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# PROPERTIES OF TRANSFORMER OIL THAT AFFECT EFFICIENCY.

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DERICK NJOMBOG TANTEH.

SHAFIQ YOUSEF AL-LIDDAWI.

DANIEL SSEKASIKO.

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*School of Engineering,  
Department of Electrical Engineering,  
Blekinge Institute of Technology, S-371 79 Karlskrona  
Phone: +46 - 455 - 38 50 00  
Fax: +46 - 455 - 38 50 57*

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## **Contact:**

**Derick Njombog Tante:**

**Email:** derickntante@gmail.com

**Shafiq Yousef Al Liddawi:**

**Email:** shafiq.liddawi@gmail.com

**Daniel Ssekasiko:**

**Email:** danielug@msn.com

## **Supervisor:**

**Dr. Mattias Eriksson.**

Senior Lecturer,

School of Engineering,

Blekinge Institute of Technology,

**Email:** mattias.eriksson@bth.se

## ***To our Parents:***

*Dominic and Beatrice Tante,  
Yousef and Tamam Al Liddawi,  
Livingstone and Ruth Kiwanuka.*

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# Abstract.

Transformer explosions caused by dielectric failure account for over 50% of the disasters. The aim of this thesis is to examine, compare and outline the differences, in function, as dielectric insulators, vegetable oil has, with respect to the mineral oil used in high-power transformers. We will first consider the vegetable oil which has less dielectric capabilities than the mineral oil used in power transformers. Later in the experiments, we will focus mainly to examine the breakdown voltage property, as we try to alter some properties of the respective oils used.

Considering the fact that vegetable oil has low viscosity, with its chemical compounds constituting less molecular masses compared to mineral oil, we endorse, from our experimental findings, that mineral oil is indeed worthy and reasonable to be used as a dielectric in high power transformers.

In this write-up, we have considered eleven transformer oil properties. In the experiment proper, we considered only the acidity, whose concentration in the transformer oil increases with aging if the transformer, moisture, and a 'suitable' impurity like  $\text{NaOH}_{(aq)}$ . At first glance, one would be tempted to think, as we were, that since the increase in acid content of the oil deteriorates its dielectric performance, an increase in alkaline content of the transformer oil, would increase its dielectric ability; reversing the acid effect. But as we see in the results from our experiments, this is false. We think that the visible degradation of the insulating property of the oil, with the introduction of  $\text{NaOH}_{(aq)}$ , is because it acts as an impurity to suitable dielectric function.

From the experiments, the heating procedures resulted in the production of toxic gases. This indicated the actual loss of chemical structure and significant breakage of chemical bonds. The resulting chemical composition of the oil does not produce the same dielectric properties as the initial oil sample.

Also, here has been considerable inconsistency in the addition of  $\text{NaOH}_{(aq)}$  or  $\text{HCl}_{(aq)}$  to both oils. We only added  $\text{HCl}_{(aq)}$ , before every measurement, in two of the experiments. The other experiments were either with moisture, or a single addition of small amounts of either  $\text{HCl}_{(aq)}$  or  $\text{NaOH}_{(aq)}$  before heating; after which several measurements were taken, at specific intervals, as the mixture cools. We did so, in the latter, in which we had only one addition of either chemical; because in real life, given the short time frame of the experiment, the total amount of acid in the oil has a negligible change. So, in a functioning heated transformer, within a short time frame, there is actually a visible tiny deterioration in oil insulation properties.

## Chapter 1: Introduction.

### 1.1 Problem statement.

Electrical faults that occur in power transformers account for over fifty percent of transformer failures' expenditures in the United States, within a five-year period<sup>[1]</sup>. The numbers are probably more in the developing world due to low technical abilities to maintain and recycle the oil.

Fig 1.1.1. Number of transformer failures, causes of failure, and expenditure.

Cause of Failure	Number	Total Paid
Insulation Failure	24	\$149,967,277
Design /Material/Workmanship	22	\$64,696,051
Unknown	15	\$29,776,245
Oil Contamination	4	\$11,836,367
Overloading	5	\$8,568,768
Fire /Explosion	3	\$8,045,771
Line Surge	4	\$4,959,691
Improper Maintenance/Operation	5	\$3,518,783
Flood	2	\$2,240,198
Loose Connection	6	\$2,186,725
Lightning	3	\$657,935
Moisture	1	\$175,000
Total	94	\$286,628,811

Fig 1.1.1. Number of transformer failures, causes of failure, and expenditure.

From Fig 1.1.1, we see that fifty percent of transformer failures' expenditures are caused by insulation, dielectric, and oil-related faults. The need for better dielectrics and transformer oils for insulation is unequivocal.

### 1.2 Scope.

There are several properties of transformer oils. We have considered the eleven most common ones. A good number of these properties are experimented upon by using the breakdown voltage to determine the value of the parameter in the considered property. Acidity, moisture

content, as well as general impurity content are some of the properties that increase with age of the oil, while viscosity, flash point, specific resistance, transformer insulation, interfacial tension decrease with age. The respective increase or decrease are detrimental to the transformer functioning. In the experiments, the only parameter for measurement we used was breakdown voltage (BDV); after altering acid content, impurity content, and moisture content, which are all processing in the artificial aging process.

### 1.3 Outline.

Chapter one introduces the main cause for concern for transformer failures specifically in the United States – dielectric breakdown. The main cause is a surge in voltage, followed by a large currents flow through a dielectric gap.

The Second chapter explains standard findings on phenomena and processes related to the study of transformer oil properties. These include the chemical and causes of the specific physical properties of the test oils.

In chapter three and four, an extended discussion on the transformer oil properties is made, taking into consideration the eleven most important ones. A further examination of the physical phenomena of partial discharge and corona, arcing, and pyrolysis is done in chapter four. For the case of pyrolysis, the respective gases from the decomposition, by overheating the oil, are reexamined.

The experimental setup, results, and discussion is done in chapters five and six respectively. Here, applying a high voltage across the electrodes, in a treated oil sample is our main tool to examine the properties tested. The properties include acidity ( $\text{HCl}_{(aq)}$ ), moisture (water) and an impurity ( $\text{NaOH}_{(aq)}$ ).

The last chapter contains the conclusion and recommendations from some world leading companies in this area like ABB in Sweden.

## Chapter 2: Background.

In a power transformer, the light emitted by a spark occurs because of the material medium fluoresces as a result of collisions from the electrons. As collisions occur between electrons and molecules in the gap, electron on the atom shells are excited to higher energy levels. When the electrons no longer get more excitation, they fall back to the previous energy level, releasing the extra energy in the form of heat, light and sometimes sound.<sup>[2]</sup> This is called the photoelectric effect. The sparks cannot form in a vacuum because there would be no air particles for collision. Without interrupting electromagnetic transitions, one can see the spark. However, in oil, it is possible for the sparks to occur but not as readily as in air. It is also worth mentioning that Oil helps extinguish arcs. Most power transformers that use oil have three dielectric materials; oil, paper (on the walls and windings), and/or paint on the windings. These “three lines of defense” is to make sure that sparks, arcs or partial discharge of any kind should not occur in the transformer.

### 2.1 Corona.

There are some vital developmental steps for a positive corona discharge to occur.<sup>[3]</sup>

First: a positive and negative electrode characteristic configuration must be met.

Second: A high voltage should be supplied.

Third: Around the gap between the electrodes, free electrons should be afloat.

Fourth: Accumulation of electrons should build up in the gap, ready to cause an avalanche breakdown.

Fifth: the up and down change of electrons from higher energy to lower energy levels produce photons; as energy is gained and lost, which in turn energize new charge carriers around the gap

Sixth: The initial avalanche breakdown causes a cascade effect to charges closer to the cathode (negative electrode).

### 2.2 Pyrolysis (Overheating)

Pyrolysis begins when the oil heats to about 200°C. At this temperature, only hydrogen is most likely to be the gaseous product of the mild decomposition. As temperature is steadily increased to about 700°C, there is almost a total decomposition of the oil, giving a mixture of methane, ethane, ethylene, acetylene, and hydrogen gas as products of severe decomposition.<sup>[4]</sup> analytically, we conclude that heating increases oil decomposition.



## 2.3 Arcing.

An arc is a luminous current discharge formed when a large current forces a dielectric gap to conduct the large current between two electrodes. <sup>[5]</sup>

The main difference between arcing and corona is that; in corona, the accumulation of charges is sustained, resulting in a breakdown. In arcing, a surge in current causes an immediate breakdown of the dielectric, releasing huge energy. Consequently, arcs are more dangerous, release more energy, and more difficult to handle.

Arcs occur usually during voltage testing, shut down and start-up of a system, accidental contact with energized components, miscalculations of rating parameters, rusting, decay and degradation of the equipment that can cause potentially harmful short-circuit paths.

Technology has however made arcs useful in welding. This came as a result of the design of Arc-welding transformers. <sup>[6]</sup>

## 2.4 Transformers.

We will begin with a simple transformer like the one pictured below <sup>[7a]</sup>.

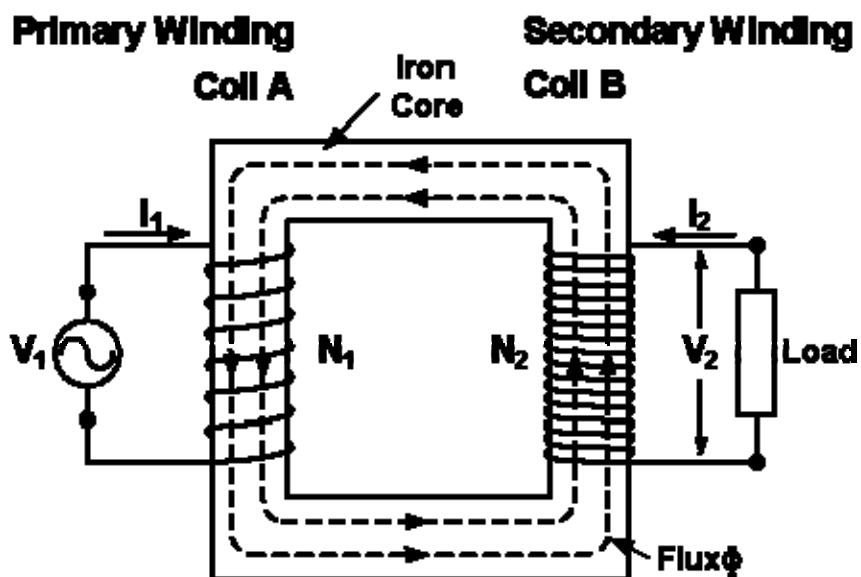


Fig 1.1.1. A simple step-up transformer.

Transformers were developed from the knowledge of the law of electromagnetic induction. Transformers can be either step-up transformer; where the number of primary turns is less than the number of secondary turns, see Fig 1.1.1, or step-down transformer; where the number of secondary turns is less than the number of primary turns.

A severe partial discharge (PD) between any number-of-turns in any part of the transformer, results in the affected number of turns to behave as one - reducing the total number of turns. Evidently, from the formula below, the number-of-turns affects voltage either way, hence, efficiency.

$$N_2/N_1 = V_1/V_2 = I_2/I_1 \dots \dots \dots (1)$$

Where power = P, current=I, voltage=V, Number of turns=N.

In an ideal transformer the power input value is same as the power output value.

$$\text{Power} = P = V_1 \times I_1 = V_2 \times I_2 \dots \dots \dots (2).$$

In a real world, equation (2) becomes invalid since there are usually losses in a functioning transformer.<sup>[7b]</sup>

Efficiency= Power output/Input power.

$$\text{Efficiency} = 1 - \frac{\text{Losses}}{\text{input power}} .$$

Where losses = copper losses + iron losses.

The transformer windings must, therefore, be insulated. The operation of the transformer produces heat. These are the main focus of this thesis: heat and insulation.

