" I hereby declare that I have read through this report entitle "*Analysis on the Effect of Pressure and Flow Rate Hydrogen Towards the Performance of Thermodynamic Potential of Proton Exchange Membrane Fuel Cell*" and found that it has complied with the partial fulfillment for awarding the degree of Bachelor of Electrical Engineering (Industrial Power)"

Signature : ....

Supervisor's Name : ....

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ANALYSIS ON THE EFFECT OF PRESSURE AND FLOW RATE HYDROGEN TOWARDS THE PERFORMANCE OF THERMODYNAMIC POTENTIAL OF PROTON EXCHANGE MEMBRANE FUEL CELL

NOR AZIELA BT AB RAHAMAN

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

Faculty of Electrical Engineering
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2015

“ I declare that this report entitle *“Analysis on the Effect of Pressure and Flow Rate Hydrogen Towards the Performance of Thermodynamic Potential of Proton Exchange Membrane Fuel Cell”* is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.

Signature : ....

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ABSTRACT

Currently, the demand for the energy source in Malaysia keeps increasing day by day. On the other hand, the energy source in Malaysia keeps decreasing as a result from the demand. Therefore, the government encouraged the use of renewable energy as an alternative energy source such as Proton Exchange Membrane (PEM) Fuel Cell. The PEM Fuel Cell used hydrogen as a fuel to produce electricity. However, the PEM Fuel Cell has some problem in which it affects the performance of PEM Fuel Cell. There are a few parameters such as pressure and flow rate hydrogen that affects on the performance of PEM Fuel Cell. Besides that, the existing method that has been used to analyze the data of the PEM Fuel Cell needs an expensive. Therefore, the problem that occurs in the PEM Fuel Cell specifically the effect of pressure and flow rate hydrogen should be investigated and analyzed. Then, the new method which is a signal processing technique will be introduced in the future. This technique is recommended to investigate the identification signal of the pressure and flow rate hydrogen towards the changing behavior in PEM Fuel Cell. From the polarization curve and periodogram results, it is clearly revealed that when the pressure hydrogen increased, the performance thermodynamic potential of PEM Fuel Cell will be increased. Besides that, when the hydrogen flow rate is increased, the performance voltage of PEM Fuel Cell will be decreased because the hydrogen flow rate is related with the moisture of hydrogen. Moreover, the identification signal of pressure and flow rate hydrogen by using signal processing technique is show that the changing pressure and flow rate hydrogen has an affects on the changing characteristic behavior in PEM Fuel Cell.

ABSTRAK

Pada masa ini, permintaan terhadap sumber tenaga di Malaysia terus meningkat dari hari ke hari. Sebaliknya, sumber tenaga di Malaysia terus berkurangan akibat dari permintaan. Oleh itu, kerajaan menggalakkan penggunaan tenaga boleh diperbaharui sebagai sumber tenaga alternatif seperti Proton Exchange Membran (PEM) Fuel Cell. PEM Fuel Cell menggunakan hidrogen sebagai bahan api untuk menghasilkan tenaga elektrik. Walau bagaimanapun, PEM Fuel Cell mempunyai beberapa masalah di mana ia memberi kesan kepada prestasi PEM Fuel Cell. Terdapat beberapa parameter seperti tekanan dan kadar alir hidrogen yang memberi kesan kepada prestasi PEM Fuel Cell. Selain itu, kaedah yang sedia ada yang telah digunakan untuk menganalisis data PEM Fuel Cell adalah sangat mahal. Oleh itu, masalah yang berlaku dalam PEM Fuel Cell khusus kesan tekanan dan kadar alir hidrogen perlu disiasat dan dianalisis. Kemudian, kaedah baru yang merupakan teknik pemprosesan isyarat akan diperkenalkan pada masa akan datang. Teknik ini adalah disyorkan untuk menyiasat isyarat pengenalan tekanan dan kadar alir hidrogen ke arah tingkah laku yang berubah-ubah dalam PEM Fuel Cell. Dari lengkung polarisasi dan keputusan periodogram, ia jelas menunjukkan bahawa apabila tekanan hidrogen meningkat, potensi termodinamik prestasi PEM Fuel Cell akan meningkat. Selain itu, apabila kadar aliran hidrogen ditambah, voltan prestasi PEM Fuel Cell akan menurun kerana kadar aliran hidrogen berkaitan dengan kelembapan hidrogen. Selain itu, isyarat pengenalan tekanan dan kadar alir hidrogen dengan menggunakan teknik pemprosesan isyarat menunjukkan bahawa tekanan yang berubah-ubah dan kadar alir hidrogen mempunyai kesan ke atas tingkah laku ciri yang berubah-ubah dalam PEM Fuel Cell.

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LIST OF ABBREVIATIONS

PEM	Proton Exchange Membrane
RE	Renewable Energy
R&D	Research and Development
MOSTI	Ministry of Sciences, Technology and Innovation
CI	Current Interruption
EIS	Electrochemical Impedance Spectroscopic
DC	Direct Current
H_2	Hydrogen
H_2O	Water
O_2	Oxygen
MCFC	Molten Carbonate Fuel Cell
SOFC	Solid Oxide Fuel Cell
AFC	Alkaline Fuel Cell
PAFC	Phosphoric Fuel Cell
DMFC	Direct Methanol Fuel Cell
IFC	Institute of Fuel Cell
UKM	Universiti Kebangsaan Malaysia
NASA	National Aeronautics and Space Administration
ECG	Electrocardiogram Signal
EEG	Electroencephalography
GNSS	Global Navitigation Satellite System Signal
AC	Alternative Current
V_{RMS}	Root Mean Square Voltage
V_{DC}	Direct Current Voltage
V_{AC}	Alternative Current Voltage

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Nowadays, Malaysia more focused on the renewable energy because of the increasing demand of electricity. Every year the demand for the energy sources in Malaysia keep increasing and hence the prices for the energy sources will become more expensive day by day. The main energy source is used in industrial, transportation, residential and commercial. The statistics of the U.S Energy Information Administration in 2012 shows that the main energy source consumed in Malaysia is petroleum, which is 40% while the natural gas is 36%. The other energy source that has been used is coal, biomass, and hydropower with 17%, 4% and 3% respectively.

Thus, the government introduces and promotes a renewable energy (RE) in Malaysia through Eight Malaysia Plan with a goal to achieve the target of 5% usage of the renewable energy [1]. In addition, the renewable energy can reduce dependency on fossil fuel and contribute towards reducing the effects of climate. Hence, the implication of the renewable energy can minimize enlargement energy utilization and conserve the environment for the future. Thus, for more than 10 years, Malaysia had tried many different policies, programs, funding and schemes that introduce and promote the implementation of renewable energy as an alternative energy [2].

National Green Technology Policy was launched on July 2009 by the Prime Minister, Datuk Seri Najib Tun Razak. The purpose of this policy is to develop new invention that used a green technology. The green technologies are related to the RE because it use clean energy that can reduce pollution and have long-term reliability. Therefore, through the government policies, the hydrogen Proton Exchange Membrane (PEM) fuel cell was introduced in Malaysia. Approximately RM40 million has been allocated for academic research institutions for fuel cell study and development [3].

There is a lot of research that develops the PEM Fuel Cell such as the Institute of Fuel Cell, Universiti Kebangsaan Malaysia (IFC, UKM) and at Hydrogen Economy, Universiti Teknologi Malaysia (HE, UTM), [3]. Ministry of Sciences, Technology and Innovation (MOSTI) are also investing almost 41 million in research and development (R&D) of hydrogen and a fuel cell. The research and development of fuel cell focused on the PEM Fuel Cell which uses hydrogen as a fuel. However, the development of fuel cell in Malaysia is rather slow and still new compared to the other country such as Japan and Switzerland. Malaysia was popular with other renewable energy such as solar, hydroelectric and biomass.

Basically, the PEM fuel cell generates electricity through the chemical reaction in the fuel cell without any combustion phenomenon takes place. It uses hydrogen as a fuel to generate electricity. However, there is a lot problem that is related to the performance of PEM Fuel Cell. Therefore, this problem has forced to study the effect of pressure and flow rate towards the performance of PEM Fuel Cell.

1.2 Problem Statement

Currently, the demand of electrical energy is keep growing, but the energy source is decreasing. Therefore, the fuel cell is introduced in the world and used in many applications. Malaysia government also encourages the usage of the renewable energy and hoping it to reach the goal of 5% usage. However, the fuel cell is rarely used and not commercial in Malaysia. To achieve the target, the RE such as the PEM Fuel Cell should be used in our industrial, transportation, residential and commercial. Government also provides the budget for the research and development on the fuel cell.

However, the PEM Fuel Cell consist some problems that will affect on the characteristic of the PEM Fuel Cell such as the physical of membrane, density of PEM Fuel Cell, type of coolant and so on. The characteristic of the PEM Fuel Cell also can have effects on the performance of the PEM Fuel Cell. There are a lot of phenomena that can affect the performance of PEM Fuel Cell such as drying, flooding and others. The changing of the performance of PEM Fuel Cell is depending on some parameter such as pressure, flow rate, humidity, and temperature. Thus, to overcome the problem, all the parameter that will be effected on the performance of PEM Fuel Cell should be identified and analyze.

In previous research, there are a lot of methods that can be used to analyze the result of the performance of PEM Fuel Cell. For example, the methods that can use are current interruption (CI) and electrochemical impedance spectroscopy (EIS) but it has a problem such as the price of equipment and long life of equipment. Therefore, the signal processing method can be used because the signal processing only used software to simulate the signal. The signal processing method is different from the others because it can used to monitor the PEM Fuel Cell in micro monitoring. However, this method is not commonly used in research of PEM Fuel Cell.

1.3 Objectives of Project

There are several objectives to accomplish to complete this project which are:

i. To study the effect of pressure and flow rate towards the performance of PEM Fuel Cell.
ii. To analyze the effect of the pressure and flow rate of the hydrogen towards the performance of thermodynamic potential in the PEM Fuel Cell.
iii. To investigate the signal identification of pressure and flow rate of hydrogen towards the changing behavior in PEM Fuel Cell by using signal processing technique.

1.4 Scope of Project

The model of PEM Fuel Cell that is used in this project is H-2000W from Horizon Fuel Cell Sdn Bhd. The H-2000W PEM Fuel Cell consists of 48 cells and the power rating of it is 2000 Watt. The pressure and flow rate of hydrogen are used as a parameter for the testing purposes. The digital flow rate meter from Vögtlin Instruments AG flow technology will be used to measure a flow rate of hydrogen. The hydrogen pressure will be varied for 0.1 Bar, 0.2 Bar, 0.3 Bar, 0.4 Bar and 0.5 Bar while the load value will be used from 0A to 36 A. However, the hydrogen pressure that used for hydrogen flow rate parameter testing is 0.2 Bar and 0.5 Bar only and the load current will be varied from 0A to 36 A. Thus, the outcome of the testing is focused on the current, voltage and the signal that produce from the oscilloscope. The oscilloscope with type GW-Instek GDS-3254 is used to capture the output voltage signal of the PEM Fuel Cell. Besides, the test also used a DC load 3353 to measure the voltage of the PEM Fuel Cell with varying the current of the PEM Fuel Cell. After that, two methods will be used which is performance analyze and periodogram analyze for analyzing process. The periodogram analyze, the Matlab version 2013a will use as a tool to produce a result of the periodogram technique.

1.5 Significant of Project

In this project, it has several significant that will be produced in this project. The first significant is the performance and behavior of the H-2000 W PEM Fuel Cell from the signal processing aspects can be know for the pressure and flow rate hydrogen parameter. The signal processing will be used because the result from the DC load is directly while by using a signal processing the result will be produced in more detail. The other significant is to represent the micro monitoring experiment of the signal that will know the behavior inside of the PEM Fuel Cell. On the other hand, the project also can recognize the signal identification of the PEM Fuel Cell by using a periodogram technique.

1.6 Outline of Report

In this thesis, it is consists of five chapters. In Chapter 1, the research background, problem statement, objectives, scope, and outline of this thesis will be described. Besides that, Chapter 2 will discuss about literature review that related to this project, that is including theory of fuel cell that consists of history, principle of PEM Fuel Cell, type of fuel cell, etc. In Chapter 3, the methodology of this project will be discussed in more detail. The explanation of the experimental setup, testing process and data analysis will be discussed in this chapter. Besides that, in Chapter 4, it will be discussed about the analysis and the final result of the project. Lastly, in Chapter 5 the conclusion of the project will be discussed and the recommendation from the funding research that have been made.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will review all of the research related to this project. It includes the principle of PEM Fuel Cell system and signal processing technique. In Section 2.2, it will be discussed regarding the history and the principle of the fuel cell, while in Section 2.3, the theory and basic principle of the fuel cell will be further discussed. In Section 2.4, it will be focused on a review of the previous related works of fuel cell about the parameter of effect the performance of PEM Fuel Cell and periodogram method.

2.2 Principle of Fuel Cell

The fuel cell is a device that used a reverse of the electrolysis process. The electrolysis process is created in 1800. However, in 1838 William Robert Grove obtains the idea to create a fuel cell that used a reverse electrolysis process [4]. The electrolysis process separated the water to the two elements which is hydrogen and oxygen as a mention in Equation 2.1.

$$2H_20_{(l)} \rightarrow 2H_{2\,(g)} + 0_{2\,(g)} \tag{2.1}$$

In the process of the fuel cell, the hydrogen (H_2) will combine with the oxygen (O_2) to produce energy, heat and water (H_2O). The fuel cell is an electrochemical device that dynamically converts the energy of a chemical reaction between hydrogen and an oxidant into electrical energy that are used for our consumption [4]. The equation for this process is presented in Equation 2.2.

$$2H_{2\,(g)} + O_{2\,(g)} \rightarrow 2H_2O_{(l)} + Energy \qquad (2.2)$$

Previous researcher produced the hydrogen by using the other renewable energy resources such as solar, wind, and biomass. Thus, it can be considered as green power because it is environmentally friendly, clean, and sustainable. In addition, it also can operate with less noise and can provide energy in a controlled way with higher efficiency than conventional power plants.

The principle of the fuel cell is the same as the principle of the battery. It consists of two electrodes which are anode and cathode. The electrolyte will be placed between anode and cathode. The hydrogen will enter into the fuel cell through the anode side, while air or oxygen will enter through the cathode side. The atoms of hydrogen will be separated into a proton and electron. The proton passes through the electrolyte while the electrons will create a separate current and the chemical reaction will occur along the catalyst [4].

Figure 2.1 shows the demonstration reaction of the hydrogen in the fuel cell. Energy is released from the PEM Fuel Cell because there are presence of chemical reaction between hydrogen and oxygen. Then, in the external of membrane, the electron will be moving and then chemical energy directly transformed into electricity.

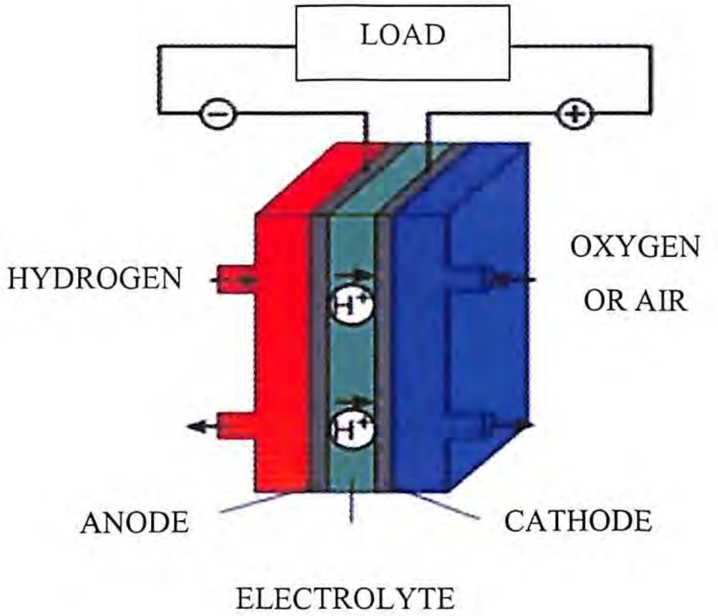


Figure 2.1: Diagram of a single PEM Fuel Cell [5]

2.3 Types of Fuel Cell

Fuel cell consists of six different types. There are several differences characteristic to distinguish the fuel cell. The differences characteristic of fuel cell types is operating temperature, materials, and a slightly different interaction.

2.3.1 Proton Exchange Membrane Fuel Cell

Proton Exchange Membrane (PEM) Fuel Cell is also known as a Polymer Electrolyte Membrane (PEM) Fuel Cell [6]. In the early 1960s, PEM Fuel Cell technology is invented at General Electric through the work of Thomas Grubb and Leonard Niedrach. Through the program with the U.S. Navy's Bureau of Ships Electronics Division and the U.S. Army Signal Corps, general electric is successfully developed a small fuel cell [4].

The electrolytes of PEM Fuel Cell use a water-based and solid polymer membrane. The catalysts of PEM Fuel Cell use platinum because it has most chemically active substance for low temperature hydrogen separation. However, the cost of platinum is more expensive than other type of fuel cell. Basically, PEM Fuel Cell operates at low temperature, which is between 70°C and 90°C and produce high power density [3,6]. The efficiency of this fuel cell is 40% and can even reach up to 50%. PEM Fuel Cell is suitable used for vehicle, building, rechargeable batteries and portable application. Figure 2.2 shows the cross-sectional of PEM Fuel Cell. It used pure hydrogen as a fuel to react the chemical in the fuel cell. The hydrogen enters to the fuel cell through anode electrode while oxygen enters through cathode electrode. Then, the water will be produced. Equation 2.3 presents the reaction in the PEM Fuel Cell.

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O \tag{2.3}$$

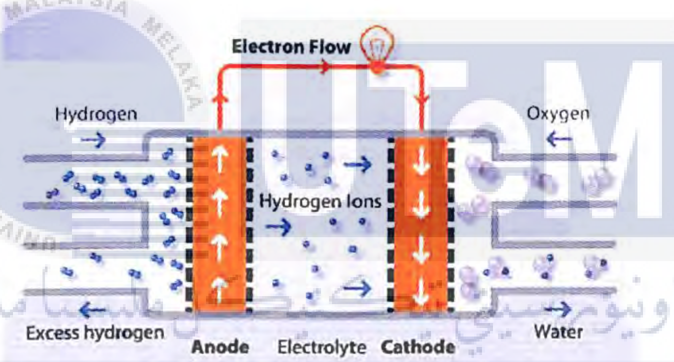


Figure 2.2: Proton Exchange Membrane Fuel Cell work [7]

2.3.2 Molten Carbonate Fuel Cell

Molten Carbonate Fuel Cell (MCFC) uses a molten carbonate salt mixture as the electrolyte fuel cell. The content of the salt mixture is lithium carbonate and potassium carbonate. It can act as an excellent conductor of ion if the temperature is higher. The electrolyte of MCFC is contained in a porous ceramic matrix [6]. Basically, MCFC can produce a higher efficiency, which is 50% to 60%. It can run continuously due to the high operating temperature from 600°C to 1000°C. Hence, MCFC is suitable for central, stand-alone and combined heat power. Most of the fuel cell power plants of megawatt capacity use MCFC as a combined heat and power plants.

Figure 2.3 shows the operation MCFC that used a hydrogen and carbon monoxide as a fuel that enter through the anode of electrode. It also required oxygen and carbon dioxide to be entered through the cathode of electrode. Then, at the electrolyte, the chemical will be reacting and carbonate ions will be active and produce electricity [6]. The overall reaction of the MCFC will be producing water and the carbon dioxide when the hydrogen, oxygen and carbon dioxide react together in the MCFC. Equation 2.4 shows the reaction of MCFC.

$$H_2 + \frac{1}{2} O_2 + CO_2 \rightarrow H_2O + CO_2 \quad (2.4)$$

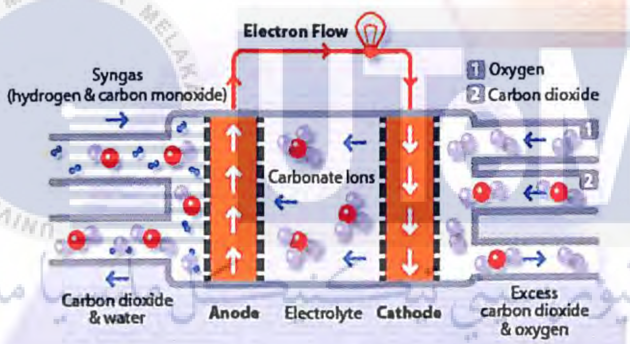


Figure 2.3: Molten Carbonate Fuel Cell cross-sectional view [7]

2.3.3 Solid Oxide Fuel Cell

In the late 1930s, Swiss scientist Emil Baur and his colleague H. Preis do an experiment on the solid oxide electrolyte by using many materials such as zirconium, yttrium, cerium, lanthanum, and tungsten [4]. These materials are an excellent conductor and also produce high temperature. The operating temperature of Solid Oxide Fuel Cell (SOFC) is 800°C to 1000°C. Thus, the efficiency of the SOFC is also higher which is from 50% to 60%.

However, the effect of the increase of temperature will occurs. For example, it can cause a thermal stress failure, coking and sulfur poisoning.

Figure 2.4 shows the operation of the SOFC. The input of fuel at anode electrode for SOFC is hydrogen and carbon monoxide, which is the same as MCFC. However, the differences between SOFC and MOFC are the cathode electrode of SOFC only used oxygen while MOFC used an oxygen and carbon dioxide. The process will produce water that shows in Equation 2.5.

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O \tag{2.5}$$

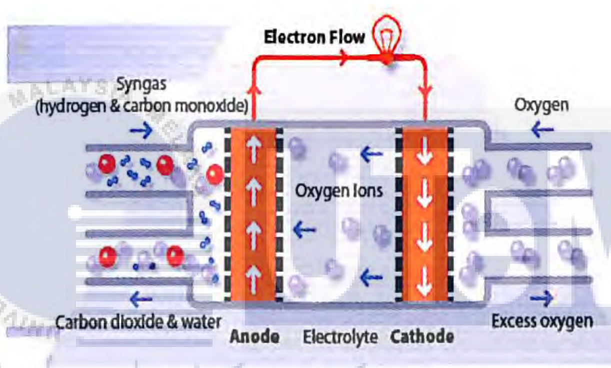


Figure 2.4: Solid Oxide Fuel Cell cross-sectional view [7]

2.3.4 Alkaline Fuel Cell

Francis Thomas Bacon had done the experiment on the alkaline in the electrolyte [4]. The solution of an Alkaline Fuel Cell (AFC) is potassium hydroxide that used as an electrolyte where the electrolyte is kept in a matrix. The hydrogen that flows inside of the AFC can pass through the anode electrode, while electrons cannot [6]. The operating temperature is 50°C to 90°C. AFC can offer and produce high efficiency from 50% to 70%. However, AFC can affect the environment because it can cause corrosion to the air. The AFC also is more expensive because of the material that used in the fuel cell. This fuel cell is suitable to be used for space application. For instance, it had been used on many National Aeronautics and Space Administration (NASA) shuttles and had also been under development by the military [6].

In general, AFC used a basic concept of fuel cell which is in the anode of the electrode, the hydrogen will be entered through it. While at the cathode, the oxygen will be entered. However, in the electrolyte, the hydroxide ion will be produced by the chemical reaction of the catalyst. The water will be produced during the process. The principle of AFC is shown in Figure 2.5.

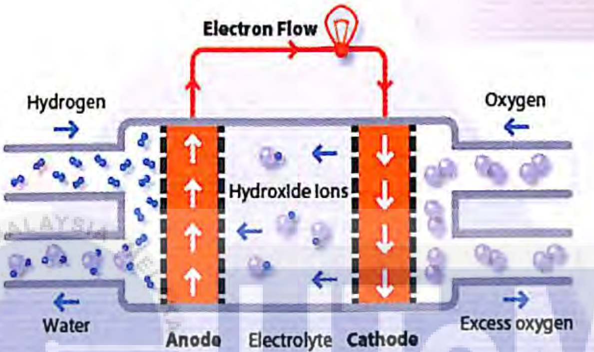


Figure 2.5: Alkaline Fuel Cell cross-sectional view [7]

2.3.5 Phosphoric Acid Fuel Cell

A liquid of phosphoric acid is used as an electrolyte in the Phosphoric Acid Fuel Cell (PAFC). This fuel cell can operate at the 175°C to 220°C. It uses a finely dispersed platinum catalyst on carbon and also quite resistant to poisoning by carbon monoxide. However, the efficiency of this fuel cell is relatively low between 40% and 45%. But if the heat is used, the overall efficiency can increase and reach over than 80%. Basically, PAFC are used in hospitals, hotels, office building, schools, utility power plants, and site water treatment plant. Besides that, the PAFC is very tolerant to impurities in the reformed hydrocarbon fuels [6]. It causes the cost of the fuel cell to decrease and cheaper than before. Figure 2.6 shows the operation of the PAFC which use hydrogen to anode and oxygen to cathode.

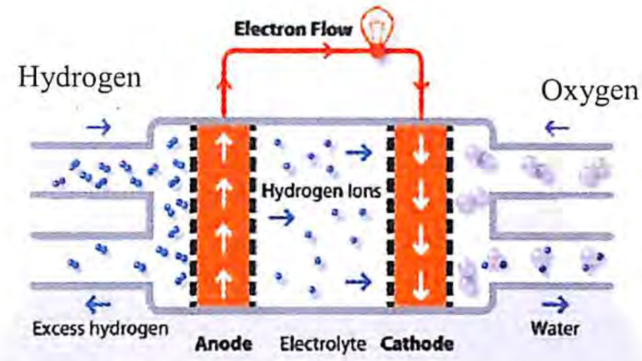


Figure 2.6: Phosphoric Acid Fuel Cell cross-sectional view [7]

2.3.6 Direct Methanol Fuel Cell

Direct Methanol Fuel Cell (DMFC) is similar to the PEM FUEL CELL in that the electrolyte is a polymer membrane. The efficiency of current DMFC is low around 25% to 40% due to the high penetration of methanol through the membrane material used, which is known as methanol crossover [3,4]. The operating temperature is about 50°C to 120°C. Thus, the catalyst will require more carbon dioxide. As a result, a larger quantity of carbon dioxide is needed. Hence it will affect the cost of the fuel cell. DMFC technology is relatively new compared with the fuel cells that are powered by pure hydrogen, and the main application is in powering mobile phones and laptop computers. DMFC products are being developed for these applications by companies such as Samsung in Korea, and by Toshiba, Hitachi and Sanyo in Japan [4].

Figure 2.7 shows the operation of the DMFC. It used a hydrogen ion as a charge carrier. Liquid methanol is oxidized in the presence of water at the anode generating carbon dioxide, hydrogen ions and the electrons that travel through the external circuit as the electric output of the fuel cell. The hydrogen ions travel through the electrolyte and react with oxygen from the air and the electrons from the external circuit to form water at the anode completing the circuit.

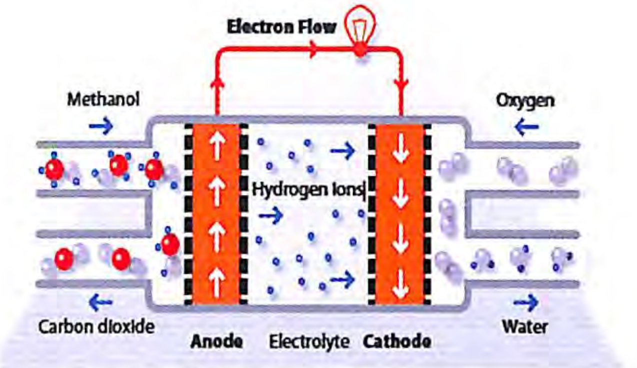


Figure 2.7: Direct Methanol Fuel Cell cross-sectional view [7]

2.4 Review of Related Previous Works

The previous work will be divided into two sections which is parameters effect on the performance of PEM Fuel Cell and signal processing system. In Section 2.4.1, the parameter that related is pressure and flow rate of the hydrogen, while in Section 2.4.2 are described of the periodogram methods that used to analyze the signal of any application.

