DESIGN AND CHARACTERISATION OF ARC DISCHARGE SYSTEM

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Science (Hons.) Physics

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"DESIGN AND CHARACTERISATION OF ARC DISCHARGE SYSTEM"** was prepared by **CHO MONG PING** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Science (Hons.) Physics at Universiti Tunku Abdul Rahman.

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Signature : _________________________

Supervisor : _________________________

Date : _________________________

Specially dedicated to

my beloved family, supervisors and lecturers in

Universiti Tunku Abdul Rahman.

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ABSTRACT

Arc discharge is a luminous current electron that is formed between two electrodes gap when a high potential gradient is applied. Arc discharge can be further understood as electrical breakdown and ongoing plasma discharge due to the ionisation of air molecules. Design on the circuitry arc discharge system is executed and followed with characterisation in distance between the electrodes, duty cycle and frequency. The operating power of each parameter is used to relate and perform analysis on the arc discharge system. The optimum parameters are determined to be at electrode distance at 2 mm, frequency of 1200 Hz and duty cycle of 50 % and above. Duty cycle of 50 % is the threshold frequency towards stable arc discharge. Arc discharge produced is an alternating current arc discharge where it is modulated by the function generator. Discharge time of 0.004 s is the lowest limit in producing arc discharge.

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LIST OF SYMBOLS / ABBREVIATIONS

A	Ampere
V	Volt
s	Second
ms	Millisecond
mm	Millimetre
nm	Nanometre
mA	Milliampere
i (a)	Instantaneous value of arc voltage
t	Instantaneous time
I	Initial current value before break
T	Discharge time
$V(a)$	Arc voltage
$Vmin$	Minimum voltage
R	Resistance
L	Inductance
P	Power
W	Watt
AU	Arbitrary Unit

AC	Alternating current
DC	Direct current
VI	Voltage-current
Ag	Silver
Cu	Copper
PCB	Printed circuit board
UV	Ultra violet

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CHAPTER 1

INTRODUCTION

1.1 Background

Arc discharge is a luminous discharge of current electrons that is formed between two points of electrodes. When current is applied to these two electrodes in contact and then pulled, an arc will be observed. The two points of electrodes which are the cathode and anode are placed in a distance with high potential difference. Cathode holds a position as emitting electrons whereas anode absorbing electrons. The gas in the distance space between two electrodes will be ionised by the heating effect and turned them into plasma properties giving them electrical charges. An electric arc produces heat and light energy as product which can be useful to apply into applications.

In detailed and precise explanations, arc is a kind of plasma with characteristics of high temperature and high conductivity due to the ionised charged gas particles. Ionised charged gas particle is a form of neutral particles which undergo dissociation process. Dissociation process is a general process where in which ionic compounds breaks into smaller molecules or ions. In a closer and zoom in observations, the electric field intensity is very high due to the very short distance between the two electrodes. The electric field intensity is so high that electrons from the cathode surface will be attracted to the electric field force in the gap and form free electrons. Accelerated motion toward the anode increased due to the free electrons emitted from the cathode and few other original electrons in the gap.

Collisions among them are frequent with the neutral protons. Moreover, due to the high electron velocity and kinetic energy, electrons are literally spitted out from the neutral particle and leads to the formation of charged ions (positive and negative ions) which also known as ionisation. Due to all this continuous ionisation it generates electric arc discharge.

This arc discharge process has been studied for nearly 150 years and is still in used.(Raizer,1991). The applications arc discharge technologies are vast now with relatively low production cost. The applications include plasma welding and cutting, semiconductor processing, material treatments and even to the extents of laser such as laser induced spark. However, in this project the set up and configurations are leading much towards the applications on fused fiber fusions.

1.2 Aims and Objectives

The objectives are set in completion to this project. Further studies and understanding on the arc discharge system has been set as the primary objectives of this establishment in this project. Furthermore the arc discharge system will be characterised into several parameters to understand deeper on the arc discharge characteristics to benefits in the applications purposes.
Objectives are set in line towards :

- To design and build the arc discharge system

- To characterise and to optimise the arc discharge system based on

    a) Distance between the electrodes
    b) Duty cycle
    c) Frequency

1.3 Project Scopes

This project is coordinate into two major parts,

i) Design and implementation of the arc discharge system hardware and
ii) Characterisation of the arc discharge system

Design of the circuit is the first phase of the project and progress onto the hardware implementations for the arc discharge system. Nevertheless, fundamental grasp of the understanding on this project is not neglected.

In the second phase of this project, characterisation on the arc discharge system is conducted. Multiple important parameter characterisations have been set as the objectives to complete this project in quality and has good impact factor.

CHAPTER 2

LITERATURE REVIEW

2.1 Types of discharge

Researchers have show different types of direct current (DC) discharges which can be observed through a simple experiment by varying its applied currents and voltages. The experimental setup consists of a pair of metal electrodes connected to a power supply and a glass tube to insert those electrodes. A graph is plotted by as shown in Figure 2.1 to show the different types of discharges under different conditions. (Loeb,2005)

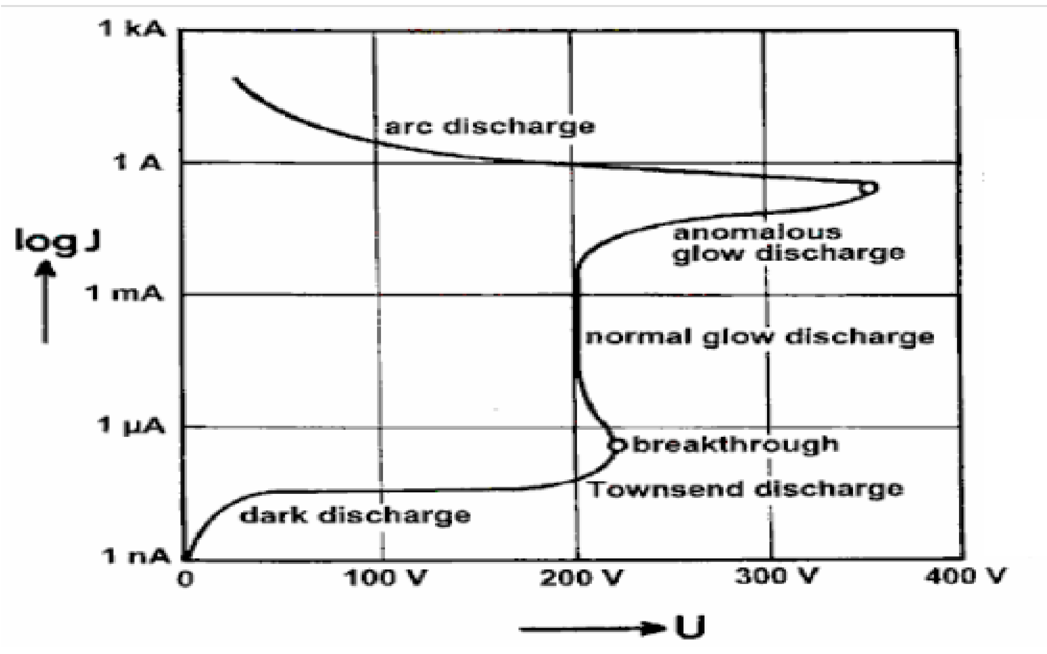


Figure 2.1: Types of Direct Current discharges

Three fundamental regions of the discharge can be identified by increasing the applied voltage to the electrodes. Whereas, the voltage-current (VI) characteristics depend on the geometry of the electrodes, materials and surrounding pressure.

At low voltage before the breakdown of a gas, the discharge is non-self sustaining and invisible to the naked eyes which is also known as dark discharge or corona discharge. Corona discharges is an electrical discharges caused by the ionisation of a fluid surrounding a conductor that is electrically energized. The discharge will occur when the potential gradient of the electric current is high enough to form a conductive region but yet not high enough to cause electrical breakdown or arc discharge.

As the voltage is increased, it reached a point where the current starts to increase rapidly and light emission can be observed. These are the signs of breakdown (marked as breakthrough in Figure 2.1). At this particular point, the discharge becomes self sustaining where it is a process in the discharge gap that ensure the reproduction of electrons removed by the field and the energy of the electrons increase while they move about in the applied electric field (Raizer,1991).

The breakdown process is followed by a glow discharge regime where it proves the description luminous, radiant plasma. With further increase of the total current after the whole electrode has been covered with discharge, the glow discharge regime is followed by an abnormal glow discharge. The term abnormal glow discharge here is explained to be anomalous, inconsistent or deviating glow discharge. Furthermore, it followed with the changes in cathode emission mechanism while electrons are generated by positive ion bombardment in the glow discharge. Moreover, increasing voltage and intense heating of the electrodes result in electron emission from the cathode surface through thermionic, field electron and thermionic field emission (Raizer,1991). From here, the discharge will undergo a transition from a glow to an arc discharge process. For most cases, the discharge voltage has an inversely proportional relationship with the current in the arc discharge action.

Taking considerations of the plasma, the main distinctions between glow discharge and arc discharge can be summarized as follows.

Table 2.1: Summary of the differences between glow discharge and arc.

	Glow discharge	Arc discharge
Ionization fractions, x	10^{-8}-10^{-6}	10^{-3}-10^{-1}
Plasma thermodynamic	Non-equilibrium	Equilibrium

The gas pressure is an important factor as well in discharge voltage –current characteristics. Low pressure increase the possibility to develop glow discharges after the breakdown whereas high gas pressures which allow higher current flows allow the observation of arc discharges just after breakdown.

2.1.1 Electrical arcs

An electrical arc is a self-sustaining electrical discharge between two electrodes and has characteristics of low burning voltages but relatively high current density. The burning voltage of an arc is the voltage in between the electrodes during the arc discharge process.

Table 2.2: Types of current arc

Operating current (Ampere,A)	**<10**	**10-30**	**>30**
Types of current arc	**Low**	**Medium**	**High**

Table 2.2 show the types of current arc based on the operating current. It is low current arc when the operating current is below 10 Amperes whereas when the operating current is between 10 Amperes to 30 Amperes, it is a medium current arc. For operating current which is more than 30 Amperes, the current arc is considered to be the high current arc type.

2.1.2 Free- burning Arcs

Free burning arc operated mostly in gas surrounding and partly in vapour as well, which it generates. The plasma of such arc is formed freely in space. The type and electrode material, the electrode gap and other electrical parameters of the discharge may directly influence arc discharge process.

2.1.3 Direct Current Arc

The most basic type of electrical current is the direct current arc. The direct current arc is fed by a source from voltage supply in between 100 volt to 300 volt. Resistor or other electrical components must be included in the circuit of the direct current arc to compensate for the negative voltage current characteristics.

2.1.4 Alternating Current Arc

The alternating current arc is fed by an alternating current supply where sometimes the voltages may reach up to thousands of volts. Alternating current arc is the type of arc discharge proposed in this project. Alternating current used much higher voltage supply than direct current type. The alternating current can be operated as thermally ignited arc without external ignition due to the high voltage supply. It will become an uncontrolled alternating current when there is no ignition used. The distance between the electrodes usually necessitates re-ignition of the arc after each half cycle. The ignition can be achieved by a high frequency discharge which is also known as ignition spark. When the ignition is triggered electronically, it will become a controlled alternating current arc. Re-ignition after every half cycle from an applied alternating current voltage is known as ignited alternating current arc.

Whereas, the ignition at every full cycle results in a rectified alternating current arc which is a unique interrupted direct current arc. In the rectified alternating current, only one half cycle of the current phase of the arc flows. Therefore, the arc must be re-ignited after each phase.

2.1.5 Non-current carrying plasma

When a direct current operating between the two electrodes in an enclosure blown by a stream of gas from the normal discharge passage through an orifice or opening hole, a non-current carrying plasma is said to be produced. The flow of gas may be parallel or perpendicular to the direction of the electric current. In other words, this type of arc has good temporal and spatial stability thus leads to the name plasma jet.

2.1.6 Arc Atmospheres

Arc mostly operates in air or in different types of atmosphere like argon, carbon dioxide or even mixture of both argon and carbon dioxide with oxygen at atmospheric or any other pressures. When a carbon burns in air, nitrogen undergo chemical reaction with nitrogen to form cyanogens which emits intense cyanogens molecular bands which often mask spectral lines. Thus by choosing a suitable controlled atmosphere which is free from nitrogen, this intense cyanogens molecular bands can be avoided and improve arc stability.

2.2 Distance between Electrodes

A Jacob's ladder or more formally known as a high voltage traveling arc is a device for producing a continuous train of large sparks that rises upwards. The spark gap is formed in between two wires which act as the electrodes distanced in vertical but diverging away from each other towards the top in a shape of '*V'* thus having the having the distance between two electrodes increasing from bottom.

A spark forms across the wire when high voltage is applied. The spark starts from the bottom of the wires where it is at the shortest distance and quickly changing to electric arc. The arc behaves like short circuit and thus drawing as much current as possible from the power supply and this heavy load decreases the voltage gap rapidly across the gap.

The heating by the arc ionizes the air causing it to rise, carrying the current path with it. As the trail of ionization gets longer, it becomes less stable, and finally breaks. The voltage across the two wires (electrodes) then rises and the spark re-forms at the bottom of the device. The process is repeated. (Deskarati , 2012).

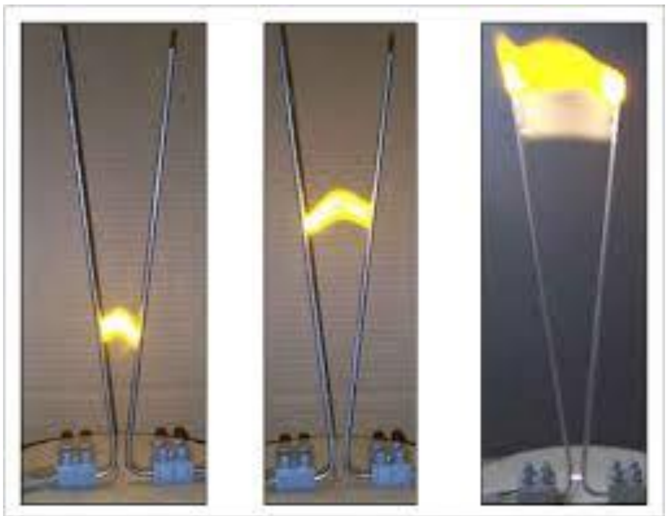


Figure 2.2: Jacob's Ladder

Jacob's ladder is however different in this project as only two sharp points are used as the electrodes but Jacob's ladder has proven that understanding the distance between the electrodes is vital as different distance produces different results. Knowing the optimum or best distance between the electrodes which give the most stable arc discharge will be beneficial to applications purposes.

Study in the arc motion in relation to the electrode distance has been done. (Zeller et al.,2001).Increase in the distance between the two electrodes will increase the delay of the arc motion in the initial period. As shown in Figure 2.3, three variables in distance which are 5 mm,10 mm and 15 mm are used to investigate the arc motion. Voltage (v) versus time in milisecond (ms) are only for electrode distance of 15mm. As observed in Figure 2.3, electrode distance of 15 mm, the arc does not have large significant changes in the first millisecond but after this time interval, the arc velocity increase rapidly. However no further explanations on this occurrence explained.

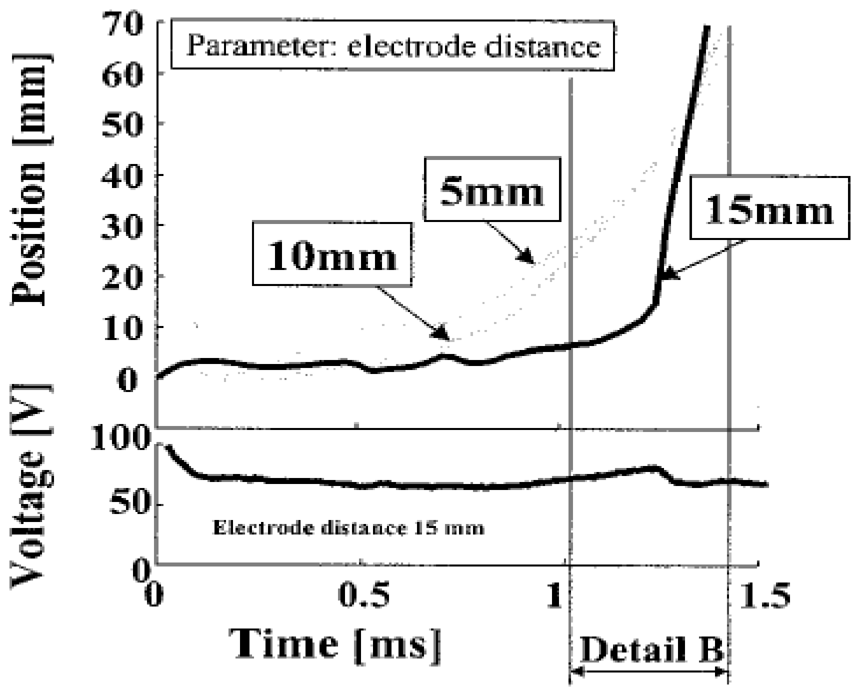


Figure 2.3: Distance between electrodes and voltage versus time

2.3 Duration of Arc Discharge

Characteristics of low energy discharge have been studied. A proposal of a mathematical model of low energy arc discharge which is known as arc current linear attenuation model based on dynamic Voltage – Current (VI) characteristics of inductive circuits have been proposed. (Meng Qinghai et al,2001). Arc current linear attenuation model can be expressed mathematically as shown in equation 2.1,

$$i(a) = I\left[1 - \frac{t}{T}\right] \qquad (2.1)$$

where :

i (a) = instantaneous value of arc voltage

t = instantaneous time

I = initial current value before break

T = discharge time

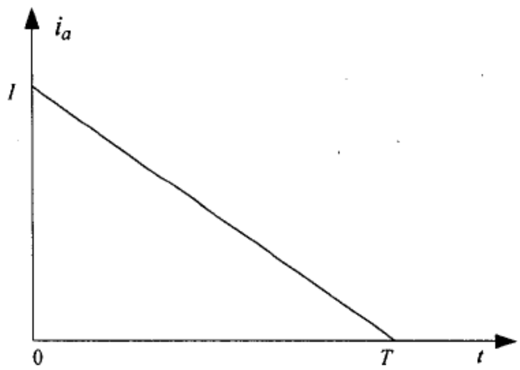


Figure 2.4: Arc current linear attenuation model

The model assumes that arc current drops to zero from initial point in a straight line for the discharge period. Based on Figure 2.4 alone, it shows the theoretical model of one discharge period. This model provided a simple analytical solution but in real case of arc discharge, this model seems way too ideal. Another drawback rises from the unknown parameter T which is difficult to determine based on the lack information provided.