Transformer oils perform at least four basic functions in an oil-immersed transformer. Oil provides insulation, cooling (heat distribution), and helps extinguish arcs (voltaic discharge). Oil also dissolves gases generated by oil degradation, deterioration, and gases and moisture from whatever atmosphere the oil is exposed to. Close observation of dissolved gases in the oil, and other oil properties, provides the most valuable information about transformer health. Dissolved Gas Analysis (DGA) is the most important transformer diagnostic tool.

The mineral oil, with the main roles of insulating and cooling in power transformers, is similar to the blood in human body. Considering the worldwide need for high efficiency of power transformers and the rising price of the oil, we have to control and monitor the transformer oil characteristics consistently. There are several characteristics which can be measured to assess the present condition of the oil. Using a combination of these diagnostic tests allows the oil to be examined for its behavior with respect to various characteristics as age increases, whether the changes are due to thermal, dielectric or chemical effects. The benefit of examining how quickly the oil is aging is that it permits the oil to be used as long as possible. If this is done properly, a replacement or purification can be done before it can cause damage to the container or other materials inside the transformer, or to the environment. We do not want the transformers to undergo leakages, explosions, sparks, fires or any kind of destruction to itself or the environment. The transformer mineral oil is one of the most expensive extracts produced by its refinement of crude oil. Refining is the collective term for the processes involved in changing

the crude oil into oil with the required properties for a particular application. Only about three percent of the crude oil is appropriate for production of transformer oil. Because of the importance of the power transformers in electrical networks, permanently taking care of the oil quality is vital.

Insulating oil in a transformer during operation is subjected to heat, oxygen and electrical discharge, which may lead to its degradation especially through the process of oxidation.<sup>[8]</sup> This severely causes the oil to carry out its primary functions of insulation and heat transfer as aging products reduce electrical properties and cooling efficiency. Oxidation products, such as acids and consequently the formation of sludge, are also vital in aging acceleration. Therefore, monitoring and maintaining oil quality is essential in ensuring the reliable operation of oil-filled electrical equipment. Even in ideal conditions, oil ages and degrades over time, as its useful service life is finite.

The rate of aging is normally a function of temperature and moisture, as we will discuss later in Dissolved gas Analysis (PDA). Oil will age rapidly at high temperatures and moisture acts as a catalyst for its aging. Therefore, oil aging in oil-filled transformers is inevitable. There are some catalysts present in a transformer that could account for oil degradation. These include copper, paint, varnish and oxygen<sup>[9]</sup>. The main process of oil deterioration is oxidation, which causes some polar compounds to be formed. These oxidation products will have a deleterious effect on the end result, giving rise to the variation we seek to get our conclusion. The principal oil properties are classified into the physical, chemical and electrical characteristics. Some of the more important properties of the oil are viscosity, specific gravity, flash point, oxidation stability, total acid number, dissipation factor, volume resistivity, breakdown voltage, and dielectric constant.

## 2.5 Transformer oils.

Generally transformer Oil exists in two types<sup>[10]</sup>:

- Paraffin based Transformer Oil
- Naphtha based Transformer Oil

On comparison of both transformer oils, paraffin oil is less oxidized than Naphtha oil, though oxidation product for instance sludge in the naphtha oil is extremely soluble compared to paraffin oil. Hence the sludge content in naphtha based oil is never precipitated at the transformer bottom. Therefore it allows oil circulation, hence the transformer cooling system running normally. For paraffin oil whose oxidation rate is lower compared to that of Naphtha oil is sludge and insoluble, it is precipitated at bottom of the tank therefore hindering the transformer cooling system.

Good transformer oil acts as a liquid insulation in an electrical power transformer and dissipates heat from the transformer (coolant). Also, because it helps preserve the core and windings of the transformer for they are dipped in it. Due to oxidation susceptibility of the cellulose paper

insulation made for the primary and secondary windings, the transformer oil prevents direct contact of atmospheric oxygen.

### 2.5.1 Mineral oil

Petroleum oil has been used for transformer oil since 1891. An overview of the source and purification process of petroleum is as follows:<sup>[11]</sup>

#### *a). Crude petroleum*

Crude oil comes from the extraction source known as crude petroleum. It contains long chains of carbon compounds and also smaller amounts of sulphur and nitrogen, deposited over millions of years with high pressure under the earth's crust. Basically, hydrocarbon molecules can be classified into three main groups as described below:

-Paraffin:

This is the main content of petroleum, in terms of percentage.

-Cycloalkanes:

Characteristically contain a ring structure with six carbon atoms (within six-membered rings) or fourteen carbon atoms (within three-membered rings).

-Aromatics:

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

#### *b). Refining petroleum*

Crude petroleum has to be refined to some of these classified petroleum products like gasoline, kerosene, liquid petroleum gas (LPG), lubricating oils, etc. Fractional distillation is the name of the process of refining of crude oil. It comprises a vacuum distillation called a fractionating tower where several catalysts and different temperatures are used to get the different products.<sup>[12]</sup> You can work out the formula of any of them using:  $C_nH_{2n+2}$ .<sup>[13]</sup>

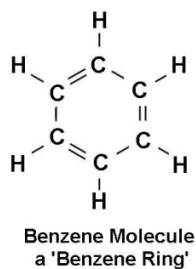
Cycloalkanes have a closed ring. They are one of three main constituents of crude oil, the other two being alkanes and aromatic compounds.

Cycloalkanes are classified into various sizes cycloalkanes, where cyclo-propane and cyclo-butane are the smallest sized cycloalkanes. cyclo-pentane, cyclohexane, cyclo-heptane are the common ones, cyclo-octane through cyclo-tridecane are the medium ones, and the rest are larger ones.

Cycloalkanes are similar to alkanes in their general physical properties, but their ring structures allow them to have higher physical properties like boiling points, melting points, and densities, than alkanes. Their melting and boiling points are 10K to 20K higher than their corresponding straight chain alkanes.<sup>[13]</sup>

The classification of alkanes is derived from their sizes and shapes from the chemical structure. Methane, being the simplest of all, has just one carbon atom. Then ethane has two carbon atoms, propane with three, butane with four, and so on.

Boiling points, melting points, and densities increase as the number of carbon atoms increase. The longer the carbon chain, the higher the total molecular mass of the molecule; thus, increase in density, boiling points, melting points, etc.



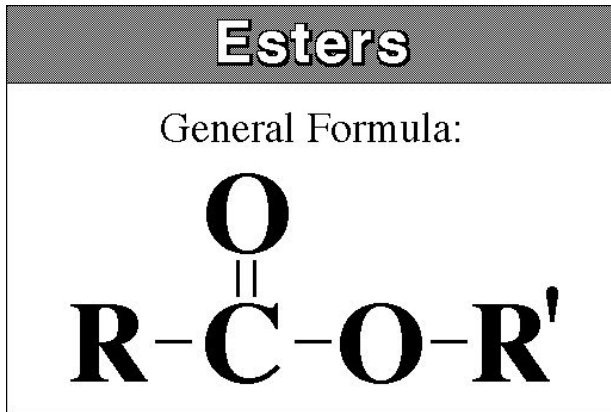
*Fig 2.5.1 Structure of benzene.*

Benzene, whose structure is depicted in Fig 2.5.1 is a petroleum component.<sup>[14]</sup> Chemical processes like selective solvent extraction, sulphuric acid extraction, fractional distillation, earth filtration, Oxidation, halogenation, Hydrogenation, cracking, re-distillation, filtration, and dehydration are used in the formation and modification of these organic compounds. Mineral oil refined from crude oil is a well-known, good insulating material has good electrical properties, aging behavior, and low viscosity. Other characteristics like the low relative permittivity give an advantage regarding their behavior for insulation in transformer operation.

**NB:** Mineral oil is produced by several countries and is relatively inexpensive. But, the main drawback occurs when there is a transformer leakage and the mineral oil will contribute to environmental hazards because of its poor biodegradability.

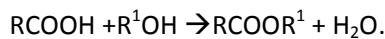
## 2.5.2 Vegetable oil.

There exist both synthetic and natural vegetable oils. Ester oils have a functional group like the one below.<sup>[15]</sup>



*Fig2.5.2. General Structure of an ester molecule.*

R and R<sup>1</sup> represent alkyl groups. The two oxygen atoms bonded to the carbon atom constitute the functional group. The remaining carbon atoms could be long chains of carbon molecules (complex) or as simple as these in the Fig 2.5.2. The general formula and the esterification process (Production of Esters, RCOOH) is the equilibrium reaction between a carboxylic acid and alcohol (R<sup>1</sup>OH). Water (H<sub>2</sub>O) is the by- product.



Esters can be extracted from palm nuts, soybeans, groundnuts etc.

Synthetic esters also exist. They are made from petroleum.

## 2.6 Oil Testing and analysis.

Statistics proof that most destroyed transformers suffered from several conditions such as overload condition, which, more often than not, is the main cause of transformer failures, as discussed and shown in the first chapter. Other components such as the material of the core and type of lamination are also vital, but the insulation system plays one of the most important roles in the transformer's life, courtesy of the statistics of most transformer failures.

A couple of tests are viewed in our study; known as Dissolved Gas Analysis (DGA) and Partial Discharge Measurement (PD). The dissolved gas analysis (DGA) is carried out on the aged samples to predict the incipient faults. Though there is no direct method to detect these incipient faults, it is known that these faults, especially in the form of overheating, arcing or partial discharge, develop certain gaseous hydrocarbons, which are retained by the insulating oil as dissolved gases. Thus the evaluation of these gas compositions and their interpretation known as Dissolved Gas Analysis (DGA) seems to be one of the life-saving diagnostic tests on condition monitoring of transformers.

The early detection of partial discharge present in a transformer is very important to avoid/reduce the losses to the catastrophic failure of transformer. Also, once the PD is detected, the location of the same is very important so that the defects can be pinpointed and solved effectively.

## Chapter 3: Transformer Oil Insulating Properties

Transformer/Insulating oil is a highly refined mineral oil that is stable at high temperatures and excellent insulating properties. It is obtained from fractional distillation process with subsequent processing of crude petroleum. It has two main functions to include:

Acting as a liquid insulation in an electrical power transformer and secondly dissipating heat of the transformer (coolant). Also, because it helps preserve the core and windings of the transformer for they are dipped in it.

Due to oxidation susceptibility of the cellulose (paper insulation) made for the windings, the transformer oil prevents direct contact of atmospheric oxygen. <sup>[16] [17]</sup>

The Transformer Oil parameters are categorized as:

- Electrical Parameters – Dielectric Strength, Specific Resistance, Dielectric Dissipation Factor, Chemical Parameters – Water Content, Acidity.
- Physical Parameters – Inter Facial Tension, Viscosity, Flash Point and others as explained in detail below.

### 3.1 Total acidity

Total acidity also called total acid number (TAN) refers to the measurement of acidity that is gotten by the amount of potassium hydroxide (expressed in milligrams) which is required to neutralize the hydrogen ions ( $H^+_{(aq)}$ ) in one gram of oil. The total acid number value shows to the crude oil refinery, the possibility of corrosion problems. To find the total acidity, different methods can be used to include:

Potentiometric titration; where toluene and propanol are dissolved with a sample and a little water then titrated with alcoholic  $NaOH_{(aq)}$ . A reference electrode and a glass electrode is immersed in the sample and connected to a voltmeter/potentiometer. The meter reading (in millivolts) is plotted against the volume of the titrant then the end point taken at the distinct inflection of the resulting titration curve corresponding to the basic buffer solution.

Color indicating titration: A right pH color indicator for instance, phenolphthalein, is used. Titrant is added to the sample by means of a burette and the volume of titrant used to cause a permanent color change in the sample is recorded and used to calculate the TAN value.

