HYDROGEN GAS HARVESTING FOR ELECTRICITY ENERGY

By

Zulfahmie bin Jalauddin

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Electrical & Electronics Engineering)

SEPTEMBER 2011

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Hydrogen Gas Harvesting For Electricity Energy

By

Zulfahmie bin Jalauddin

A project dissertation submitted to

Electrical and Electronics Engineering Programme

Universiti Teknologi PETRONAS

in partial fulfillment of the requirements for the

BACHELOR OF ENGINEERING (Hons)

(ELECTRICAL AND ELECTRONICS ENGINEERING)

Approved:

Dr. Nursyarizal Mohd Nor

Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

SEPTEMBER 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

ZULFAHMIE BIN JALAUDDIN

ACKNOWLEDGEMENT

First and foremost, the author would like to express the deepest gratitude to Allah S.W.T for giving me strength and with His blessing the author managed to complete the Final Year Project.

The author would like to express greatest appreciation to his supervisor Dr Nursyarizal Mohd Nor for giving support and guidance by means of sharing their thought and knowledge throughout the project completion.

Many thanks and appreciation also go to Universiti Teknologi PETRONAS especially Electrical and Electronics Engineering Department that have contributed directly and indirectly by providing the necessary assets and resources to the success of this Final Year Project.

Last but not least, the author would like to express a special thank to his friends and family members for their priceless support, encouragement, valuable advices, and their understanding. Without all of them, the author would not go further like where his standing right now. Thank you so much.

ABSTRACT

Nowadays, the temperature of the world is rising due to the increasing concentrations of greenhouse gases, which cause from by human activities such as the combustion of the fossil fuel. As we know, a lot of the plants, vehicles, machines, electrical and electronics appliances need the source of energy either from the fossil fuel or the other energy sources to operate. The global warming issue can be prevented if we provide the alternative source of energy to reduce the usage of the current source of energy. So, the aim of this project is to use the fuel cell concept to generate electricity from the hydrogen gas. This project will use the hydrogen gas produced from the hydrolysis of water process by using solar electrolyzer and to be converted to the electrical energy by using the fuel cell system. The electrical energy produced can be used direct power supply or as a backup power supply. The design of this project involves the green technology which is fuel cell, solar electrolyzer and ultra capacitor that convert the hydrogen gas to the electrical energy. Based on the fuel cell theory the current and voltage is created by using the special membrane that only allow the hydrogen ion to travel through it and the electron will travels through an electrical wire to produce the electrical energy. This project uses the Polymer Electrolyte Membrane Fuel Cell (PEMFC) unit to convert the hydrogen gas to the electricity. There are two storage of the electrical energy which are storing the hydrogen gas and also the ultra capacitor. The ultra capacitor can be used as the secondary backup supply when the storage of hydrogen gas is empty. This project is the new innovation where it can produce the hydrogen gas itself and the gas produced can directly be used to generate electricity with having the backup supply from the ultra capacitor. The multifunction of this design make it can be applied to many applications especially for the vehicles, machine, electrical and electronic appliances that need continuous power supply like the air pump in the fish pond and solar hybrid car. This green innovation is the absolutely clean with no emission of the greenhouse gas and become one of the unique alternative energy.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABREVIATIONS

PEMFC	Polymer Electrolyte Membrane Fuel Cell
PEM	Polymer Electrolyte Membrane
FYP	Final Year Project
EMF	Electromagnetic Field
MEA	Membrane Electrode Assembly
DC	Direct Current
AFC	Alkaline Fuel Cell
DMFC	Direct Methanol Fuel Cell
SOFC	Solid Oxide Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
CAD	Computer Aided Design
LED	Light-Emitting Diode
PWM	Pulse Width Modulation
PIC	Programmable Integrated Circuit

CHAPTER 1

INTRODUCTION

1.1 Background of study

The major issue of the global warming is that the environment of the world becomes worst. A new innovation is really needed in order to reduce the emission of the greenhouse gas which leads to the climate change. Alternative energy is the best way to counter all of this issue. This project entitled Hydrogen Gas Harvesting for Electricity Energy will design a new innovation which produce the hydrogen gas and converts the hydrogen gas to the electrical energy at the same time. The energy produced will be used as a direct power supply or as a backup supply to the any machines, vehicles, electrical and electronic appliances. This green technology innovation will replace the usage of the fossil fuel and current battery to the hydrogen gas which is cleaner to the environment. Many companies like Motorola, NEC, Casio, Toshiba, Fuji, Intel, MTI, ISE and Polyfuel are seeking miniature fuel cell as a replacement of traditional electrochemical batteries [1]. Fuel cells are an efficient and non-polluting power source producing little noise. Fuel used in fuel cell provides much higher power density compare to batteries [2].

The hydrogen gas is produced from the water hydrolysis where the solar is used as energy source to perform the hydrolysis process. By using the fuel cell, the hydrogen gas will be converted to the electrical energy. In particular, proton exchange membrane (PEMFC), also known as polymer electrolyte membrane fuel cell, is considered to be more developed than other fuel cell technologies [3]. The fuel cell is design in stack, so by add up the stack of fuel cell yielding a voltage that is large enough for practical applications [4]. The ultra capacitor is used to store the energy and also will function as a backup supply when the storage of the hydrogen gas is empty.

This project will design a circuit to produce the hydrogen gas and control the output voltage. There are three main parts which are the solar electrolyzer circuit, PEMFC circuit and the ultra capacitor circuit. The prototype model design of this project is based on the ability to produced efficient electricity. The factors that affect the performance and efficiency of the PEMFC also will be determined to ensure it is applicable to the applications used in this project.

1.2 Problem statement

Every year a lot of manufacturers produce new vehicles, electrical and electronic appliances to make our life easier. All of these products are really dependent to the fossil fuel and electricity as a source of energy. This will increase the emission of the green house gas which is very dangerous for us especially to the environment of the world. Therefore, new approach is required to improve the alternative energy in order to replace the current energy source in order to save our world.

Nowadays, a lot of alternative energy has been produced to reduce the usage of the fossil gas but only minority of people are fully utilized this alternative energy. Even though the alternative energy maybe expensive compared to the current source of energy but it make the environment safe and clean. By improvising the available fuel cell by adding special features and design, it will encourage people to use it since it only use water as a source of hydrogen and oxygen gas to produce electricity. Thus, this can be the best alternative to produce clean energy without affecting the environment.

For this new innovation it can be used as a power supply and also the backup supply in critical case at the same time. This innovation focuses to those who require the continuous power supply. The application of the power supply produced by this innovation can be used to the solar hybrid car and air pump for the fish pond and also for the electronics appliances such as mobile phone. This is the first portable power supply that has two backup supplies which are hydrogen gas and the ultra capacitor. Thus, this green innovation is the absolutely clean with no emission of the greenhouse gas and become one of the efficient alternative energy.

1.3 Objectives

Some objectives set and satisfy the scopes of study that have been highlighted, which are relevant to the requirement to complete the FYP. The objectives of this project are as follows:

1. To investigate factors that affects the performance and efficiency of PEMFC.

2. Design the portable prototype model using the PEMFC and solar electrolyzer.

3. Design the application model for the air pump for the fish pond and motor for the solar hybrid car.

1.4 Scope of study

The scope of study will consists of three major parts which are:

1. Research and survey on the fuel cell unit application. The research is to give some ideas and relevant solutions to create and improve new application especially for the green technology.

2. The experimental work is analysis, data gathering and identifying the processes and disturbance model of the application.

3. Design the prototype model to operate with high efficiency and performance.

CHAPTER 2

LITERATURE REVIEW

2.1 Fuel Cell Theory

Fuel cell is the electrochemical cell that uses hydrogen gas to convert the chemical reaction directly to the electrical energy. The components of a fuel cell consist of an electrolyte layer, electrodes and conductor wire. The electrolyte is assembled together in between the anode and cathode electrode. Figure 1 shows the diagram of a fuel cell with the reactant gases which are hydrogen and oxygen gas and ion flow directions through the cell.

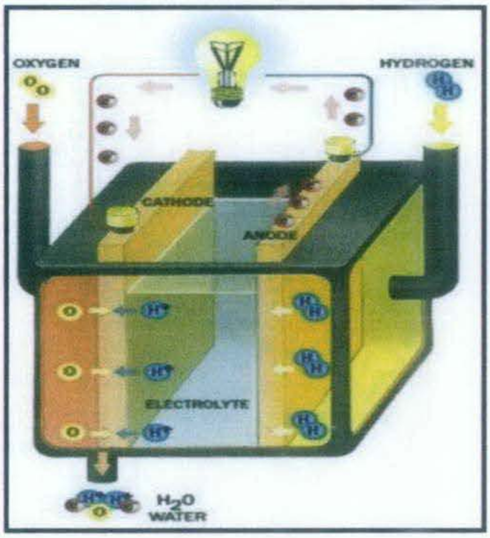

Figure 1: Fuel cell unit [5]

In the fuel cell, gaseous fuel which is hydrogen gas is fed continuously to the anode which is the negative electrode and oxygen gas from air is fed continuously to the cathode which is the positive electrode. At these two electrodes, the electrochemical reactions will occur to produce an electrical power and water. The higher concentrations and pressure of gaseous fuels are fed into the cell, the higher voltage can be generated. Figure 2 shows the effect of different pressure given to the fuel cell. The voltage drop increases when the pressure of hydrogen gas increases for the certain limit to avoid the electrolyte layer from damage.

