FACULTY OF ELECTRICAL ENGINEERING

BACHELOR OF ELECTRICAL ENGINEERING

(INDUSTRIAL POWER) WITH HONOR

FINAL YEAR PROJECT 2

(SEMESTER 2 - 2016/2017)

DEVELOPMENT OF HIGH VOLTAGE RECTIFIER

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B011310200

940515-11-5449

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DEVELOPMENT OF HIGH VOLTAGE RECTIFIER

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A report submitted in partial fulfilment of the requirements for the degree of Bachelor of Electrical Engineering (Industrial Power)

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2017

I declare that this report entitled "*Development of High Voltage Rectifier*" is the result of my own research except as cited in the references. The report has not been accepted for any degree and it is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : Muhammad Ridwan bin Yusoff

Date : ....

To my beloved parents and siblings

Yusoff Mohamad

Khatijah Jusoh

Radhiyah Yusoff

Rashidah Yusoff

"Thank you for your support"

ACKNOWLEDGEMENT

Alhamdulillah, with the willing of Allah SWT, I have successfully completed my final year project, with the title of “Development of High Voltage Rectifier”. This report was prepared in order to fulfil the requirements of the undergraduate program of degree in Bachelor of Electrical Engineering (Industrial Power) in Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM).

I would like to express my deepest appreciation to Dr Aminudin bin Aman, my supervisor for all the efforts and guidance that he had provided during the period of two semesters in completing my final year project. I would also like to thank En Mohd Wahyudi bin Md Hussain, an assistant engineer in the High Voltage Engineering Research (HVER) Laboratory in UTeM for his helpful guidance during the completion period of my final year project.

In addition, a big thanks to my parents, siblings, friends, and others for their supports and encouragement in completing my project.

I hope that all the knowledges gained during the process of completion of this project will brings benefits to anyone who read it.

ABSTRACT

A lot of researches and studies had been carried out on the non-ceramic (polymeric) insulation since it was well accepted and applied in high voltage engineering. One of the key indicators to determine the polymeric insulation performance is its tracking and erosion resistance. In order to study the tracking and erosion resistance of outdoor polymeric insulation, an Inclined Plane Tracking and Erosion (IPT) test is conducted according to standard BS EN 60587: 2007 under AC voltage. However, with the increasing of the HVDC systems across the global, then the polymeric insulation has to deal with the DC voltage. Therefore, the rectification of AC-to-DC voltage is compulsory in order to conduct the DC IPT test in high voltage laboratory. The aim of this project is to develop a full-wave bridge high voltage rectifier with the rated output voltage up to 6kV DC. In addition, the rectifier circuit is first simulated by using PSpice software to obtain simulation waveform of the desired DC output voltage. The simulation waveform obtained from PSpice shows that the DC output voltage is pure and it contains low ripple. By this simulation result, the hardware of the DC high voltage rectifier will be developed. The development of the high voltage rectifier will be using several power electronic components such as power diodes and power capacitors as the waveform filtering element. The power capacitors used have two different values of capacitance which are 0.01uF and 820pF. With 0.01uF capacitor, the ripple percentage of the rectifier when 6kV DC output voltage is 25.1%. Meanwhile, with 820pF capacitor, the ripple percentage of the rectifier when 6kV DC output voltage is 18.6%. Therefore, it is proven that the high voltage rectifier developed with 820pF capacitor has better performance compared to the rectifier that developed by using 0.01uF capacitor.

ABSTRAK

Banyak penyelidikan dan pengajian telah dijalankan terhadap penebatan bukan-seramik (polimer) sejak ia telah diterima and diaplikasikan dalam kejuruteraan voltan tinggi. Salah satu petunjuk utama untuk menentukan prestasi penebatan polimer ialah rintangan mereka terhadap aliran dan hakisan. Untuk mempelajari rintangan aliran dan hakisan terhadap penebatan polimer luar premis, ujian *Inclined Plane Tracking and Erosion* (IPT) dijalankan mengikut piawaian BS EN 60587: 2007 dibawah voltan AC. Walaubagaimanapun, dengan peningkatan system HVDC di seluruh dunia, penebatan polimer perlu berurusan pula dengan voltan DC. Oleh itu, penukaran voltan AC-ke-DC adalah wajib untuk menjalankan ujian DC IPT di dalam makmal voltan tinggi. Maklamat projek ini adalah untuk membangunkan sebuah alat penukar voltan tinggi *full-wave bridge* dengan nilai voltan keluaran 6kV DC. Selain itu, litar alat penukar pada mulanya akan disimulasi dengan perisian PSpice untuk memperoleh bentuk gelombang simulasi voltan keluaran DC yang dikehendaki. Bentuk gelombang simulasi yang diperoleh daripada perisian PSpice menunjukan bahawa voltan keluaran DC ialah tulen dan mengandungi tahap ganguan yang rendah. Melalui keputusan simulasi, perkakasan alat pengubah voltan tinggi akan dibangunkan. Pembangunan perkakasan alat pengubah voltan tinggi akan menggunakan beberapa komponen electronik kuasa seperti beberapa diod kuasa dan kapasitor kuasa sebagai elemen penapis bentuk gelombang. Kapasitor-kapasitor kuasa yang digunakan mempunyai dua nilai kemuatan iaitu 0.01uF dan 820pF. Dengan kapasitor 0.01uF, peratusan gangguan daripada alat penukar semasa voltan keluaran 6kV DC ialah 25.1%. Sementara itu, dengan kapasitor 820pF, peratusan gangguan daripada alat penukar semasa voltan keluaran 6kV DC ialah 18.6%. Oleh hal yang demikian, ia telah terbukti bahawa alat penukar voltan tinggi yang dibangunkan dengan menggunakan kapasitor 820pF mempunyai prestasi yang lebih baik jikalau dibandingkan dengan alat penukar yang dibangunkan dengan menggunakan kapasitor 0.01uF.

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LIST OF ABBREVIATIONS

SiR	Silicon Rubber
EPM	Ethylene Propylene Monomer
EVA	Ethylene Vinly Acetate
HTV	High Temperature Vulcanized
AC	Alternating Current
DC	Direct Current
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ATH	Alumina Trihydrate
IPT	Inclined Plane Tracking and Erosion
DBA	Dry-band Arching
RBV	Reverse Breakdown Voltage
PIV	Peak Inverse Voltage
FVD	Forward Voltage Drop

LIST OF SYMBOLS

kV	Kilovolt
mV	Milivolt
pF	Picofarad
µF	Microfarad
Ω	Ohm
A	Ampere
f	Frequency
%	Percent
V_{max}	Maximum output voltage
V_0	Average output voltage
V_p	Peak voltage
V_{rms}	RMS voltage
Hz	Hertz
X_C	Capacitive reactance
C	Capacitance value

CHAPTER 1

INTRODUCTION

1.1 Introduction

In modern times, high voltage is used in many applications including the power system industry and research laboratories. Such applications are vital to maintain our modern civilization. The insulators are the most important material in high voltage applications to ensure the current flow in its own path [1].

Previously, the insulation industries were dominated by the ceramic and glass insulator. However, in the middle of the twenty century, a new concept of composite insulation introducing polymeric materials was developed in USA [2]. Non-ceramic (polymeric) insulation is well accepted by the industries and utilities to replace the old-type porcelain and glass insulation due to their advantages such as light in weight, easy to handle, good contamination performance and low installation and maintenance costs [3]. Besides, polymeric insulation has good hydrophobic characteristic in fog, dew and rain condition [4]. These good hydrophobic characteristics will lower the transmission losses during early year of installation [5]. Silicone rubber (SiR), ethylene propylene monomer (EPM) and ethylene vinly acetate (EVA) are the examples of most common polymer composites used in high voltage insulation [3].

However, the polymeric insulation has main disadvantage which is the deterioration due to environmental and operation conditions [6]. For instance, although the polymeric insulation is hydrophobic at the beginning of their service, it may become hydrophilic under certain condition especially in polluted environment. This will lead to leakage current flow, dry-band arching (DBA) and ageing by tracking and erosion [7].

Nevertheless, insulation with silicone rubber (SiR) composite has extraordinary performance in the contaminated environment. In spite sharing the hydrophobic surface characteristic with others polymeric insulation materials, the surface of silicone rubber (SiR) composite remains hydrophobic in contaminated area and the hydrophobicity losses in extreme condition are temporary. According to R. J. Hill [8], the High Temperature Vulcanized (HTV) silicon rubber (SiR) is favorable insulation in extremely polluted environment.

Polymeric outdoor insulation is the suitable option for High Voltage Alternating Current (HVAC) power transmission lines to replace ceramic insulations. Since the introduction of power electronic devices, High Voltage Direct Current (HVDC) has become the possible option in power transmission [5]. Nowadays, it is an undeniable proof that HVDC system is growing rapidly around the world as lots of power transmission projects are adopting this type of system [9]. The first polymer insulator for DC transmission was introduced in the mid-1970 on the Pacific DC Intertie line at +/- 400kV, at the southern terminus of the line near Los Angeles [10]. One thing to be concerned about the HVDC power transmission is its line insulator, as for the same electric field condition, the insulator accumulated pollutant under Direct Current (DC) voltage is 1.2 to 1.5 times larger compared to Alternate Current (AC) voltage [5].

A rectifier is very crucial in HVDC power transmission system. Theoretically, the purpose of rectifier is to produce the purely output DC voltage or current waveform that has specified DC components [11]. Therefore, the design characteristic of a rectifier must be able to deal with the high voltage application. Moreover, in the reference [5], the high voltage DC power supply was used as the input voltage for Inclined Plane Tracking and Erosion (IPT) test under DC voltage of insulating polymeric material. This highlights the importance of rectifier in producing DC voltage. In this project, the high voltage rectifier with maximum output of 6kV positive DC will be developed. The rectifier built will be used to generate high voltage DC power supply that will be used as the input voltage for DC IPT test of insulating polymeric material which usually done according to the standard BS EN 60587: 2007.

1.2 Problem Statement

The IPT test is carried out to analysis the ageing performances of the polymeric insulation under AC voltage previously. However, the use of DC polymeric insulation has gained a lot of interest in the HVDC projects worldwide. Besides, study on silicone rubber properties of high voltage insulation is moving towards the DC voltage lately such as in the reference [12] and in the reference [13] .Therefore, the use of the polymeric insulation under DC voltage needs to be examined [10]. Nowadays, the standard IPT tests involve only for AC voltage. Even though there is no standard test method for DC voltage, a lot of researchers carry out the IPT test under DC voltage by referring to the AC IPT test standard [14]. Therefore, more researches need to be done to allow the development of new standard of DC tracking and erosion. Since the power source AC voltage needs to be changed to DC voltage in order to carry out IPT test under DC voltage, a high voltage rectifier is required to rectify the high voltage AC waveform to high voltage DC waveform through a process called rectification. Therefore, with the construction of the rectifier, the DC IPT test can be carried out in the high voltage laboratory and thus it opens up larger opportunity to study the ageing performance of polymeric insulations under DC voltage.

1.3 Objective

The following are the objectives of the project:

1. To develop a high voltage rectifier that could produce DC voltage up to 6kV for high voltage insulator application.
2. To apply full-wave bridge rectification technique to study the behavior of DC IPT Test.
3. To produce a high quality of rectifier that has low ripple DC output voltage waveform.

1.4 Scope

The following are the scopes of the project:

1. Designing of full-wave bridge rectifier circuit which will be developed for DC IPT test.
2. The input voltage of the rectifier is varied from 0V to 240V.
3. The rated output DC voltage of the developed high voltage rectifier is 6kV.

1.5 Project Outline

Chapter 1 is an overall outline of the project including the problem statement, objectives and scopes. The project works that will be carried out are based on the objectives and scopes that have been reviewed earlier.

Chapter 2 explains the literature review and previous studies that have been carried out previously. In this chapter, the selection criteria and the development of high voltage rectifier is explained. Next, the review of DC IPT Test procedures and the study of ageing mechanism toward the polymeric insulation in laboratory were also discussed.

Chapter 3 discusses about the methodology that was adopted for this project. It includes the development process of high voltage rectifier by using software and hardware approach. The software approach uses the PSpice simulation software while the hardware approach applies the usage a few of power electronic components and several high voltage equipment in the high voltage engineering research laboratory.

Chapter 4 presents the result and discussion regarding the developed high voltage rectifier. The DC voltage output waveform characteristics are obtained by using PSpice simulation software and also from the digital oscilloscope. The calculation of ripple percentage is also done in this chapter to determine the performance of the rectifier.

Chapter 5 concludes the all the procedures that has been presented and carried out in previous chapters and the overall result of this project.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Electrical insulation is one of the important issue to be considered in the electrical engineering field. The generation and transmission of electrical power system critically depend on the performance of electrical insulation. The polymeric composite insulation is widely used in high voltage engineering due to its advantages compared to old-type glass insulation. Since the development of HVDC power transmission system, a large number of significant research and studies has been made to improve the insulation performance under DC stress.

The following subsections of this literature review discuss the overview of polymeric insulation composite including its major components and the factor that influence the ageing performance of insulators. It also explains the development of high-voltage rectifier, as a DC power source to be used in the DC IPT test of insulation materials.

2.2 History of Polymeric Insulation

The history of polymeric insulation began in the 1940s when epoxy as organic material was used in indoor high voltage insulation. The discovery of alumina trihydrate (ATH) filler that increases the tracking and erosion resistance in 1950s led the usage of polymeric insulator in outdoor high voltage insulation. Until late 1960s and early 1970s, there was no development of outdoor polymeric insulators until they became operational on transmission lines system in the 1980s [15]. Since the introduction in high voltage applications, the polymeric composite insulation has been improved in its quality and performance involving material formulation, manufacturing process and reliable testing and monitoring methods. The applications of polymer insulating composite in electrical engineering field include the arrestors, bushings, joints and cable terminations [16][17]. The early design of a polymeric insulation design is illustrated in Figure 2.1.

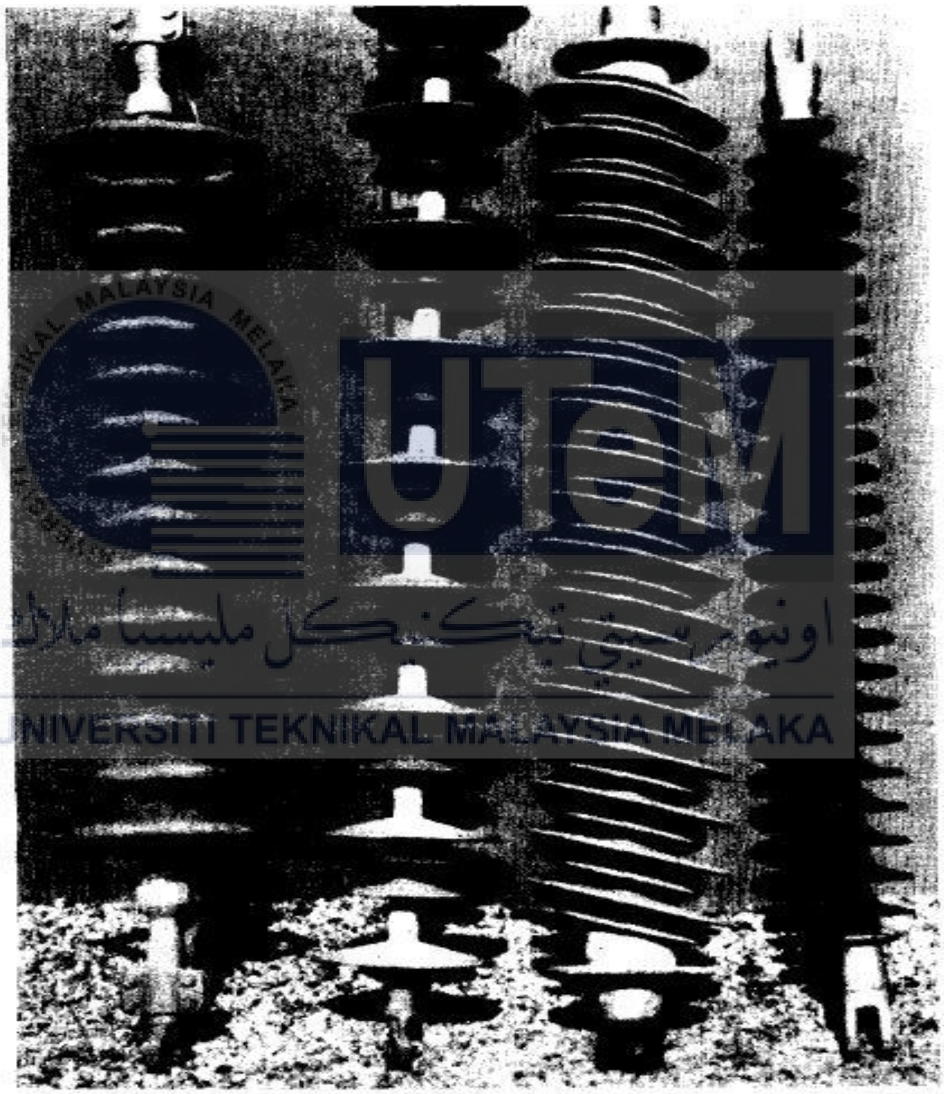

Figure 2.1: Example of early polymeric insulation design [15].