**Transformer oil** acidity is never good for the performance of the transformer, if at any moment, oil gets acidified then the moisture content in the oil shall get high solubility levels. This shall later affect the paper insulation of the winding. Acidity increases the oxidation process in the transformer oil. Acid presence also accelerates rusting of iron in combination with moisture. The

KOH in mg is used to combat acidity of oil by neutralizing it in every gram of oil. This is referred to as neutralization number. <sup>[18]</sup>

### 3.2 Breakdown voltage

The breakdown voltage of an insulator refers to the minimum voltage which results in part of an insulator to become an electric conductor. It is usually a unique property of an insulator that defines the maximum voltage difference that can be put across the material before its insulator conducts. In solid insulating materials, this often creates a weakened path within the material by creating permanent molecular or physical changes by the sudden high current.

The breakdown voltage of a material is not a definite value. Breakdown voltage is also referred to as withstand voltage where the probability of failure at a given voltage is so low that it is considered at the moment of designing insulation, with assurance that the material will not fail at this voltage.

There exists two ways for measurement of breakdown voltage of a material which include the impulse breakdown and the AC breakdown voltages. AC voltages are the line frequencies of the mains, while with the impulse breakdown voltages, they are simulating lightning strikes. <sup>[19]</sup>

### 3.3 Viscosity

Here we mainly focus of liquids/fluids and the viscosity of a fluid refers to a measure of its resistance with reference to its gradual deformation by shear stress or tensile stress.

It corresponds to the informal notion of "thickness"; if we focus on liquids. For example, water has a lower viscosity compared to honey. Viscosity is brought about by high friction between neighboring molecules of the fluid that are moving at different speeds. On forcing a fluid into a tube, it will move faster slowest near the walls of a container when poured out. Therefore a little stress is needed to overcome the friction between layers and keep the fluid moving. So generally, viscosity of a fluid is highly dependent on the shape and size of its particles plus attractions across the particles. <sup>[20]</sup>

At very low temperatures, when viscosity can be observed in super fluids. A fluid with no resistance to shear stress is called an ideal fluid. Otherwise all fluids have positive viscosity. For instance if the viscosity is very high at pitch, the fluid is most likely to appear as a solid in short while, A liquid with a viscosity greater than water is referred to as a viscous liquid and the other liquid whose viscosity is lower than that of water is called a mobile liquid.



With emphasis on Viscosity of transformer oil, viscosity refers to opposition to flow at all factors constant (normal condition). With reference to transformer oil, resistance to flow simply describes opposition to convection circulation of oil in the transformer.

**Oil used in transformers** with low **viscosity** is essential and simultaneously important in that, transformer oil viscosity should not change much if temperature is decreased. It should be noted that all liquids get more viscous with decrease in temperature. Low viscosity is one that's better recommended in order to provide environment for low resistance to conventional flow of oil hence proper transformer cooling.

It is worth mentioning that viscosity of a liquid, more often than not, is used to determining it as a cooling agent. Thus transformer oil, which is thick and scarcely facilitates convection, inhibits the spread of heat by convection in a transformer. However, since every liquid becomes less viscos with temperature increase, convection takes place to facilitate cooling as well. <sup>[21]</sup>

### 3.4 Dielectric dissipation factor (tan-delta).

Dissipation factor refers to a measure of loss-rate of energy of a mode of oscillation in a dissipative system. It is as well referred to as loss factor. The dielectric dissipation factor of an insulating material is the **tangent of the dielectric loss angle**. This is an angle in which the phase difference between the applied voltage and consequential current diverges from  $\pi/2$  rad, at the point where the capacitor's dielectric encompasses only of insulating material.

The dielectric dissipation factor in relation to transformer oil is broken down as in this simple description: The loss angle is a vital property of dielectric oil. With an ideal dielectric material, voltage and current has a phase angle as  $90^\circ$  between them. But because of impurities, certain leakage current flows through the dielectric and actual phase angle is slightly less than  $90^\circ$ . A rising dissipation factor is an indication of oil contamination or oil ageing. Polar components strongly influence the dissipation factor and are therefore a very sensitive parameter. The tan delta of transformer oil happens when an insulating material is placed between the live part and grounded part of an electrical circuit; resulting in leakage current flow. The insulation ideally leads the voltage by  $90^\circ$  because of the insulating material being dielectric naturally, thereby creating instantaneous voltage between live part and ground of the equipment. In a practical world, no insulating materials are perfect dielectric in nature. This is simply called Dielectric Dissipation Factor or simply **tan delta of transformer oil** courtesy of tangent of an angle slightly short of  $90^\circ$  due to imperfections in insulating materials and their dielectric properties. <sup>[22]</sup>

We are going to illustrate the aforesaid with a graph that illustrates that as the transformer ages, impurities increase, therefore decreasing dielectric resistance. Impurities will increase current flow through the dielectric. <sup>[23]</sup> The angle delta is less than  $90^\circ$  when the impurities are more.

**NB:** "The Tan Delta test works on the principle that any insulation in its pure state acts as a capacitor. The test involves applying a very low frequency AC voltage. The voltage is generally double the rated voltage of the cable or winding.

A low frequency causes a higher value of capacitive reactance which leads to lesser power requirement during the test. Besides, the currents will be limited enabling easier measurement.

In a pure capacitor, the current is ahead of the voltage by 90 degrees. The insulation, in a pure condition, will behave similarly. However, if the insulation has deteriorated due to the entry of dirt and moisture, the current which flows through the insulation will also have a resistive component.

This will cause the angle of the current to be less than 90 degrees. This difference in the angle is known as the loss angle. The tangent of the angle which is  $I_r/I_c$  (opposite/adjacent) gives us an indication of the condition of the insulation. A higher value for the loss angle indicates a high degree of contamination of the insulation.

Re resistance will reduce as Fig3.4.1 below illustrates."<sup>[17]</sup>

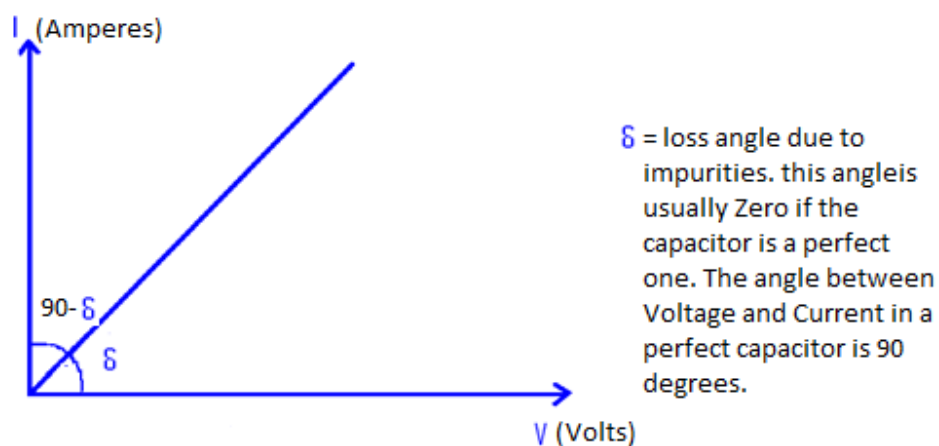


Fig3.4.1. Tan-delta illustration.

### 3.5 Specific resistance.

Specific resistance with reference to electrical resistance of an electrical conductor refers to the opposition in the passage of an electric current through a conductor. The SI unit of electrical resistance is the ohm ( $\Omega$ ), and that of electrical conductance is Siemens (S).<sup>[19]</sup>

Any conductor with specified cross section has a resistance relatively proportional to its resistivity, length and is inversely proportional to its cross-sectional area. Apart from superconductors, which have a resistance of zero, the rest of the materials show some

resistance at any given point in time. A conductor's material and temperature greatly determines its specific resistance.

Resistance (R) of an object is defined as the ratio of voltage across it (V) to current through it (I). And conductance (G) is the inverse:

$$R = \frac{V}{I}, \quad G = \frac{I}{V}, \quad G = \frac{1}{R}$$

Where voltage (V) and current (I) are directly proportional for a wide range of materials. This automatically sets R and G as constants but can as well depend on other factors like temperature as earlier explained.

Specific Resistance of transformer oil focuses on measure of resistance between two opposite sides of one cm<sup>3</sup> block of oil, the standard unit is taken as ohm-cm at a specific temperature. The resistivity of oil reduces drastically when temperature increases. When a transformer has been shut off for a long time, its oil temperature shall be the same as that at ambient. With a full load, the temperature can rise up to 90°C especially at an over loaded condition. Therefore insulating oil resistance should be able to accommodate the needs of both the high and low temperatures; that is at ambient level.

It is highly recommended to measure specific resistivity of transformer oil both at 27°C as well as 90°C hence covering the expected high temperatures and minimum.

The standards are as follows:

The actual minimum standard for specific resistance of transformer oil at 90°C is 35X 10<sup>12</sup> ohm – cm (maximum) and at the lower boundary is estimated at 27°C is 1500X10<sup>12</sup> ohm – cm (minimum).<sup>[25]</sup>

### 3.6 Flash point.

The flash point of a chemical or any volatile material is the lowest temperature at which it can evaporate to form an ignitable mixture in air or combustible concentration of gas. This point indicates how hard or easy this volatile material may burn. Materials with higher flash points are less flammable or hazardous than chemicals with lower flash points. Determining a flash point requires an ignition source. The flash is not dependent on the temperature of the ignition source.

Mineral oil is a derived product of crude petroleum. At higher temperatures, it will vaporize. After a certain temperature, the mixture of this oil vapor and atmospheric air produces a highly combustible product which is easily ignitable by any kind of spark. Any burning fire or open flame will not necessarily ignite the gas but a hot surface like a heater will do for chemicals with more than high hazard.

The flash point has commonly been used to explain and distinguish liquid fuel, and as well help uniquely identify the fire hazards of liquids.

So basically “Flash point” means both flammable liquids and combustible liquids. Various standards for defining each term exist.

This can be evidenced more as follows; Liquids with a flash point less than 37.8 °C are considered flammable and those with a flash point above the previously mentioned temperatures are considered combustible.

This temperature is the flash point of transformer oil. Generally, 140° C is the minimum threshold flashing point for standard power transformers.

Flash point with reference to transformer oil applies in the same way as has been expressed above for the other liquids. It is the temperature at which oil evaporates to produce a flammable mixture with air. The main importance of the mixture is to briefly give a flash on application of flame under standard condition.

This process is very vital for it signifies the chances of fire hazard in the transformer for that reason a higher levels of temperature points of transformer oil flash point are desired. <sup>[25]</sup>

### **3.7 Moisture content.**

Moisture content is described as the amount of water contained in a material, such as soil - soil moisture, apple, food and others. Moisture content is used in both technical and scientific areas plus day to day life activities. It is often used in rations which vary from 0 to mean when the material is completely moisture free (dry) up to the value of the materials' being porous at saturation point. The moisture content is always measured in volume or mass as contained in the material in focus.

Water is a very undesirable pollutant to transformer oil and other insulators in a transformer. Firstly, considering moisture in oil, moisture makes the oil less thick with a lower boiling point than oil. Moisture content is a direct proportionality to transformer oil aging.

Secondly, the paper winding, which is also an insulator and a dielectric in the oil transformer, is also adversely affected by moisture. The moisture slowly soaks the paper as the transformer oil ages. A soaked paper, on transformer windings, decreases insulation, and thus the transformer's functioning and efficiency. When the temperature has increased in the transformer environment, this very soaked paper again releases water into the transformer oil. This leads to oxidation, hence, increases the amount of acid and water. This causes oil quality reduction due to oil decomposition. <sup>[19]</sup>

For the above reasons, it is highly recommended to avoid water in transformer oil for increased performance.