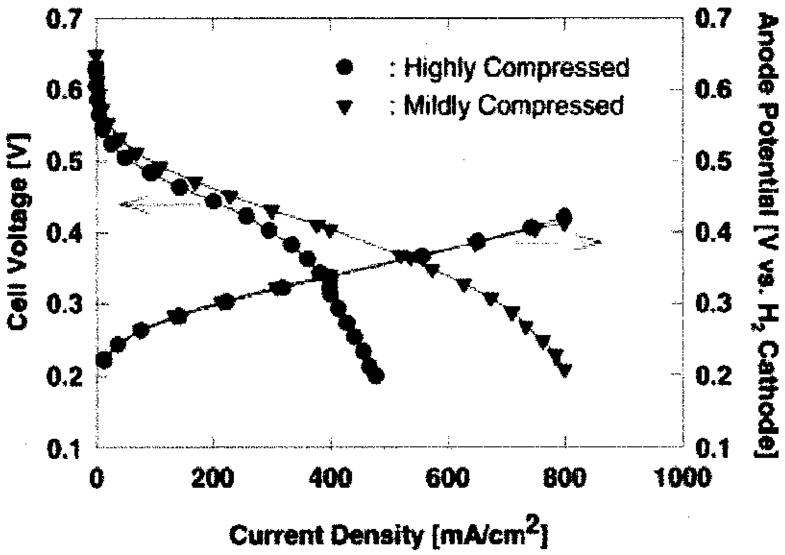

Figure 2: Effects of pressure on the cell [6]

The equation to calculate the voltage can be obtained from the Nernst equation:

$$E = E^{\circ} + \frac{RT}{2F}\ln\left(\frac{\alpha\beta^{\frac{1}{2}}}{\delta}P^{\frac{1}{2}}\right)$$

$$E = E^{\circ} + \frac{RT}{2F}\ln\left(\frac{\alpha\beta^{\frac{1}{2}}}{\delta}P^{\frac{1}{2}}\right) + \frac{RT}{4F}\ln P$$

(1)

Where

R= Gas constant = 8.314 J/mol·K

F = Faraday constant = 96485 C / mol

T =Temperature in Kelvin = 25+273 = 298K

E^0 is the electromagnetic field (EMF), 1.229V at standard pressure and P is the pressure of the system. The symbol of α, β and δ are the constant that depend on the molar masses and concentrations of hydrogen gas, H_2, oxygen gas, O_2 and water, H_2O. From the equation above, it shows that the fuel cell depends on the concentration and pressure of the hydrogen gas flow. If the partial pressure of O_2 and H_2O are unchanged and the H_2 partial pressure changes pressure change from the cathode to the anode, we can determine the above formula to be approximately as [6]:

$$\Delta V = \frac{RT}{2F} \ln\left(\frac{P_2}{P_1}\right) \tag{2}$$

Where

ΔV= Voltage drop

R= Gas constant = 8.314 J/mol·K

F = Faraday constant = 96485 C / mol

T =Temperature in Kelvin = 25+273 = 298K

P_2/P_1= Pressure change from the cathode to the anode

The voltage is produced from the electrochemical reaction in the fuel cell by splitting the hydrogen molecule to the positive ion hydrogen, H^+ and electrons, e^-. These electrons will flow from anode to cathode through the conductor wire to produce electricity to the load. There are many type of fuel cells available in the market such as Alkaline Fuel Cell (AFC), Molten Carbonate Fuel Cell and Direct Methanol Fuel Cells (DMFC) and Polymer Electrolyte Membrane Fuel Cell (PEMFC). Although all fuel cells are electrochemical energy conversion devices and operate on similar principle, each fuel cell type mentioned earlier has different operating characteristics, different materials of construction, different range of operating temperatures, and different applications [7] [8].

2.2 Polymer Electrolyte Membrane Fuel Cell (PEMFC)

Polymer Electrolyte Membrane Fuel Cell (PEMFC) is also known as Proton Exchange Membrane Fuel Cell. In particular, among the available fuel cells, PEMFC fuel cells offer excellent features, such as compact structure, high power density, solid electrolyte, low-operating temperature (50^0C–100^0C), relatively fast start-up, low sensitivity to orientation, favourable power-to-weight ratio, long cell and stack life and low corrosion [9] [10].

As one of the type of fuel cells, it produces electricity energy from the chemical reaction of the hydrogen gas in the cell. The structure of PEMFC is similar to the other fuel cells which have two electrodes coated with the platinum catalyst separated by a polymer electrolyte membrane (PEM) in the middle. The combination of the electrodes and the PEM is called as membrane electrode assembly (MEA).

The function of platinum catalyst is to split the hydrogen gas molecule into hydrogen ions and electrons. It is very stable and will not easily oxidized compare to the other noble metals such as nickel and silver. So, the output power of the PEMFC that uses the platinum catalyst is high due to its stability from oxidized. The chemical reaction that will occur at the anode and cathode electrode can be represented in the half reactions:

$$\text{Anode reaction: } 2H_2 \rightarrow 4H^+ + 4e^- \quad (3)$$

$$\text{Cathode reaction: } O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \quad (4)$$

At the anode, the hydrogen molecule is split into the hydrogen ions and electrons. The PEM will allow the hydrogen ions to flow from the anode to the cathode while the electron will flow through the external wire to produced electrical power. The hydrogen ions will combine with the oxygen gas and the electrons at the cathode to produce water.The PEM only allows the hydrogen ion, H^+ to pass through it while preventing the electron conduction. It is made from the

Nafion because of the effectiveness as a membrane. Nafion polymer has excellent chemical stability while at the same time allowing ion transport [11]. The process to split the hydrogen molecule is exothermic which produce heat. So, there is a limitation to the membrane performance because for Nafion the operating temperature is only from 50^0C -120^0C [8] [9].

2.3 PEMFC Solar Electrolyzer

Solar Electrolyzer is the device that performs the electrolysis process to produce hydrogen and oxygen gas from the water which also known as hydrolysis process. The function of PEMFC is not only produce electrical power but it also can be used to perform hydrolysis process to produce hydrogen gas. This device is called reversible PEMFC where it can produce hydrogen gas and generate electricity at the same device. By using a direct current (DC) supply to the anode and cathode, the hydrolysis of water can be done. We can use any DC supply such as battery and solar panel but to ensure no pollution occur it is better to used solar panel as a supply. The chemical reaction occurs during the hydrolysis process are:

$$\text{DC supply (solar)} + 2H_2O \rightarrow O_2 + 2H_2 \quad (5)$$

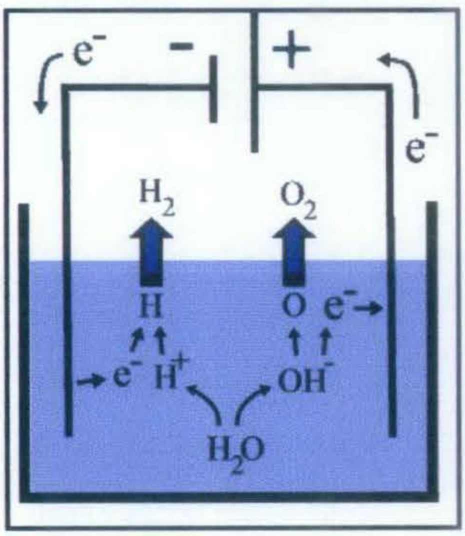

Figure 3: Hydrolysis of water

According to the Figure 3 above, the water molecule is split into positive hydrogen ion, H^+ and negative hydroxide ion, OH^- :

$$H_2O \rightarrow H^+ + OH^- \quad (6)$$

The electrodes polarity is different from the PEMFC because the supply is given to the electrodes. At the cathode the negative electrode, the electrons are pushed into the water and the hydrogen ion will attract to it to form hydrogen molecule. The combination of the two hydrogen molecules will produce hydrogen gas.

$$\text{Cathode reaction: } H^+ + e^- \rightarrow H \quad (7)$$

$$: H + H \rightarrow H_2 \quad (8)$$

At the anode the positive electrode, the extra electrons from the hydroxide ion are absorbed. The combination of four hydroxide molecules will produce oxygen gas and water.

$$\text{Anode reaction: } 4OH^- \rightarrow O_2 + 2H_2O + 4e^- \quad (9)$$

The hydrogen and oxygen gas produced will be stored into the storage tank so that it can be used by PEMFC to generate electrical power. Figure 3 below shows the storage of hydrogen and oxygen gas.

Figure 4: Gas storage tank

2.4 PEMFC Stack Efficiency

A PEMFC produces electical energy from the flow of the hydrogen gas through the MEA. The electrons produced from the chemical reaction will generate the current and voltage. By using only one stack of PEMFC , the voltage produced is very small. So, to achieve a higher voltage, many stack cells need to be connected in series just like battery series connection.

At zero current the voltage is the highest which is the open circuit voltage. Usually at the standard condition, the value for the hydrogen-oxygen couple is 1.23 V but under practical conditions the open-circuit potential will settle at values slightly below 1 V. To achieve a high output power of fuel cell stack, it should be operated at high current densities. However, the current cannot be increased at will, as the power output will reach a maximum due to the voltage drop. After this maximum the power output will decrease with increasing current. Figure 5 shows the characteristics of the performance of PEMFC. The maximum power of a PEMFC stack is highly dependent on the operating parameters [12].

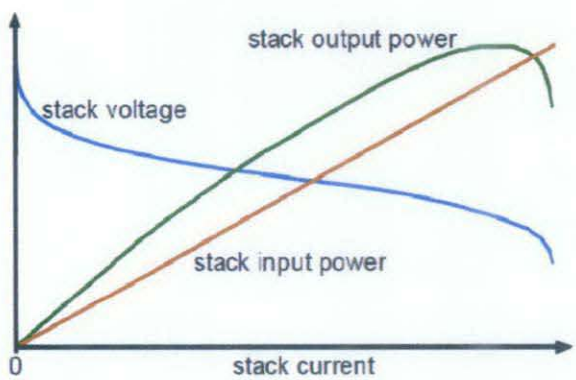

Figure 5: Stack voltage with input and output power [13]

The efficiency of a PEMFC can be defined as:

$$\eta = \frac{P_{OUT}}{P_{IN}} \tag{10}$$

$$\eta = \frac{V_{stack}\ x\ I_{stack}}{I_{stack}\ x\ N_C\ x\ 1.481}$$

(11)

Where

V_{STACK}= Stack voltage

I_{STACK}= Stack current

N_C = Number of stack

From the equation above, the number of the stack current, i_{stack} is in the numerator and denominator, so the efficiency become a function of stack voltage only [13].

$$\eta = \frac{V_{stack}}{N_C\ x\ 1.481}$$

(12)

There are many operating parameters that affect the performance and efficiency of PEMFC but the most critical parameters are:

A. Pressure feed air
B. Humidity of air

A. Pressure feed air

Air is provided to the fuel cell cathode at low pressure by a blower or at high pressure by an air compressor. When the pressure feed gas is high thereby the cell operating pressure is high too. Higher cell operating pressure results in more even distribution of the local current density due to the high oxygen concentration at the catalyst layer [14]. Increasing the pressure of the air improves the kinetics of the electrochemical reactions and leads to higher power density and higher stack efficiency [9]. However, a higher air flow rate means a higher power consumption of the air compressor, which influences the net power available [15]. So, the required pressure need to be determined in order to optimizes the overall PEMFC performance for each current density.

B. Humidity of air

Humidification of PEMFC is needed to prevent the electrolyte from drying out [16]. From the fuel cell reaction, the water will exist but it must be removed from the exhaust gas, stored, and pumped to a pressure suitable for the various operations [9]. A low air flow rate increases the humidity of the membrane, which decreases the electrical resistance and improves the performance of the fuel cell, while a high air flow rate increases the rate of water removal that causes drying of the membrane which increases the electrical resistance. However, a high air flow rate increases the availability of oxygen at the cathode membrane which improves the performance of the fuel cell [17] [18]. With the high humidity, the efficiency of the PEMFC decreases possibly due to the fuel cell beginning to flood and the quantity of oxygen gas available in the cell also decreases [16].

