STUDY ON THE DURABILITY OF TRANSFORMER INSULATING OILS UNDER REPEATED ELECTRICAL BREAKDOWN CONDITIONS

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This report is submitted in partial fulfilment of the requirements for the award of a Bachelor of Electrical Engineering with Honour

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DECLARATION

I declare that this thesis entitled "STUDY ON THE DURABILITY OF THE TRANSFORMER INSULATING OILS UNDER REPEATED ELECTRICAL BREAKDOWN CONDITIONS" 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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Date : 5/07/2021

APPROVAL

I hereby declare that I have checked this report entitled "Study On The Durability Of The Transformer Insulating Oils Under Repeated Electrical Breakdown Conditions" and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Electrical Engineering with Honour.

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DEDICATION

Special thanks to my beloved father and mother, my siblings, project supervisor and friends. Thank for their motivation and their sacrifice.

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Alhamdulillah, all praise to Allah and Prophet Muhammad S.A.W. I would like to express my deepest gratitude to Almighty Allah for giving me the strength, blessing, and opportunity to complete this research entitled "The Study on Dielectric Strength Durability of Transformer Insulating Oils Under Repeated Electrical Breakdown Conditions".

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ABSTRACT

Transformers play a significant role in power generation networks. Transformer insulating oil is an essential fluid that ensures the proper working of the transformer. Hence, it is crucial to monitor the state of a transformer insulating oils to avoid premature malfunction. However, transformer insulating oils do not last forever because the degradation caused by repeated electrical breakdown, thermal ageing and mechanical stress subjected to the oils during its functional period. Thus, it is essential to study the durability and properties of transformer insulating oil to maximise its performance as the insulating oil in the transformer. This research is intended to study the dielectric strength durability of transformer insulating oils under repeated electrical breakdown conditions and to analyse the result of dielectric strength durability of transformer insulating oil subjected to repeated electrical breakdown conditions via statistical evaluation tool. The portable oil dielectric strength tester and Karl Fischer Titration Coulometer (KFC) are used to conduct the AC breakdown voltage and moisture content measurement test according to the test standard of ASTM D1816 and D1533, respectively. The analysis of the results is performed via statistical evaluation tools, which intended to evaluate the test result via statistical tools such as linear correlation and regression, scatterplot, and histogram. The result found that natural ester has better dielectric strength durability than mineral insulating oil by looking at statistical tools. This might be due to the hydrophilic (the substance that attracts water) substance of the natural ester that capable of mixing well and dissolving water with a five to eight times greater water saturation limit than mineral insulating oil. However, many unknown factors may also contribute to the reduction of the dielectric strength of the oil. Hence, the factors that might affect breakdown voltage have also been discussed.

ABSTRAK

Transformer memainkan peranan penting dalam rangkaian penjanaan kuasa. Minyak penebat transformer adalah cecair penting yang memastikan transformer berfungsi dengan baik. Oleh itu, sangat penting untuk memantau keadaan minyak penebat transformer untuk mengelakkan kerosakan pramatang. Walau bagaimanapun, minyak penebat transformer tidak bertahan lama kerana kemerosotan disebabkan oleh kerosakan elektrik berulang, penuaan terma dan tekanan mekanikal yang dikenakan pada minyak semasa tempoh fungsinya. Oleh itu, adalah penting untuk mengkaji daya tahan dan sifat minyak penebat transformer untuk memaksimumkan kinerjanya sebagai minyak penebat didalam transformer. Penyelidikan ini bertujuan untuk mengkaji ketahanan kekuatan dielektrik minyak penebat transformer dalam keadaan kerosakan elektrik berulang dan untuk menganalisis hasil ketahanan kekuatan dielektrik minyak penebat transformer yang mengalami keadaan kerosakan elektrik berulang melalui alat penilaian statistik. Penguji kekuatan dielektrik minyak mudah alih dan Karl Fischer Titration Coulometer (KFC) digunakan untuk menjalankan ujian pengukuran voltan kerosakan dan kandungan kelembapan masing-masing mengikut standard ujian ASTM D1816 dan D1533. Analisis hasil dilakukan melalui alat penilaian statistik, yang bertujuan untuk menilai hasil ujian melalui alat statistik seperti korelasi dan regresi linier, scatterplot, dan histogram. Hasil kajian mendapati bahawa ester semula jadi mempunyai daya tahan kekuatan dielektrik yang lebih baik daripada minyak penebat mineral dengan melihat alat statistik. Ini mungkin disebabkan oleh zat hidrofilik (bahan yang menarik air) ester semula jadi yang mampu mencampurkan dengan baik dan melarutkan air dengan had tepu air lima hingga lapan kali lebih besar daripada minyak penebat mineral. Walau bagaimanapun, banyak faktor yang tidak diketahui boleh menyumbang kepada pengurangan kekuatan dielektrik minyak. Oleh itu, faktor-faktor yang mempengaruhi voltan kerosakan juga telah dibincangkan.