### 3.8 Dielectric constant (relative permittivity $\epsilon_r$ )

Relative permittivity, in this context, is the measure of the resistance encountered in the formation of electric fields between the electrodes in the oil insulation medium.

A dielectric material is an electrical insulator that gets polarized when an electric field is applied to it. When a dielectric is placed in an electric field, electrical charges never flow through the material as compared to the way they flow in a conductor; they just slightly shift from their mean equilibrium positions causing dielectric polarization. The effect of dielectric polarization is that: positive charges are displaced towards the field and negative charges shift in the opposite direction.

Dielectric constant is an element of an electrical insulating material which is equal to the ratio of the capacitance of a capacitor filled with the given material to the capacitance of an identical capacitor in a vacuum without the dielectric material. As a result, an internal electric field is created that reduces the overall field within the dielectric itself. Molecules of a dielectric material that are weakly bonded shall be polarized and their axis of symmetry will get re-organized to the field. <sup>[26]</sup>

Studies focused on dielectric properties emphasize storage, dissipation of electric and magnetic energy in materials.

A material with a relative permittivity equaling to a frequency of zero is referred to as its static relative permittivity. <sup>[27]</sup>

### 3.9 Interfacial Tension.

This is described as surface tension at the surface separating two non-miscible liquids. It is a tension with a contractive tendency of the surface of a liquid that gives it the potential to resist an external force. What actually happens is; all molecules at the surface of the liquid form a weak bond with each other creating a surface "blanket" to the other molecules of the liquid beneath. A good example is floating objects on the surface of water, even though they are more dense compared to water. <sup>[19]</sup>

Interfacial tension has dimension of energy per unit area, this kind of energy is used commonly in surface tension or surface free energy.

Cohesive forces between liquid molecules create interfacial/surface tension. When referring to a heavy or bulk of the liquid, every molecule is separated equally in every direction by neighboring liquid molecules hence a net force equaling to zero. The molecules at the top of the liquid have

no neighboring molecules on top of them so they are only pulled inwards or neighboring molecules under them. As a result, internal pressure will be created causing the liquid surfaces to contract to the minimal area.

Surface tension is responsible for the shape of liquid drops; droplets of water tend to be pulled into a spherical shape by the cohesive forces of the surface layer even if they are easily de-shaped. Without forces for instance gravity, drops of almost all liquids would normally be spherical which shape reduces the necessary "wall tension".

Also with emphasis to energy, molecules in contact with their neighbors are in a lower state of energy than if they were not in contact with adjacent neighbors. Inside molecules have many neighbors as much as they could but the molecules on the boundary miss neighbors and so automatically have higher energy. Therefore, if a liquid is to reduce its energy state, the number of molecules of higher energy on the boundary should be reduced. This will definitely reduce surface area.

With minimizing the surface, it will have a smooth shape hence high energy will be gained, and gravitational potential energy shall as well be reduced.

With surface tension is responsible for separation of oil and water due to tension in the surface between dissimilar liquids. Newly acquired transformer oil shows high interfacial tension while contaminants, due to oxidation, lower the Inter facial tension. This phenomenon is useful in determining the presence of polar contaminants and transformer oil decay products. <sup>[28]</sup>

### 3.10 Dielectric Strength.

The term dielectric strength (can as well mean voltage breakdown) has different meanings depending on the primary focus, with reference to an insulating material it refers to the maximum electric field strength that the material can withstand continuously without breaking down; to be specific, without experiencing failure of its insulating properties. <sup>[19]</sup>

With major focus on transformers, dielectric strength applies to transformer oil. The dielectric strength is determined taking note of at what voltage, sparks between two electrodes immersed in oil and a specific gap between them. Low value of dielectric strength shows presence of moisture and maybe other conducting substances in the oil. This is done with a break down voltage measuring kit in which one pair of electrodes is fixed and has a gap measuring about 2,5mm apart. Then voltage shall be applied to the pair of electrodes.

With careful increasing of voltage on both electrodes, critical observation should then be taken on when the sparks between electrodes happen; exactly when the dielectric strength of transformer oil between electrodes has been broken down. <sup>[29]</sup>

### 3.11 Transformer insulation (Paper insulation)

Paper insulation is used for several insulation purposes in the electrical field; several electrical insulation paper types exist and are used in many applications, this is because pure cellulose has unbelievably great electrical properties. Cellulose is an outstanding insulator as well as a polar substance. This is because of its having a dielectric constant significantly greater than one. Classification of electrical paper depends on thickness from less than 1.5mm to over 20mils (0.508mm) thickness. <sup>[19]</sup>

Moisture content in transformer oil is never a good combination for it interferes greatly the oil dielectric properties. The water content in oil also affects the paper insulation of the core and winding of transformer. Paper is extremely hygroscopic so it absorbs a lot of water from oil which affects paper insulation property plus lowering its lifespan. With a loaded transformer, oil temperature increases, resulting in the solubility of water in oil increase. Hence the paper releases moisture, resulting to an increase in the water content in the transformer oil. <sup>[30]</sup>

## Chapter 4: Transformer Oil Analysis.

### 4.1 Partial discharge (PD)

Signs of partial discharge were first observed in an oscilloscope in the Sixties. Later in the Eighties, computerized data acquisition became commonly available. This greatly enhanced storage and digital processing of discharge patterns. <sup>[31]</sup>

PD, more often than not, starts inside tiny bubbles, voids, cracks, or inclusions within a solid insulator (dielectric), at conductor – dielectric interfaces within solid or liquid dielectrics, or in voids that occur in liquid insulators used as dielectrics. Since PDs only occur at a particular portion in the electrode, the faults created by the discharges only partially connect the separation of the electrodes.

PD in transformers degrades the properties of the insulating materials and can lead to eventual failures. PDs can be identified by using analysis from acoustic measurements or by measurements of the electrical signals. Another preferred method is by doing chemical tests to analyze the gases produced from the partial discharges.

PDs cause considerable deterioration to the insulation (dielectric) it occurs in. It is worth mentioning again that when the gases are collected by upward delivery or downward displacement of air, and the result of the analysis of the gases can be used to determine the type of fault that occurred. For the case of partial discharge, hydrogen gas is produced. Generally, and for all oil types, the partial discharge experiments show that the rate of partial discharge is directly proportional to age of the oil. This is reasonable because during partial discharge, many chemical bonds are broken to form several gases and this effectively shortens then hydrocarbon chains of the oil. PD, therefore, would be worthwhile to be detected early for technical intervention; else, it can ruin the transformer.

Some of the gases dissolve in the oil. This brings us to Dissolves Gas Analysis.

### 4.2 Dissolved gas Analysis (DGA)

Dissolved gas analysis is the study of dissolved gasses in transformer oil. The gasses come from the deterioration of the materials that form the container of the transformer oil. These materials include both the electrical equipment, the insulating materials for the coils, and the ore.

When the gases are analyzed, the statistics can be used to deduce the real electrical fault of the transformer, or the equipment at fault.



Since the oil is in contact with the internal equipment, the gases formed by oxidation, vaporization, decomposition, insulation, oil breakdown and electrolytic action, are dissolved in the transformer oil. At that instance, the oil is hot. The heat enhances the dissolution of the gasses.

During normal transformer operation, gasses are produced. But when there is a fault, the gasses are produced in larger quantities. The gasses produced are proportional to the fault. Below, are the most common faults and gasses produced; in increasing severity. <sup>[32]</sup>

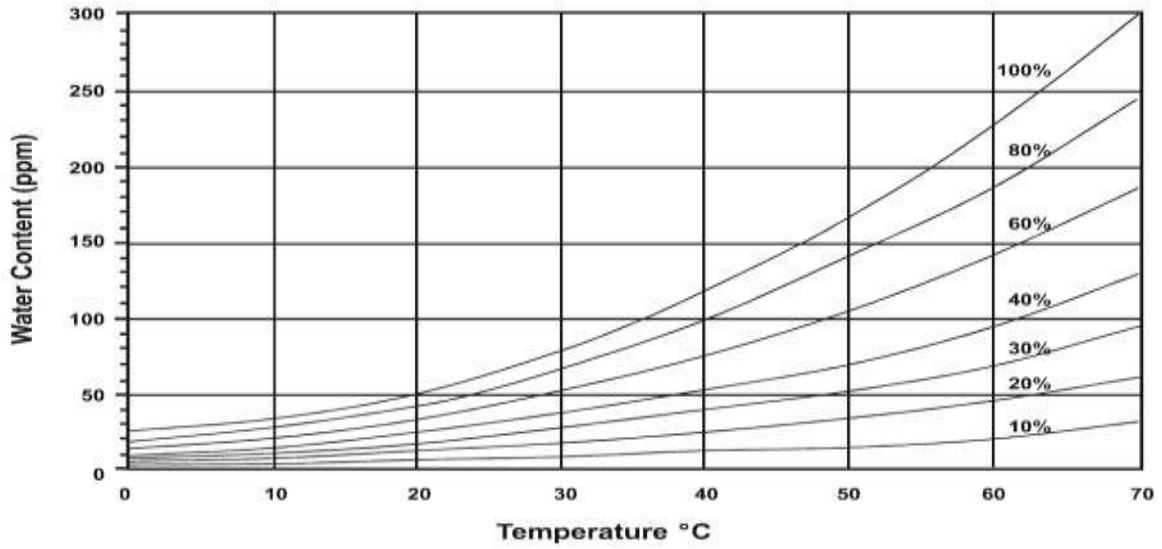
- Partial discharge or corona: Produces hydrogen gas ( $H_{2(g)}$ ).
- Localized hot spots (Pyrolysis or thermal heating): At lower temperatures, it produces  $CH_4$ ,  $C_2H_6$  and at high temperatures, it produces a mixture is methane,  $C_2H_4$  (ethylene), ethane and hydrogen gas.
- Arcing: produces a mixture of ethane acetylene ( $C_2H_2$ ), ethylene, methane, and hydrogen gas. <sup>[33]</sup>

#### 4.2.1 Dissolved Moisture in Transformer Oil.

Free water causes few problems with the dielectric strength of oils in transformers; however, it should be drained as soon as it is noticed.

Moisture is given in the dissolved gas analysis in ppm, and some laboratories also give percent saturation. Percent saturation means percent saturation of water in the oil. This is a percentage of how much water is in the oil compared with the maximum possible saturation of water in oil. The saturation of water in oil greatly depends on temperature.

The curves, in Fig 4., below show some percent saturation curves. On the left line, find the ppm of water from your DGA. From this point, draw a horizontal line and extrapolate to read the corresponding temperature and corresponding level of percentage saturation on or between the curves. <sup>[34]</sup>



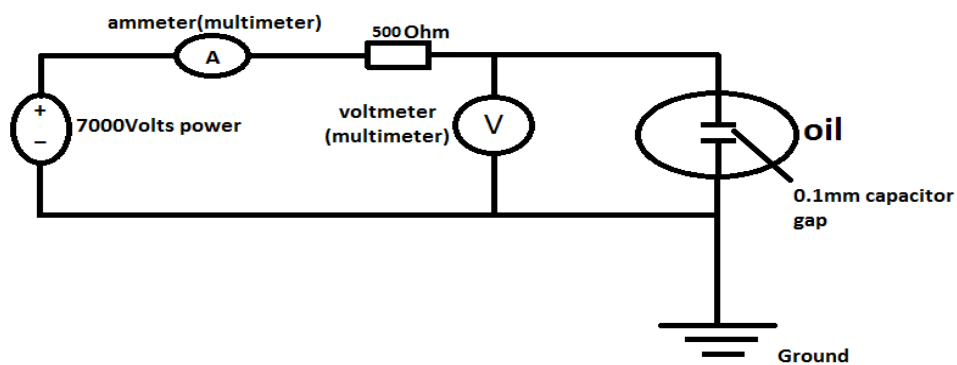
*Fig 4.: Transformer Oil Percent Saturation Curves.*

For example, if the oil is 50 ppm and the temperature is 40°C, you can see on the curves that this point of intersection falls about halfway between the 20% curve and the 30% curve. This means that the oil is approximately 35% saturated.