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

In order to achieve the objectives of the project, researches have been done on numerous resources including articles, journals and internet. The details of progress to finish this project can be referred to the APPENDIX A. The important activities need to be done during the FYP period are:

1. Defining problem:

   The emission of the green house gas is increasing every day. Majority of people still depend on the fossil fuel as a main source of energy. All of this leads to the global warming which is very dangerous for any living creatures in this world. So, this project will use the hydrogen gas as the fuel to produce electricity energy by using the PEMFC.

2. Research and analysis:

   The understanding of the fuel cell concept is very important in this project since the prototype model need to be designed to convert the chemical reaction of the hydrogen gas into the electrical energy. The research and analysis must be done properly in order to produce high performance power supply model. Besides, the criteria and specifications of the prototype model are constructed according to the size, performance, material, quality and the most important is the production of the green energy.

3. Results:

   From the prototype model design, the testing will be conducted to determine the efficiency and performance of the PEMFC to generate electrical energy to supply the load which is the air pump. The results will indicate whether the objective is achieved or not to produce electrical energy from the hydrogen gas.

3.2 Project Workflow

The workflow need to be done during this FYP period is shown in Figure 6. The objective of having this project workflow is to ensure that the prototype model is designed according to the plan.

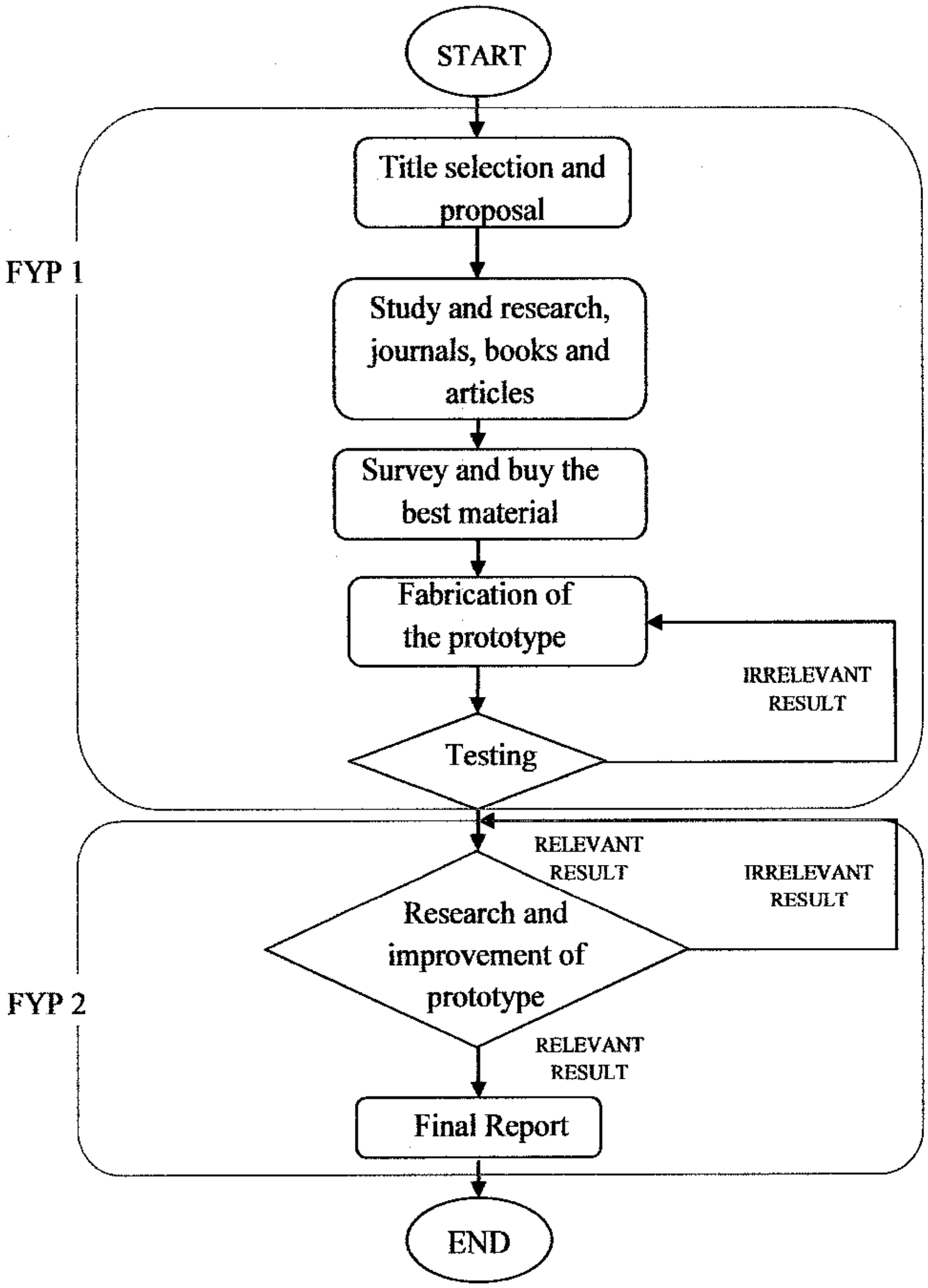

Figure 6: Project workflow

3.3 Tools and Equipments Required

3.3.1 E-loader

E-loader is an electronic load bank that is used to act as a real load applied to the power source for the testing. Figure 7 shows the E-loader device. This device is used to test the efficiency of the PEMFC that has been designed. By using the E-loader we can check wether the PEMFC can withstand the maximum load without any damage. The E-loader will be connected to the terminal of anode and cathode of PEMFC and the current can be set to determine the voltage and output power. The results gain will be used to analyze the the efficiency of the PEMFC system.

Figure 7: E-loader

3.3.2 Hydrogen Pressure Tank and Pressure Regulator

The hydogen gas is the heart of this project. The hydrogen gas can be produced in many process such as electrolysis of water and thermolysis. The hydrogen gas produced will be stored in the storage tank. The pressure storage tank is one of the tank used to store the hydrogen gas. Pressure regulator is need to be used together to control the pressure of the hydrogen gas output from the pressure tank. Figure 8 shows the hydrogen pressure tank with pressure regulator.

For the testing purpose, the hydrogen pressure tank and pressure regulator will be used to check the efficiency by continously feeding with required pressure of hydrogen gas to the PEMFC.

Figure 8: Hydrogen pressure tank with pressure regulator

3.4 Material Justification

3.4.1 Fuel cell unit

Fuel cell is like a generator but it uses hydrogen gas as a fuel to generate electricity. There are many type of fuel cell that can be used in this project such as Solid Oxide Fuel Cell (SOFC), Phosphoric Acid Fuel Cell (PAFC), Direct Methanol Fuel Cell (DMFC) and Polymer Exchange Membrane Fuel Cell (PEMFC). All of these fuel cells use a different fuel to generate electrical energy. For example, DMFC uses methanol as a fuel while PEMFC uses hydrogen gas as a fuel. Both types of fuel cell can produce electricity but the PEMFC is more efficient compare to the DMFC. So, this project uses PEMFC to convert the chemical reaction energy to the electrical energy to supply the air pump.

The PEMFC is used in many fuel cell applications because of fast start-up and response times. In addition, the operating temperature is less than 100°C, which allows rapid start-up [9] [10]. From the structure of the PEMFC, Nafion is used as a membrane which is very stable material. For other type of fuel cell the operating temperature can be up to 1000^0 C and above which is not convenient for this project. If we use the DMFC, the consumption of methanol arises because the boiling point of methanol is low which will easily vaporise. So, by using the PEMFC the consumption of hydrogen fuel is very efficient due to the lower kinetics of hydrogen oxidation. Besides that, the efficiency of the PEMFC is much better compare to the DMFC. According to the Figure 9 shown below, the power produced by PEMFC is higher than the DMFC which prove that the PEMFC is very efficient to be used in this project.

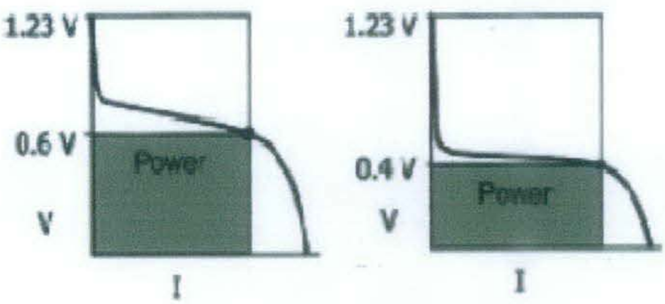

Figure 9: Performance differences of PEMFC and DMFC [6]

After done some researches and surveys, the best solution to use in this project is using the PEMFC. The specification of this PEMFC is according to the design of this project for the application of air pump and motor. The properties of the PEMFC are:

- Convert hydrogen gas directly into electricity
- The project is 4 stack cells, 3.6 V, 10 W
- Hydrogen pressure 0.3 bar
- Need cooling fan
- Solid state device with no moving parts

Figure 10: PEMFC unit

3.4.2 Solar Electrolyzer and Storage Tank

The hydrogen gas is used by the PEMFC to produce electricity energy. So, hydrogen gas needs to be produced and stored in the proper storage tank. The electrolyzer is used to produce the hydrogen gas from the water hydrolysis. In this project, the reversible PEMFC is used as an electrolyzer. It will separate the water molecule to the hydrogen and oxygen gas and these gases will be stored in the tank. The source of power to perform the electrolysis process is only using the 1 W solar panel. If we high power of solar panel the gas production also increases. Figure 11 shows the specification of the reversible PEMFC chosen for this project. The properties of the reversible PEMFC are [19]:

- Input Voltage: 1.7 V ~ 3 V (Solar)
- Input Current: 0.3 A
- Hydrogen production rate: 7 mL/min
- Oxygen production rate: 3.5 mL/min
- Dimensions: 54 mm x 54 mm x 17 mm
- Total Weight: 67.7 g

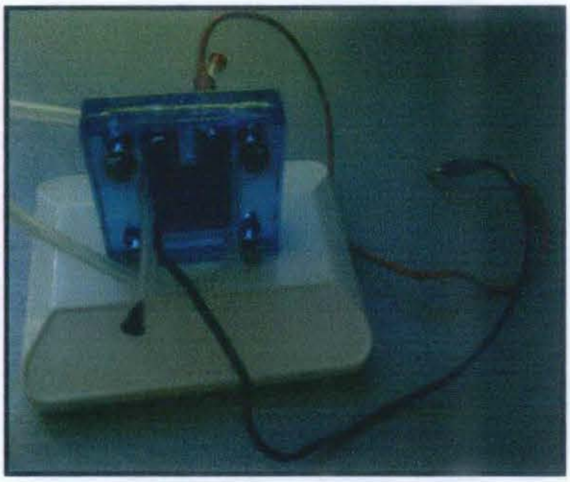

Figure 11: Electrolyzer

The production of the hydrogen gas of reversible PEMFC is very small compare to the usage of the hydrogen gas to produce electrical power to run the bigger load. So, the big storage tank is used to store the hydrogen gas. Since this project is the portable power supply, the storage tank is design to be compact and portable in size to suite with this project. The fabrication of the storage tank needs to consider many factors for the safety purposes.