2.4.1 Review on the Parameter Effect towards the Performance of PEM Fuel Cell

In recent year, the PEM Fuel Cell is widely used for many applications in the world. However, the PEM Fuel Cell has unstable operation and makes an effect on the performance of the PEM Fuel Cell. There is a lot of researcher that had done a research on the PEM Fuel Cell and they focus a research on different aspects. For example, Larbi et al. [8] studied the effect of the porosity and pressure on the performance of PEM Fuel Cell. Maher and Sadiq [9] studied how to optimize the performance of hydrogen and oxygen of the PEM Fuel Cell. Mousa et al. [10] studied the effect of the stack orientation of the hydrogen or air on the performance of the hydrogen PEM Fuel Cell. Guvelioglu and Stenger [11] studied the flooding effect on the performance and operation PEM Fuel cell. Ji and He [12] studied a humidifier controller and the effect of the humidifier on the PEM Fuel Cell.

However, the performance of the PEM Fuel Cell will be affected by four important parameters which are pressure, flow rate, temperature and humidity. Therefore, according to the reference [13-21], the report has done a research on the four parameters, but they used a different method to know the effect on the performance of the PEM Fuel Cell. Hence, Amirinejad et al. [13] do a testing of the temperature, pressure, and humidity of the reactant gases on the fuel cell with a constant operating temperature (70 °C) and humidified but a variable pressure at the cathode and anode side from 1 atm to 3 atm. They focused on the pressure in the cathode and anode side of the stack PEM Fuel Cell. The pressure at the cathode side is better affecting the performance of the PEM Fuel Cell than the pressure at the anode side.

Moreover, Wang et al. [14] represent the effect on the performance PEM Fuel Cell by using a different operating pressure, humidity, temperature and combination of all the parameters on the anode side of the PEM Fuel Cell. The ranged of the pressure is from 1 atm to 3.72 atm and each of the parameter is controlled by using specific equipments. The result of this experiment shows that the polarization is increased when the pressure is increased. Different with Lee et al. [15], they do a design and fabrication a flexible integrated micro-sensor to overcome the flooding problem. They know that the flooding problem can affect the performance of the PEM Fuel Cell. Therefore, the micro-sensor has done designed to monitor the pressure and flow rate hydrogen to reduce a flooding and increase the performance of PEM Fuel Cell. Other than that, Pei et al. [16] also testing a hydrogen pressure on 10kW PEM Fuel Cell stack to know the effect for flooding diagnostic systems. They used purge hydrogen to avoid a flooding and then measure the pressure drop when the flow rate between the inlet and outlet changed.

According to Soltani and Bathaee [17], authors focused on the effect of the temperature, pressure of fuel and the different situation load of resistance. They used a MATLAB to show their simulation results and compare it with the experimental test. The output characteristics of the PEM Fuel Cell are affected dramatically when the temperature, pressure of fuel, and difference resistance load are varied. In addition, Moldrik and Chvalek [18] have done a research that finds the optimal operating parameter that will produce a good operation. They varied the pressure interval between 1.2 atm and 2 atm. Based on the experiment, the polarization curve raised when the operating pressure increased. The output operation of PEM Fuel Cell is increased because of the reaction of the hydrogen in the PEM Fuel Cell that pushed the hydrogen and oxygen to place the contact with the membrane. Thus, the effect of the pressure becomes higher if the current is higher.

Besides that, Chu and Jiang [19] is elaborating the effect flow rate when the temperature and humidity are constant. Based on the experiment, the flow rate of hydrogen is an important parameter that will be affected the polarization curve of the PEM Fuel Cell. The over pressure of the hydrogen will make a membrane of the PEM Fuel Cell ripped. Therefore, they take a constant at low pressure of hydrogen while the flow rate of hydrogen will be varied. The result shows that the different flow rate of hydrogen does not have a significant effect on the polarization curve of the PEM Fuel Cell until current achieve high point. Meanwhile, Wahdamea et al. [20] has designed a new method to combine all four parameters in one experiment and the result shows that the increasing of the pressure was produced a higher voltage for PEM Fuel Cell.

Based on the review, a lot of previous projects used a pressure, flow rate, humidity and temperature as a parameter that was used in their experiments. However, a different author used different equipment and components to produce a data for their experiment. Authors also used a different technique and method to analyze the data that gets from the experiments.

2.4.2 Review of Periodogram Methods

The periodogram method is one of the techniques of signal processing system. It also a class of the spectral analysis that used based on the basic sampled from the observation [21]. This method used to analyze the data signal that gets from any system or application. The periodogram represents the signal power over frequency which is the frequency shows as an x-axis while the magnitude as a y-axis [22]. In recent year, many of the research used the periodogram methods to analyze the signal of their research because it helps them determine the signal in more details. According to Font et al. [21], they used a periodogram method to analyze the multiband signal. The periodogram method is analyzed in a cognitive radio scenario. As a result, they know that the periodogram method provides a good resolution for the spectral analysis. In addition, Olabiyi and Annamalai [23], periodogram used to investigate the performance of spectrum sensing to analyze the frequency domain. However, they modified the periodogram to produce a better signal.

Authors in [22], they used a periodogram method to analyze the electrocardiogram (ECG) signal from the heart block detection. The ECG signal is calculated and then the frequency of the signal is represented in term of discrete-time waveform. The Matlab is used to compute the signal for the pre-processing signal and then implementation it into the visual basic. The result of periodogram provides a real time of heart block problems and used to compare the data between the normal condition and heart block condition. In addition, according to Zhou et al. [24], the electroencephalography (EEG) signal is analyzed by using the periodogram method based on the time interval to maximum periodogram. Then, it has provided a good time and frequency resolution of the EEG signal.

On the other hand, Jun et al. [25] also uses the periodogram method to analyze the global navigation satellite system (GNSS) signal. They simulate the 3dB-bandwidth of GNSS signal through the periodogram method and produce a large bandwidth that is suitable for analyzing GNSS signal. However, in Yili et al. [26], the periodogram is used to analyze the signal of the robotic sensitive skin. The result of the periodogram method is produced from the simulation and used to reduce the effect of a noised and improve the accuracy of the robotic sensitive skin. According to reference [21-26], the periodogram method can be used to analyze any signal in any application or system. The result will be produced a signal that consists of the frequency and magnitude. Therefore, this technique can be used to analyze the data of the PEM Fuel Cell in more detail in term of the signal processing system.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

Chapter 3 will discussed the research methodology of the project. Section 3.2 will show the detail about the flow chart methodology that will started with the literature on the project. In Section 3.3 and Section 3.4, the experimental setup and testing process will be discussed step by step. While in Section 3.5, the process of the data analysis will be explained. However, in this section, it will be divided into three parts which is the performance characteristics analysis and signal processing analysis. Then, the Section 3.6 is the summary of this chapter.

3.2 Flowchart of Methodology

Figure 3.1 represents the flow chart of the methodology for this research that start with literature review, or the study of the previous work that related to this research and last with the writing a report. The flow chart is divided into four stages which are literature review, experiment setup, testing, and data analysis.

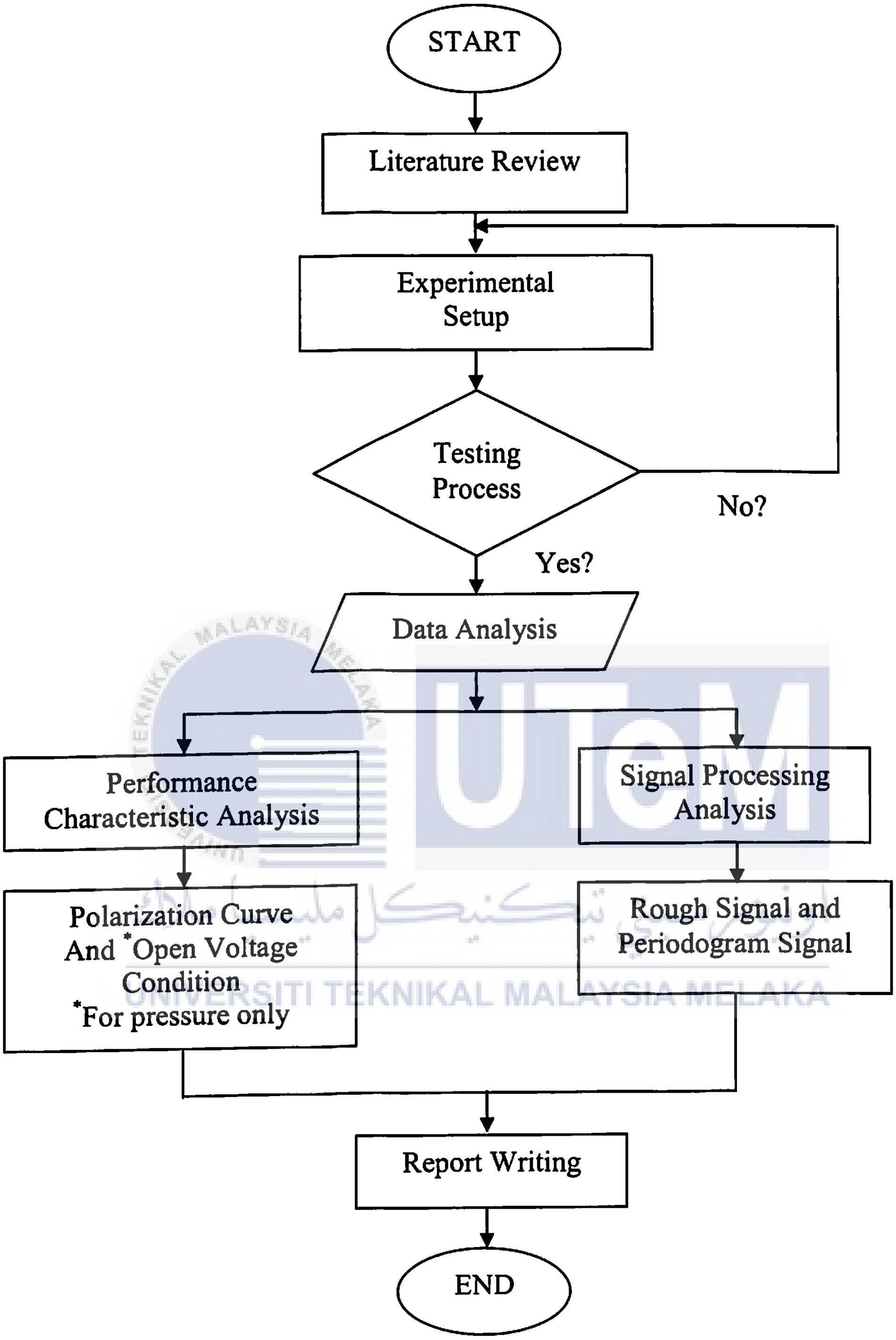


Figure 3.1: Flow chart of methodology

i. Literature Review

The literature reviews regarding on previous research work in identifying any important issue about the fuel cell method from IEEE journals, articles, books, and others. This stage involved more study on the concept of fuel cell system that focused on the hydrogen PEM Fuel Cell. Besides that, the research on previous work that related to PEM Fuel Cell, renewable energy, and DC load will be done in this stage. The research also focuses on the signal processing system that used a periodogram technique to analyze the data of the PEM Fuel Cell.

ii. Design and Setup the Experiment

Stage two is the design circuit and set up of the experimental project. Before setup the system of PEM Fuel Cell, the circuit should be designed first. The design must be including of two important equipments for measurement of the pressure and flow rate. The pressure regulator will be used to measure the pressure of the hydrogen, while flow rate meter will be used to measure a flow rate of hydrogen flow in the PEM Fuel Cell.

iii. Testing Process

The next stage is a testing process. This stage will started after all the equipment is set up. The testing process will use a DC load to vary the value of current and also to measure the output voltage of the PEM Fuel Cell. However, the oscilloscope is used to capture the signal that is produced during the testing process.

iv. Analysis Process

At the last stage, all the data that collected and recorded during the testing process will be analyzed. The analysis process is divided into three sections. The first section is focused on the basic analysis of the performance characteristic PEM Fuel Cell that including the voltage, current and power characteristics. The polarization will be plot based on the result. The second section focuses on the periodogram technique. All the signal that is captured by using oscilloscope will be transferred to the Microsoft Excel and then simulate by using a Matlab.

3.3 Experimental Setup of Pressure and Flow Rate

The schematic drawing is designed as a guideline to set up the experiment of this project. The schematic of the overall system is shown in Figure 3.2.

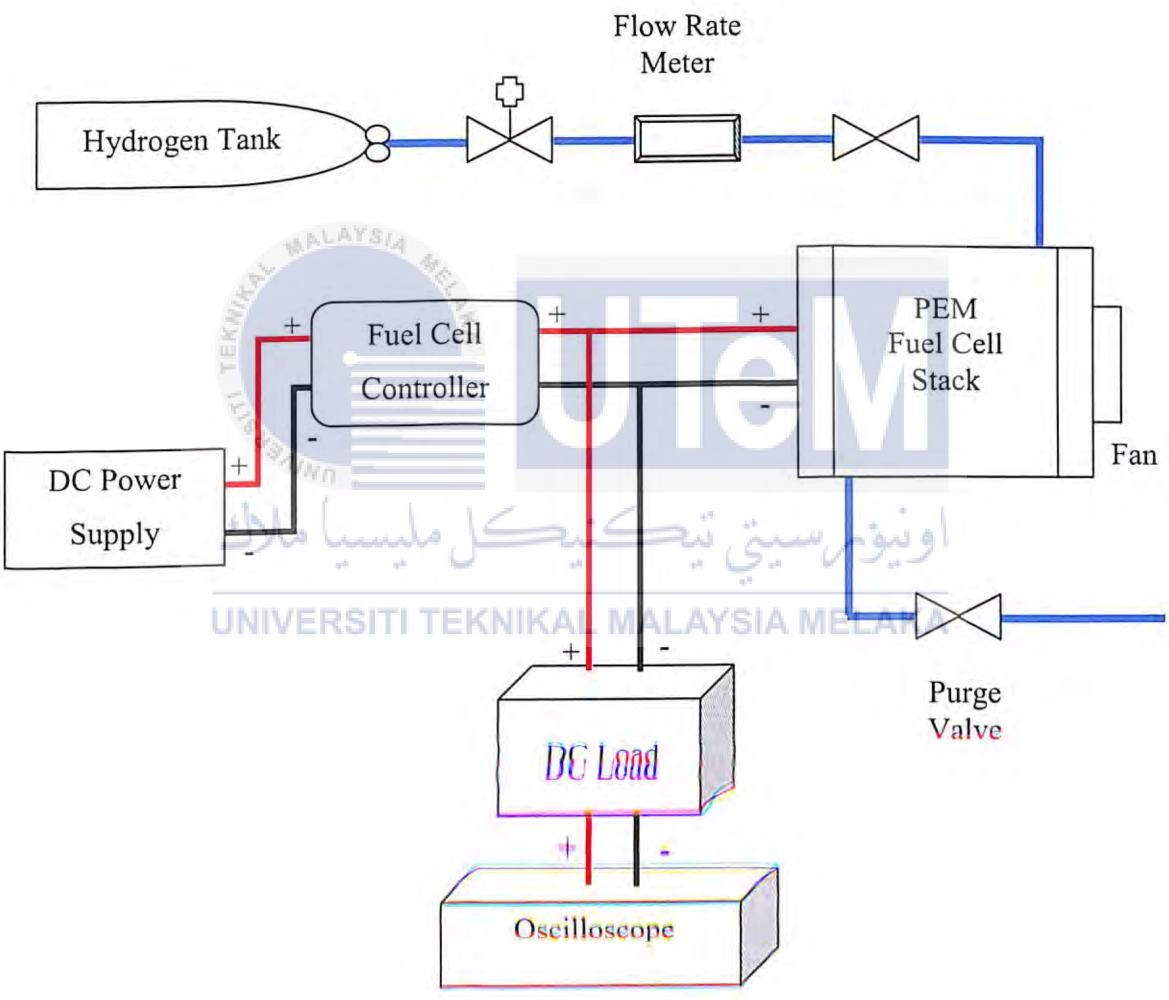


Figure 3.2: Schematic drawing of the system

Based on Figure 3.2, the pure hydrogen is served as a fuel to operate the PEM Fuel Cell to produce electricity. The pure hydrogen is stored in the specific tank to avoid the hydrogen release. Then, the pure hydrogen will be connected directly to the PEM Fuel Cell as shown in the Figure 3.2. The experiment should be setup by following schematic drawing in Figure 3.2.

3.4 Testing Process of Pressure and Flow Rate

In the testing process, the pure hydrogen is used directly from the tank in Figure 3.3. The stack of the PEM Fuel Cell and hydrogen is connected by using a polyurethane pipe. Between the hydrogen tank and stack PEM Fuel Cell, the pressure regulator and the flow rate is placed in the system as a component that used to measure the pressure of the hydrogen and the flow rate of the hydrogen. This component is important because it is used as a parameter that can affect the performance of the PEM Fuel Cell. The pressure and flow rate of hydrogen will be varied, but the others parameter is fixed such as temperature and humidity. The temperature will be fixed at the 25 °C while humidity is 0 % or dry.

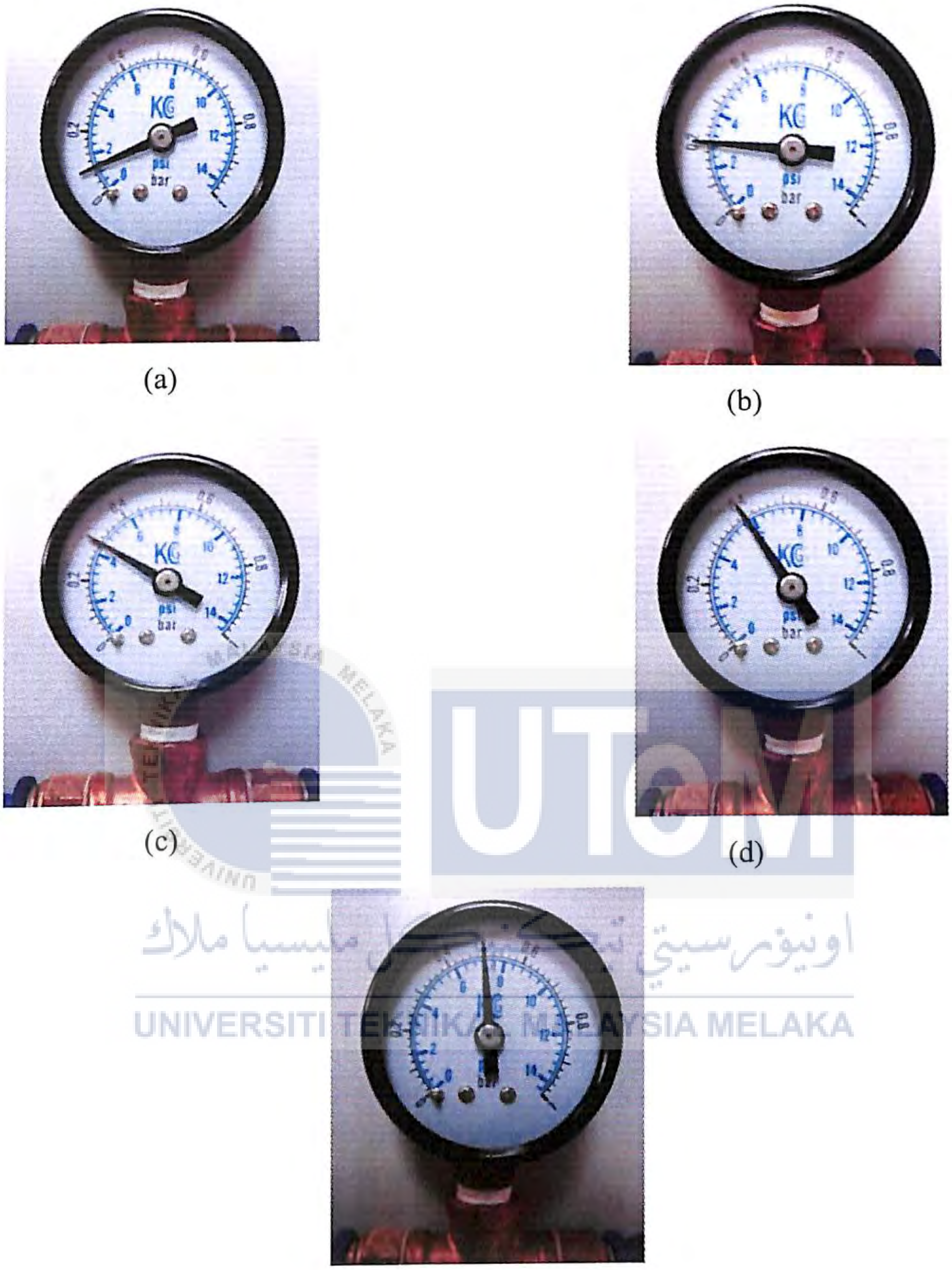
Figure 3.3: Hydrogen tank system

Then, the connection of the polyurethane pipe will be connected to the inlet of the stack PEM Fuel Cell. The H-2000 W PEM Fuel Cell will be used in this experiment and it is from the Horizon Fuel Cell Technologies. The PEM Fuel Cell is an open cathode type and has a cooling fan at the cathode side as a cooling system. The power supply used to operate cooling fan is around 12 V to 13 V. The cooling fan, inlet valve and purge valve will be controlled by a controller that provided from the Horizon with the stack of the PEM Fuel Cell. The time of purging valve is already set in the controller of the PEM Fuel Cell. The function of the purge valve is used to release a balanced hydrogen and water in the stack. The outlet of the purging should be connected far away from the stack because to avoid from the hydrogen from the purge valve flow back to the stack and will make a damage on the stack. Table 3.1 shows the specification of the H-2000 W PEM Fuel Cell that consists of 48 cells in the stack of PEM Fuel Cell.

Table 3.1: Specification of the H-2000W of PEM Fuel Cell

Number of cells	48 cells
Rated power	2000W
Performance	28.8 V @70A
Input valve voltage	12V
Cooling fan voltage	12V
Purging valve voltage	12V
Efficiency of stack	40% @ 28.8V
Maximum stack temperature	65°C
Reactants	Hydrogen and Air
Hydrogen pressure	0.45-0.55

The output of the PEM Fuel Cell will be measured by using a DC load 3353 from Prodigit and the oscilloscope GW-Instek GDS-3254. The load current variation is obtained from the DC load. The current is varied from 0 A until the maximum of the PEM Fuel Cell can be operated. The output signal of the PEM Fuel Cell will be captured by using an oscilloscope. The signal data is captured for 1 minute for every current. The testing will be tested with the pressure of hydrogen 0.1 Bar and continued with 0.2 Bar to 0.5 Bar. The setting of the pressure regulator cannot be more than 0.55 Bar because it can carry out damage on the membrane of the PEM Fuel cell will be ripped. Figure 3.4(a) to Figure 3.4(e) represents the diagram of the pressure regulator for the 0.1 Bar to 0.5 Bar.



(a) (b) (c) (d) (e)

Figure 3.4: Reading of hydrogen pressure on the pressure regulator;
(a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure
(d) 0.4 Bar hydrogen pressure (e) 0.5 Bar hydrogen pressure

However, the digital flow rate meter from the Vögtlin Instruments AG flow technology will be used and record for every changing of the current of the load. The data of the hydrogen flow rate will be recorded for the pressure 0.2 Bar and 0.5 Bar because it will be used to compare the flow rate in a different pressure of hydrogen. Figure 3.5 shows the digital flow rate meter from the Vogtlin Instrument.

Figure 3.5: Digital hydrogen flow rate meter

Figure 3.6 shows the experimental setup of the PEM Fuel Cell. All the components and equipment is setup by following the schematic drawing in Figure 3.2.

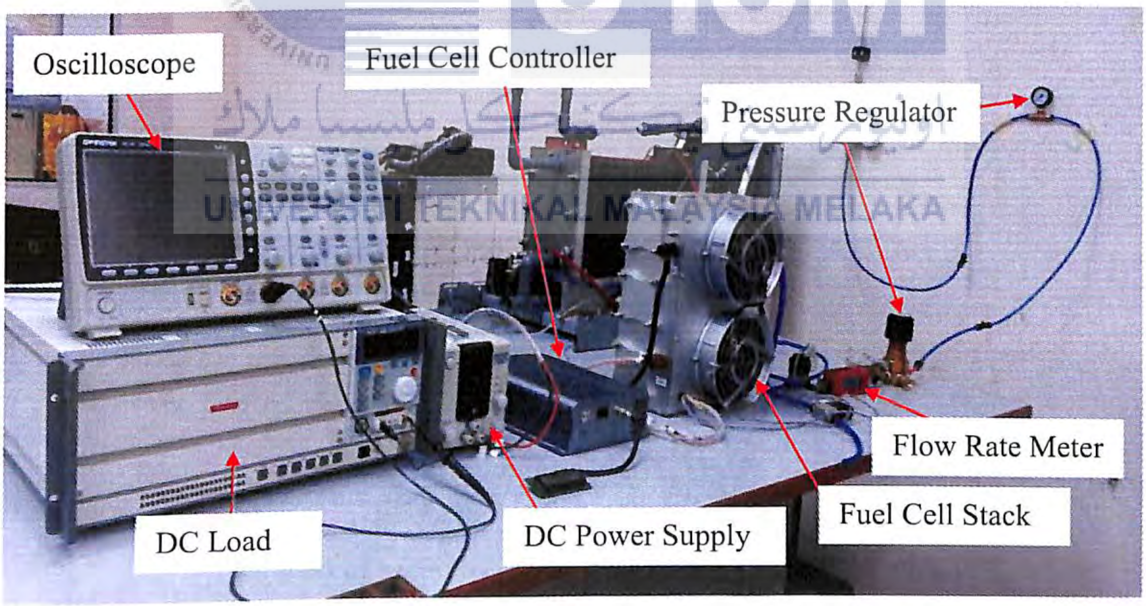


Figure 3.6: Experimental setup of the PEM Fuel Cell system

3.5 Analysis Methods

The data that are recorded from the experiment will be analyzed using two methods which are basic performance characteristics analysis and signal processing system analysis.

3.5.1 Basic Performance Characteristic Analysis

Firstly, the data performance of the PEM Fuel Cell will be analyzed by using a basic method which is in term of the polarization curve. Basically the polarization curve is present the data of the voltage against the current of the performance PEM Fuel Cell. The polarization curve will be explained the reaction of the effect parameter of the PEM Fuel Cell on the performance characteristic that produce [27]. Most of the experiment that has published used a polarization curve to illustrate the results of the experiment. Figure 3.7 represents the sample of the polarization curve of the PEM Fuel Cell that shows in the literature review.