However, experts disagree on how to tell how much moisture in the insulation based on how much moisture is in the oil (ppm). At best, methods to determine moisture in the insulation based solely on DGA are not very accurate inaccurate.

## Chapter 5: Experimental Setup.

This chapter will discuss the experimental setups used in this thesis project, including the aging process on both types of oil, the measurement procedure of Breakdown voltage.



*Fig (5.1.1.) Diagram of the experimental setup.*

As it shown in the diagram of the experimental setup, it has, installed, two poles (electrodes) in the middle of the container, immersed in test oil, one of them connected to the high voltage side and other to ground.

### 5.1 Requirements for experiment.

#### Ac voltage control (7K Volts Power supply):

Used to control the value of voltage that applied to the oil, and included of ours made a protection system that will be operated when the breakdown voltage appear in the insulation.

#### Resistors:

The resistors have connected in series with set value to 500 (ohms).

#### Syringe:

It has used as a unit of measurement to add the solution to the mineral and vegetable oil.

#### Multi-meter (Volt-Ohm meter):

It used to measure the voltage, current, resistant in the experiment.

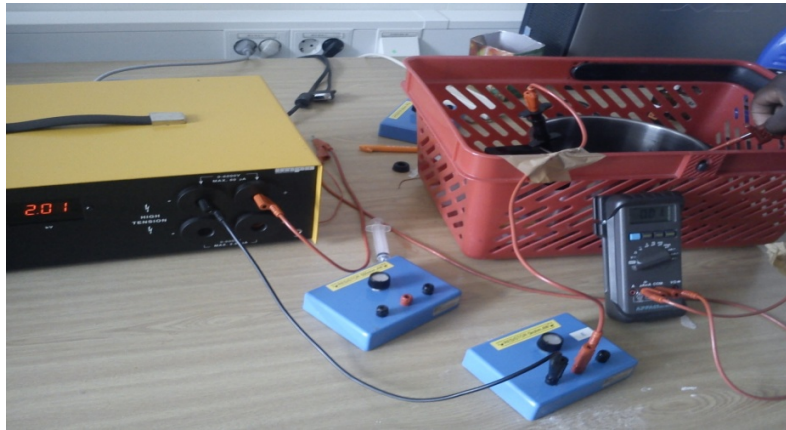
#### Heat source – (Extreme temperature):

It used to heat the oil and increase its aging time. A 600<sup>0</sup>C heat source was used.

Additional requirements used in the experiment:

1. Hydrochloric Acid (HCL).
2. Sodium Hydroxide  $\text{NaOH}_{(aq)}$ .

The old samples are pre-conditioned. Then, the accelerated thermal aging process is started. First, the sample container is cleaned before it is filled with new oil sample.



*Fig(5.1.2): Shows the experiment equipment.*

The setup was as shown in the picture above that they were used in the experimental measurements. After add the oil sample in the container, the oil sample is subjected to a steadily increasing alternating voltage until breakdown occurs in the dielectric in the BDV test kit. The breakdown voltage is the voltage reached at the time of the first spark appears between the electrodes. The spark voltage, which indicates the high surge of current, is recorded. The test is carried out nine times on each sample. The electrodes are mounted on a horizontal axis with a test spacing of about 0.1 mm.

Fig (5.1.1) shows the logical layout of the physical experimental layout we conducted as shown in Fig (5.1.2). The next page contains the pictures during the artificial aging process. In Fig (5.1.3), the oil was heated with a heat source of  $600^{\circ}\text{C}$ , as well as the oil's physical state during the thermal disintegration.



*Fig (5.1.3): The operation of heating the mineral oil about 60 minute with a 600 degrees heat source. Figures of artificial aging in the lab.*

## 5.2 Conditions of the oil samples

Before starting the accelerated thermal aging process, the old sample was replaced before the accelerated thermal aging process is started. After that, the complete setup was connected as in the layout above and then the results were taken. This oil treatment procedure elevates the humidity of the oil during and after the heating.

Also, treatment of the respective oil samples with HCl and NaOH, include the introduction of calculated amounts of the chemicals; as later shown in chapter six. The moisture content of the oil affects its dielectric properties, such as breakdown voltage and dielectric loss angle (tan-delta).

## 5.3 Breakdown voltage measurement in oil

The Breakdown voltage, known as the minimum voltage that the sparks occur between the electrodes, causes a portion of an insulator to become electrically conductive.

In our measurements the electrodes were installed in horizontal position.

The electrodes were polarized, and the axis of the electrode system shall be horizontal and at least 20mm below the surface of the test oil. The gap between the electrodes is set to 0.1mm, and the container should be almost filled with oil sample. The measurements are carried out until nine breakdowns on each sample, and then the oil sample is subjected to a steadily increasing alternating voltage until breakdown occurs in the dielectric in the BDV test kit.

## Chapter 6: Experimental results and Discussion.

All presented data from the dielectric property measurements which include the breakdown voltage, relative permittivity, and humidity content are measured and the data are presented in trend plots to be used for comparing the dielectric characteristics between mineral oil and (vegetable) ester oil.

### 6.1 Vegetable Oil experiment

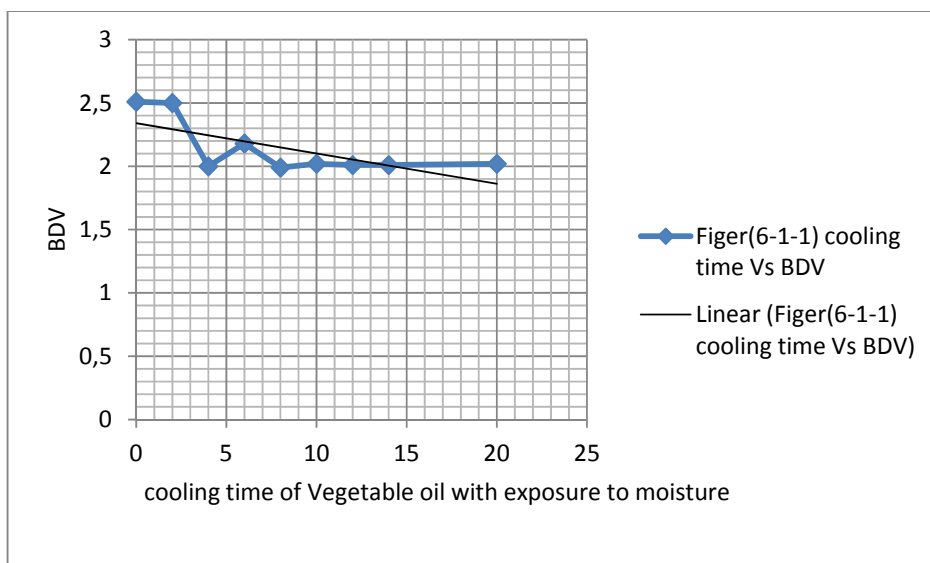
HCL was added with different percentage. We used a 4M HCL solution applied voltage to the oil and increased the voltage carefully by an AC voltage control until break down occurs.

- First reading: 3.1 KV rms.
- Second reading: 3.1 KV rms.
- Third reading: 3.1 KV rms.
- Average: 3.1 KV rms.

The results of breakdown voltage (BDV) measurements for the vegetable oil's cooling are listed in tables.

Cooling time for vegetable oil	Breakdown voltage
0	2.51
2	2.50
4	2.00
6	2.18
8	1.99
10	2.02
12	2.01
14	2.01
20	2.02

*Table (6.1.1): Shows minutes of cooling after heated for 60 minutes with 10ml of water against breakdown voltage.*



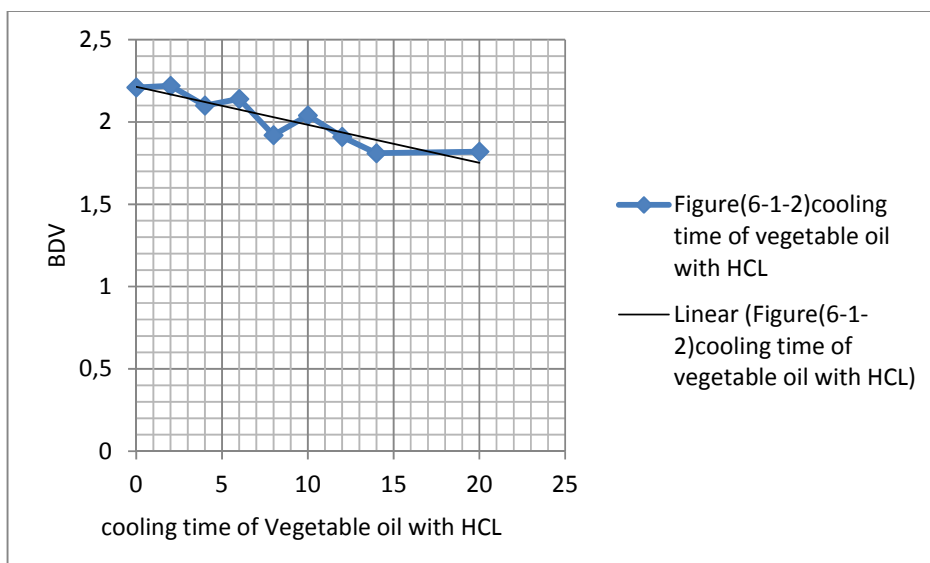
*Fig (6.1.1): A graphic representation of the breakdown voltage of vegetable oil along the time.*

The oil is artificially moisturized by heating the oil for sixty minutes with 10ml of water. At the beginning of the plotting on Fig (6.1.1), the Breakdown Voltage of vegetable oil has not changed between 0-2 minutes. Then the breakdown voltage decreased slightly towards the fourth minute. When approaching the 6<sup>th</sup> minute, the BDV slightly went up again, before going down again at eighth minute. Approaching the tenth minute, the BDV increased slightly to value which was still lower than the BDV at the beginning of test, and it becomes more stable to the end of aging time. In spite of inconsistencies, the general trend is a slight negative gradient. The general slope detected by the computer is a slight decrease; indicated by the black line. The irregularity of the graph can be accounted for by the unstable dielectric gap and tiny dust particles from the environment that entered the oil. When heating stopped, there is a continuous decomposition of the oil's chemical components. This gradually decreases as the oil cools, giving rise to the negative gradient of the graph.

Cooling time of Vegetable oil with HCl.	Breakdown voltage
0	2.21
2	2.22
4	2.10
6	2.14
8	1.92
10	2.04
12	1.91
14	1.81
20	1.82

*Table (6.1.2): Shows minutes of cooling after heated for 60 min with addition of 2ml of 4mol/dm<sup>3</sup> HCL solution against Breakdown voltage.*





*Fig (6.1.2): A graphic representation of the breakdown voltage comparison vegetable oil along the time with HCL.*

After the addition of HCL solution to vegetable oil, a similar trend to Fig 6.1.1 was plotted. When we monitor the BDV and minutes of cooling after heating for 20 min we see the initial breakdown value for new vegetable oil with HCL was lower than vegetable oil in the previous measurement. In the beginning it jumped up in the 2<sup>nd</sup> minute. Later, the BDV decreased slightly as cooling approached to 4<sup>th</sup> minute, and then the graph showed a tendency of declining until 20th minute of ‘artificial’ aging. The general slope detected by the computer is a slight decrease; indicated by the black line. The irregularity of the graph can be accounted for by the unstable dielectric gap and tiny dust particles from the environment that entered the oil. When heating stops, there is a continuous decomposition of the oil’s chemical components. This gradually decreases as the oil cools, giving rise to the negative gradient of the graph in Fig 6.1.2.