2.3 Fundamental of Polymeric Composite Insulation

A composite substance is made up from the combination or mixture of two or more micro components which are different in shape and chemical composition, and not soluble in each other, according to Smith [18]. The consideration in selection the polymeric composite material for electrical purpose especially for outdoor application, as mentioned by Cherney [17], where the material must be light in weight and has excellent performance in electrical and environment condition. The basic design of polymeric insulator is shown in Figure 2.2.

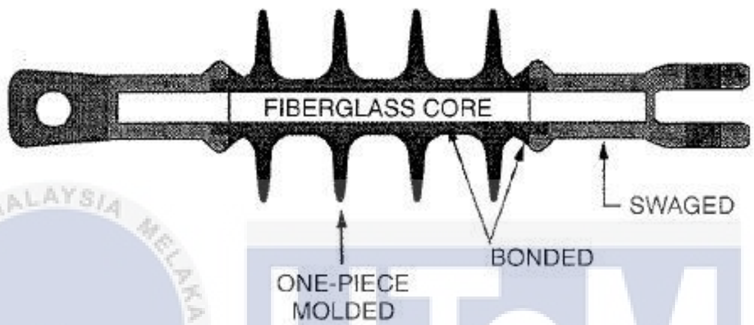

Figure 2.2: The design of polymeric (non-ceramic) insulator [17].

One of the major factors that contribute to the low efficiency of high voltage insulation is the pollution. According to Salam *et al* [19], different types of pollution such as sea salt, chemicals, ashes and dust will affect the performance of the insulators. Muniraj *et al* [20] explained that when these insulators are installed near agricultural or industrial areas, the airborne particles will be accumulated on the surface of insulators and this condition will lead to the flow of leakage current (LC) during wet condition such as dew and fog.

Silicone rubber (SiR), ethylene propylene monomer (EPM) and ethylene vinly acetate (EVA) are the examples of most commonly used polymer in high voltage insulation [3]. Vas *et al* [5] stated that silicone rubber (SiR) is a favorite choice of the polymeric insulation used in outdoor application. At the beginning, epoxy called Bisphenol Type A was widely used for the insulation purpose, but after some poor experiences, the hydrocarbon and silicone has become new alternative option [1].

2.3.1 Silicon Rubber Composite

In electrical engineering field, the polymeric composite of SiR has been generally accepted especially for high voltage outdoor application. This is because the silicon's low density composite reduces the total weight of electrical equipment compared to old type ceramic insulators. Besides that, it is capable of maintaining its water-repellent properties (hydrophobicity) during bad weather and in highly polluted areas. The applications of SiR in electrical engineering includes the overhead insulators, bushings, circuit breakers, fuse cutouts and surge arresters [21]. According to a report by Swift *et al* [22], there are more than 600,000 SiR insulators have been installed in China.

However, the SiR polymeric insulation especially for outdoor installation has disadvantages such as the temporary loss of hydrophobicity and the formation of carbonaceous track (tracking) and material erosion of surface during electrical discharges. Besides that, the degradation of the polymer surface due to corona is another disadvantage of the SiR insulation. The ageing of SiR was basically due to electrical and environmental stress. As a result, their long term endurance as an outdoor insulator had always been a concern and therefore a lot of studies have been carried out in laboratories and field for better understanding of ageing of SiR polymeric composite installed in outdoor application [5].

2.4 Polymeric Insulation under DC Voltage System

Recently, the implementation of HVDC technology and the composite overhead line insulators has become viable options for power transmission sector. The HVDC projects are growing rapidly in most of the countries in the world, and the achievement of this technology is quite succeeded. In the same time, the polymeric composite insulation implemented on the HVDC system have many benefits. The polymeric insulators have a weight only 10% of old-type ceramic insulators and this factor contributes to the reduced cost of installing and replacing those components [23].

Nowadays, concern about the DC polymer insulations rises as the increase of interest in DC transmission system. The dry-band arching (DBA) under DC and AC voltage is different from each other. In highly polluted and wet areas, the heat from the DBA causes the degradation of the polymeric insulators surface. This condition will lead to the tracking and erosion on the material and thus results the insulation failure on the DC system. Therefore, a better understanding about the tracking and erosion of the polymeric composite material will help to design a proper DC outdoor insulation, especially in polluted areas [24].

2.4.1 DC IPT Test of Silicon Rubber (SiR) Polymeric Composite

In order to evaluate the performance of SiR polymer outdoor insulation used in HVDC transmission, a DC Inclined-Plane Tracking and Erosion (IPT) needs to be carried out on the SiR sample in the high voltage laboratory. Until today, although many researchers refer to the AC voltage standard IPT test for the DC voltage, the test method for DC voltage has not been standardized yet [14]. A lot of research about IPT test of SiR composite insulation have been carried out by researchers as the combination of HVDC technology and SiR insulation offers great advantages in electrical engineering field [23].

In addition, the electrostatic field is fixed and has no direction under DC voltage and this will lead the airborne contaminated particles to the insulator surface. According to a report, the pollutant on the SiR surface is 1.2 to 1.5 times under DC compared to AC. The IPT test on High Temperature Vulcanized (HTV) Silicone Rubber (SiR) insulations with 2.5kV shows that severe performance of SiR under AC compared to DC [5]. Next, the tracking and erosion resistance of SiR polymeric insulation is reduced under DC than AC, reported by Cherney *et al* [14].

On the other hand, an IPT test was conducted by Bruce *et al* [23] to study the behavior and performance of SiR sample under DC voltage, in both positive and negative polarities. It is concluded that the erosion level of the sample is lower under negative DC compared to positive DC at the same voltage level. Moreover, a deeper erosion and greater mass reduction are recorded at positive and negative electrode due to electrolysis and oxidation process respectively [23]. Figure 2.3 shows the Inclined Plane Tracking and Erosion (IPT) test under DC voltage.

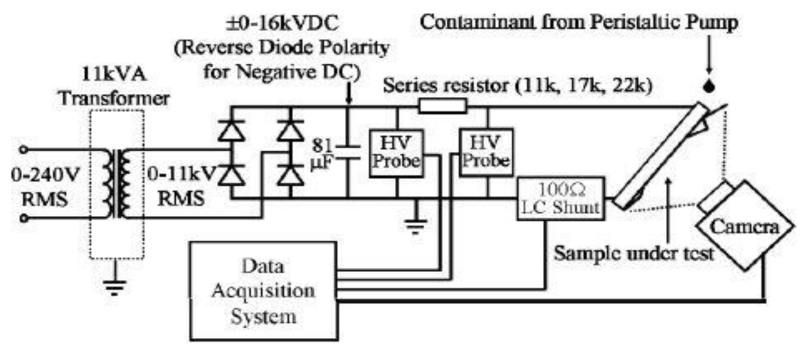

Figure 2.3: Inclined Plane Tracking and Erosion (IPT) test under DC voltage [23].

2.5 Diode

Diode is a power electronic device that function to allow the current to flow in only one direction. The function of the diode is similar to the function of the valve and that is why the first name of diode is called electronic valve. The schematic symbol of a diode that has anode terminal and cathode terminal is shown in Figure 2.4 and Figure 2.5 respectively. The anode terminal is known as positive terminal of the diode while the cathode terminal is known as negative terminal. The arrow in the figure is the direction of current flowing through the diode. The condition where the diode is forward biased occurs when the positive supply voltage is applied to the anode terminal of the diode and the negative supply voltage is applied to the cathode terminal of the diode. When this situation happens, the diode will conduct and allow the current to flow through the diode, as shown in Figure 2.4. Thus, the diode acts like the short circuit [25].

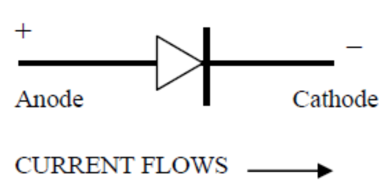

Figure 2.4: The forward biased diode [25].

Otherwise, when the polarity of the supply voltage is changed where the negative supply voltage is applied to the anode terminal of the diode and the positive supply voltage is applied to the cathode terminal of the diode, the diode will not conduct. This condition is called diode reverse biased where the diode blocks the current from flowing through the diode, as shown in Figure 2.5. Then, the diode is described as the open circuit [25].

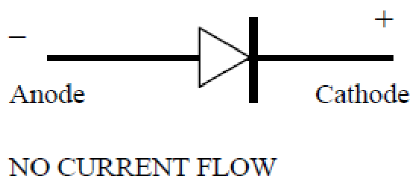

Figure 2.5: The reverse biased diode [25].

2.5.1 Forward Voltage Drop (FVD) and Peak Inverse Voltage (PIV)

The diode especially made from silicon likely has small voltage drop approximately 0.7V across it and is called Forward Voltage Drop (FVD). However, the FVD of a diode is nearly fixed regardless how much the value of the current flowing through the diode. By referring to voltage-current characteristic as shown in Figure 2.6, the diode has very steep characteristic [25].

The Peak Inverse Voltage (PIV) refers to the limits of the reverse electrical pressure that the silicon diode can withstand even though the diode is not operated during the reverse polarity. If the value of voltage applied to the diode exceeds the value of PIV specified by the manufacturer, the diode will fail to operate and lead to the diode breakdown because larger current will flow through the diode in the reverse direction. In other word, the PIV is also known as Reverse Breakdown Voltage (RBV) of the diode as indicated in Figure 2.6 [25]

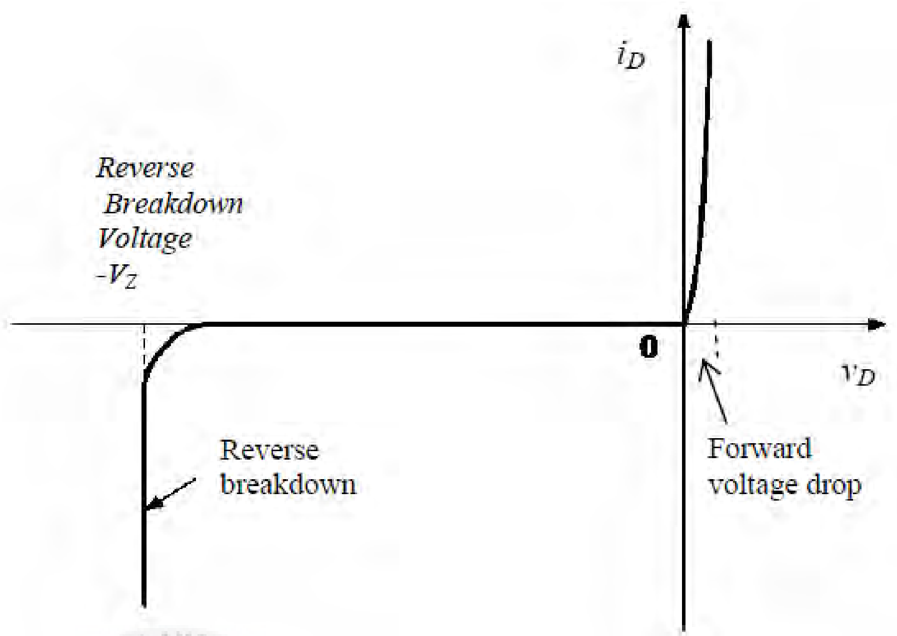

Figure 2.6: Voltage-current characteristic of a silicon diode [25].

2.6 High Voltage Rectifier

High voltage DC is needed in electrical engineering study for purposes such as particle accelerators in nuclear physics and electron microscopes and also for the insulation testing of high voltage equipment [26]. Bruce *et al* [23] explained the importance of the high voltage DC power supply to perform the DC IPT test.

DC IPT test requires high voltage DC power supply as the input voltage to analyze the performance of SIR polymeric insulating material used in DC transmission system. The DC voltage source is generated by a single phase rectifier and also a capacitor for smoothing purpose [23]. Therefore, a high voltage rectifier needs to be developed in order to obtain the DC input voltage for the DC IPT test.

The purpose of rectifier is to convert the AC voltage to smooth DC output voltage and this process is called rectification process. The rectification process is divided to two categories which are half-wave rectification and full-wave rectification. There are three popular circuit configuration used in single phase rectification process including the half-wave rectifier circuit, the full-wave center tap and the full-wave bridge rectifier circuit [27].

The rectifier circuit is divided into two types which are half-wave rectifier and full-wave rectifier. The details of these types of rectifier are explained in the flowing subsections.

2.6.1 Half-wave Rectifier

The half-wave rectifier is used mostly in low power applications. The basic circuit of half-wave rectifier is shown in Figure 2.7. This configuration circuit contains only a single diode and this rectifier can rectifier only a half of the AC waveform. The diode in half-wave rectifier circuit should be rated at least 1.5 times the maximum peak AC voltage at the secondary winding of the transformer [28].

The effective output voltage of this half-wave rectifier is lower than the peak transformer output voltage [28]. Figure 2.8 below shows the effective output voltage of half-wave rectifier.

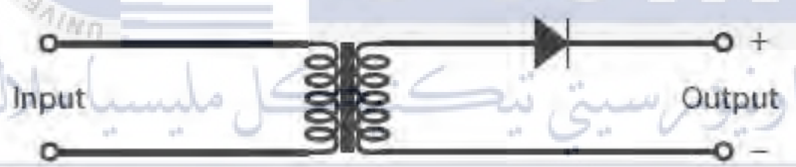

Figure 2.7: The basic circuit of half-wave rectifier using only one diode [28].

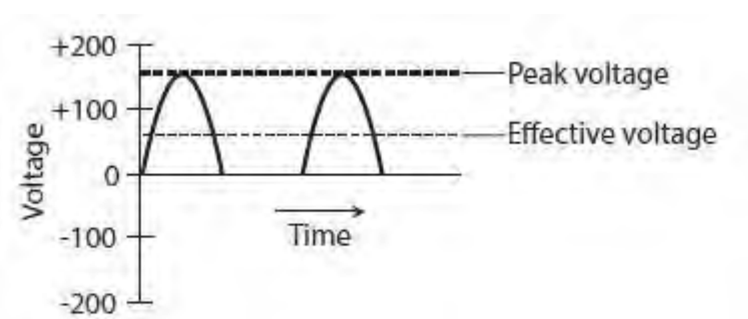

Figure 2.8: The output voltage of half-wave rectifier [28].

2.6.1.1 Advantages and Disadvantages of Half-wave Rectifier

Table 2.1: The advantages and disadvantages of half-wave rectifier [28].

Advantages	Disadvantages
1) Cost effective because the circuit involves fewer parts.	1) The output waveform is difficult to be filtered.
2) The voltage can be varied without affecting the behavior of the equipment because the rectifier delivers much less output current.	2) The output voltage can drop considerably when the supply must deliver high value of current.

2.6.2 Full-wave Rectifier

Full-wave rectification is a process of rectifying both of the positive and negative cycle of AC sinusoidal waveform. Basically, the full-wave rectifier is used mostly in high power applications. The full-wave rectification is divided into two configuration circuits. These circuits are full-wave centre tap circuit and full-wave bridge circuit.

2.6.2.1 Full-wave Centre Tap Rectifier Circuit

Figure 2.9 below shows the full-wave centre tap circuit with two diodes. Besides that, a transformer that has a connection at the center of its secondary winding called tap is also a part of this circuit. The tap is connected directly to the ground. The minimum Peak Inverse Voltage (PIV) rating of each diode is 2.8 times of the peak AC voltage of the secondary winding of the transformer [28].

The effective output voltage obtained from this type of rectifier circuit is greater than the half-wave rectifier circuit effective output voltage. Furthermore, the output voltage waveform of full-wave centre tap configuration is closer to obtain to pure DC voltage waveform, compared to half-wave rectifier [28]. The effective output voltage of full-wave centre tap is shown in Figure 2.10.

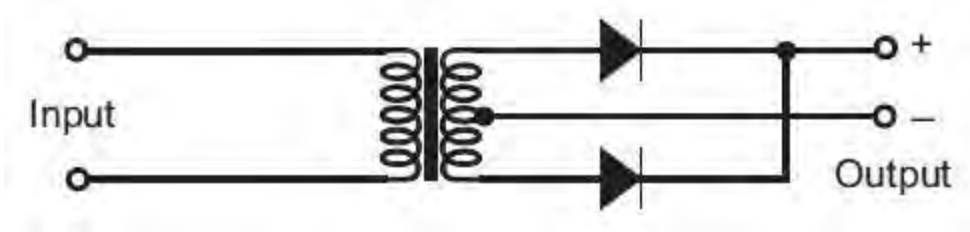

Figure 2.9: The basic circuit of full-wave centre tap rectifier using two diodes [28].

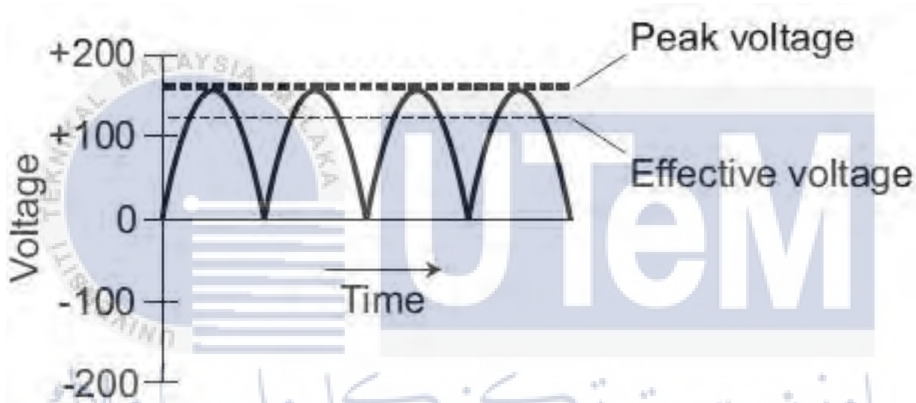

Figure 2.10: The output voltage of full-wave centre tap rectifier [28].