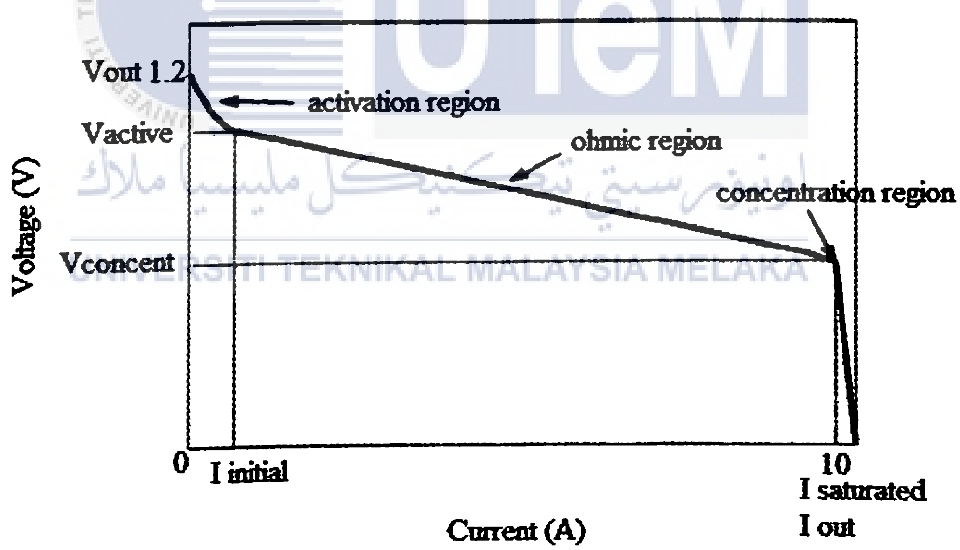


Figure 3.7: Polarization curve (voltage against current) [28]

Basically, based on the theory, the performance of the output characteristic is separated into three regions which is activation region, ohmic region, and concentration region. This region represents the losses of the PEM Fuel Cell during the operation. However, all the losses are not considered in this experiment. Based on the basic polarization curve, the data will be analyzed in term of voltage against current and power against current.

3.5.2 Periodogram Method

This section gives the explanation on the programming of the signal processing system analysis which is periodogram analyze. The periodogram will be used to analyze the data from the oscilloscope. This technique is a new method that can be used to analyze the data. The periodogram method will plotted a graph in term of the magnitude versus frequency. The Matlab will be used as a simulator or tool to simulate the data of the PEM Fuel Cell. The data form oscilloscope will be saved in Microsoft Excel. Then, the data will be transferred and link with the Matlab in analyzing process to produce periodogram signal.

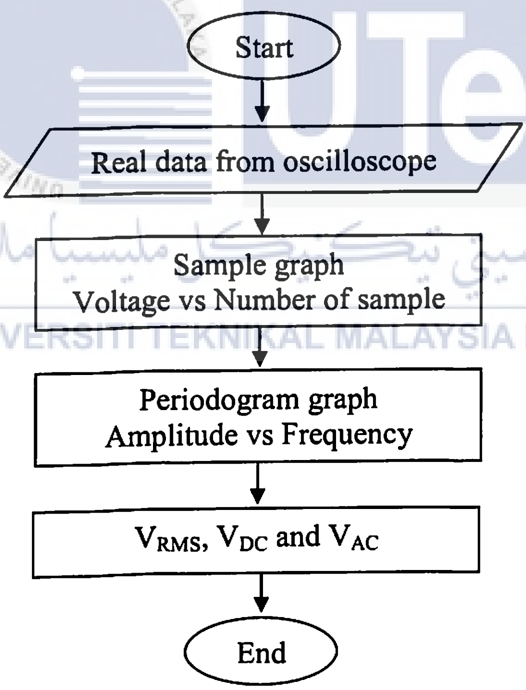


Figure 3.8: Flow chart of the periodogram method

Figure 3.8 shows the flow of the periodogram coding that will be used in the Matlab. The program will started with the clear all the unneeded instruction in the Matlab. Then, the data from the excel will be called first and produce a graph for the real data from the oscilloscope. After that, the real data from the oscilloscope also will be used to create a periodogram graph. The periodogram graph will be plotted in term of magnitude against frequency. In the part of the periodogram coding, it used some of the equations to produce a periodogram results. It will be defined as in Equation 3.1 and from the equation the results will be produced a periodogram in term of frequency domain.

$$S_v(f) = \left| \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} v(t) e^{-j2\pi f t} dt \right|^2 \tag{3.1}$$

The S_v (f) is a periodogram in term of frequency domain while V(t) is a voltage waveform of the data. Therefore, the voltage of root mean square (V_{RMS}) can be calculated as in Equation 3.2 while a direct current voltage (V_{DC}) can be calculated as in Equation 3.3.

$$V_{RMS}(t) = \sqrt{\int_{-\frac{f_{max}}{2}}^{\frac{f_{max}}{2}} S_v(f) df} \tag{3.2}$$

$$V_{DC}(t) = \sqrt{\int_{-\frac{\Delta f}{2}}^{\frac{\Delta f}{2}} S_v(f) df} \tag{3.3}$$

Where $f_{max}/2$ is the maximum frequency of interest and $\Delta f/2$ is define as power system frequency. At the last, the simulation will be calculated the alternating current voltage (V_{AC}). The calculation the V_{AC} is shown in Equation 3.4.

$$V_{AC}(t) = \sqrt{V_{RMS}(t)^2 - V_{DC}(t)^2} \tag{3.4}$$

Hence, the coding of the periodogram simulation will be shown in Figure 3.9 that is including all the element that is needed and also the equation that will be used to produce a periodogram graph, V_{RMS}, V_{DC} and V_{AC}.

```
clear all;
clc;
close all;

Fs0=500;
Fs=10;

load('p0200.mat');

%----------------------------resample graph-------------------------------%%

Nsample=length(p0200);
x=p0200(1:Nsample);

time1=([0:1/Fs:(Nsample-1)/Fs]);
%------------------------------periodogram--------------------------------%%
xb=p0200;
N=length(xb);

xa=smooth(xb,100);

x0=resample(xa,Fs,Fs0);

N0=length(x0);
x1=x0(10:N0-10);
Na=length(x1);

Y1=fft(xb);
Ny,Nx]=size(Y1)
Y1=Y1.*conj(Y1)/Ny/Ny;

freq=[0:Fs/Ny:(Ny-1)*Fs/Ny];
time=([0:1/Fs:(Na-1)/Fs]);

figure(1);plot(xa);grid;ylabel('Voltage (V)','Fontsize',24);xlabel('Number
of sample','Fontsize',24);title('Fuel Cell','Fontsize',24);
figure(2);plot(time,x1);grid;ylabel('Voltage(V)','Fontsize',24);xlabel
('Time(sec)','Fontsize',24);title('Fuel Cell','Fontsize',24);
figure(3);plot(freq,Y1);grid;ylabel('Amplitude','Fontsize',24);xlabel('Freq
uency(Hz)','Fontsize',24);title('Periodogram','Fontsize',24);

    y(1:Ny)=Y1(1:Ny);
   % looking for end point for DC
   m=1;
   for k=2:Ny-2
       if (y(k)<=y(k+1))
           a(m)=k;
```

```
            m=m+1;
        end
    end
    Nend=a(1);
      % looking for start point for DC
     m=1;
    for k=1:Ny-2
        if (y(Ny-k)<=y(Ny-k-1))
            a(m)=Ny-k;
            m=m+1;
        end
    end
    Nstart=a(1);

    Vdc=(sum(Y1(Nstart:Ny))+sum(Y1(1:Nend)))^0.5;
    Vrms=sum(Y1(1:Ny))^0.5;
    Vac=(Vrms^2-Vdc^2)^0.5;

VRMS=Vrms
VDC=Vdc
VAC=Vac
```

Figure 3.9: Coding of periodogram method

3.6 Summary

Chapter 3 is started with the flow chart methodology in Section 3.2 that shows the flow of the project process. The explanation of the project is detailed in Section 3.3 and Section 3.4. Hence, it includes the experimental setup and testing process and also the process of analysis the data. However, the process of data analysis is divided into three parts that include the performance characteristic analysis and periodogram analysis.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In Chapter 4, the result and discussion of the project will be analyzed and discussed. The result of the experiment is divided into two parts. In section 4.2, the results from the DC load will be analyzed using a performance characteristic analysis while in Section 4.3 the results of the periodogram analysis will be explained in detail.

4.2 Results of Performance Characteristic Analysis

The results of the experiment are divided into two parts which are pressure of hydrogen parameter and flow rate of hydrogen parameter. Section 4.2.1 will focused on the pressure effect, while Section 4.2.2 focused on the flow rate effect on the performance characteristics of PEM Fuel Cell.

4.2.1 Results of Hydrogen Pressure (Polarization Curve and Open Voltage Condition)

The data performance of PEM Fuel Cell that is taken from the DC load is recorded as in Table 4.1. The current that has done varied is from 0 A to 36 A for the pressure of hydrogen 0.1 Bar to 0.5 Bar. The voltage each of the experiments is recorded in Table 4.1 and then, the power is calculated based on the current and voltage from the experiment.

Table 4.1: Data of voltage and power of the pressure parameter

Current (A)	Voltage					Power				
	0.1 Bar	0.2 Bar	0.3 Bar	0.4 Bar	0.5 Bar	0.1 Bar	0.2 Bar	0.3 Bar	0.4 Bar	0.5 Bar
0	43.50	43.80	44.80	45.20	45.70	0.00	0.00	0.00	0.00	0.00
1	38.40	39.00	40.70	41.50	41.80	38.40	39.00	40.70	41.50	41.80
2	37.10	37.80	39.40	40.10	40.60	74.20	75.60	78.80	80.20	81.20
3	36.50	37.40	38.60	39.30	39.80	109.50	112.20	115.80	117.90	119.40
4	35.90	36.90	38.10	38.50	39.00	143.60	147.60	152.40	154.00	156.00
5	35.30	36.60	37.40	38.00	38.50	176.50	183.00	187.00	190.00	192.50
6	35.00	36.40	37.00	37.60	38.00	210.00	218.40	222.00	225.60	228.00
7	34.70	36.10	36.50	37.20	37.50	242.90	252.70	255.50	260.40	262.50
8	34.50	35.80	36.30	36.80	37.10	276.00	286.40	290.40	294.40	296.80
9	34.16	35.60	35.90	36.30	36.60	307.44	320.40	323.10	326.70	329.40
10	33.90	35.40	35.60	36.00	36.30	339.00	354.00	356.00	360.00	363.00
11	33.70	35.10	35.40	35.70	36.00	370.70	386.10	389.40	392.70	396.00
12	33.50	34.80	35.10	35.40	35.80	402.00	417.60	421.20	424.80	429.60
13	33.20	34.50	34.80	35.10	35.40	431.60	448.50	452.40	456.30	460.20
14	33.00	34.30	34.60	34.90	35.20	462.00	480.20	484.40	488.60	492.80
15	32.80	34.00	34.40	34.70	35.00	492.00	510.00	516.00	520.50	525.00
16	32.70	33.80	34.10	34.40	34.80	523.20	540.80	545.60	550.40	556.80
17	32.60	33.60	33.90	34.20	34.50	554.20	571.20	576.30	581.40	586.50
18	32.40	33.30	33.70	34.00	34.30	583.20	599.40	606.60	612.00	617.40
19	32.20	33.10	33.50	33.80	34.00	611.80	628.90	636.50	642.20	646.00
20	32.10	32.90	33.30	33.60	33.80	642.00	658.00	666.00	672.00	676.00
21	31.90	32.60	33.10	33.30	33.60	669.90	684.60	695.10	699.30	705.60
22	31.80	32.30	32.90	33.20	33.50	699.60	710.60	723.80	730.40	737.00
23	31.60	32.10	32.70	33.00	33.30	726.80	738.30	752.10	759.00	765.90
24	31.40	31.80	32.60	32.80	33.10	753.60	763.20	782.40	787.20	794.40
25	31.30	31.70	32.40	32.60	32.90	782.50	792.50	810.00	815.00	822.50
26	31.10	31.40	32.20	32.40	32.80	808.60	816.40	837.20	842.40	852.80
27	31.00	31.30	32.10	32.30	32.70	837.00	845.10	866.70	872.10	882.90
28	30.80	31.20	32.00	32.20	32.50	862.40	873.60	896.00	901.60	910.00
29	30.60	31.00	31.80	32.00	32.30	887.40	899.00	922.20	928.00	936.70
30	30.40	30.90	31.60	31.80	32.20	912.00	927.00	948.00	954.00	966.00
31	30.20	30.70	31.40	31.70	32.00	936.20	951.70	973.40	982.70	992.00
32	30.10	30.60	31.20	31.50	31.90	963.20	979.20	998.40	1008.00	1020.80
33	29.90	30.40	31.00	31.40	31.70	986.70	1003.20	1023.00	1036.20	1046.10
34	29.70	30.20	30.90	31.20	31.50	1009.80	1026.80	1050.60	1060.80	1071.00
35	29.50	30.00	30.70	31.00	31.30	1032.50	1050.00	1074.50	1085.00	1095.50
36	29.40	29.90	30.50	30.80	31.10	1058.40	1076.40	1098.00	1108.80	1119.60

The polarization curve for H-2000 W PEM Fuel Cell from Horizon Fuel Cell Technologies is shown in Figure 4.1 and Figure 4.2 respectively. The polarization curve with the different operating pressure of the hydrogen ranges from 0.1 Bar to 0.5 Bar is represented in Figure 4.1 with a relationship between voltage and current (IV-Curve). It shows the different pressure of hydrogen is affected the output performance of the PEM Fuel Cell. The pressure at the 0.1 Bar produces a lower voltage than the pressure of 0.5 Bar. It shows that, the performance voltage of the PEM Fuel Cell is increased when the pressure of the hydrogen is increased. The voltage of 0.5 Bar hydrogen pressure is reached at 45.70 V while voltage 0.4 Bar, 0.3 Bar, 0.2 Bar, and 0.1 Bar only reached 45.20V, 44.80 V, 43.80 V and 43.50 respectively which is lower than 0.5 Bar of hydrogen pressure. However, Figure 4.1 also shows the relationship between the voltage and current. When the current increased, the performance voltage of the PEM Fuel Cell is decreased. At 0.1 Bar hydrogen pressure, when the current is set at 0 A, the voltage of the PEM Fuel Cell produced 43.50 V while when current is set at 36 A, the performance voltage only produced 29.40 V. It shows that the load current of the PEM Fuel Cell that applied in the system also has an affected on performance characteristic of the PEM Fuel Cell.

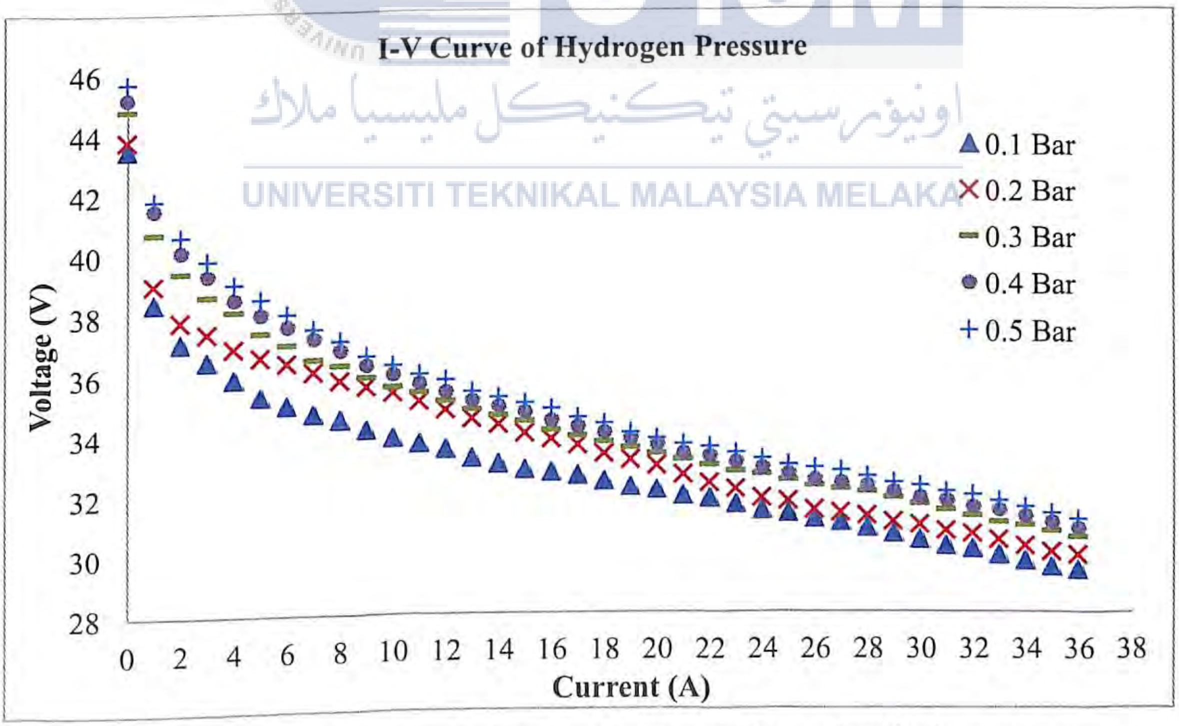


Figure 4.1: Polarization curve of voltage against current for various hydrogen pressures

On the other hand, Figure 4.2 shows the relationship between the power and current (PI-Curve) of PEM Fuel Cell. The power of the PEM Fuel Cell is raised up when the current of the PEM Fuel Cell is increased for all of the variable hydrogen pressure. At 0 A, the power performance of the PEM Fuel Cell is zero because no load is applied on the PEM Fuel Cell. However, for the 1 A, the power of the PEM Fuel Cell only has a small power at each of the different hydrogen pressure where at 0.1 Bar, it only produced 38.40 W while at 0.2 Bar, 0.3 Bar, 0.4 Bar and 0.5 Bar it is produced 39.00 W, 39.00 W, 40.70 W, and 41.80 W in that order. However, when the current is raised up to 36 A, the power of the PEM Fuel Cell produced a higher power performance. At 0.1 Bar hydrogen pressure, the power that produced is 1058.4 W while for 0.2 Bar, 0.3 Bar, 0.4 Bar and 0.5 Bar is produced a power 1076.40 W, 1098 W, 1108.80 W and 1119.60 W respectively. Therefore, it is proved that the changing power also affected from the variation of hydrogen pressure that flow through the inlet stack of PEM Fuel Cell.

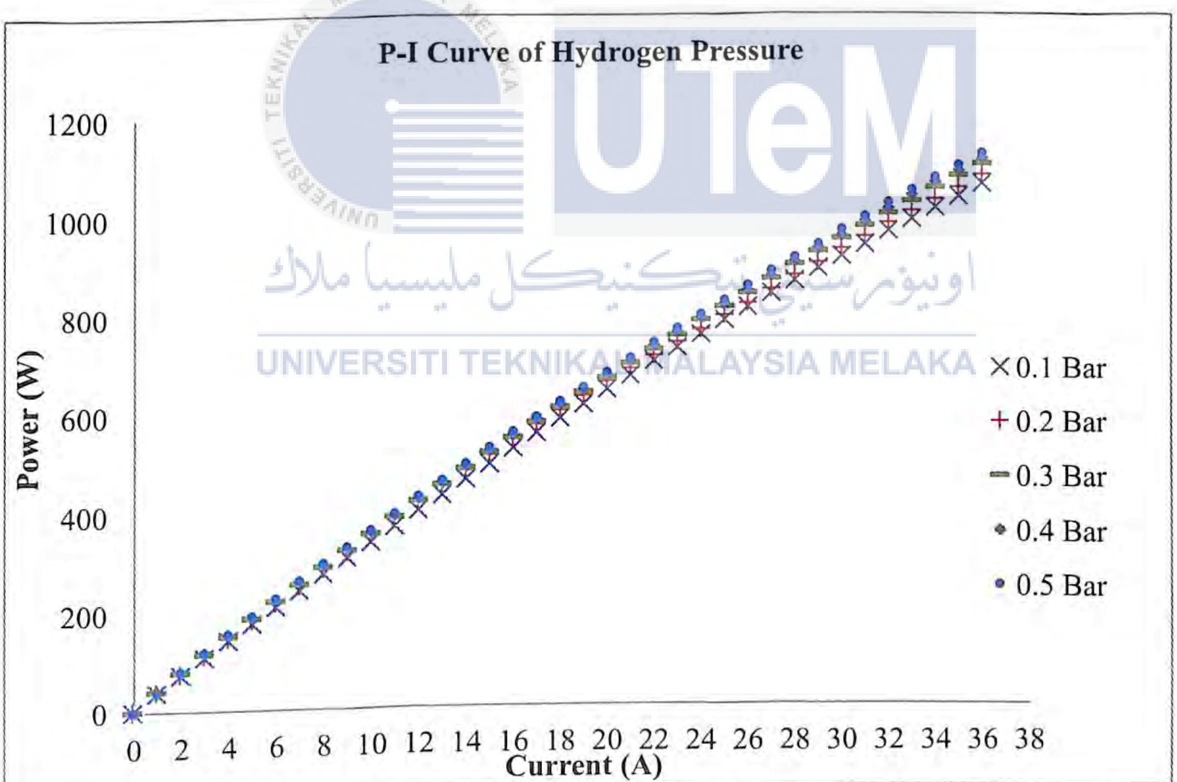


Figure 4.2: Polarization curve with power versus current

Figure 4.3 indicates the graph for the open voltage condition or 0 A load current with various hydrogen pressures of PEM Fuel Cell. The output performance voltage of 0.1 Bar hydrogen pressure only produced 43.50 V. Then, the voltage is increased to 43.80 V with an incremental 0.69 % when the hydrogen pressure varied to 0.2 Bar. Besides that, the performance voltage at the 0.3 Bar also increased with the increment 2.28 % to 44.80 V from the 0.2 Bar voltage. During the 0.4 Bar and 0.5 Bar, the performance voltage is increased to 45.20 V and 45.70 V respectively with the increment 0.9 % and 1.1 %. Therefore, it proved that when the parameter of hydrogen pressure is increased, the output voltage of PEM Fuel Cell also increased. It shows that the performance output voltage of the PEM Fuel Cell is sensitive to the changing of hydrogen pressure parameters. Thus, the hydrogen pressure parameter is important in the system of PEM Fuel Cell.

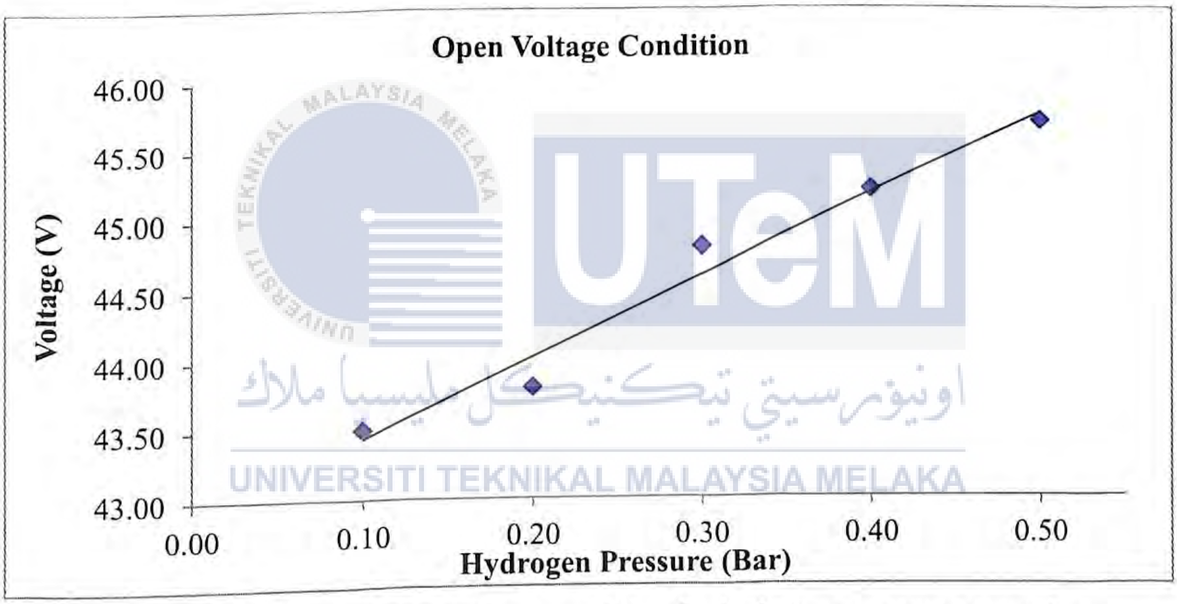


Figure 4.3: Graph of open voltage condition for hydrogen pressure parameter

4.2.2 Results of Hydrogen Flow Rate (Polarization Curve)

The data for the hydrogen flow rate testing is recorded in Table 4.2. The hydrogen pressure of the flow rate testing is fixed with 0.2 Bar and 0.5 Bar only while the load current is varied from 0 A to 36 A for both of hydrogen pressure.

Table 4.2: Data of the hydrogen flow rate parameter for pressure 0.2 Bar and 0.5 Bar

Current (A)	Pressure 0.2 Bar			Pressure 0.5 Bar		
	Voltage (V)	Power (W)	Flow rate (L/Min)	Voltage (V)	Power (W)	Flow rate (L/Min)
0	43.80	0.00	0.35	45.70	0.00	0.30
1	39.00	39.00	0.55	41.80	41.80	0.65
2	37.80	75.60	0.80	40.60	81.20	0.95
3	37.40	112.20	1.10	39.80	119.40	1.30
4	36.90	147.60	1.45	39.00	156.00	1.65
5	36.60	183.00	1.70	38.50	192.50	2.00
6	36.40	218.40	2.15	38.00	228.00	2.35
7	36.10	252.70	2.55	37.50	262.50	2.70
8	35.80	286.40	2.85	37.10	296.80	3.05
9	35.60	320.40	3.20	36.60	329.40	3.40
10	35.40	354.00	3.55	36.30	363.00	3.75
11	35.10	386.10	3.90	36.00	396.00	4.10
12	34.80	417.60	4.25	35.80	429.60	4.45
13	34.50	448.50	4.60	35.40	460.20	4.75
14	34.30	480.20	4.96	35.20	492.80	5.10
15	34.00	510.00	5.35	35.00	525.00	5.45
16	33.80	540.80	5.70	34.80	556.80	5.80
17	33.60	571.20	6.00	34.50	586.50	6.20
18	33.30	599.40	6.35	34.30	617.40	6.55
19	33.10	628.90	6.70	34.00	646.00	6.85
20	32.90	658.00	7.05	33.80	676.00	7.25
21	32.60	684.60	7.40	33.60	705.60	7.55
22	32.30	710.60	7.75	33.50	737.00	7.85
23	32.10	738.30	8.05	33.30	765.90	8.15
24	31.80	763.20	8.45	33.10	794.40	8.55
25	31.70	792.50	8.80	32.90	822.50	8.95
26	31.40	816.40	9.10	32.80	852.80	9.25
27	31.30	845.10	9.45	32.70	882.90	9.65
28	31.20	873.60	9.80	32.50	910.00	9.90
29	31.00	899.00	10.10	32.30	936.70	10.30
30	30.90	927.00	10.55	32.20	966.00	10.65
31	30.70	951.70	10.95	32.00	992.00	11.00
32	30.60	979.20	11.30	31.90	1020.80	11.40
33	30.40	1003.20	11.65	31.70	1046.10	11.75
34	30.20	1026.80	12.00	31.50	1071.00	12.00
35	30.00	1050.00	12.40	31.30	1095.50	12.40
36	29.90	1076.40	12.70	31.10	1119.60	12.70

According to Table 4.2, the polarization curve of hydrogen flow rate is created in Figure 4.4 for IV- curve, while Figure 4.5 shows for PI-curve of polarization curve for hydrogen flow rate parameters. The different value of hydrogen pressure parameter in flow rate testing, it shows as the relationship between the changing of the pressure and flow rate parameter on the performance of PEM Fuel Cell. Figure 4.4 show the voltage of PEM Fuel Cell for both pressures is inversely proportional to the current. It indicates the performance voltage of the 0.5 Bar is decreased when the load current of PEM Fuel Cell is arising. On the other hand, the voltage of 0.5 Bar is higher than voltage of the 0.2 Bar. The voltage increment between 0.5 Bar and 0.2 Bar for 0 A is 4.34 %.

