TRACKING AND EROSION PERFORMANCE OF SILICONE RUBBER UNDER AC AND -DC VOLTAGE

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“I hereby declare that I have read through this report entitle “*Tracking and Erosion Performance of Silicone Rubber Under AC and -DC Voltage*” and found that it has comply the partial fulfilment for awarding the degree of Bachelor of Electrical Engineering (Industrial Power)”

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A thesis submitted in fulfilment of the requirement for the degree of Bachelor of Electrical Engineering (Industrial Power)

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I declare that this report entitle "*Tracking and Erosion Performance of Silicone Rubber under AC and -DC Voltage"* is the result of my own research excepts as cited in the references. This report has not been accepted for any degree and is not concurrently submitted in candidature of any degree.

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Name : Omar Bin Ismail

Date :

To my beloved mother and father

For their endless love, support and encouragement

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ABSTRACT

Silicone rubber (SIR) are broadly used as the insulation materials in high voltage engineering either in AC or DC electrical power system due to their advantages. The increase of interested in polymeric high voltage insulation technology has been driving the force for a lot of research on silicone rubber performance. However, the life term performance or aging of silicone rubber is still questionable. The most common method to determine their aging is by conducting tracking and erosion test, but the tracking and erosion test is only available in AC voltage. Thus the study on silicon rubber (SIR) in DC voltage is vital. In this study, tracking and erosion of SIR were evaluated under DC and AC voltage. Since there is no standard method for DC tracking and erosion, AC Incline Plane Tracking (IPT) BS EN 60587:2007 international standard was complied. Method 1 in BS EN 60587:2007, the application of constant tracking voltage was applied in this test. The test parameter voltage and flow rate for this test are -3.5kV DC, 3.5kV AC and 0.3ml/min respectively. Besides, surface temperature of SIR was measured for every 30 minutes during both AC and DC IPT test. The surface temperature was measured by using IRISYS IRI – 4010 Thermal Imager. In terms of tracking and erosion, SIR under -DC voltage test experienced more severe damage as compared to SIR under AC voltage test. Moreover, surface temperature of SIR in -DC IPT test were also higher than surface temperature of SIR in AC IPT test.

ABSTRAK

Getah silikon secara umumnya digunakan sebagai bahan penebat dalam bidang kejuruteraan voltan tinggi sama ada dalam sistem kuasa elektrik arus ulang-alik (AU) mahupun arus terus (AT) kerana kelebihan mereka. Peningkatan tumpuan terhadap teknologi penebatan polimer voltan tinggi telah membawa kepada pelbagai penyelidikan mengenai kebolehan getah silikon. Walau bagaimanapun, prestasi jangka hayat atau penuaan getah silikon masih menjadi persoalan. Kaedah yang biasa digunakan untuk menentukan penuaan mereka adalah dengan menjalankan ujian pengesanan dan hakisan, tetapi ujian pengesanan dan hakisan hanya terdapat dalam voltan AU. Oleh itu, kajian mengenai getah silikon dalam voltan AT adalah sangat penting. Dalam kajian ini, pengesanan dan hakisan terhadap getah silikon telah dinilai dengan menggunakan voltan AU dan voltan AT. Oleh kerana tiada kaedah khusus untuk menilai pengesanan dan hakisan terhadap getah silikon dengan menggunakan voltan AT, piawaian antarabangsa Pengesanan Satah Condong (PSC) BS EN 60587: 2007 telah digunakan sebagai panduan. Kaedah 1 dalam BS EN 60587: 2007, penggunaan voltan pengesanan tetap telah digunakan dalam ujian ini. Nilai voltan dan kadar alir bagi ujian ini adalah masing-masing -3.5kV AT, 3.5kV AU dan 0.3ml/min. Selain itu, suhu permukaan getah silikon diukur bagi setiap 30 minit semasa ujian AT dan ujian AU. Suhu permukaan diukur dengan menggunakan IRISYS IRI - 4010 Pengukur Haba. Dari segi pengesanan dan hakisan, getah silikon yang diuji menggunakan voltan -AT mengalami kerosakan yang lebih teruk berbanding getah silikon yang diuji menggunakan voltan AU. Selain itu, suhu permukaan getah silikon dalam ujian -AT juga lebih tinggi daripada suhu permukaan getah silikon dalam ujian AU.

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LIST OF ABBREVIATIONS

IPT - Incline Plane Tracking

DC - Direct Current

AC - Alternating Current

SIR - Silicone Rubber

LC - Leakage Current

UV - Ultraviolet

STRI - Swedish Transmission Research Institute

LMW - Low Molecular Weight

FYP - Final Year Project

LV - Low Voltage

HV - High Voltage

CHAPTER 1

INTRODUCTION

1.1 Research Background

Insulation is the most important part to avoid the flow of current to the unwanted path in high voltage engineering or its application [1]. There are two type of solid insulation in high voltage application which are glass/ceramic and polymer. In 1940s, the history of polymeric insulation material had begun when epoxy resin was used as insulating material [2]. Then, in 1950s polymeric insulation material was develop for AC transmission line [3]. Previously, before the introduction of polymeric insulation, the industry of high voltage insulation was dominated by the ceramic and glass insulation. The ceramic insulation were slowly replaced by polymeric insulation due to the excellent properties of polymer such as their light weight which reduces the installation cost, transporting and easy of handling. Polymeric insulation materials are also flexible in design and it has a hydrophobic nature. The hydrophobic properties of polymer reduces transmission losses especially during the initial years of their service [4][5].

The most temptation characteristic of polymeric insulation is the hydrophobic behaviour. Hydrophobic properties can be defined as a water repellent properties on the surface of the material. The hydrophobic characteristic of materials can reduce the existence of contaminant since it avoid the water droplets from spreading over the surface of the insulation material. Thus, preventing the occurrences of tracking and erosion on the surface of polymer during wet condition. Besides of tracking and erosion, the major factors that determine the insulation failure are the dielectric strength and electrical field strength which are the main properties of insulating material [1].

Moreover, polymeric insulation materials has high capability of handling of mechanical shock loads which also improved the resistance to vandal damage Next, their performance in contaminated condition also improve since polymeric insulation might be produced with a slighter surface area and longer leakage part [6].

The used of polymeric materials are widely applied in many application of outdoor high voltage insulation such as the bus bar insulation, surge arresters and cable termination. However, despite of their great function ability, polymeric insulation materials also have their weaknesses such as the temporary loss of hydrophobicity which will affect their long term endurance as a high voltage insulator [4]**.** Thus, the questions about the life long performance of polymeric insulation still exist even though this type of insulator had been used for decades of service. The capability of the polymeric insulation to resist physical and chemical degradation effectively when expose to continuous voltage stress and variety of environmental stress such as rain, heat, salt fog, ultraviolet radiation and industrial pollution were still dubious. The degradation of polymeric insulation materials will usually lead to failure of the insulation and this was due to the tracking and erosion phenomenon caused by the contaminated condition and environmental factors [1][7].

In addition, mostly the study done on polymeric insulation were usually based on AC voltage [8]. Less study were done on DC voltage supply. Therefore, this study focused on comparison between alternating current (AC) and the direct current (DC) tracking and erosion on polymeric insulation material. The reliability of DC outdoor insulation need to be understand since the market share of high voltage transmission distribution is increase

[9]. There were some reports propose that the insulator under DC have higher conductivity and higher leakage current than under AC since the contaminants are more easily to accumulate on insulation`s surface under DC [10][8]. That means there will be greater challenge face by the insulator under DC transmission lines. Furthermore, there are standard tests to evaluate the performance of the material based on tracking and erosion by using AC voltage while the standard test method for DC voltage has not yet been standardized. However, there were many researchers did the test for DC voltage by using the standard test for AC voltage [11].

1.2 Problem Statement

There are a few type of polymeric insulation materials but SIR is the most common materials that have been used as high voltage insulation. Some advantages of silicone rubber such as their light in weight and high hydrophobicity is well known but this type of insulator still have their own disadvantage which is the aging. Aging can be defined as the degradation of the insulator due to electrical stresses and different environmental effects. The ability of polymeric insulation and their long term performance need to be evaluated in order to know their reliability on the AC and DC transmission lines. Nowadays, the high voltage DC technology is increasingly applied in electrical power system. There is standard test to investigate tracking and erosion of AC on polymeric insulation materials which is IPT test (BS EN 60587:2007) international standard. However, there is no standardized test under DC voltage tracking and erosion on polymeric insulation. Besides, several study suggest that the tracking and erosion of insulation materials are more severe on DC voltage. Therefore, there is a need to study the comparison in terms of tracking and erosion and thermal characteristics for DC and AC IPT test for this type of materials for a better understanding and knowledge regarding the performances of Silicone Rubber under DC and AC voltage.

1.3 Objective

The main purposes of this study are as follows:

1. To conduct -DC and AC tracking and erosion test on silicone rubber (SIR) material by complying AC IPT test BS EN 60587:2007 standard as a reference.
2. To compare the performance of silicon rubber (SIR) polymer in terms of thermal characteristic, tracking and erosion under -DC and AC voltage.

1.4 Scope

The scopes of study are limited to:

1. The IPT test comply with BS EN 60587:2007 will be use as a reference to determine the tracking and erosion on polymeric insulation material.
2. IPT test will be conduct by using constant tracking voltage method at -3.5kV DC and 3.5kV AC voltage.
3. Silicon rubber which are readily processed with no filler will be use as the polymeric insulation material.
4. The performance of SIR are compared in terms of thermal characteristic, tracking and erosion for both AC and DC IPT test.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Insulation is one of the aspects that have to be consider in order to determine the obtainability and dependability of the AC and DC power system. Nowadays, polymeric material is commonly used as insulation due to the advantages of it over glass and ceramic materials. Besides, there were a lot of important studies have been made for improvement on the performance of polymeric insulation material since they were accepted as an insulator material.

This chapter include the sub topic that discusses about the general idea of AC and DC in high voltage power system, solid insulation materials, the advantages of SIR material, hydrophobicity behaviour, aging of polymeric insulation materials, tracking and erosion, and IPT test. Besides, this chapter also discuss about previous study on DC tracking and erosion on polymeric insulation material.

2.2 AC and DC

AC can be defined as a current that varies sinusoidally with time while DC is a current that remains constant with time. The first polymer insulator for AC transmission lines was develop in the late 1950s while the first polymer insulator for DC was trialled in the mid-1970s [3]. The reliability of both AC and DC transmission line is depend on the ability of the insulator on the transmission line. DC system have been used in submarine cable links for many years and the technology is regularly used for long distance transmission where it is more economic and energy efficient than AC [9].

2.3 Solid Insulation Material

There are two types of solid insulation materials which are glass/ceramic materials and polymeric materials. Both ceramic/glass insulation materials and polymeric insulation materials have their own advantages and disadvantages in certain properties. Table 2.1 shows the comparison of this two type of solid insulation materials.