#### **Vegetable oil with NaOH<sub>(aq)</sub> testing:**

We were given 4mol/dm<sup>3</sup> NaOH<sub>(aq)</sub> but without the percentage mass. To calculate the mass, we need the number of moles. Since molar mass, M of NaOH is 34 we can calculate the number of grams (of NaOH) used in the experiment by using molarity as follows:

$$\text{Total Mass, } m_{\text{tot}} = 4 \times 34 = 136\text{g.}$$

$$136 \div 1000 \times 100\% = 13.6\%.$$

For each experiment, we used 2cm<sup>3</sup> of NaOH.

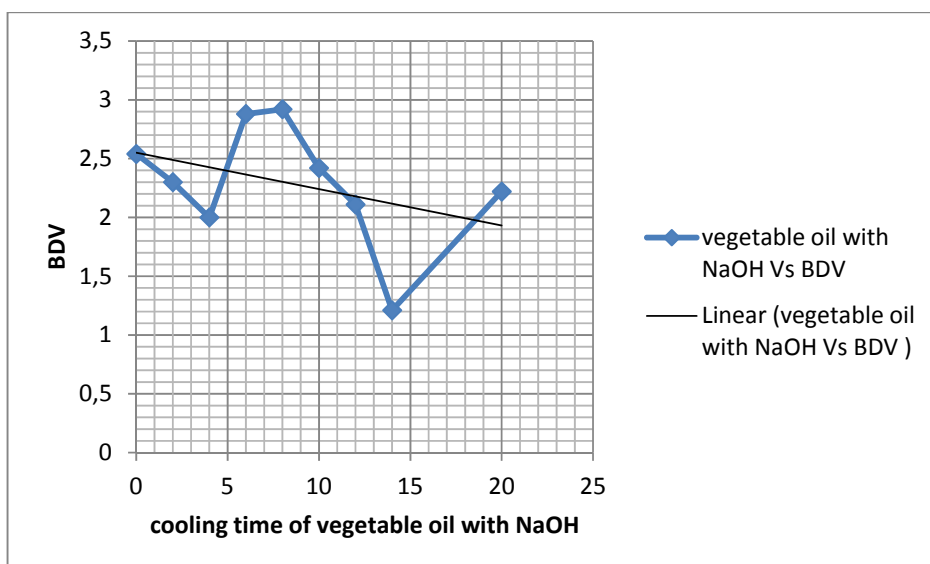
$$\text{Mass of NaOH in each drop, } m_{\text{exp}} = 2\% \times 136 = 0.27\text{g.}$$

$$\text{Volume of oil is } 250\text{cm}^3. \text{ Therefore, } 0.27 \div 252 \times 100 = 0.11\text{g}$$

0.11g is the amount of solute NaOH<sub>(aq)</sub> we use in the experiment below.

Time of cooling after adding 2cm <sup>3</sup> of NaOH and heating for 60mins.	Breakdown voltage
0	2.54
2	2.30
4	2.00
6	2.88
8	2.92
10	2.42
12	2.11
14	1.21
20	2.22

*Table (6.1.3): Shows minutes of cooling after heated for 60 min with added NaOH<sub>(aq)</sub> solution Vs Breakdown voltage.*



*Fig (6.1.3): A graphic representation of the breakdown voltage comparison vegetable oil along the time with NaOH<sub>(aq)</sub>.*

As shown in these measurements and the resulting graph on Fig 6.1.3, the minutes of cooling after the oil is heated for 60 minutes with added NaOH<sub>(aq)</sub> solution against breakdown voltage; the initial breakdown value for a new sample with NaOH<sub>(aq)</sub> solution showed consistent results for the first 4 minutes. It then jumped up higher than the first value between 6-8 min before going down again at 14 minutes. Between 14-20 minutes, BDV value increased to the highest value which was still lower than the Breakdown value at the beginning of test. When cooling started, there was a continuous decomposition of the oil's chemical components. This gradually decreases as the oil cools, giving rise to the negative gradient of the graph. The general slope detected by the computer is a slight decrease; indicated by the black line. The irregularity of the

graph can be accounted for by the unstable dielectric gap and tiny dust particles from the environment that entered the oil.

In table (6.1.4), we got the solute percentage content of HCL in the vegetable oil by this equation,

12% of HCL => 120g/dm<sup>3</sup> of solution because 12g exist in 100g (given acid solution mass).

Therefore 0.24g exists in 2g of solution.

To get the percentage mass of HCL in 250g of oil in the experiment,

So we say that  $(0.24) \div (250+2)$

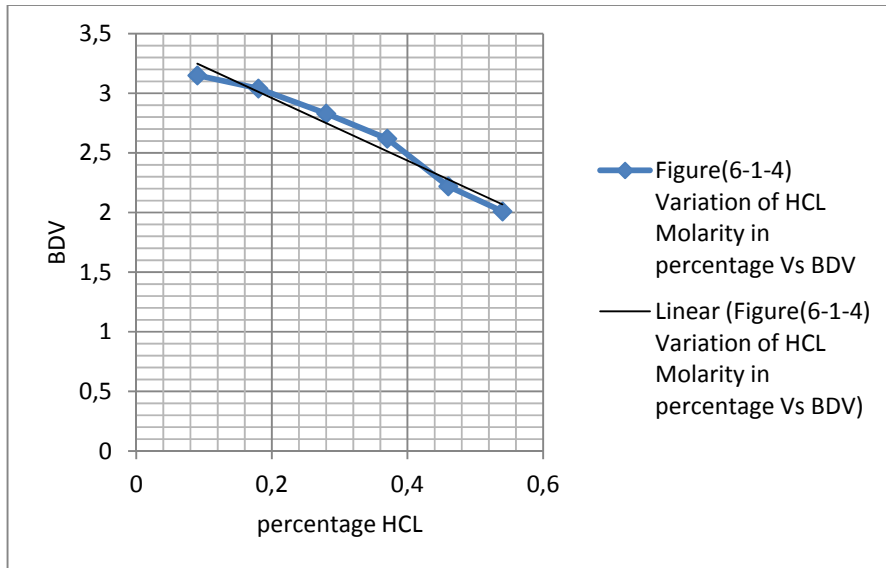
Volume of oil is 250cm<sup>3</sup>. Therefore, the general equation will be  $[(N \times 0.24) \div (250+M)] \times 100$ .

N: is the experiment number.

M: number of milliliters of 12% of HCL.

Variation of HCL Molarity in percentage	Breakdown voltage (BDV)
0.09	3.15
0.18	3.04
0.28	2.83
0.37	2.62
0.46	2.22
0.54	2.01

*A graphic presentation of the breakdown voltage comparison vegetable oil along the time is described in Figure (6.1.4.)*



*Fig (6.1.4): Relation between BDV Versus HCL in vegetable oil.*

After adding the solution and at applying the voltage, the breakdown voltage decreased slightly between 3.15 to 3.04 and the BDV slightly went down to 2.83kV and then continuously goes down till 2.01kV. The BDV value of vegetable oil was reduced from 3.15kV (new oil) to 2.01 kV (end of aging). Fig (6.1.4) is a concise characteristic graph of artificially aged vegetable oil's breakdown voltage characteristic.

## 6.2 Mineral oil experiment.

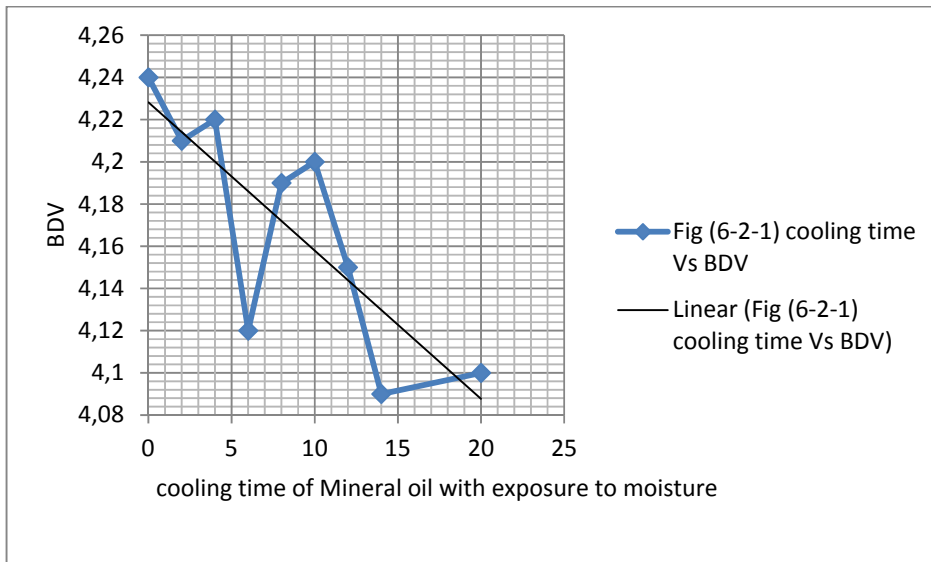
The oil sample is subjected to a steadily increasing alternating voltage until breakdown occurs in a BDV test kit. The breakdown voltage is the voltage reached at the time of the first spark appears between the electrodes. The test is carried out nine times on each sample. The electrodes are mounted on a horizontal axis with a test spacing of about 0,1 mm. We replace the old oil by a new sample, and then we added HCL with different quantities.

We used a 4M HCL solution, applied voltage to the oil, and increased the voltage carefully by an Ac voltage control until break down occurs.

- First reading: 4.50 KV rms.
- Second reading: 4.45 KV rms.
- Third reading: 4.44 KV rms.
- Average: 4.46 KV rms

Cooling time of heated mineral oil	Breakdown voltage
0	4.24
2	4.21
4	4.22
6	4.12
8	4.19
10	4.20
12	4.15
14	4.09
20	4.10

*Table (6.2.1): Minutes of cooling after heated 60 minutes with 10ml of water against recordings for breakdown voltage .*



*Fig (6.2.1): Minutes of cooling after heated for about 60 minutes.*

The oil is first artificially moisturized by heating with 10ml of water for 60 minutes. At the beginning of the recording time, the curve on Fig (6.2.1) shows that the Breakdown voltage of mineral oil decreased slightly between 0-2 minutes. Then the BDV slightly jumped up as time approaches 4 minutes before going down again during the 6th minute. Between the 6<sup>th</sup> -10<sup>th</sup> minutes, the BDV value increased to a very high value, which was still lower than the breakdown voltage at the beginning of test. It then decreases to the lowest value between 10-14 minutes of cooling, before slightly increasing slightly till 20 min. In spite of inconsistencies, the general trend is a slight negative gradient. The general slope detected by the computer is a slight decrease; indicated by the black line. The irregularity of the graph can be accounted for by the unstable dielectric gap and tiny dust particles from the environment that entered the oil.

Cooling time of mineral oil after heated with HCl.	Breakdown voltage
0	4.20
4	4.23
8	4.25
12	4.29
16	4.27
20	4.28
24	4.15
28	4.05
32	3.77

Table (6.2.2): Minutes of cooling after heated 60 minutes with add HCL solution to the mineral oil against breakdown voltage.