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CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter presents the background of the study, motivation, problem statement, research objective, the scope and limitation of the study.

1.2 Background of the Study

Transformers are one of the important components in power generation networks. The primary function of transformers is to reduce the transmission losses by regulating the voltage level of electricity flowing in a circuit. The failure of transformer may cause serious problems. Therefore, the main factor that effect the lifetime of the transformers was identified as the deterioration of insulation paper [1]. It is crucial to monitor the operation of a transformer to avoid premature malfunction or breakdown from occurring. There are various properties of transformer insulating oils that need to be considered to determine its durability. These included the breakdown voltage, dielectric strength, viscosity, water contents and etc [2]. There are several types of transformer oil which are known as mineral insulating oil, natural-ester insulating oil, and synthetic-ester insulating oil. Mineral oil is the most used oil in impregnated power transformer. These is because it has low dielectric losses, good cooling properties, and compatibility with cellulose paper etc. [3]. However, due to the need for using environmentally friendly and sustainable oils, other types of oil such as natural esters seen possess better properties for replacing mineral oil. Natural esters are highly biodegradable and demonstrate better environmental performances compared to Mineral Oil. Thus, this project is focused on studying the dielectric strength durability of transformers insulating oils under repeated electrical breakdown conditions.

1.3 Motivation

Transformer insulating oils were used over 100 years ago. The main functions of transformer insulating oils are to act as a cooling medium, electrical insulation, and as an information carrier [3]. The transformer cooling system circulates the oil through the core and wind to the cooler of the transformer for the heat dissipation process. The viscosity of oil plays an important role in the cooling system of a transformer. Lower viscosity promotes better cooling process. Transformer oil acts as an electrical insulation where generally low water content in oil will result in good breakdown voltage. Besides, transformer oil also acts as an information carrier when it contained abnormal quantities of particles, compounds, water, and acids. This indicates there is an abnormal operation of the transformer that can lead to catastrophic failure. Transformer oil also provides information on paper degradation, water content, and temperature inside the transformer. Thus, it is important to study the dielectric strength durability and transformer insulating oils properties under repeated electrical breakdown to avoid the catastrophic breakdown of the transformer.

1.4 Problem Statement

Transformer oil is essential to maximise the life of impregnated power transformers. However, transformer insulating oils do not last forever because of the degradation that may causes by repeated electrical breakdown, thermal ageing and mechanical stress subjected to the oils during its functional period. Numerous properties such as dielectric strength and dissipation factor (electrical properties), water content and acid number (chemical properties), viscosity, relative density, flashpoint, and fire point (physical properties) need to be considered when qualifying oils as the transformer insulating oil [4]. This research aims to study the dielectric strength durability of insulating oil under repeated electrical breakdown conditions to observe and understand the dielectric strength performance of mineral and natural ester insulating oils under repeated breakdown conditions.