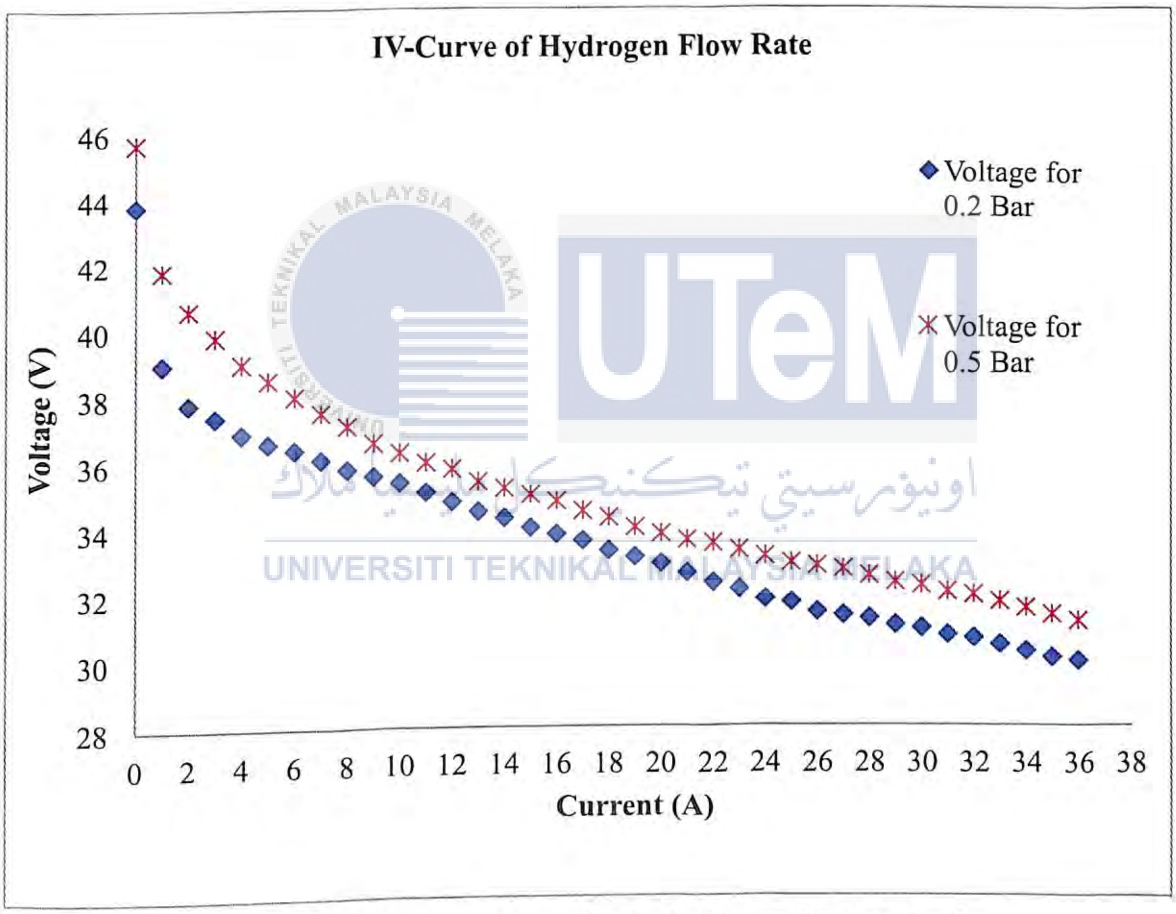


Figure 4.4: Polarization curve for the hydrogen flow rate testing

Furthermore, Figure 4.5 shows the polarization curve for the performance power against the current. The power of the 0.5 Bar is higher than the 0.2 Bar. The polarization curve of the flow rate testing has a similar with the pressure testing which is the higher hydrogen pressure and higher load current is produced a higher power performance of PEM Fuel Cell. The PI-curve of hydrogen flow rate parameter is represents the power is directly proportional to the current. When the load current of PEM Fuel Cell is increased, the power also increased.

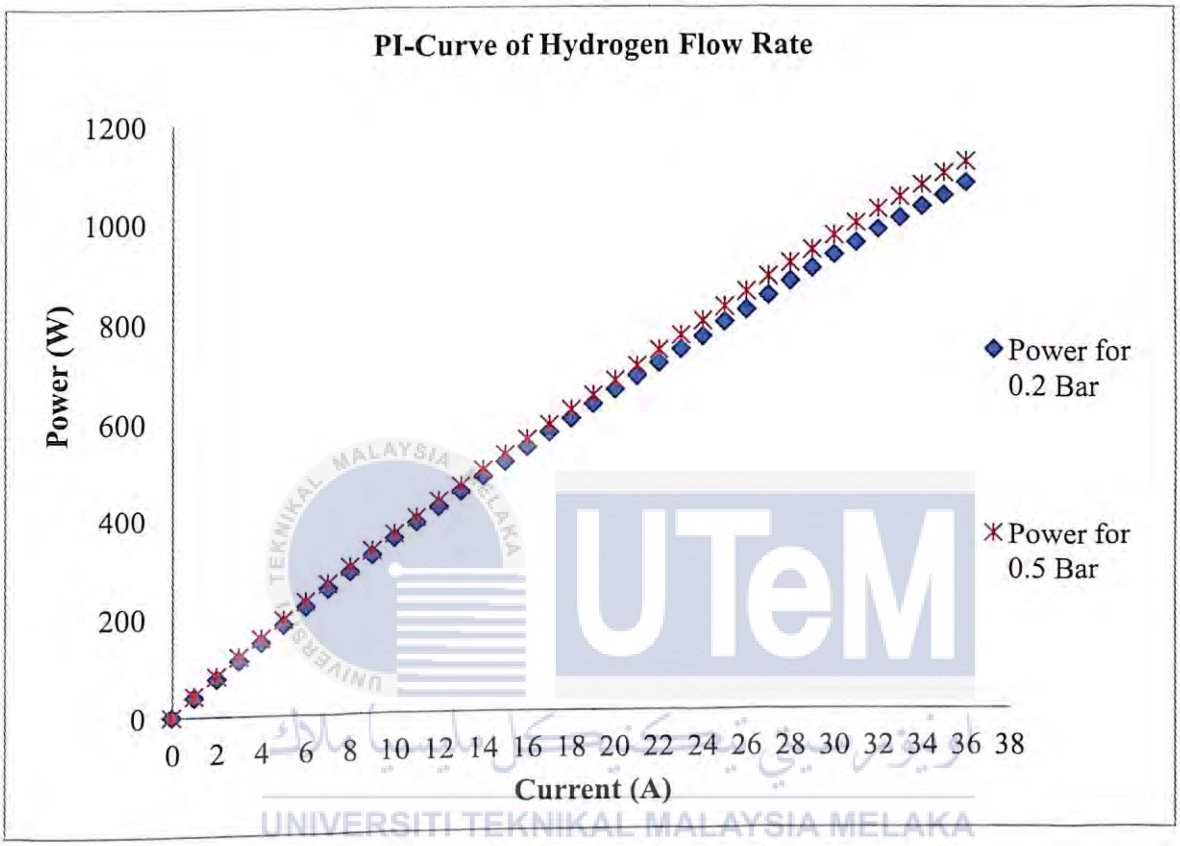


Figure 4.5: Polarization curve of the power against current

Based on Table 4.2, the relationship between hydrogen flow rate and current also plotted in Figure 4.6. It shows that the flow rate of hydrogen increased when the load current of PEM Fuel Cell is increased. Therefore, the increasing of hydrogen flow rate is affected by the changing of the load current that used in the system. At 0 A, the flow rate of hydrogen for both pressures is approximate to 0.3 L/min where at 36 A for both pressure is approximate to 12.70 L/min.

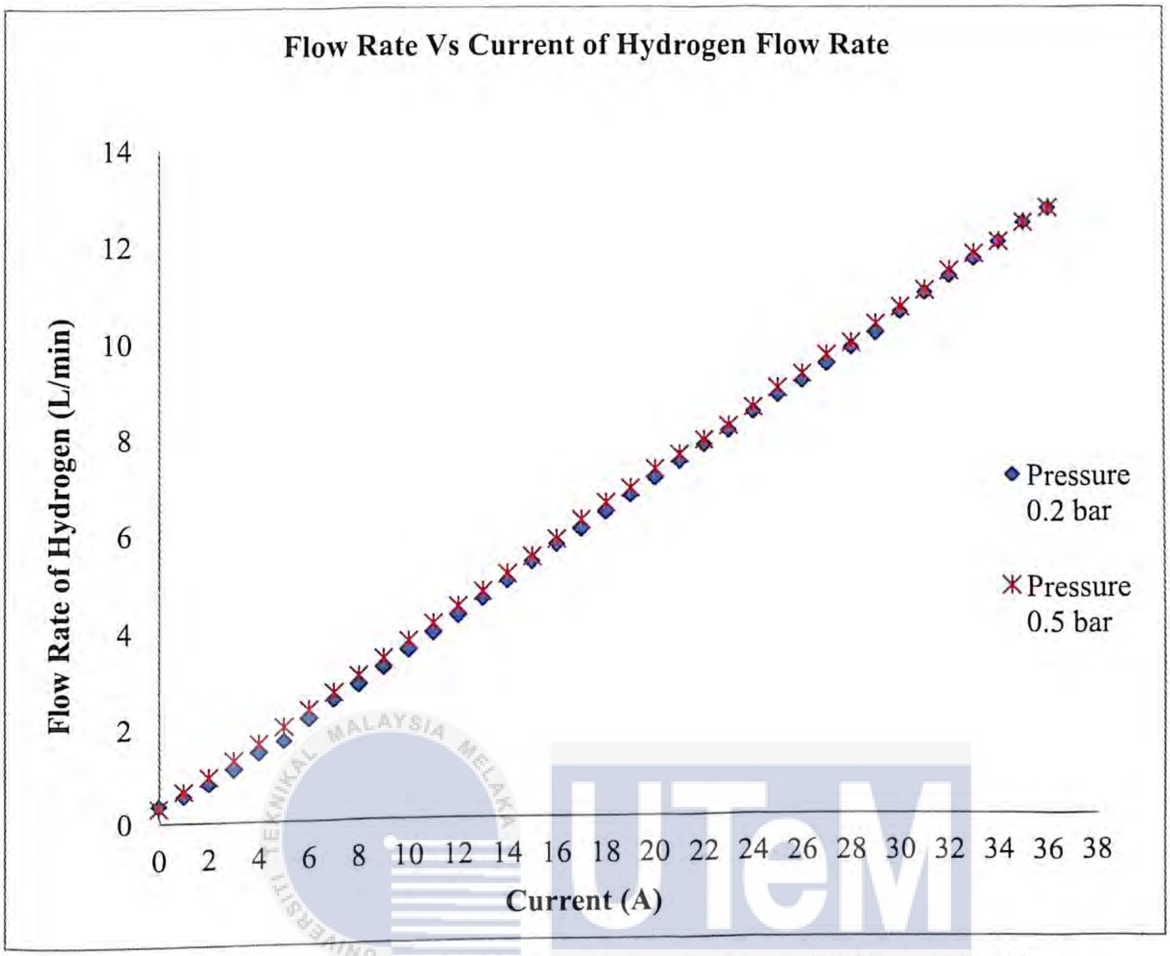


Figure 4.6: Comparison of flow rate between pressure 0.2 Bar and 0.5 Bar

Figure 4.7 presents the graph of the voltage against flow rate of hydrogen. When the hydrogen flow rate increased, the voltage decreased because the flow rate of the hydrogen has a higher influenced on the moisture of the hydrogen in the PEM Fuel Cell. When the flow rate hydrogen is 0.3 L/min the performance voltage of 0.2 Bar is 43.8 V while for 0.5 Bar, the voltage is around 45.7 V. Then, when the hydrogen flow rate at the higher level for 0.2 Bar which is 12.70 L/min, the performance voltage become dropped to 29.90 V and 31.10 V for 0.5 Bar. It is proved that the flow rate has an influenced on the performance output voltage of PEM Fuel cell.

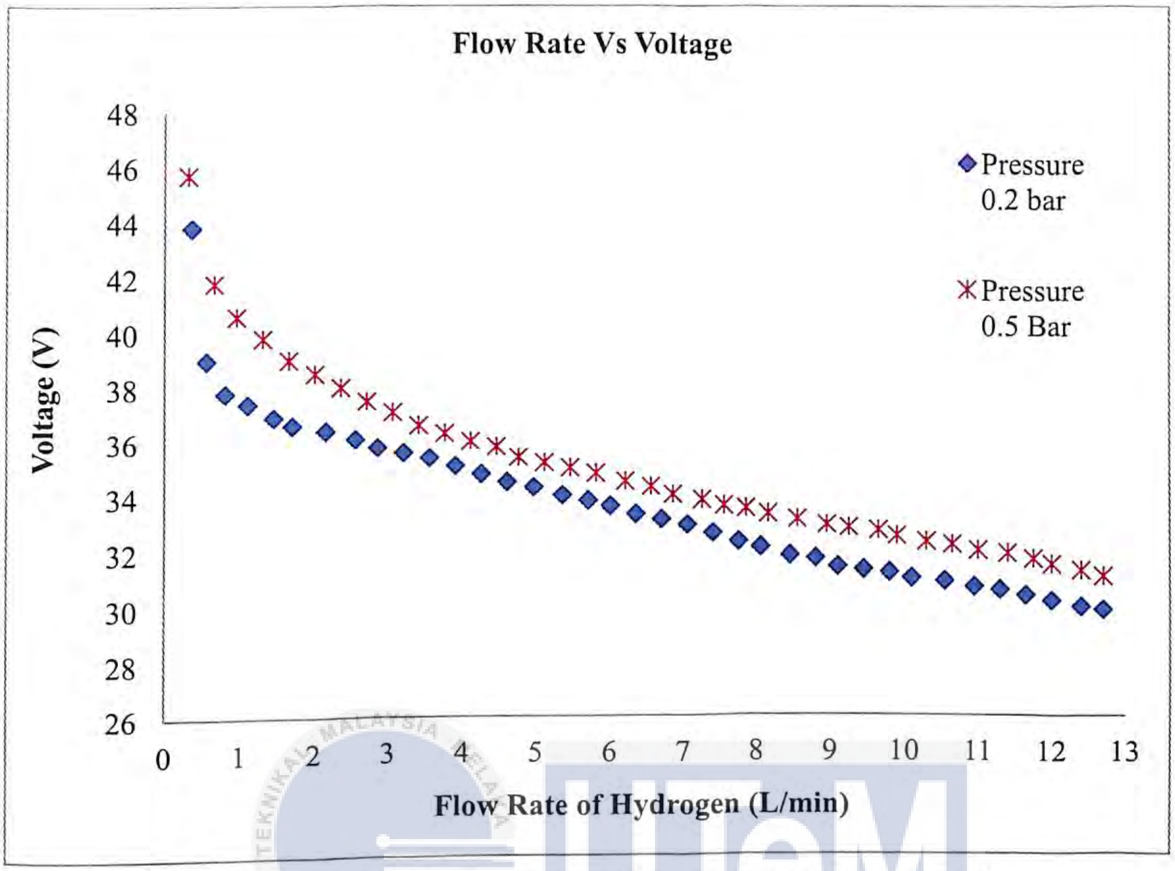


Figure 4.7: Graph of voltage versus flow rate for 0.2 Bar and 0.5 Bar

4.3 Results of Signal Processing Analysis

In this section, the result and analysis of periodogram method will be discussed. The data that is captured from the oscilloscope is analyzed using this method. The data are divided into two parts which are pressure and flow rate of hydrogen parameter. Both of the parameter will created a rough signal and periodogram signal. The rough signal is included of the voltage of root-mean square (V_{RMS}) while periodogram signal is produced the direct current voltage (V_{DC}) and alternating current voltage (V_{AC}) for the PEM Fuel Cell.

4.3.1 Results of Hydrogen Pressure (Rough Signal and Periodogram Signal)

According to Equation 3.2, V_{RMS} is plotted in rough signal that represent the relationship between V_{RMS} of the PEM Fuel Cell against time for each of changing hydrogen pressure. Figure 4.8 to Figure 4.10 show the rough signal that produced from the periodogram analysis. Figure 4.8 represents a rough signal 20 A current, while Figure 4.9 for 25 A and Figure 4.10 for 30 A of load current. The other rough signal result for 0 A, 5 A, 10 A, 15 A and 35 A are illustrated in Appendix A. The pressure of hydrogen is varied from 0.1 Bar to 0.5 Bar for each of the current changing. The data of V_{RMS} from the rough signal is recorded in Table 4.3 for current 0 A to 35 A with 5 A interval with varied the hydrogen pressure parameters.

Table 4.3: V_{RMS} of rough signal with various pressure parameters

Current (A)	V_{RMS} (0.1 Bar)	V_{RMS} (0.2 Bar)	V_{RMS} (0.3 Bar)	V_{RMS} (0.4 Bar)	V_{RMS} (0.5 Bar)
0	43.43	43.67	45.02	45.17	45.69
5	35.51	36.62	37.45	38.36	38.20
10	33.97	35.63	35.64	36.24	36.25
15	32.94	34.12	34.29	34.77	34.94
20	32.16	32.99	33.33	33.71	33.86
25	31.28	31.72	32.40	32.70	32.96
30	30.50	30.92	31.74	31.89	32.16
35	29.57	30.04	30.70	30.98	31.31

Figure 4.8 (a) to Figure 4.8 (e) show the current that used is fixed at 20 A while the hydrogen pressure is varied from 0.1 Bar to 0.5 Bar consecutively. At 0.1 Bar, V_{RMS} of PEM Fuel Cell produced 32.16 V while when pressure is increased to 0.2 Bar, V_{RMS} also increase to 32.99 V. Therefore, it has a 2.58% increment between of the increasing of hydrogen pressure. Then, the hydrogen pressure is varied to 0.3 Bar, 0.4 Bar and 0.5 Bar. The V_{RMS} of PEM Fuel Cell also raised to 33.33 V, 33.71 V and 33.86 V respectively. The percentage voltage that is increased between 0.2 Bar and 0.3 Bar is 1.03 % while for 0.3 Bar to 0.4 Bar is 1.14%. Then, the increment of the voltage for 0.4 Bar and 0.5 Bar is 0.45%.

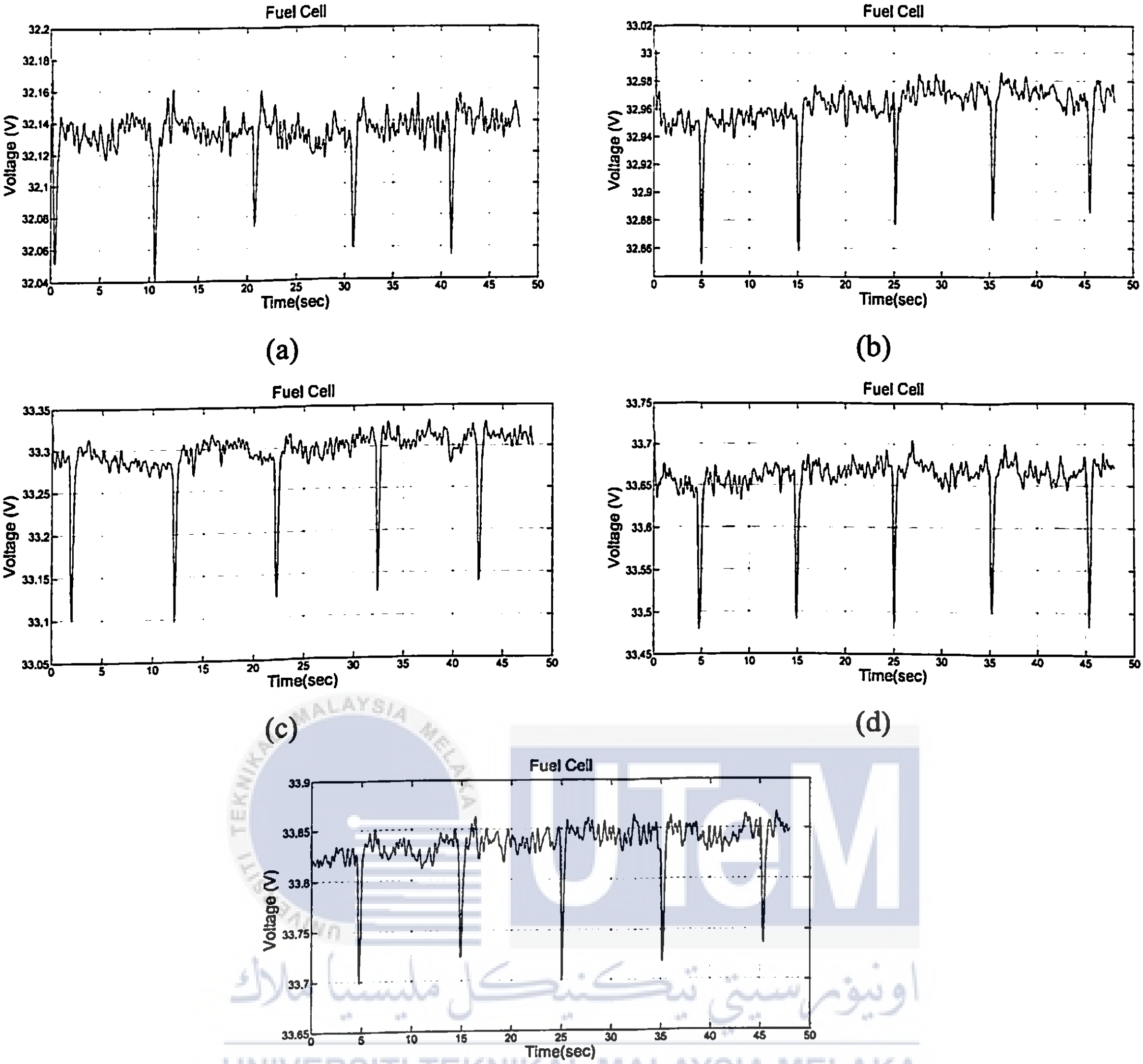


Figure 4.8: Rough signal for performance voltage of 2000 W PEM Fuel Cell of 20 A load current with different of hydrogen pressure; (a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure (d) 0.4 Bar hydrogen pressure (e) 0.5 Bar hydrogen pressure

The rough signal for current 25 A is shown in Figure 4.9 with variation hydrogen pressure. The V_{RMS} for 0.1 Bar, 0.2 Bar, 0.3 Bar, 0.4 Bar and 0.5 Bar are 31.28 V, 31.72 V, 32.40 V, 32.70 V and 32.96 V respectively. Therefore, the voltage of the PEM Fuel Cell also increased for every changing of the hydrogen pressure parameter.

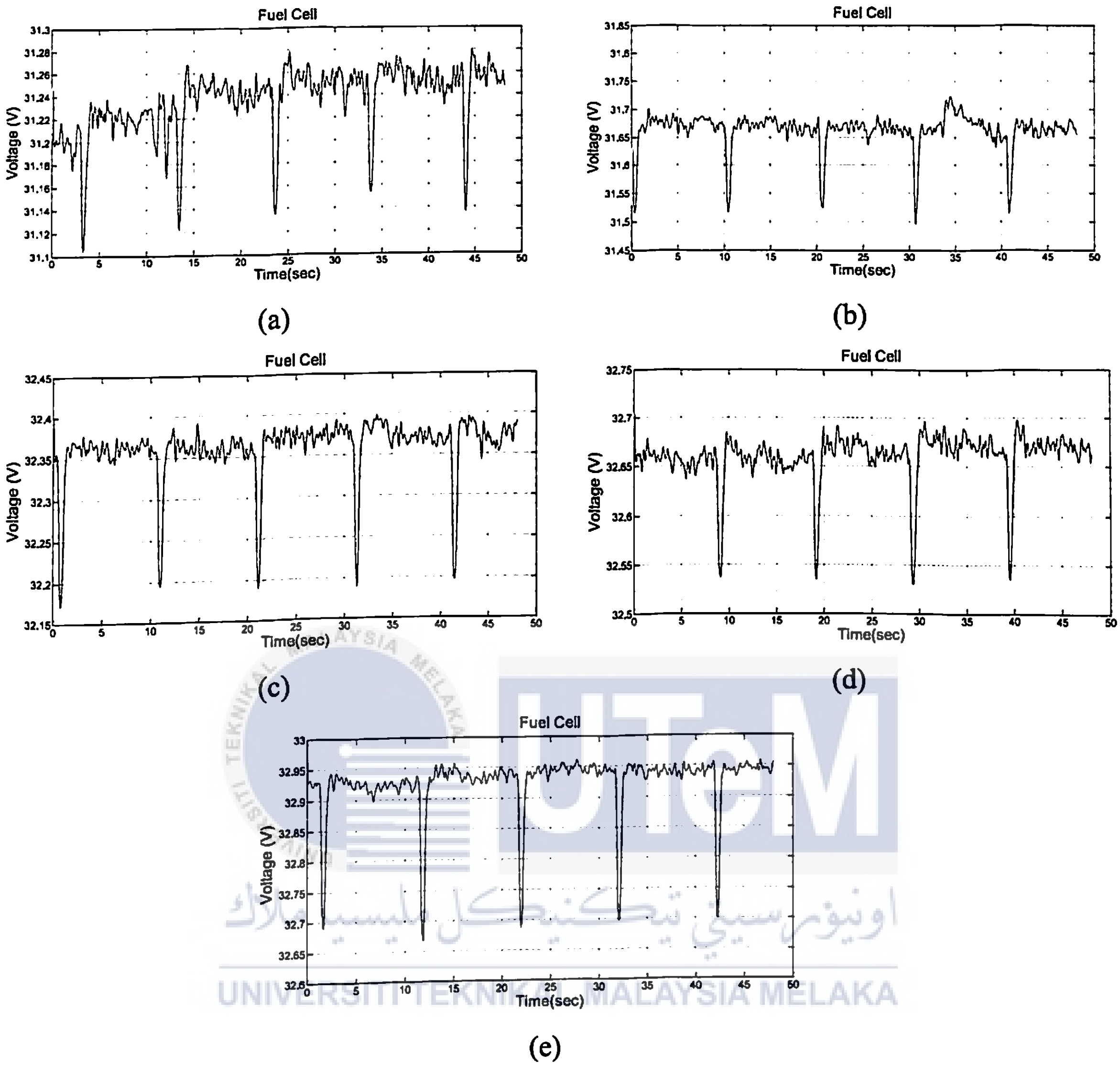


Figure 4.9: Rough signal for performance voltage of 2000 W PEM Fuel Cell of 25 A load current with different of hydrogen pressure; (a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure (d) 0.4 Bar hydrogen pressure (e) 0.5 Bar hydrogen pressure

The analysis also has done for the 30 A. Figure 4.10 demonstrates the rough signal for 30 A current with varied pressure hydrogen for these load and arranged in Figure 4.10 (a) to Figure 4.10 (e) for 0.1 Bar to 0.5 Bar. The V_{RMS} for 0.2 Bar pressure hydrogen is increased from 30.50 V for 0.1 Bar to 30.92 V. Next, the hydrogen pressure is varied to 0.3 Bar, 0.4 Bar and 0.5 Bar then it produced 31.74 V, 31.89 and 32.16 V V_{RMS} respectively.