3.4.3 Air Pump

Air pump as shown in Figure 12 is a device that forces air usually through tubing for various purposes especially to add oxygen to the water for the use of aquatic life. Usually the air pump is used in the aquarium but for the bigger scale it can be used in the fish pond. The continuous oxygen supply from the air pump is really crucial. In order to operate the pump continuously for 24 hours we need to ensure that the supply continuously can power up the pump.

Mini air pump is chosen in this project as the output of the supply from this innovation. It symbolizes the real application to show that the PEMFC can be used as a generator when there is no power supply from the grid. The properties of air pump used are:

- Rating 3 V, 4 W
- Powerful to run 1 air stone
- Portable size
- Good to break surface of water for oxygen

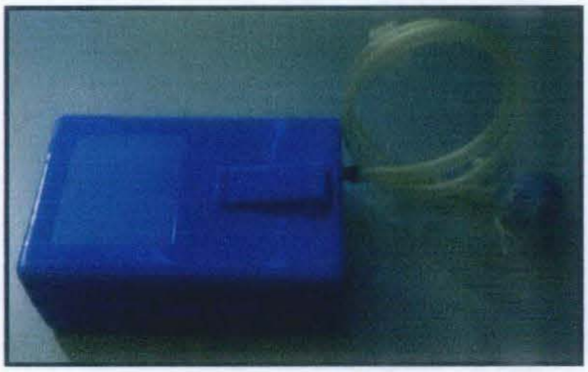

Figure 12: Air pump

3.5 Construct the solar electrolyzer and hydrogen gas storage

This project uses the reversible PEMFC as the electrolyzer to produce the hydrogen gas from the electrolysis process. The components that needed to construct the electrolyzer are the solar panel, reversible PEMFC, tube distilled water, syringe and gas storage cylinders. Figure 13 shows the complete assemble of PEMFC electrolyzer.

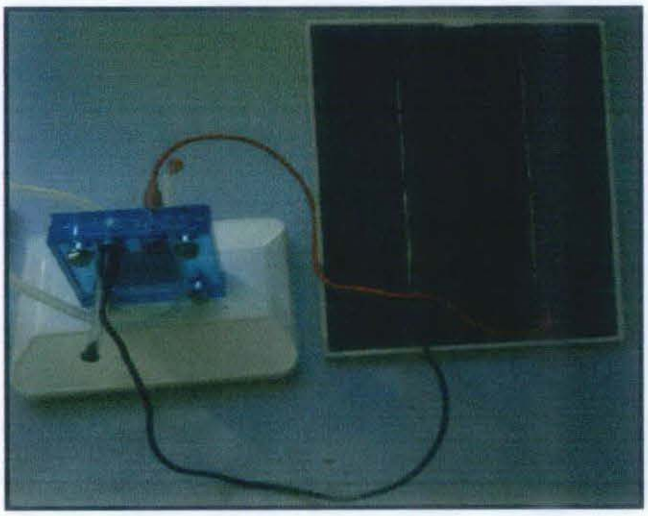

Figure 13: Solar electrolyzer

In this project the storage cylinders is designed to have 15 cm height and 21.5 cm diameter which can store 500 mL at 1 atm. The design of the tank is done using the Computer Aided Design (CAD) drawing as shown in Figure 14. Then, the storage tank is fabricated according to the CAD design. Figure 15 shows the storage tanks that have been constructed. Both of the hydrogen and oxygen gas in the storage tanks will be used in the PEMFC to generate electricity. The bigger the size of the cylinder the higher amount of hydrogen and oxygen gas can be stored. So, more electrical power can be produced for a long period.

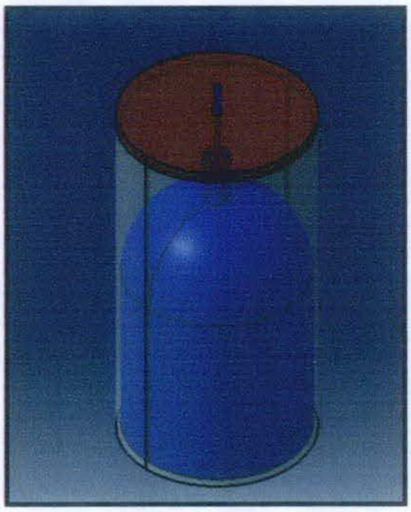

Figure 14: CAD design of storage tank

Figure 15: Fabricated storage tank

The procedures to construct the solar electrolyzer with the storage tank are:

1. Cut 2 x 4 cm length pieces of rubber tube and insert a black pin into the end of one tube. Place the tube with the black pin into the top pin on the hydrogen side. Place the other tube firmly onto the top input nozzle on the oxygen side.

2. Fill the syringe with distilled water. On the red oxygen side of the reversible PEMFC, connect the syringe to the uncapped tube. Fill it until water begins to flow out of the tube. Attach a red plug to the oxygen side tube.

3. Place inner containers into outer cylinders and ensure that the gaps are not blocked by inner plastic rims. Connect the two pieces of tubing to the top nozzles on the inner containers.
4. Connect the other end of the long tube on the hydrogen side to the bottom end of the black hydrogen side of the reversible PEMFC. Connect the other end of the long tube on the oxygen side to the bottom end of the red oxygen side.
5. Connect the reversible PEMFC to the solar panel using the cables and expose to direct sunlight.

3.5 Construct the portable power supply PEMFC

The PEMFC cannot operate without other main components such as gas storage tank, tube, cooling fan and wiring cable. All of these components will be assembled together to produce electrical energy. For the PEMFC unit construction, the combination of PEM, electrodes and platinum catalyst will form a stack of cells which is called MEA. In this project, we are using the open cathode PEMFC with four stack cells are combined together in series to produce the desired output 3.6 V, 10 W as shown in CAD drawing design in Figure 16. The design surface area is 21.5 cm x 7 cm and the total thickness of MEA is 2 cm.

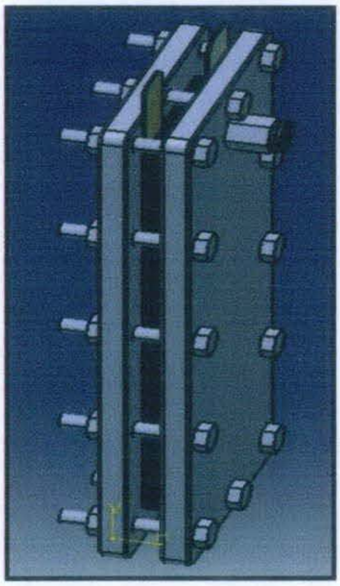

Figure 16: CAD design of PEMFC unit

There will be a fitting hole at the anode electrode for the hydrogen gas inlet. The tube is connected to the fitting of the inlet to flow the hydrogen and from the storage tank to the PEMFC. For the output connection, two plates with 0.2 cm x 3.5 cm surface area of anode and cathode electrode will be connected with the two conductor wires for the positive and negative terminals. Figure 17 shows the CAD design of the PEMFC with the storage tank and terminal anode and cathode connectors.

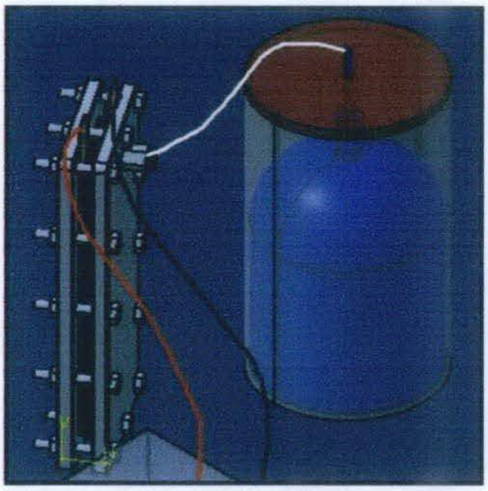

Figure 17: CAD design of PEMFC with storage tank

The cooling fan is not only used to reduce the temperature of the PEMFC but it also used to remove the water and feed the oxygen gas to the cell. The size of cooling fan depends on the size of the PEMFC. In this project, two units of 12 V, 1.2 A cooling fan are used and it will be installed at the side of the cell. Figure 18 shows the cooling fans used in this project.

Figure 18: Cooling fans

The fabrication of the PEMFC unit is done by the G-Energy Technologies Sdn. Bhd. according to the specification design given to them. Figure 19 shows the complete design of PEMFC after the fabrication process. So, the design of this fuel cell is complete and ready to be used to generate electricity.

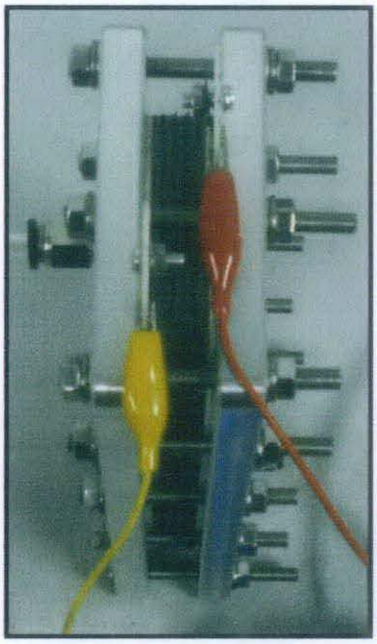

Figure 19: PEMFC unit

3.7 Prototype fabrication (initial design)

The prototype almost complete based on design concept and drawing from CAD. This prototype can be used for air pump for the fish pond and motor with controller circuit for the solar hybrid car. The solar electrolyzer with PEMFC that had been fabricated can produce about 3.6 V with 10 W output power which is suitable for the applications of the air pump and motor since it can produce high current and output power. For the air pump it can be used directly the output of PEMFC without any additional circuit because the rating is approximately same as the rating of PEMFC. The air pump is successful operated to produce maximum oxygen gas to the aquatic life as shown in Figure 20.