Table 2.1: Comparison between polymeric and ceramic insulation materials [1].

Property	**Ceramic**	**Polymer**
Compressive strength	+	-
Size	--	++
Weight	--	++
Breakage	-	+++
Processing and Fabrication	-	++
Material cost	+	-
Aging	+++	++
Compatibility		
Pollution flashover	---	--
Resistance/Weathering		
Degradation		
Hydrophobicity	--	++
Creepage/Unit length	-	++

+ good, -weak

2.3.1 Glass and Ceramic

Ceramic material such as porcelain has over one century of service history as an insulating material. This type of materials were said not generally degraded by environmental stress such as humidity, surface electrical activity and UV. Besides, ceramic insulation were also tend to be very stable. Ceramic materials housing such as porcelain that used for cable termination, surge arresters and bushing do not need other materials or mechanisms for strength.

However, ceramic materials are easily broken in handling, transit and installation due to their properties which is hard but liable to break easily. Ceramic materials are also easily broken by vandalism that is a primary contributor to in-service mechanical damage. Moreover, ceramic materials bodies are very heavy due to their very dense nature. This means that expensive and large support are also necessary due to difficult in handling which will require the use of cranes [12].

2.3.2 Silicone Rubber

The broadly used of Silicon Rubber as insulation material in transmission lines is due to the brilliant electrical and mechanical properties of the material [10]. SIR insulator have a hydrophobic surface which is water form separate droplets instead of making a water film. This phenomena have make this type of insulator to be better than traditional insulator in terms of formation of a conducting surface layer. However, the hydrophobicity behaviour of SIR will be reduced due to the build-up of contaminant on the surface of the insulator, environmental effects and electrical discharge activity. The reduced in hydrophobicity behaviour will lead to the degraded insulation performance but the hydrophobicity properties of SIR has been reported that its may recover even in the present of surface contaminant.

Thus, SIR insulators is one of the most reliable insulator for use in polluted environments [13]. Besides, SIR composite insulators are an attractive alternative to traditional ceramic insulators in almost all new builds, replacements and upgrade. Thus, a lot of research on SIR including AC tracking and erosion tests have been done due to the phenomena [9].

2.4 Advantages of Silicone Rubber Material

One of the important infrastructures in the world is the power sector. Power sector can gets affected due to disasters leading to disruption in generation, transmission and distribution of electric power. The deposition of pollutants on the insulators which start conducting during foggy weather condition resulting in flashover and interruption of power in one of the reasons of the disasters.

SIR insulator is better equipped to deal with flashover problems as compared to others polymeric insulation materials, due to its unique hydrophobicity property. The formation of water forming on surface of SIR can be avoided due the hydrophobicity property. Therefore, it prevent the flow of leakage current (LC) on the surface on the insulation materials [14]. Moreover, there are many advantages of SIR insulator as compared to ceramic and glass insulators such as easy handling, light weight, maintenance free high strength to weight ratio, high impact resistance and perform well in contaminated environment. Therefore, SIR materials are accepted universally and replacing the traditional ceramic and glass insulators in electrical power system all over the world due to their advantages over ceramic and glass insulation materials [15].

2.4.1 Hydrophobicity Behaviour

Hydrophobicity can be defined as the ability of the insulators to repel water on its surface. Thus the water droplet forming as individual droplets rather than a film. It is more difficult for water to bridge the gap between adjacent shed edges on a hydrophobic insulator than on hydrophilic insulator. The measurement of hydrophobicity has been very widely used and investigated since it is the most important property of polymeric insulation materials. Hydrophobicity can be quantified using static or dynamic contact angles, the Swedish Transmission Research Institute (STRI) index, sliding angle or a water soaking test.

Nevertheless, the simplest way in order to quantify the hydrophobicity is by measuring the static contact angle of a water drop. The smaller the contact angle, the more wettable is the surface, when the contact angle is less than 35° the surface is assumed to be hydrophilic while for contact angle greater than 90° the surface is assumed to be hydrophobic. Figure 2.1 shows that the material which easily wettable allows water to touch a large surface area and hence makes a contact angle less than 90° while hydrophobic material allow less water surface contact and therefore makes a contact angle greater than 90°. However, hydrophobicity is not a fixed property instead can be lost and gained depending on the surface conditions [16][14].

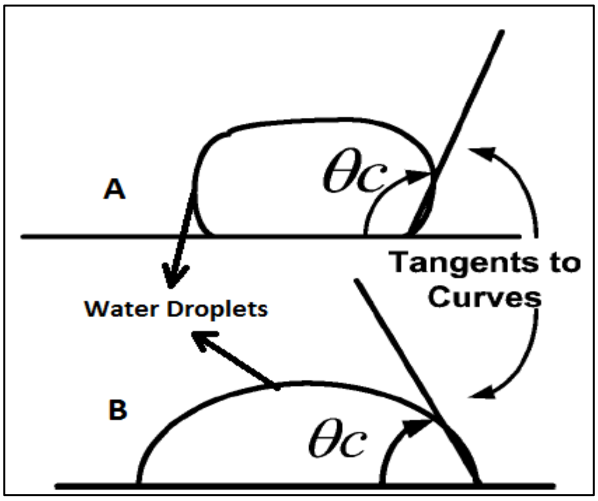


Figure 2.1: The shape of a water droplet on a (A) Hydrophobic surface and (B) Less Hydrophobic surface [16].

The basic reason for the excellent pollution flashover performance of SIR materials is the good hydrophobicity and unique hydrophobicity transfer property. The hydrophobicity transfer from the latter to the pollutants even though a layer of non-soluble pollution covers the underlying SIR. Thus, the outer layer of this polluted insulation is then reduce hydrophobic. The hydrophobicity transfer property is mainly due to a diffusion process, whereby low molecular weight (LMW) polymer chains from the bulk migrate to the surface to re-form a low energy surface. Besides, even when the surface loses hydrophobicity due to severe weather conditions like long time wetting conditions, hydrophobicity recovers with time due to further LMW transfer from the bulk. Nevertheless, the speed at which this transfer takes place and what happens to the flashover performance at the same time as this is happening have not been totally researched [17][18].

2.5 Aging

Aging can be defined as any major change in the electrical, chemical and mechanical properties of the insulation materials. Aging is one of the factors that can cause the failure of polymeric insulation or reduce their service performance in AC or DC transmission lines [7][6]. Tracking and erosion of polymeric insulation materials under contaminated condition can cause aging and at the same time can lead to the failure of the insulators. Nowadays, aging is still one of the main causes of the registered failures of polymer insulators in the field. Therefore, it is important to understand the mechanism of aging as well as the factors surrounding aging in order to improve both materials and insulators design [19].

The factors that influenced the long term performance of polymeric insulation materials had been discussed in many previous study [20]. Aging process may effect in different ways such as the surface, the interfaces of materials and the bulk. Aging of the bulk may be extremely slow while surface aging can occur extremely fast.

According to IEEE Std 1133-1988, environmental, electrical, thermal, contaminated condition and mechanical stress are the factors that affect the long term performance of polymeric insulation materials. Meanwhile, the effects stating to the natural processes that cause a failure of surface polymeric insulation material is named as aging effects [21]. Aging can be measured by diagnostic test in terms of mechanical, electrical, physical properties test or by chemical and environment test. The dissipation factor, dielectric strength, arc resistance, tracking and erosion and insulation resistance test are the example of electrical properties test that can be conducted in order to measure the aging of polymeric insulation materials [20].

2.6 Thermal Characteristics

All insulation materials will experience changeable marks of deteriorating or aging beneath standard operating conditions. The level of aging will be reliant upon the degree of the electrical, mechanical and thermal stresses. Besides, heat is constantly produced within the dielectric once the insulation material is stressed. The conductivity increases with temperature, conditions of unsteadiness are reached when the amount of heating outdoes the amount of cooling and the specimen might experience thermal breakdown [22][23].

In order for heat to be efficiently degenerate, high thermal conductivity is needed. By this way, the operating temperature can be kept low and at the same time avoiding dielectric failure due to overheating. Polymers display a low thermal conductivity because of their relatively low atomic density, complex crystal structure and weak interactions or chemical bonding. Thus, thermal conductivity of polymers can be enhanced by the addition of thermally conductive fillers[24].

2.7 Tracking and Erosion

One of the important task performed in the development of outdoor insulators is evaluating the electrical tracking and erosion resistance of the polymeric housing materials. Tracking can be defined as the formation of a surface carbonaceous path and erosion can be defined as the weight loss of the housing material. It is not possible to have an absolute measurement of the tracking and erosion resistance but only relative ranking of composites can be achieved using standard tracking and erosion test. Failure due to tracking was a major concern during the early se of organic insulating materials. Thus, standard screening methods were proposed in order to evaluate the tracking rather than erosion method. There were several test method have been proposed to evaluate tracking and erosion resistance of polymeric insulation materials such as IPT test, dust and fog, tracking wheel and salt fog [25][26].

The advantages and disadvantages of each method for tracking and erosion of the polymeric insulation materials had been discussed by many researchers on their review paper [27] [26]. Incline plane test is often used for tracking and erosion test on polymeric insulation materials because the test is simple in terms of the procedure and have low cost of the equipment [1]. The advantages and disadvantages of the test method in order to evaluate tracking and erosion of polymeric insulation materials is shown in Table 2.2.

Table 2.2: Testing methods for polymeric insulation materials [1]

Pattern Methods	Properties measured	Advantages	Disadvantages
Incline plane	Time to track Tacking voltage erosion	Fast Good educational tool Required close attention and cheap	Initial tracking voltage is difficult to be determined Erosion end point is too deep
Dust and fog	Time to track Erosion	Reliable to all material	Takes long time Relatively laborious Erosion method unclear
Salt fog	Time to track Erosion	Imitate natural condition of seacoast area	Takes very long time
Tracking wheel	Time to track Erosion	Reproducible and easy to run	Interaction between difference materials

2.7.1 Incline Plane Tracking (IPT) test

IPT is one of the tests that can be carry out in order to determine the tracking and erosion of outdoor polymer insulating materials [3]. Mathes and McGowan [28] had proposed the inclined-plane liquid-contaminant test (IPT) in the year of 1961, which was standardized in ASTM D2303 and IEC 60587. The test must exactly follow the procedures in the international standard for the test to be conducted well and get the accurate results. The experimental set-up including method of test, dimensions of test specimens, preparation of contaminant, procedure for conducting the test and the electrical apparatus [1].

The schematic diagram of IPT test according to BS EN 60587:2007 international standard is shown in Figure 2.2. A specimen with $50mm \times 120mm$ sizing and a $6mm$ thickness is placed incline at an angle of 45 degrees, with conductive solution is drop on filter paper and will flow down through the specimens from top electrode to the bottom electrode. The contaminant is supply by a peristaltic pump that have a specific flow rate according to the value of the preferred test voltage. A power resistance is place in series at high voltage side and the value of the resistance is set based on the test voltage. Since this test will be conducted in high voltage, a variable single phase high voltage transformer 0-6kV is connected to the circuit as a high voltage supply [29].