2.6.2.2 Full-wave Bridge Rectifier Circuit

Figure 2.11 and Figure 2.12 show the basic circuit of full-wave bridge rectifier and their output voltage waveform respectively. Based on this configuration, the circuit consists of four diodes instead of one diode in half-wave rectifier circuit. The diodes are arranged in special configuration called bridge configuration. Each diode in this circuit has the Peak Inverse Voltage (PIV) value at least 1.4 times of the AC peak voltage of the transformer's secondary winding [28].

The effective output voltage obtained from this type of rectifier circuit is same with the full-wave centre tap rectifier which is less than the peak voltage. Similar with the full-wave centre tap rectifier, the output voltage waveform of full-wave bridge configuration is nearly pure DC voltage waveform, compared to half-wave rectifier [28].

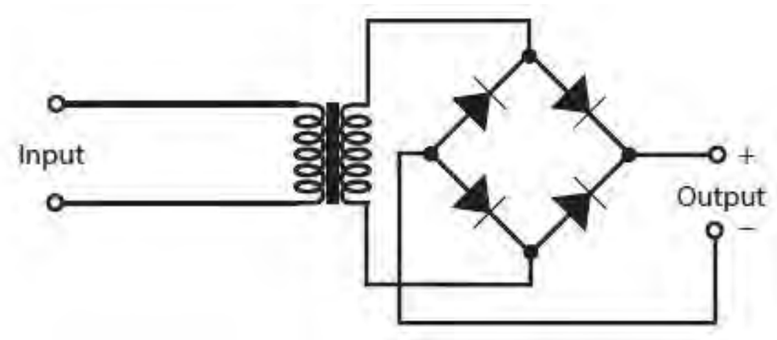

Figure 2.11: The basic circuit of full-wave bridge rectifier using four diodes [28].

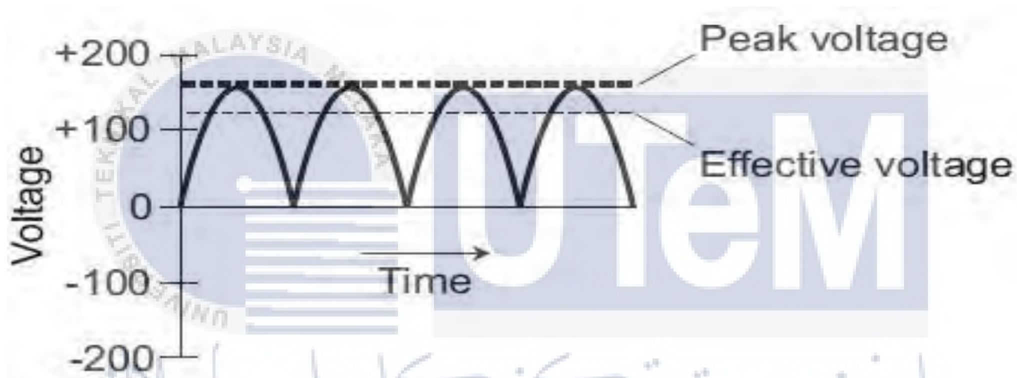

Figure 2.12: The output voltage of full-wave bridge rectifier [28].

2.6.2.3 Different of Half-wave, Full-wave Centre Tap and Full-wave Bridge Rectifier

The differences of three type of rectifier circuits which are half-wave circuit, full-wave centre tap circuit and also full-wave bridge circuit are explained in Table 2.2. The parameters that are compared between each of the rectifier circuits include the PIV value, the rectified waveform and the effective output voltage.

Table 2.2: Different of half-wave, full-wave centre tap and full-wave bridge rectifier [28].

Half-Wave Rectifier	Full-Wave Centre Tap Rectifier	Full-Wave Bridge Rectifier
1) Used in low power application.	1) Used in high power application.	1) Used in high power application.
2) The circuit contains only a single diode.	2) The circuit contains two diodes.	2) The circuit contains four diodes.
3) PIV of the diode is 1.5 times of peak AC voltage.	3) PIV of the diode is 2.8 times of peak AC voltage.	3) PIV of the diode is 1.4 times of peak AC voltage.
4) A center tap transformer is not required	4) A center tap transformer is required	4) A center tap transformer is not required
5) Rectification involves only half of the AC sinusoidal waveform.	5) Rectification involves both positive and negative cycle of AC sinusoidal waveform.	5) Rectification involves both positive and negative cycle of AC sinusoidal waveform.
6) The DC output voltage obtained is much lower from the peak input voltage.	6) The DC output voltage obtained is closer to the peak input voltage.	6) The DC output voltage obtained is closer to the peak input voltage

2.7 Filter Circuit for the Rectifier

The rectifier is used to convert AC voltage to DC voltage. During the AC-DC rectification process, the DC output waveform contains undesired component called ripple. The ripple can cause effects to the system such as stray heating and audible noise. Therefore, a lot of electrical systems that require rectifier application needs to contain lower ripple percentage than the rated or specified value [29].

The ripple percentage is the ratio of RMS voltage of the ripple, V_{rms} of ripple to the average voltage of the rectifier, V_o. The parameters required to calculate the ripple percentage of the rectifier is displayed in Figure 2.13. Based on the Figure 2.13, it is assumed that the ripple voltage has sinusoidal waveform. The formula for calculating the ripple percentage is explained by S.Pyakurnal *et al* [29].

Calculation of ripple percentage [29]:

V_p ripple = V_{max} - V_0

V_{rms} of ripple = V_p ripple / $\sqrt{2}$

Ripple percentage = (V_{rms} ripple / V_0) x 100%

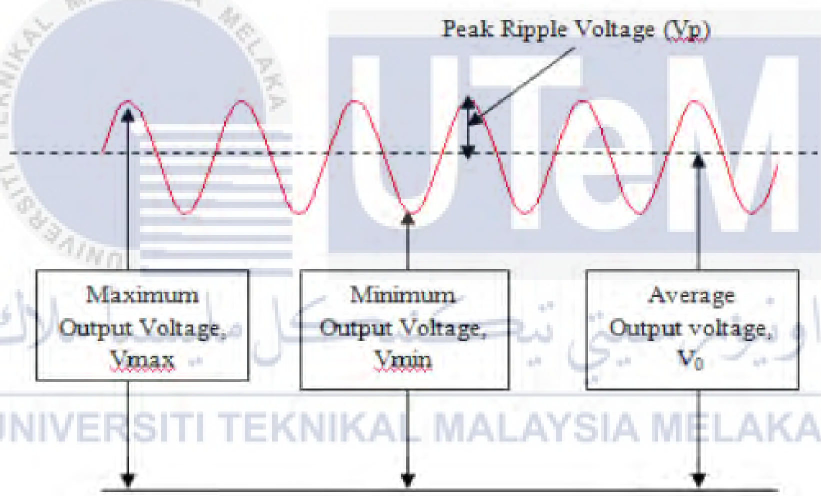

Figure 2.13: Parameters required to determine ripple percentage [29].

2.8 Power Electronic Equipment Used in the High Voltage Rectifier

In this section, the power electronic equipment used in this project is discussed. Section 2.7.1 discussion about the power diode, while subsection 2.7.2 and subsection 2.7.3 discuss regarding the capacitors that has capacitance value of 0.01uF and 820pF respectively.

2.8.1 Power Diode

The power diode is the main part in constructing the high voltage rectifier especially the full-wave bridge rectifier circuit. In this project, the power diode used in the project as shown in Figure 2.14, is made of silicon material from Diotec Company with rated current is 1A. Besides, the maximum rated voltage or the repetitive peak reverse voltage, V_{RRM} of this power diode is 1kV [30].

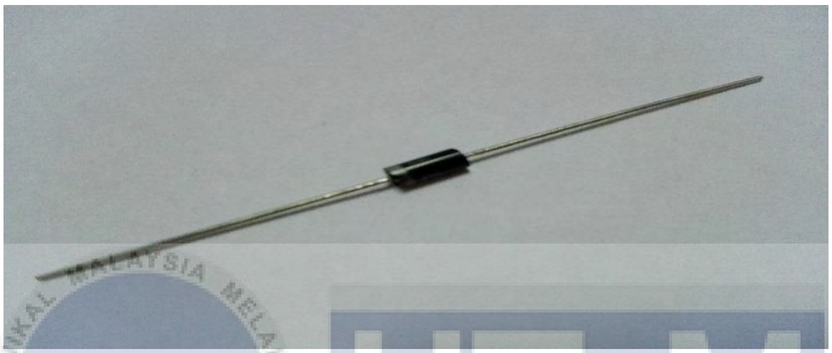

Figure 2.14: The 1A, 1kV-silicone power diode by Diotec.

2.8.2 Power Capacitor with Capacitance Value of 0.01uF

Apart from power diode, another power electronic component that is vital in the rectifier circuit is the power capacitor. The function of power capacitor is to filter the output DC voltage waveform to obtain pure DC waveform. The power capacitor from Murata Company is chosen in this project. This type of ceramic capacitor has capacitance value of 0.01uF and rated voltage of 2kV DC [31]. This ceramic high voltage power capacitor is displayed in Figure 2.15.

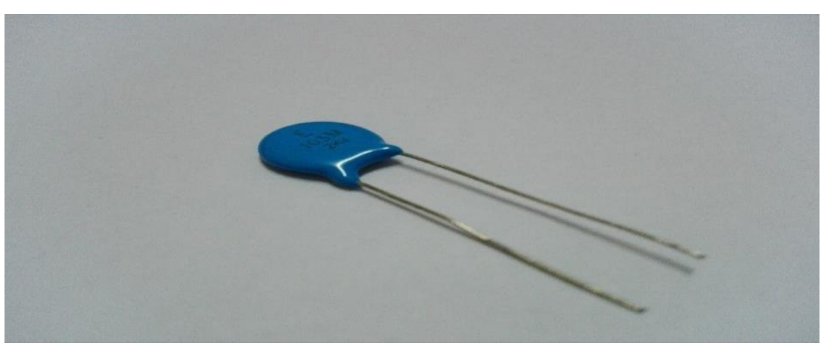

Figure 2.15: The 0.01uF, 2kV DC-ceramic power capacitor by Murata.

2.8.3 Power Capacitor with Capacitance Value of 820pF

Besides the 0.01uF capacitor, the other capacitor that is used in this project is the 820pF capacitor, as shown in Figure 2.16 below. This ceramic power capacitor that has capacitance value of 820pF and rated voltage of 2kV DC is supplied by the Vishay Company [32]. The 0.01uF capacitor and 820pF capacitor are applied in the high voltage rectifier circuit in order to analyze the performance of the developed rectifier based on the ripple percentage calculation of the output DC voltage waveform.

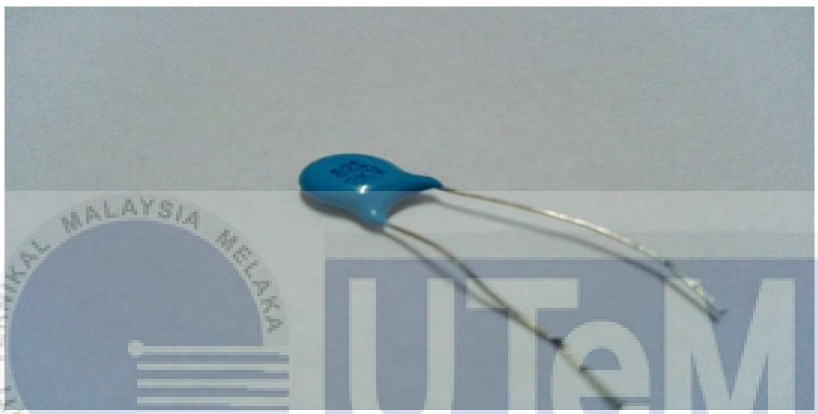

Figure 2.16: The 820pF, 2kV DC-ceramic power capacitor by Vishay.

2.9 Review of Previous Study

Vas *et al* [5] stated that the addition of the micro and nano filler on the SiR composite would improve the tracking and erosion performance of the SiR as an outdoor high voltage insulation. By applying the DC IPT test, the SiR polymeric insulation samples composed of micro and nano sized particles were tested under positive polarity and negative polarity of DC voltages to observe their performances. To understand the filler effects of the SiR composite, Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) studies was carried out on the samples. The results showed that the small filler loading (4%) of nanocomposite performed similar to the higher filler loading (30%) of micro composite. It was also shown that the SiR performance is poor under positive DC compared to negative DC.

According to Cherney *et al* [14], the paper revises the DC IPT test that has been done and the recommended DC voltage similar to AC voltage referring to the ASTM D2303 liquid-contaminant IPT test of the insulations sample. The SiR polymeric insulation was tested in five different samples in five different laboratories in order to determine the suitable DC voltage level which is identical to AC voltage. The results of the test concluded that the value of positive DC and negative DC is 67% and 87% of the AC voltage, respectively. Moreover, both of the percentages are rounded up to 70% and 90% for practical applications.

A paper from Mariun *et al* [26] reviewed the main criteria to develop a high voltage DC power source which is capable of generating 15kV DC output voltage. Therefore, the AC-to-DC rectification process by adapting the concept of the voltage multiplier circuit is emphasized in the paper. Moreover, designing and the construction the power supply is based on the simulation and the hardware processes in the high voltage laboratories. The software of PSCAD and PSpice are used as the simulation tool for the designed voltage multiplier circuit. It was concluded that the high voltage DC power source with 15kV is developed and tested in the high voltage laboratory. The simulation and hardware results are on par with each other. In addition, the cascaded voltage multiplier circuit is vital in application that requires increased DC voltage output while maintaining the input voltage of the transformer.

2.10 Summary of Previous Study

From the review of the previous works, Mariun *et al* [26] explained the importance of the DC power supply in the high voltage laboratories. The DC power supply can be used to do testing procedure of various applications of the high voltage applications. Besides that, the method of rectification by using the voltage multiplier circuit is also explained. Next, the review paper from Cherney et al [14], suggested that the appropriate DC voltage level for both positive and negative DC to be used in DC IPT test, with respect to AC voltage level. Therefore, 67% and and 87%, of the AC voltage, are the suitable DC voltage for conducting DC IPT. Meanwhile, Vas *et al* [5], argued that the addition of the micro and nano filler would affect the performance of the SiR polymeric composite insulation under DC voltage. It is found out that the nano filler is better compared to micro filler for both negative and positive DC voltages.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In Chapter 3, the priority is given on the discussion of the design methodology of the project. In this section, the design procedure and simulation process, hardware development and experimental testing procedures are discussed. The purposed circuit is included along with its working principle. Besides, the project flow chart which involves the steps of the project will be explained in the chapter. Project Gantt chart and project Milestone is also presented in the appendix to indicate the timeline of project is conducted.

3.2 Project Flow Chart

Figure 3.1 explains the flow of overall the project. The first method used in this project is the literature review. In this section, a lot of research regarding the Direct Current (DC) Inclined Plane Tracking and Erosion (IPT) test and the development of high voltage rectifier is taken as a source of references. The source of references obtained from the previous researcher through magazines, journals and books will not only allow the gathering of knowledge but it will also help in building up understanding related to the high voltage rectifier.

After reviewing the references from the literature review, the designing criteria of the high voltage rectifier is taken into consideration. The configuration circuit of the high voltage rectifier is designed. After that, the designed circuit is simulated in the software PSpice. If the simulation process is working properly, then the proposed hardware circuit is constructed by using the electric and electronic hardware equipment. However, if the simulation goes wrong, the circuit needs to be adjusted and redesigned. The process of constructing the hardware circuit will not be conducted unless the simulation circuit works in proper condition.

After the hardware circuit is completed, it is the time to test the circuit's function ability and its performance. In this part, the data such as the signal waveform is observed, recorded and analyzed. The data obtained is compared with the simulation result obtained by the PSpice software previously. After that, the conclusion and recommendation of this project are discussed regarding the result obtained from this experiment.

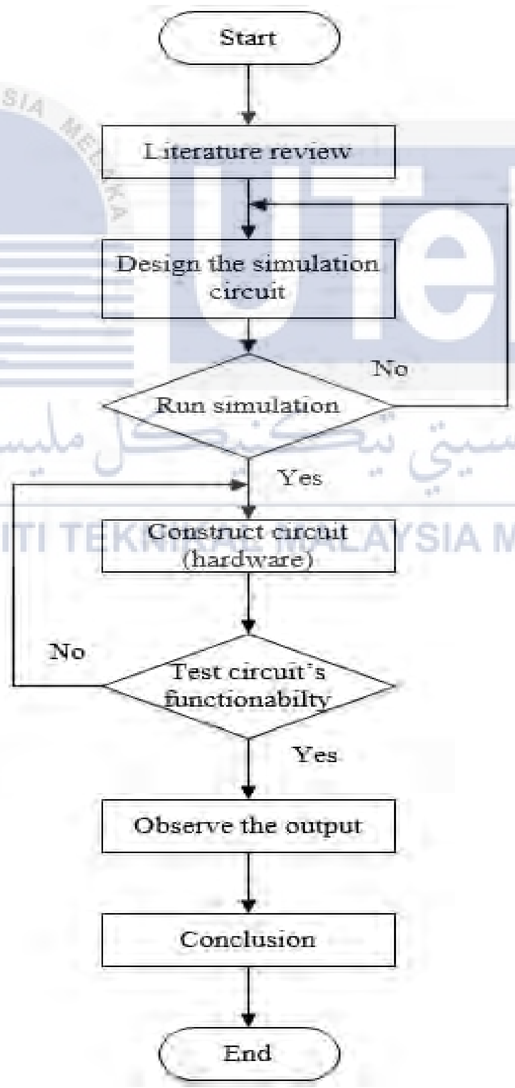

Figure 3.1: The flow chart of the project methodology.