The analytic expression of arc discharge on arc current and arc voltage versus discharge time are as shown in equation 2.2 and equation 2.3. Figure 2.5 and Figure 2.6, shows the experimental results and theoretical results from the mathematical modeling which proves their mathematical modeling successful.

$$ia = I - \frac{Vmin}{R-13L}\{1\text{-exp}[\frac{13L-R}{L}T]\} \quad (2.2)$$

$$Va = I - \frac{Vmin}{R-13L}\{\text{R-13Lexp}[\frac{13L-R}{L}T]\} \quad (2.3)$$

where:

$i(a)$ = Arc current

$V(a)$ = Arc voltage

$Vmin$ = minimum voltage

R = resistance

L = inductance

T = discharge time

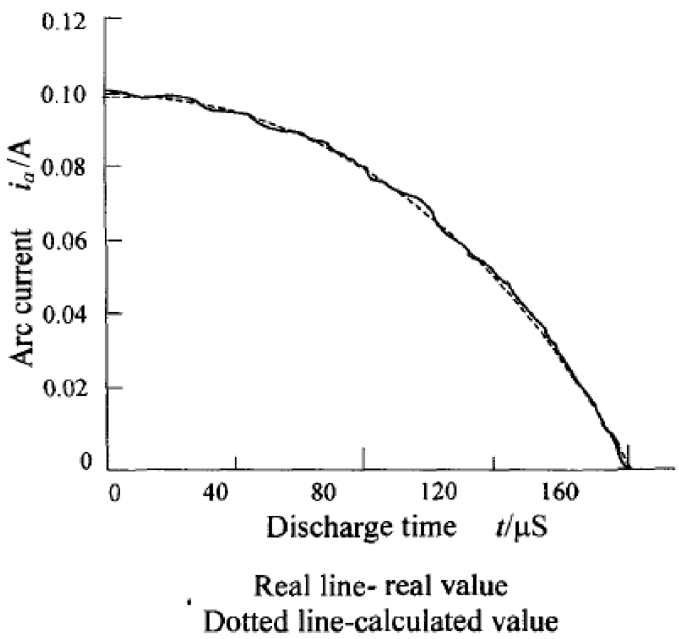


Figure 2.5: Arc Current (A) versus discharge time (μs)

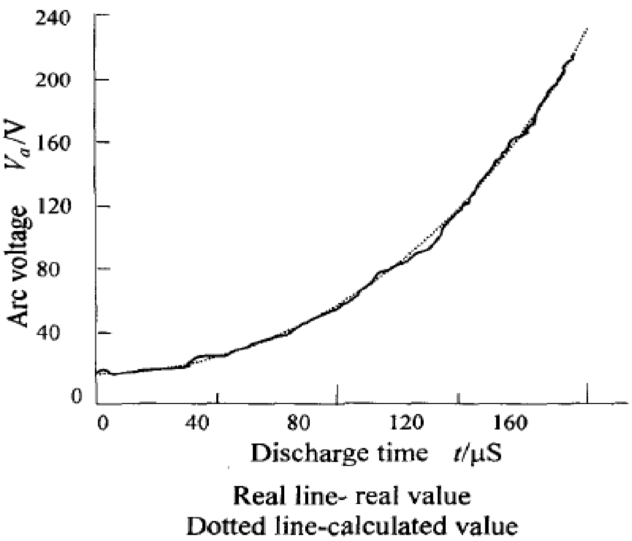


Figure 2.6: Arc Voltage (V) versus discharge time (μs)

An observation on arc emitted light using high speed camera (1000frames/s) is studied with a pair of silver (Ag) and copper (Cu) as the electrode and are separated at constant speed of 1.0m/s.(Sekikawa et al., 2004). Figure 2.7 show the characteristics of arc breaking points over a certain period of time and 30 samples are taken. The characteristics of arc durations for Ag contacts does not show significant changes with the increase of the number of breaking operations whereas for Cu contacts, the arc duration tends to become long and less stable.

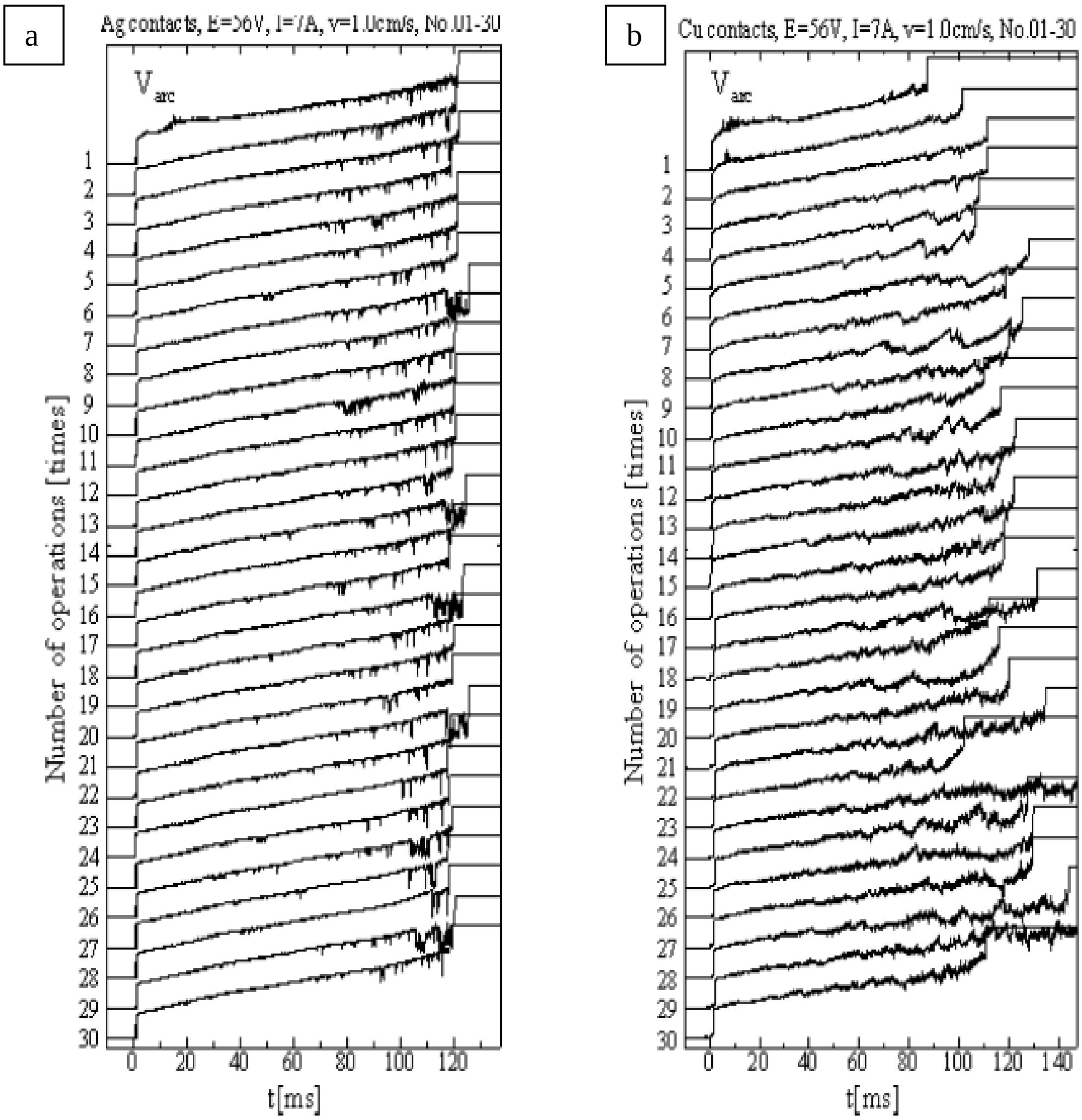


Figure 2.7: Time evolutions of arc voltage for (a) Ag contacts (b) Cu contacts

2.4 Arc discharge Power

The relationship between the arc voltage and arc current are studied, as the product of these two parameters equals to the power as shown in equation 2.4.

$$P = VI \tag{2.4}$$

Where:

P = Power

V = Voltage

I = Current

High speed camera is used as an advanced technology tools to distinguish the difference between the cathode and anode spots and the arc column for silver (Ag) and copper (Cu) electrodes, (Sekikawa et al., 2004).

The typical arc breaking of Ag contacts without large fluctuations is caught by camera and arranged into table form as shown in Figure 2.8 and Figure 2.9. The photographs are taken for every 10 ms interval and the spots between the cathode and anode are able to be distinguished after 20 ms. The evolution of the arc begins with the arc spots on the surface of the contact. The brightness of the arc column decreases slowly with the increasing length gap. However, just before the arc disappear, the arc voltage decreases and the arc current increases suddenly. This is due to the inversely proportional relationship between voltage and current in relation to power.

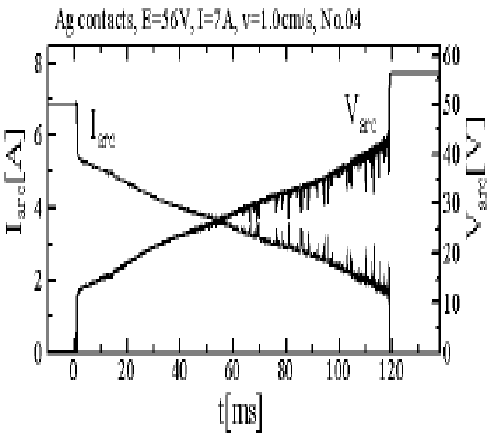


Figure 2.8 (a)

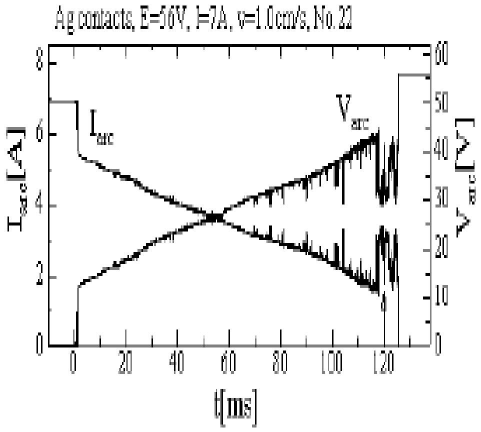


Figure 2.8(b)

Figure 2.8:Time evolutions of arc voltage and current for Ag contacts at arc (a) no.4 and (b)no.22

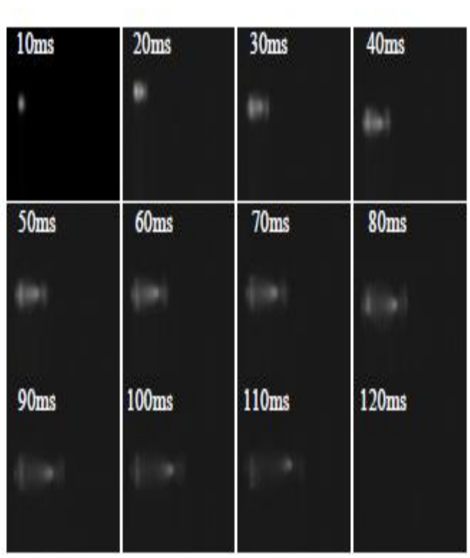


Figure 2.9 (a)

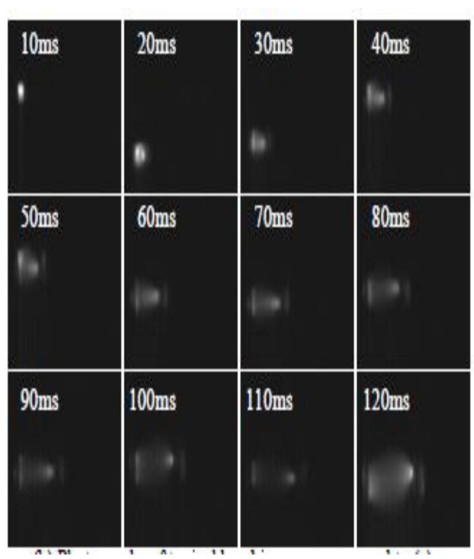


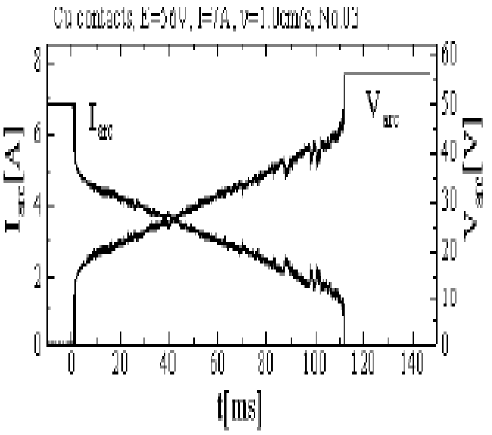
Figure 2.9(b)

Figure 2.9: Breaking arc with large fluctuations for Ag contacts at arc (a) no.4 and (b)no.22

The typical arc breaking of Cu contacts are as shown in Figure 2.10 and Figure 211. As shown in Figure 2.10, the breaking arc without large fluctuations of Cu contacts shows that the arc voltage increases linearly after arc ignition. The brightness of the arc column decreases with increasing the gap length.

Figure 2.11 shows a breaking arc with large fluctuations of the arc voltage and current of Cu contacts which indicates that the arc voltage and current have large fluctuations in the latter part of the arc duration. The arc current increases with the intensity simultaneously.

Nevertheless, the effective resistance decreased with the increase input power which would reach up to 97 Watt (W) in this case, (Sekikawa et al, 2004). The decrease of the effective resistance is caused by the expansion of the cross-sectional area of the arc column when the arc current increases suddenly. Brightness of the arc column decrease gradually with increasing gap length for both materials. However the brightness of the arc column increased rapidly in the second half of the arc duration and this is due to the decrease of effective resistance. The increase of brightness of the arc emitted light corresponds to the increase of number of the excited and ionized metallic atoms.



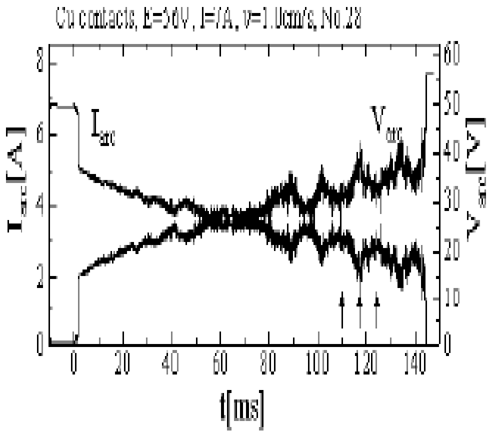
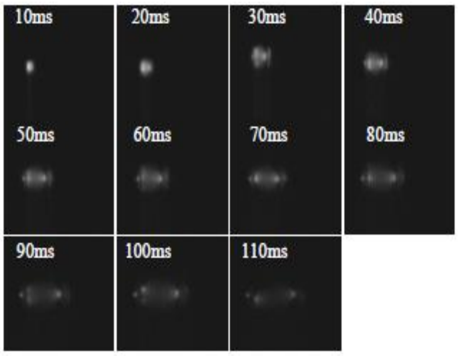


Figure 2.10(a) **Figure 2.10(b)**

Figure 2.10 (a) : Time evolutions of arc voltage and current for Cu contacts at arc (a) no.3 and (b) no.28



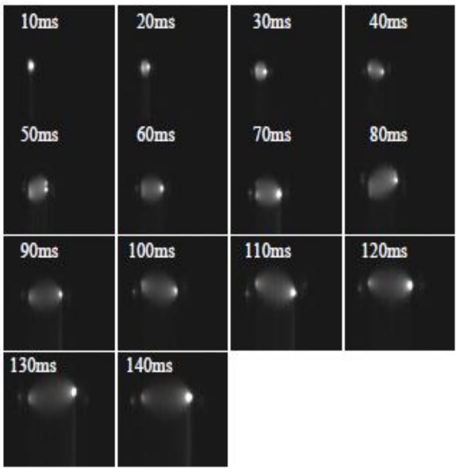


Figure 2.11 (a) **Figure 2.11(b)**

Figure 2.11: Typical breaking arc for Cu contacts (a) without large fluctuations at arc no.3 and (b) with large fluctuations at arc no.28

CHAPTER 3

METHODOLOGY

3.1 Overview

Figure 3.1 shows the flow chart progress of this project. This project started from an idea and study on the literature review which further initiated with the circuitry board design. Hardware implementations and characterisation is conducted to complete this project in quality and impactful.

MultiSim simulation program is used to design the electrical circuitry board and perform simulation. Set up and implementations started when the simulations on the design is completed and confirmed. Prototyping on breadboard are first built to ensure the circuit designs are working in practical case. The circuitry design next implemented on the Printed Circuit Board (PCB) to eliminate the possibilities of instability connections from the breadboard. The components are soldered to the PCB. The project timeline progress onto troubleshooting during set up.

Characterisation on the frequency, duty cycle, and distance between the electrodes parameters are carried out when the set up and troubleshooting stage is completed. Data collections and interpretations are the most vital stage to completion in this project.