1.5 Research Objective

The general objective of this study is outlined below:

1) To study the dielectric strength durability of transformer insulating oils under repeated electrical breakdown conditions.

2) To analyse the result of dielectric strength durability of transformer insulating oil subjected to repeated electrical breakdown conditions via statistical evaluation tool.

1.6 Scope and Limitation

This study covered the durability of transformer insulating oils under repeated electrical breakdown conditions. The equipment used in this project is a portable oil dielectric strength tester (Model: OTS60PB, Megger Ltd., UK). The experiment conducted was to observe the dielectric strength of the mineral and natural ester insulating oil under repeated electrical breakdown. The dielectric strength of transformer oil was observed through the AC breakdown voltage test that complied with ASTM D1816 standard. ASTM D1816 is a Standard Test Method for Dielectric Breakdown Voltage of Insulating Liquids Using VDE Electrodes with the gap distance between the electrodes set at 1 mm. The test procedure was followed carefully according to ASTM D1816 to execute and obtain the correct value of dielectric strength of the tested insulating oil. Besides, the Karl Fischer Titration (KFC) method is used to measure transformer insulating oils' moisture content by complying with the ASTM D1533 standard. ASTM D1533 is a Standard Test Method for Water in Insulating Liquids by Coulometric Karl Fischer Titration.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter reviews the literature related to this study. Related theories and relevant information such as types of transformer insulating oil tested, factors that influence the dielectric breakdown voltage of the insulating oil, method and standard use in this project and statistical evaluation tools to analyse the data are described in this chapter.

2.2 Types of Insulating Oil

There are several types of insulating oil that commercially available for transformers, such as mineral insulating (MI) oil, natural-ester insulating (NEI) oil, and synthetic-ester insulating (SEI) oil. However, this report is focused only on MI and NEI oils.

2.2.1 Mineral Insulating Oil

Petroleum oil was used for transformer oil since 1891, which is also known as mineral insulating (MI) oil. MI oil plays a major role as an electrical insulation and a cooling medium in the transformer. MI oil is usually obtained from distillation and treatment of crude oil of the petroleum [4]. It is the most used oil as an insulating liquid because it offers good properties and low cost [5]. MI oil has good cooling properties; low viscosity, good aging properties, and low cost compared to other types of insulating liquid.

However, MI oil is a non-biodegradable product that may cause serious environmental issues if spillage occurs. This may harm living organisms and ecosystems at the spill areas. Besides, low flash point and fire point. The raw materials of MI oil are unstable and flammable and start evaporating at a high temperature [6].

After a certain temperature, the mixture of this oil vapour and atmospheric air produces a highly combustible product. Moreover, MI oil is a petroleum-based product that will exhaust in the future because it is a non-renewable product [5]. Thus, understanding the properties of insulating liquid is important to study the behaviour of the MI oil in the transformer insulating liquid.

2.2.2 Ester-Based Insulating Oil

Ester-based oils, also known as vegetable oils, are dielectric fluids that are alternative to MI oil that commonly used in distribution and power transformers over a century ago. There are two types of ester-based oils: natural ester insulating (NEI) oil and synthetic ester insulation (SEI). These oils are seen to be alternatives to replace MI oil as they offered better environmental properties. Besides, Ester-based oil is renewable, biodegradable, and less flammable than MI oil, making them suitable as an alternative to mineral oils.

However, ester-based oil has a higher viscosity, affecting the circulation of oil for heat transfer in the transformer. The higher pour point of oils also makes it unsuitable to be used as transformer oil in cold region countries. However, ester fluids have higher thermal conductivity and heat capacity compared to mineral oil. These better properties compensate for the higher viscosity of natural ester, the viscosity of oil decreases as the temperature increases [7]. Thus, this research only focussing on NEI oil. According to [9], NEI oil needs to be purified to improve the insulation properties. BIOTEMP and Envirotemp FR3 are examples of the purified type of natural esters which are commercially available as an alternative to MI oil.