3.3 Software Development

First of all, the rectifier circuit applied in this project is the full-wave bridge rectifier circuit instead of half-wave rectifier circuit and full-wave center tap rectifier circuit. In this section, there will be explanation on how the high voltage rectifier is developed by using the PSpice software. The simulation circuit of the full-wave bridge rectifier is developed by using several power electronic components such as power diodes and power capacitors. Besides that, there are two types of capacitors used in the project. These capacitors have different value of capacitance value which are 0.01uF and 820pF. For the subsection 3.2.1, it is explained about the simulation of rectifier circuit with 0.01uF capacitor and 820pF capacitor altogether.

3.3.1 The Rectifier Simulation Circuit with 0.01uF Capacitor and 820pF Capacitor

The basic configuration of this rectifier uses four diodes arranged in bridge connection is shown in Figure 3.2 below. Apart from that, the smoothing capacitor with capacitance value of 0.01uF is used to reduce the ripple of the output waveform. The AC voltage supply injected to this rectifier circuit is 1kV peak with the frequency of 50Hz.

In order to develop the full-wave bridge rectifier with 820pF capacitor, the circuit configuration is similar to the Figure 3.2. However, the capacitance value of the capacitor is changed to 820pF.

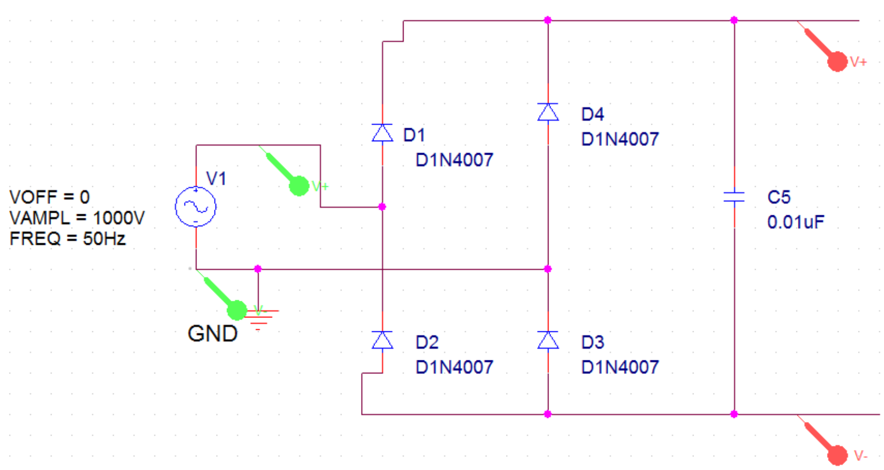

Figure 3.2: The simulation circuit of full-wave bridge rectifier with four diodes in PSpice.

In order to generate 6kV DC output voltage, the diodes used is increased from four diodes to 24 diodes. This is because the maximum rating voltage for one diode is only 1kV. Therefore, to prevent the breakdown of the diodes, six diodes are connected in series for each branch of the circuit to increase the maximum voltage rating of diodes up to 6kV. Since the bridge circuit has four branches, so the total diodes applied is 24. The use of 24 diodes arranged in full bridge is crucial to generate the DC output voltage up to 6kV. The circuit of the 24 diodes is shown in Figure 3.3 with the 0.01uF smoothing capacitor for the filtering purpose. Furthermore, the 0.01uF capacitor is then swapped with 820pF capacitor in order to develop the full-wave bridge rectifier that has 820pF capacitor. The AC input voltage applied is 6kV peak with 50Hz frequency.

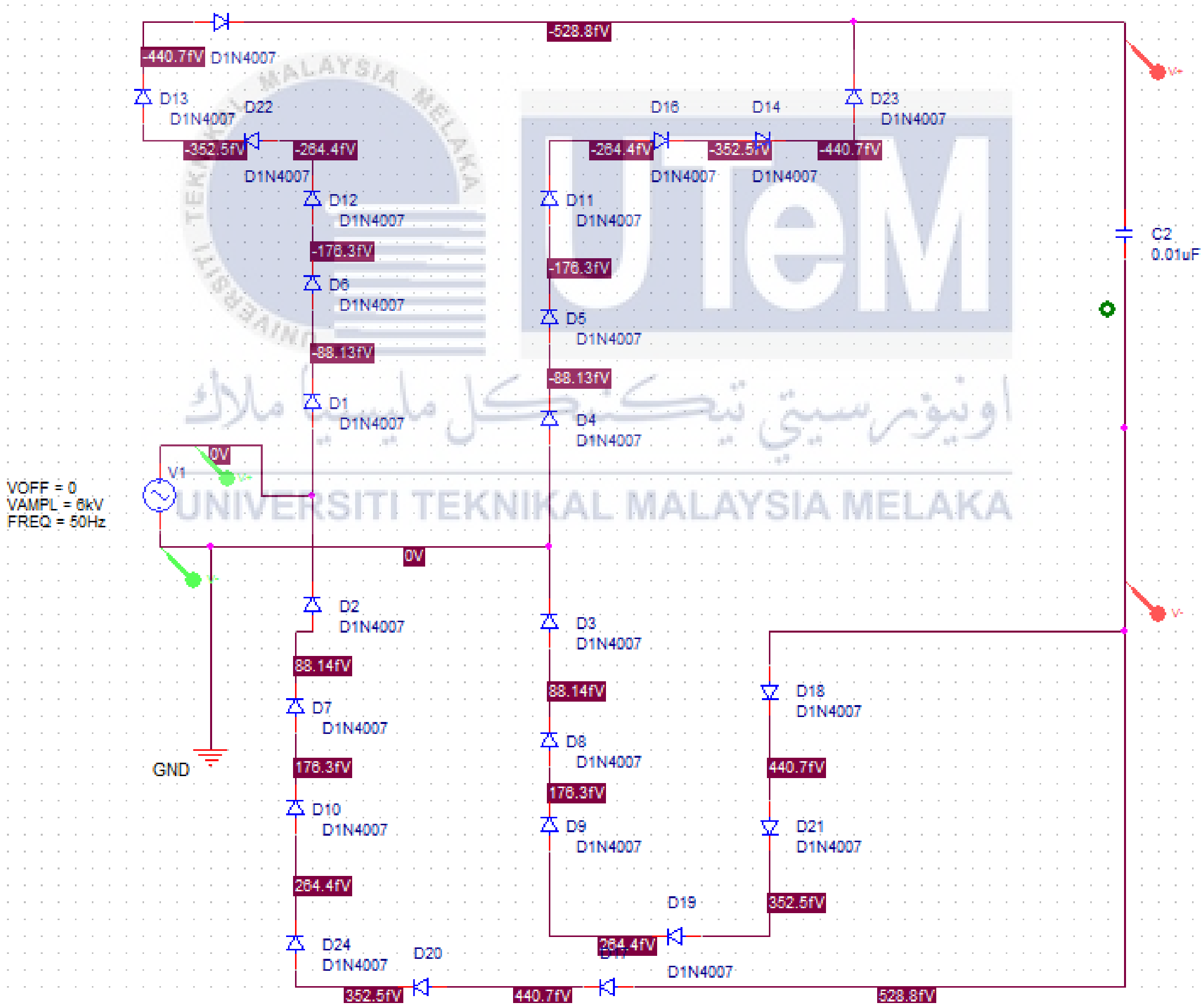

Figure 3.3: The simulation circuit of full-wave bridge rectifier with 24 diodes in PSpice.

3.4 Hardware Development

In this section, there are a subsection which is subsection 3.3.1 that describes the development of the high voltage full-wave bridge rectifier with two different value of capacitance which are 0.01uF and 820pF. Besides, the several power electronic components involved in the development of the high voltage rectifier are also explained.

3.4.1 The Rectifier Hardware Circuit with 0.01uF Capacitor and 820pF Capacitor

In the hardware development, the power diodes with rated voltage of 1kV are used in this project. Apart from that, two types of capacitors that have different capacitance value are also applied in this high voltage rectifier circuit. One type of capacitor has voltage rating of 2kV and capacitance value of 0.01uF. Meanwhile, the other type of capacitor has voltage rating of 2kV and capacitance value of 820pF.

Moreover, all the power diodes and power capacitors are connected between each other by using several electrical connectors and some 2.5mm electrical cable with their specified rating. For example, the electrical connector has current rating of 20A and the electrical cable has current rating of 13.5A. The connections of the power diodes and power smoothing capacitors are based on the full-wave bridge rectifier circuit as discussed in the software simulation circuit same as Figure 3.3 above.

In the full-wave bridge rectifier circuit, there are four branches to make it becoming full-bridge circuit. Each branch of the circuit is connected with only a diode for normal operation. However, in this experiment, each of the branch is connected with nine diodes to make it full-bridge rectifier circuit. The nine diodes in each branch of this rectifier circuit are connected in series connection. Since, the maximum voltage rating of a single diode is only 1kV, so in order to generate 6kV DC output voltage, the 1kV-diode needs to be connected in series connection to increase the maximum voltage rating up to 6kV (1kV times 6 diodes). By doing this, the input AC peak voltage from the high voltage transformer can be injected up until 6kV AC peak to the rectifier circuit in order to generate 6kV DC output voltage from the rectifier developed.

However, in the reference [28], it states that the peak inverse voltage (PIV) of the diode is 1.4 times the maximum AC peak input voltage injected to the diode or to the full-wave bridge rectifier circuit. Since, the maximum input AC peak voltage is 6kV AC peak injected to the rectifier circuit, in order to generate 6kV DC output voltage, thus the new maximum voltage rating of the power diodes is 8.4kV (1.4 times 6kV). Therefore, there are at least nine power diodes to be implemented in each branch of this full-wave bridge rectifier circuit. With four branches at all, thus the total of power diodes in this high voltage rectifier circuit is 36 diodes.

On the other hand, there are nine power capacitors connected in series connection used in the experiment. The usage of nine capacitors is due to sum up the total voltage that will be injected to the full-bridge rectifier circuit which is 6kV. This is because a single capacitor is rated at 2kV. Thus, the total voltage of nine power capacitors connected in series connection will be 18kV (2kV times 9 capacitors). Therefore, the sum up voltage of these nine capacitors exceeds the input voltage which is 6kV and as a result, the power capacitors is not going to break down during the laboratory experimental testing. The full connection of 36 power diodes and nine power capacitors is illustrated in Figure 3.4.

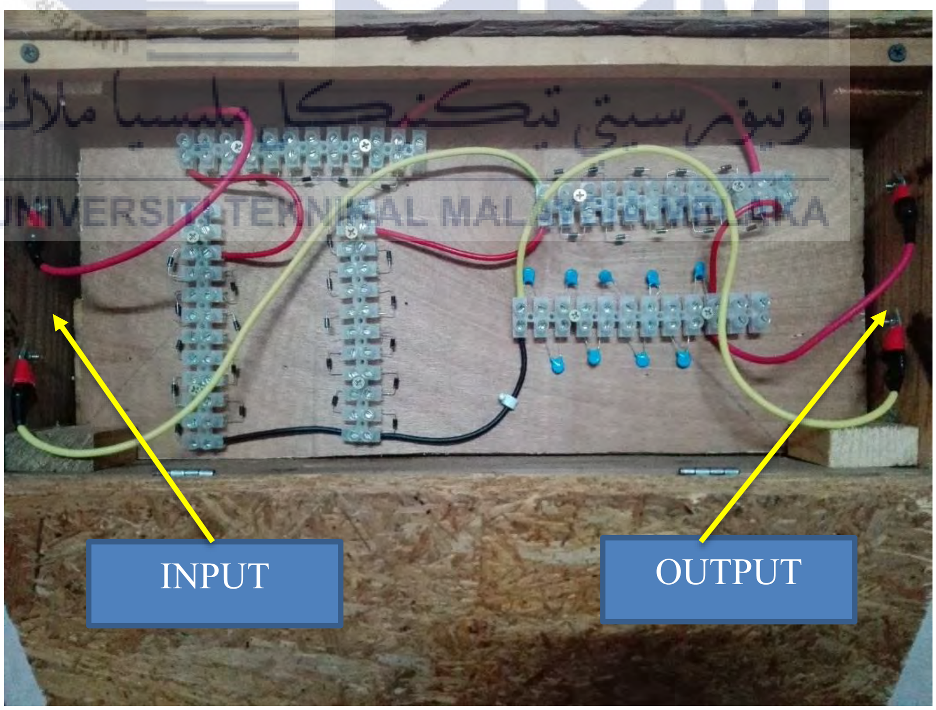

Figure 3.4: The full-wave bridge rectifier circuit with 36 power diodes and nine power capacitors.

3.5 Experimental Testing Procedures

Next, this rectifier circuit is then connected to high voltage power supply and also the measuring unit. The input of the circuit is connected to a variable single-phase high voltage transformer 6kV at power frequency of 50Hz as the high voltage power supply to the rectifier circuit. The primary voltage of this transformer is 0V to 240V while the secondary voltage is varied from 0V to 6kV. The high voltage transformer is shown in Figure 3.5.

Figure 3.5: The variable single-phase high voltage transformer 0-6kV.

Besides that, the output of the full-wave bridge rectifier circuit is connected to the measuring unit. The measuring unit includes the equipment such as a high voltage probe, low voltage probe and a digital oscilloscope. As the output of the rectifier circuit is high voltage, the application of the high voltage probe is important in order to capture the DC voltage signal or waveform on the digital oscilloscope.

The high voltage probe as shown in Figure 3.6 has a voltage ratio of 1kV:1V while the low voltage probe shown in Figure 3.7 has voltage ratio of 1V:100mV. These two probes are connected in series. The aim of connecting these two probes in series is to decrease the higher

DC output voltage from the rectifier circuit and thus enables the digital oscilloscope to capture the voltage waveform in lower voltage magnitude. Therefore, the voltage ratio of these two probes will be 1kV:1V:100mV. This ratio means that when the AC power supply voltage injected from the high voltage transformer is 1kV, then the signal displayed on the oscilloscope will be 100mV. Without using the high voltage probe will probably damaging the measuring equipment especially the digital oscilloscope used in the experiment.

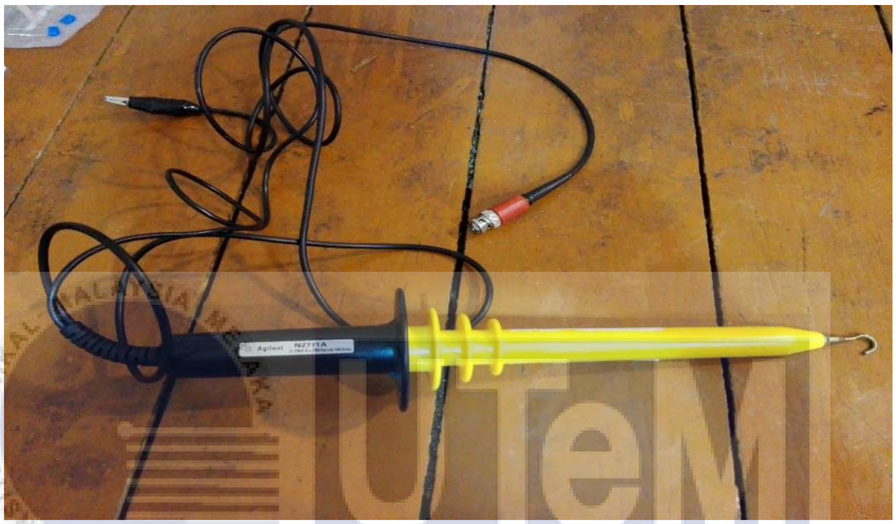

Figure 3.6: The Agilent high voltage probe with voltage ratio of 1kV:1V.

Figure 3.7: The Agilent low voltage probe with voltage ratio of 1V:100mV.

Next, the digital oscilloscope is used to capture the DC output voltage waveform from the high voltage full-wave bridge rectifier circuit. The full-wave bridge rectifier and the oscilloscope are connected via the series connection of the high voltage probe and low voltage probe to as the protection from overvoltage condition. The Tektronix digital oscilloscope is shown in Figure 3.8.

Figure 3.8: The Tektronix digital storage oscilloscope.

Meanwhile, Figure 3.9 shows the high voltage full-wave bridge rectifier test setup in high voltage engineering research laboratory. The experiment is started by connecting the variable single-phase high voltage transformer.to the input of the developed high voltage full-wave bridge rectifier circuit. After that, the output of the rectifier circuit is then connected to the digital oscilloscope via the series connection of high voltage probe and low voltage probe. Then, the AC supply voltage from the high voltage transformer is injected and DC output voltage waveform of the high voltage rectifier is recorded every 1kV up until 6kV. It is noted that the experimental procedure for both 0.01uF and 820pF capacitor is similar to each other. After getting the DC voltage waveform, the ripple percentage of the DC voltage waveform is calculated based on the information such as maximum output voltage, V_{max} and average output voltage, V_0 displayed by the oscilloscope. The calculation of ripple percentage of the rectifier is made for every 1kV DC output voltage up until 6kV DC output voltage, for 0.01uF capacitor and 820pF capacitor.

