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Simulation And Analysis Of Pem Fuel Cell System Using Matlab

Syasya Nurmaisarah Mohd Hamzah[1], **Omar Mohd Faizan Marwah**[1,*,]

[1]Faculty of Mechanical and Manufacturing Engineering,
University Tun Hussein Onn Malaysia, Parit Raja 86400 Batu Pahat, Johor, MALAYSIA

*Corresponding Author Designation

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Abstract: The proton exchange membrane fuel cell is one of the renewable energy technologies that has become an essential technology to create electricity that is hugely beneficial for human activities. It is one of the technologies that has contributed to the rise in the popularity of renewable energy. The study's observation is to design a model and simulate the PEM fuel cell system by using three different electrical loads. The proton exchange membrane fuel cell (PEMFC) uses a chemical process to generate energy from hydrogen and oxygen. PEMFC stack modelling aims to establish a foundation for the efficient and effective design of fuel cell systems. For modelling, it may be described by the structure of the PEMFC as well as the working principle. The open-circuit voltage of the PEMFC may be calculated using the Nernst equation in conjunction with several voltage drops determined from the polarization curve of the PEMFC. MATLAB may be used in the construction of a PEMFC model. The MATLAB/Simulink program simulates the PEMFC system, which produces the necessary analysis. Fuel cells are able to be fuelled by combinations of hydrogen and oxygen. The construction of an infrastructure that is both secure and efficient in terms of cost is going to be necessary to make use of hydrogen both as a fuel and as a carrier for energy. The simulation results in this project reveal the amount of power generated and consumed by the PEMFC system, the efficiency of the PEMFC system, and the amount of hydrogen used by the fuel cell.

Keywords: Proton Exchange Membrane (PEMFC), MATLAB/Simulink

1. Introduction

Nowadays, the development of fuel cell as a renewable energy technology has become very popular due to its clean and sustainable source of energy. Fuel cell has become a good choice to replace the dependency on fossil fuels to improve the increasing energy demand [1] Fuel cell can produce electrical energy from the conversion of chemical energy based on an electrochemical process. Various types of fuel cells can generate electricity according to their characteristics such as Phosphoric Acid Fuel Cells

*Corresponding author: mdfaizan@uthm.edu.my

(PAFC), Molten Carbonate Fuel Cell (MCFC), Proton Exchange Membrane Fuel Cells (PEMFC) and Solid Oxide Fuel Cells (SOFC). Proton Exchange Membrane Fuel Cell (PEMFC) which is also known as a Polymer Electrolyte Membrane fuel cell is one of the better choices for the electrical system based on its good benefits such as high efficiency, low-temperature operation (50-100 ^{O}C), zero-emission potential and high power density [2]. One of the main advantages of PEMFC is it has a low operating temperature which allows a short start-up time and provides high power density.

Compared to heat engines, PEM fuel cells have higher efficiency, making their usage in modular electricity production and the powering of electric vehicles an exciting and potentially lucrative prospect. At partial loads, which represent the vast majority of driving situations seen in urban and highway environments, the efficiency of fuel cells is at its highest. At a standard driving speed of thirty miles per hour, the fuel cell electric drive that derives its hydrogen directly from natural gas boasts an efficiency two times greater than that of a traditional internal combustion engine. In highly crowded metropolitan areas, eliminating local emissions concerns is possible by using pure hydrogen as a fuel. We will be able to become less reliant on fossil fuels if we build a hydrogen generating and distribution system that is powered by renewable energy sources like wind, water, and sun, as well as fuel processors [3].

The inquiry and study of alternative energy sources have seen tremendous growth in recent years, mainly due to the rapid progress in technology and the increased need for energy. One of the kinds of fuel cells that have been produced is called a PEMFC, and its performance has been the basis for developing various software programmes. Several fuel cells may be distinguished from one another by the electrolyte, the temperature at which they operate, and the electrodes. In this investigation, a proton exchange membrane fuel cell, also known as a PEMFC, is utilised because of its low operating temperature, which ranges from 70 to 100 degrees Celsius and high dry membrane densities (up to 2000 kg/m3). As a result, the innovation of PEMFC may be used to replace the traditional engine, also known as an internal combustion engine (ICE). It will take much less time to construct the model of PEMFC if the dynamic behaviour of PEMFC is first studied for a shorter period. In addition, estimating the parameter value for the PEMFC system is fundamentally simplified when done using MATLAB. As a result, the PEMFC system method will provide benefits in terms of good modelling for the whole continent.