2.3 Electrical Breakdown Conditions of Insulating Oil

Electrical breakdown condition happens when the insulating liquid becomes a conductor under the influence of high voltage stress. In a transformer, insulating oil is continuously exposed to repeated electrical discharge resulted in breakdown of electrical insulation under the abnormal circumstances. Since the electrical discharge is unavoidable, it is important to know the behavior of insulating oil properties under repeated electrical discharge to avoid insulation failure and the breakdown of transformer happened. The ability of the insulating oil to resist decomposition under repeated electrical discharged is one of the important factors for the safety of the transformer. Repeated electrical discharges in the presence of heat, moisture, and oxygen oxidize the oil and produce free radicals, acids, and sludge that are harmful to the transformer [16]. So that, it is crucial to study the dielectric strength durability of insulating oil to avoid catastrophic failure of the transformer.

2.4 Factors That Affect the Dielectric Breakdown Voltage of the Insulating Liquid

Dielectric breakdown voltage or also known as dielectric strength, is one of the important parameters in defining the durability of insulating oil in a transformer. Dielectric strength is defined as the maximum strength of the material that can continuously withstand electrical stress without causing breakdown. According to authors [2], dielectric strength is the maximum electrical stress in terms of voltage, which transformer oil can withstand to sustain its performance without breakdown and normally monitored by sampling during its functional lifetime. It has been reported that breakdown voltage is affected by several factors, such as water contents (moisture), contamination (foreign particles), etc. This study on dielectric strength durability of transformer insulating oils under repeated electrical breakdown conditions is performed by controlling the amount of moisture content allowed in insulating oils according to the standard before the Ac breakdown voltage test performed. This is because moisture is one of the most crucial parameters determining dielectric strength, as oxygen may frequently infiltrate into oils. However, the literature review on electrical discharge, temperature and gassing tendency also has been made to add up some knowledge about the factors that affected the dielectric breakdown voltage of the insulating oil.

2.4.1 Moisture/Water Content

Moisture or water content is an essential factor that influences the lifetime of an insulating oil system. The presence of moisture affects the breakdown voltage of the insulating liquid. Besides, moisture can alter the physicochemical property of an oil and drastically affects the breakdown voltage [10]. This is because the presence of moisture breaks down the molecular chains of the insulating oil [11]. Internal sources and atmosphere form the moisture in insulating oils. Water enters the transformer through the leaking gasket, cracked insulation, degradation of paper etc. The increase of water content in insulating oil will lead to an increase of dielectric loss and electric conductivity while reducing breakdown voltage of insulating oil [10]. According to the standards, ASTM D3487 and D6871, the water contents in MI oil and NEI oil should not exceed 35 ppm and 200 ppm, respectively. Table 2.1 compares the specification values of water content between the mineral and natural ester insulating oil in accordance with the standard ASTM D3487 and D6871.

Table 2.1: Comparison specification values of water content between mineral and natural ester insulating oil

Properties		ASTM standard test method	Mineral oil (ASTM D3487)	Natural Ester (ASTM D6871)
Chemical properties	Water content (ppm)	D1533	≤ 35	≤ 200

2.4.2 Contamination/Particles

Contamination or particles in an insulating liquid is a foreign product that can affect the dielectric strength of insulation oil. The foreign product may be introduced by the formation of sludge, oxidation of a material in transformer such as paper, paint, and others. There are several properties that indicate the contamination level in insulating oil such as dielectric strength, acid number, interfacial tension, colour, and water content [12]. The breakdown strength can be enhanced by reducing the number of dispersed particles in transformers [13]. This is because contaminating particles (metallic or non-metallic) in a high electric field can lead to particle discharge which results in a catastrophic failure in transformers [13]. According to the standard ASTM D3487 and D6871, the dielectric strength, acid Number, interfacial tension, colour, and water content in MI oil and NEI oil should not exceed or less than the specified value. Table 2.2 shows the specification values of the dielectric strength, acid Number, interfacial tension, colour, and water content between the mineral oil and natural ester fluid.