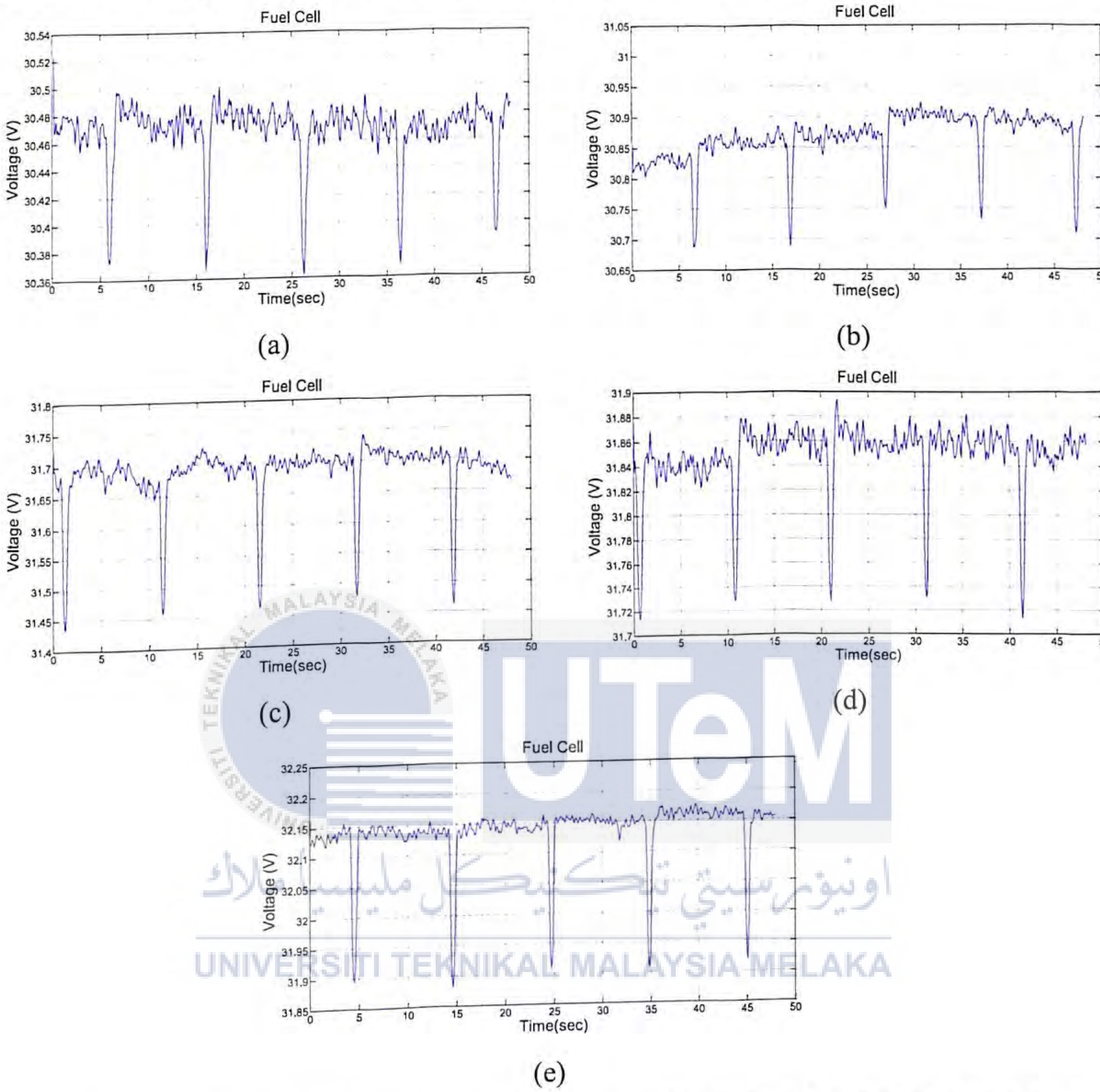


Figure 4.10: Rough signal for performance voltage of 2000 W PEM Fuel Cell of 30 A load current with different of hydrogen pressure; (a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure (d) 0.4 Bar hydrogen pressure (e) 0.5 Bar hydrogen pressure

According to the all rough signals, it shows a drastically decreased on the performance voltage of PEM Fuel Cell in the signal. Basically, it is not a noise but it was a disturbance from the purging process of PEM Fuel Cell itself. The Horizon Fuel Cell Technologies provide a purging valve with their own controller for H-2000 W PEM Fuel Cell. The setting time of the purging valve operate is controlled by a controller. Based on the observation, the purge valve is operated for every 10 second. The balances of hydrogen inside of the stack PEM Fuel Cell are released during a purging process. Therefore, the voltage become suddenly decreasing during the purging process and voltage also increasing drastically after purging process. Therefore, the purging process is used to improve the performance of the PEM Fuel Cell during their operation. On the other hand, all the value of V_{RMS} is increased when the hydrogen pressure is increased. This condition happened because the hydrogen that flow through the inlet valve is forced by a higher pressure. The stack of the PEM Fuel Cell is sensitive to the higher of hydrogen pressure. However, the pressure of hydrogen that flow to the inlet valve of stack PEM Fuel Cell has a limitation because if the hydrogen pressure is more than 0.55 Bar, the membrane of the PEM Fuel Cell will be damaged or ripped.

The periodogram method also produced a periodogram signal which is to represent the micro monitoring on characteristic behavior of the PEM Fuel Cell. The periodogram signal illustrates the relationship between the frequency and amplitude of the PEM Fuel Cell. The amplitude that produced on the periodogram signal consists of V_{DC} and V_{AC}. Basically, V_{DC} is located at 0 Hz of the periodogram signal while the other frequency demonstrates the value of V_{AC}. The data from the periodogram signal in Figure 4.11 to Figure 4.13 and Appendix B is recorded in Table 4.4 to Table 4.6. Table 4.4 shows the value of V_{DC} while Table 4.5 shows the value of V_{AC} of each of hydrogen pressure parameters.

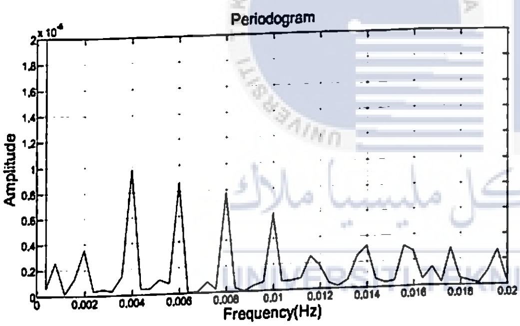
Table 4.4: V_{DC} of rough signal with various pressure parameters

Current (A)	V_{DC} (0.1Bar)	V_{DC} (0.2 Bar)	V_{DC} (0.3 Bar)	V_{DC} (0.4 Bar)	V_{DC} (0.5 Bar)
0	43.42	43.59	45.00	45.13	45.62
5	35.50	36.61	37.44	38.35	38.20
10	33.94	35.62	35.62	36.24	36.25
15	32.94	34.10	34.26	34.76	34.93
20	32.16	32.98	33.32	33.67	33.85
25	31.26	31.69	32.39	32.68	32.95
30	30.49	30.89	31.70	31.87	32.16
35	29.54	29.96	30.68	30.97	31.28

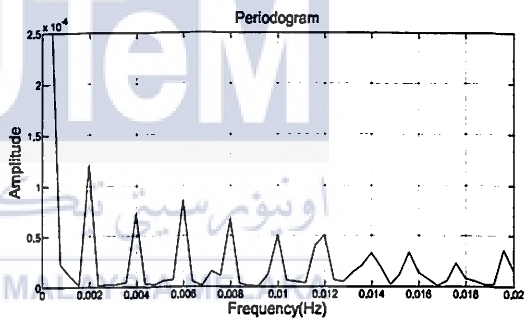
Table 4.5: V_{AC} of rough signal with various pressure parameters

Current (A)	V_{AC} (0.1 Bar)	V_{AC} (0.2 Bar)	V_{AC} (0.3 Bar)	V_{AC} (0.4 Bar)	V_{AC} (0.5 Bar)
0	1.08	2.66	1.34	1.82	2.56
5	0.98	1.01	0.71	0.7	0.49
10	1.4	0.7	1.1	0.58	0.25
15	0.21	1.08	1.34	0.98	0.9
20	0.52	0.58	0.94	1.54	0.71
25	1.2	1.47	0.87	1.14	0.6
30	0.81	1.43	1.56	0.99	0.52
35	1.26	2.12	1.09	0.6	1.38

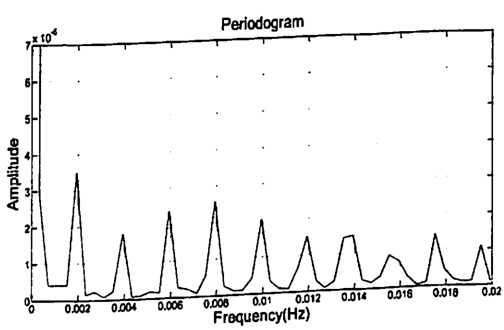
Figure 4.11 illustrated the graph of periodogram signal of PEM Fuel Cell for current of 20 A. Figure 4.11 (a) to (e) represents the periodogram for 0.1 Bar to 0.5 Bar respectively. The value of V_{AC} is smaller and it cannot be read using a DC load. Therefore, periodogram method is used to analyze and produced the identification signal of PEM Fuel Cell. The entire periodogram signal produced a same trend, but it has different amplitude.



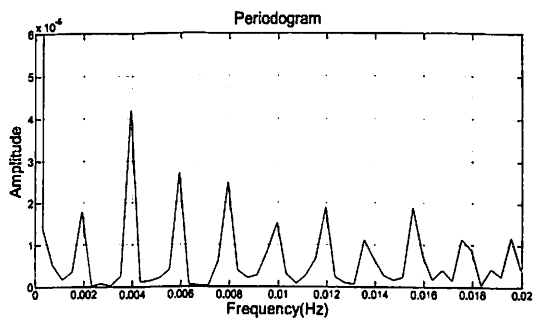
(a)



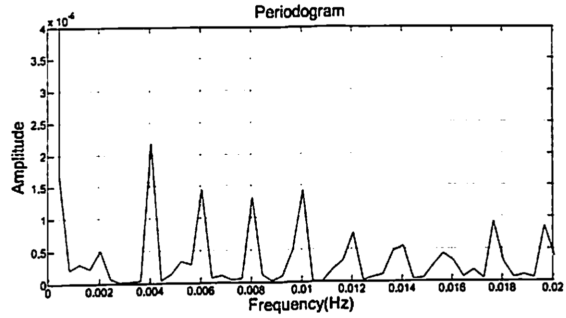
(b)



(c)



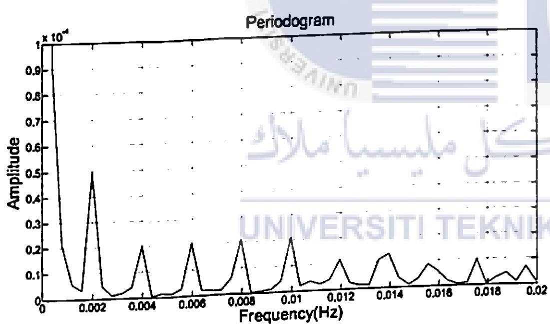
(d)



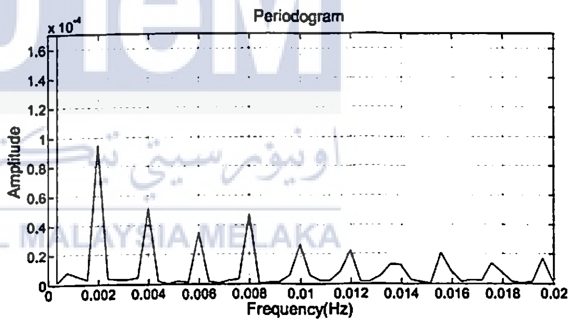
(e)

Figure 4.11: Periodogram signal of 2000 W PEM Fuel Cell of 20 A with different of hydrogen pressure at anode side; (a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure d) 0.4 Bar hydrogen pressure e) 0.5 Bar hydrogen pressure

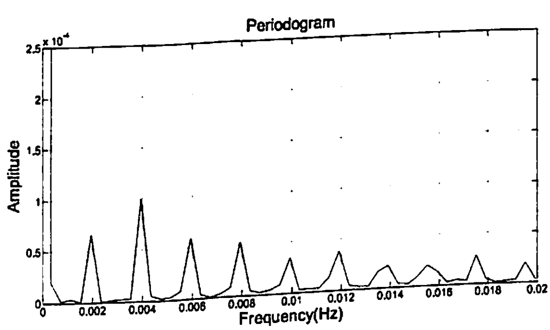
Figure 4.12 demonstrates the periodogram signal for 25 A loads current. This periodogram signal of 25 A shows a similar trend with the current 20 A. However, the value of the amplitude for the 25 A is higher than the 20 A. Therefore, when the current is increased, the distortion voltage (V_{AC}) also increased.



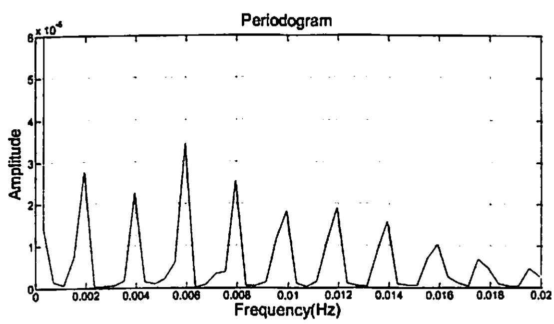
(a)



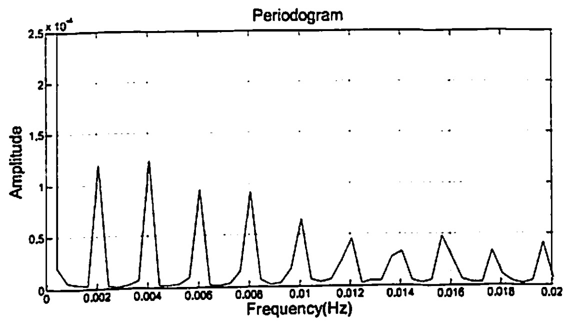
(b)



(c)



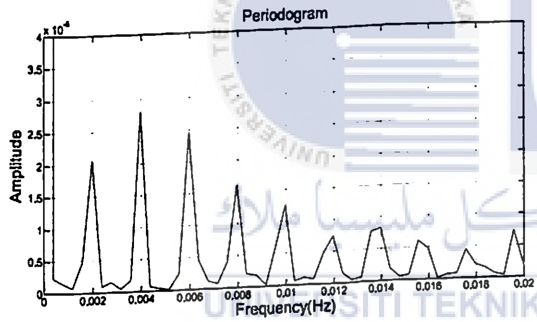
(d)



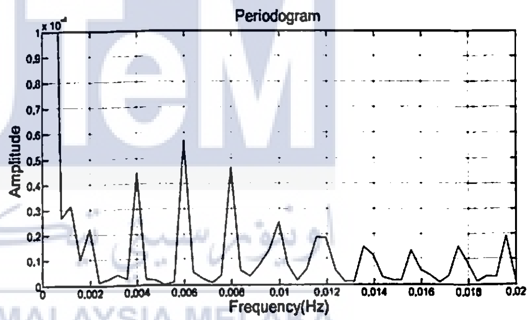
(e)

Figure 4.12: Periodogram signal of 2000 W PEM Fuel Cell of 25 A with different of hydrogen pressure at anode side; (a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure (d) 0.4 Bar hydrogen pressure (e) 0.5 Bar hydrogen pressure

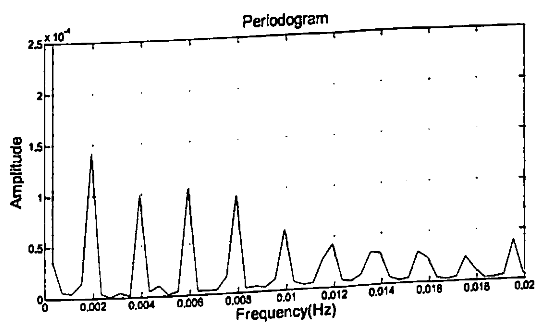
In addition, Figure 4.13 shows a periodogram signal for 30 A of load. The pattern of the periodogram signal in Figure 4.13 is same between each other. At 0.1 Bar, the higher point of V_{AC} is at 0.004 Hz, while at 0.2 Bar the peak point of the V_{AC} is at 0.006 Hz.



(a)



(b)



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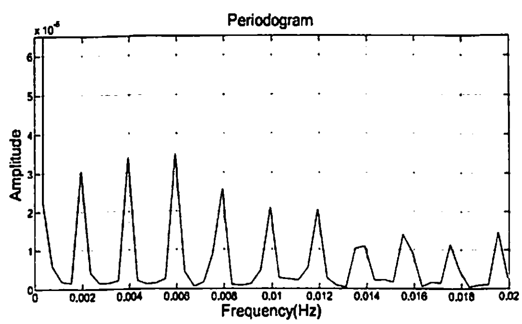

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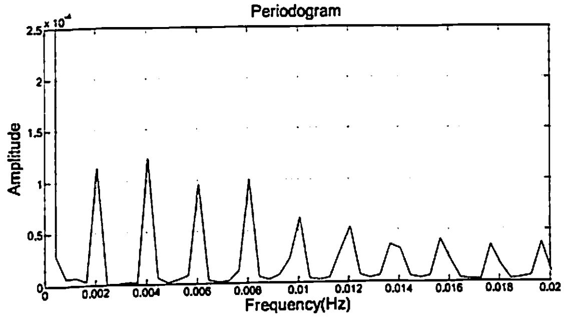


(e)

Figure 4.13: Periodogram signal of 2000 W PEM Fuel Cell of 30 A with different of hydrogen pressure at anode side; (a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure (d) 0.4 Bar hydrogen pressure (e) 0.5 Bar hydrogen pressure

According to periodogram signal in Figure 4.11 to Figure 4.13 and Appendix B, the amplitude for the PEM Fuel Cell is recorded in Table 4.6. In Table 4.6, the value of amplitude at each frequency is recorded. The interval frequency of periodogram signal is 0.002Hz and the maximum frequency that is recorded is 0.02 Hz. This range is selected because the size of distortion or V_{AC} is smallest and it needs to standardize with all experiments. Basically, the value of V_{AC} that occurred in periodogram signal represents the distortions that happened in the operation of the PEM Fuel Cell. This condition will affect the performance of the PEM Fuel Cell. Therefore, this analysis is very crucial in determining the distortions that occurred in the system. On the other hand, the relationship between frequency and amplitude of the PEM Fuel Cell is important in the application of the PEM Fuel Cell. The frequency of the periodogram that produced in the periodogram signal helps to show the time of the distortions that occurred in the PEM Fuel Cell.

Table 4.6: Frequency of 0.1 Bar, 0.2 Bar and 0.3 Bar pressure that produced from periodogram method

		Frequency (Hz)										
Pressure	Current (A)	0	0.002	0.004	0.006	0.008	0.01	0.012	0.014	0.016	0.018	0.02
0.1 Bar	0	1900	4.7E-05	1.2E-04	5.1E-05	4.8E-05	2.1E-05	1.4E-05	1.0E-05	6.3E-06	6.6E-06	1.7E-06
	5	1340	7.2E-05	2.9E-05	1.8E-05	1.5E-05	7.8E-06	4.7E-06	4.8E-06	3.3E-06	3.9E-06	2.7E-06
	10	1269	3.1E-05	2.2E-05	1.8E-05	9.0E-06	9.7E-06	6.0E-06	3.7E-06	3.6E-06	4.3E-06	1.9E-06
	15	1163	1.8E-05	1.4E-05	1.4E-05	1.1E-05	9.8E-06	9.1E-06	9.8E-06	5.1E-06	5.5E-06	2.3E-06
	20	1088	1.2E-05	7.2E-06	8.6E-06	6.7E-06	5.1E-06	5.1E-06	3.3E-06	1.3E-06	8.2E-07	1.6E-06
	25	1004	9.5E-05	5.1E-05	3.5E-05	4.8E-05	2.6E-05	2.3E-05	1.2E-05	8.4E-06	7.6E-06	1.7E-06
	30	954	2.2E-05	4.4E-05	5.7E-05	4.6E-05	2.5E-05	1.8E-05	1.1E-05	5.7E-06	8.1E-06	2.0E-06
	35	898	2.9E-05	2.9E-05	4.2E-05	2.2E-05	3.1E-05	1.5E-05	5.8E-06	7.8E-06	3.5E-06	1.9E-06
0.2 Bar	0	1900	4.7E-05	1.2E-04	5.1E-05	4.8E-05	2.1E-05	1.4E-05	1.0E-05	6.3E-06	6.6E-06	1.7E-06
	5	1340	7.2E-05	2.9E-05	1.8E-05	1.5E-05	7.8E-06	4.7E-06	4.8E-06	3.3E-06	3.9E-06	2.7E-06
	10	1269	3.1E-05	2.2E-05	1.8E-05	9.0E-06	9.7E-06	6.0E-06	3.7E-06	3.6E-06	4.3E-06	1.9E-06
	15	1163	1.8E-05	1.4E-05	1.4E-05	1.1E-05	9.8E-06	9.1E-06	9.8E-06	5.1E-06	5.5E-06	2.3E-06
	20	1088	1.2E-05	7.2E-06	8.6E-06	6.7E-06	5.1E-06	5.1E-06	3.3E-06	1.3E-06	8.2E-07	1.6E-06
	25	1004	9.5E-05	5.1E-05	3.5E-05	4.8E-05	2.6E-05	2.3E-05	1.2E-05	8.4E-06	7.6E-06	1.7E-06
	30	954	2.2E-05	4.4E-05	5.7E-05	4.6E-05	2.5E-05	1.8E-05	1.1E-05	5.7E-06	8.1E-06	2.0E-06
	35	898	2.9E-05	2.9E-05	4.2E-05	2.2E-05	3.1E-05	1.5E-05	5.8E-06	7.8E-06	3.5E-06	1.9E-06
0.3 Bar	0	2025	6.4E-05	3.3E-05	2.2E-05	2.2E-05	1.6E-05	1.0E-05	4.8E-06	7.1E-06	4.9E-06	4.3E-06
	5	1402	3.0E-05	3.6E-05	1.4E-05	7.3E-06	1.3E-05	7.1E-06	5.3E-06	3.6E-06	3.2E-06	1.6E-06
	10	1269	7.2E-05	2.8E-05	3.9E-05	2.1E-05	1.9E-05	9.7E-06	9.1E-06	5.3E-06	3.5E-05	1.9E-06
	15	1174	1.4E-05	1.4E-05	1.6E-05	1.1E-05	9.0E-06	9.2E-06	4.0E-06	2.3E-06	8.8E-07	1.9E-06
	20	1110	3.5E-05	1.8E-05	2.4E-05	2.6E-05	2.1E-05	1.5E-05	1.5E-05	7.2E-06	4.6E-06	7.8E-07
	25	1049	6.7E-05	1.0E-04	5.9E-05	5.2E-05	3.4E-05	3.8E-05	2.1E-05	1.3E-05	4.4E-06	1.7E-06
	30	1005	1.4E-04	9.9E-05	1.0E-04	9.5E-05	5.9E-05	4.2E-05	3.1E-05	2.4E-05	1.1E-05	5.4E-06
	35	941	4.5E-05	5.5E-05	5.1E-05	3.8E-05	4.2E-05	3.0E-05	1.6E-05	1.0E-05	3.4E-06	1.1E-06

Table 4.7: Frequency of 0.1 Bar, 0.2 Bar and 0.3 Bar pressure that produced from periodogram method

Pressure	Current (A)	Frequency (Hz) 0	0.002	0.004	0.006	0.008	0.01	0.012	0.014	0.016	0.018	0.02
0.4 Bar	0	2037	6.6E-05	3.8E-05	2.3E-05	2.2E-05	1.4E-05	8.7E-06	1.2E-05	7.4E-06	3.0E-06	1.4E-06
	5	1471	4.5E-05	5.4E-05	2.6E-05	1.7E-05	1.1E-05	1.3E-05	6.7E-06	7.3E-06	7.9E-07	2.4E-06
	10	1313	1.3E-05	9.4E-06	7.7E-06	6.8E-06	4.4E-06	3.9E-06	3.4E-06	3.6E-06	2.2E-06	2.4E-06
	15	1208	2.3E-05	2.8E-05	2.8E-05	1.8E-05	1.7E-05	7.3E-06	1.3E-05	5.3E-06	3.8E-06	3.4E-06
	20	1134	3.5E-05	1.8E-05	2.4E-05	2.6E-05	2.1E-05	1.5E-05	1.5E-05	7.2E-06	4.6E-06	7.8E-07
	25	1068	2.8E-05	2.3E-05	3.4E-05	2.6E-05	1.8E-05	1.9E-05	1.6E-05	1.0E-05	4.6E-06	2.6E-06
	30	1016	3.0E-05	3.4E-05	3.5E-05	2.6E-05	2.1E-05	2.0E-05	1.1E-05	9.3E-06	4.3E-06	2.9E-06
	35	959	8.0E-05	5.6E-05	5.0E-05	4.8E-05	3.3E-05	2.4E-05	2.2E-05	1.3E-05	7.4E-06	3.4E-06
0.5 Bar	0	2081	3.8E-04	1.0E-04	5.8E-05	5.4E-05	2.0E-05	1.8E-05	8.3E-06	3.6E-06	6.3E-06	5.5E-07
	5	1459	3.9E-05	3.7E-05	2.8E-05	2.1E-05	1.7E-05	1.4E-05	1.0E-05	6.4E-06	4.6E-06	1.2E-06
	10	1314	3.1E-05	2.2E-05	1.8E-05	9.0E-06	9.7E-06	6.0E-06	3.7E-06	3.6E-06	4.3E-06	1.9E-06
	15	1220	3.8E-05	3.3E-05	2.4E-05	2.4E-05	2.8E-05	1.6E-05	1.4E-05	1.1E-05	7.1E-05	3.3E-05
	20	1146	5.1E-06	2.2E-05	1.5E-05	1.3E-05	1.4E-05	7.5E-06	5.4E-06	3.1E-06	2.9E-06	3.9E-06
	25	1086	1.2E-04	1.2E-04	9.5E-05	9.2E-05	6.5E-05	4.6E-05	3.3E-05	2.7E-05	1.1E-05	6.8E-06
	30	1034	1.1E-04	1.2E-04	9.7E-05	1.0E-04	6.3E-05	5.3E-05	3.2E-05	2.1E-05	1.6E-05	9.3E-06
	35	978	1.4E-04	1.2E-04	1.1E-04	1.0E-04	7.6E-05	4.4E-05	3.8E-05	3.1E-05	1.8E-05	4.7E-06

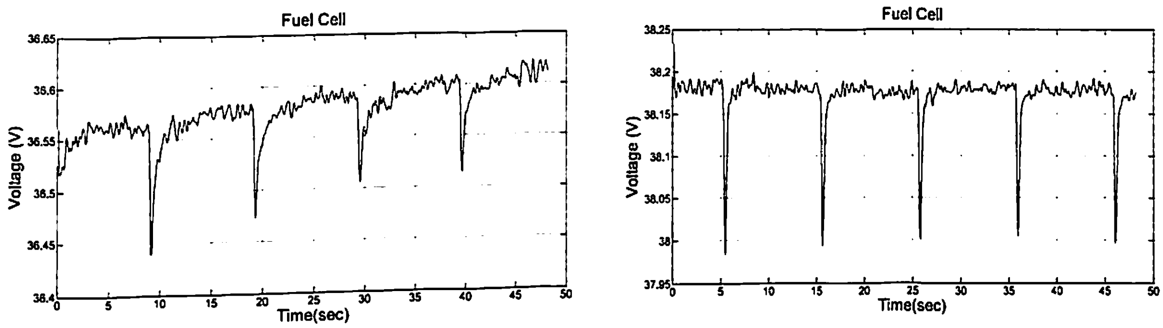
4.3.2 Results of Hydrogen Flow Rate (Rough Signal and Periodogram Signal)

The performance data of hydrogen flow rate parameter also has been analyzed using a periodogram method. The result for hydrogen flow rate parameter produced a rough signal and periodogram signal. The pressure that used for the flow rate parameter is 0.2 Bar and 0.5 Bar. The rough signal for hydrogen flow rate is shown in Figure 4.14 to Figure 4.16 while for periodogram signal is shown in Figure 4.17 to Figure 4.19. The load current is varied for 0 A to 36 A. However, Figure 4.14 to Figure 4.19, it shows a load current of 5 A, 10 A and 15 A. The others result of rough signal and periodogram signal is shown in Appendix C and Appendix D. Based on the rough signal and periodogram signal, the value of V_{RMS}, V_{DC}, and V_{AC} are recorded in Table 4.8. It shows the changing of the performance voltage of that affected by hydrogen flow rate with varied the hydrogen pressure and load current of PEM Fuel Cell.