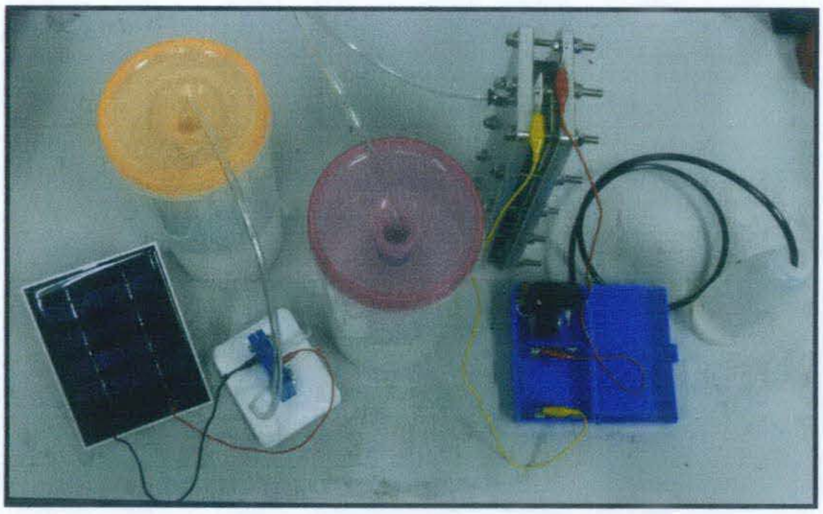

Figure 20: Air pump application

This project also is applied to the DC motor with the controller circuit to symbolize the motor for the solar hybrid car. Since the solar hybrid car already has the solar panel, this innovation takes the opportunity to utilize the solar power to power up the electrolyzer to produce the hydrogen gas. The controller circuit of the motor is designed to be located at the middle of the car as shown in the CAD drawing in Figure 21.

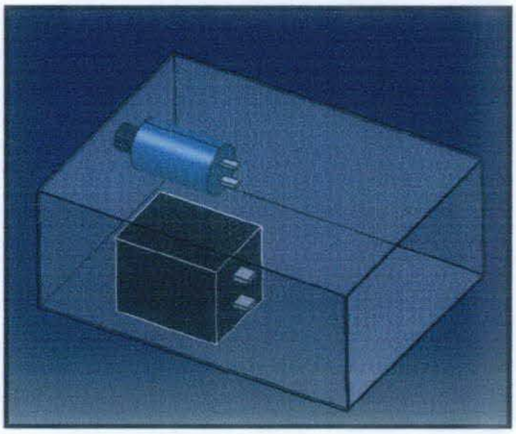

Figure 21: CAD design motor circuits

The booster is used to boost the voltage of PEMFC to 5V to improve the performance of the motor. As addition feature, the ultra capacitor circuit also designs as a backup supply if the hydrogen gas is empty. For the safety purposes, the storage tank of the hydrogen gas is located at the back of the car because the hydrogen gas can easily explode if there is spark or fire. Figure 22 shows the complete model of the motor for the solar hybrid car. The performance of this innovation very depends on the climate of the surroundings such as humidity and quantity of air feed into the PEMFC. This innovation have no limit of usage, it can be use anywhere and anytime since have source of sun radiation to produce the hydrogen gas using electrolyzer.

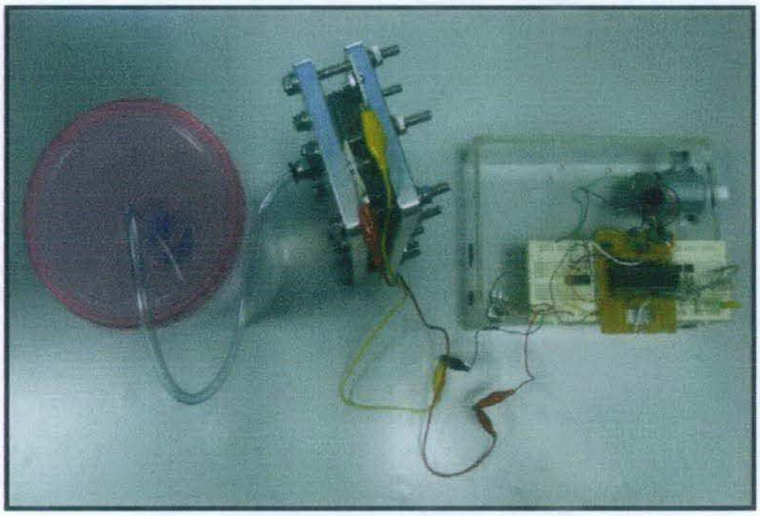

Figure 22: Motor application

3.8 Electrical Circuit

3.8.1 Booster circuit

The booster circuit is constructed using LT1073 which is a versatile micro power DC/DC converter that can easily be configured as a buck or boost converter. In this project, it is basically being used to step up 1.5 V of voltage that was produced by the battery to achieve 5 V of output. The schematic design of the booster circuit used in this project is shown in Figure 23. In the steady-state analysis, the output filter capacitor is assumed to be very large to ensure a constant output voltage.

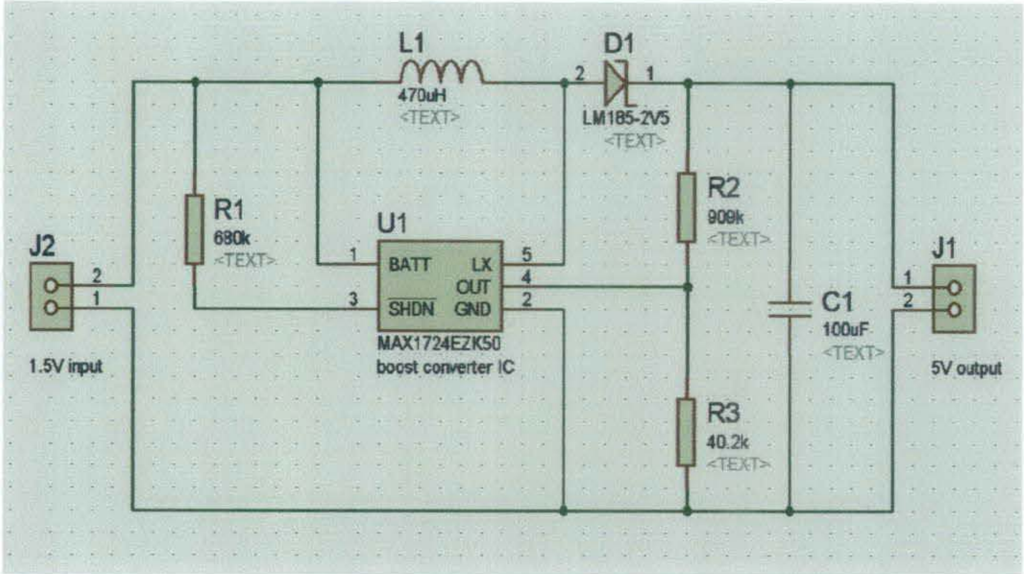

Figure 23 : Booster circuit

3.8.2 Main circuit (PEMFC and Ultra capacitor)

The main idea of this project is to supply the continuous power supply to the air pump and motor. The PEMFC will charge the ultra capacitor and at the same time supply power to the applications.

The complete circuit of this project is shown in Figure 24. When the 2.5 V, 10 F, ultra capacitor is used, the switch is turn on to logic 1, the diode LED indicator (D1) will light up for indication that the applications are supplied by the ultra capacitor and at the same time it is recharged by the PEMFC. When the switch is turn off to logic 0, the D1 will light off to indicate that the PEMFC supply the electrical power.

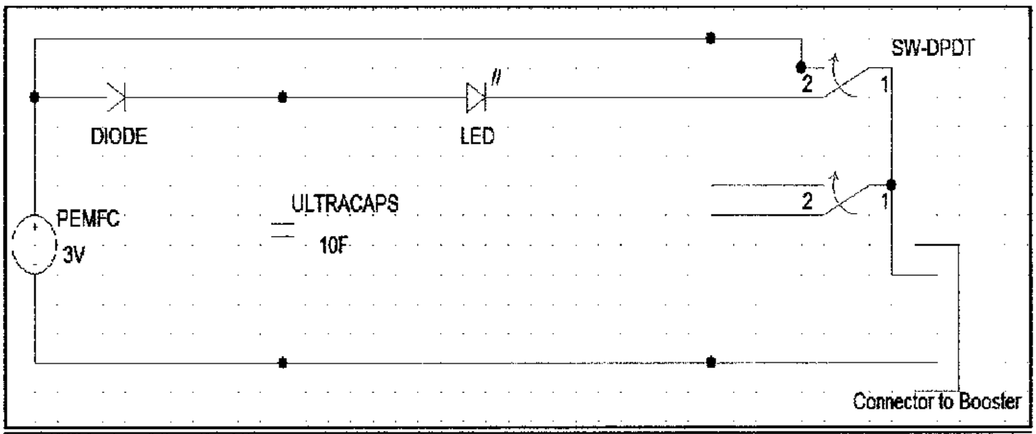

Figure 24: Main circuit

3.8.3 *Controller circuit for motor*

The Pulse Width Modulation (PWM) speed controller is used in this project. The function of the controller circuit is to control the speed of the motor by varying the voltage magnitude. It also designed to have the ability to control the rotation of the motor and stop the motor. The Programmable Integrated Circuit (PIC) is used to programme all of the functions of the controller circuit. The coding for the PWM speed controller can be referred to the APPENDIX C. Figure 25 below shows the circuit diagram of the motor.

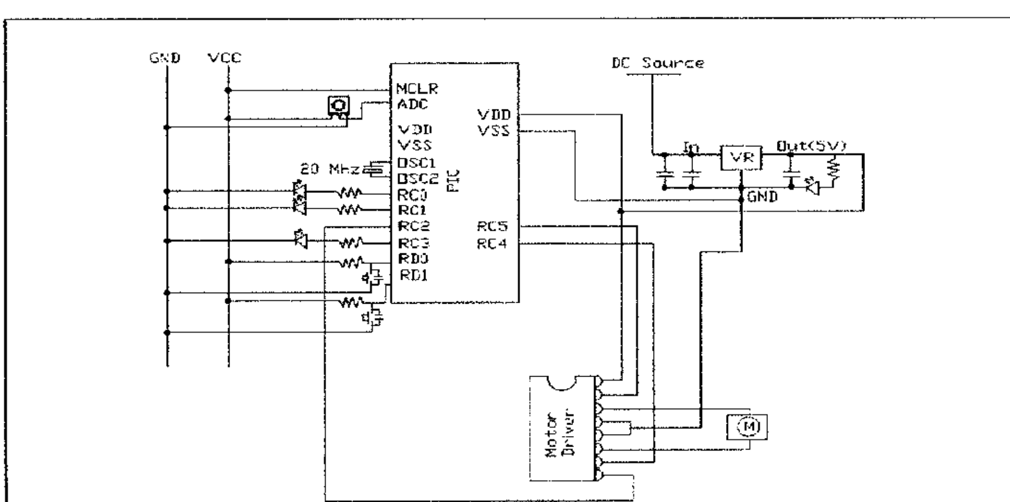

Figure 25: Controller circuit for motor

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Data Gathering and Analysis

The expected result that is targeted to be achieved at the end of this project is to complete the prototype of the air pump and motor applications. The parameters that affect of the performance and efficiency of the PEMFC also will be investigated to build the efficient prototype model. Several experiments need be done in order to find the effects of high humidity climate to the performance of PEMFC which are humidity and air pressure.