Table 2.2: The specification values of the dielectric strength, acid number, interfacial tension, colour and water content between mineral oil and natural ester fluid.

Properties		ASTM standard test method	Mineral oil (ASTM D3487)	Natural-Ester (ASTM D6871)
Electrical properties	Dielectric strength (kV)	D1816 (1-mm gap)	≥ 20	≥ 20
		D1816 (2-mm gap)	≥ 35	≥ 35
Chemical properties	Water content (ppm)	D1533	≤ 35	≤ 200
	Acid number (mg KOH/g)	D974	≤ 0.03	≤ 0.6
Physical properties	Colour	D1500	≤ 0.5	≤ 1.0
	Visual examination	D1524	Clear and bright	Clear and bright
Interfacial tension (dyne/cm)		D971	≥ 40	—

2.4.3 Temperature

Temperature is one of the factors that affects the breakdown voltage in the power transformer insulating oil. Moisture is generated in transformers as the cellulose insulation ages at elevated temperatures. As a result, the dielectric strength of the insulating system decreasing as the moisture content rises due to high temperature. Temperature affects the moisture content of the insulating liquid. According to researchers [11], the average breakdown voltage of insulating oil decreases to be below 60 kV as the temperature increases to 60°C. However, the average breakdown voltage regains to increase to 55, 60, and 59 kV when the temperature was increased to 80, 100, and 120°C, respectively. Table 2.3 shows the effect of temperature on the breakdown voltage of the insulating oil samples.

Table 2.3: The effect of temperature on the breakdown voltage of the insulating oil samples [11]

Effect of Temperature on the breakdown voltage of the insulating oil samples

Temperature (°C)	Breakdown voltage (kV) 1	2	3	4	5	6	Average
22 (ambient temperature)	60	60	60	60	60	60	60
40	43	50	54	39	36	43	44
60	51	42	43	40	34	34	41
80	60	53	53	51	55	58	55
100	59	60	60	60	60	60	60
120	57	59	60	60	60	60	59

Table 2.3 depicts that when insulating oil samples are heated nearly to the boiling point temperature, the water began to vaporize which resulted in the increased breakdown voltage. A similar trend was also reported in [14] which described that there is a clear tendency of reduction of water content when the thermal ageing time increased. The moisture content increased in the first stage of ageing (before 90h) and decrease after that. According to the authors, this is because no precaution regarding to the temperature and humidity of the experimental room was taken when filling the bottles with the oil samples. Moreover, significant quantities of oxygen can infiltrate the bottle during the process of filling the oil sample into the bottle. This justifies why the water increases at the beginning of the heating process. However, the water content decrease after the 90h of the heating process as it evaporates when temperature increased. Therefore, as the water content decreases, the breakdown voltage increases. Figure 2.1 shows the relationship between the water content and breakdown voltage toward ageing time.

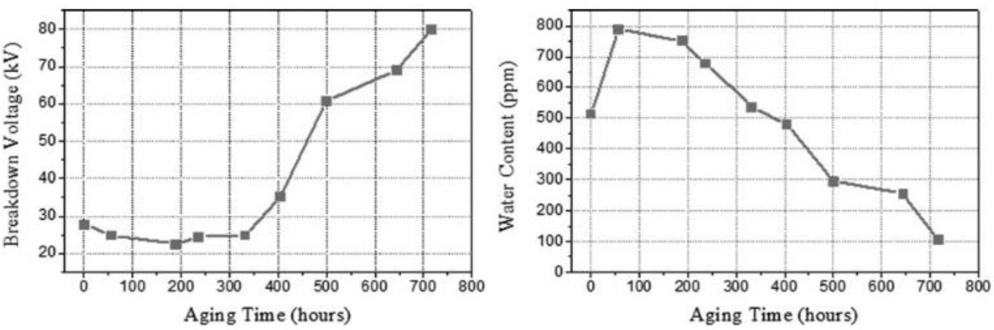

Figure 2.1: The relationship between the water content and breakdown voltage toward ageing time [14]