Table 4.8: V_{RMS}, V_{DC}, and V_{AC} of flow rate parameter with 0.2 Bar and 0.5 Bar pressure

	V_{RMS}		V_{DC}		V_{AC}	
Current (A)	0.2 Bar	0.5 Bar	0.2 Bar	0.5 Bar	0.2 Bar	0.5 Bar
0	43.67	45.69	43.59	45.62	2.66	2.56
5	36.62	38.20	36.61	38.20	1.01	0.49
10	35.63	36.25	35.62	36.25	0.7	0.25
15	34.12	34.94	34.10	34.93	1.08	0.9
20	32.99	33.86	32.98	33.85	0.58	0.71
25	31.72	32.96	31.69	32.95	1.47	0.6
30	30.92	32.16	30.89	32.16	1.43	0.52
35	30.04	31.31	29.96	31.28	2.12	1.38

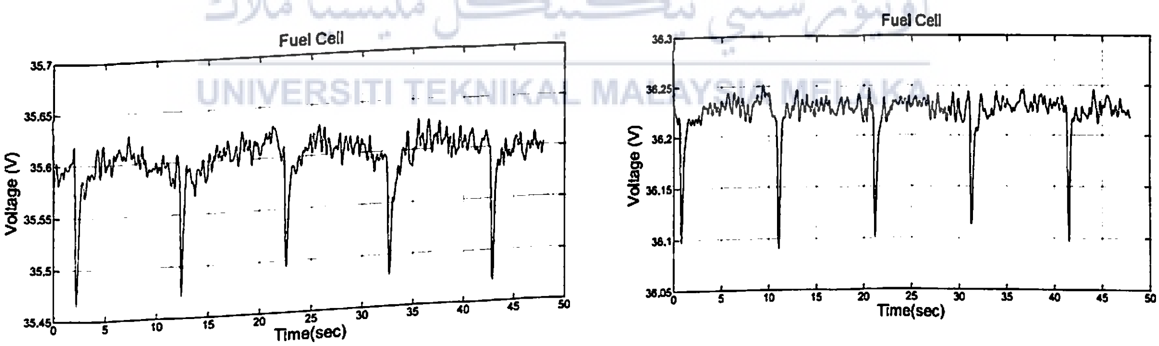
Figure 4.14 shows a rough signal for 5 A while Figure 4.15 and Figure 4.16 represent a rough signal for 10 A and 15 A. The V_{RMS} for 0.2 Bar of 5 A is 36.62 V and for 0.5 Bar is 38.20 V. At this level, the flow rate of hydrogen that flow through the inlet valve is 1.70 L/min and 2 L/min. Therefore, it shows that the increasing of the performance of PEM Fuel Cell is affected by the increasing of hydrogen flow rate parameters.



(a) (b)

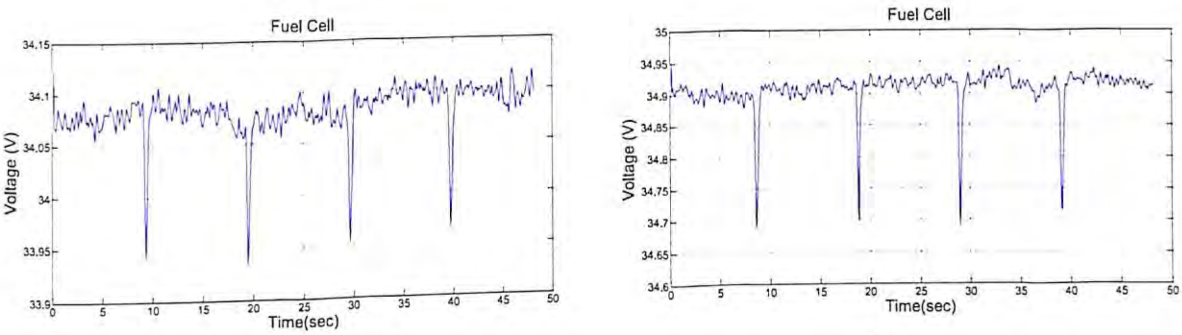
Figure 4.14 : Rough signal for flow rate effect on the performance 2000 W PEM Fuel Cell with a different pressure of hydrogen for 5 A; (a) 0.2 Bar hydrogen pressure (b) 0.5 Bar hydrogen pressure

In Figure 4.15, the load current that used is 10 A. It produced a 35.63 V_{RMS} for 0.2 Bar and 36.25 V for 0.5 Bar. The hydrogen flow rate that used is 3.55 L/min and 3.75 L/min. It also proved that the arising of hydrogen flow rate produced a higher performance voltage of PEM Fuel Cell. However, the arising of the current is affected on the flow rate parameter and also on the performance of PEM Fuel Cell. When the current is increased, the flow rate value also increased, but the performance voltage of PEM Fuel Cell becomes decreased. It proved that with the Figure 4.16. It shows that the performance voltage is decreased.



(a) (b)

Figure 4.15: Rough signal for flow rate effect on the performance 2000 W PEM Fuel Cell with a different pressure of hydrogen for 10 A; (a) 0.2 Bar hydrogen pressure (b) 0.5 Bar hydrogen pressure

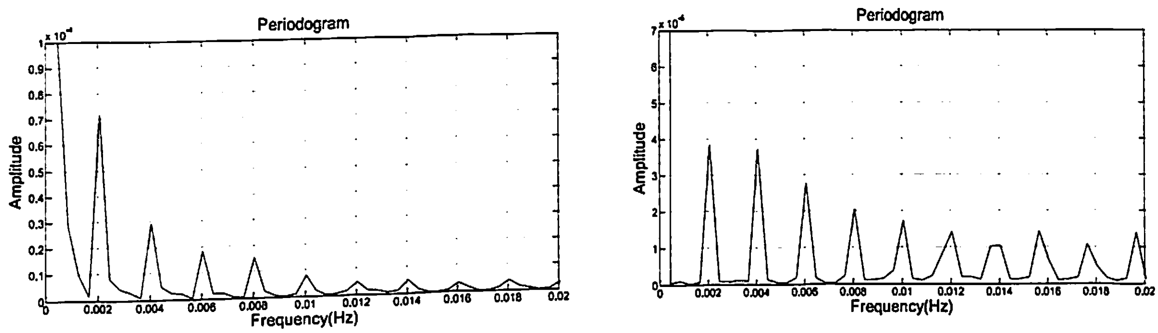


(a) (b)

Figure 4.16: Rough signal for flow rate effect on the performance 2000 W PEM Fuel Cell with a different pressure of hydrogen for 15 A; a) 0.2 Bar hydrogen pressure b) 0.5 Bar hydrogen pressure

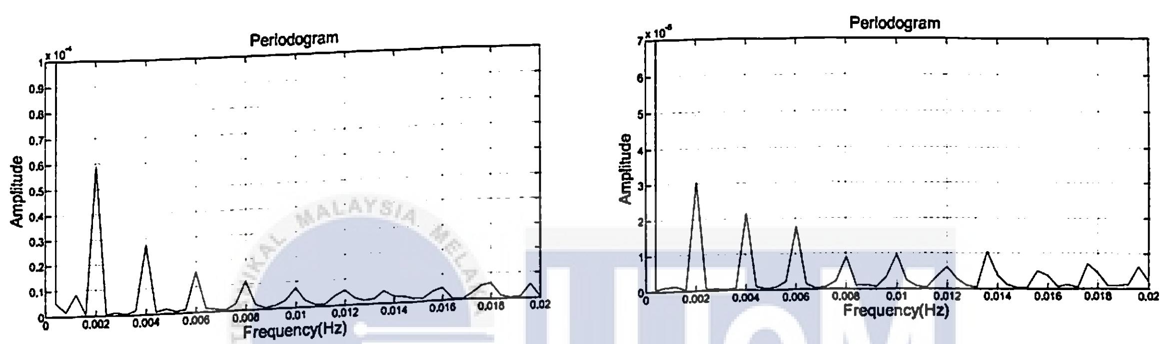
Therefore, based on the observation on the output for both experiment and rough signal, the flow rate of the hydrogen is affected from the variation of the load in the PEM Fuel Cell itself. The flow rate hydrogen is increased when the current of the load is increased. Therefore, the characteristic behavior of the PEM Fuel Cell is increased. This effect occurs because the hydrogen flow rate is related with the humidity of the hydrogen. In addition, the level of moisture becomes increased when the value of hydrogen flow rate is increased.

On the other hand, the periodogram signal shown in Figure 4.17 to Figure 4.19, while the data frequency of flow rate parameter is shown in Table 4.9. Based on Table 4.8 and Figure 4.17 to Figure 4.19, the value of V_{DC} is located at the 0 Hz, while the other frequency represents the value of V_{AC}. The values of frequency V_{AC} in the PEM Fuel Cell are slighter than V_{DC}. According to Figure 4.17, it is shown that a periodogram signal for 5 A with a V_{AC} value for 0.2 Bar at 0.002 Hz is higher than 0.005 Hz. Furthermore, Figure 4.18 illustrates a periodogram signal for 10 A load of current, while in Figure 4.19 demonstrates for 15 A. The trend of the periodogram signal has a similar pattern for all different current and pressure parameters. The V_{AC} value of the periodogram is lowest but it also provided an effect on the operation of the PEM Fuel Cell. The value of V_{AC} is represented as a distortion that occurs in the system. Therefore, the flow rate parameters also give an impact on the performance of the PEM Fuel Cell because it produces a distortion in the system.



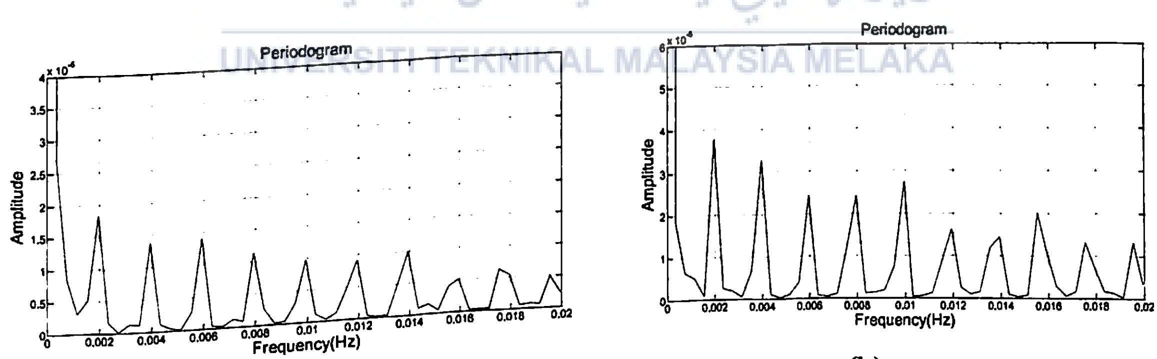
(a) (b)

Figure 4.17: Flow rate effect on the periodogram signal of PEM Fuel Cell with a different pressure of hydrogen for 5 A; (a) 0.2 Bar hydrogen pressure (b) 0.5 Bar hydrogen pressure



(a) (b)

Figure 4.18: Flow rate effect on the periodogram signal of PEM Fuel Cell with a different pressure of hydrogen for 10 A; (a) 0.2 Bar hydrogen pressure (b) 0.5 Bar hydrogen pressure



(a) (b)

Figure 4.19: Flow rate effect on the periodogram signal of PEM Fuel Cell with a different pressure of hydrogen for 15 A; (a) 0.2 Bar hydrogen pressure (b) 0.5 Bar hydrogen pressure

		Frequency (Hz)										
Pressure	Current (A)	0	0.002	0.004	0.006	0.008	0.01	0.012	0.014	0.016	0.018	0.02
0.2 Bar	0	1900	4.7E-05	1.2E-04	5.1E-05	4.8E-05	2.1E-05	1.4E-05	1.0E-05	6.3E-06	6.6E-06	1.7E-06
	5	1340	7.2E-05	2.9E-05	1.8E-05	1.5E-05	7.8E-06	4.7E-06	4.8E-06	3.3E-06	3.9E-06	2.7E-06
	10	1269	3.1E-05	2.2E-05	1.8E-05	9.0E-06	9.7E-06	6.0E-06	3.7E-06	3.6E-06	4.3E-06	1.9E-06
	15	1163	1.8E-05	1.4E-05	1.4E-05	1.1E-05	9.8E-06	9.1E-06	9.8E-06	5.1E-06	5.5E-06	2.3E-06
	20	1088	1.2E-05	7.2E-06	8.6E-06	6.7E-06	5.1E-06	5.1E-06	3.3E-06	1.3E-06	8.2E-07	1.6E-06
	25	1004	9.5E-05	5.1E-05	3.5E-05	4.8E-05	2.6E-05	2.3E-05	1.2E-05	8.4E-06	7.6E-06	1.7E-06
	30	954	2.2E-05	4.4E-05	5.7E-05	4.6E-05	2.5E-05	1.8E-05	1.1E-05	5.7E-06	8.1E-06	2.0E-06
	35	898	2.9E-05	2.9E-05	4.2E-05	2.2E-05	3.1E-05	1.5E-05	5.8E-06	7.8E-06	3.5E-06	1.9E-06
0.5 Bar	0	2081	3.8E-04	1.0E-04	5.8E-05	5.4E-05	2.0E-05	1.8E-05	8.3E-06	3.6E-06	6.3E-06	5.5E-07
	5	1459	3.9E-05	3.7E-05	2.8E-05	2.1E-05	1.7E-05	1.4E-05	1.0E-05	6.4E-06	4.6E-06	1.2E-06
	10	1314	3.1E-05	2.2E-05	1.8E-05	9.0E-06	9.7E-06	6.0E-06	3.7E-06	3.6E-06	4.3E-06	1.9E-06
	15	1220	3.8E-05	3.3E-05	2.4E-05	2.4E-05	2.8E-05	1.6E-05	1.4E-05	1.1E-05	7.1E-05	3.3E-05
	20	1146	5.1E-06	2.2E-05	1.5E-05	1.3E-05	1.4E-05	7.5E-06	5.4E-06	3.1E-06	2.9E-06	3.9E-06
	25	1086	1.2E-04	1.2E-04	9.5E-05	9.2E-05	6.5E-05	4.6E-05	3.3E-05	2.7E-05	1.1E-05	6.8E-06
	30	1034	1.1E-04	1.2E-04	9.7E-05	1.0E-04	6.3E-05	5.3E-05	3.2E-05	2.1E-05	1.6E-05	9.3E-06
	35	978	1.4E-04	1.2E-04	1.1E-04	1.0E-04	7.6E-05	4.4E-05	3.8E-05	3.1E-05	1.8E-05	4.7E-06

4.4 Summary

In Chapter 4, the result and discussion of the project are explained and discussed in detail. The results are divided into two sections which are Section 4.2 and Section 4.3. In Section 4.2, it shows the result of DC load for hydrogen pressure and flow rate parameters, while Section 4.3 represents the result of the periodogram analysis for both parameters.

CHAPTER 5

CONCLUSIONS

5.1 Conclusion

As a conclusion, all of the objectives were achieved. The first objective; to study on the performance and characteristic of PEM Fuel Cell is greatly achieved. The second objective; to investigate the effect of the pressure and flow rate of the hydrogen towards the performance of thermodynamic potential in the PEM Fuel Cell is determined. Therefore, at the end of the project, it is proved that the both parameters were affected on the performance of the PEM Fuel Cell. In the result, it shows that when the pressure is increasing, the performance voltage of the PEM Fuel Cell also increased. It is similar with the flow rate of hydrogen parameter where, it has effect on the performance voltage of the PEM Fuel Cell. When the value of flow rate hydrogen is raised up the performance voltage is decreased because the flow rate will make a flooding in the stack of PEM Fuel Cell. The third objective; to analyze the effect of the pressure and flow rate of hydrogen by using a periodogram analyzes on the performance of PEM Fuel Cell has been done. Thus, the analyze method not only used a performance characteristic analysis, but the signal processing method also is used to find the effect of parameters on the performance PEM Fuel Cell. This method produced a micro monitoring result of pressure and flow rate parameter affected on the behavior of characteristics PEM Fuel Cell.

5.2 Recommendation

According to the result and discussion, this project could be improved for the next future project. Firstly, the result 2000 W PEM Fuel Cell can be compared with the other rating of the PEM Fuel Cell because in different rating it will produce a different performance of the PEM Fuel Cell. Besides that, the future suggestion use the other parameter such as temperature, humidity and purge time as a parameter that can affect the performance of PEM Fuel Cell. In addition, the technique of the analysis will be improved by using a spectrogram technique because it will be more detail and it will produce an output in term of time and amplitude.

REFERENCES

[1] M. R. Islam, R. Saidur, N. A. Rahim and K. H. Sol, *"Renewable Energy Research In Malaysia,"* Engineering e-Transaction, vol. 4, no. 2, pp.69-72, December 2009.

[2] H. Haslenda and W. S. Ho, *"Renewable Energy Policies And Initiatives For A Sustainable Energy Future In Malaysia,"* Renewable and Sustainable Energy Reviews, 2011.

[3] Y. Sina and W. Najmi, *"Industrial and Academic Collaboration Strategies on Hydrogen Fuel Cell Technology Development in Malaysia,"* Procedia - Social and Behavioral Sciences 90, pp. 879 – 888, 2013.

[4] E.I. Ortiz-Rivera; A.L. Reyes-Hernandez; R.A. Febo, *"Understanding The History of Fuel Cells,"* Electric Power, 2007 IEEE Conference on the History of, pp.117-122, 3-5 August 2007.

[5] B. Cook, *"An Introduction To Fuel Cells And Hydrogen Technology,"* Canada: Heliocentris 3652 West 5th Avenue, December 2001.

[6] J.A. Smith; M.H. Nehrir; V. Gerez; S.R. Shaw, *"A Broad Look At The Workings, Types, And Applications Of Fuel Cells,"* Power Engineering Society Summer Meeting, 2002 IEEE , vol.1, pp.70-75, 25-25 July 2002.

[7] Fuel Cell Today, *"Fuel Cell Basic Technology Types,"* Fuel Cell Today, May 2012. [Online]. Available: www.fuelcelltoday.com [Accessed 23 October 2014].

[8] B. Larbi; W. Alimi; R. Chouikh; A. Guizani, *"Effect of Porosity and Pressure on the PEM Fuel Cell Performance,"* International Journal of Hydrogen Energy, pp.8542-8549, 2013.

[9] A.R .Maher and Sadiq Al-Baghdadi, *"Performance Optimization of a PEM Hydrogen-Oxygen Fuel Cell,"* International Journal of Energy and Environment, vol.4, pp.175-184, Issues 2, 2013.

[10] A.Mousa; S. El-Emam; M. Awad, *"Effect of Stack Orientation on the Performance of H_2/Air PEM Fuel Cell,"* Thermal Issues in Emerging Technologies Theory and Applications, 3rd International Conference on, pp.301-307, 19-22 December 2010.

[11] G.H. Guvelioglu and H.G. Stenger, *"Flow Rate and Humidification Effects on a PEM Fuel Cell Performance and Operation,"* Journal of Power Sources, pp.882–891, 2007.

[12] Jie Hui and He Jie, *"Research of the Humidity Control System of PEM Fuel Cell,"* International Conference, pp.548-551, 15-16 November 2010.

[13] M.Amirinejad; S. Rowshanzamir; M.H. Eikani, *"Effects of Operating Parameters on Performance of a Proton Exchange Membrane Fuel Cell,"* Journal of Power Sources, pp.872–875, 2006.

[14] L.Wang; A.Husar; T.Zhou; H.Liu, *"A Parametric Study of PEM Fuel Cell Performances,"* International Journal of Hydrogen Energy, pp.1263 – 1272, 2003.

[15] C.Lee; T.Yang; T.H.Chien; Y.M. Chang, *"Pressure and Flow Rate Monitoring in PEM Fuel Cells by Embedded Flexible Micro-Sensors,"* Nano/Micro Engineered and Molecular Systems (NEMS), *2010 IEEE*, pp.752-756, 20-23 January 2010.

[16] P.Pei; M.Ouyang; W.Feng; L.Lu; H.Huang; J.Zhang, *"Hydrogen Pressure Drop Characteristics in a Fuel Cell Stack,"* International Journal of Hydrogen Energy, pp.371 – 377, 2006.

[17] M.Soltani and S.M.T.Bathaee, *"A New Dynamic Model Considering Effects of Temperature, Pressure and Internal Resistance for PEM Fuel Cell Power Modules,"* pp.2757-2762, 6-9 April 2008

[18] P.Moldrik; R.Chvalek, *"PEM fuel cells — The effect of fuel parameters on efficiency and quality of electric power supply,"* Environment and Electrical Engineering (EEEIC), 2011 10th International Conference on, pp.1-4, 8-11 May 2011.

[19] D.Chu and R.Jiang, *"Performance of Polymer Electrolyte Membrane Fuel Cell PEMFC/Stacks Part I. Evaluation and Simulation of an Air-breathing PEMFC Stack,"* Journal of Power Sources, pp.128–133.

[20] B.Wahdame; D.Candusso; J.M.Kauffmann, *"Study of Gas Pressure and Flow Rate Influences on a 500W PEM Fuel Cell, Thanks to the Experimental Design Methodology,"* Journal of Power Sources, pp.92–99, 2006.

[21] J.Font-Segura; G.Vazquez; J.Riba, *"Novel Periodogram and Capon Spectral Analysis Based on Nonuniform Sampling,"* Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE, pp.1-5, 5-9 December. 2011.

[22] N.M.Saad; A.R.Abdullah; Y.F.Low, *"Detection of Heart Blocks in ECG Signals by Spectrum and Time-Frequency Analysis,"* Research and Development, 2006. SCOReD 2006. 4th Student Conference, pp.61-65, 27-28 June 2006

[23] O.Olabiyi and A.Annamalai, *"Analysis and New Implementations of Periodogram-Based Spectrum Sensing,"* Sarnoff Symposium (SARNOFF), 2012 35th IEEE , pp.1-5, 21-22 May 2012.

[24] Q.Zhou; M.Brenneman; J.Morton, *"Analysis of EEG Data Using an Adaptive Periodogram Technique,"* BioMedical Engineering and Informatics, 2008. BMEI 2008. International Conference, vol.2, pp.353-357, 27-30 May 2008.

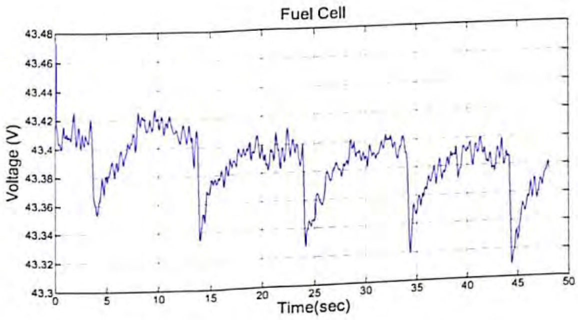
[25] X.Jun; C.Xiaozhun; L.Chonghua; L. Tianxiong, *"Analysis Technique of Signal Bandwidth for GNSS,"* Wireless, Mobile and Multimedia Networks (ICWMMN 2013), 5th IET International Conference, pp.168-171, 22-258 November 2013.

[26] F.Yili; W.Guangguo; W.Shuguo; J.Bao, *"Signal Processing of Robotic Sensitive Skin Based on DSP+FPGA,"* Information Acquisition, 2006 IEEE International Conference, pp.398-403, 20-23 August 2006.

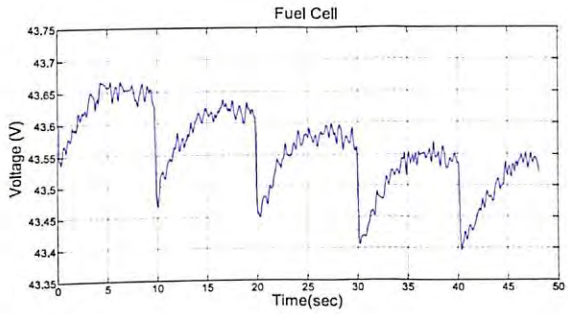
[27] J.B.Benziger; M.B.Satterfield; W.H.J.Hogarth; J.P.Nehlsen, I.G.Kevrekidis, *"The Power Performance Curve for Engineering Analysis of Fuel Cells,"* Journal of Power Sources, pp.272–285, 2006.

[28] T.W.Lee; S.H.Kim; Y.H.Yoon; S.J.Jang; C.Y. Won, *"A 3 kW fuel cell generation system using the fuel cell simulator,"* Industrial Electronics, 2004 IEEE International Symposium, vol.2, pp.833-837 , 4-7 May 2004.