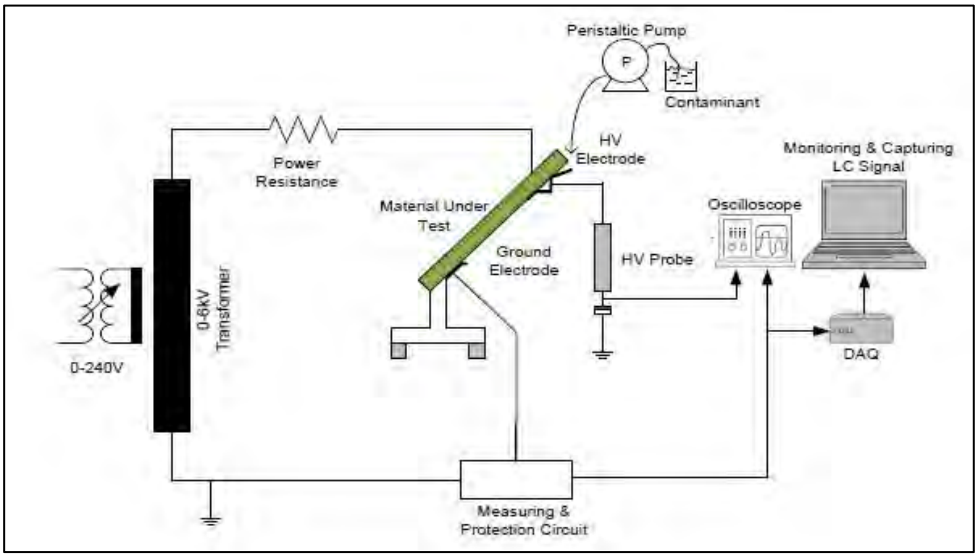


Figure 2.2: Schematic diagram for incline plane tracking (IPT) test [1]

BS EN 60587:2007 standard have describe two test method in order to determine the performance of polymeric insulator materials in terms of their tracking and erosion. The first method in BS EN 60587:2007 is the application of constant tracking voltage. The voltage is raise to one of chosen test voltage, 2.4kV, 3.5kV or 4.5kV which should be reached within a maximum of 10s and the timing device is started. The contaminant must flow uniformly at the specified rate according to Table 2.3. The test voltage shall be maintained constant for 6 hours. A further set of five specimens shall be tested for each selected preferred voltage in case the test has to be repeated at a higher or lower voltage. Besides, the maximum voltage withstood by the specimens for six hours is the constant tracking voltage [29].

Next, the second method is stepwise tracking voltage where a multiple of 250V voltage is selected, such that failure which current exceeding 60mA does not occur sooner than the third voltage step. The contaminant must flow uniformly at the specified rate, switch on and raise the voltage to the selected value. The voltage need to be maintained for one hour and increase the voltage by a step of 250V for every following hour till failure which the current exceeding 60mA is recorded. The contaminant flow rate and the series resistance value are increase according to Table 2.3 as the voltage is increased. The maximum voltage resisted by the five specimens for 1 hour is the stepwise tracking voltage [29].

According to BS EN 60587:2007 the flow rate of contaminant and the series resistance value are need to be set to a specified value for both constant tracking voltage and stepwise tracking voltage test methods. Table 2.3 shows the parameter for both test method in the standard.

Table 2.3: Test parameter according to BS EN 60587 standard [26]

Test voltage (kV)	Preferred Test Voltage for Method 1 (kV)	Contaminant Flow Rate (ml/min)	Series Resistor, Resistance ($k\Omega$)
$1.0\ to\ 1.75$	-	0.075	1
$2.0\ to\ 2.75$	2.5	0.15	10
$3.0\ to\ 3.75$	3.5	0.3	22
$4.0\ to\ 4.75$	4.5	0.6	33
$5.0\ to\ 6.0$	-	0.9	33

2.8 Review of Previous Study on Tracking and Erosion test

There are a lot of study have been done to determine the performance of polymeric insulation materials on tracking and erosion under AC and DC voltage [30]. According to G. P. Bruce and S. M. Rowland [9] that had conducted a test under three different voltage levels for both polarities of DC voltage, a higher degree in surface damage and higher leakage current is observe in positive DC test. More severe tracking was shown under DC condition than for AC in the previous study. Besides, more irregular and deeper erosion and greater sample mass loss was observed under positive DC than for negative DC. The erosion of the surface of materials are usually start at the bottom electrode and spread toward the top electrode.

In reference [30], R. A. Ghunem et al had did a test by using AC and DC voltages on the dry-band arching (DBA) characteristics in inclined plane tracking and erosion test. The lowest leakage current was obtained under negative DC followed by AC and positive DC while the dry band arching length is less for DC compared to AC with advance reduction was observed under positive DC as compared to negative DC voltage. Moreover, the resistivity for the dry band arching column under positive DC is lower than under AC as compared to the negative DC. This happen due to metallic ions from electrode corrosion under positive DC as compared to negative DC voltage. Furthermore, the voltage type give some impacts to the inception behaviour of the discharge influencing the length of the dry band arc.

According to E. A. Cherney et al [3] DC voltage give more severe effects of dry-band arching on polymer materials compared to AC voltage. This is said to be happened due to the apparatus-related factors such as corrosions of the test electrode, electro hydrodynamic effects, and accumulated deposits from contaminants. Therefore, the relevance of the apparatus and methods specified in the standard AC IPT (BS EN 60857:2007) for DC testing need to validate. There are also a need to determine whether the greater severity of the effects of DC DBA, relative to AC DBA is indeed due to apparatus related or mechanism factors or both. However, there are a lot of previous study suggest that the DC IPT setup can be the same as the existing setup for AC IPT.

On the other hand, in other to determine the relative DC performance of SIR, a few studies have been conducted. One of the study was compared the erosion of SIR under AC and DC using the constant voltage method of IPT test. In this study, the erosion of SIR was more severe under positive DC as compared to negative DC. Besides, the electrolysis that influence the corrosion of the upper test electrode under positive DC and caused an increase in the conductivity of the liquid contaminant leading to higher magnitude of LC and consequently damage on the surface of the polymeric materials. Moreover, the LC was reported higher under positive DC than under negative DC and positive DC have shorter discharge duration as compared to negative DC. Furthermore, the most inferior erosion class was observed under positive DC followed by negative DC and the AC in the initial tracking voltage test method of the incline plane test on the SIR composites containing 0, 10, 30 wt % loading of silica filler [8].

According to Hang Xu, et al [10] increasing the thermal conduction ability of the SIR will improve their resistance to tracking and erosion. A test was conducted on the samples that had been prepared by dispersing nano-BN particles into SIR at concentration 0%, 2.5% and 5% by weight. IPT and erosion tests were conducted based on IEC 60587 in order to compare the phenomena occurring during the tests.

The study was reported that the thermal properties were improved as the concentration of nano-BN is increase from 0% to 5% by weight. Besides, a decreasing trend of erosion depth and weight loss were observed which proves that the resistance of SIR to tracking and erosion is improved. That means by the addition of BN, the thermal conduction ability of silicone rubber is enhance which increase its resistance to tracking and erosion.

All the study above stated that higher LC was observed under DC voltage as compare to AC voltage. Besides, the severe tracking and erosion were observe under positive DC followed by negative DC and AC voltage. furthermore, the corrosion of upper test electrode under DC due to the electrolysis that lead to an increase in the contaminant`s conductivity caused the higher LC and surface damage on the insulation materials. Hence, to increase the resistance to tracking and erosion of polymeric insulation material, inorganic filler should added to the SIR as suggested by the previous study on resistance to tracking and erosion of polymeric insulation materials.

2.9 Summary of Literature Review

Figure 2.3 shows the flow of the literature review of this study.

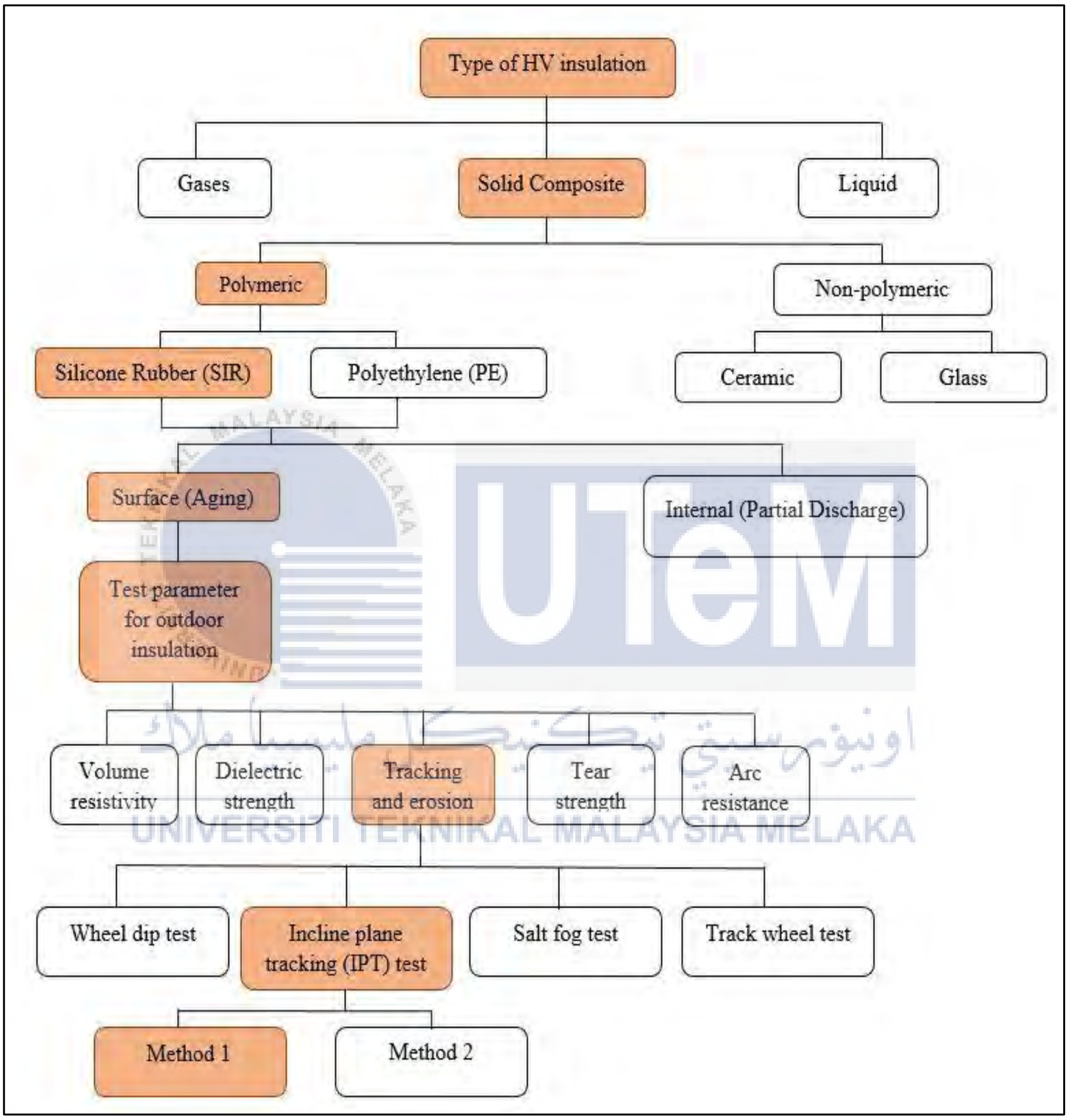


Figure 2.3: Flowchart for the literature review

CHAPTER 3

METHODOLOGY

3.1 Introduction

AC and -DC tracking and erosion test on polymeric insulation material was carried out by complying BS EN 60587:2007 (Electrical Insulating Material Used under Severe Ambient Conditions- Test Method for evaluating Resistance for Tracking and Erosion) international standard as a reference [29]. SIR were used as the test sample for both AC and DC IPT test. Besides, both test were done based on method 1 in BS EN 60587 which is the constant tracking voltage method.