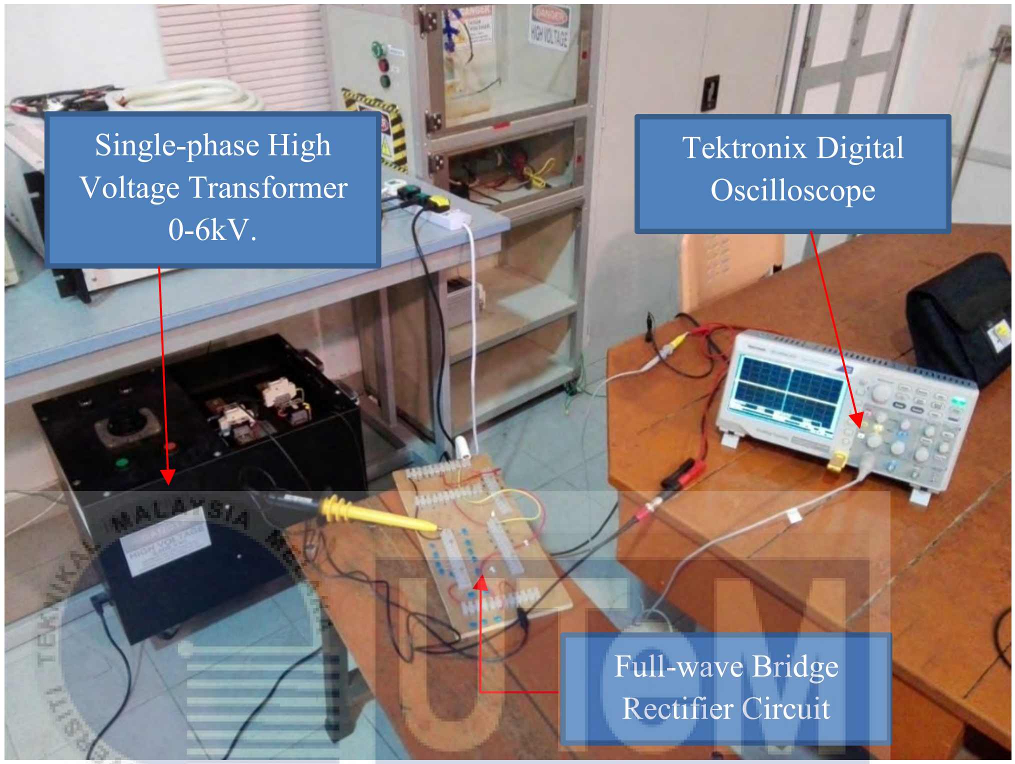

Figure 3.9: The high voltage full-wave bridge rectifier experimental test setup.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

Chapter 4 consist of the results and discussion of this project. In this chapter, it is divided into four sections which are introduction in section 4.1, software development in section 4.2, hardware development in section 4.3. Meanwhile in section 4.4, it consists the data tabulated and also the discussion of data obtained.

4.2 Software Development Result

This section is divided into two section which are subsection 4.2.1 and subsection 4.2.2. In subsection 4.2.1, there are waveforms of DC output voltage of the high voltage rectifier with capacitance value of 0.01uF while in subsection 4.2.2, there are also waveforms DC output voltage of the high voltage rectifier with capacitance value of 820pF. The simulation of the rectifier circuit is done by using PSpice software.

4.2.1 Waveform of High Voltage Rectifier with 0.01uF Capacitor

The subsection 4.2.1.1 shows the 1kV DC output waveform with the capacitor 0.01uF while subsection 4.2.1.2 displays the 6kV DC output waveform with also the capacitor 0.01uF as filtering purpose.

4.2.1.1 Waveform 1kV DC Output Voltage

The waveform of 1kV DC output voltage is displayed in Figure 4.1. This waveform is obtained by simulation of full-wave bridge rectifier that implements 4 high voltage-1kV diodes with 0.01uF capacitor. In this figure, peak-to-peak input AC voltage is indicated by the green line. Meanwhile, the output of the DC voltage is indicated by the red line. The AC input voltage from the transformer is 1kV peak or 707V RMS. From the figure, it can be noted that the maximum voltage, V_{max} is 1kV and there is no minimum voltage, V_{min} and average voltage, V_0 because the waveform obtained is straight line which is pure DC and contains no pulse signal. Thus, the value maximum voltage, V_{max} equal with the minimum voltage, V_{min} and also the average voltage, V_0 which is 1kV. Therefore, there are no ripple voltage on the waveform because the waveform obtained is pure DC voltage and the ripple percentage is zero. Thus, the value of DC output voltage obtained after rectification process is 1kV with the 0.01uF capacitor as a filter.

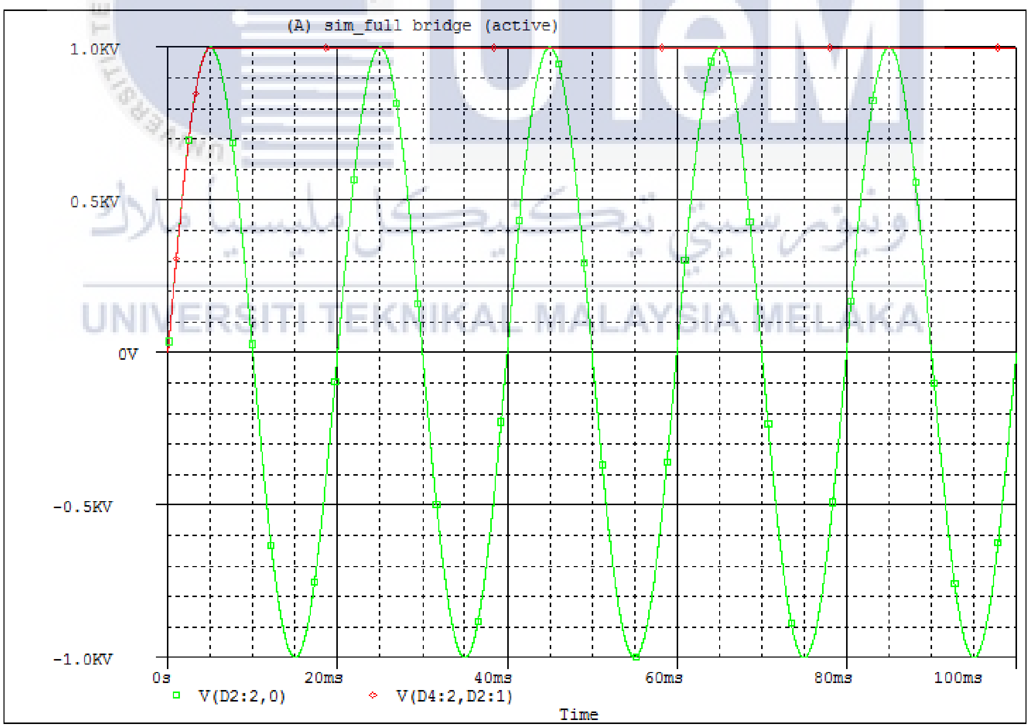

Figure 4.1: The simulation waveform of 1kV DC output voltage with 0.01uF capacitor.

4.2.1.2 Waveform 6kV DC Output Voltage

The waveform of 6kV DC output voltage is displayed in Figure 4.2 below. This waveform is obtained by simulation of full-wave bridge rectifier that implements 24 high voltage-1kV diodes with 0.01uF capacitor. In this figure, peak-to-peak input AC voltage is indicated by the green line. Meanwhile, the output of the DC voltage is indicated by the red line The AC input voltage from the transformer is 6k peak or 4.2kV RMS. From the figure, it can be noted that the maximum voltage, V_{max} is 6kV and there is no minimum voltage, V_{min} and average voltage, V_0 because the waveform obtained is straight line which is pure DC and contains no pulse signal. Thus, the value maximum voltage, V_{max} equal with the minimum voltage, V_{min} and also the average voltage, V_0 which is 6kV. Therefore, there are no ripple voltage on the waveform because the waveform obtained is pure DC voltage and the ripple percentage is zero. Thus, the value of DC output voltage obtained after rectification process is 6kV with the 0.01uF capacitor as a filter for this high voltage rectifier.

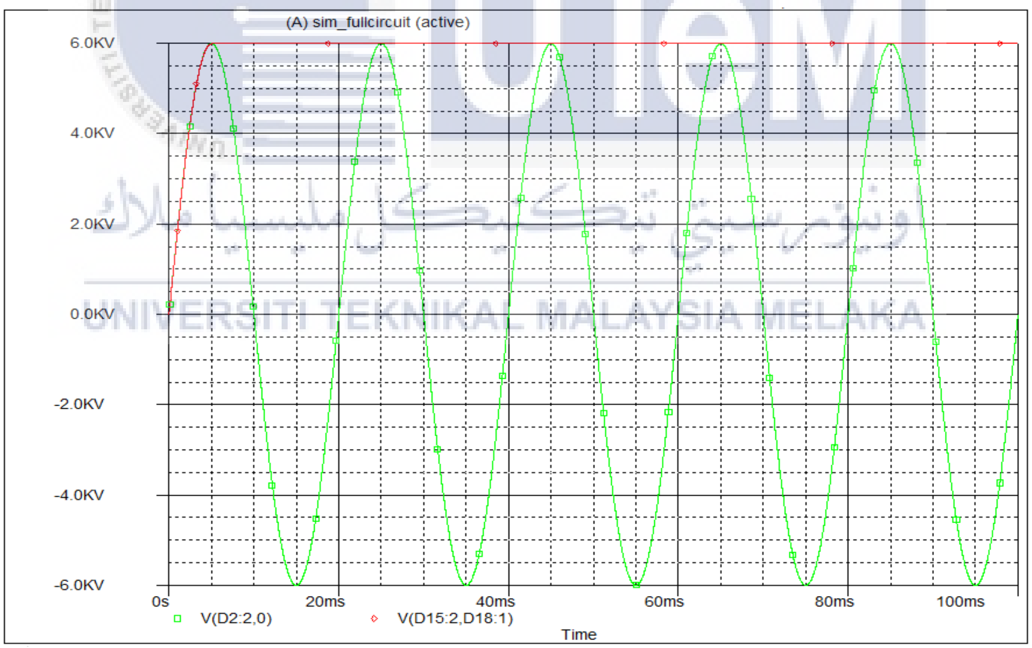

Figure 4.2: The simulation waveform of 6kV DC output voltage with 0.01uF capacitor.

4.2.2 Waveform of High Voltage Rectifier with 820pF Capacitor

The subsection 4.2.2.1 shows the 1kV DC output waveform with the capacitor 820pF while subsection 4.2.2.2 displays the 6kV DC output waveform with also the capacitor 820pF for filtering purpose.

4.2.2.1 Waveform 1kV DC Output Voltage

The waveform of 1kV DC output voltage is displayed in Figure 4.3. This waveform is obtained by simulation of full-wave bridge rectifier that implements four high voltage-1kV diodes with 820pF capacitor. In this figure, peak-to-peak input AC voltage is indicated by the green line. Meanwhile, the output of the DC voltage is indicated by the red line. The AC input voltage from the transformer is 1kV peak or 707V RMS. From the figure, it can be noted that the maximum voltage, V_{max} is 1kV and there is no minimum voltage, V_{min} and average voltage, V_0 because the waveform obtained is straight line which is pure DC and contains no pulse signal. Thus, the value maximum voltage, V_{max} equal with the minimum voltage, V_{min} and also the average voltage, V_0 which is 1kV. Therefore, there are no ripple voltage on the waveform because the waveform obtained is pure DC voltage and the ripple percentage is zero. Thus, the value of DC output voltage obtained after rectification process is 1kV with the 820pF capacitor as a waveform's filter.

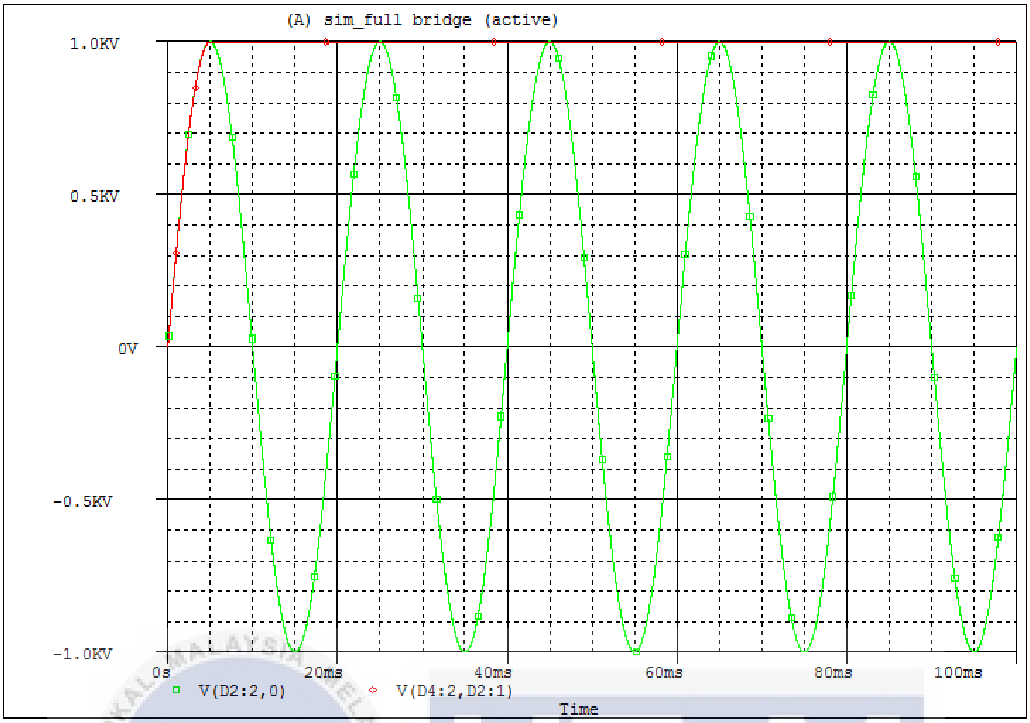

Figure 4.3: The simulation waveform of 1kV DC output voltage with 820pF capacitor.

4.2.2.2 Waveform 6kV DC Output Voltage

The waveform of 6kV DC output voltage is displayed in Figure 4.4 below. This waveform is obtained by simulation of full-wave bridge rectifier that implements 24 high voltage-1kV diodes with 820pF capacitor. In this figure, peak-to-peak input AC voltage is indicated by the green line. Meanwhile, the output of the DC voltage is indicated by the red line The AC input voltage from the transformer is 6k peak or 4.2kV RMS. From the figure, it can be noted that the maximum voltage, V_{max} is 6kV and there is no minimum voltage, V_{min} and also the average voltage, V_0 because the waveform obtained is straight line which is pure DC and contains no pulse signal. Thus, the value maximum voltage, V_{max} equal with the minimum voltage, V_{min} and also the average voltage, V_0 which is 6kV. Therefore, there are no ripple voltage on the waveform because the waveform obtained is pure DC voltage and the ripple percentage is zero. Thus, the value of DC output voltage obtained after rectification process is 6kV with the 820pF capacitor as a filter for this high voltage rectifier.

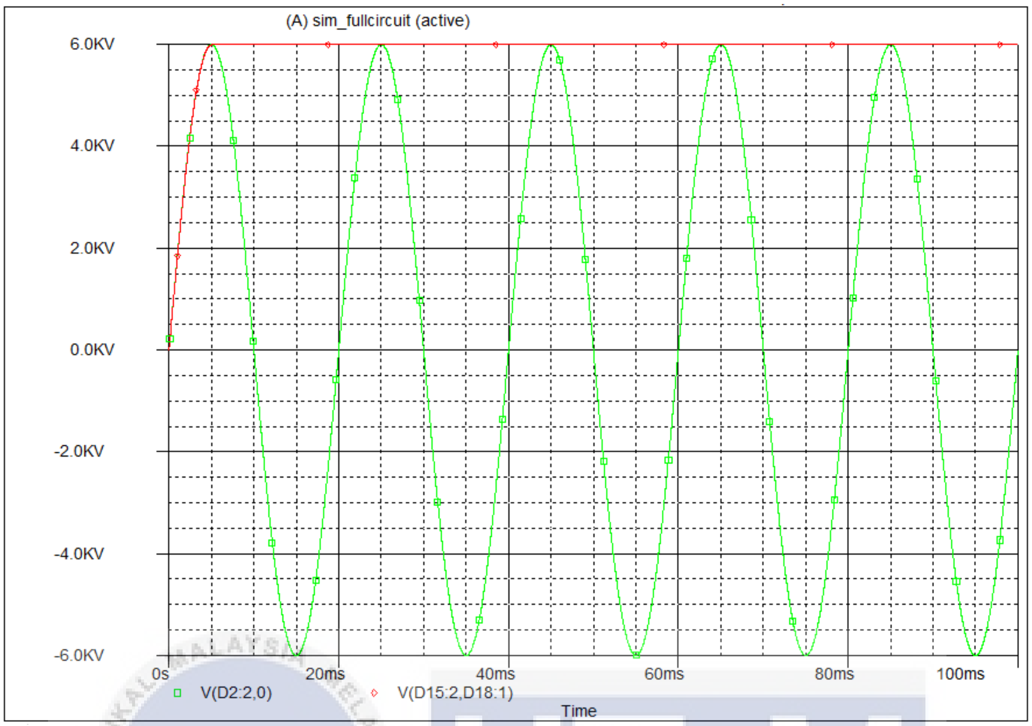

Figure 4.4: The simulation waveform of 6kV DC output voltage with 820pF capacitor.