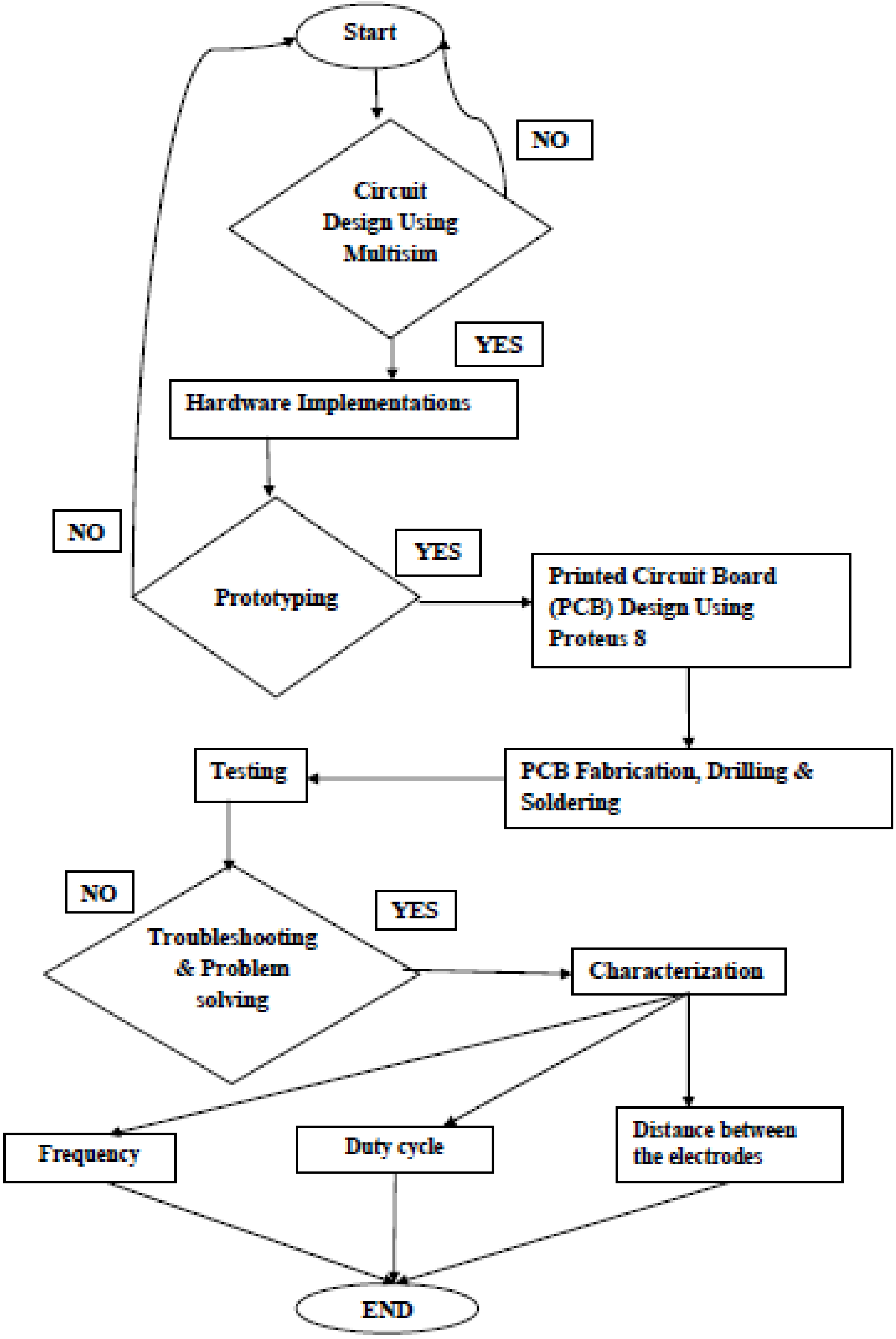


Figure 3.1: Flow chart of the project flow

3.2 Circuitry Design

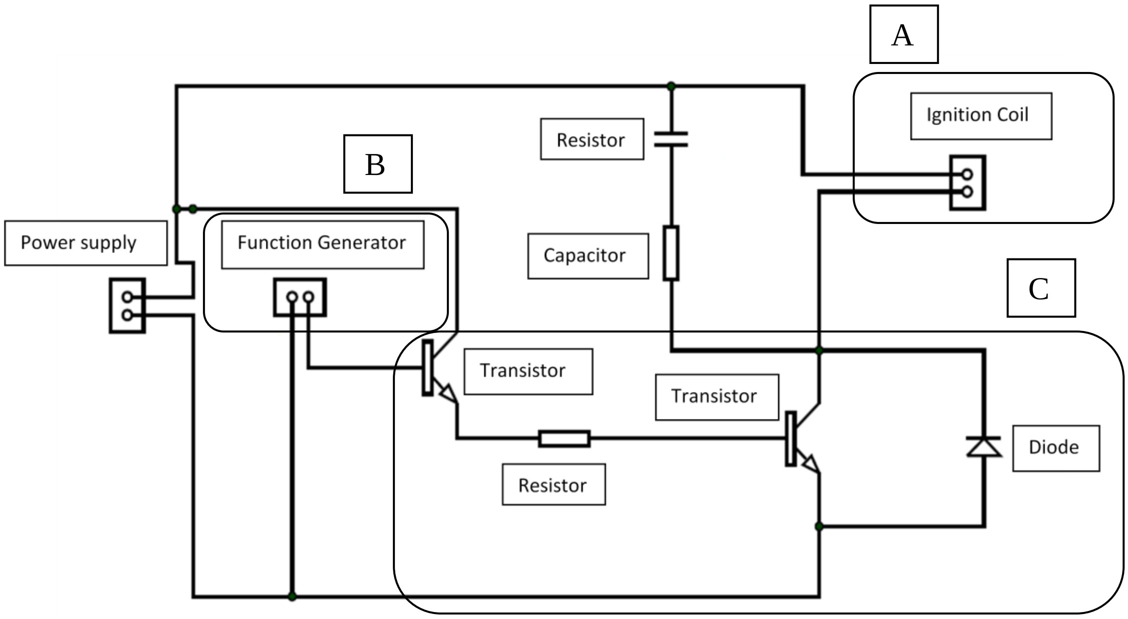


Figure 3.2 : Circuitry design of the Arc Discharge System

Figure 3.2 shows the schematic circuitry board design for the arc discharge system in this project. The main aim in designing the circuit for this project is to create a high enough potential to produce electric arc discharge. In order to have a better understanding on every part of this design, 3 main parts have been divided.

Part A – Consists of a step up ignition coil to create high potential difference between the two electrodes where one of the electrodes will be grounded. Electric arc discharge will be produced at part A.

Part B – To provide a repetition of charge and discharge cycle of arc discharge in a certain frequency and thus providing the arc discharge a stable discharge over a certain period of time.

Part C – Transistor acts as an electronic signals switch and to modulate the current according to the function generator. Thus using two transistors will improve the electric circuit operating system.

3.3 Prototype

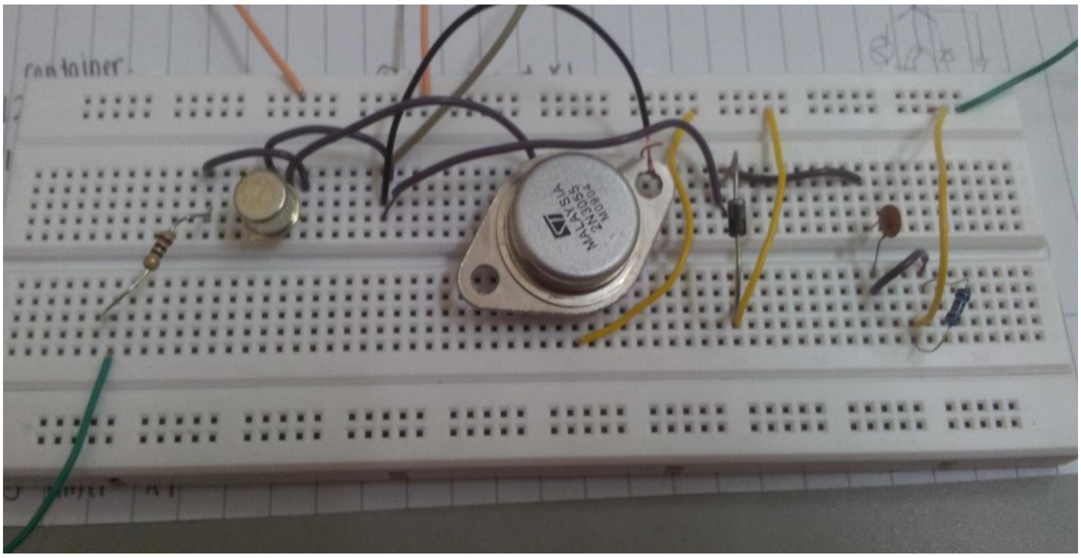


Figure 3.3 : Prototype on breadboard

Prototype has been done to conduct the testing before implementing the design on the real Printed Circuit Board (PCB). Prototype has been done first on a breadboard to check on the connections of every component to ensure the connections able to work well.

It has been found that the circuitry design on the connections works well and fit the aim to build an arc discharge system. The connection on breadboard will not be finalised and proceed to data collection because the loose wiring connections and instable connections due to impermanent wiring connections. Prototyping is meant to test and prove the circuitry design is feasible.

The design is implemented onto the Printed Circuit Board (PCB) to ensure stability of the connections.

3.4 Printed Circuit Board Design

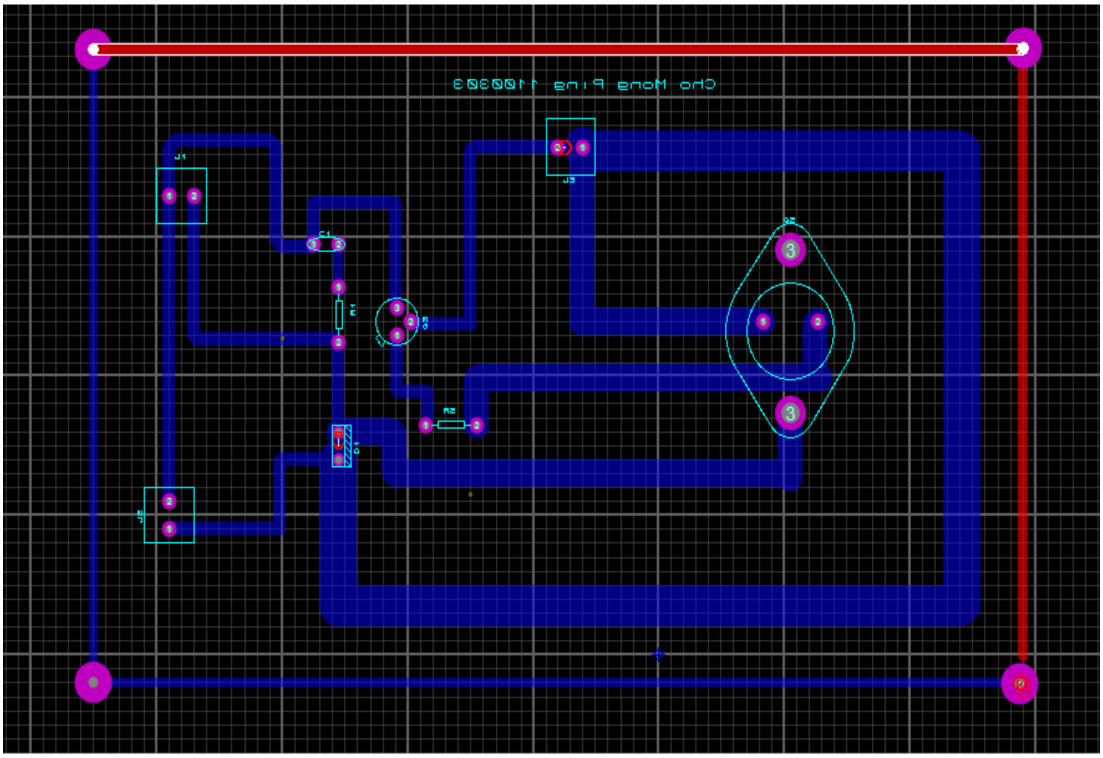


Figure 3.4: Schematic design on the Printed Circuit Board (PCB)

Figure 3.4 shows the schematic design on the Printed circuit design (PCB) using Proteus 8 Professional program. This design is implemented onto a Printed Circuit Boards (PCB) to have a more stable connections compared to wiring connections through breadboard.

During the schematic design, it is important to arrange the components in way that it is convenient for the implementation process that include drilling and soldering process. Components should not be arranged too closely to one another.

Thicker copper wiring is chosen in the design in order to dissipated heat faster. This method able to protect the components from damaged and helped in the dissipation of heat. Heat sink paste is used on components to reduce heating on the components during arc discharge process.

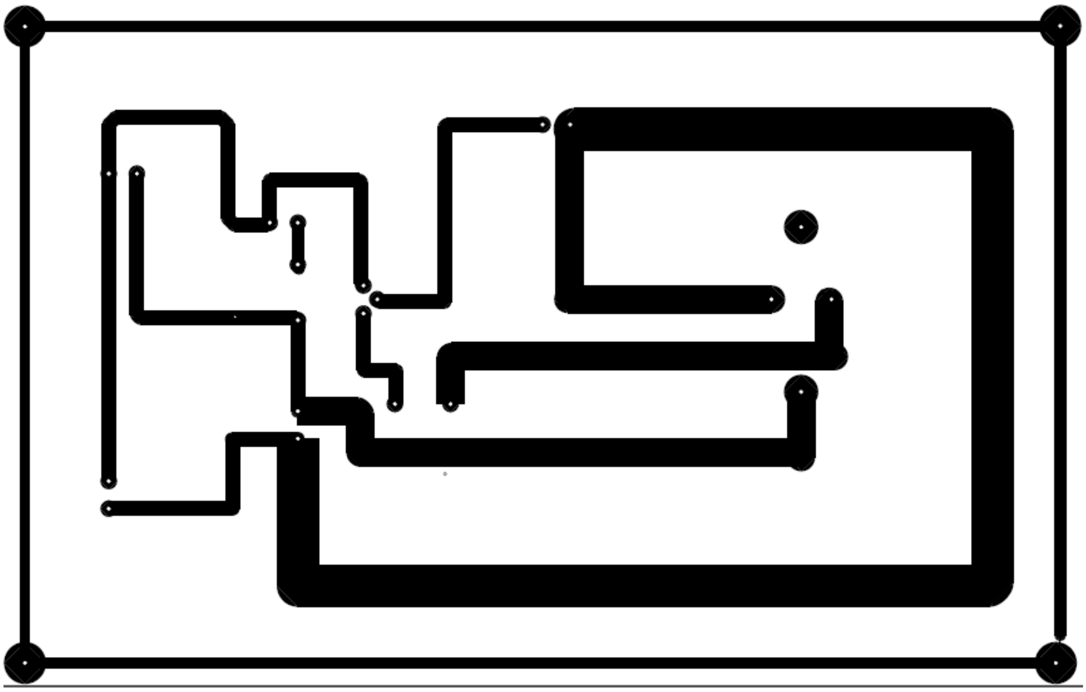


Figure 3.5: Printed Circuit Board (PCB) design

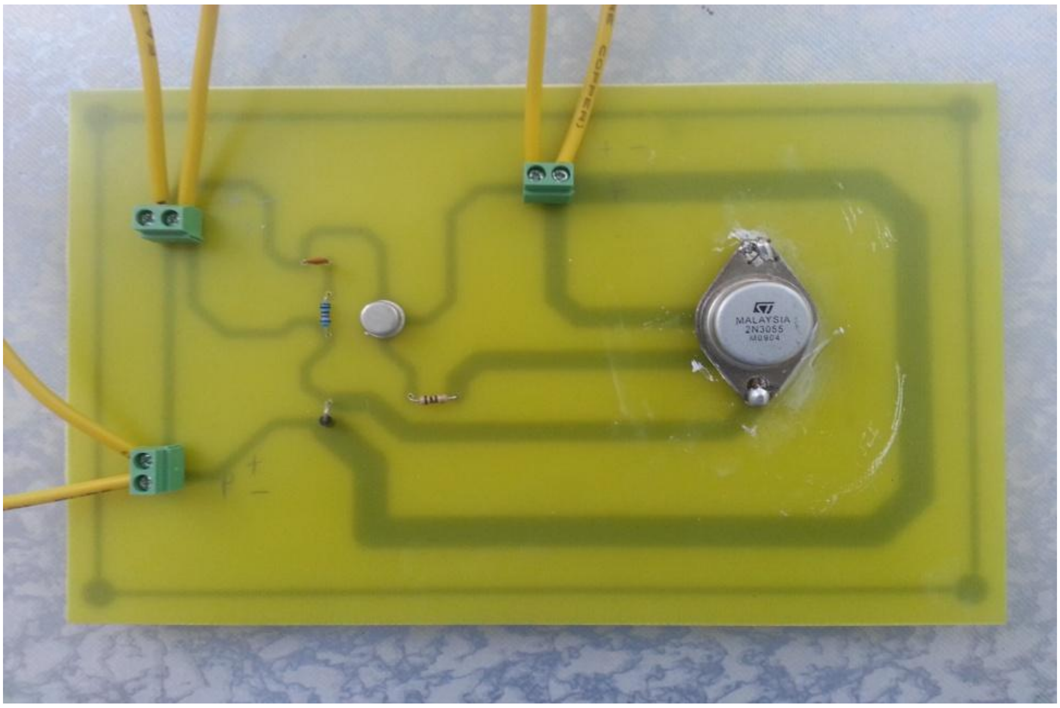


Figure 3.6: Real product of the Printed Circuit Board (PCB)

Printed circuit board (PCB) design as shown in Figure 3.5 is sent to fabrication process and the end product is as shown in Figure 3.6. Components are soldered onto the printed circuit board.