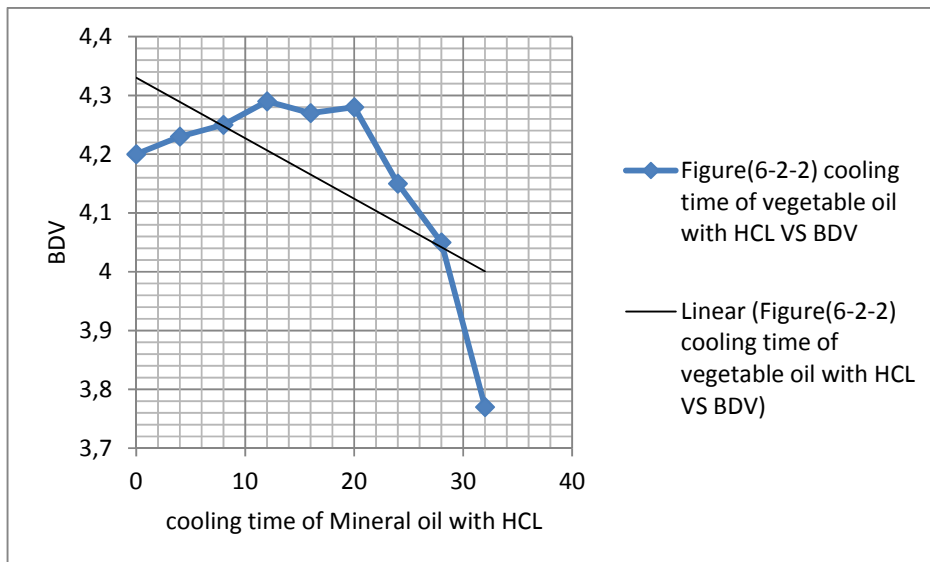


Fig (6.2.2): A graphic representation of the breakdown voltage of Mineral oil versus cooling time with HCL in mineral oil.

Fig (6.2.2) shows another figure of breakdown voltages as a property of mineral oil affected by heating with  $HCl_{(aq)}$ . The Breakdown voltage of mineral oil increases slightly between 0-12 minutes. Then the BDV slightly decreased between 12-16 minutes before it increased again to 20 minutes, after which, the decrease becomes more and more evident till the 32<sup>nd</sup> minute. In spite of inconsistencies, especially in the beginning, the general trend is a slight negative gradient. The general slope detected by the computer is a slight decrease; indicated by the black line. When cooling starts, at the beginning of the graph, there is a continuous decomposition of the oil's chemical components. This gradually decreases as the oil cools, giving rise to the negative gradient of the graph. The irregularity of the graph can be accounted for by the unstable dielectric gap and tiny dust particles from the environment that entered the oil.

We were given  $4\text{mol/dm}^3 \text{NaOH}_{(\text{aq})}$  but without the percentage mass. To calculate the mass, we need the number of moles. Since molar mass,  $M$  of  $\text{NaOH}$  is 34 we can calculate the number of grams (of  $\text{NaOH}$ ) used in the experiment by using molarity as follows:

$$\text{Total Mass, } m_{\text{tot}} = 4 \times 34 = 136\text{g.}$$

$$136 \div 1000 \times 100\% = 13.6\%.$$

For each experiment, we used at  $2.0\text{cm}^3$  of  $\text{NaOH}$ .

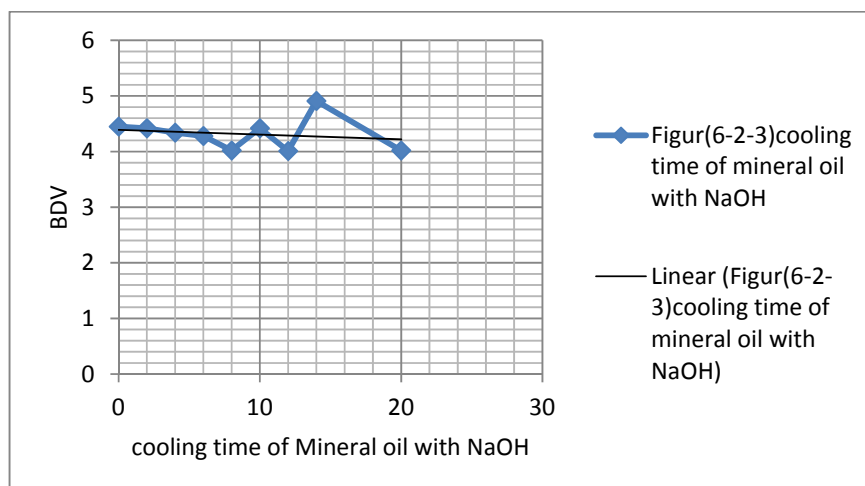
$$\text{Mass of NaOH in each drop, } m_{\text{exp}} = 2\% \times 136\% = 0.27\text{g.}$$

$$\text{Volume of oil is } 250\text{cm}^3. \text{ Therefore, } 0.27 \div 252 \times 100 = 0.11\text{g}$$

0.11g is the amount of solute  $\text{NaOH}_{(\text{aq})}$  we use in the experiment below.

Mineral oil (NaOH)	Breakdown voltage
0	4.45
2	4.42
4	4.34
6	4.28
8	4.02
10	4.42
12	4.01
14	4.91
20	4.02

*Table(6.2.3): Minutes of cooling after heated for about 60 minutes with NaOH.*



*Fig (6.2.3): Minutes of cooling after heated for about 60 minutes with NaOH against BDV.*

In the above experiment, after heating the oil with NaOH solution for 60mins, and cooling for 20minutes, the behavior of the dielectric property slightly deteriorates, almost uniformly till the 8<sup>th</sup> minute as seen on the first part of Fig (6.2.3). Later, we recorded irregular results till the 20<sup>th</sup> minute. In spite of inconsistencies, especially in the beginning, the general trend is a slight negative gradient. The general slope detected by the computer is a slight decrease; indicated by the black line. From the beginning of this experiment, there is a continuous decomposition of the oil's chemical components. This gradually decreases as the oil cools, giving rise to the negative gradient of the graph. The irregularity of the graph can be accounted for by the unstable dielectric gap and tiny dust particles from the environment that entered the oil.

In the following experiment, we got the solute percentage content of HCl<sub>(aq)</sub> in the mineral oil by this equation:

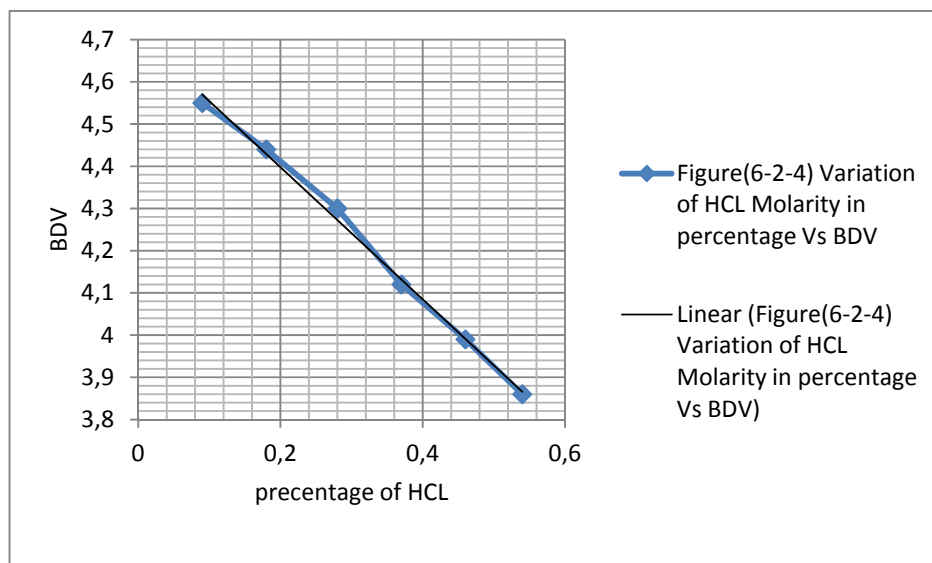
$(N \times 0.24) \div (250 + M) \times 100$ . where:

N: is the experiment number.

M: number of milliliters of 12% of HCL.

Variation of HCL Molarity	Breakdown voltage
0.09	4.55
0.18	4.44
0.28	4.30
0.37	4.12
0.46	3.99
0.54	3.86

*Table (6.2.4): The solute percentage content of HCL in the mineral oil by multiplying the 12% 4M HCL we had, by the quantity of mineral oil we used (250cm<sup>3</sup>).*



*Fig (6.2.4): Relation between BDV Versus HCL in mineral oil.*



After adding the solution and at applying the voltage, the breakdown voltage decreased slightly between 4.55 to 4.44 and the BDV slightly went down to 4.30 and then continuously goes down till 3.86. The BDV value of mineral oil was reduced from 4.55kV (new oil) to 3.86 kV (end of aging). Fig (6.2.4) is a concise characteristic graph of artificially aged mineral oil's breakdown voltage characteristic.

### 6.3 Comparison between Vegetable and Mineral Oil Characteristics

As earlier mentioned, Mineral oil can be obtained from petroleum and it is a good insulating material because of its good electrical properties. Other characteristics such as high BDV also enhance transformer operation. The most important thing is that mineral oil is already produced worldwide and offered at a low cost. But the biggest problem will occur when there is a transformer leakage and the mineral oil will endanger the environment because of its poor biodegradability.

The vegetable oil has nearly the same dielectric constant as that found in mineral oil. The mineral oil mainly consists of refined petroleum which contains non polar alkane molecule. So we can compare the two types of different oils by looking at their experiment results.

Vegetable oil can be obtained from fish oil, animal fats, palm fruits or seeds with different processes. Several typical oil seeds which are obtained and processed before they are ready to be used as the transformer insulation are represented.

When we mention comparison between mineral oil and vegetable oil characteristic, we have to mention several Criteria between both of those types:

For example; Key properties for mineral oil characteristic: produced from petroleum crude and nonrenewable power and scarce sources.

Key properties for vegetable oil characteristic: Produced from domestically grown and from renewable sources, such as soybeans and corn.

Environmental Properties for the mineral oil: Contains compounds that do not readily biodegrade. It may also contain traces of a confirmed carcinogen.

Environmental Properties for the vegetable oil: Highly biodegradable; non-toxic; does not contain petroleum, silicone, or halogens.

Leaks and Spills for the mineral oil: The latest findings of the scientists of genetic engineering to eliminate this problem. Some bacteria have the ability to absorb these substances' toxic oils and synthetically convert it into a food items. It could be formed by hybridization for more than one type of bacteria found in nature. This could possibly cause a large number of exchanges between different genes to reach the desired qualities to produce a new type of bacteria that do not exist in nature.

Leaks and Spills for vegetable oil: Relatively rapid biodegradation may eliminate the need for environmental awareness related to find new complicated dynamic processes to curb eco-concerns during spills.

Fire Risk for the mineral oil characteristic: Catches fire more easily, leading to higher probability of transformer fires

Fire Risk for the vegetable oil characteristic: reduces the frequency and impact of transformer fires; virtually eliminates sustained fires.

Transformer Performance for the mineral oil: Does not slow down the standard insulation aging rate, requires special and expensive processing to dry out the paper insulation.

Transformer performance for the vegetable oil: it has proven to slow down the aging rate of the insulation system, resulting in an increase in the expected life of a transformer by decades, also promotes automatic dry-out of paper insulation.

Utility Cost for the mineral oil: It leads to shortened life of the transformer and diminished economic returns; increases liability

Utility Cost for the vegetable oil: It prolongs transformer life and leads to longer-term economic benefits.

## 6.4 Discussion.

The accelerated thermal aging process showed a different effect to the color of the various oil samples. The color of the aged mineral oil changed more than aged vegetable oil to darker probably because of their specific chemical properties. There was also indicated sludge content in aged mineral oil, while in the vegetable oil, it was hardly observed. The BDV of both types of oil showed a dynamic behavior along the accelerated thermal aging process. There was a tendency of all oil samples to get lower BDV at the end of aging. We note that pure transformer oil reach break down voltage at value around 4.46 KV rms. When contamination is present in the oil then the break down voltage and dielectric strength of the oil will decrease.

All the heating procedures results in the production of some gases. This indicated the actual loss of chemical structure and significant breakage of chemical bonds. The resulting chemical composition of the oil does not produce the same effect as the initial oil sample.