The test voltage for AC and DC IPT test is 3.5kV and -3.5kV respectively. In AC IPT test, 6kV transformer was used to supply the voltage while in DC IPT test, an amplifier was used to produce -3.5kV DC voltage. The specimen used was Silicon Rubber (SIR) which are readily processed with no filler. Besides, the surface temperature or thermal characteristic of SIR was measured during both AC and DC IPT test by using IRISYS – 4010 Thermal Imager.

3.2 Flowchart of Methodology

Figure 3.1 shows the flowchart of methodology for this project.

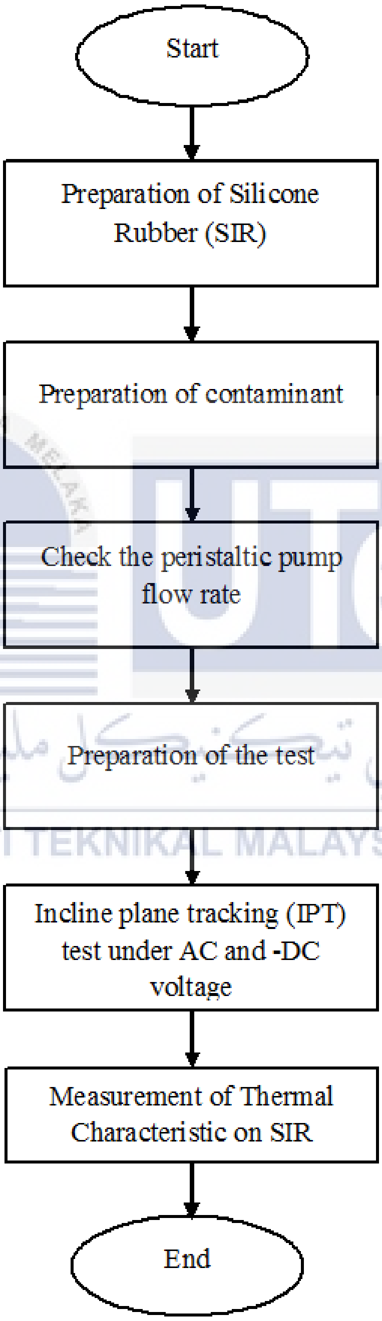


Figure 3. 1: Flowchart of methodology

3.3 Tracking and Erosion Test

Tracking can be define as the effect of the local discharge to form conducting path or partially conducting paths that will result in degradation of the surface of a solid insulation material while electrical erosion can be defined as the loss of the insulation by LC or electrical discharge [1][3]. The tracking and erosion can lead to aging of the polymeric insulation material and aging can affect the reliability of the insulation material as well.

There are a lot of test in order to determine the tracking and erosion such as track wheel, dielectric strength, wheel dip and IPT test. This study will focused more on the IPT test according to BS EN 60587:2007 standard. Moreover, the time taken to form track between top and bottom electrodes and the time taken to erode through the specimen are recorded to determine the performance of specimens on tracking and erosion.

For the purpose to determine the performance of the polymeric insulation materials in tracking and erosion, the British Standard BS EN 60587:2007 have provide two methods of experiment. First method is the application of the constant tracking voltage while the second method is the stepwise tracking voltage. The flow rate of contaminant and the series resistance value for the experiment are depends on the preferred test voltage. Method 1 will be used to carry out this test. Moreover, the preferred test voltage for method 1 is $3.5kV$ DC. Table 3.1 shows the contaminant flow rate and value of the resistance according to the preferred test voltage.

Table 3.1: Test parameter for DC and AC IPT test

Test voltage (kV)	Preferred Test Voltage for Method 1 (kV)	Contaminant Flow Rate (ml/min)	Series Resistor, Resistance $(k\Omega)$
1.0 to 1.75	-	0.075	1
2.0 to 2.75	2.5	0.15	10
3.0 to 3.75	3.5	0.3	22
4.0 to 4.75	4.5	0.6	33
5.0 to 6.0	-	0.9	33

3.4 Preparation of Silicone Rubber

The preparation of the specimens should follow BS EN 60587 standard. The size of flat SIR is $50mm \times 120mm$ and the thickness is $6mm$ as shown in Figure 3.2.

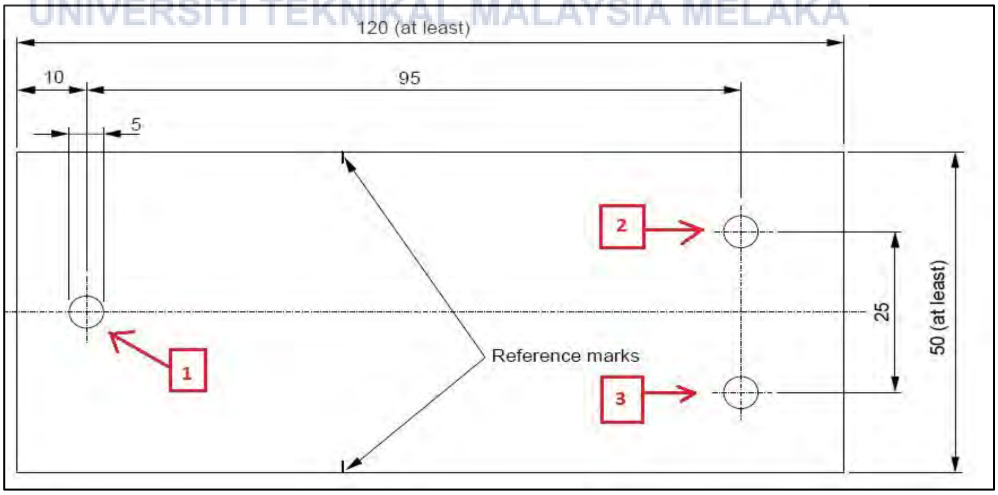


Figure 3.2: Dimension of Silicone Rubber [26]

The SIR were drilled in order to attach the electrodes. The diagram for the test specimen after the drilling process as shown in the Figure 3.3. This figure shows that the distance between hole 1 to hole 2 and hole 3 is $95mm$ apart while the distance between hole 2 and 3 is $25mm$ apart.

Figure 3.3: Silicone Rubber (SIR)

Then, SIR was washed with a suitable solvent such as isopropyl alcohol. This step is needed to ensure there is no leftover such as fat from handling is left on the SIR. Moreover, the SIR that have been cleaned was carefully mounted in order to avoid contamination. Next, the surface of the SIR can be slightly abraded in case of the contaminant does not wet the surface consistently within the time mentioned in BS EN 60587:2007 standard which is 10 minute. The SIR was cleaned with distilled water after finish the abrasion process. Lastly, reference marks was drawn on both edges, $25mm$ above the lower electrode to verify the end point criteria for the SIR.

3.5 Preparation of Contaminant

The contaminant solution was made from $0.1\% \pm 0.002\%$ by mass of ammonium chloride (NH4CI) in distilled water. A $0.02\% \pm 0.002\%$ by mass non-ionic wetting agent Triton X-100 (isooctylphrnoxypolyethoxythanol) were added to the solution in order to make sure the contaminant wets out smoothly and rapidly to the SIR surface. Moreover, the resistivity of the contaminant should be $3.95\Omega m \pm 0.05\Omega m$ which is equal to $2.53mS/cm$ in terms of conductivity. The materials used to produce the contaminant solution is shown in Figure 3.4 until Figure 3.6.

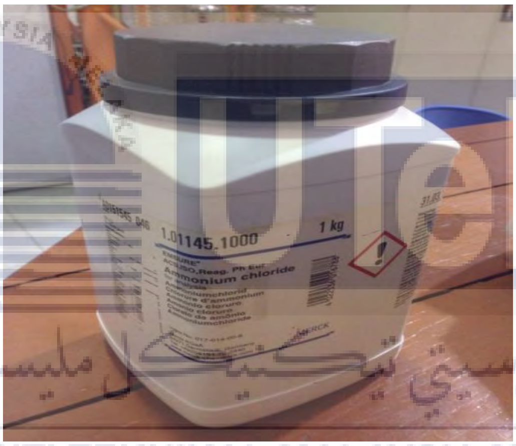


Figure 3.4: Ammonium Chloride (NH4CI

Figure 3.5: Triton X-100

Figure 3.6: Distilled water

Thus, conductivity test meter is needed to measure the conductivity of the contaminant. Furthermore, before each series of tests, the contaminant`s conductivity was measured. Besides, the solution was not more than four weeks prepared before the test was conducted. Figure 3.7 shows the conductivity meter and the reading of the contaminant`s conductivity.

Figure 3.7: Conductivity meter

3.6 Peristaltic Pump Flow Rate

In order to control the contaminant continuously flow through the SIR from top electrode to bottom electrode, a peristaltic pump was used. Then, the contaminant solution was dropped down to the 8 layers of filter paper that had been fastened between the top electrode and the SIR. Thus, before the test voltage was applied, the contaminant was fed onto the filter paper pad thus a constant contaminant flow among top and bottom electrode could happen. Figure 3.8 shows the peristaltic pump that had been used in the test.