3.5 Fixture Fabrication

Fixture to hold the electrodes in the correct and straight position are fabricated in the mechanical lab using polyethylene materials. Machining, milling process is used to fabricate the fixture.

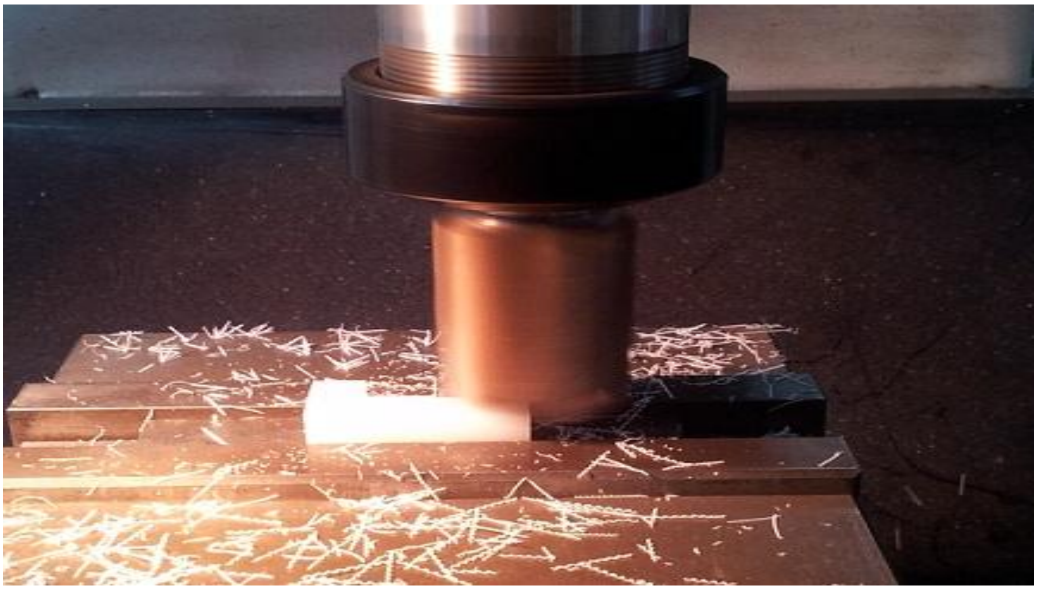


Figure 3.7 : Milling Process

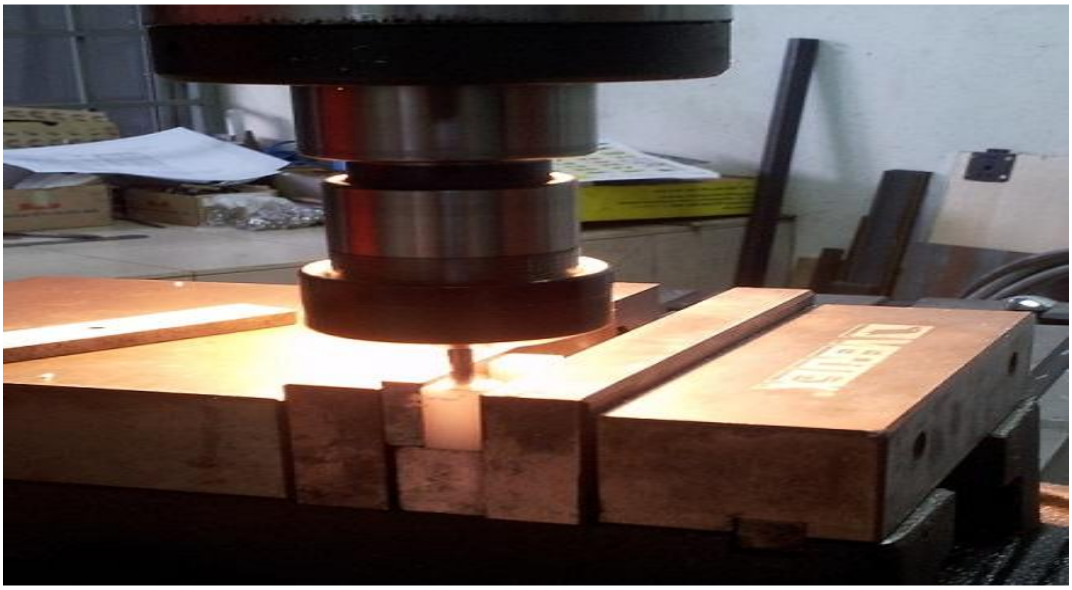


Figure 3.8 : Drilling using Machining Process

Figure 3.7 and Figure 3.8 shows the machining process to fabricate the fixture. Milling process is a machining process of using a rotary cutter to remove unwanted section of the material to form a desire work piece.

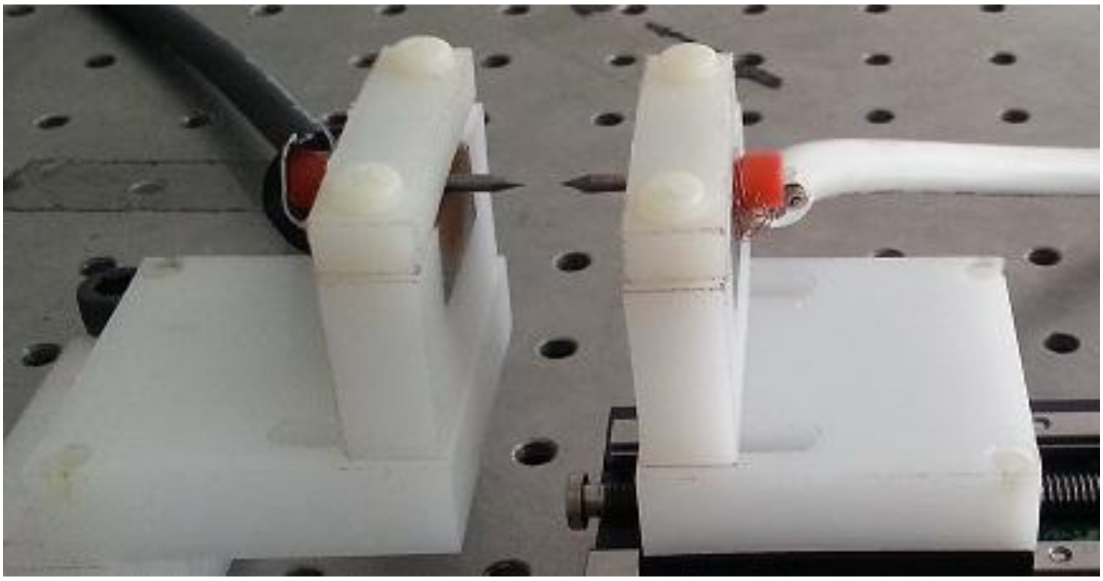


Figure 3.9: Final product of fixture

Figure 3.9 show the final product of the fixture used to hold the electrodes in position for arc discharge process. The diameter of the electrodes used in this project is only 20 mm thus it is important to have a fixture to be able to hold the electrodes in the right and straight position. Furthermore, the electrode tip is sharp and in specification the tips of the electrodes should be aligned during the arc discharge process.

A nylon screw is used as part of the fixture instead of the conventional type of metal screw. This is to avoid the possibilities of the arc discharge attracted to the metal screw which is relatively close to the position of the electrodes. Arc discharge is conductive thus will be attracted to any conductive materials nearby.

3.6 Experiment Setup

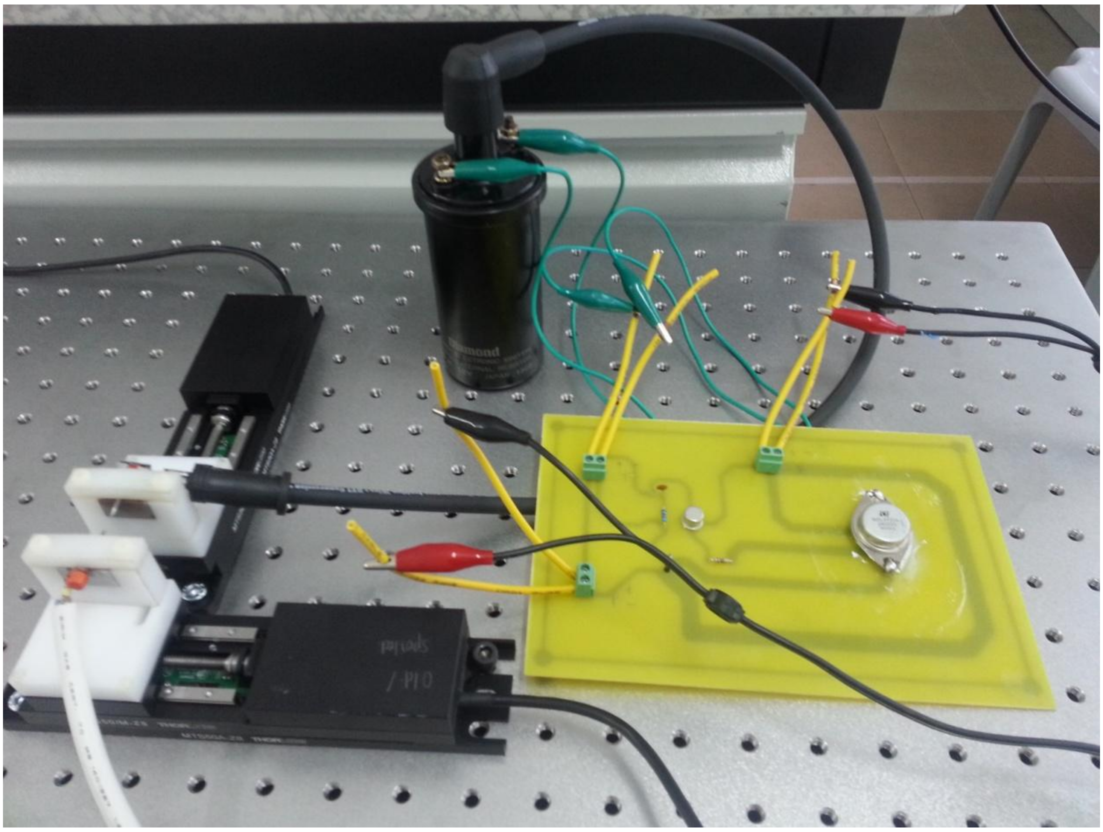


Figure 3.10: Overview of the experiment set up

The fixture that holds the electrodes are mounted onto the motorised stages for the purpose in characterisation on the distance between the electrodes. In order to eliminate parallax error from human, the motorised stages are used to control the distance between the electrodes as the distance characterisation is in the order millimetre (mm). The characterisation distance between the electrodes in this project are 2 mm , 4 mm and 6 mm. Distance in order of mm is relatively hard to control in accurate thus motorised stages are implemented into the setup to increase the accuracy.

Electrode which acts as the cathode is connected to the secondary ignition coil whereas the electrode which acts as the anode is grounded. The anode is grounded properly in a ground terminal of itself. The ground terminal of the anode should not be shared to avoid ground loop.

3.7 Experiment precautions

Precautions when handling arc discharge system must not be taken lightly. Arc system is a system of high power system due to the high step up ratio provided by the ignition coil. Experimenter must not stand near to the electrodes when the arc discharge system is turned on. Arc discharge at the electrodes is at very high power and can be extremely dangerous and may cause fatal to the experimenter if touched.

Any other electrical conductivity materials must not placed near to the experiment setup while the arc discharge system is turned on. This is to ensure the electrical arc do not get attracted to other conducting material which would be dangerous to experimenter.

Experimenter must always ensure proper grounding of the system before turning on the power supply to start the system. The high voltage arises from the ignition coil where the step-up ratio is approximately to ten thousand times which is estimated to be in the range of twenty-four thousand volt. High power and low power equipments are isolated in order to protect the equipment due to ground loop. Ground loop relate to a conductor connecting two terminals where usually one of the terminal is ground but misconduct to other lower potential terminals.

The tip of the electrodes is cleaned with alcohol after each period of arc discharge activity. The dust particles may deposited at the tip of the electrodes due to ionisation in the process of arc discharge and to ensure a clean arc discharge on the next arcing session.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

In this chapter, the results on the simulation circuitry design and characterisation based on the frequency, duty cycle and distance between the electrodes are discussed in line with the objectives in this project.

Simulation using MultiSim program is used to confirm the feasibility on the circuitry design. Results on the characterisation are discussed and analysed in depth to understand the arc discharge system. Graphs are plotted to assist in a clearer presentations of a series of data collected. Analysis on the data collections are done thoroughly through the presentations of data in plotted graphs.

Analysis and optimisation on the characterisation on the frequency, duty cycle and distance between the electrodes are discussed in this chapter. In addition to that, the stability of arc and colour of the arc observed is also being discussed.

4.2 Simulation using MultiSim.

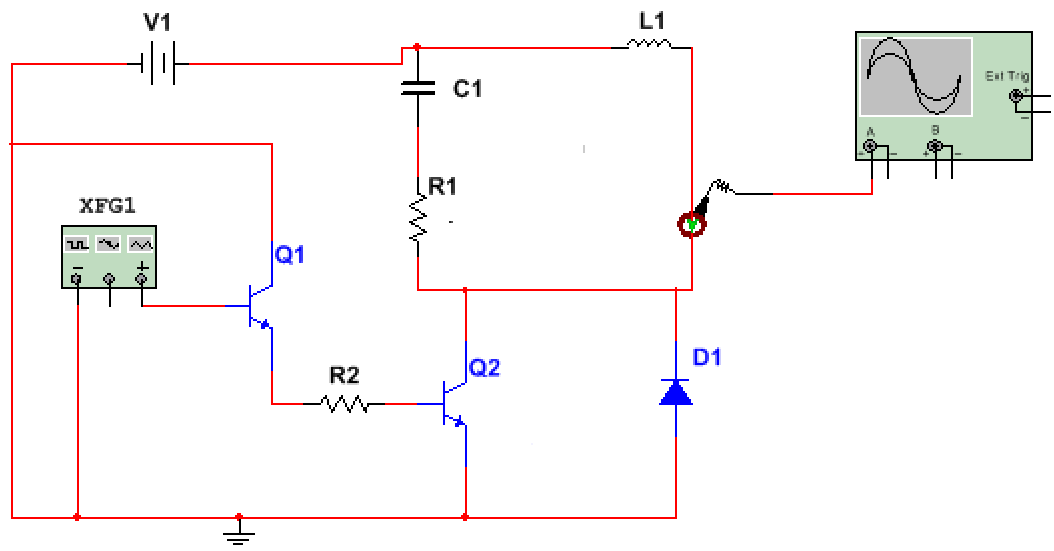


Figure 4.1: Circuitry design using MultiSim

MultiSim programme is used to simulate the circuitry design. Analysis through simulation can be done before implementation on the practical case. Current and voltage across the ignition coil can be identified beforehand.

Figure 4.1 shows the electric circuit design using MultiSim where an oscilloscope is used to observe the current and voltage to the ignition coil. L1 is to represent the inductance of the ignition coil.