2.4.4 Gassing Tendencies

The gassing tendency is defined as the rate of gas evolved or absorbed by an insulating oil when subjected to electrical stress of sufficient intensity to cause ionization. The high voltage during electrical stress provides the required energy for the decomposition of weak hydrocarbons bond. According to the authors [17], during the decomposition or breakdown of the certain vulnerable hydrocarbon chain, a small fraction evolves as a gas and a chemically large free radical. As a result, the breakdown of the hydrocarbon bonds may form free radicals such as H*, CH_3*, CH_2* and CH*.

All these radicals then recombine to form fault gases such as H*+H*→H_2 (hydrogen gas), H*+CH_3*→CH_4 (methane gas), CH_3*+CH_3*→C_2H_6 (ethane gas), CH_2*+ CH_2*→C_2H_4 (ethylene gas), and CH*+ CH*→C_2H_2 (acetylene gas). The breakdown of the hydrocarbon bond results in the emergence of flammable gases, such as ethylene (C_2H_4) and acetylene (C_2H_2) [11]. Thus, the presence of flammable gases especially acetylene (C_2H_2), may significantly affect the flash point of oil [14]. This indirectly also lowers the breakdown voltage of insulating oils.

2.5 Standard Related to the Study of Transformer Insulating oil

To determine whether the insulating oils are in good and suitable condition for using in a transformer as insulating oil, it must refer to a standard that provides the information on the values that the oils must be fulfilled. There are a few standards specification for insulating oil such as ASTM D3487, ASTM D6871, IEC 60296, and IEC 62770. However, the standard used to determine the properties of transformer insulating oils for this study is ASTM D3487 and ASTM D6871. These two standards provide the information for standard specification for mineral insulating oil and natural ester (vegetable oil) fluids used in electrical apparatus. Besides, ASTM D1816 and ASTM D1533 also being used as a guideline while conducting the AC breakdown voltage and water content measurement testing. The ASTM D1816 and ASTM D1533 are the "Standard Test Method for Dielectric Breakdown Voltage of Insulating Liquids Using VDE Electrodes and "Standard Test Method for Water in Insulating Liquids by Coulometric Karl Fischer Titration". Table 2.4 summarise several specification values of mineral and natural ester insulating oils in accordance with the standard ASTM D3487 and D6871.

Table 2.4: Summarization of specification values of mineral oil and natural ester fluid

Properties			ASTM standard test method	Mineral oil (ASTM D3487)	Natural-Ester (ASTM D6871)
Electrical properties	Dielectric strength (kV)		D1816 (1-mm gap)	≥ 20	≥ 20
			D1816 (2-mm gap)	≥ 35	≥ 35
	Dissipation	25°C	D924	≤ 0.05	≤ 0.20
		100°C	—	≤ 0.30	≤ 4.0
Chemical properties	Water content (ppm)		D1533	≤ 35	≤ 200
	Acid number (mg KOH/g)		D974	≤ 0.03	≤ 0.6
Physical properties	Colour		D1500	≤ 0.5	≤ 1.0
	Visual examination		D1524	Clear and bright	Clear and bright
	Relative density		D1298	≤ 0.91	≤ 0.96
	Flash point (°C)		D92	≥ 145	≥ 275
	Fire point (°C)		D92	—	≥ 300
	Viscosity	100 (°C)	D445	≤ 3.0	≤ 15.0
		40 (°C)	—	≤ 12	≤ 50
Pour point (°C)			D97	≤ −40	≤ −10
Interfacial tension (dyne/cm)			D971	≥ 40	—

2.6 Statistical Evaluation Tools to Analyses the Data

To analyse the data, there are a few techniques that can be utilised which are linear correlation and regression, scatterplot, and histogram analysis. This statistical evaluation tools are used to forecast the data in a graphical format so that the relationship of the data may be easily assessed.