4.3 Hardware Development Result

This section is divided into two section which are section 4.3.1 and section 4.3.2. In section 4.2.1, there are waveforms of DC output voltage of the high voltage rectifier with capacitance value of 0.01uF while in section 4.2.2, there are waveforms DC output voltage of the high voltage rectifier with capacitance value of 820pF.

In each section, the calculation of ripple will be done in every stage from 1kV up until 6kV of DC output voltage waveform to see the effectiveness of the rectifier constructed. The calculation of ripple percentage of this rectifier is based on formula stated by S. Pyakuryal *et al* [29]. In this experiment, there are two probes used to measure the signal waveform from the output of the rectifier circuit to the measurement device which is an oscilloscope. The probes are the high voltage probe and low voltage probe. The high voltage probe has voltage ratio of 1kV:1V. The low voltage probe has voltage ratio of 1V:100mV. These two probes are connected in series. Therefore, it should be noted that the voltage ratio of the two probes used is 1kV:1V:100mV. It means that when the output voltage of the rectifier circuit is 1kV, then the voltage waveform signal displayed on the oscilloscope is 100mV.

4.3.1 Waveform of High Voltage Rectifier with 0.01uF Capacitor

There are six more subsections to be explained in this section**.** The subsection 4.3.1.1 shows the 1kV DC output waveform, subsection 4.3.1.2 shows 2kV DC output waveform, subsection 4.3.1.3 displays 3kV DC output waveform, subsection 4.3.1.4 shows 4kV DC output waveform, subsection 4.3.1.5 shows 5kV DC output waveform and subsection 4.3.1.6 displays 6kV DC output waveform. All the subsections include the implementation of 0.01uF capacitor for filtering purpose of the output voltage waveform. Besides, the calculation of ripple percentage of this high voltage rectifier is based on formula stated by S. Pyakuryal *et al* [29].

4.3.1.1 Waveform and Ripple Percentage of 1kV DC Output Voltage

The output waveform of 1kV DC voltage is shown in Figure 4.5 below. The AC input voltage of secondary transformer is 1.1kV peak or 0.8kV RMS. From the figure, the maximum voltage, V_{max} is 1kV and the minimum voltage, V_{min} is 600V. The average voltage, $V_0$of the rectifier is about 828V.

Calculation of ripple percentage [29]:

V_p ripple = V_{max} - V_0 = 1kV – 828V = 172V

V_{rms} of ripple = V_p ripple / $\sqrt{2}$ = 172 / $\sqrt{2}$ = 121.62V

Ripple percentage = (V_{rms} ripple / V_0) x 100 = (121.62V / 828V) x 100 = 14.7 %

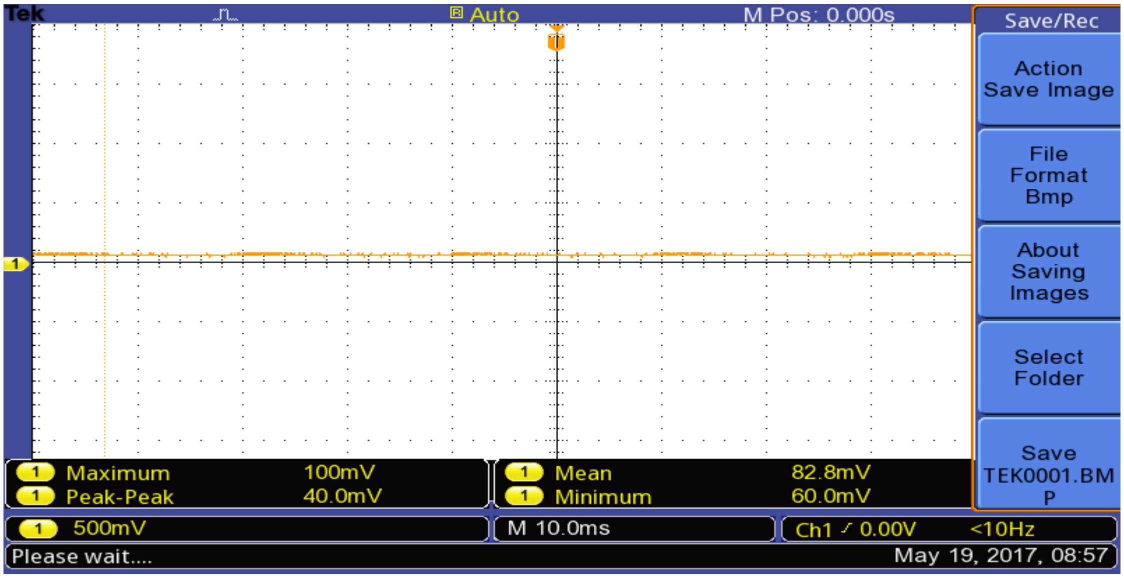

Figure 4.5: The waveform of 1kV DC output voltage with 0.01uF capacitor.

4.3.1.2 Waveform and Ripple Percentage of 2kV DC Output Voltage

The output waveform of 2kV DC voltage is shown in Figure 4.6. The AC input voltage of secondary transformer is 2kV peak or 1.4kV RMS. From the figure, the maximum voltage, V_{max} is 2kV and the minimum voltage, V_{min} is 1.2kV. The average voltage, V_0 of the rectifier is about 1.64kV.

Calculation of ripple percentage:

V_p ripple = V_{max} - V_0 = 2kV – 1.64kV = 360V

V_{rms} of ripple = V_p ripple / $\sqrt{2}$ = 360 / $\sqrt{2}$ = 254.56V

Ripple percentage = (V_{rms} ripple / V_0) x 100 = (254.56V / 1.64kV) x 100 = 15.5%

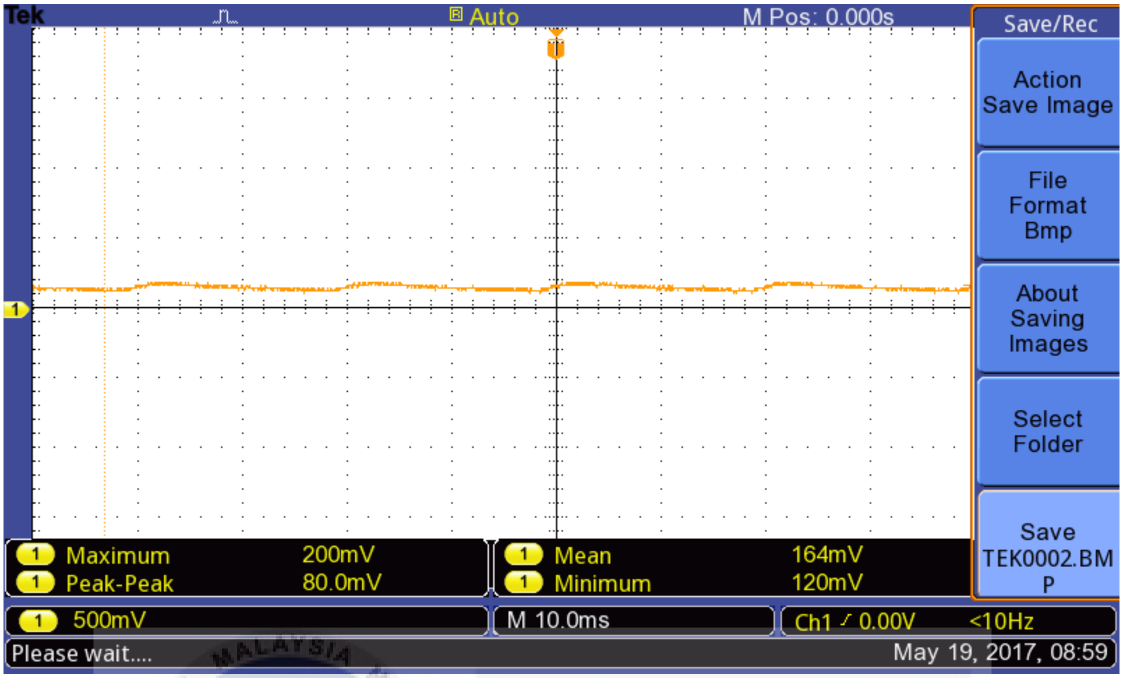

Figure 4.6: The waveform of 2kV DC output voltage with 0.01uF capacitor.

4.3.1.3 Waveform and Ripple Percentage of 3kV DC Output Voltage

The output waveform of 3kV DC voltage is shown in Figure 4.7. The AC input voltage of secondary transformer is 3.3kV peak or 2.3kV RMS. From the figure, the maximum voltage, V_{max} is 3kV and the minimum voltage, V_{min} is 1.6kV. The average voltage, $V_0$of the rectifier is about 2.33kV.

Calculation of ripple percentage:

V_p ripple = V_{max} - V_0 = 3kV – 2.33kV = 670V

V_{rms} of ripple = V_p ripple / $\sqrt{2}$ = 670 / $\sqrt{2}$ = 473.76V

Ripple percentage = (V_{rms} ripple / V_0) x 100 = (473.76V / 2.33kV) x 100 = 20.3%

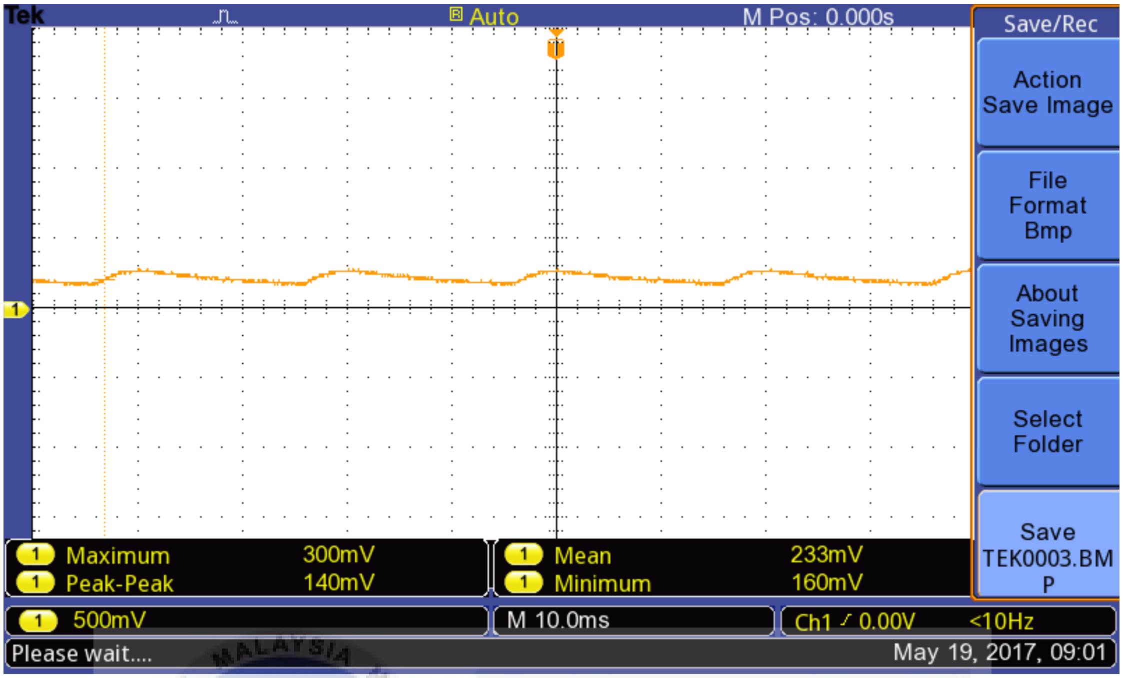

Figure 4.7: The waveform of 3kV DC output voltage with 0.01uF capacitor.

4.3.1.4 Waveform and Ripple Percentage of 4kV DC Output Voltage

The output waveform of 4kV DC voltage is shown in Figure 4.8 below. The AC input voltage of secondary transformer is 4kV peak or 2.8kV RMS. From the figure, the maximum voltage, V_{max} is 4kV and the minimum voltage, V_{min} is 2.2kV. The average voltage, $V_0$of the rectifier is about 3.03kV.

Calculation of ripple percentage:

V_p ripple = V_{max} - V_0 = 4kV – 3.03kV = 970V

V_{rms} of ripple = V_p ripple / $\sqrt{2}$ = 970 / $\sqrt{2}$ = 685.89V

Ripple percentage = (V_{rms} ripple / V_0) x 100 = (685.89V / 3.03kV) x 100 = 22.6%

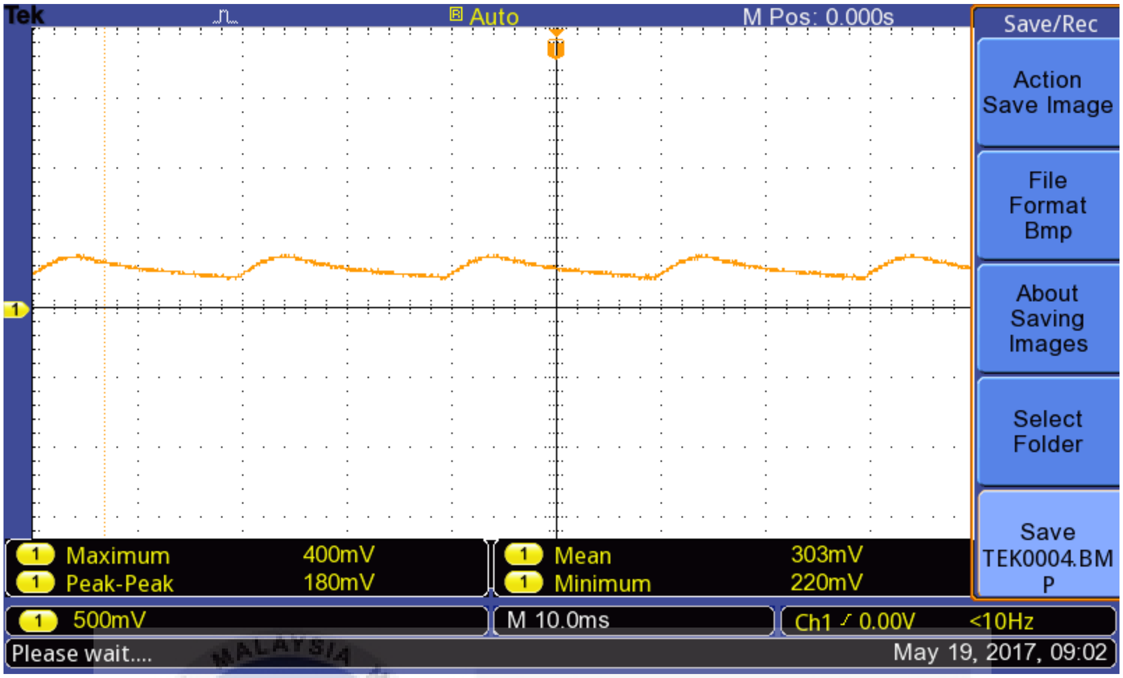

Figure 4.8: The waveform of 4kV DC output voltage with 0.01uF capacitor.

4.3.1.5 Waveform and Ripple Percentage of 5kV DC Output Voltage

The output waveform of 5kV DC voltage is shown in Figure 4.9. The AC input voltage of secondary transformer is 5.1kV peak or 3.6kV RMS. From the figure, the maximum voltage, V_{max} is 5kV and the minimum voltage, V_{min} is 2.8kV. The average voltage, V_0 of the rectifier is about 3.72kV.