APPENDIX A - ROUGH SIGNAL FOR PRESSURE PARAMETER



(a)



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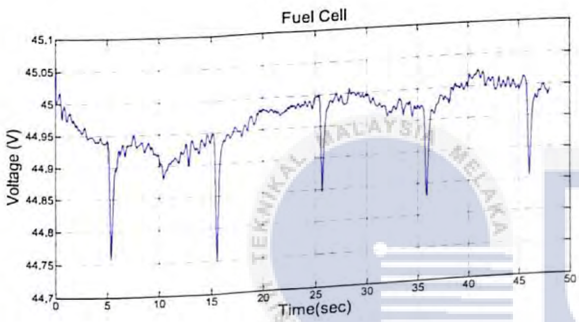
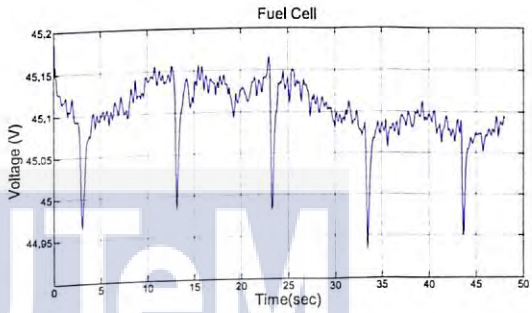
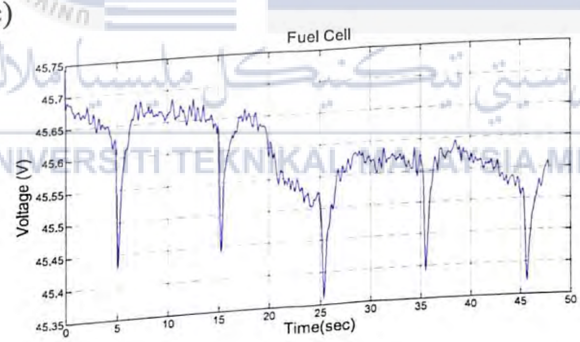


(c)



(d)



(e)

Figure A1: Rough signal for performance voltage of 2000 W PEM Fuel Cell of 0 A load current with different of hydrogen pressure; (a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure (d) 0.4 Bar hydrogen pressure (e) 0.5 Bar hydrogen pressure

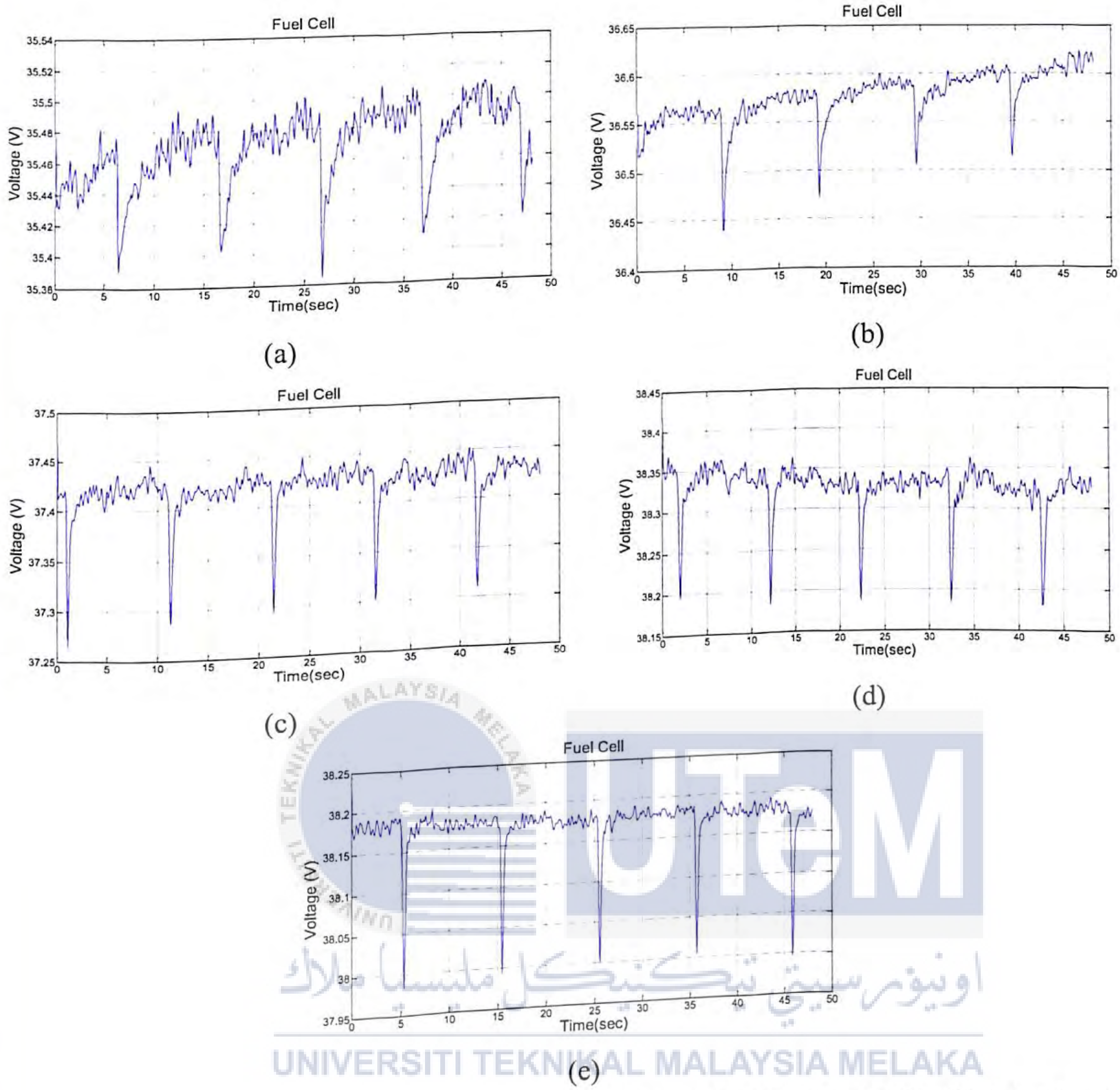


Figure A2: : Rough signal for performance voltage of 2000 W PEM Fuel Cell of 5 A load current with different of hydrogen pressure; (a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure (d) 0.4 Bar hydrogen pressure (e) 0.5 Bar hydrogen pressure

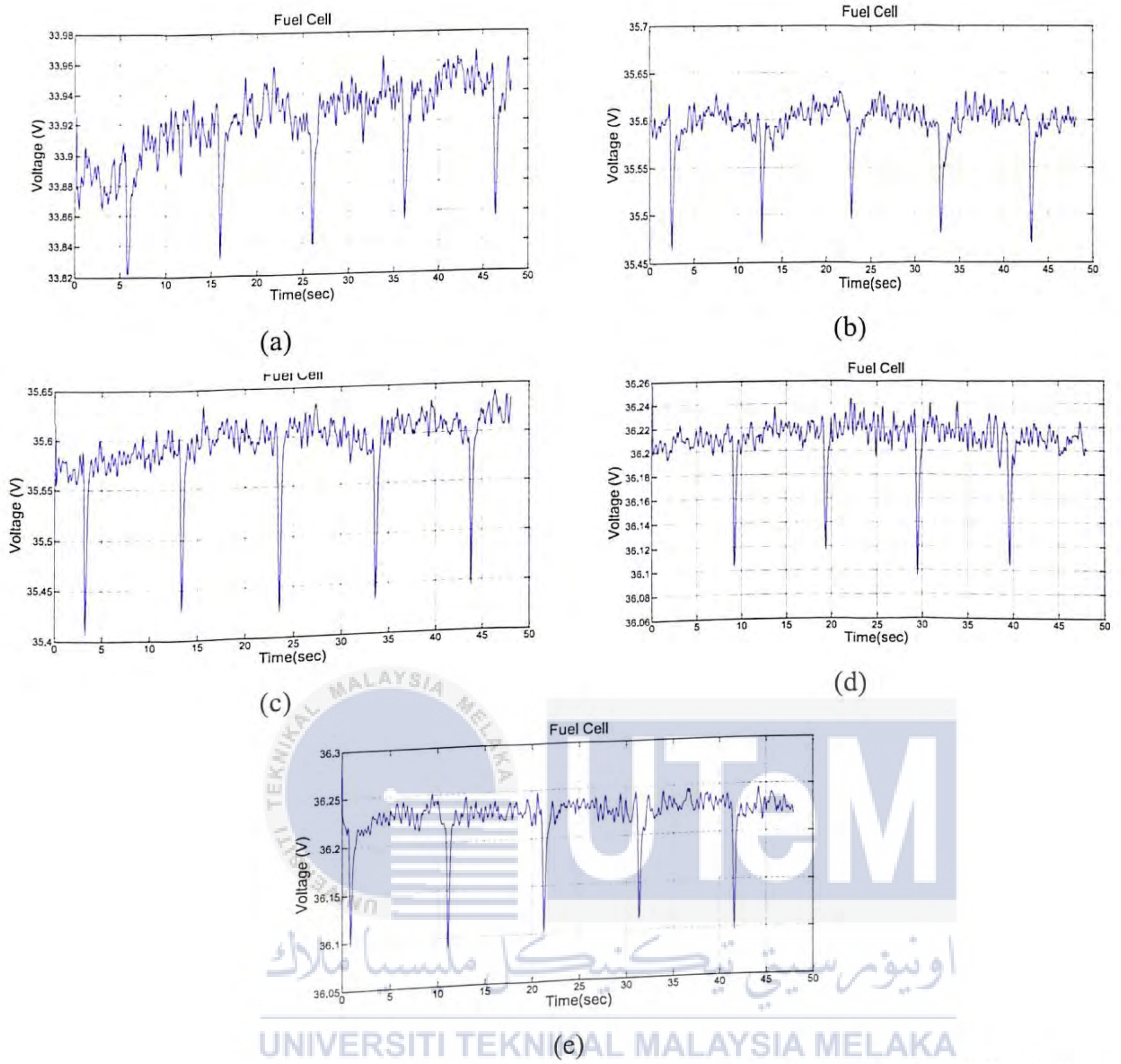


Figure A3: Rough signal for performance voltage of 2000 W PEM Fuel Cell of 10 A load current with different of hydrogen pressure; (a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure (d) 0.4 Bar hydrogen pressure (e) 0.5 Bar hydrogen pressure

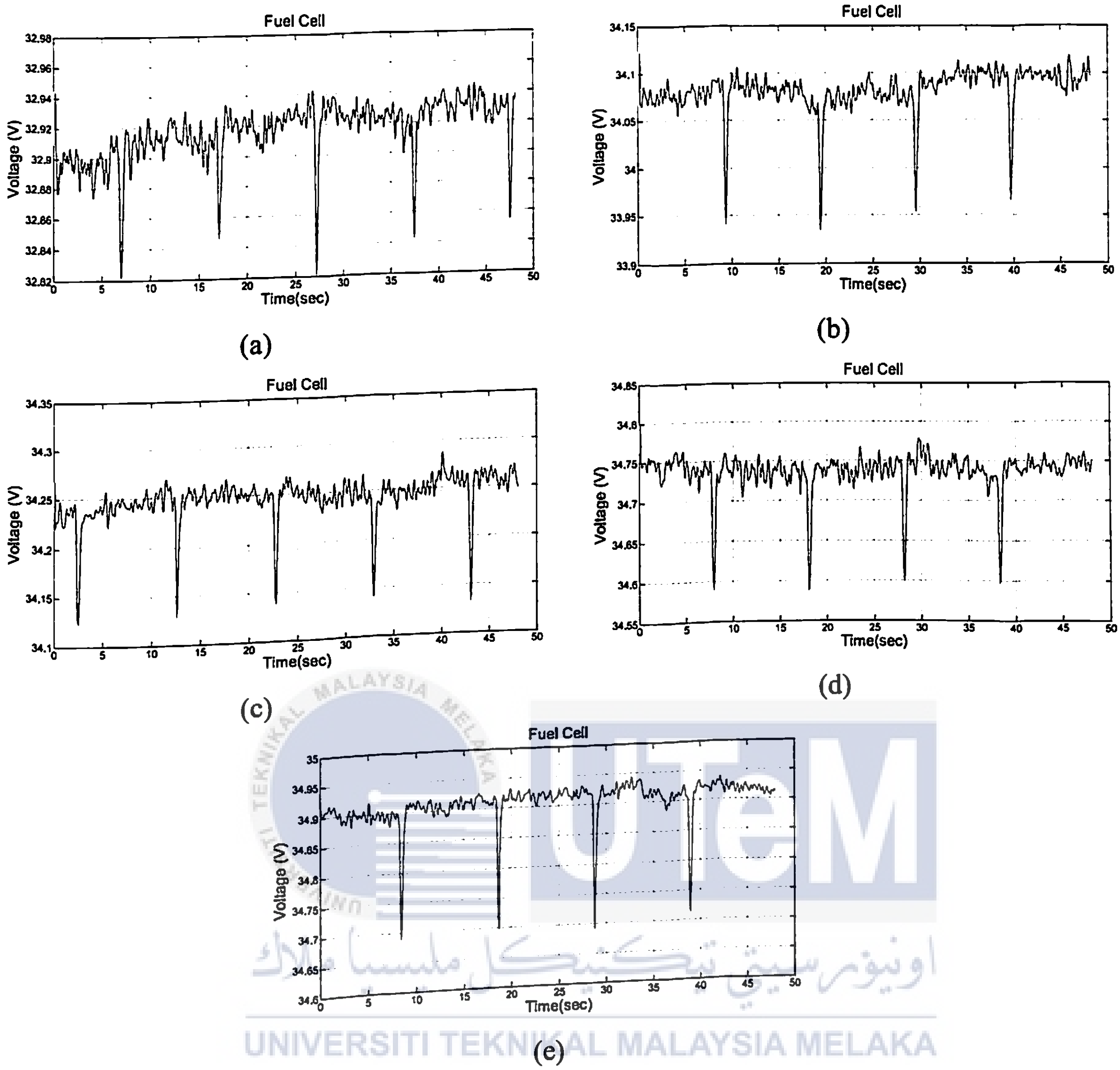


Figure A4: Rough signal for performance voltage of 2000 W PEM Fuel Cell of 15 A load current with different of hydrogen pressure; (a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure (d) 0.4 Bar hydrogen pressure (e) 0.5 Bar hydrogen pressure

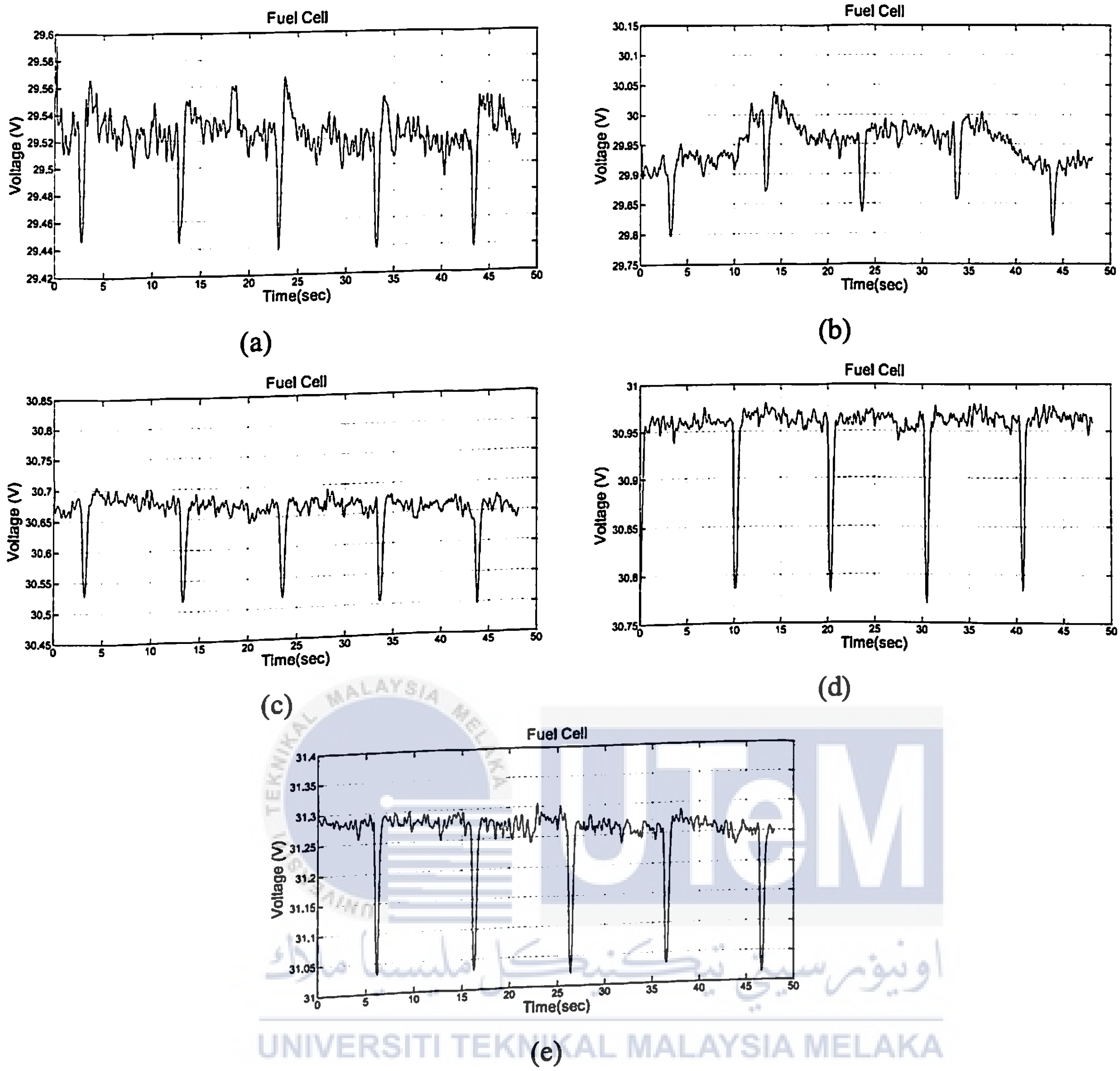


Figure A5: Rough signal for performance voltage of 2000 W PEM Fuel Cell of 35 A load current with different of hydrogen pressure; (a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure (d) 0.4 Bar hydrogen pressure (e) 0.5 Bar hydrogen pressure

APPENDIX B - PERIODOGRAM SIGNAL FOR PRESSURE PARAMETER

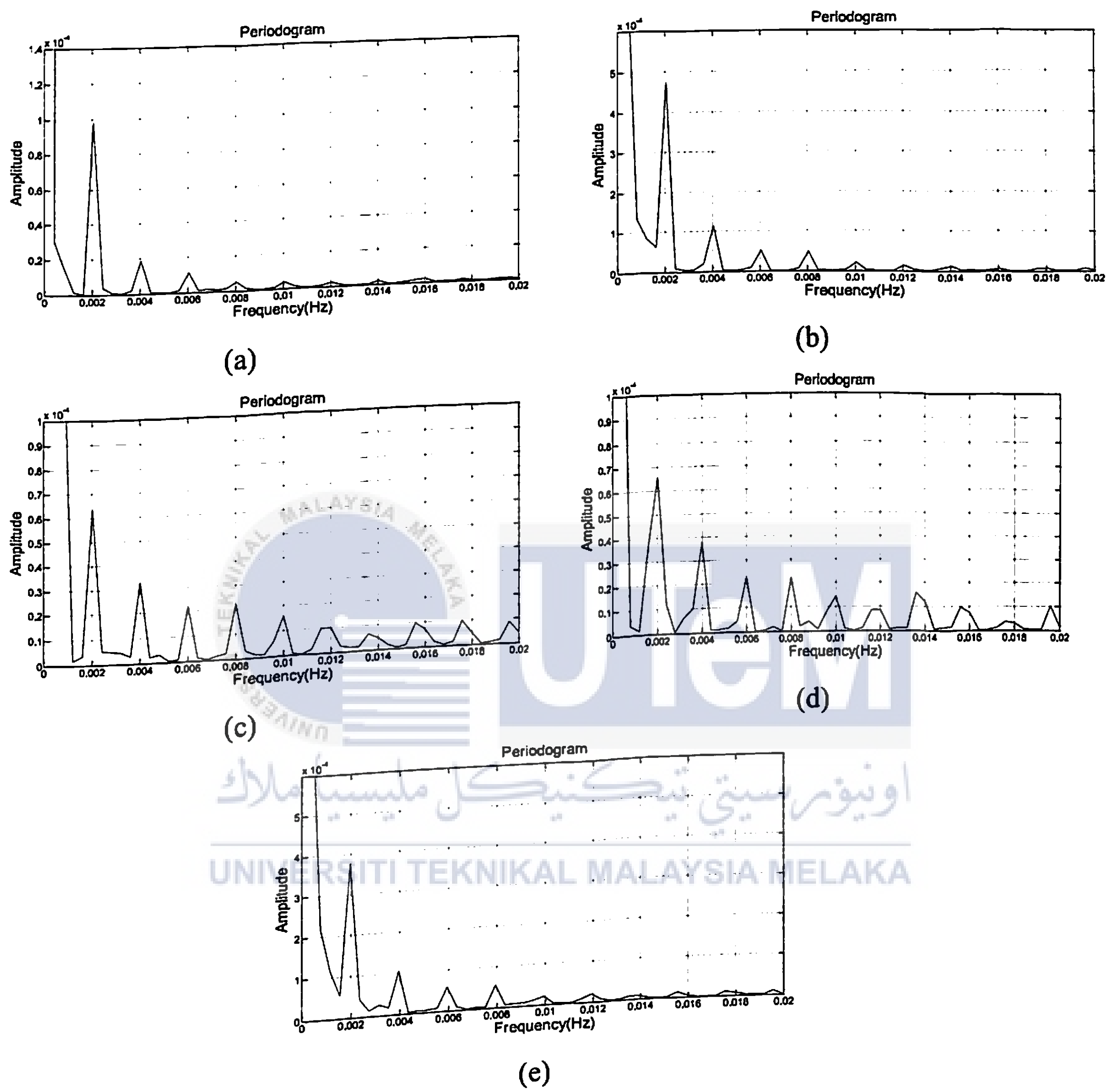


Figure B2: Periodogram signal of 2000 W PEM Fuel Cell of 0 A with different of hydrogen pressure at anode side; (a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure d) 0.4 Bar hydrogen pressure e) 0.5 Bar hydrogen pressure

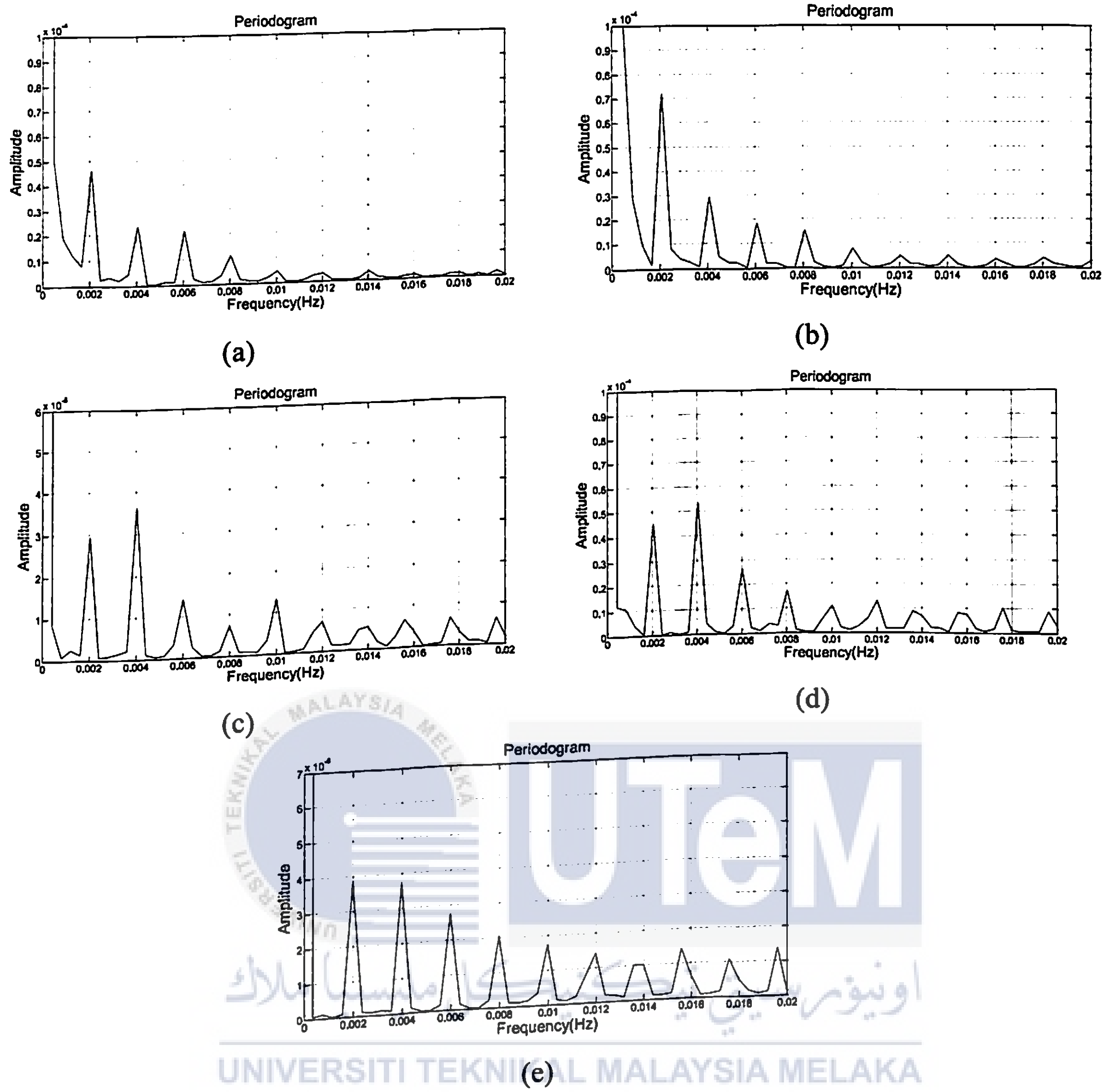


Figure B2: Periodogram signal of 2000 W PEM Fuel Cell of 5A with different of hydrogen pressure at anode side; (a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure d) 0.4 Bar hydrogen pressure e) 0.5 Bar hydrogen pressure

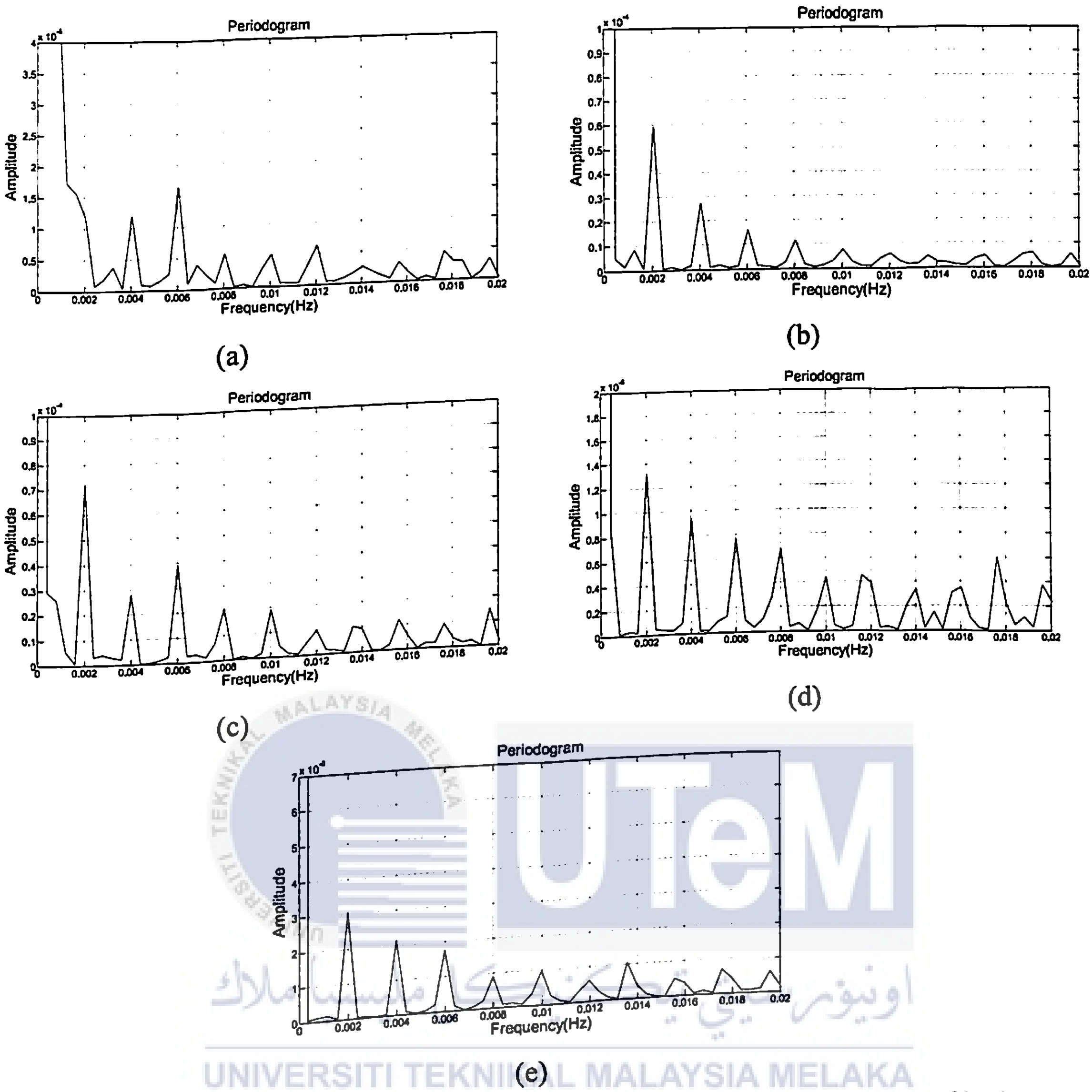


Figure B3: Periodogram signal of 2000 W PEM Fuel Cell of 10 A with different of hydrogen pressure at anode side; (a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure d) 0.4 Bar hydrogen pressure e) 0.5 Bar hydrogen pressure