4.1.1 Open circuit test for PEMFC unit

This experiment will test the PEMFC without supplying the hydrogen gas to the cell. Four stacks of cell is used and connected with series to produce more voltages. The result of this experiment is tabulated in Table I. At this level, the more stack is connected in series connection, the larger is the output voltage can be produced. In order to get 3.6 V of output constantly to operate the motor application, a constant 5 V output is needed. Thus, the boost converter is used in this project.

Table I: PEMFC stacks connected in series experiment

No of stacks	Output Voltage (V)		
	1st reading	2nd reading	Average
1	0.902	0.902	0.902
2	1.801	1.799	1.800
3	2.698	2.697	2.698
4	3.596	3.597	3.597
Using boost converter	5.6	5.6	5.6

4.1.2 PEMFC efficiency test (after fabrication)

After completed the fabrication of the PEMFC by the G-Energy Technology Sdn. Bhd., the testing is done to check the efficiency of the system. Using the Fuelcell Test Station, E-loader and continuous hydrogen gas supply, the voltage, output power and temperature of cells can be measured. The setup of the testing done is shown in Figure 26. The load current is applied by using the E-loader and the voltage, output power and temperature is measured and the results can be referred to Table II.

Table II: PEMFC efficiency testing result

Current (A)	Voltage (V)	Input power (W)	Output power (W)	Efficiency, η (%)	Temperature (^{O}C)
0	3.630	0	0	0	24.7
0.2	3.378	1.18	0.6	50.85	24.7
0.4	3.270	2.37	1.2	50.63	24.7
0.6	3.190	3.55	1.8	50.70	24.7
0.8	3.120	4.74	2.4	50.63	24.9
1.0	3.060	5.92	3.0	50.68	24.9
1.2	3.010	7.11	3.5	49.23	25.0
1.4	2.950	8.29	4.1	49.46	25.1
1.6	2.900	9.48	4.6	48.52	25.2
1.8	2.840	10.66	5.1	47.84	25.3
2.0	2.790	11.85	5.5	46.41	25.4
2.2	2.740	13.03	5.9	45.28	25.6
2.4	2.680	14.22	6.4	45.01	25.7
2.6	2.620	15.40	6.7	43.51	25.8
2.8	2.550	16.59	7.1	42.80	25.9
3.0	2.480	17.77	7.4	41.64	25.9
3.2	2.400	18.96	7.6	40.08	26.1
3.4	2.280	20.14	7.7	38.23	26.2
3.6	1.970	21.33	7.0	32.82	27.7
3.8	1.920	22.51	7.2	31.99	28.1
4.0	1.870	23.70	7.4	31.22	28.5

Figure 26: Testing setup

Figure 27 and 28 show graphs of the results. From the graphs, when the load current increases, the voltage drop, output power and temperature also increases. Our target to get the 3.6 V, 10 W output is achieved but according to the literature reviews, but the graph should be smoother than the results gain in this testing to indicate the high efficiency of the PEMFC. This is because the membrane is not fully activated since it needs to be supplied with the continuous hydrogen gas at for 40 hours to operate in optimum condition. After that, further investigations need to be done on how the humidity and air pressure affect the performance of PEMFC in order to get the high efficiency of power supply.

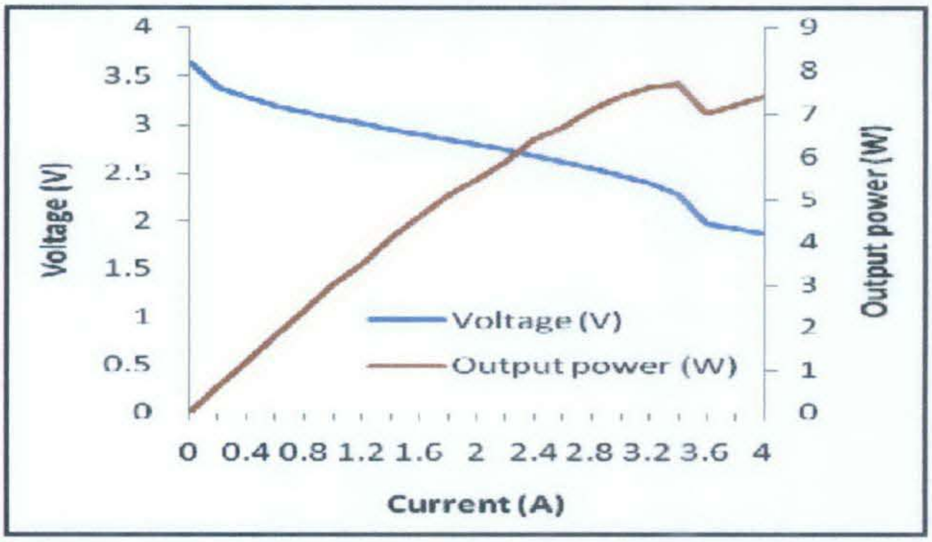

Figure 27: Graph current vs voltage, output power

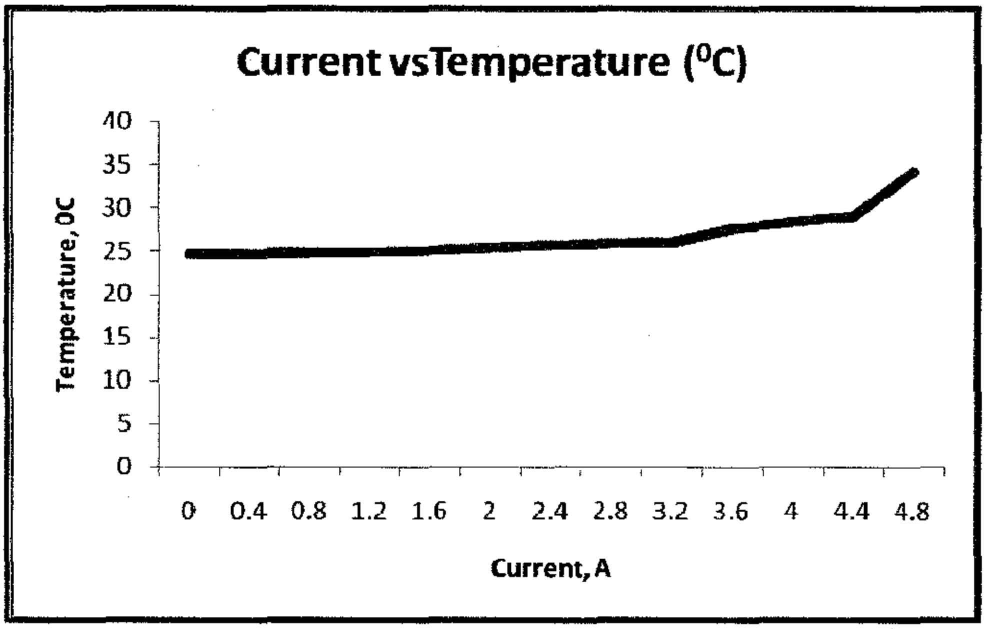

Figure 28: Graph current vs temperature

4.1.3 Effect of humidity and air pressure on the PEMFC efficiency

The humidity and air pressure feed into the membrane give impact to the performance of the PEMFC. Both parameters are related to each other in water management of PEMFC. As we know, water is one of the outputs when this fuel cell generates electricity energy and the amount of water in the membrane will affect the performance of PEMFC. The quantity of water need to be managed in optimum level to get the better results. This experiment is using the humidifier and DC cooling fan as the variable of the humidity and air pressure with the continuous 0.3 bar hydrogen gas.

Figure 29 shows the effect of high air pressure and high humidity on the polarization curve of fuel cell by using the humidifier and high speed fan. As can be observed from the graph, the slope of the linear region of the stack voltage versus current plot remains almost constant. On the other hand, Figure 30 shows the effect when the humidifier is not used and the graph shows the slope is not constant at the maximum output. From both results, the performance of PEMFC varies when one of this parameter change. The high air pressure increases the availability of the oxygen gas at the cathode membrane which improves the performance of the fuel cell but it also increase the rate of water removal that cause the membrane dry which increase the resistance of cell. By supplying water vapour using the humidifier, the quantity of water in membrane will increase which can avoid the membrane from dry. If the quantity of the water too high at the membrane the performance will decrease due to flood of water which affect the chemical reaction between the oxygen and hydrogen gas.