Calculation of ripple percentage:

V_p ripple = V_{max} - V_0 = 5kV – 3.72kV = 1.28kV

V_{rms} of ripple = V_p ripple / $\sqrt{2}$ = 1.28kV / $\sqrt{2}$ = 905.10V

Ripple percentage = (V_{rms} ripple / V_0) x 100 = (905.10V / 3.72kV) x 100 = 24.3%

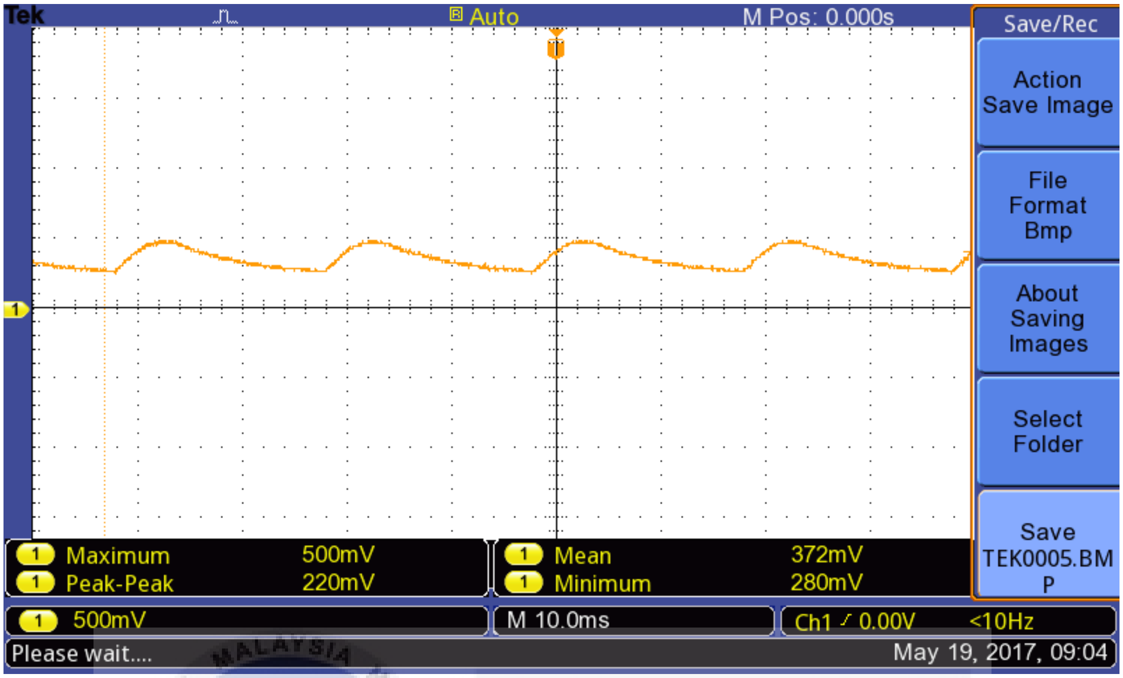

Figure 4.9: The waveform of 5kV DC output voltage with 0.01uF capacitor.

4.3.1.6 Waveform and Ripple Percentage of 6kV DC Output Voltage

The output waveform of 6kV DC voltage is shown in Figure 4.10 below. The AC input voltage from the transformer is 6kV peak or 4.2kV RMS. From the figure, the maximum voltage, V_{max} is 6kV and the minimum voltage, V_{min} is 3.2kV. The average voltage, V_0 of the rectifier is about 4.43kV.

Calculation of ripple percentage:

V_p ripple = V_{max} - V_0 = 6kV – 4.43kV = 1.57kV

V_{rms} of ripple = V_p ripple / $\sqrt{2}$ = 1.57kV / $\sqrt{2}$ = 1.11kV

Ripple percentage = (V_{rms} ripple / V_0) x 100 = (1.11kV / 4.43kV) x 100 = 25.1%

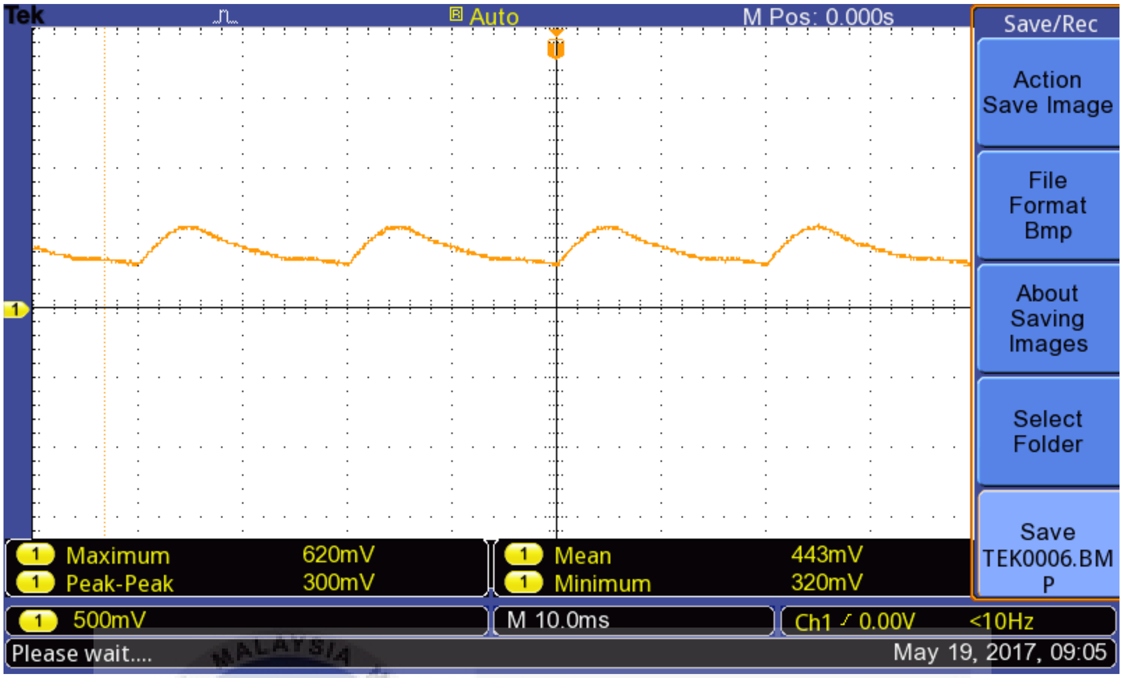

Figure 4.10: The waveform of 6kV DC output voltage with 0.01uF capacitor.

4.3.2 Waveform of High Voltage Rectifier with 820pF Capacitor

There are six more subsections to be explained in this section. The Subsection 4.3.2.1 shows the 1kV DC output waveform, Subsection 4.3.2.2 shows 2kV DC output waveform, Subsection 4.3.2.3 displays 3kV DC output waveform, Subsection 4.3.2.4 shows 4kV DC output waveform, Subsection 4.3.2.5 shows 5kV DC output waveform and Subsection 4.3.2.6 displays 6kV DC output waveform. Apart from that, all the subsections include the implementation of 820pF capacitor for filtering purpose of the output voltage waveform. Besides, the calculation of ripple percentage of this high voltage rectifier is based on formula stated by S. Pyakuryal *et al* [29].

4.3.2.1 Waveform and Ripple Percentage of 1kV DC Output Voltage

The output waveform of 1kV DC voltage is shown in Figure 4.11 below. The AC input voltage from high voltage transformer is 1.1kV peak or about 800V RMS. From the figure, the maximum voltage, V_{max} is 1kV and the minimum voltage, V_{min} is 600V. The average voltage, V_0 of the rectifier is about 796V.

Calculation of ripple percentage:

V_p ripple = V_{max} - V_0 = 1kV – 796V = 204V

V_{rms} of ripple = V_p ripple / $\sqrt{2}$ = 204 / $\sqrt{2}$ = 144.25V

Ripple percentage = (V_{rms} ripple / V_0) x 100 = (144.25V / 796V) x 100 = 18.1 %

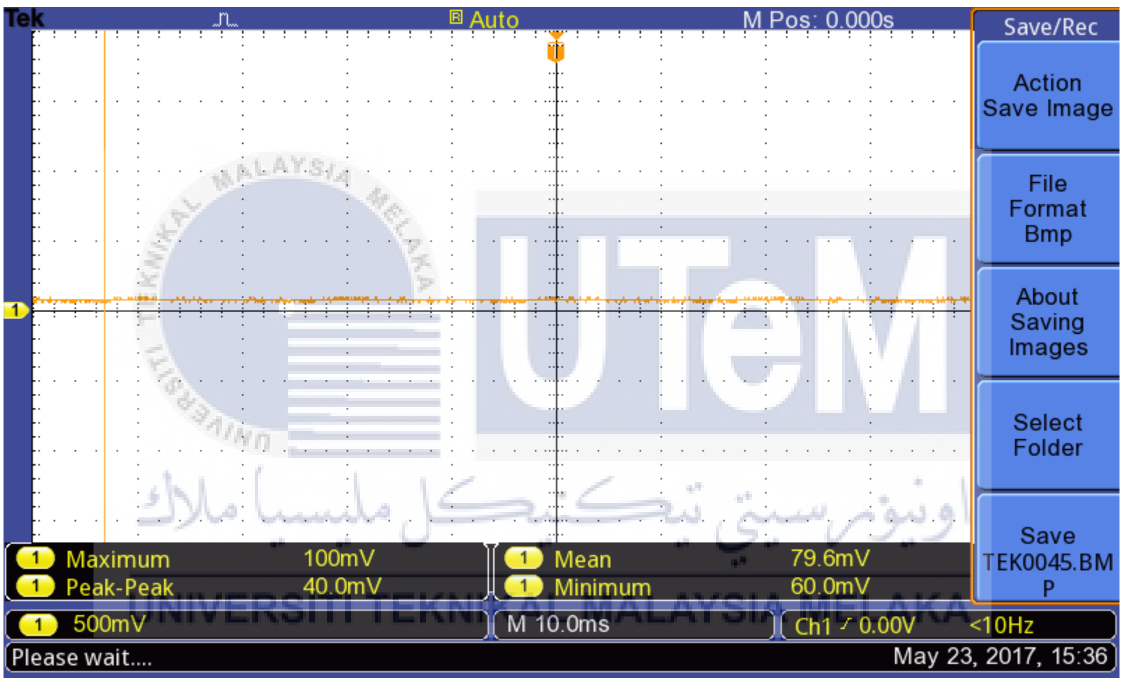

Figure 4.11: The waveform of 1kV DC output voltage with 820pF capacitor.

4.3.2.2 Waveform and Ripple Percentage of 2kV DC Output Voltage

The output waveform of 2kV DC voltage is shown in Figure 4.12. The AC input voltage from the transformer is 2kV peak or 1.4kV RMS. From the figure, the maximum voltage, V_{max} is 2kV and the minimum voltage, V_{min} is 1.2kV. The average voltage, V_0 of the rectifier is about 1.58kV.

Calculation of ripple percentage:

V_p ripple = V_{max} - V_0 = 2kV – 1.58kV = 420V

V_{rms} of ripple = V_p ripple / $\sqrt{2}$ = 420 / $\sqrt{2}$ = 296.98V

Ripple percentage = (V_{rms} ripple / V_0) x 100 = (296.98V / 1.58kV) x 100 = 18.8 %

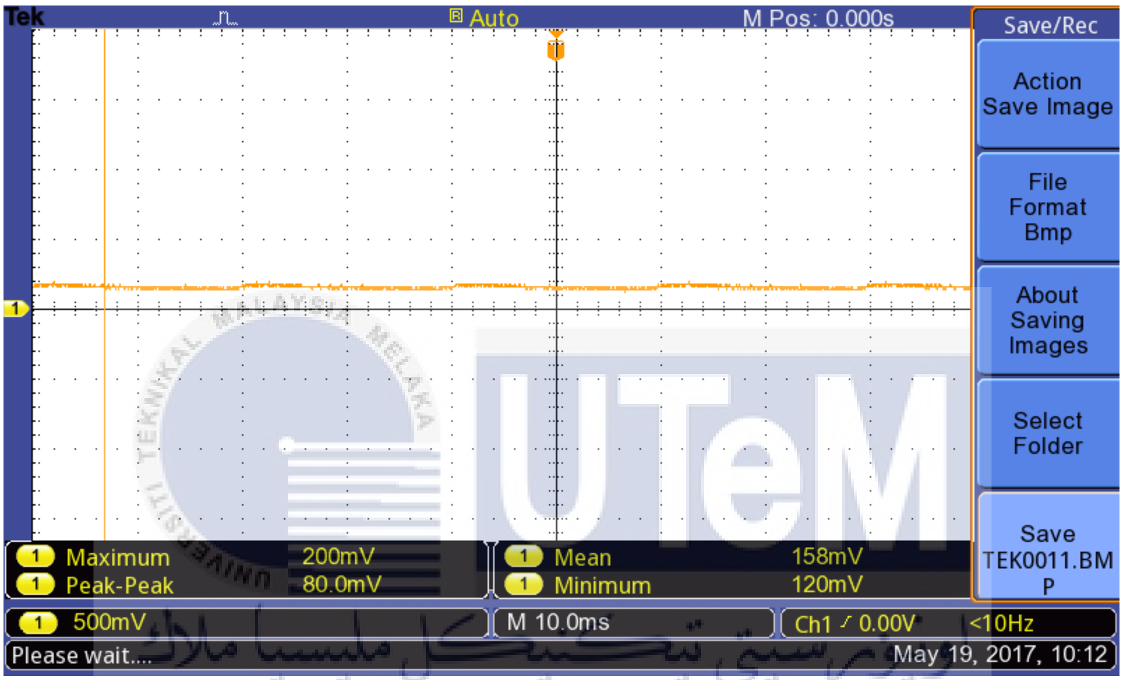

Figure 4.12: The waveform of 2kV DC output voltage with 820pF capacitor.

4.3.2.3 Waveform and Ripple Percentage of 3kV DC Output Voltage

The output waveform of 3.2kV DC voltage is shown in Figure 4.13 below. The AC input from the transformer is 3.3kV peak or 2.3kV RMS. From the figure, the maximum voltage, V_{max} is 3.2kV and the minimum voltage, V_{min} is 2kV. The average voltage, $V_0$of the rectifier is about 2.54kV.

Calculation of ripple percentage:

V_p ripple = V_{max} - V_0 = 3.2kV – 2.54kV = 660V

V_{rms} of ripple = V_p ripple / $\sqrt{2}$ = 660 / $\sqrt{2}$ = 466.69V

Ripple percentage = (V_{rms} ripple / V_0) x 100 = (466.69V / 2.54kV) x 100 = 18.4 %

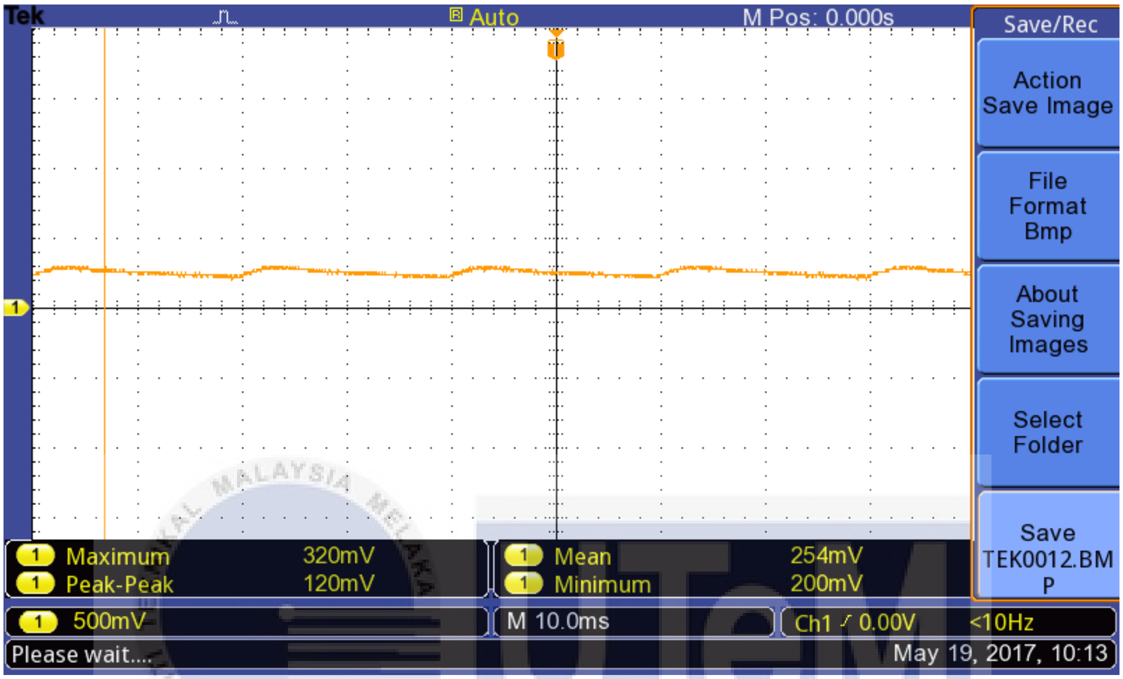

Figure 4.13: The waveform of 3kV DC output voltage with 820pF capacitor.

4.3.2.4 Waveform and Ripple Percentage of 4kV DC Output Voltage

The output waveform of 4kV DC voltage is shown in Figure 4.14 below. The AC input voltage from the high voltage transformer is 4kV peak or 2.8kV RMS. From the figure, the maximum voltage, V_{max} is 4kV and the minimum voltage, V_{min} is 2.6kV. The average voltage, V_0 of the rectifier is about 3.18kV.