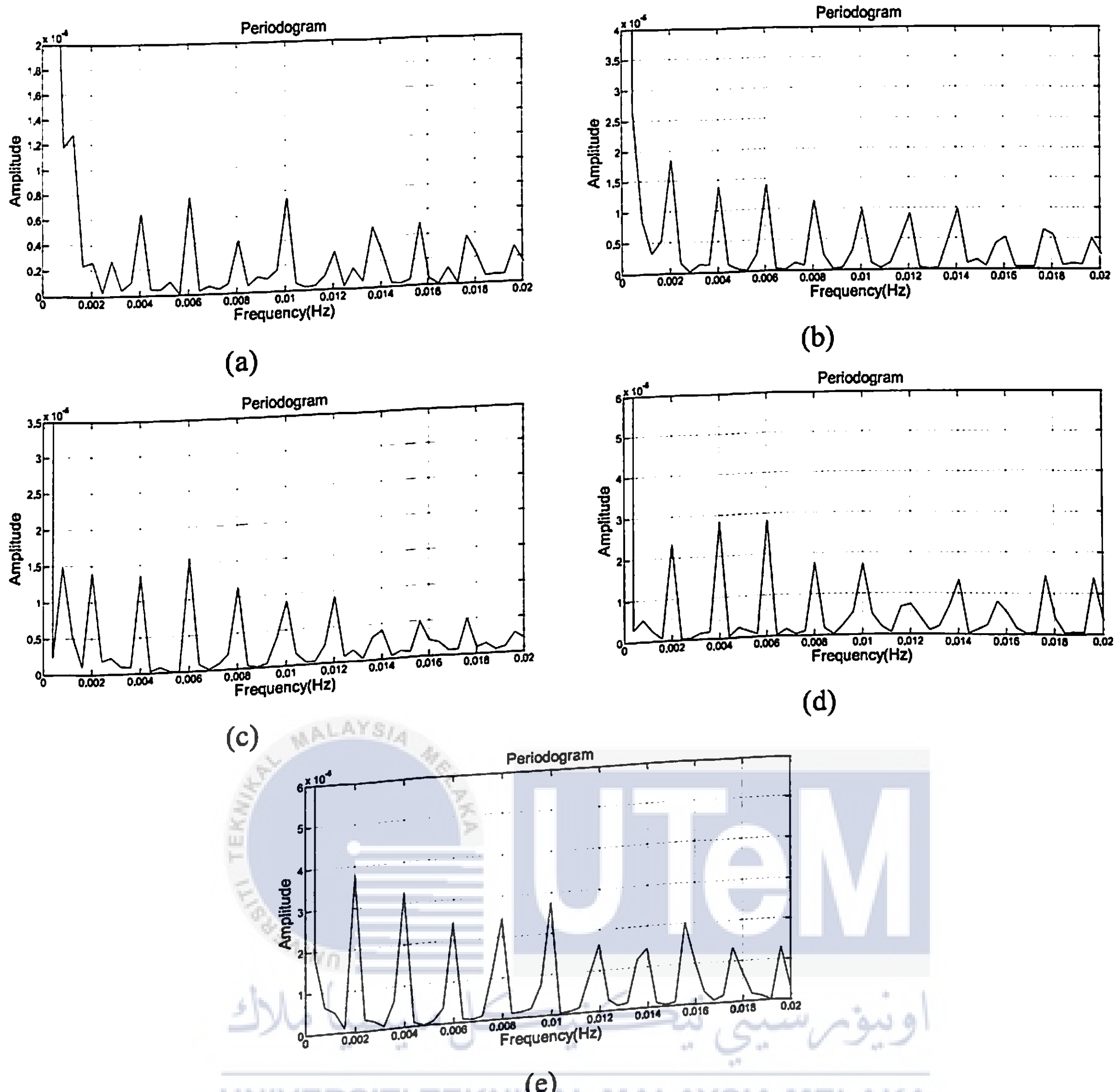


Figure B4: Periodogram signal of 2000 W PEM Fuel Cell of 15 A with different of hydrogen pressure at anode side; (a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure d) 0.4 Bar hydrogen pressure e) 0.5 Bar hydrogen pressure

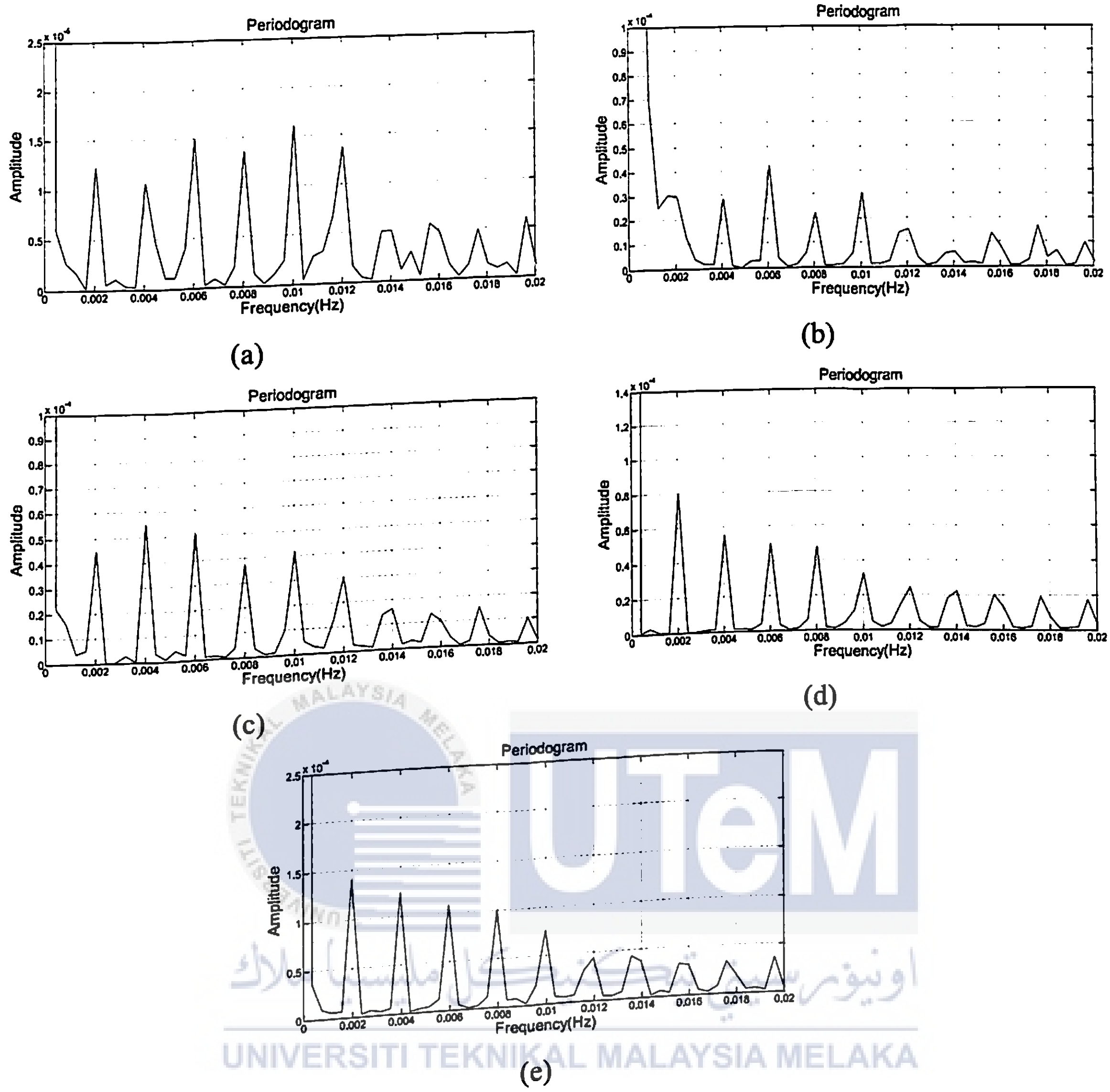
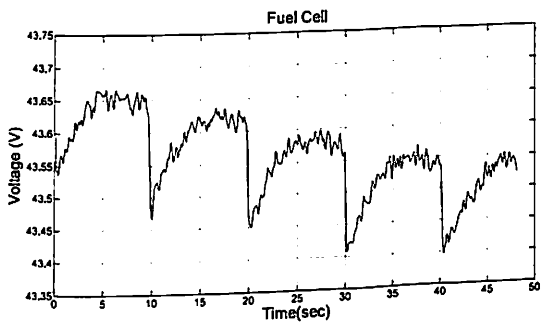
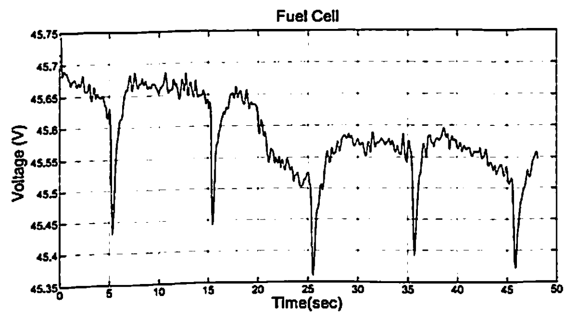


Figure B5: Periodogram signal of 2000 W PEM Fuel Cell of 35 A with different of hydrogen pressure at anode side; (a) 0.1 Bar hydrogen pressure (b) 0.2 Bar hydrogen pressure (c) 0.3 Bar hydrogen pressure d) 0.4 Bar hydrogen pressure e) 0.5 Bar hydrogen pressure

APPENDIX C - ROUGH SIGNAL FOR FLOW RATE PARAMETER

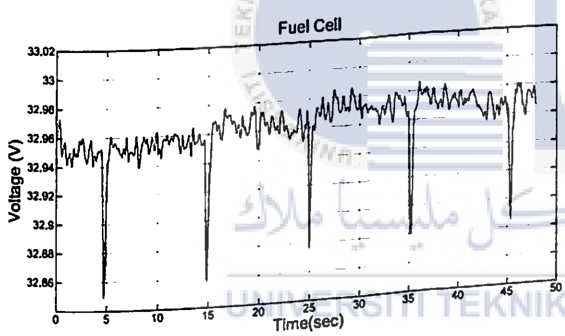


(a)

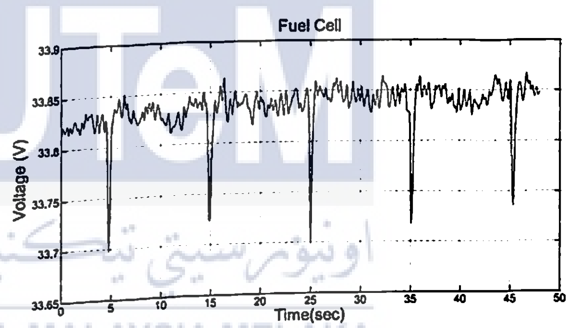


(b)

Figure C1 : Rough signal for flow rate effect on the performance 2000 W PEM Fuel Cell with a different pressure of hydrogen for 0 A; (a) 0.2 Bar hydrogen pressure (b) 0.5 Bar hydrogen pressure

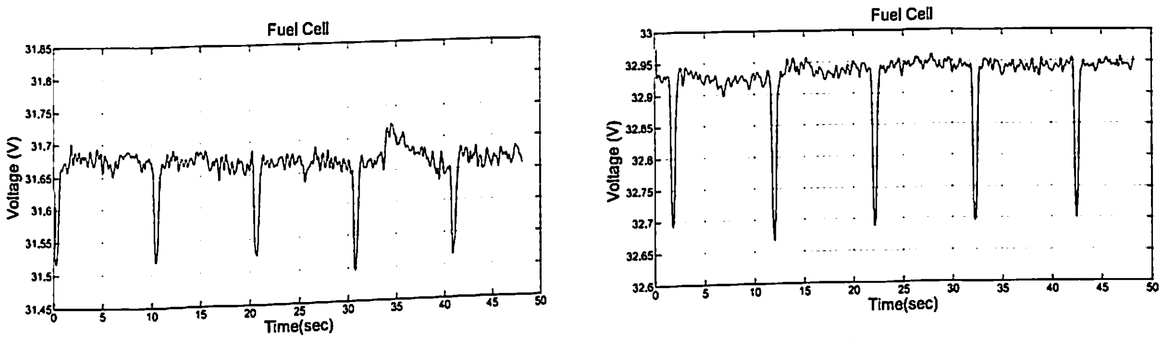


(a)



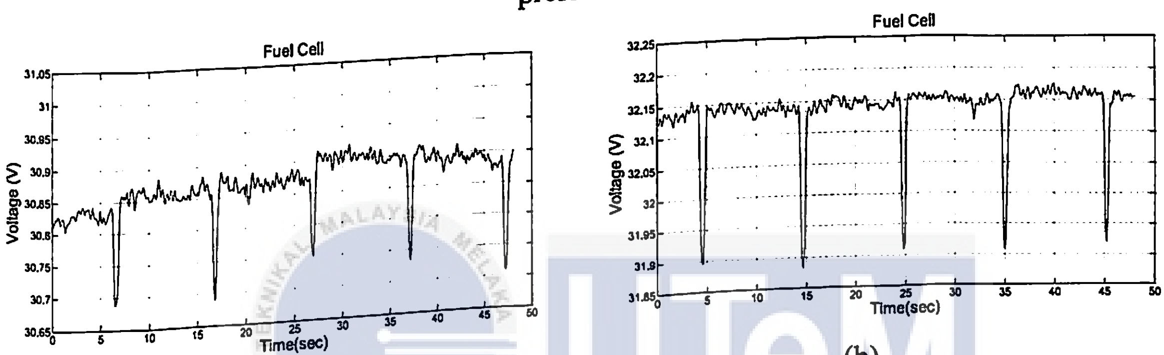
(b)

Figure C2 : Rough signal for flow rate effect on the performance 2000 W PEM Fuel Cell with a different pressure of hydrogen for 20 A; (a) 0.2 Bar hydrogen pressure (b) 0.5 Bar hydrogen pressure



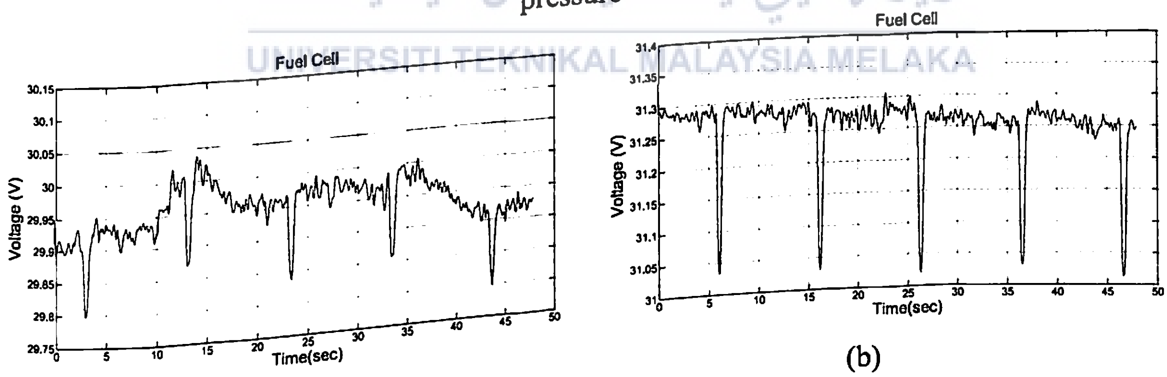
(a) (b)

Figure C3 : Rough signal for flow rate effect on the performance 2000 W PEM Fuel Cell with a different pressure of hydrogen for 25 A; (a) 0.2 Bar hydrogen pressure (b) 0.5 Bar hydrogen pressure



(a) (b)

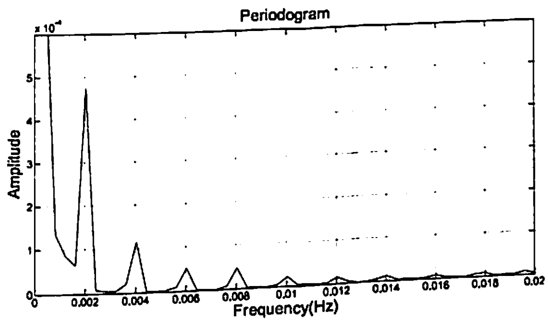
Figure C4 : Rough signal for flow rate effect on the performance 2000 W PEM Fuel Cell with a different pressure of hydrogen for 30A ; (a) 0.2 Bar hydrogen pressure (b) 0.5 Bar hydrogen pressure



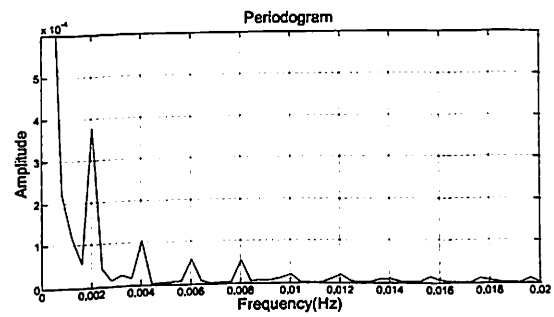
(a) (b)

Figure C5 : Rough signal for flow rate effect on the performance 2000 W PEM Fuel Cell with a different pressure of hydrogen for 35 A; (a) 0.2 Bar hydrogen pressure (b) 0.5 Bar hydrogen pressure

APPENDIX D - PERIODOGRAM SIGNAL FOR FLOW RATE PARAMETER

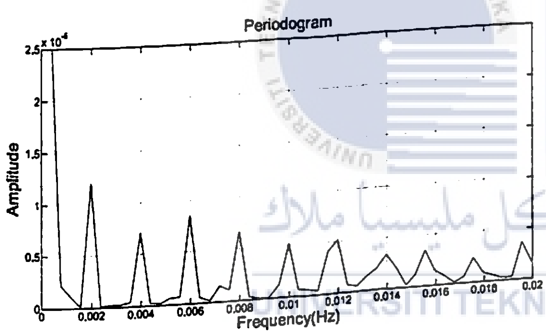


(a)

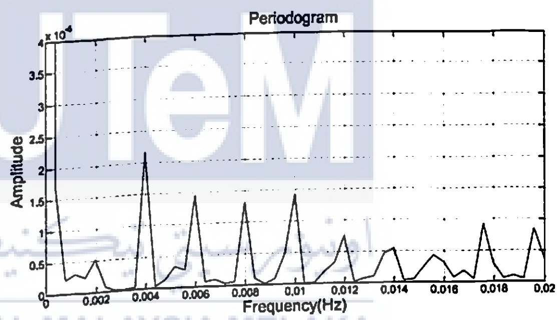


(b)

Figure D1: Flow rate effect on the periodogram signal of PEM Fuel Cell with a different ressure of hydrogen for 0 A; (a) 0.2 Bar hydrogen pressure (b) 0.5 Bar hydrogen pressure

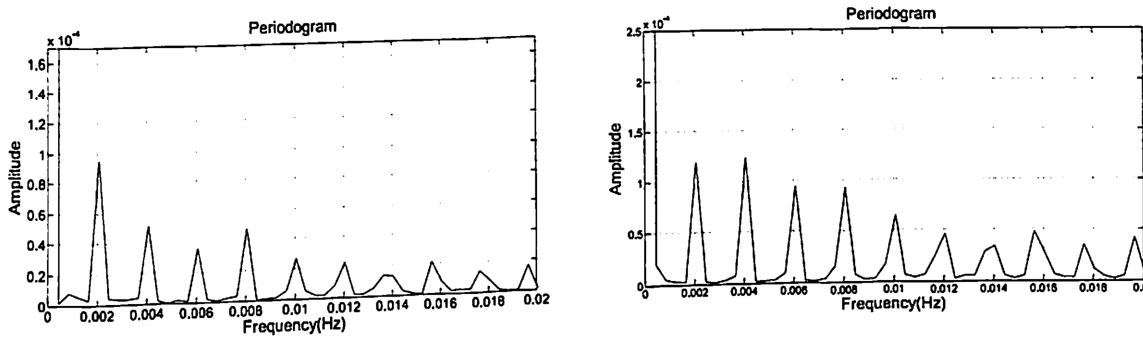


(a)



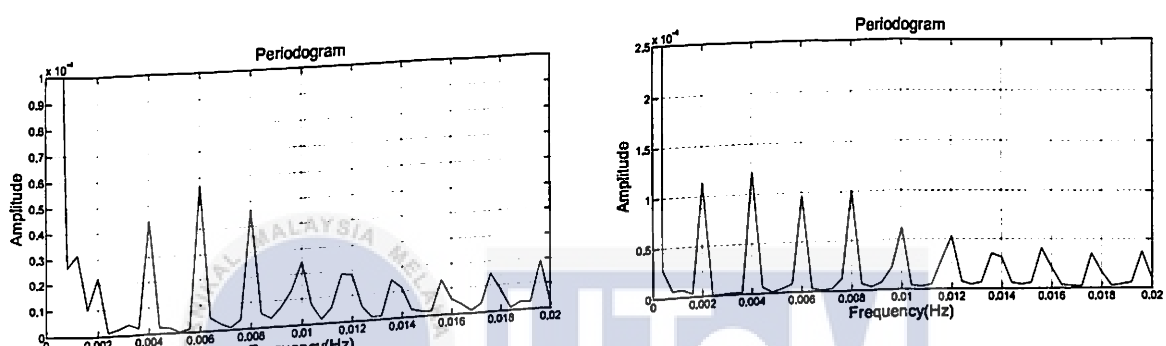
(b)

Figure D2: Flow rate effect on the periodogram signal of PEM Fuel Cell with a different pressure of hydrogen for 20 A; (a) 0.2 Bar hydrogen pressure (b) 0.5 Bar hydrogen pressure



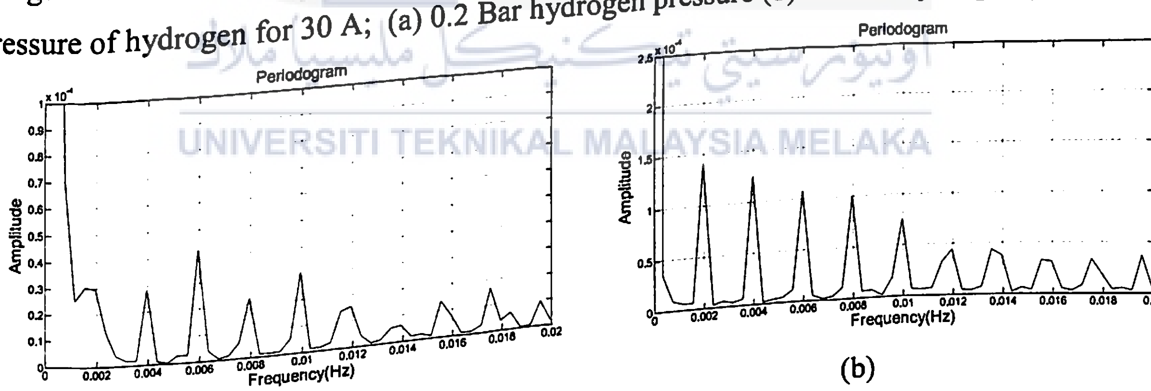
(a) (b)

Figure D3: Flow rate effect on the periodogram signal of PEM Fuel Cell with a different pressure of hydrogen for 25 A; (a) 0.2 Bar hydrogen pressure (b) 0.5 Bar hydrogen pressure



(a) (b)

Figure D4: Flow rate effect on the periodogram signal of PEM Fuel Cell with a different pressure of hydrogen for 30 A; (a) 0.2 Bar hydrogen pressure (b) 0.5 Bar hydrogen pressure



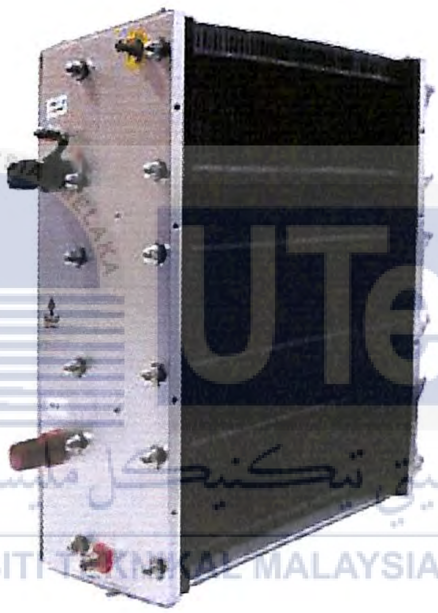
(a) (b)

Figure D5: Flow rate effect on the periodogram signal of PEM Fuel Cell with a different pressure of hydrogen for 35 A; (a) 0.2 Bar hydrogen pressure (b) 0.5 Bar hydrogen pressure

APPENDIX E - DATASHEET OF H-2000W PEM FUEL CELL FROM HORIZON FC TECHNOLOGIES

Horizon
Fuel Cell Technologies

2000W Fuel Cell Stack
User Manual



Updated 19 Aug. 2013

Model No.:FCS-C2000
Manual_FCS-C2000_V1.1_EN

Horizon Fuel Cell Technologies

4. Technical Specifications

Control electronics included:

Type of fuel cell	PEM
Number of cells	48
Rated Power	2000W
Performance	28.8V @ 70A
H2 Supply valve voltage	12V
Purging valve voltage	12V
Blower voltage	12V
Reactants	Hydrogen and Air
External temperature	5 to 30°C
Max stack temperature	65°C
H2 Pressure	0.45-0.55bar
Hydrogen purity	≥99.995% dry H2
Humidification	self-humidified
Cooling	Air (integrated cooling fan)
Weight (with fan & casing)	10Kg (±200grams)
Controller	2.5Kg (±100grams)
Dimension	30.3cm x 35cm x 18.3cm
Flow rate at max output*	26 L/min
Start up time	≤30S at ambient temperature
Efficiency of stack	40% @ 28.8V
Low voltage shut down	24V
Over current shut down	90A
Over temperature shut down	65°C
External power supply**	13V(±1V), 5A~8A

* The flow rate may change with the power output
** System electronics need external power supply
*** The Specification is subject to change without notice.

Horizon
Fuel Cell Technologies

8. Polarization curves

Performance characteristics of the stack are presented. All performance data is given for baseline operating conditions, defined at sea-level and room ambient temperature.