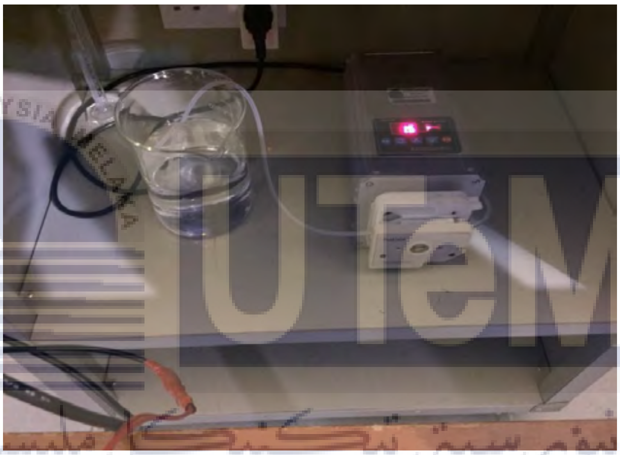


Figure 3.8: Peristaltic pump

Moreover, the thickness of the filter paper is of $0.2mm \pm 0.02mm$. The contaminant should not flow from the sides or upper side of the filter paper. Hence, the contaminant should flow from the quill hole of the upper electrode to the lower electrode. Contaminant flow rate should be based on the voltage that will be applied. Table 3.2 shows the flow rate of the contaminant based on the applied voltage. The flow rate of the peristaltic pump for the test is 0.3 ml/min which is equal to 0.14 rpm.

Table 3.2: The contaminant flow rate based on the test parameter voltage

Preferred Test Voltage for Method 1 (kV)	Contaminant Flow Rate (ml/min)
-	0.075
2.5	0.15
3.5	0.30
4.5	0.60
-	0.90

3.7 Preparation of the test

The SIR was placed at an angle of $45° \pm 2°$ from the horizontal with the flat surface on the underside. The SIR was attach with the top and bottom electrode and both electrode is placed $50mm \pm 0.5mm$ apart. Figure 3.9 shows the setup of the test sample. This test was carried out on sets of at least five specimens of SIR. Besides that, an insulating mounting support was used for the specimens because the specimens is not self-supporting. Thus, the material should be electrically insulating and heat resistance.

There are two methods that have been describe in the BS EN 60587:2007 standard to determine tracking and erosion of insulation which is:

1. Method 1: The used of constant tracking voltage by the contaminant is flowing constantly at the stated rate. The experiment parameter voltage need to raise to the preferred voltage and must be constant for 6 hours.
2. Method 2: Application of stepwise tracking voltage. The test voltage should be raise to the selected value. As the voltage had been raised the resistance value of the series resistor and contaminant flow rate also must be increased

to the specified value. This method is usually used to determine the initial and continuously tracking for the insulating materials.

Figure 3.9: The setup of SIR

3.8 Incline Plane Tracking (IPT) test set-up

Inclined plane tracking test were exactly follow the procedures of the international standard in order to conduct the test successfully. The experimental set-up including method of test, contaminant preparation, dimension of specimens under the test, electrical apparatus and procedures for the test have been provided in the standard.

In AC IPT test, the transformer is needed since the test will be carried out at high voltage and the transformer can be varied up to $6kV$. Moreover, in DC IPT test, a DC power supply was connected to an amplifier in order to provide -3.5kV DC voltage. The transformer, DC power supply and HV amplifier that had been used in this test were shown in Figure 3.10, 3.11 and Figure 3.12 respectively.

Figure 3.10: 6kV Transformer

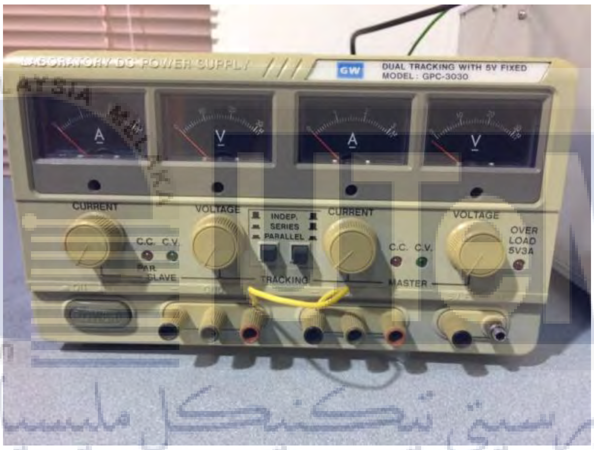


Figure 3.11: DC Power Supply

Figure 3.12: High voltage amplifier

Besides, the power resistor is connected in series with the specimen at the HV side. The value of the resistance should be taken according to the value of the test voltage. The $60mA$ fuse overcurrent protective device is connected in series with the specimen at the LV side for the safety precaution and determination of end point criteria purpose. Moreover, top and bottom electrode, stuffs and assembly elements connected with both top and bottom electrodes should be made of stainless steel. The schematic diagram for the AC and DC IPT test according to BS EN 60587:2007 is shown in Figure 3.13 and Figure 3.14.

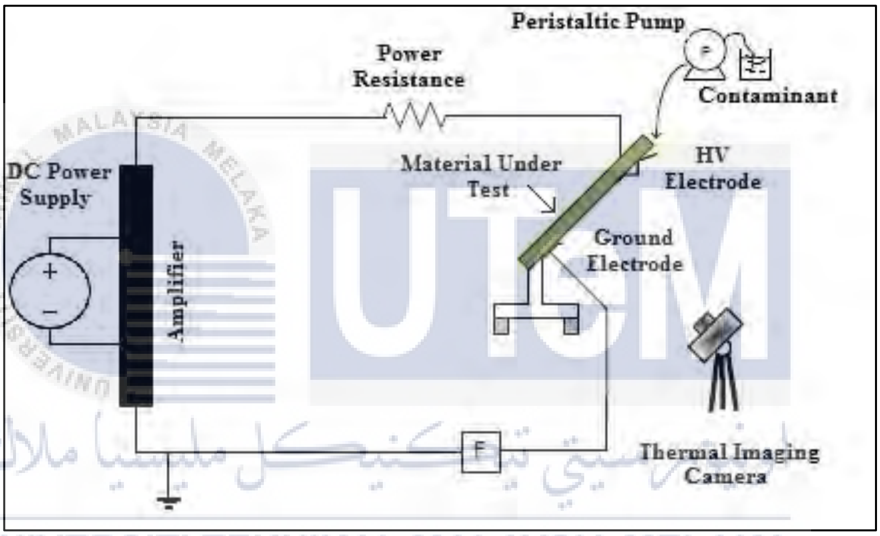


Figure 3.13: Schematic diagram for DC Incline Plane Tracking (IPT) test

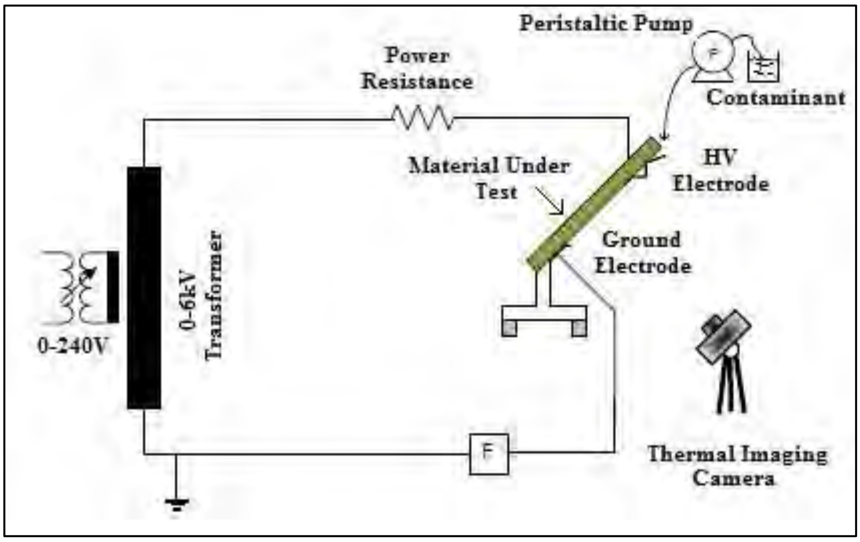


Figure 3.14: Schematic diagram for AC Incline Plane Tracking (IPT) test

3.9 Measurement of Temperature using IRISYS IRI – 4010 Thermal Imager

In order to obtain the thermal characteristic of the SIR for both AC and DC IPT test, thermal imager IRI – 4010 had been used. The surface temperature of SIR was capture for every 30 minutes during the IPT test.

Then, the image captured were analyse using IRI – 4010 thermal imager software. Besides, the temperature spectrum produced by this thermal imager made the analysis process to obtain the change of surface temperature became easier. IRISYS IRI – 4010 thermal imager is as shown in Figure 3.15.

Figure 3.15: IRISYS IRI – 4010 Thermal Imager

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter discuss the comparison between AC and DC Incline plane tracking (IPT) test in terms of thermal characteristics. Besides, this chapter also discuss the tracking and erosion of the sample in both AC and DC IPT test. The tests was comply by BS EN 60587. IRISYS – 4010 Thermal Imager had been used to obtain the thermal characteristic of the test sample for both AC and DC IPT test. The IRISYS – 4010 thermal imager software had been used to study the temperature change by producing temperature spectrum and also for the information collecting. The insulating material that was used in AC and DC IPT test was the virgin SIR. Some of the parameter were kept constant for both AC and DC IPT test such as the method of the test, test voltage, contaminant flow rate and the frequency. The constant tracking voltage method was used in the tests and the applied voltage was 3.5kV AC and -3.5kV DC. Next, the contaminant was 0.3ml/min or 1.4rpm for both AC and DC IPT test. Then, the frequency during tests was 50Hz. The tracking and erosion of the test sample for both AC and DC IPT test was evaluated based on the end point criteria that have been provided in BS EN 60587.

4.2 Thermal Characteristic of Silicon Rubber

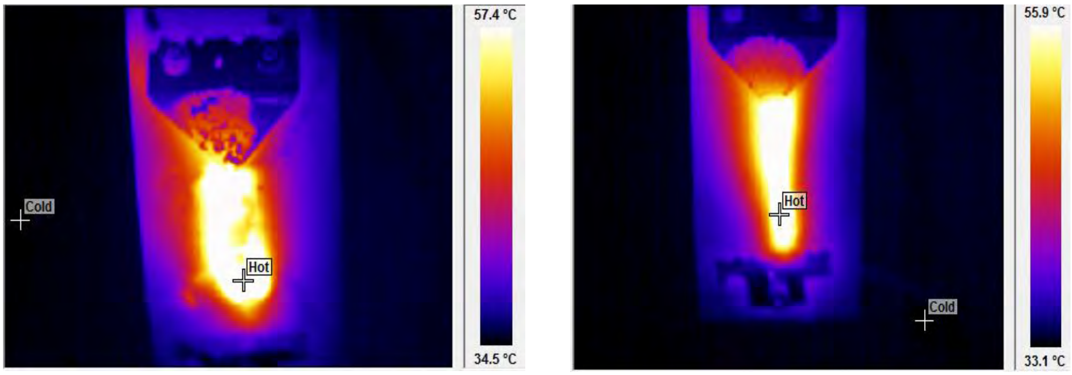
This sub-topic discuss the thermal characteristics of SIR at a certain time during the test. The test for AC and DC IPT were conducted for 6 hours according to the BS EN 60587. The thermal image were captures at every 30 minutes during the test. There were 12 images that had been captured during the 6 hours test.