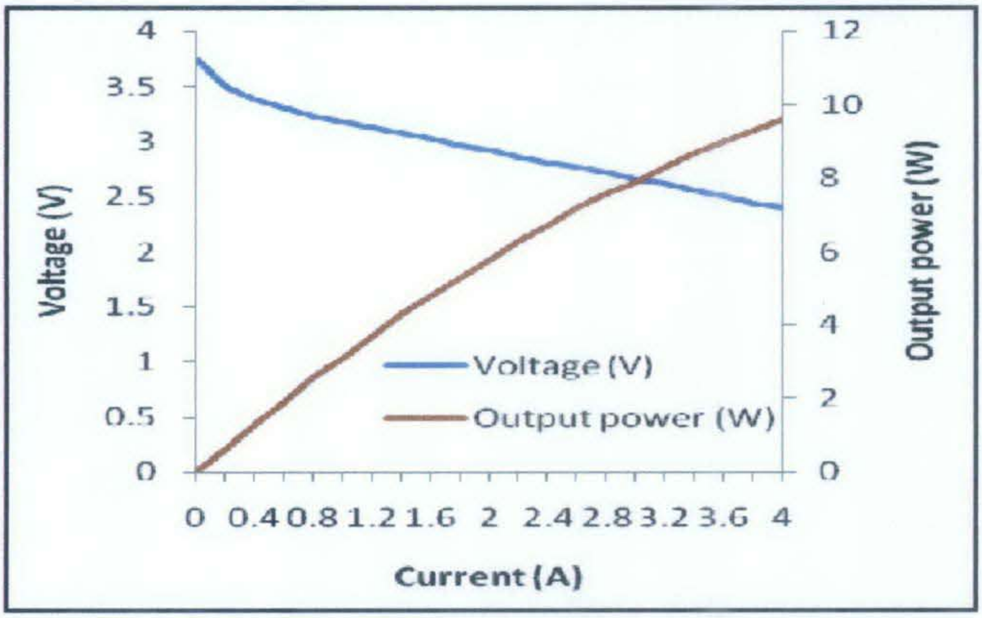

Figure 29: Graph high air pressure and high humidity effect

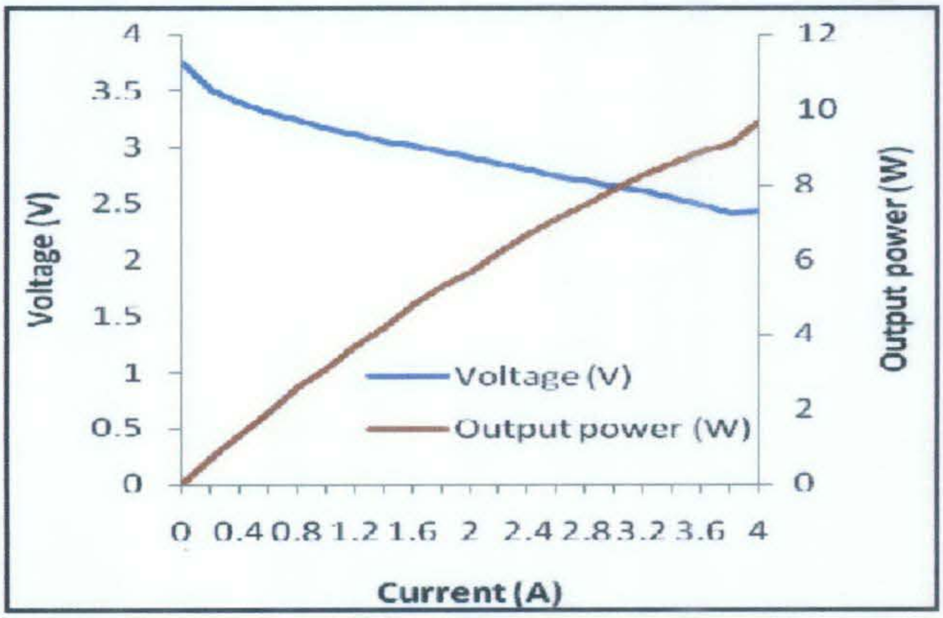

Figure 30: Graph high air pressure and no humidity effect

According to the Figure 30, the slope of graph is not constant even though the high air pressure distribute more oxygen through the cathode membrane but a lot of water has been blown out from the membrane which make the membrane to be dried and decrease the efficiency. To counter that problem, the supply of the water vapour from the humidifier will reduce the dryness of the membrane. This can be observed in Figure 29. From all of these results, both air pressure and humidity are related in water management to increase the performance of the PEMFC. The data of the results can be referred at Appendix D and E.

4.1.4 Effect of high humidity climate on the PEMFC efficiency

To operate the PEMFC in maximum power output of the must have high humidity and high air pressure. Both of these parameters need to use the humidifier and high speed fan or air compressor to achieve the target power output with the highest efficiency. For the country that has high humidity in their climate, this is the huge advantage to boost the performance of the fuel cell. For example, Malaysia climate has approximately 70% average humidity and this will reduce the dryness of the membrane which increases the performance of the PEMFC. So, the humidifier is not needed anymore as the medium to supply the humidity to the membrane.

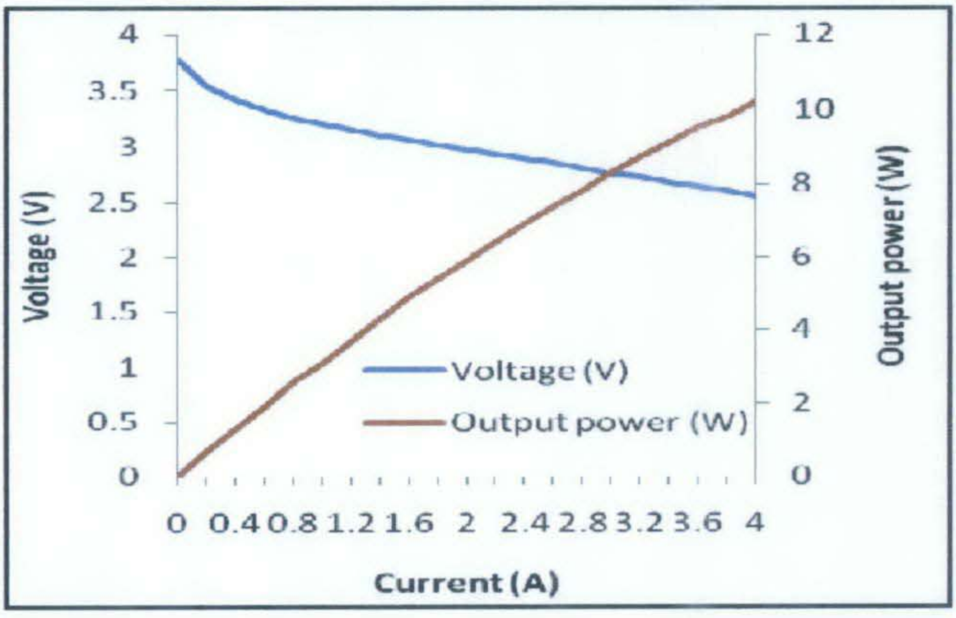

Figure 31: Graph effect of the mild air pressure and no humidity

Figure 31shows the effect of reducing the speed of the fan to give the mild air pressure and without using the humidifier. From the data result in Appendix F and the graph above shows that the maximum power output is higher than using the high speed fan. The slope of the graph also almost constant that indicate the good performance of the fuel cell. The mild air pressures supplies enough oxygen and reduce the water to be blown out from the membrane. Even though not using the humidifier, the surrounding climate already has the high humidity to reduce the dryness of the PEMFC. Thus, we can reduce the auxiliary energy to run the fan and also neglect the humidifier.

4.1.5 Calculation of prototype application

The prototype models use the hydrogen storage tank at pressure of 1 bar and the PEMFC is operating at a pressure of 0.3 bar. The rating of the fuel cell is rated at 10 W maximum power output and the voltage of the fuel cell stacks is 3.6 V. The power requirement to operate the application is 5 W for motor and 4 W for mini air pump. From all of this information, the flow rate and amount of the hydrogen storage requirement can be calculated for the target operating time of 1 hour.

Calculation for motor application:

Power required is 5 W = 5 J/s

Note that:

i. For every mole of H_2O produced one mole of H_2 is required

ii. Power output (in J/s) = Gibbs free energy, $\Delta G_{H2O(l)}$ (in J/mol) x flow rate (in mol/s)

Therefore;

Flow rate = Power output / $\Delta G_{H2O(l)}$

= (5 J/s) / (|- 237.3 kJ/mol|)

= 2.107×10^{-5} mol/s of H_2 is required

Molecular weight of H_2 is about 2 g/mol, so:

Flow rate = 2.107×10^{-5} mol/s x 2 g/mol

= 4.214×10^{-5} g/s of H_2 is required

The fuel cell need to operate for 1 hour, therefore:

Amount of fuel needed, $m_{hydrogen}$ = time x flow rate

= (1h x 3600 s/h) x (4.214×10^{-5} g/s)

= 0.152 g

Given at P = 1 bar, the density of hydrogen gas is 0.09 g/L and if we are store the required fuel amount at a pressure of 1 bar;

$$\text{Volume}_{hydrogen@1bar} = m_{hydrogen} / \rho_{hydrogen@1atm} \quad (\rho = m/V \rightarrow V = m/\rho)$$

$$= 0.152\ g / 0.09\ g/L$$

$$= 1.686\ L$$

At storage pressure of 1 bar, the amount of storage volume required will be much less and notice that since the fuel cell operating pressure is 0.3 bar, we can only utilize a pressure differential, dP of (1 – 0.3) = 0.7 bar from the storage tank.

From ideal gas law,

$$P_1V_1 = P_2V_2 \rightarrow V_2 = (P_1V_1)/P_2$$

$$\text{Volume}_{hydrogen@1bar,\ dP=0.7} = \{(1/0.7) \times (1\ bar \times 1.686 \times 10^{-3}\ L)\} / (1\ bar)$$

$$= 2.408\ L$$

For different target operating time the flow rate will remain while the amount of the hydrogen gas will increase as shown in Figure 32. The data of results can be referred to the Appendix G. The step above is repeated for the mini air pump. The flow rate and amount of the hydrogen storage requirement are lower than the motor application since the required power is low.

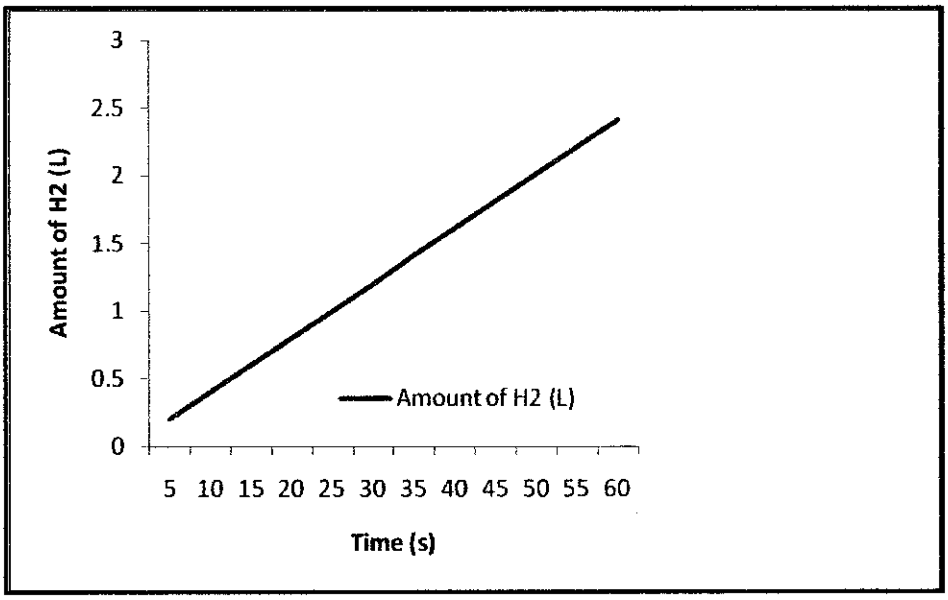

Figure 32: Graph amount of H_2 used for required time

CHAPTER 5

CONCLUSSIONS & RECOMMENDATION

Based on the researches, PEMFC is the best fuel cell to be used in this project. The advantage of using this type of alternative energy is very environmental friendly because no emission of greenhouse gas which can damage the ozone layer. In this work, the testing was done using the 3.6 V, 5W PEMFC to monitor and control the parameters that affect the performance of the fuel cell.

There are many parameters need to be consider to improve the performance of the fuel cell but humidity and air pressure feed into the membrane was found to have the significant effect to the performance of PEMFC. From the experimental results, the polarization curves have shown the efficiency of the fuel cell varies when both parameters change. The high humidity climate also influenced the performance of this green technology since the testing is done in Malaysia which has the highest humidity in this world. This give advantage to operate in optimum level without using the humidifier and the auxiliary energy to run the cooling fan also can be reduced.