4.2.1 Results on the design using MultiSim

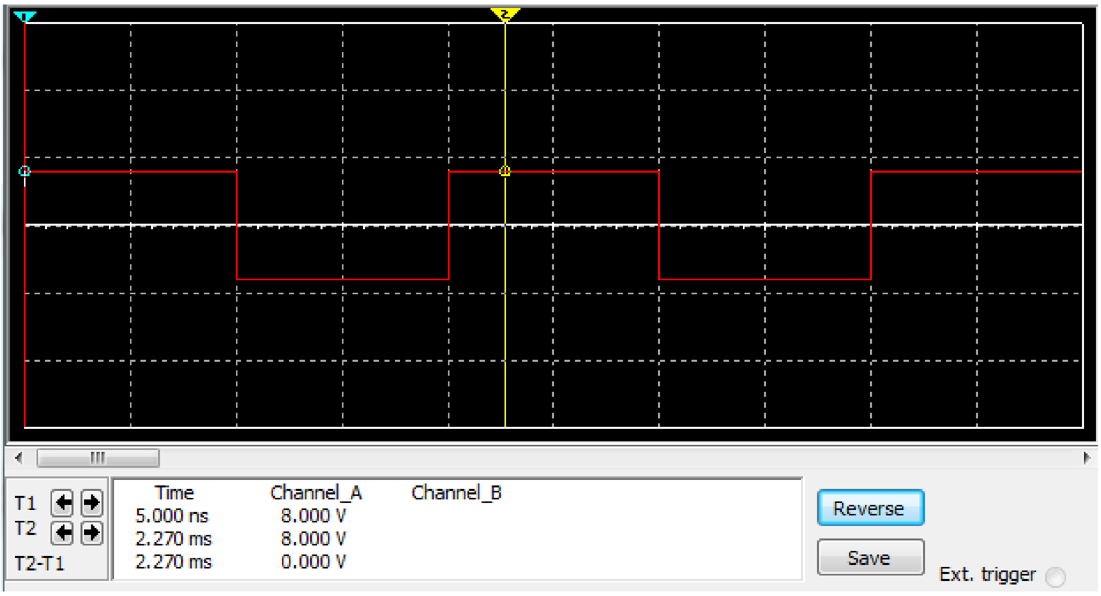


Figure 4.2: Voltage at function generator

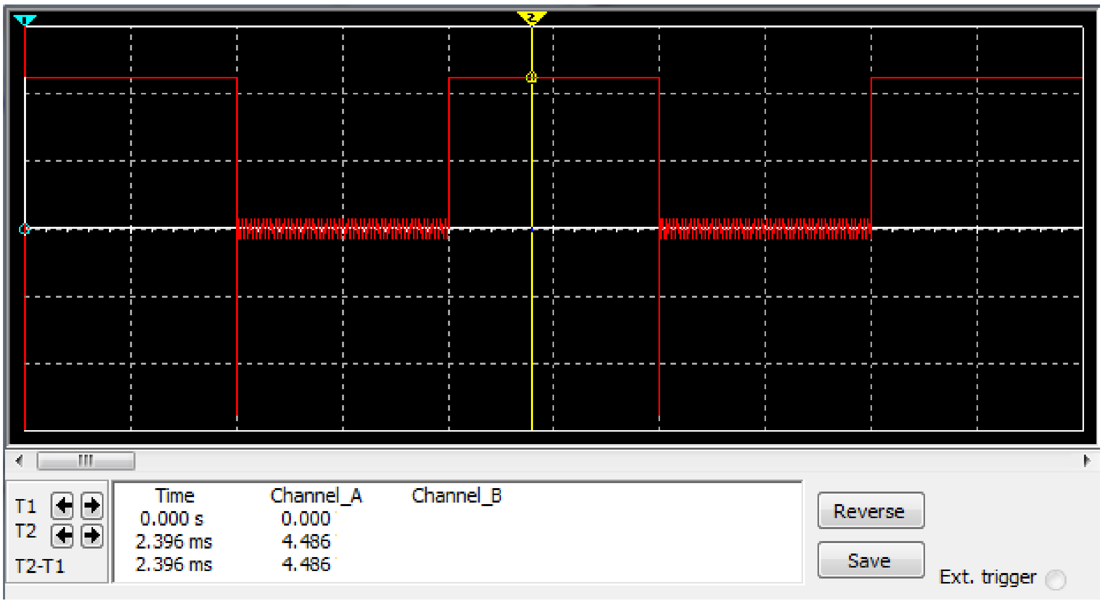


Figure 4.3: Current at function generator

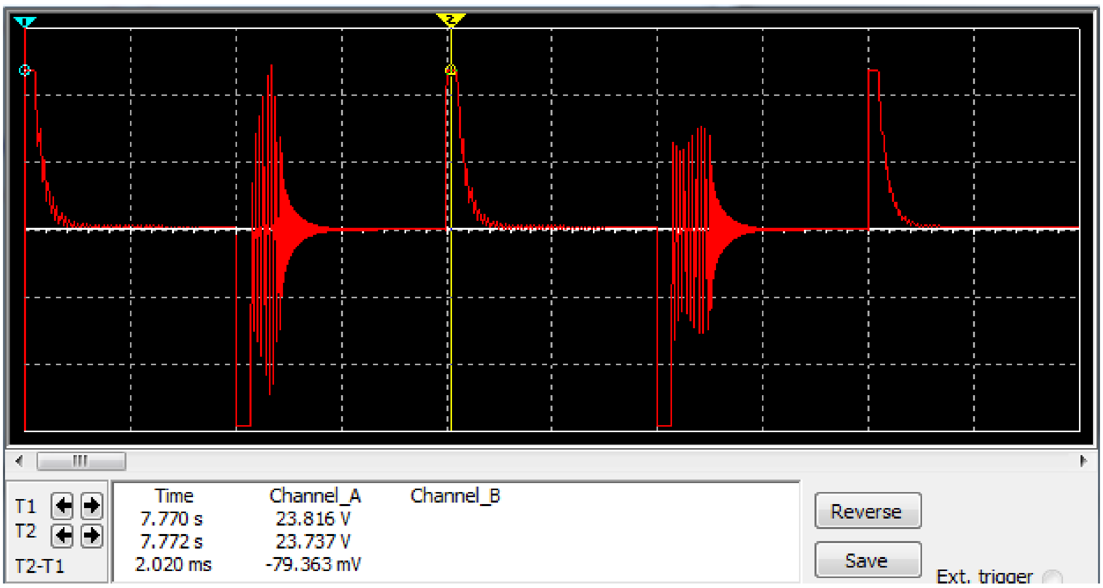


Figure 4.4: Voltage across Ignition Coil

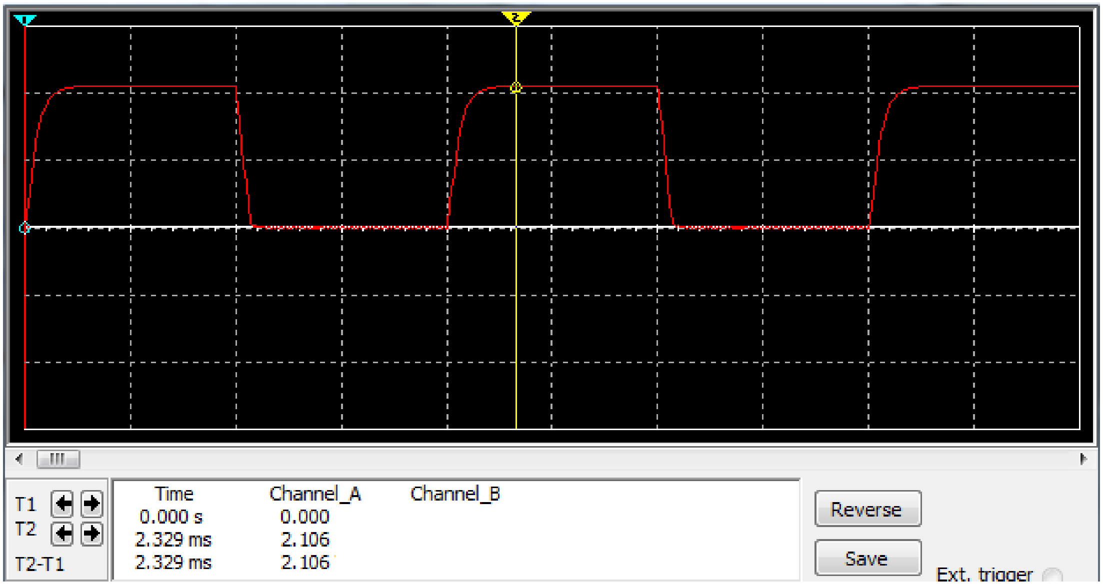


Figure 4.5: Current across Ignition Coil

Table 4.1: Summary of voltage and current across function generator and ignition coil respectively

	Voltage (v)	Current (A)
Function Generator	**8.000**	**4.486**
Across Ignition Coil	**23.816**	**2.106**

Voltage and current across the function generator and ignition coil as simulated is summarised in Table 4.1.The function generator is set to a constant value of 8 V peak to peak and in square waveform. The waveform observed which modulated by the function generator is square wave holds true. The function generator is set to square waveform to produce a constant value of on and off signal to the arc discharge system to produce constant re-ignition.

The power of the primary coil of the ignition coil can be estimated using the simulation results. Power at the primary ignition coil is estimated to be 50.156 W according to equation 2.4. Power at the secondary coil can be determined with the estimated power at the primary coil. The step-up ratio of the ignition coil is ten thousand times, thus the power at the secondary coil is estimated to be 0.5 MW.

The results and analysis of the simulation results able to determine the power of arc discharge produced at the secondary ignition coil is in the range of megawatt. These results have proven the feasibility of the circuitry design to produce arc discharge.

Based on the simulation result, the arc discharge is categorised as low current arc according to Table 2.2. The operating current of the arc discharge according to the simulation results is lower than ten ampere thus being categorised under low current arc.

4.3 Types of Arc Discharge

Arc discharge and dark discharge are observed in this project. Dark discharge is the early stage of arcing process and is invisible to the naked eyes where it is also known as corona discharge. Discharge at this region is high enough to form conductive region but not high enough to cause electrical breakdown. (Loeb,2005),

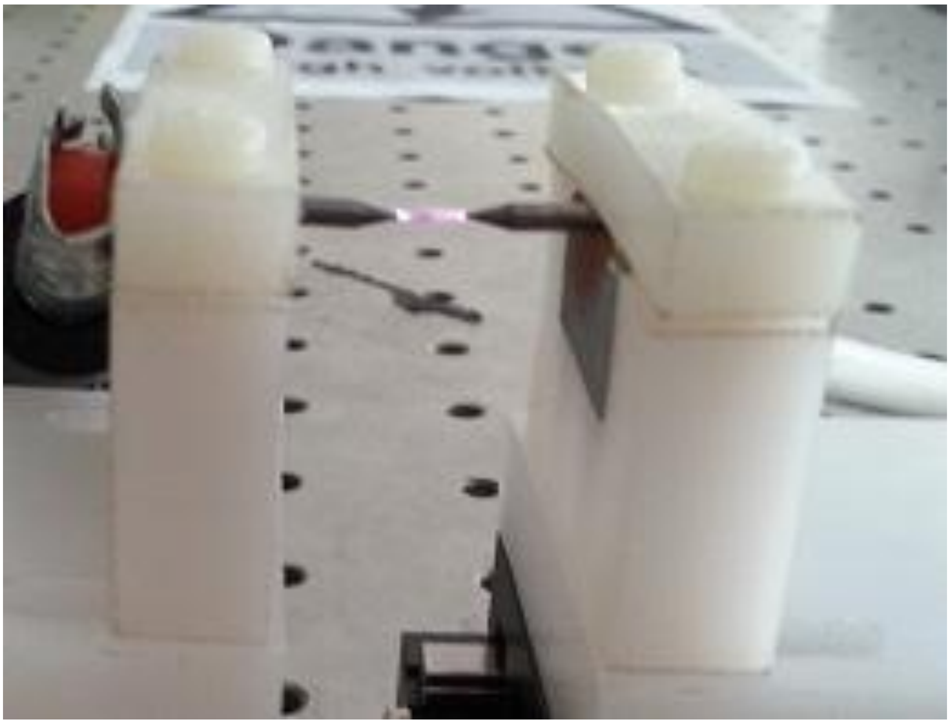


Figure 4.6: Close up on the arc discharge between the electrodes

The colour of the arc discharge is observed to be the colour of violet as shown in Figure 4.6. Based on the observations, an approximate wavelength and frequency of the arc discharge can be determined.

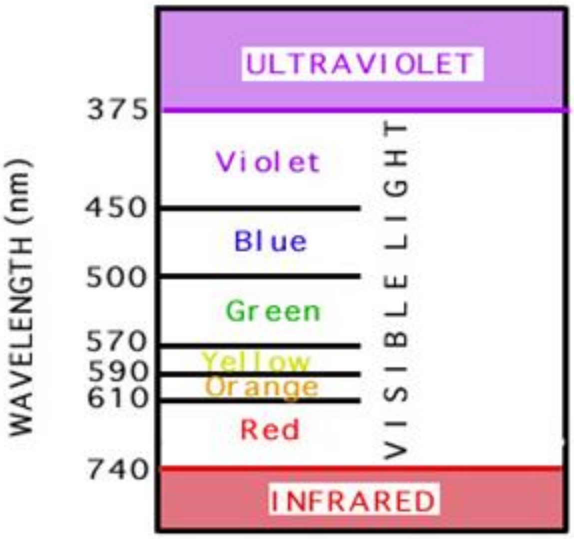


Figure 4.7: The visible light spectrum scale

Figure 4.7 shows the visible light spectrum where the wavelength and frequency of a violet arc discharge can be determined. A violet arc discharge is in a wavelength range between 375 nm to 450 nm and frequency range between 668 Hz to 789 Hz. In this region, purple arc discharge is in a region near to the ultraviolet (UV) region.

Violet visible arc discharge contains the highest energy in the visible colour spectrum. This statement can be supported based on Equation 4.1.

$$E = hf \tag{4.1}$$

where,

E= energy

h= Plank's constant

f= frequency

Having a high energy transitions, the arc discharge appear to be in violet colour. The colour of arc discharge is also determined by the composition of air as which composed primarily of oxygen and nitrogen. Ionisation of air molecules in between the electrodes gap causes the arc discharge to appear in violet colour, the same colour of with plasma discharge in air. Thus this observation proven the arc discharge produced in this project is an arc discharge plasma and not glow arc discharge. Glow arc discharge is of the colour of white-yellowish which resembles the colour of neon lighting.

Arc discharge produced in this project is an alternating current arc. The alternating current arc is fed with an alternating current supply where is it modulated by the function generator. The arc discharge is ignited by the frequency factor and triggered electronically. The arc discharge is rectified every cycle with the controlled parameters which turns to a unique interrupted direct current arc.

4.4 Data collection

Parameters in variations

a) Distance between electrodes (mm)
b) Duty cycle (%)
c) Frequency (Hz)

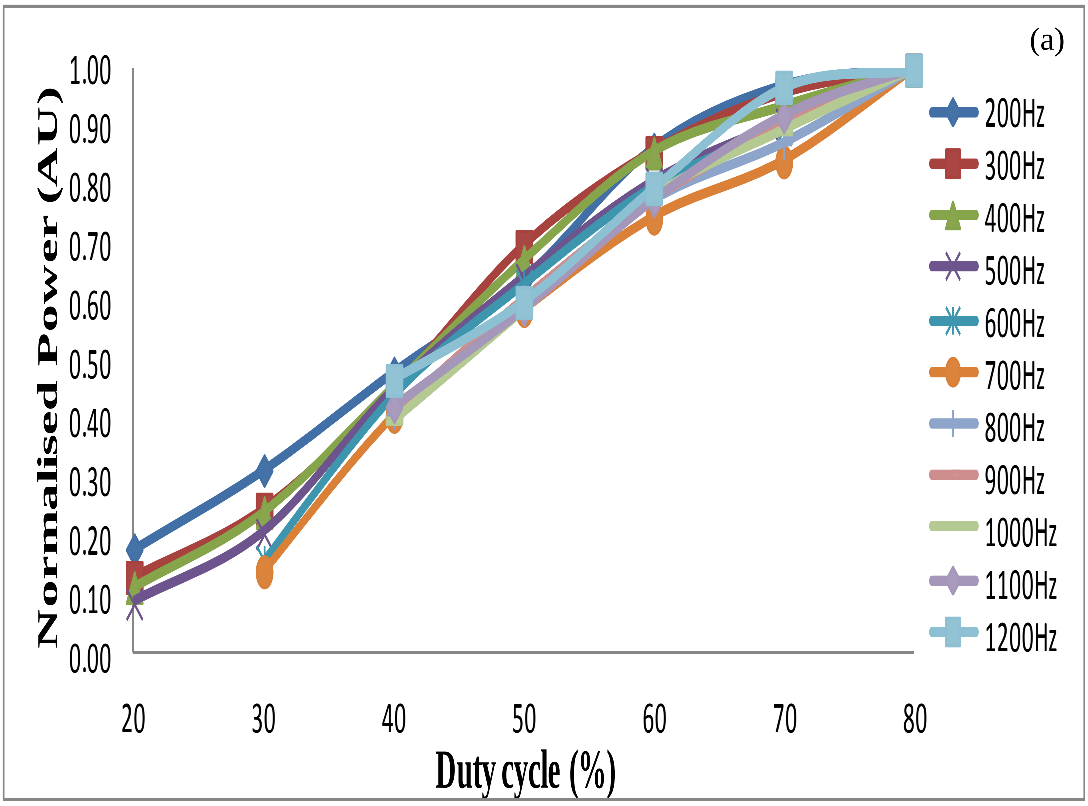
The data are arrange in 3 major categories which are divided based on the distance between the electrodes (2 mm ,4 mm and 6 mm) and further subdivided into variations in duty cycle (20 % to 80 %) and frequency (200 Hz to 1200 Hz). Data collections are taken in the form of power (W) supplied which is obtained from the multiplications of voltage and current shown on the power supply device.

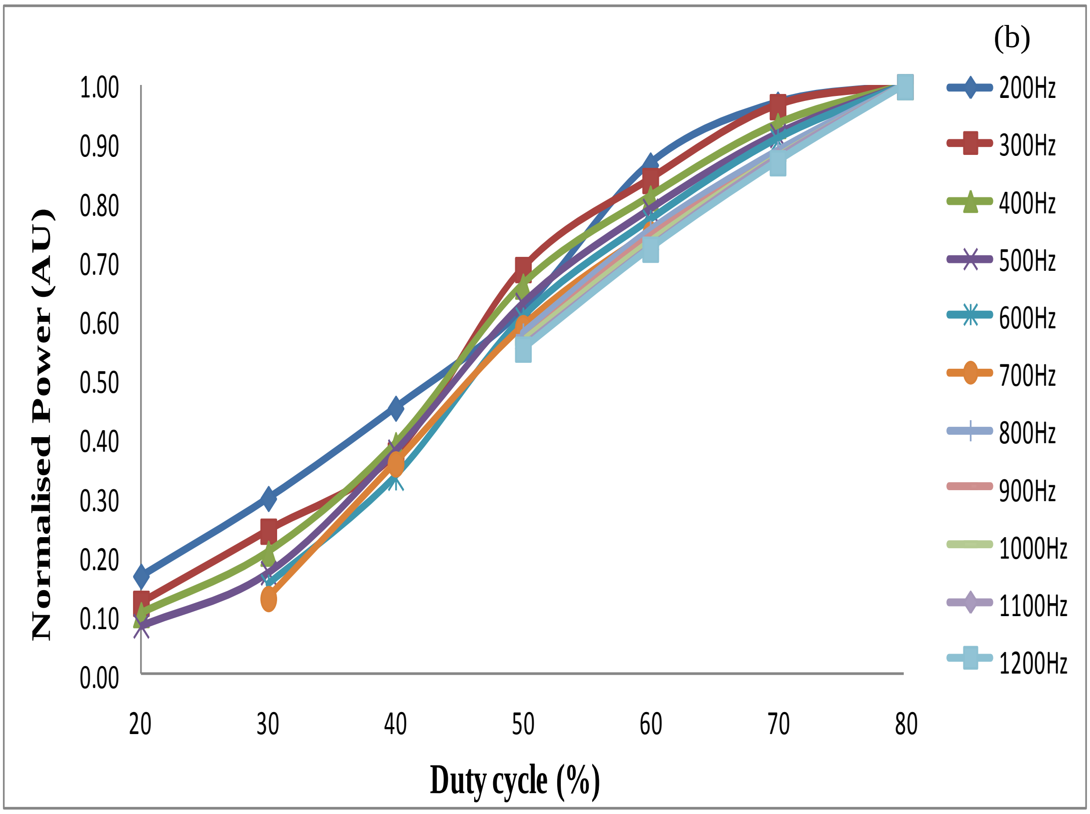
Data are taken in the form of power supplied instead of the power of the arc discharge. This action is taken because the power of the arc discharge is too high to be measured with any instrument due to the limitation of high power measurement instrument. The estimated high power of the arc discharge which is in the range of megawatt capable in damaging the measuring instrument. Thus data are taken based on the power supplied to relate to the characteristics of the arc discharge system.