Figure 4.1 shows the thermal characteristic of the test sample during first 30 minutes of AC and DC IPT test. The temperature of the sample for AC test in the first 30 minutes is 54.4°C. Besides, for the -DC test the temperature seem to be lower than in the AC test which is 53.5°C.

(AC) (-DC)

Figure 4.1: Thermal characteristic of the sample at 30 minutes

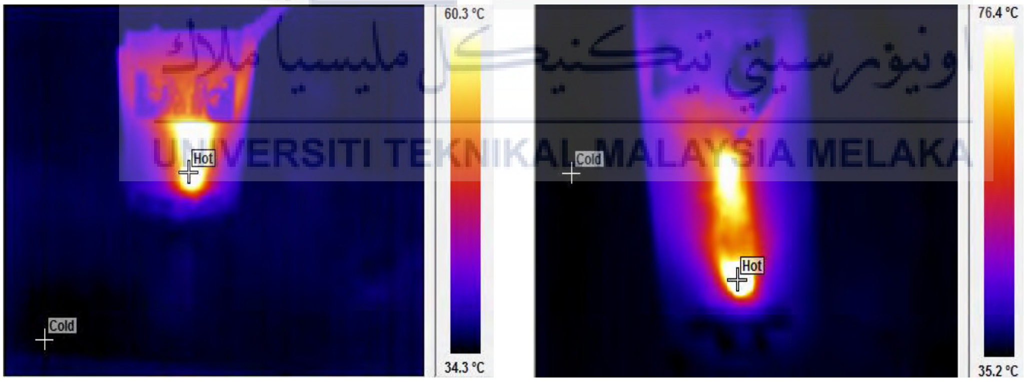
Figure 4.2 shows thermal characteristic of SIR for AC and -DC test at 60 minutes. There were slight increase of temperature for both AC and -DC test. The temperature of sample in AC test increase from 54.4°C to 57.5°C while increase from 53.5°C to 55.9°C in the -DC test. However, the temperature of the test sample for AC test still seem to be higher than in -DC test.



(AC) (-DC)

Figure 4.2: Thermal characteristic of the sample at 60 minutes

Figure 4.3 shows the thermal characteristic for SIR after 90 minutes for both AC and -DC test. The temperature of the sample for -DC test is increase by 20.5°C while for the AC test the temperature sample is increase by 2.9°C. Besides, the temperature of the test sample is higher in this -DC test as compared to in AC test which 76.4°C and 60.3°C respectively.

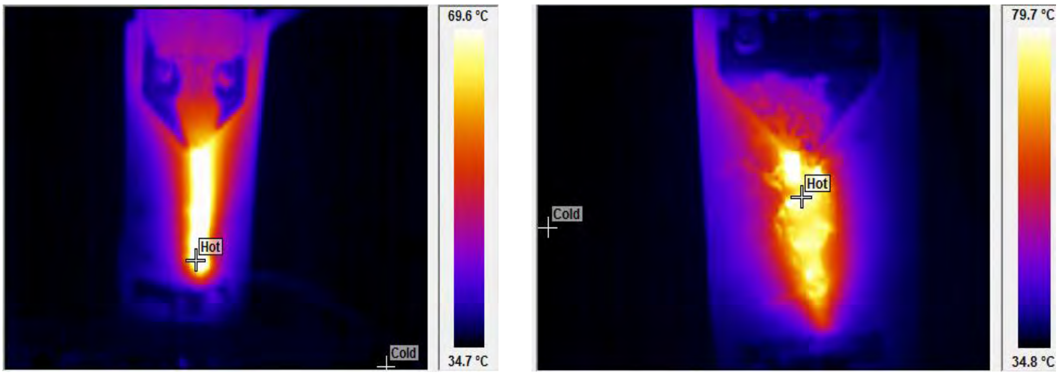


(AC) (-DC)

Figure 4.3: Thermal characteristic of the sample at 90 minutes

Figure 4.4 shows the thermal characteristic for SIR after 120 minutes for both AC and -DC test. The temperature of the sample in AC and DC IPT test seem to have marginally increase from 60.3°C to 69.6°C in AC test and from 76.4°C to 79.7°C in

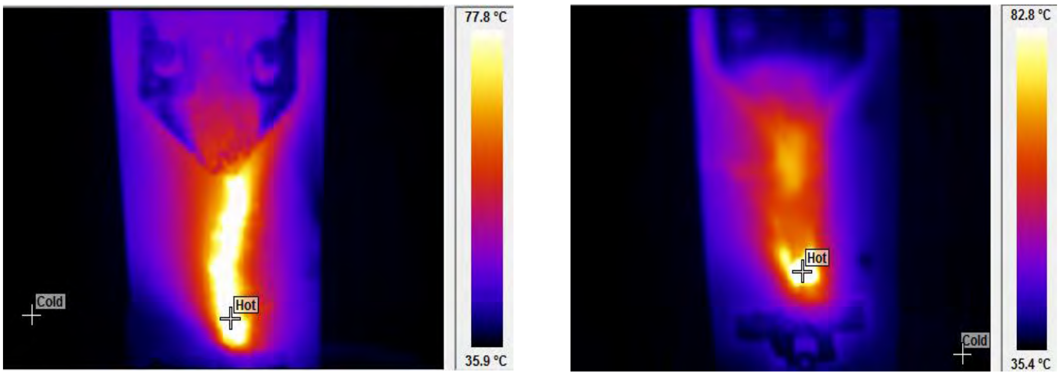
-DC test. Furthermore, the temperature of the test sample at 120 minutes of the test was observed to be higher in -DC test as compared to AC test.



(AC) (-DC)

Figure 4.4: Thermal characteristic of the sample at 120 minutes

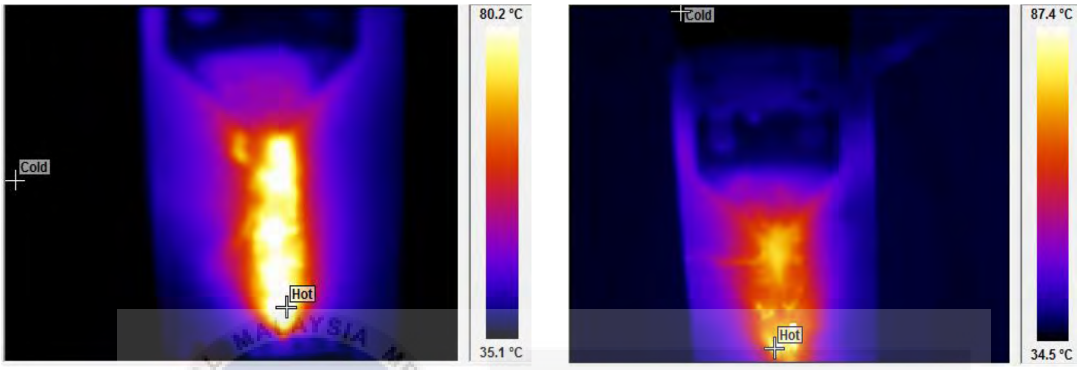
Figure 4.5 shows thermal characteristic of SIR for AC and -DC test at 150 minutes. The range of the temperature spotted by the thermal image at the surface sample in AC test is from 35.9°C to 77.8°C while from 35.4°C to 82.8°C in -DC test. The temperature in AC and -DC test are increase from the previous temperature by 8.2°C and 3.1°C respectively.



(AC) (-DC)

Figure 4.5: Thermal characteristic of the sample at 150 minutes

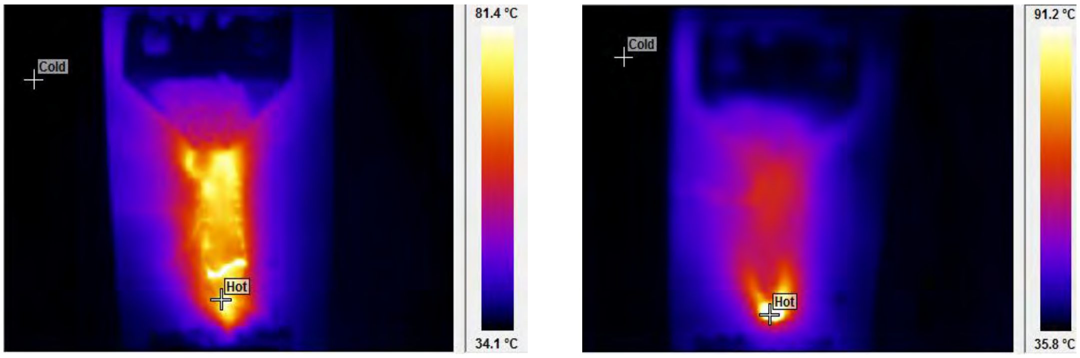
Figure 4.6 shows the thermal characteristic of the test sample at 180 minutes of AC and DC IPT test. The temperature of the sample at 180 minutes of the test is higher in -DC test as compared to the AC test. The temperature of the sample in -DC test is increase from 82.8°C to 87.4°C and also increase in AC test which is from 77.8°C to 80.2°C.



(AC) (-DC)

Figure 4.6: Thermal characteristic of the sample at 180 minutes

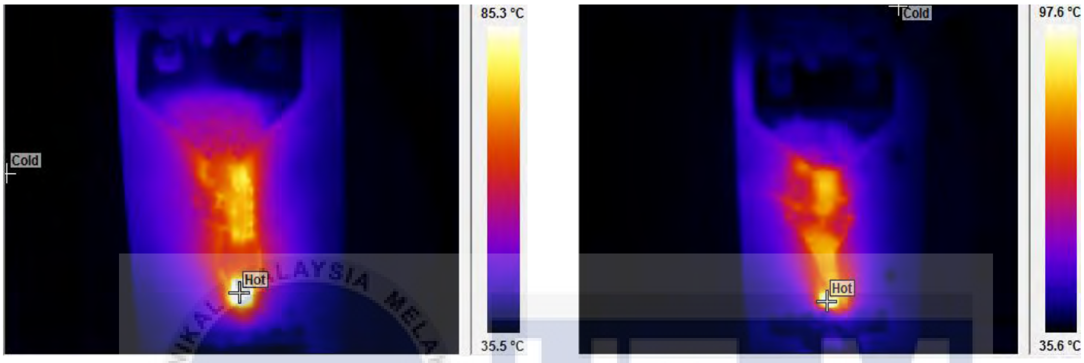
Figure 4.7 shows the thermal characteristic of the test sample at 210 minutes of AC and DC IPT test. The sample temperature is slightly increase from previous temperature by 1.2°C in AC test and 3.8°C in -DC test. The temperature is higher in DC test than in AC test which is 91.2°C for the -DC test and 81.4°C for the AC test.



