\upsilon$
Repeatability	A	Student-T	NA	NA	6.368673331	1	24	6.3686733	40.56	1645.1136	68.5464
Calibration	B	Student-T	NA	NA	0.00225	1	888,888,888	0.0022500	5.0625E-06	2.56289E-11	2.88325E-20
Resolution	B	Rectangular	0.5	1.7320508	0.288675135	1	999,999,999	0.2886751	0.083333333	0.006944444	6.94444E-12
Accuracy (Drift)	B	Rectangular	NA	0	NA	1	NA	0.0000000	0	0	0
Method (Precision)	B	Rectangular	NA	NA	NA	1	NA				
Voltage Rise	B	Rectangular	0.025	1.7320508	0.014433757	1	999,999,999	0.0144338	0.000208333	4.34028E-08	4.34028E-17
								SUM	40.64354673	1645.120544	68.5464

Combined Standard Uncertainty	$u_c = \sqrt{\sum (c_i u_i)^2}$	6.375229151	
Effective Degrees of Freedom	$\nu_{eff} = \dfrac{(u_c)^4}{\dfrac{(c_1u_1)^4}{\nu_1} + \dfrac{(c_2u_2)^4}{\nu_2} + \dfrac{(c_3u_3)^4}{\nu_3} + \ldots \dfrac{(c_nu_n)^4}{\nu_n}}$	24.0989737	
Coverage Factor from Student-t Table	k_{95}	2.06	
Expanded Uncertainty	$U = ku_c$	Value 13.13297205	Percentage 42.09285914

M/S 73 k=T95(25)=2.06

Max	41	
Min	22	
Upper Bound	44.33297	
Lower Bound	18.06703	

Reporting The Result

Breakdown Voltage=(31.20±13.13297)kV, k=2.06 at CL=95%

Breakdown Voltage=(31.20±42.09285%)kV, k=2.06 at CL=95%

APPENDIX J MEASUREMENT UNCERTAINTY OF VEGETABLE OIL FOR ASTM D877

MU OIL BREAKDOWN VOLTAGE TEST FOR ASTM D877 OF VEGETABLE OIL

Measurement Info				From CC:	
Resolution=	1kV			Ucalb	0.0045
Accuracy=	3% of 60kV	Voltage Rise=	3kV±0.05%	K=	2
Bias=	NA			Vi(From Table)=	888888888
				Error=	1kV
Repeatability Data				Ci:	1

Test Run	BDV	x1-mean	(xi-mean)^2
1	47	7.5600	57.1536
2	53	13.5600	183.8736
3	47	7.5600	57.1536
4	43	3.5600	12.6736
5	51	11.5600	133.6336
6	50	10.5600	111.5136
7	49	9.5600	91.3936
8	39	-0.4400	0.1936
9	25	-14.4400	208.5136
10	41	1.5600	2.4336
11	43	3.5600	12.6736
12	49	9.5600	91.3936
13	40	0.5600	0.3136
14	29	-10.4400	108.9936
15	27	-12.4400	154.7536
16	34	-5.4400	29.5936
17	35	-4.4400	19.7136
18	39	-0.4400	0.1936
19	34	-5.4400	29.5936
20	41	1.5600	2.4336
21	38	-1.4400	2.0736
22	30	-9.4400	89.1136
23	29	-10.4400	108.9936
24	36	-3.4400	11.8336
25	37	-2.4400	5.9536
	986		
Total	986		1526.160
Number of data,n	25		
Average,Mean(x)		39.4400	
Standard Deviation(s)		7.9743	
Std Uncr,Ur,ESDM		1.5949	
DoF,Vi		24	

Sources of Uncertainty x_i	Evaluation Type A or B	Distribution Type	Semi Range a	Divisor	Standard Uncertainty u_i	Sensitivity Coefficient c_i	Degrees of Freedom υ_i	Uncertainty Contribution $c_i u_i$	$(c_i u_i)^2$	$(c_i u_i)^4$	$(c_i u_i)^4/\upsilon$
Repeatability	A	Student-T	NA	NA	8.050656288	1	24	8.0506563	64.81306667	4200.733611	175.0306
Calibration	B	Student-T	NA	NA	0.00225	1	888,888,888	0.0022500	5.0625E-06	2.56289E-11	2.88E-20
Resolution	B	Rectangular	0.5	1.7320508	0.288675135	1	999,999,999	0.2886751	0.083333333	0.006944444	6.94E-12
Accuracy (Drift)	B	Rectangular	NA	0	NA	1	NA	0.0000000	0	0	0
Method (Precision)	B	Rectangular	NA	NA	NA	1	NA				
Voltage Rise	B	Rectangular	0.15	1.7320508	0.08660254	1	999,999,999	0.0866025	0.0075	5.625E-05	5.63E-14
								SUM	64.90390506	4200.740611	175.0306

Combined Standard Uncertainty	$u_c = \sqrt{\sum (c_i u_i)^2}$	8.056295989	
Effective Degrees of Freedom	$\nu_{eff} = \dfrac{(u_c)^4}{\dfrac{(c_1 u_1)^4}{\nu_1} + \dfrac{(c_2 u_2)^4}{\nu_2} + \dfrac{(c_3 u_3)^4}{\nu_3} + \dots \dfrac{(c_n u_n)^4}{\nu_n}}$	24.06732128	
Coverage Factor from Student-t Table	k_{95}	2.06	
		Value	Percentage
Expanded Uncertainty	$U = k u_c$	16.59596974	42.07903077

M/S 73 k=T95(25)=2.06

Max	53	
Min	25	
Upper Bound	56.03597	
Lower Bound	22.84403	

Reporting The Result

Breakdown Voltage=(39.4±16.596)kV, k=2.06 at CL=95%

Breakdown Voltage=(39.4±42.079%)kV, k=2.06 at CL=95%

APPENDIX K GANTT CHART

No	Topics	Month													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Discussion with supervisor for improvement from FYP 1														
2	Literature Review														
3	Preparation on oil sampling for mineral oil														
4	Preparation on oil sampling for vegetable oil														
6	Run experiment for breakdown voltage														
7	Writing report														
8	Draft of progress report FYP 2														
9	Preparation of slide for FYP seminar														
10	Seminar FYP 2 evaluation														
11	Final check for FYP report														
12	Submit Final Report and CD														