Calculation of ripple percentage:

V_p ripple = V_{max} - V_0 = 4kV – 3.18kV = 820V

V_{rms} of ripple = V_p ripple / $\sqrt{2}$ = 820 / $\sqrt{2}$ = 579.83V

Ripple percentage = (V_{rms} ripple / V_0) x 100 = (579.83V / 3.18kV) x 100 = 18.2 %

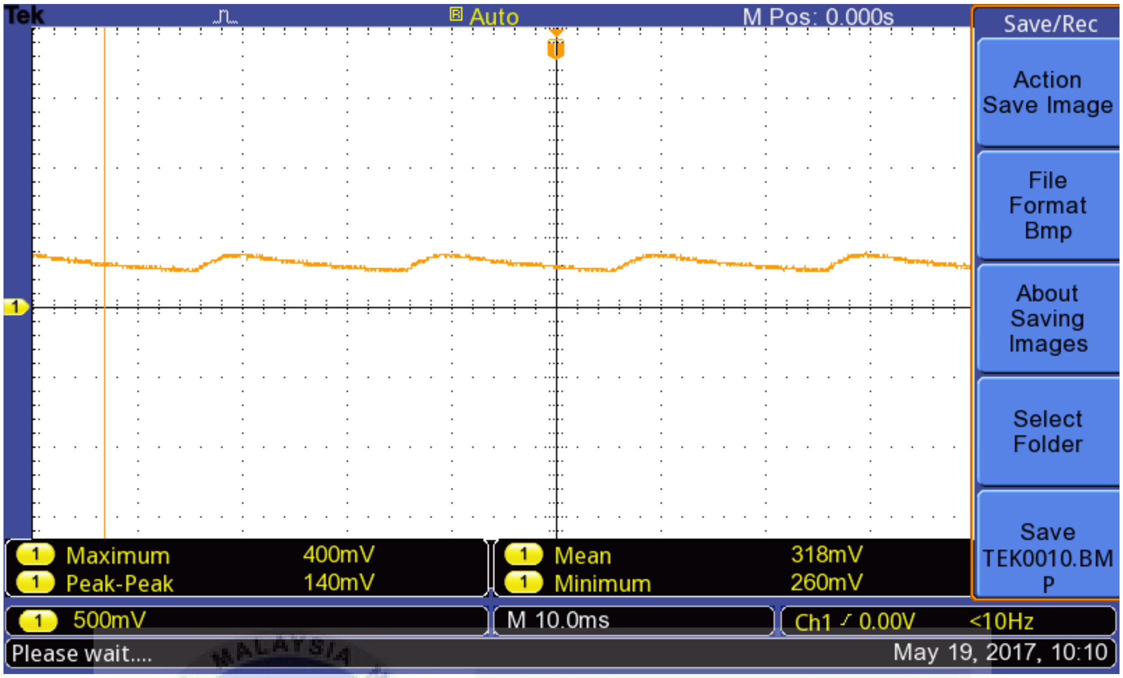

Figure 4.14: The waveform of 4kV DC output voltage with 820pF capacitor.

4.3.2.5 Waveform and Ripple Percentage of 5kV DC Output Voltage

The output waveform of 5kV DC voltage is shown in Figure 4.15. The AC input voltage from the transformer is 5.1kV peak or 3.6kV RMS. From the figure, the maximum voltage, V_{max} is 5kV and the minimum voltage, V_{min} is 3kV. The average voltage, V_0 of the rectifier is about 3.99kV.

Calculation of ripple percentage:

V_p ripple = V_{max} - V_0 = 5kV – 3.99kV = 1.01kV

V_{rms} of ripple = V_p ripple / $\sqrt{2}$ = 1.01kV / $\sqrt{2}$ = 714.18V

Ripple percentage = (V_{rms} ripple / V_0) x 100 = (714.18V / 3.99kV) x 100 = 17.9 %

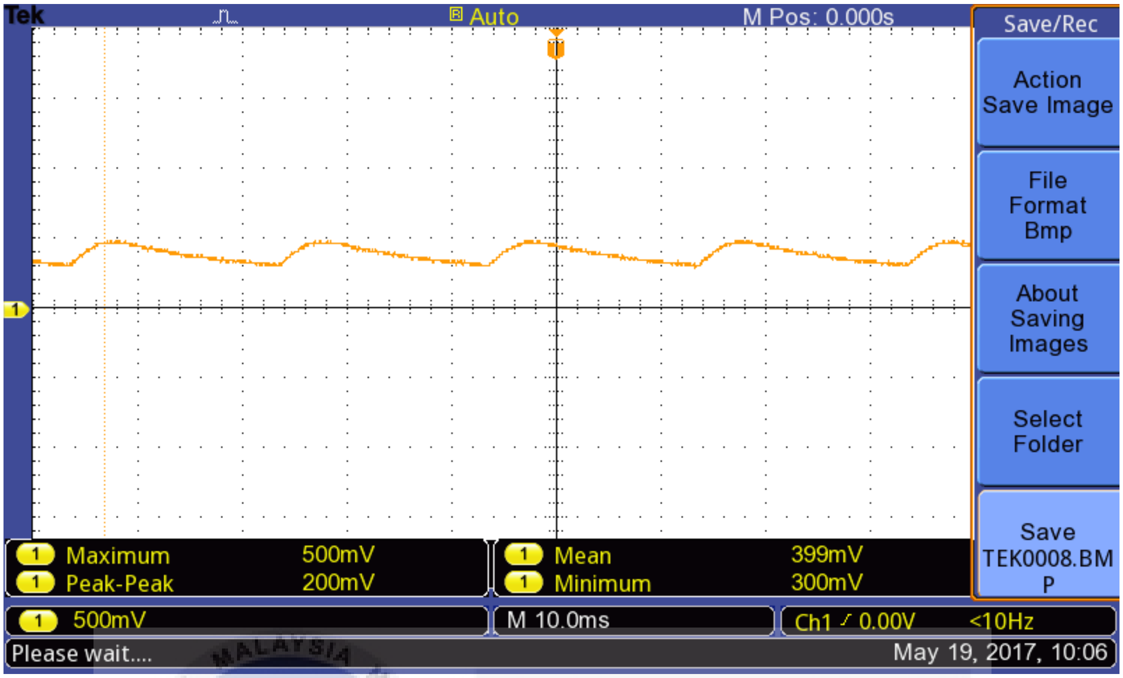

Figure 4.15: The waveform of 5kV DC output voltage with 820pF capacitor.

4.3.2.6 Waveform and Ripple Percentage of 6kV DC Output Voltage

The output waveform of 6kV DC voltage is shown in Figure 4.16. The AC input voltage from the high voltage transformer is 6kV peak or 4.2kV RMS. From the figure, the maximum voltage, V_{max} is 6kV and the minimum voltage, V_{min} is 3.4kV. The average voltage, $V_0$of the rectifier is about 4.75kV.

Calculation of ripple percentage:

V_p ripple = V_{max} - V_0 = 6kV – 4.75kV = 1.25kV

V_{rms} of ripple = V_p ripple / $\sqrt{2}$ = 1.25kV / $\sqrt{2}$ = 883.88V

Ripple percentage = (V_{rms} ripple / V_0) x 100 = (883.88V / 4.75kV) x 100 = 18.6 %

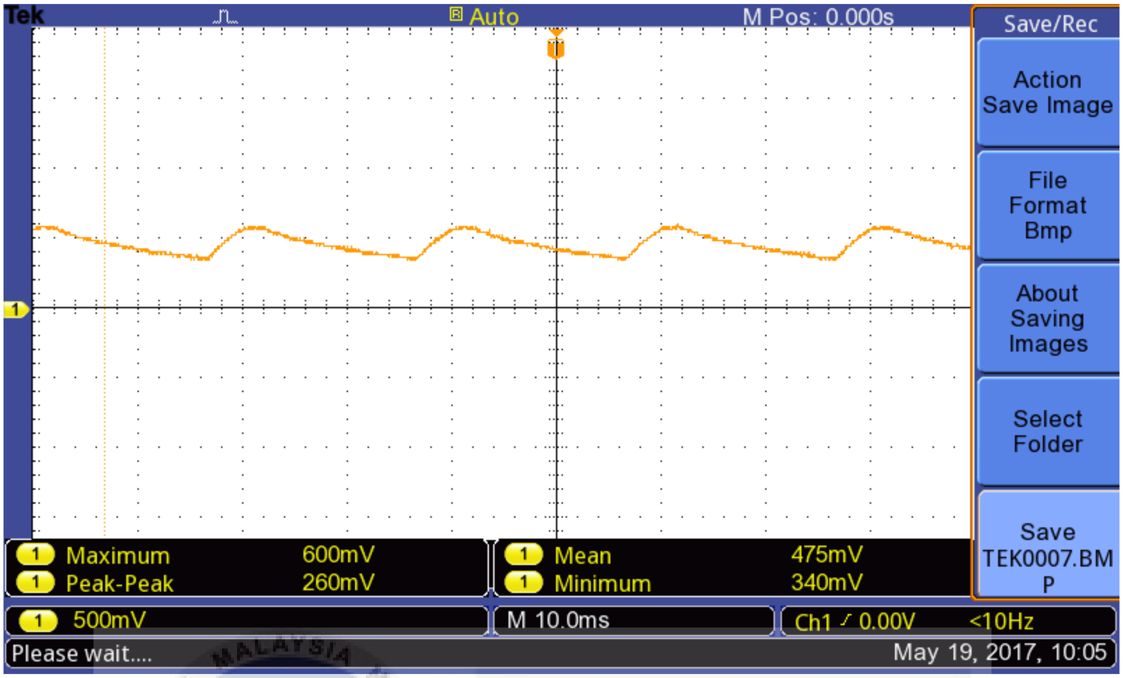

Figure 4.16: The waveform of 6kV DC output voltage with 820pF capacitor.

4.4 Data Analysis and Discussion

In this section, it is divided into two subsections which are subsection 4.4.1 that will tabulate the data in form of table. Then, subsection 4.4.2 that will display the tabulated data in form of line graph as well as the discussion of this project based on the calculation done and data obtained during experiment is carried out.

4.4.1 Tabulated Data

Table 4.1 is tabulated based on the calculation of ripple percentage that has been done in section 4.3 between different value of capacitance which are 0.01uF and 820pF. Besides that, the value of AC input voltage and DC output voltage of the high voltage rectifier are also mentioned in the table.

Table 4.1: The ripple percentage of two different types of capacitance value.

		Ripple Percentage (%)	
		Capacitance Value (F)	
AC Input Voltage (kV) RMS / peak	**DC Output Voltage (kV)**	**0.01uF**	**820pF**
0.8 / 1.1	**1**	**14.7**	**18.1**
1.4 / 2.0	**2**	**15.5**	**18.8**
2.3 / 3.3	**3**	**20.3**	**18.4**
2.8 / 4.0	**4**	**22.6**	**18.2**
3.6 / 5.1	**5**	**24.3**	**17.9**
4.2 / 6.0	**6**	**25.1**	**18.6**

4.4.2 Analysis and Discussion

The tabulated data in Table 4.1 is displayed in the line graph in Figure 4.17. Based on the Figure 4.17, it can be noted that the ripple percentage of high voltage rectifier with 0.01uF is higher compared to the rectifier with 820pF capacitor. Furthermore, the high voltage rectifier with 0.01uF capacitor shows that ripple percentage increases with the increase of the DC output voltage. With 0.01uF capacitor, the ripple percentage calculated is 14.7% when 1kV DC output voltage is recorded, which is the lowest ripple percentage compared to the other DC output voltage. The ripple percentage is increasing as the DC output voltage increases. When the DC output voltage of rectifier is 6kV, the ripple percentage is 25.1% which is higher than 14.7% during 1kV DC output voltage of the high voltage rectifier is applied.

Besides that, when 820pF is applied to the high voltage rectifier circuit, the ripple percentage calculated is lower compared to the rectifier connected to 0.01uF capacitor. In addition, the trend of the ripple percentage of the rectifier with 820pF is slightly changed even though the DC output voltage is increasing. This situation shows that the ripple percentage does not have specific trends, sometimes it increases and sometimes it decreases. Based on the Figure 4.17, the ripple percentage calculated is 18.1% when the DC output voltage recorded is 1kV. Moreover, when the DC output voltage of high voltage rectifier is 6kV, the ripple percentage is 18.6% which is higher than 18.1%, calculated during 1kV DC output voltage with 820pF capacitor. The lowest ripple percentage calculated by 820pF capacitor is 17.9% when 5kV DC output voltage of the rectifier is applied.

In other words, the ripple percentage of these two types of capacitors is different from each other especially when the DC output voltage of high voltage rectifier is 6kV. The ripple percentage of rectifier with 820pF capacitor is 18.6% which is lower compared to the rectifier with 0.01uF capacitor that records ripple percentage of 25.1%. This occurs when 6kV DC output voltage of the rectifier is applied. This ripple percentage calculation proves that when the lower capacitance value (820pF) is used, the ripple voltage is minimized and thus the ripple percentage obtained is lower.

The lower ripple percentage recorded by the rectifier with 820pF capacitor is related to the theory regarding the capacitive reactance, X_C of the capacitor itself. The capacitive reactance is assumed as the value of the capacitor in ohm (Ω) and the formula is given by the reference [33]:

$$X_C = \frac{1}{2\pi f C}$$

Where: C = capacitance value (F)

f = frequency (Hz)

X_C = capacitive reactance (Ω)

If the value of capacitive reactance is small, a higher current magnitude will be drawn by the capacitor that acts as the load in this rectifier. This situation will result the average output voltage, V_0 of the rectifier will decrease and the ripple voltage will be very high at the output of the rectifier [29]. Below are the calculations of capacitive reactance for 0.01uF and 820pF capacitor.

Calculation of the capacitive reactance for 0.01uF capacitor:

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(50Hz)(0.01uF)} = 318.31\text{k}\,\Omega$$

Calculation of the capacitive reactance for 820pF capacitor:

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(50Hz)(820pF)} = 3881.83\text{k}\,\Omega$$

From the calculation, the value of the capacitive reactance for 0.01uF capacitor is lower compared to the value of capacitive reactance calculated for 820pF capacitor. Therefore, the high voltage rectifier along with the 0.01uF capacitor will draw larger magnitude of current and the average voltage V_0 will largely drop to zero. Hence, the ripple voltage of the rectifier is higher as well as its ripple percentage. Furthermore, as the capacitive reactance of the 820pF capacitor is higher than the 0.01uF capacitor, there will be only small current drawn by the 820pF capacitor. Thus, the average voltage, V_0 of the rectifier will not be dropping too much compared to the rectifier with 0.01uF capacitor. As a result, the ripple voltage and the ripple percentage of the rectifier with 820pF capacitor is lower compared to the rectifier with 0.01uF capacitor.

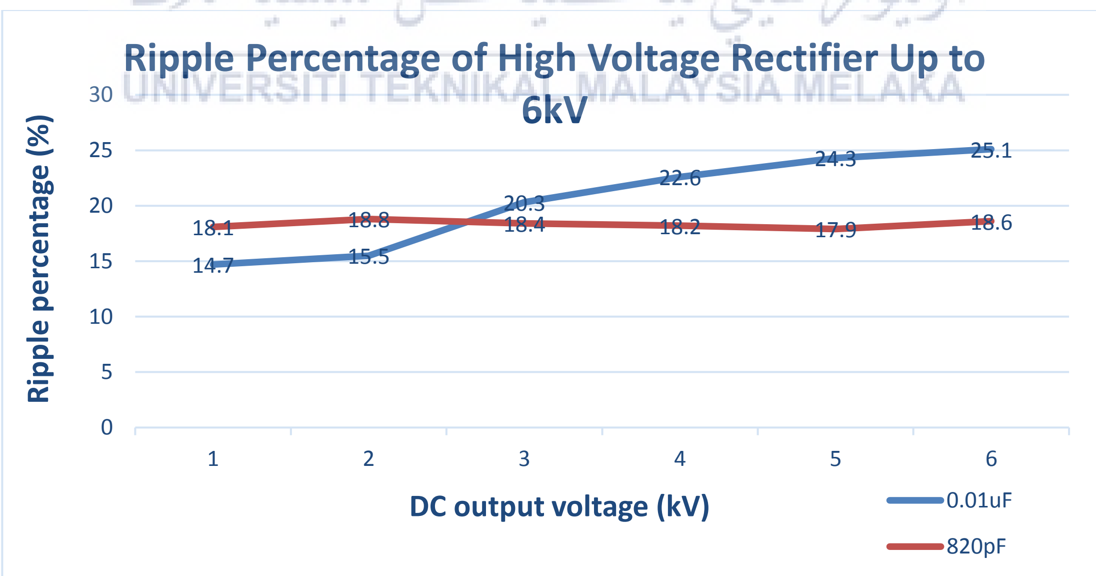

Figure 4.17: The comparison of ripple percentage of high voltage rectifier between 0.01uF capacitor and 820pF capacitor.

CHAPTER 5

CONCLUSION

5.1 Conclusion

Since the HVDC system is growing rapidly in the global, the request for the outdoor polymeric insulation especially Silicon Rubber (SiR) composite to be installed in the HVDC system is increasing. Based on that statement, a lot of significant researches and important studies have been carried out for the sustainability and improvement of the polymeric insulation material under DC voltage. The DC IPT test, although has not been standardized yet, is performed on the polymeric insulation sample complying with the AC IPT test standard of BS EN 60587: 2007. The DC IPT test is an appropriate method to indicate the performance of the polymeric insulation material by determining its tracking and erosion resistance under DC voltage. On top of that, the development of the high voltage rectifier is crucial to ensure the DC IPT test can be conducted in the high voltage laboratory. Moreover, the rectifier built can generate a DC output voltage up to 6kV. Besides that, output waveform of the rectifier must be smooth and contain low ripple in order to produce high quality of a high voltage rectifier. The high voltage rectifier of 6kV DC voltage with 820pF capacitor has better performance than the high voltage rectifier of 6kV DC voltage 0.01uF capacitor. This is due to the ripple percentage calculated with 820pF capacitor is 18.6% and it is lower compared with the 0.01uF capacitor that has ripple percentage of 25.1%. By doing this project, the relationship between the high voltage rectifier and the DC IPT test will be fully understood and hence it contributes to the improvement of the tacking and erosion resistance of polymeric insulation material used in outdoor HVDC applications.

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