When we add HCL to the vegetable oil with percentage of 4M and heated for 20 minutes, then applied voltage to the oil, with distance of about 0.1mm between the electrodes, the break down voltage decreased to 3.1 KV.

We can conclude that the addition of HCL and heated moisture badly decreases the BDV of the oil as when we compare Figures (6.1.1) with (6.1.2).

When we add  $\text{NaOH}_{(\text{aq})}$  to the vegetable oil with percentage 4M Fig (6.1.3) and heated for 20 minutes, then applied voltage to the oil, the break down voltage decreased then increase and at the decreased. So we can conclude that when we heat the oil and add a percentage of  $\text{NaOH}_{(\text{aq})}$  is badly decreasing the BDV of the oil.

We got the solute percentage content of HCL in the vegetable oil by multiplying the 12%  $4\text{mol}/\text{dm}^3$  of HCL we had, by the quantity of vegetable oil we used, which was  $0.25\text{dm}^3$ . Fig (6.1.4) was then obtained with the other specifications kept same. When we add  $\text{HCl}_{(\text{aq})}$  to the vegetable oil with percentage of  $4\text{mol}/\text{dm}^3$  and heated for 20 minutes, then applied voltage to the oil, with distance 0.1mm between the electrodes, the break down voltage decreased from 3.15KV to 2.01 KV.

When we heat the mineral oil for about 60 minutes with exposure to moisture, we get Fig (6.2.2). The same distance of 0.1mm between the electrodes was used  
When we add  $\text{HCl}_{(\text{aq})}$  to the mineral oil with percentage of 4M and heated for 60 minutes, then applied voltage to the oil, with distance 0.1mm between the electrodes, the break down voltage decreased to 3.77 KV .

When we add  $\text{NaOH}_{(\text{aq})}$  to the mineral oil with percentage of 4M and heated for 60 minutes, then applied voltage to the oil, with distance of about 0.15mm between the electrodes, the break down voltage decreased from 4.45KV to 4.02KV .

We got the solute percentage content of  $\text{HCl}_{(\text{aq})}$  in the mineral oil by multiplying the 12% 4M  $\text{HCl}_{(\text{aq})}$  we had, by the quantity of mineral oil we used ( $0.25\text{dm}^3$ ). So the BDV decreased to 3.86KV .

We can conclude that the addition of moisture,  $\text{HCl}_{(\text{aq})}$  and  $\text{NaOH}_{(\text{aq})}$  to the mineral oil and vegetable oils, as well as the heating, for some reasonable amount of time, badly decreases the BDV of the oil.

## Chapter 7: Conclusion and recommendations.

Following the fact that all the heating procedures results in the production of a toxic gas, we conclude that there was the actual loss of chemical structure and significant breakage of chemical bonds. The resulting chemical composition of the oil does not produce the same effect as the initial oil sample. There is, in effect, a reasonable point to conclude that; viewing the interesting trends we got from our graphs, and considering the already-proven scientific statements on transformer oil properties, we came out with the following conclusions:

1. Aged (acidified) transformer oil has a lower breakdown voltage. It can ruin the transformer's smooth functioning. This our conclusion is analogous to the following publication by **Power Substation Services**.<sup>[35]</sup>

Acid content in Oil. (N)	Oil status
0.01 – 0.03	Excellent
0.05 – 0.10	Good
0.11 – 0.15	Marginal
0.16 – 0.40	Bad
0.41 – 0.65	Very Bad
0.66 – 1.50	Extremely bad
Over 1.50	High Risk (Transformer failure imminent)

N= Normality.

2. Moisturized transformer oil has a lower breakdown voltage. Heat increases moisture solubility and soaking of the paper on the transformer windings.
3. Contaminated transformer oil can also reduce breakdown voltage by decreasing its dielectric insulation properties. We see that in the decreasing trend in the experiments with  $\text{NaOH}_{(\text{aq})}$ .
4. Also we would not leave out commenting on the beautiful trendy graph we got from the experiment with moisturized and overheated transformer and vegetable oil. There was a remarkable decrease in the transformer oil insulation properties. This was definitely because of the breaking of bonds and formation of smaller molar mass compounds which do not have good insulation and dielectric properties. As we can see from Fig(6.2.1), we observed the formation of many bubbles when we reached high temperatures. Bubbles, which considerably decrease surface tension, are a veracious indication of the presence of impurities; in this case, moisture.
5. Arcing horn gaps can be used to prevent over-voltages and other impulse voltage surges.<sup>[36]</sup>
6. Corona rings could also be used to distribute the electrical fields, preventing the protected hardware and the corona ring itself from corona. This can be used on 138Kv voltage lines or higher.
7. Most importantly, acknowledging the fact that transformer oil, despite its fantastic insulation and cooling properties, it has a major disadvantage of being highly toxic to

the environment, and very low biodegradability. We would love to borrow, word for word, **Sweden's ABB's** ideals on transformer oil purification and recycling with the main goal of sustainability:<sup>[37]</sup>

*“Reclaiming oil with a reactivated Fullers earth system is the only economical method to restore the properties of the transformer oil to close to the values of new oil with a lasting effect. Also reclaiming oil provides an environmental advantage – instead of replacing a non-renewable resource, the oil is processed”.*

## References.

[1] Accessed on the 26<sup>th</sup> of January 2014. <https://www.hsb.com/TheLocomotive/AnAnalysisofInternationalTransformerFailuresPart1.aspx>

[2] Accessed on 26<sup>th</sup> January 2014 <http://physics.info/photoelectric/>

[3] Accessed in January 2014 <http://www.phys.tue.nl/FLTPD/invited/veldhuizen.pdf>

[4] Accessed in January 2014 [http://www.buenomak.com.br/publicacoes/pdf/FALHAS-pyrolysis\\_add\\_electrical\\_arcing\\_faults.pdf](http://www.buenomak.com.br/publicacoes/pdf/FALHAS-pyrolysis_add_electrical_arcing_faults.pdf)

Also:

[5] Accessed in January 2014  
[http://www.willis.com/Documents/publications/Services/Property/Arc\\_Flash.pdf](http://www.willis.com/Documents/publications/Services/Property/Arc_Flash.pdf)

Also: <http://www.electricalinfo.co.in/difference-between-arcing-horn-gap-and-corona-ring/>

[6] Electronic and Electrical Engineering Principles and Practice. By Lionel Warnes. Page 310.

[7] Accessed in January 2014  
[http://macao.communications.museum/eng/exhibition/secondfloor/moreinfo/2\\_4\\_2\\_transformer.html](http://macao.communications.museum/eng/exhibition/secondfloor/moreinfo/2_4_2_transformer.html)

Also: Electrical Circuit Theory and Technology by John Bird. Second Edition. Equation 20.11. page 330.

[8] Accessed in January 2014  
[http://www.electricenergyonline.com/show\\_article.php?mag=&article=54](http://www.electricenergyonline.com/show_article.php?mag=&article=54)

[9] Accessed in January 2014 page 384(1) of "Aging Study and Lifetime Estimation of Transformer Mineral Oil" ISSN 1941-7020

[10] Accessed in January 2014 <http://www.electrical4u.com/transformer-insulating-oil-and-types-of-transformer-oil/>

[11] Accessed in January 2014 "The J & P Transformer Book, 13th ed" page 77.

[12] Accessed in January 2014 "The J & P Transformer Book, 13th ed" page 79.

[13] Accessed in January 2014  
<http://www.chemguide.co.uk/organicprops/alkanes/background.html>

[14] Accessed in January 2014 <http://www.inchem.org/documents/ehc/ehc/ehc150.htm> chapters 2.4.1, and 2.1 .

Also: Chemistry in Context, 4<sup>th</sup> Edition page 159.

[15] Accessed in January 2014. <http://mmthkpjds.blogspot.se/2011/05/esters.html>

[16] Accessed in October 2013. [http://en.wikipedia.org/wiki/Transformer\\_oil](http://en.wikipedia.org/wiki/Transformer_oil)

[17] Accessed in October 2013. Tan delta. <http://www.electrotechnik.net/2009/05/tan-deltatest-on-insulation.html>

[18] Accessed in October 2013. <http://www.monashscientific.com.au/TotalAcidity.htm>

[19] Accessed in October 2013. <http://www.electrical4u.com/transformer-insulating-oil-and-types-of-transformer-oil/>

[20] J. K. Nelson "Electric Strength of Transformer Oil for Large Electrode Areas", *Proc. IEE*, vol. 118, no. 2, pp.388 -393 1971

[21] A study of electrical characteristics of mineraltransformer oils with reduced and increased viscosity by Pompili, M; Campi, R

[22] Accessed in November 2013. <http://electrical-engineering-portal.com/resources/knowledge/electrical-machines/dielectric-dissipation-factor>

[23] S. Cygan and J. R. Laghari "Dependence of the Electric Strength on Thickness, Area and Volume of Polypropylene", *IEEE Trans. on Elec. Insul.*, vol. EI-22, no. 6, pp.835 -837 1987

[24] Accessed in February 2014.  
[http://www.guvnl.com/Tender/File/GETCO/Corporate%20Office/02/BBBB/TECH\\_SPECIFICAION\\_Trans\\_oil\\_as\\_%20IS335\\_R\\_1\\_Jan\\_09.pdf](http://www.guvnl.com/Tender/File/GETCO/Corporate%20Office/02/BBBB/TECH_SPECIFICAION_Trans_oil_as_%20IS335_R_1_Jan_09.pdf) page 7.

[25] Accessed in November 2013. [http://en.wikipedia.org/wiki/Flash\\_point](http://en.wikipedia.org/wiki/Flash_point)

[26] Accessed in November 2013. <http://schools.matter.org.uk/SchoolsGlossary/permittivity.html>

[27] Accessed in November 2013. [http://en.wikipedia.org/wiki/Relative\\_permittivity](http://en.wikipedia.org/wiki/Relative_permittivity)

[28] Accessed in December 2013.  
<http://www.attension.com/applications/measurements/interfacial-tension>

[29] Accessed in December 2013. [http://en.wikipedia.org/wiki/Dielectric\\_strength](http://en.wikipedia.org/wiki/Dielectric_strength)

[30] Accessed in December 2013. [http://en.wikipedia.org/wiki/Electrical\\_insulation\\_paper](http://en.wikipedia.org/wiki/Electrical_insulation_paper)

[31] Accessed in December 2013. <http://www.eatechnology.com/partial-discharge>

[32] Accessed in December 2013. Joseph B. DiGiorgio, Ph.D.

<http://www.nttworldwide.com/tech2102.htm>

[33] Accessed in December 2013. <http://www.nttworldwide.com/dga.htm>

[34] Accessed in December 2013. IEEE Guide for Diagnostic Field Testing of Electrical Power Apparatus, Part 1: Oil Filled Power Transformers, Regulators, and Reactors, Institute of Electrical and Electronic Engineers. IEEE 62-1995

[35] Accessed in January 2014. Power Substation Services. USA.

<http://www.powersubsvcs.com/images/PSS%20Oil%20Results%20Summary.pdf>

[36] Accessed in January 2014. <http://www.electricalinfo.co.in/difference-between-arcing-horn-gap-and-corona-ring/>

[37] Accessed in November 2013. ABB. Sweden.

[http://www05.abb.com/global/scot/scot252.nsf/veritydisplay/a6e0f19742f55df5c1257959002fed03/\\$file/DEABB%201572%2010%20en\\_Datasheet\\_Oil%20reclaiming%20Solutions%20for%20aged%20oil.pdf](http://www05.abb.com/global/scot/scot252.nsf/veritydisplay/a6e0f19742f55df5c1257959002fed03/$file/DEABB%201572%2010%20en_Datasheet_Oil%20reclaiming%20Solutions%20for%20aged%20oil.pdf)