Arc discharge is observed at most of the parameters set. Attention in this project will be mostly given to the arc discharge. During the experiment data collection, only arc discharge data are taken. Thus, the data of dark discharge are excluded in the data collection.

Arc discharge is of higher power and categorised as stronger arc discharge. Arc discharge is the main studies in this project which will further benefits in applications purpose.

4.5 Normalised power versus duty cycle at different frequencies





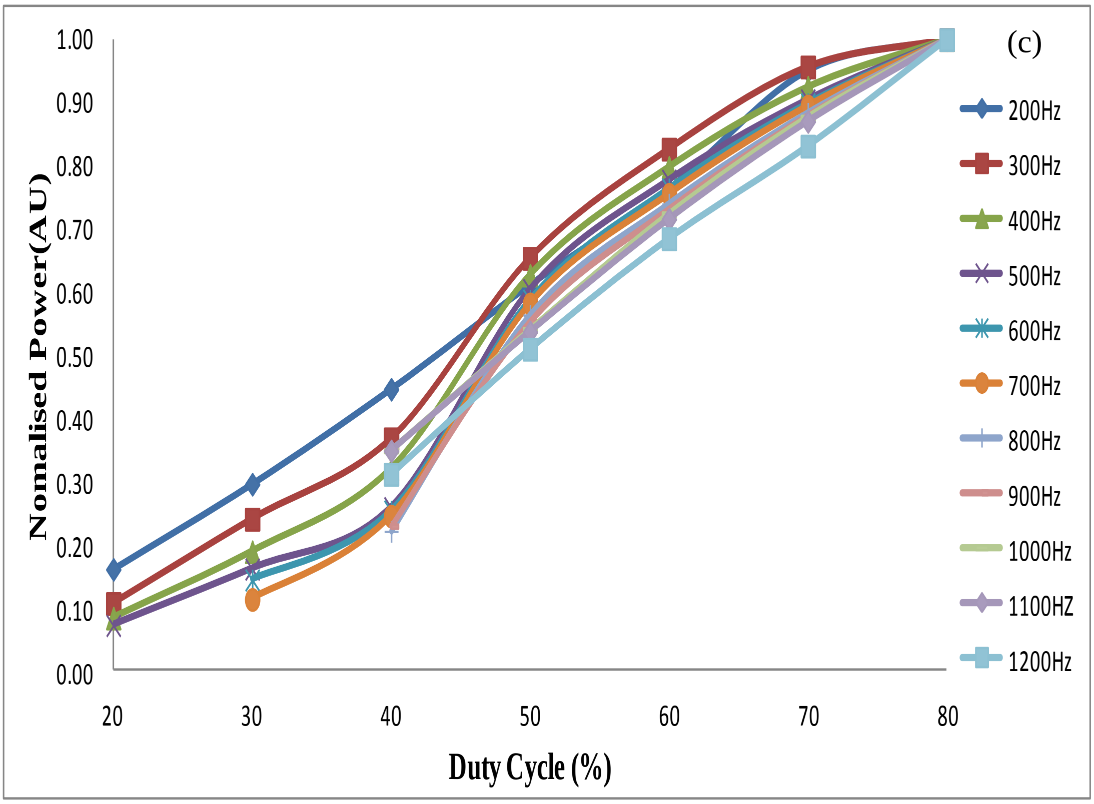


Figure 4.8: Normalised power versus duty cycle at different frequencies at distance (a) 2 mm, (b) 4 mm, and (c) 6 mm

Figure 4.8 shows the normalised power versus duty cycle at different frequencies. Normalised power is conducted in respect to duty cycle to find the relation from one another.

All the frequencies range from 200 Hz to 1200 Hz posses a rather similar pattern. The power supplied increase with increasing duty cycle. The maximum power for all the frequencies falls at the maximum duty cycle, 80 %. This is because at the maximum duty cycle, the discharge time is the longest thus drawing the most power to sustain the arc discharge. However at lower duty cycle, the discharge time is shorter thus drawing less power to sustain the arc discharge.

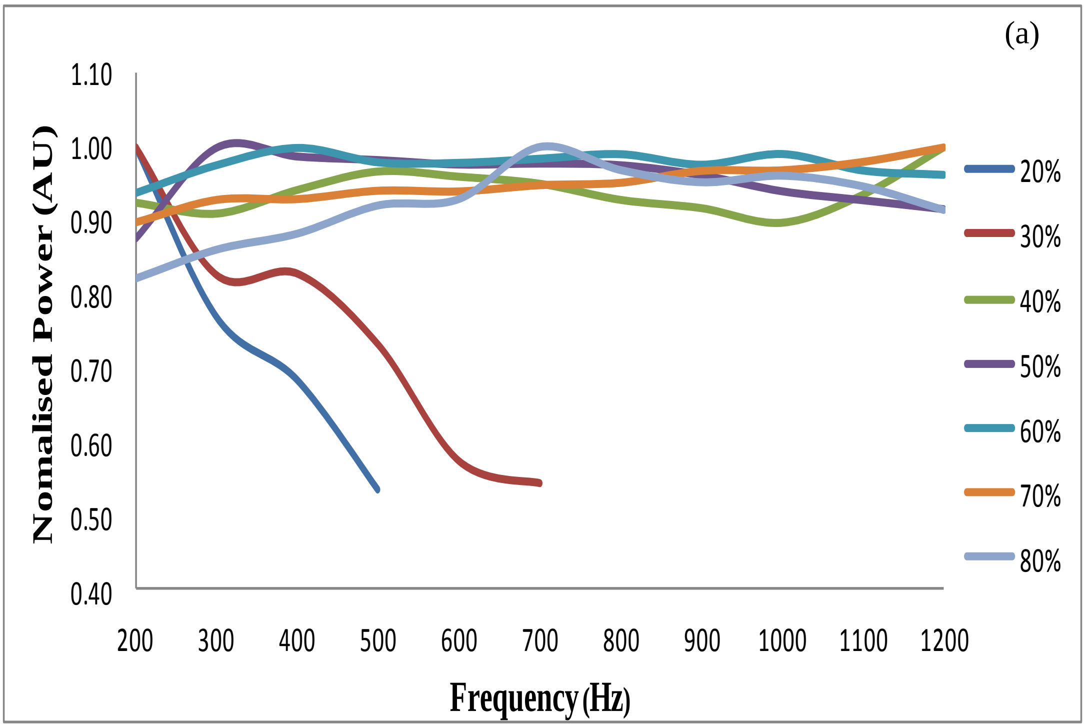
Dark discharge can be observed at duty cycle 20 % starting from 600 Hz to 1200Hz and at 30 % from 800 Hz to 1200 Hz for all three distances between the electrodes (2 mm, 4 mm and 6 mm).

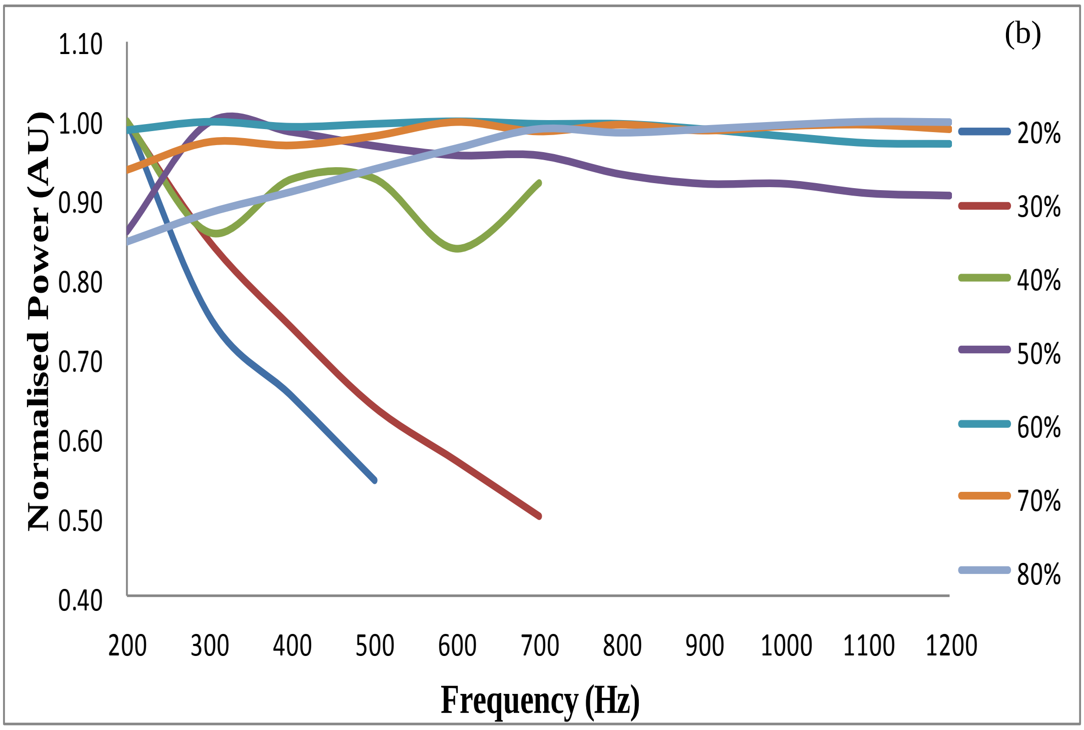
This can be explained in terms of the discharge time where this statement is supported by literature review.(Meng Qinghai et.al, 2001). Longer discharge time allows the ionization process to occur and leads to arc discharge. Discharge time in this project is as calculated and shown in Appendix D. Based on the data in Appendix D, discharge time of 0.0004 second (s) is found to be the lowest limit in producing arc discharge. Discharge time which is lower than 0.0004 s will fail to produce arc discharge and fall under the region of dark discharge.

Discharge time for duty cycle of 20% with frequency of 600 Hz and above are too short to produce arc discharge. The discharge time is 0.0003 s which falls below 0.0004 s the lowest limit to produce arc discharge.

The same explanations can be understood to explain the production of dark discharge that is observed at duty cycle of 30 % with frequency of 800 Hz and above. Benchmarking at 0.0004 s to produce arc discharge can be made conclusively.

4.6 Normalised power versus frequency at different duty cycle





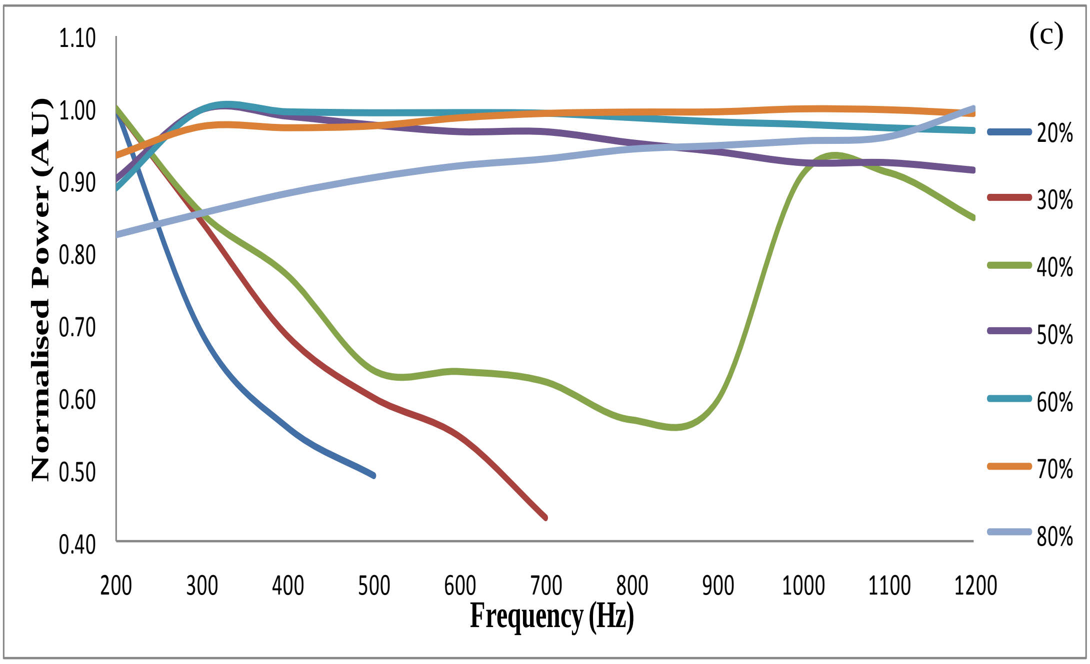


Figure 4.9: Normalised power versus frequency in variation to duty cycle at distance (a) 2 mm, (b) 4 mm, and (c) 6 mm

Figure 4.9 shows the normalised power versus frequency at different duty cycle. Normalised power is conducted in respect to frequency to find the relation from one another.

The duty cycle range from 20 % and reach maximum at 80 %. This range is chosen due to the limitations provided by the function generator. Duty cycle of 20 % and 30 % stopped producing arc discharge at 500 Hz and 700 Hz respectively. The power supplied for this section decreases as the frequency increase. These observations is valid for all distances between the electrodes, (2 mm ,4 mm and 6 mm). Duty cycle of 20 % and 30 % are not suitable to produce arc discharge due to the characteristics observed.

Whereas duty cycle of 40 % behaves differently for all distances. Duty cycle of 40 % at electrodes distance at 2 mm, the power supplied fluctuates slightly between 0.90 AU. and 1.00 AU. and shows a rather stable characteristic. However, at electrodes distance at 4 mm, production of arc discharge stops at 700 Hz. The power supplied shows unstable characteristics. Whereas for electrodes at distance 6 mm with duty cycle 40 %, arc discharge is observed for all frequency range but the power supplied shows a large fluctuations from 1.00 AU. to 0.55 AU. and appear to be unstable as well. Data collected for duty cycle 40 % at electrodes distance 6 mm are not convinced to produce good arc discharge.

However, duty cycle of 50% to 80% shows a consistent pattern power supplied behavior for all electrodes distance. The power supplied only fluctuates slightly between 0.8 AU. to 1.00 AU. Duty cycle from 50 % to 80 % is identified as the range that able to produce more stable arc discharge as the fluctuations of power supplied is small.

According to Figure 4.9, electrodes at distance 2 mm shows the best characteristics to produce arc discharge compare to distance at 4 mm and 6 mm. This deduction is supported with the observation for duty cycle of 40 % and above, stable arc discharge can be produced. Whereas for distance 4 mm and 6 mm, minimum duty cycle as high as 50 % need to obtained in order to produce more stable arc discharge. Distance of 2 mm provides a wider flexibility range to produce visible arc discharge.