(AC) (-DC)

Figure 4.7: Thermal characteristic of the sample at 210 minutes

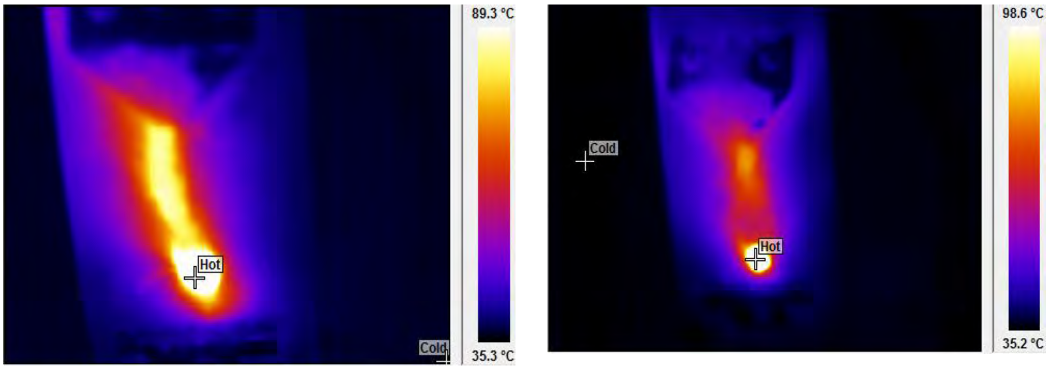
Figure 4.8 shows thermal characteristic of SIR for AC and -DC test at 240 minutes. . The range of the temperature spotted by the thermal image at the surface sample in AC test is from 35.5°C to 85.3°C while from 35.6°C to 97.6°C in -DC test. The temperature in AC and DC test are increase from the previous temperature by 8.2°C and 3.1°C respectively. At 240 minutes of the test, -DC test shown higher temperature as compared to AC test.



(AC) (-DC)

Figure 4.8: Thermal characteristic of the sample at 240 minutes

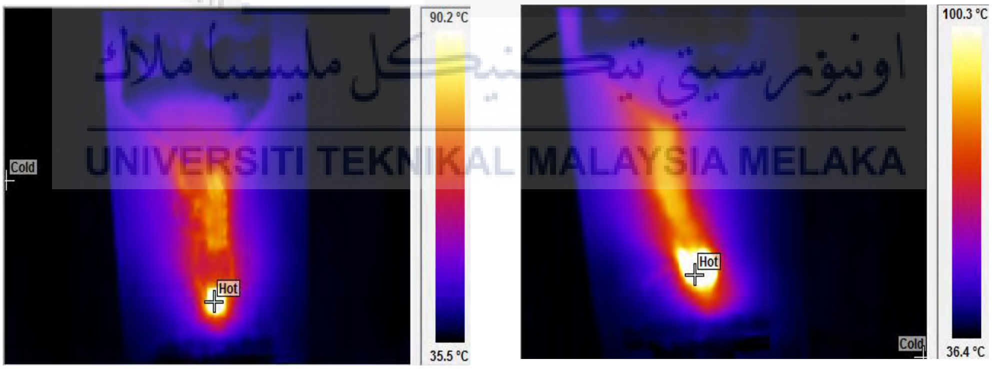
Figure 4.9 shows the thermal characteristic for SIR after 270 minutes for both AC and -DC test. The temperature of the sample in AC and DC IPT test seem to have marginally increase from 85.3°C to 89.3°C in AC test and from 97.6°C to 98.6°C in -DC test. Furthermore, the temperature of the test sample at 270 minutes of the test was observed to be higher in -DC test as compared to AC test.



(AC) (-DC)

Figure 4.9: Thermal characteristic of the sample at 270 minutes

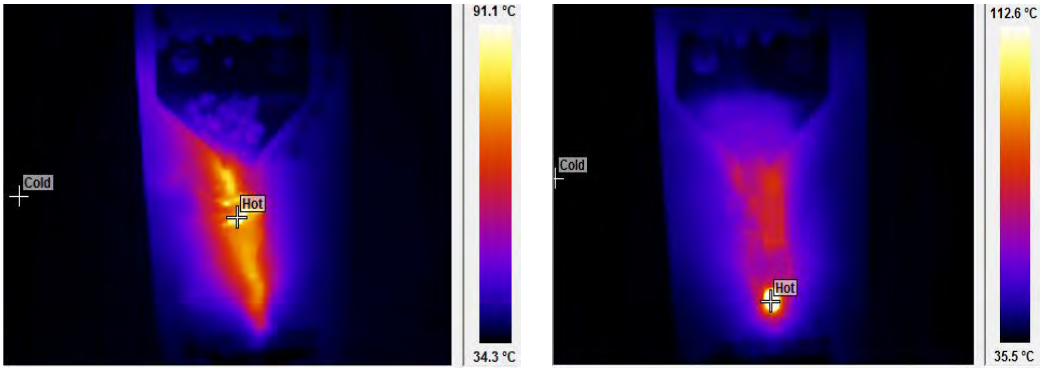
Figure 4.10 shows the thermal characteristic for SIR after 300 minutes for both AC and -DC test. The temperature of the sample at 300 minutes of the test is higher in -DC test as compared to the AC test. The temperature of the sample in -DC test is increase from 98.6°C to 100.3°C and also increase in AC test which is from 89.3°C to 90.2°C.



(AC) (-DC)

Figure 4.10: Thermal characteristic of the sample at 300 minutes

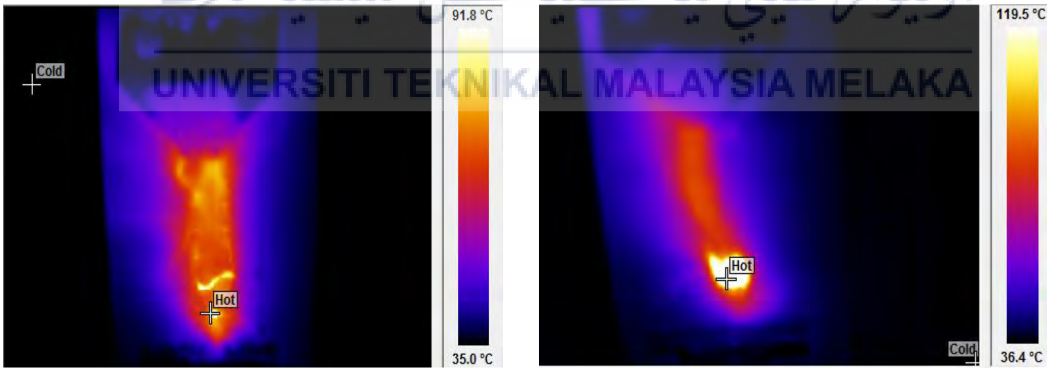
Figure 4.11 shows the thermal characteristic of the test sample at 330 minutes of AC and DC IPT test. The temperature of the sample for AC test at 330 minutes of the test is 91.1°C. Besides, for the -DC test the temperature of the sample seem to be higher than in the AC test which is 112.6°C.



(AC) (-DC)

Figure 4.11: Thermal characteristic of the sample at 330 minutes

Figure 4.12 shows thermal characteristic of SIR for AC and -DC test at 360 minutes. There were slight increase of temperature for both AC and -DC test. The temperature of sample in AC test increase from 91.1°C to 91.8°C while increase from 112.6°C to 119.5°C in the -DC test. Still, the temperature of the test sample for -DC test seem to be higher than in AC test at 360 minutes of the test.



(AC) (-DC)

Figure 4.12: Thermal characteristic of the sample at 360 minutes

Figure 4.13 shows the graph of temperature against time for both as AC and DC IPT test. As the time increase, the temperature of SIR in both test is also increase. Initially, the surface temperature of SIR in AC IPT test is higher at first 30 and 60 minutes of the test as compared to DC IPT test. However, after 90 minutes of the test, surface temperature of SIR in DC IPT test become higher than in AC IPT test. Surface temperature of SIR in DC IPT test remain higher till the end of the test as compared to AC IPT test. Towards the end of the tests, the surface temperature of the test samples are seem to be highest on a spot near to lower electrode. The hot spot occurred due to the development of dry band arching[5].

The temperature of the samples increase cause by the heat produced by dry band arcing and the leakage current. Furthermore, during the inclined plane test, discharges happened between droplets and between the droplets and electrodes, which are similar to the formation of droplets and water film on the silicone rubber insulators surface in some degree. Then, when discharges happened, a large number of charged particles with high energy and great heat were released and the heat released was a main cause for the degradation. In addition, due to the reduction of sample surface hydrophobicity, the water film was easily formed. The joule heat of leakage current across the sample also caused severe damage to the sample surface[10].

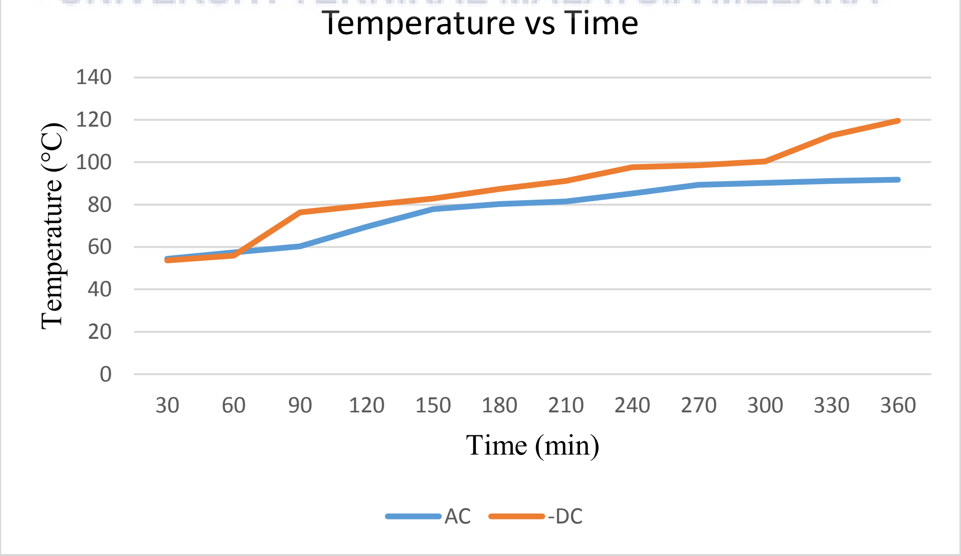
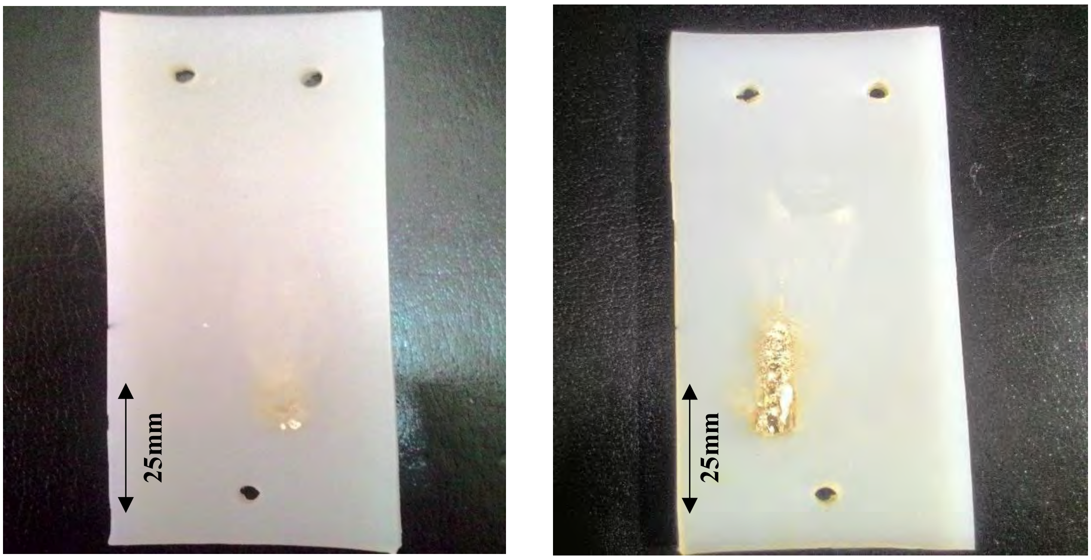


Figure 4.13: Graph of Temperature against Time for both AC and -DC test.