The correlation analysis gives information on the strength and direction of the linear relationship between two variables. Meanwhile, linear regression analysis is used to estimates parameters in a linear equation the values of one variable based on the values of the other. The data is presented in scatter plots diagram. Scatter plot are pairs of numerical data that are linked to one another by a variable on each axis. The points of data will fall along a line or curve if the variables are correlated. The position of the point on the best fit line determines the degree of correlation between two variables. The tighter the points lie along the best fit line, the stronger the correlation. Besides, if the point fall randomly or without any pattern, it is said that the two variables are weak or not correlated. A part of that, scatterplot also give information about type of correlation between two variables. There is a positive relationship (positive correlation) between the variables if the points on the scatter plot seem to form a line that slants up from left to right. Meanwhile, negative relationship (negative correlation) between the variables occurred when the points on the scatter plot seem to form a line that slants down from left to right. Figure 2.2 shows the degrees and types of correlation of variable on each axis.

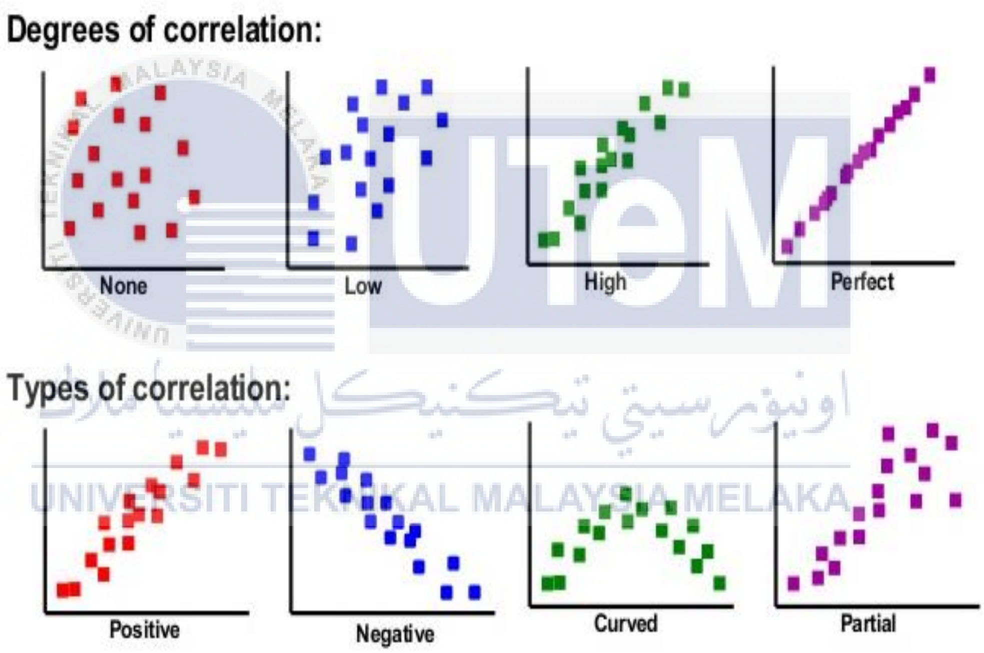

Figure 2.2: The degrees and types of correlation of variables [25]

The histogram is a graphical data representation that shows the frequency of occurrence of each value in a set of data. This tool allows the user to visualise the distribution of data. The typical histogram shape is normal distribution, bimodal, positively, and negatively skewed. The normal distribution or also known as a bell-shaped curve is a typical pattern where the points are equally likely to occur on either side of the average of the distribution. Furthermore, bimodal is a distribution with two