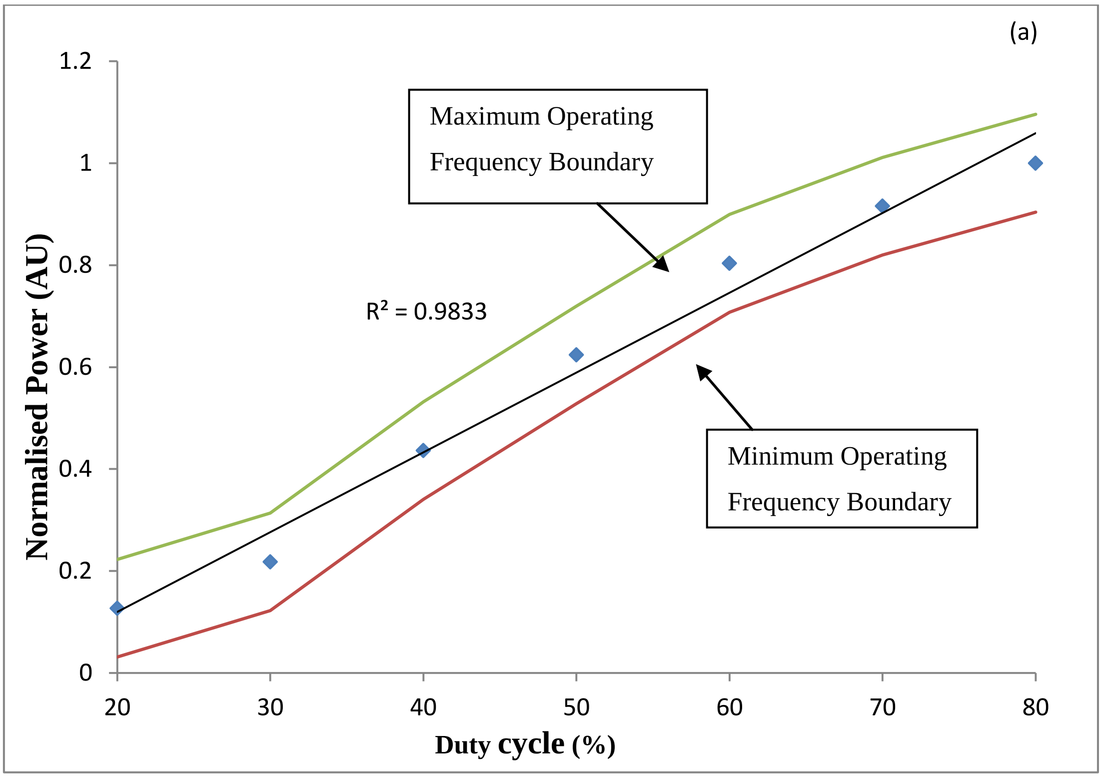
4.7 Data analysis

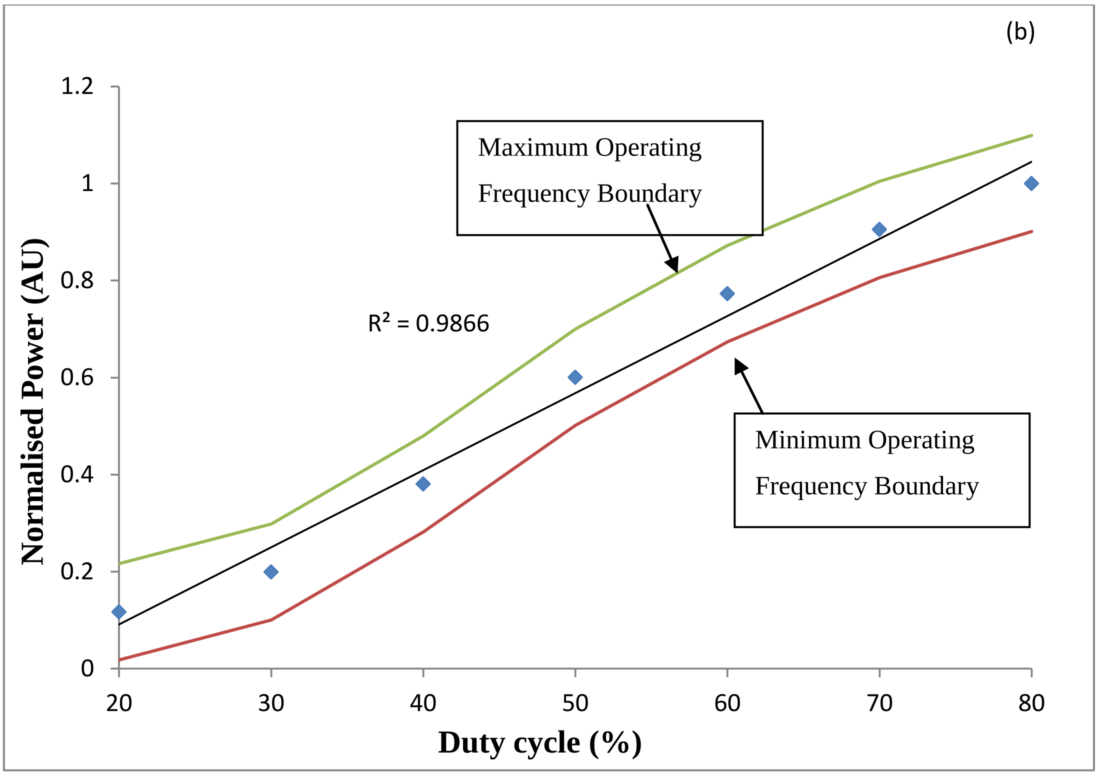
Interpretation and presentations on the data collected are done is several form to present a clearer and better understanding on the arc discharge system.

4.7.1 Normalised power versus duty cycle at different frequencies

Figure 4.8 which show the normalised power versus duty cycle at different frequencies is difficult to analyse in details due to the similarity characteristics of each frequency and formation of a pattern. The overlapping of every frequency makes it harder to analyse the data in details.

The data corresponding in Figure 4.8 have been analysed in a more general approach and shown in Figure 4.10.





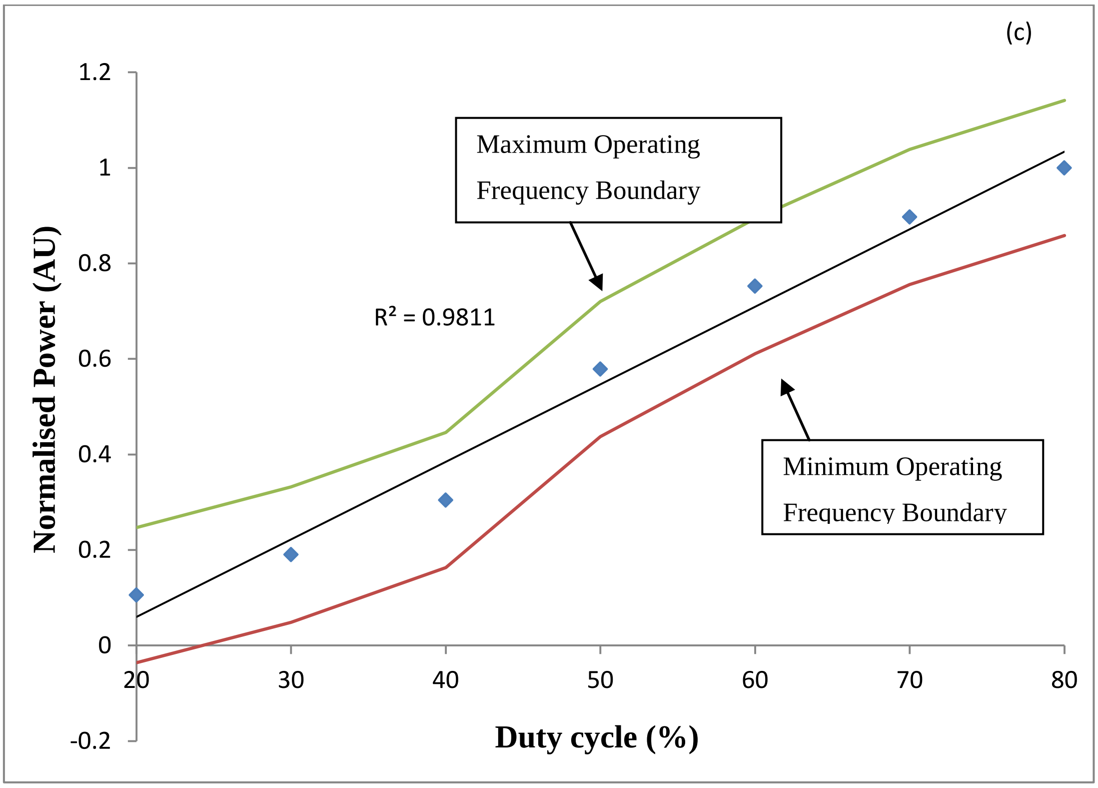


Figure 4.10: Normalised power versus duty cycle at electrodes distance of (a) 2 mm, (b) 4 mm, and (c) 6 mm

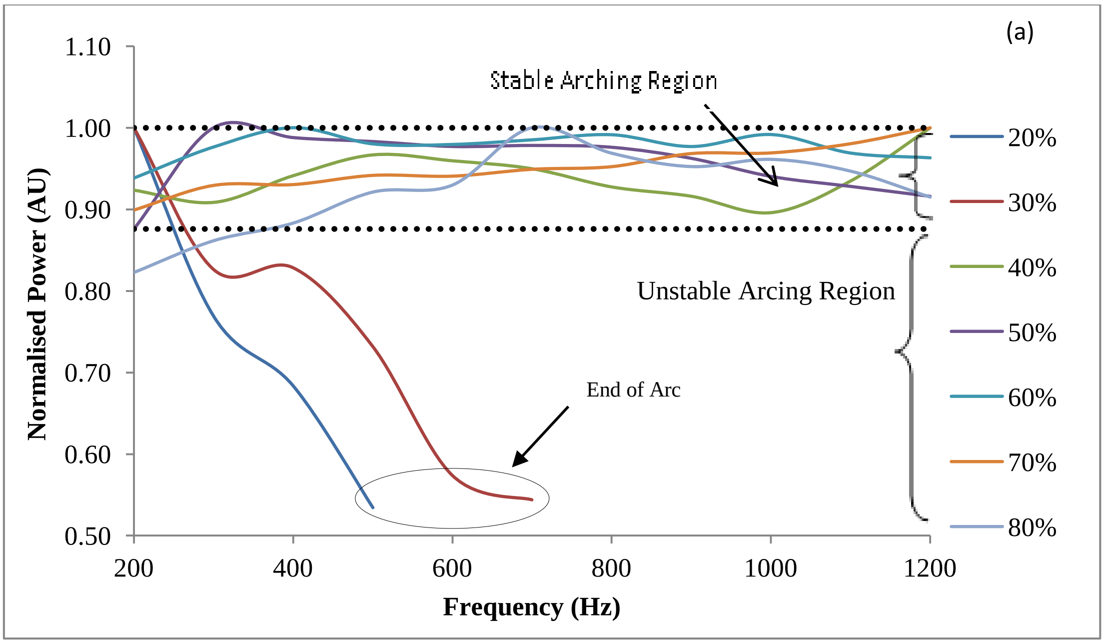
The average power of 11 data collected in the frequency range from 200 Hz to 1200 Hz is plotted. Figure 4.10 is plotted with indication of the average normalised power with maximum and minimum operating frequency boundary.

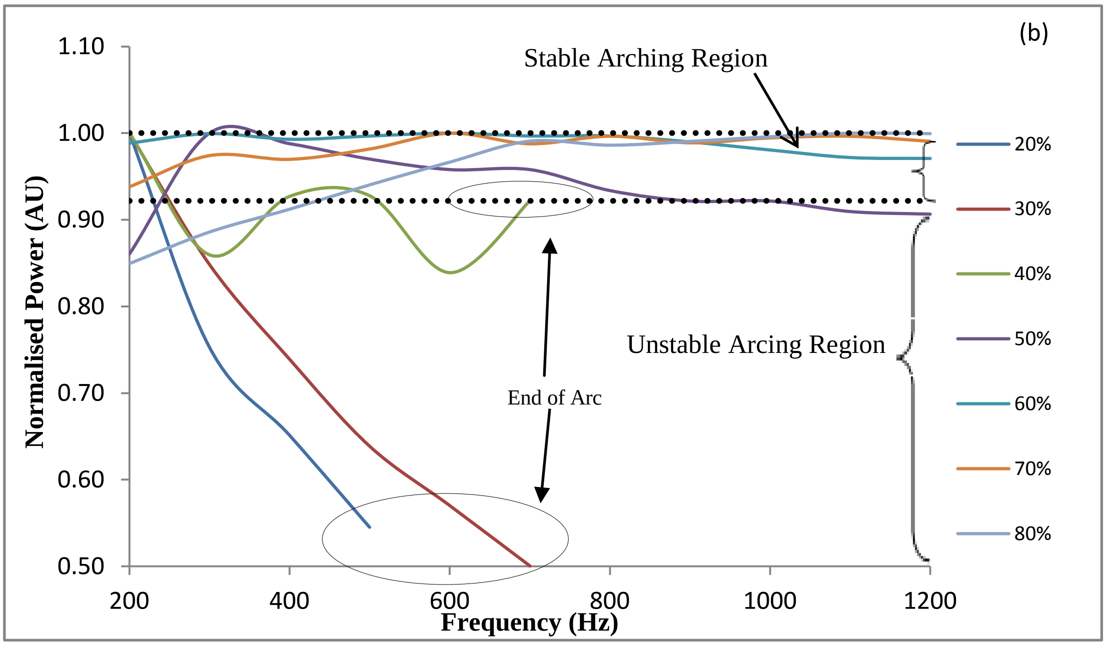
Arc discharge is produced in the operating frequency boundary giving a guideline limit to produce arc discharge. Higher frequency consumed more power input compare to lower frequency in order to produce arc discharge. An increasing trend of frequency with power is clearly observed.

Higher frequencies which indicate higher number of electron bombardment per unit time are definitely preferable to produce stable and strong arc discharge. Higher concentration of electrons bombardment per unit will induce more power thus creating more heat source for application purpose. Highest frequency based on the system limitations, 1200 Hz is chosen to be the optimum frequency.

4.7.2 Normalised power versus frequency at different duty cycle

The data corresponding to Figure 4.9 is being analysed and Figure 4.11 is plotted to assist in the analysis of the data into a deeper understanding.





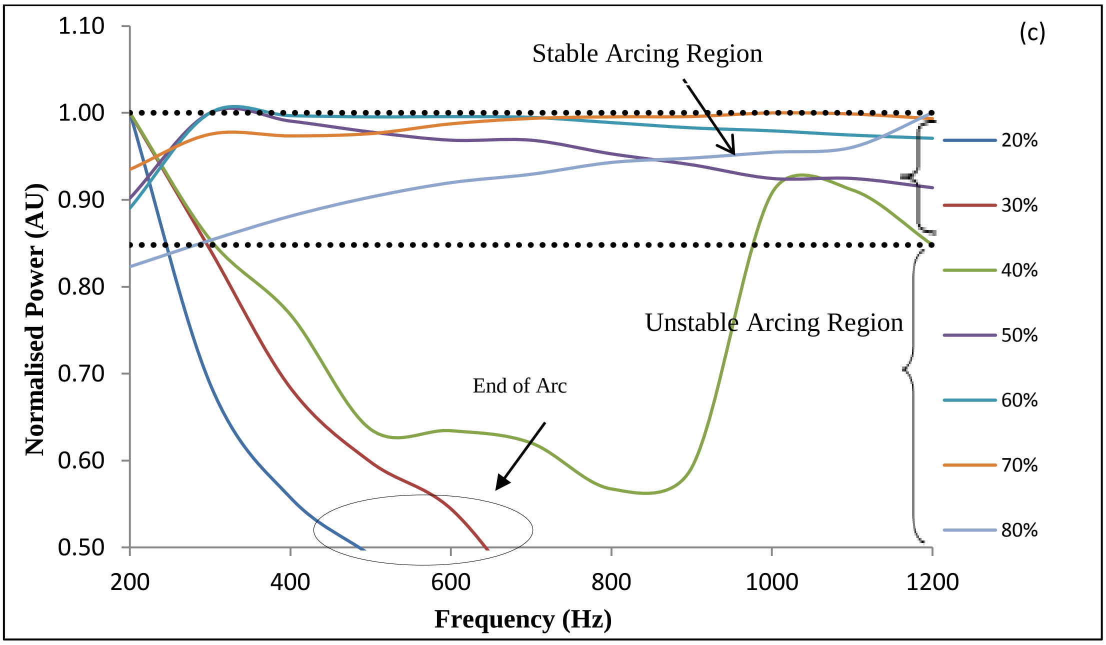


Figure 4.11: Normalised power versus frequency at electrodes distance of (a) 2 mm, (b) 4 mm, and (c) 6 mm

Figure 4.11 shows the normalised power versus frequency at different duty cycle with respect to electrodes distance at 2 mm, 4 mm and 6 mm. Region of stable and unstable arc discharge has been identified as shown in Figure 4. These regions can be used as guideline to operate arc discharge.

As observed for all distances (2 mm,4 mm and 6 mm) , duty cycle of 20 % and 30 % are unable to produce arc discharge at frequency of 500 Hz and 700 Hz respectively. The discharge time above 500Hz (20 % duty cycle) and 700 Hz (30% duty cycle) is too short to produce arc discharge.

Whereas at duty cycle of 40 %, the power characteristic of the arc discharge varies for all distance. At 2 mm, arc discharge can be observed for all range of frequencies but when the distance increase to 4 mm, the arc discharge ends at 700 Hz. Frequency higher than 700 Hz for distance 4 mm unable to produce arc discharge. As for distance of 6 mm, arc discharge can be observed for all range of frequency but the power characteristics of the visible arc discharge appeared to be very unstable. Arc discharge at duty cycle of 40 % is unstable at 4 mm and 6 mm of the electrodes gap.

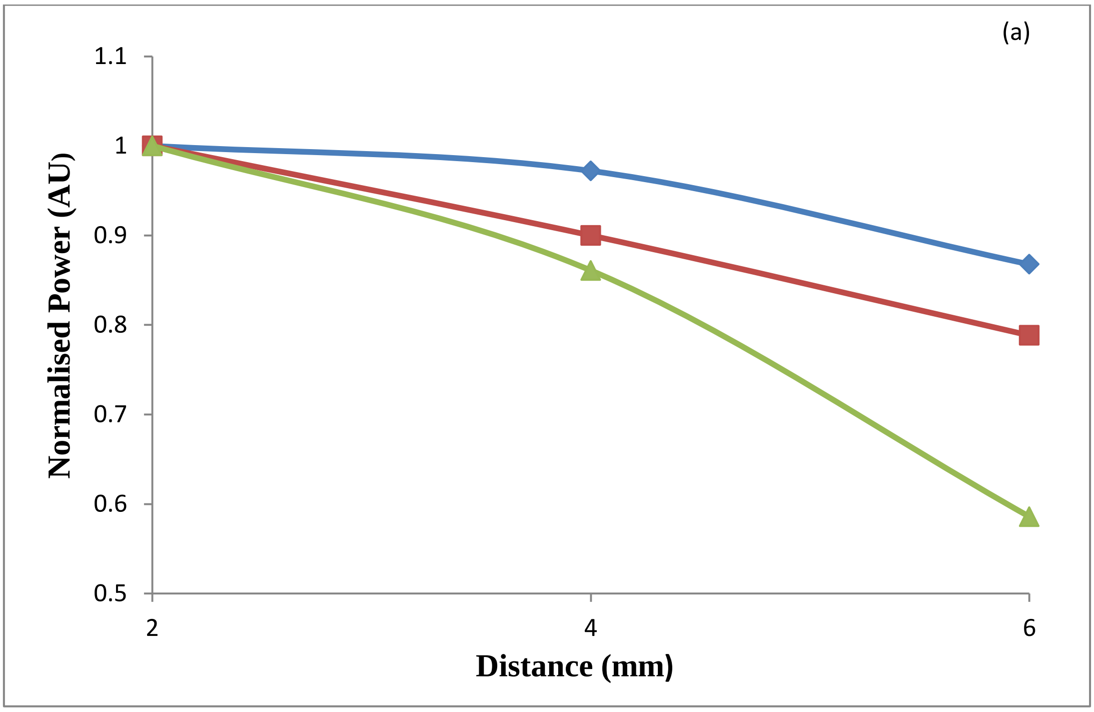
Starting from duty cycle of 50 % and above, arc discharge can be observed for all range of frequency and stability of arc discharge has attained. Nevertheless, the power input is higher in order to produce stable arc discharge. Duty cycle of 50 % is the threshold percentage of duty cycle towards stable arc discharge effect.