4.3 Tracking and Erosion of Silicone Rubber

Figure 4.14 shows the tracking and erosion of SIR in both AC and DC IPT test. According to BS EN 60587 in order for the test sample to pass the test, the tracking should not be more than 25 mm from the lower electrode. The tracking and erosion of SIR in both AC and -DC test start from the bottom electrode and spread towards the upper electrode. Besides, from observation during the test, the time taken for the sample in DC IPT test to track is faster as compared to the sample in AC IPT test. In DC IPT test, the tracking is more severe as compared to the sample in AC test. Moreover, the track of the sample in DC IPT test is exceed 25 mm from the lower electrode which indicates that the samples do not survive 6 hours at 3.5kV and had failed the test.

However, the samples in AC IPT test has survive the test since the track has not reach 25 mm from the lower electrode. Furthermore, from the observation, erosion of SIR seem to be more severe in DC IPT test as compared to AC IPT test. The erosion of the test electrode is one of the factor that lead to severe erosion under DC voltage. The accumulation of metallic ions in the liquid contaminant due to electrolysis of test electrodes generates higher leakage current and more severe erosion.



(AC) (-DC)

Figure 4.14: Tracking and erosion of SIR under AC and -DC voltage.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this report, the performance of Silicone Rubber (SIR) in terms of tracking and erosion was evaluated under AC and -DC voltage. The tracking and erosion of SIR was evaluated by conducted Inclined Plane Tracking (IPT) test for both AC and -DC voltage. IPT test was conducted by complying with BS 60587 as a reference. Method 1 in BS EN 60587 which is constant tracking voltage method had been used in this study for both AC and DC IPT test. The applied voltage for AC and DC test is 3.5 kV and -3.5 kV respectively. Besides that, the contaminant flow rate was also constant for each test which is 0.3 ml/min while the frequency is 50 Hz.

Furthermore, thermal characteristic of SIR surface was obtained during both AC and DC IPT test. The surface temperature of SIR was measured every 30 minutes of AC and DC IPT test by using IRISYS – 4010 Thermal Imager. The sample in DC IPT test showed higher surface temperature as compared to the sample in AC IPT test. Furthermore, the surface temperature of SIR in both AC and DC IPT test were increased as the time increased. Moreover, in terms of tracking and erosion the sample under -DC voltage displayed more severe tracking and erosion as compared to the sample under AC voltage. The tracking and erosion was evaluated by using the end point criteria provided in BS EN 60587. The maximum length of tracking that acceptable for the test sample to pass the test is 2.5 mm from the lower electrode. Since the tracking of SIR under DC voltage exceed 2.5 mm, SIR under DC voltage had failed the test. However, under AC voltage, SIR had passed the test because the tracking not exceed 2.5 mm. Thus, selection of –DC voltage levels equivalent to the corresponding standard AC voltages should be recognized in order to rank the insulation materials in terms of their tracking and erosion performance.

5.2 Recommendation

In this study, the performance of SIR in terms of tracking and erosion for both AC and DC IPT test was compared. Besides, the thermal characteristic of SIR was also obtained during the IPT test. SIR under -DC voltage test experienced more severe tracking and erosion as compared to SIR in under AC voltage test. Moreover, surface temperature of SIR also higher in the DC IPT test than the surface temperature of SIR in AC IPT test. This indicate that SIR faced higher challenge in HVDC application. Therefore, there is a need of an improvement in SIR composition for HVDC application.

REFERENCE

[1] A. Aman, "'New Leakage Current Parameters for Newly Developed Composite Optimized by Response Surface Methodology,'" 2013.

[2] J. F. Hall, "History and bibliography of polymeric insulators for outdoor applications," *IEEE Trans. Power Deliv.*, vol. 8, no. 1, pp. 376–385, 1993.

[3] R. Ghunem, S. Jayaram, and E. Cherney, "The DC inclined-plane tracking and erosion test and the role of inorganic fillers in silicone rubber for DC insulation," *IEEE Electr. Insul. Mag.*, vol. 31, no. 1, pp. 12–21, 2015.

[4] J. V. Vas, B. Venkatesulu, and M. J. Thomas, "Tracking and erosion of silicone rubber nanocomposites under DC voltages of both polarities," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 19, no. 1, pp. 91–98, 2012.

[5] L. H. Meyer, S. H. Jayaram, and E. A. Cherney, "Correlation of damage, dry band arcing energy, and temperature in inclined plane testing of silicone rubber for outdoor insulation," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 11, no. 3, pp. 424–432, 2004.

[6] E. A. Cherney, "Non-ceramic insulators - A simple design that requires careful analysis," *IEEE Electr. Insul. Mag.*, vol. 12, no. 3, pp. 7–15, 1996.

[7] R. A. Bernstorf, "Ageing tests of polymeric housing materials for non-ceramic insulators," *IEEE Electr. Insul. Mag.*, vol. 14, no. 2, pp. 26–33, 1998.

[8] R. A. Ghunem, S. H. Jayaram, and E. A. Cherney, “Erosion of silicone rubber composites in the AC and DC inclined plane tests,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 20, no. 1, pp. 229–236, 2013.

[9] G. P. Bruce, S. M. Rowland, and A. Krivda, “Performance of silicone rubber in DC inclined plane tracking tests,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 2, pp. 521–532, 2010.

[10] H. Xu, B. X. Du, Z. Li, Y. Liu, and Y. Li, “Tracking and erosion resistance of silicone rubber/BN nanocomposites under DC voltage,” *Proc. IEEE Int. Conf. Solid Dielectr. ICSD*, pp. 218–221, 2013.

[11] E. Cherney *et al.*, “DC inclined-plane tracking and erosion test of insulating materials,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 1, pp. 211–217, 2015.

[12] J. Mackevich and M. Shah, “Polymer outdoor insulating materials Part I: Comparison of porcelain and polymer electrical insulation,” *IEEE Electr. Insul. Mag.*, vol. 13, no. 3, pp. 5–12, 1997.

[13] G. P. Bruce, S. M. Rowland, and A. Krivda, “DC inclined-plane testing of silicone rubber formulations,” *Annu. Rep. Conf. Electr. Insul. Dielectr. Phenom.*, pp. 196–199, 2008.

[14] J. P. Reynders, I. R. Jandrell, and S. M. Reynders, “Review of aging and recovery of silicone rubber insulation for outdoor use,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 6, no. 5, pp. 620–631, 1999.

[15] D. Pathak, M. Satwani, M. Patel, and C. Patel, “The development of silicone rubber composite insulators in power system,” *2009 Int. Conf. Control. Autom. Commun. Energy Conserv.*, no. June, pp. 4–7, 2009.

[16] M. Amin, M. Akbar, and S. Amin, “Hydrophobicity of silicone rubber used for outdoor insulation (An overview),” *Rev. Adv. Mater. Sci.*, vol. 16, no. 1–2, pp. 10–26, 2007.

[17] D. A. Swift, C. Spellman, and A. Haddad, “Hydrophobicity transfer from silicone rubber to adhering pollutants and its effect on insulator performance,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 13, no. 4, pp. 820–829, 2006.

[18] Z. Guan, K. Niu, G. Peng, F. Zhang, L. Wang, and B. Lutz, “Hydrophobicity transfer property of silicone rubber material,” *Proc. 2012 IEEE Int. Conf. Cond. Monit. Diagnosis, C. 2012*, vol. 4, no. 2, pp. 324–327, 2012.

[19] A. H. El-hag and L. H. Meyer, “Experience With Salt-Fog and Inclined- Plane Tests for Aging Polymeric Insulators and Materials Key,” pp. 42–50.

[20] O. Applications, “IEEE Application Guide for Evaluating Noncerarnic Materials for High-Voltage Outdoor Applications,” *Society*, 1988.

[21] R. S. Gorur, J. Montesinos, L. Varadadesikan, S. Simmons, and M. Shah, “A laboratory test for tracking and erosion resistance of HV outdoor insulation,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 4, no. 6, pp. 767–774, 1997.

[22] “High Voltage Engineering.”

[23] M. Noureddine, A. Besma, and R. Khaled, “A Correlation Between the Flashover Voltage and the Electrical Bulk Conductivities AC and DC on Silicone Rubber Insulator During Thermal Ageing,” 2013.

[24] I. A. Tsekmes, R. Kochetov, and J. J. Smit, “Thermal Conductivity of Polymeric Composites : A Review,” pp. 678–681, 2013.

[25] R. A. Ghunem, “Using the Inclined-Plane Test to Evaluate the Resistance of Outdoor Polymer,” *IEEE Electr. Insul. Mag.*, vol. 31, no. 5, pp. 16–22, 2015.

[26] R. Bärsch, H. Jahn, J. Lambrecht, and F. Schmuck, “Test methods for polymeric insulating materials for outdoor HV insulation,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 6, no. 5, pp. 668–675, 1999.

[27] W. T. Starr, “Polymerie Outdoor Insulation,” *IEEE Trans. Electr. Insul.*, vol. 25, no. 1, pp. 125–136, 1990.

[28] K. Mathes and E. Mc Gowan, “Surface Electrical Failure in the Presence of Contaminants : The Inclined-Plane Liquid-Contaminant Test,” *AIEE Trans.*, pp. 281–289, 1961.

[29] IEC 60587:2007, “Electrical insulating materials used under severe ambient conditions — Test methods for evaluating resistance to tracking and erosion,” vol. 3, pp. 1–14, 2007.

[30] R. A. Ghunem, S. H. Jayaram, and E. A. Cherney, “Dynamics of Dry-Band Arcing on Silicone Rubber in the Inclined Plane Test under AC , + DC and – DC Voltages,” pp. 55–58, 2014.