The complete prototype model has been fabricated for the solar hybrid car and air pump application. Both models have operated well without emit any dangerous greenhouse gas which is very clean and environmental friendly. For the future improvement that can be done is the design of fan need to be designed to feed directly the air into the hole of the membrane stacks to improve the performance of PEMFC. Besides that, the special tank needs to be designed to be refilled and purge the gas at the same time.

REFERENCES

[1] F. Barbir, PEM Fuel Cells Theory and Practice, second edition Elsevier, Burlington, 2001, 15–16, 101–102, 117–120.

[2] J.P. Meyers, H.L. Maynard, *Journal of Power Sources,* 2002, 109, 76–88.

[3] M. W. Ellis, M. R. Von Spakovsky and D. J. Nelson "Fuel cell systems: Efficient, flexible energy conversion for the 21st century", *Proceeding of the IEEE,* 2001, vol. 89, 1808.

[4] Explore Fuel Cells, 2011, 1 June 2011 from http://www.nmsea.org/Curriculum/7_12/Fuel_Cells/fuel_cells.htm

[5] Fuel cells, 2010, 2 June 2011 from http://www.warmair.net/html/fuel_cells.html

[6] Introduction to Fuel Cell Technology, Chris Rayment and Scott Sherwin, Department of Aerospace and Mechanical Engineering University of Notre Dame, May 2003, 115.

[7] Chen, B., Research and Development of Fuel Cell Technology, *Power and Energy Engineering Conference (APPEEC), Asia-Pacific, 2011* , 1-4.

[8] Puranik, S., Keyhani, A., & Khorrami, F., Neural Network Modeling of Proton Exchange Membrane Fuel Cell, *IEEE Transactions On Energy Conversion* , June 2010. Vol. 25, No. 2, 474 – 483.

[9] M. W. Ellis, M. R. Von Spakovsky and D. J. Nelson "Fuel cell systems: Efficient, flexible energy conversion for the 21st century", *Proceedings of the IEEE,* 2001, vol. 89, 1808.

[10] J. T. Pukrushpan, A. G. Stefanopoulou, and H. Peng, "Control of fuelcell breathing," *IEEE Control Systems Magazine*, April 2004, vol. 24, no. 2, 30–46.

[11] Catalyzed Fuel Cell Membranes, 2004, 8 June 2011 from http://www.ion-power.com/products.html

[12] P. Rodatz, F. Büchi, C. Onder, L. Guzzela. *Journal of Power Sources*, 2004, 128, 208-217.

[13] PEM Fuel Cell Calculations, Joseph Barbetta, 2002, 10 June 2010 from http://fuelcellhelp.com

[14] Maher A.R. Sadiq Al-Baghdadi, Haroun A.K. Shahad Al-Janabi. *Renewable Energy*, 2007, 32, 1077-1101.

[15] Marignetti, F., Minutillo, M., Perna, A., & Jannelli, E. Assessment of Fuel Cell Performance Under Different Air Stoichiometries and Fuel Composition. *IEEE Transactions on Industrial Electronics* , June 2011, 2420 - 2426.

[16] J. Huson, P. C. Lundberg, R. Herry, A. Bourgeau, A. Snyder, S. K. Das, Etim U. Ubong, Experimental evaluation of the effect of humidification on the performaance of PEM fuel cell stack, *Electrical Insulation Conference and Electrical Manufacturing Expo, 2007,* 418-422.

[17] Q. Yan, H. Toghiani, H. Causey. *J. Power sources,* 2006, 492-502.

[18] C. Ramos-Paja, R. Giral, L. Martinez-Salamero, J. Romano, A. Romero, and G. Spagnuolo, "A PEM fuel-cell model featuring oxygen-excess-ratio estimation and power-electronics interaction," *IEEE Transactions on Industrial Electronics,* June 2010, vol. 57, no. 6, 1914–1924.

[19] PEM Electrolyzers, 2007, 18 June 2011 from http://www.horizonfuelcell.com/store/peme.htm

APPENDICES

APPENDIX A

GANTT CHART FYP 1

PROJECT ACTIVITIES	WEEK													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Select the topics from FYP lists														
Confirmation of the topic														
Study on literature review of the topic														
Work on Preliminary Report														
Material research and design														
Methodology analysis														
Work on Project Defence and Progress Evaluation														
Fabrication of PEMFC														
Finalization of PEMFC model														
Work on Final Report														

APPENDIX B

GANTT CHART FYP 2

PROJECT ACTIVITIES	WEEK														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
esting (air pressure and humidity ffects)															
lardware synchronization															
ompletion of application model															
ubmission of progress report															
ubmission of draft report															
ubmission of dissertation (soft opy)															
ubmission of technical paper															
)ral presentation (Viva)															
ubmission of final report (hard ound)															

APPENDIX C

CODING FOR PWM SPEED CONTROLLER

```
#include "config.h"

void main (void)
{
      int forward_indicator=1;
      int reverse_indicator=0;
      init_io();
      init_motor();
      setup_pwm();
      setup_adc();
      ledr=0;
      ledf=0;
      input1=0;
      input2=0;


while(1)
{
      pwm=read_adc(1);
      ledb=0;
      if(forward_indicator)
      {
      input2=0;
      input1=1;
      delay(50000);
      ledf=1;
      ledr=0;
      }
      else if(reverse_indicator)
      {
      input2=1;
      input1=0;
      delay(50000);
      ledf=0;
      ledr=1;
      }

      if(!rot)
      {

          if(forward_indicator)
          {
          forward_indicator=0;
          reverse_indicator=1;
          }
          else if(reverse_indicator)
          {
          forward_indicator=1;
          reverse_indicator=0;
          }
```

```
        delay(50000);
        }


        if(!brake)
        {
            input1=0;
            input2=0;
            ledr=0;
            ledb=1;
            ledf=0;
            delay(50000);
            while(1)
            {
            if(!brake)
            break;
            }
         }
      }
}
```

APPENDIX D

HIGH AIR PRESSURE AND HIGH HUMIDITY

Current (A)	Voltage (V)	Input power (W)	Output power (W)	Efficiency, η (%)	Temperature (^{0}C)
0	3.749	0	0	0	28.8
0.2	3.496	1.18	0.6	50.85	28.7
0.4	3.383	2.37	1.3	54.85	28.6
0.6	3.302	3.55	1.9	53.52	28.7
0.8	3.234	4.74	2.6	54.85	28.7
1.0	3.175	5.92	3.1	52.36	28.7
1.2	3.123	7.11	3.7	52.04	28.7
1.4	3.072	8.29	4.3	51.87	28.8
1.6	3.019	9.48	4.8	50.63	28.8
1.8	2.966	10.66	5.3	49.72	28.9
2.0	2.918	11.85	5.8	48.95	29.0
2.2	2.864	13.03	6.3	48.35	29.0
2.4	2.810	14.22	6.7	47.12	29.0
2.6	2.769	15.40	7.2	46.75	29.2
2.8	2.717	16.59	7.6	45.81	29.2
3.0	2.661	17.77	7.9	44.46	29.4
3.2	2.614	18.96	8.3	43.87	29.5
3.4	2.558	20.14	8.7	43.20	29.6
3.6	2.500	21.33	9.0	42.19	29.7
3.8	2.445	22.51	9.3	41.31	29.9
4.0	2.403	23.70	9.6	40.51	30.1

APPENDIX E

HIGH AIR PRESSURE AND NO HUMIDITY

Current (A)	Voltage (V)	Input power (W)	Output power (W)	Efficiency, η (%)	Temperature (^oC)
0	3.744	0	0	0	27.0
0.2	3.507	1.18	0.7	59.32	27.1
0.4	3.393	2.37	1.3	54.85	27.1
0.6	3.299	3.55	1.9	53.52	27.3
0.8	3.234	4.74	2.6	54.85	27.4
1.0	3.166	5.92	3.1	52.36	27.5
1.2	3.110	7.11	3.7	52.04	27.4
1.4	3.054	8.29	4.2	50.66	27.4
1.6	3.005	9.48	4.8	50.63	27.4
1.8	2.957	10.66	5.3	49.72	27.5
2.0	2.905	11.85	5.7	48.10	27.5
2.2	2.854	13.03	6.2	47.58	27.6
2.4	2.804	14.22	6.7	47.12	27.5
2.6	2.750	15.40	7.1	46.10	27.7
2.8	2.702	16.59	7.5	45.21	27.7
3.0	2.652	17.77	7.9	44.46	27.7
3.2	2.616	18.96	8.3	43.78	28.0
3.4	2.554	20.14	8.6	42.70	28.2
3.6	2.491	21.33	8.9	41.73	28.3
3.8	2.416	22.51	9.1	40.43	28.3
4.0	2.423	23.70	9.7	40.93	28.5

APPENDIX F

MILD AIR PRESSURE AND NO HUMIDITY

Current (A)	Voltage (V)	Input power (W)	Output power (W)	Efficiency, η (%)	Temperature (^oC)
0	3.770	0	0	0	28.3
0.2	3.527	1.18	0.7	59.32	28.2
0.4	3.414	2.37	1.3	54.85	28.2
0.6	3.324	3.55	1.9	53.52	28.2
0.8	3.252	4.74	2.6	54.85	28.3
1.0	3.196	5.92	3.1	52.36	28.3
1.2	3.144	7.11	3.7	52.04	28.3
1.4	3.100	8.29	4.3	51.87	28.4
1.6	3.055	9.48	4.9	51.69	28.6
1.8	3.010	10.66	5.4	50.66	28.7
2.0	2.973	11.85	5.9	49.79	28.9
2.2	2.932	13.03	6.4	49.12	29.0
2.4	2.891	14.22	6.9	48.52	29.0

2.6	2.853	15.40	7.4	48.05	29.2
2.8	2.811	16.59	7.8	47.02	29.4
3.0	2.763	17.77	8.3	46.71	29.5
3.2	2.726	18.96	8.7	45.18	29.6
3.4	2.681	20.14	9.1	45.18	29.6
3.6	2.641	21.33	9.5	44.54	29.8
3.8	2.603	22.51	9.8	43.54	30.1
4.0	2.554	23.70	10.2	43.04	30.3

APPENDIX G

AMOUNT OF HYDROGEN GAS FOR 1 HOUR

Time (min)	Flow rate of H_2 (g/s)	Amount of H_2 (L)
5	4.214×10^{-5}	0.201
10	4.214×10^{-5}	0.401
15	4.214×10^{-5}	0.602
20	4.214×10^{-5}	0.803
25	4.214×10^{-5}	1.003
30	4.214×10^{-5}	1.204
35	4.214×10^{-5}	1.405
40	4.214×10^{-5}	1.605
45	4.214×10^{-5}	1.806
50	4.214×10^{-5}	2.007
55	4.214×10^{-5}	2.207
60	4.214×10^{-5}	2.408