Duty cycle of 20 % and 30 % are not suitable to produce stable arc discharge for application purpose due to the characteristics of dark discharge observed at higher frequency. Data collected for duty cycle 40 % are not convinced to produce good arc discharge because of the observed fluctuations power supplied and production of invisible arc discharge. Range of duty cycle from 50% to 80% able to produce stronger arc discharge as the changes of power supplied is small and show good characteristics in the power supplied.

Stable arching region for electrode distance at 2 mm is from 0.88 AU. to 1.00 AU. whereas, for electrodes distance at 4 mm is 0.93 AU. to 1.00 AU. Electrodes distance at 6 mm provides the widest range of stable arching region which is from 0.85 AU. to 1.00 AU.

However the optimized electrodes distance is still maintained as 2 mm as discussed in Section 4.6. The difference in stable arcing region for electrodes at distance 2 mm and 6 mm is only of small range at 0.03 AU. The argument at Section 4.6 is more vital in providing wider range of selection in producing stable arc discharge.

4.8 Stability of arc discharge



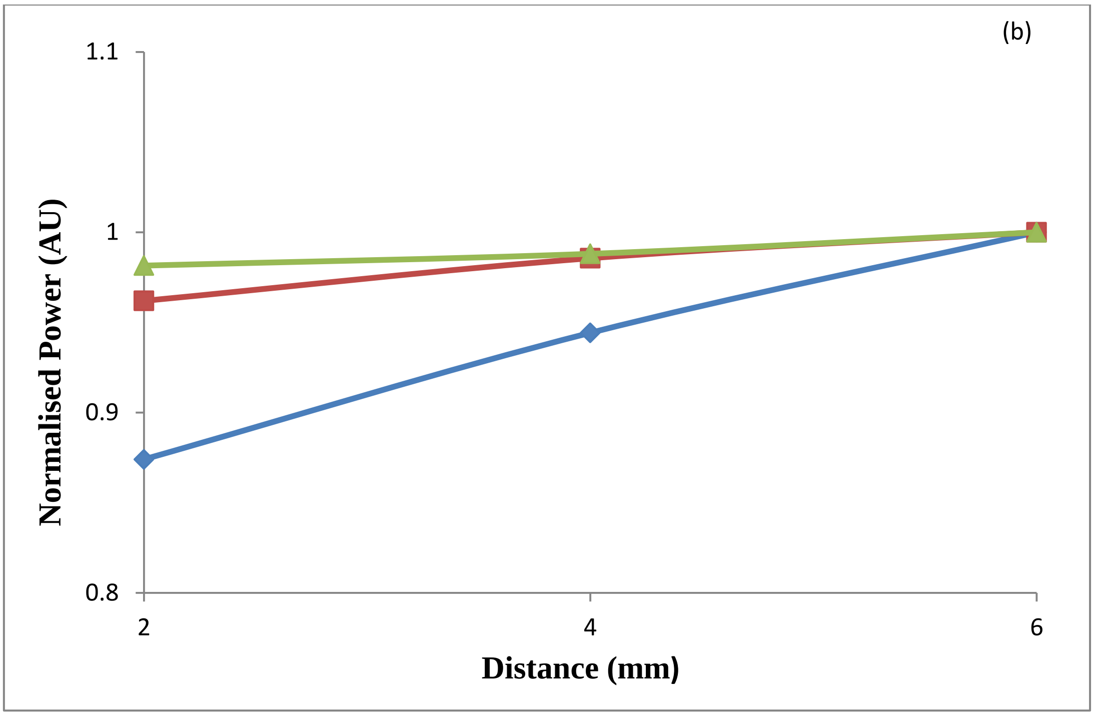


Figure 4.12 : Normalised power versus distance for (a) unstable arc discharge and (b) stable arc discharge

Figure 4.12 shows the trend for both unstable and stable arc in relation to electrodes distance at 2 mm, 4 mm and 6 mm. Stability of an arc discharge is difficult to judge through observations by naked eyes. Data collected are analysed and the characteristics of the stability arc discharge are determined. Stability of the arc discharge is determined with the power characteristics in relation to variable in distance where frequency and duty cycle is fixed.

An increase in distance will require more power input to assist the electrons to jump a further distance. This hypothesis is valid for stable arc discharge. Stable arc discharge can be determined with the characteristics in increasing power input with increasing distance which is in line with the hypothesis. Stable arc discharge is also being supported by the long discharge time which allows the duration of electron bombardment per unit period is longer. Thus this leads to higher number of electrons bombardment which draws more input power.

Unstable arc has a decrease power trend against increasing distance due to the power drawn which is insufficient to produce stable arc discharge. This condition occurs when the discharge time is too short for stable arc discharge to perform. Short discharge time is unable to support in the production of stable arc discharge because the electron bombardment per unit period too low.

2 mm is the optimum distance based on the parameters chosen to apply into application. The power consumption to achieve stable arc discharge is lower compare to further distance. At shorter distance the concentration of electrons at any point in the gap will be higher which will leads to even stronger arc discharge.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The design of the circuitry arc system is successfully feasible and able to produce arc discharge. Arc discharge system had been characterised based on frequency, duty cycle and distance between the electrodes. Optimum parameters to produce stable arc discharge are found to be at electrode distance at 2 mm, frequency of 1200 Hz and duty cycle of 50 % and above. Duty cycle of 50 % is the threshold frequency towards stable arc discharge. Discharge time is identified to affect the production of arc discharge. Discharge time of 0.0004 s is the minimum limit to produce arc discharge.

5.2 Future Improvements

There are no limitations on how far this project may go in the future. It would be interesting to further extent the study in characterisation of arc system into the cross-sectional area of the arc column and brightness of the arc discharge. A microscope can be used to monitor the sectional area as it difficult to observe with human naked eyes. The characteristics of arc discharge can be characterised under different gas as well where different effects can be observed.

Arc system is a low cost high power system which can be further benefits into applications. Based on the experiment setup where the distance between the electrodes is in millimetre, it would be suitable to extend the study on arc discharge system as a fusion heat source for fused fiber components in characterising the diameter profile of the fiber. Arc discharge system can be used to fabricate the micro fiber sensor which is suitable to monitor and detect changes in the water quality.

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APPENDICES

APPENDIX A: Raw data for electrode at distance 2mm.

Table I: Raw data for distance 2mm in variation of frequency and duty cycle

Frequency (Hz)	Duty cycle (%)						
	20	30	40	50	60	70	80
200	6.6767	11.7607	18.0310	24.0050	32.4157	36.3943	37.4957
300	5.1347	9.7183	17.7383	27.4053	33.7267	37.6197	39.2693
400	4.5637	9.7427	18.3783	27.0733	34.5403	37.6607	40.2567
500	3.5670	8.6080	18.8767	26.9410	33.8580	38.1180	41.9890
600	-	6.7483	18.7353	26.7737	33.8340	38.0797	42.3810
700	-	6.3957	18.5450	26.8090	34.0293	38.4193	45.5877
800	-	-	18.1087	26.7480	34.2433	38.5513	44.1627
900	-	-	17.8853	26.3763	33.7470	39.2013	43.4140
1000	-	-	17.4919	25.7693	34.2523	39.2340	43.8183
1100	-	-	18.2500	25.4347	33.4720	39.6903	43.1600
1200	-	-	19.5260	25.1000	33.2693	40.4800	41.7073

(-) dark discharge.

Table II : Normalised power in respect to frequency with variations in duty cycle

Duty cycle (%)	**Frequency (Hz)**						
	20	**30**	**40**	**50**	**60**	**70**	**80**
200	0.1781	0.3137	0.4809	0.6402	0.8645	0.9706	1.0000
300	0.1308	0.2475	0.4517	0.6979	0.8589	0.9580	1.0000
400	0.1134	0.2420	0.4565	0.6725	0.8580	0.9355	1.0000
500	0.0850	0.2050	0.4496	0.6416	0.8064	0.9078	1.0000
600	-	0.1592	0.4421	0.6317	0.7983	0.8985	1.0000
700	-	0.1403	0.4068	0.5881	0.7465	0.8428	1.0000
800	-	-	0.4100	0.6057	0.7754	0.8729	1.0000
900	-	-	0.4120	0.6076	0.7773	0.9030	1.0000
1000	-	-	0.3992	0.5881	0.7817	0.8954	1.0000
1100	-	-	0.4228	0.5893	0.7755	0.9196	1.0000
1200	-	-	0.4682	0.6018	0.7977	0.9706	1.0000

(-) dark discharge

Table III : Normalised power in respect to duty cycle in variation of frequency

Frequency(Hz)	**Duty Cycle (%)**						
	20	**30**	**40**	**50**	**60**	**70**	**80**
200	1.0000	1.0000	0.9234	0.8759	0.9385	0.8991	0.8225
300	0.7690	0.8263	0.9084	1.0000	0.9764	0.9293	0.8614
400	0.6835	0.8284	0.9412	0.9879	1.0000	0.9304	0.8831
500	0.5342	0.7319	0.9667	0.9831	0.9802	0.9417	0.9211
600	-	0.5738	0.9595	0.9770	0.9796	0.9407	0.9297
700	-	0.5438	0.9498	0.9782	0.9852	0.9491	1.0000
800	-	-	0.9274	0.9760	0.9914	0.9524	0.9687
900	-	-	0.9160	0.9625	0.9770	0.9684	0.9523
1000	-	-	0.8958	0.9403	0.9917	0.9692	0.9612
1100	-	-	0.9347	0.9281	0.9691	0.9805	0.9467
1200	-	-	1.0000	0.9159	0.9632	1.0000	0.9149

(-) dark discharge

APPENDIX B: Raw data for electrode at distance 4 mm.

Table IV: Raw data for distance 4mm in variations of frequency and duty cycle

Frequency (Hz)	Duty cycle (%)						
	20	**30**	**40**	**50**	**60**	**70**	**80**
200	6.3603	11.4287	17.3133	23.6523	33.1800	37.1460	38.2843
300	4.7877	9.6937	14.8833	27.4900	33.5453	38.5700	39.9283
400	4.1423	8.4443	16.0500	27.1560	33.3263	38.3990	41.1180
500	3.4673	7.2973	16.0607	26.6667	33.4530	38.8700	42.3870
600	-	6.5150	14.5277	26.3333	33.5650	39.5907	43.5740
700	-	5.7200	15.9630	26.3333	33.4560	39.1093	44.6660
800	-	-	-	25.6667	33.4560	39.4577	44.4563
900	-	-	-	25.3333	33.2247	39.1547	44.6533
1000	-	-	-	25.3333	32.9120	39.3790	44.8947
1100	-	-	-	25.0000	32.6190	39.4527	45.0800
1200	-	-	-	24.9167	32.5833	39.2210	45.0567

(-) dark discharge

Table V: Normalised power in respect to frequency with variations in duty cycle

Frequency (Hz)	**Duty cycle (%)**						
	20	30	40	50	60	70	80
200	0.1661	0.2985	0.4522	0.6178	0.8667	0.9703	1.0000
300	0.1199	0.2428	0.3728	0.6885	0.8401	0.9660	1.0000
400	0.1007	0.2054	0.3903	0.6604	0.8105	0.9339	1.0000
500	0.0818	0.1722	0.3789	0.6291	0.7892	0.9170	1.0000
600	-	0.1495	0.3334	0.6043	0.7703	0.9086	1.0000
700	-	0.1281	0.3574	0.5896	0.7490	0.8756	1.0000
800	-	-	-	0.5773	0.7526	0.8876	1.0000
900	-	-	-	0.5673	0.7441	0.8769	1.0000
1000	-	-	-	0.5643	0.7331	0.8771	1.0000
1100	-	-	-	0.5546	0.7236	0.8752	1.0000
1200	-	-	-	0.5530	0.7232	0.8705	1.0000

(-) dark discharge

Table VI: Normalised power in respect to duty cycle with variations in frequency

Frequency (Hz)	Duty Cycle (%)						
	20	**30**	**40**	**50**	**60**	**70**	**80**
200	1.0000	1.0000	1.0000	0.8604	0.9885	0.9383	0.8493
300	0.7527	0.8482	0.8596	1.0000	0.9994	0.9742	0.8857
400	0.6513	0.7389	0.9270	0.9879	0.9929	0.9699	0.9121
500	0.5451	0.6385	0.9276	0.9700	0.9967	0.9818	0.9403
600	-	0.5701	0.8391	0.9579	1.0000	1.0000	0.9666
700	-	0.5005	0.9220	0.9579	0.9968	0.9878	0.9908
800	-	-	-	0.9337	0.9968	0.9966	0.9862
900	-	-	-	0.9215	0.9899	0.9890	0.9905
1000	-	-	-	0.9215	0.9805	0.9947	0.9959
1100	-	-	-	0.9094	0.9718	0.9965	1.0000
1200	-	-	-	0.9064	0.9708	0.9907	0.9995

(-) dark discharge

APPENDIX C: Raw data for electrode at distance 6 mm.

Table VII: Raw data for distance 6mm with variation in frequency and duty cycle

Frequency (Hz)	Duty Cycle (%)						
	20	**30**	**40**	**50**	**60**	**70**	**80**
200	6.3083	11.6047	17.5133	23.9920	29.9613	37.3313	39.2687
300	4.3387	9.7750	14.9600	26.6060	33.6463	38.9467	40.7163
400	3.5140	7.9323	13.4483	26.3550	33.5380	38.8700	42.0420
500	3.0957	6.9410	11.1380	26.0203	33.4923	38.9760	43.0910
600	-	6.3163	11.1093	25.7693	33.5013	39.4233	43.8820
700	-	5.0113	10.8623	25.7693	33.4723	39.6703	44.3430
800	-	-	9.9360	25.3510	33.2697	39.7460	44.9920
900	-	-	10.3647	25.0163	33.0667	39.7600	45.2333
1000	-	-	15.8967	24.5980	32.9510	39.9257	45.5493
1100	-	-	15.9590	24.5980	32.7850	39.8750	45.8233
1200	-	-	14.8533	24.3147	32.6627	39.6617	47.7177

(-) dark discharge

Table VIII: Normalised power in respect to frequency with variations in duty cycle

Frequency (Hz)	**Duty Cycle (%)**						
	20	**30**	**40**	**50**	**60**	**70**	**80**
200	0.1606	0.2955	0.4460	0.6110	0.7630	0.9507	1.0000
300	0.1066	0.2401	0.3674	0.6534	0.8264	0.9565	1.0000
400	0.0836	0.1887	0.3199	0.6269	0.7977	0.9246	1.0000
500	0.0718	0.1611	0.2585	0.6038	0.7772	0.9045	1.0000
600	-	0.1439	0.2532	0.5872	0.7634	0.8984	1.0000
700	-	0.1130	0.2450	0.5811	0.7549	0.8946	1.0000
800	-	-	0.2208	0.5635	0.7395	0.8834	1.0000
900	-	-	0.2291	0.5531	0.7310	0.8790	1.0000
1000	-	-	0.3490	0.5400	0.7234	0.8765	1.0000
1100	-	-	0.3483	0.5368	0.7155	0.8702	1.0000
1200	-	-	0.3113	0.5096	0.6845	0.8312	1.0000

(-) dark discharge

Table IX: Normalised power in respect to duty cycle with variations of frequency

Frequency (Hz)	Duty Cycle (%)						
	20	**30**	**40**	**50**	**60**	**70**	**80**
200	1.0000	1.0000	1.0000	0.9018	0.8905	0.9350	0.8229
300	0.6878	0.8423	0.8542	1.0000	1.0000	0.9755	0.8533
400	0.5570	0.6835	0.7679	0.9906	0.9968	0.9736	0.8811
500	0.4907	0.5981	0.6360	0.9780	0.9954	0.9762	0.9030
600	-	0.5443	0.6343	0.9686	0.9957	0.9874	0.9196
700	-	0.4318	0.6202	0.9686	0.9948	0.9936	0.9293
800	-	-	0.5673	0.9528	0.9888	0.9955	0.9429
900	-	-	0.5918	0.9403	0.9828	0.9959	0.9479
1000	-	-	0.9077	0.9245	0.9793	1.0000	0.9546
1100	-	-	0.9112	0.9245	0.9744	0.9987	0.9603
1200	-	-	0.8481	0.9139	0.9708	0.9934	1.0000

(-) dark discharge

APPENDIX D: Discharge time

Table X : Conversion into discharge time

Discharge time can be obtained using equation I as shown below.

$$T = \frac{1}{f} \times \alpha \qquad \text{(I)}$$

where,

T = discharge time

f = frequency

α = duty cycle

Frequency (Hz)	**Duty cycle (%)**						
	20	**30**	**40**	**50**	**60**	**70**	**80**
200	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040
300	0.0007	0.0010	0.0013	0.0017	0.0020	0.0023	0.0027
400	0.0005	0.0008	0.0010	0.0013	0.0015	0.0018	0.0020
500	0.0004	0.0006	0.0008	0.0010	0.0012	0.0014	0.0016
600	0.0003	0.0005	0.0007	0.0008	0.0010	0.0012	0.0013
700	0.0003	0.0004	0.0006	0.0007	0.0009	0.0010	0.0011
800	0.0003	0.0003	0.0005	0.0006	0.0008	0.0009	0.0010
900	0.0002	0.0003	0.0004	0.0006	0.0007	0.0008	0.0009
1000	0.0002	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008
1100	0.0002	0.0003	0.0004	0.0005	0.0005	0.0006	0.0007
1200	0.0002	0.0003	0.0003	0.0004	0.0005	0.0006	0.0007