In PEMFC, the hydrogen is activated by a catalyst to form a proton ion and eject electrons at the anode. The proton passes through the membrane while the electron is forced to flow to the external; circuit and generate electricity. The electron then flows back to the cathode and interact with oxygen and proton ion to form water. Basically, the PEMFC is comprised of bipolar plates and membrane electrode assembly (MEA). The MEA is composed of a dispersed catalyst layer, carbon sloth or gas diffusion layer and the membrane. The membrane is to transport protons from the anode to the cathode and blocks the passage of electrons and reactants. The gas diffusion layer is to access the fuel uniformly. Electrons at the anode pass through the external circuit and generate electricity [4].

PEMFCs are low-temperature fuel cells with operating temperatures between 60 and 100oC. They are lightweight compact systems with rapid start-up processes. In addition, they have longer lifetimes and are cheaper to manufacture. From an efficiency point of view, the higher the working temperature the higher efficiency can be gained. This is due to the higher reaction rate. The electrical efficiency of PEMFCs is between 40 and 50% and the output power can be as high as 250 kW. PEMFC require minimum maintenance because there are no moving parts in the power-generating stacks of the fuel cells. Fuel cell vehicles are the most promising application of PEMFC systems. The reason is the observability of technology development by people which can significantly improve the acceptability of such systems among communities. McNicol states that an FCV can successfully contend against conventional ICE vehicles [5].

There are several benefits that fuel cells provide over internal combustion engines (ICE) and batteries. Before it can create mechanical energy, the ICE must first transform the energy stored in the fuel into thermal energy by burning the fuel with oxygen at a high temperature. The usage of thermal energy generates mechanical power. The efficiency of the conversion process is restricted by the Carnot Cycle due to the involvement of thermal energy in operation [6] Unlike internal combustion engines (ICE), fuel cells transform fuel energy directly into electrical power, and their optimum efficiency is not constrained by the Carnot Cycle. Fuel cells have the potential to attain a higher energy conversion efficiency than other technologies. When hydrogen is utilised as fuel, the reaction in the fuel cell results in the production of water and heat. As a result, fuel cells are regarded as a source of electricity that does not produce emissions. They do not produce harmful by-products such as hydrocarbons or oxides of nitrogen in their operations. Another example of an electrochemical device is a battery, which may transform chemical energy into direct electrical power [7]. On the other hand, the reactants of the battery are held within, and if they are depleted, the battery must be recharged and replaced. The fuel cell's reactants are kept on the outside of the device. Oxygen is extracted from ambient air, whereas hydrogen is typically observed in refuellable high-pressure or cryogenic tanks. Oxygen may remove from ambient air. Comparatively, refilling gasoline tanks takes much less time than charging batteries [8].

The objective of this project is to develop a Proton Exchange Membrane fuel cell stack system using MATLAB. Next, to analyse and simulate the system using three different electrical loads that will be used for developing the system.

The primary goal of this project is to use MATLAB to create a model of the PEMFC system and conduct an analysis of it. In order to create the PEMFC model, it is necessary to gather input-output data by simulating the current PEMFC model in the MATLAB/Simulink programme. This is essential in order to go on with the development of the PEMFC model. For the input element, the necessary data to be gathered were the channel pressure of oxygen (O_2) and hydrogen (H2), the fuel flow rate, and the setting of the electrical load with the drive cycle, ramp, and step load. At the same time, the voltage and power generated by PEMFC are included in the output element. These models are often quite complicated, and they frequently incorporate mathematical models.

2. Materials and Methods

Many approaches, such as project planning and methodology, have been thought about and implemented to complete this project. The planning for this project has to be adequately controlled to guarantee that the flow of this project will go without any problems. It is essential to model the equivalent circuit of the PEMFC in the MATLAB/Simulink programme since the primary goal of this project is to simulate the performance of the PEMFC by utilising the R2021a version of MATLAB/Simulink. Simulating the circuit is the initial step in ensuring that all of the connections in the circuit are made correctly once the circuit diagram has been produced. If there are any mistakes, you will need to go back to the stage before this one, which was designing the circuit. The mathematical equation and the parameter are what make up the intended circuit. They both affect the output result of the simulation in different ways. The behaviour of the performance of the PEMFC will be shown in the MATLAB/Simulink simulation.

2.1 System Design Specification

A system design parameter is a written description of how a model is made and what it is supposed to do. The model development parameter is based on the table below.

Table 1:Electrical Load Parameter

No	Parameter	Value
1	Electrical load	• Drive cycle • Step • Ramp

Table 2:Environment condition parameter

No	Parameter	Value
1	Press	0.101 MPa
2	Temperature	20ºC
3	Relative humidity	0.5
4	Oxygen mole fraction	0.21

Table 3:Hydrogen fuel parameter

No	Parameter	Value
1	Fuel Tank Pressure	70 MPa
2	Hydrogen mole fraction	0.9997
3	Fuel Tank Volume	120 m^3

Table 4:Fuel cell stack parameter

No	Parameter	Value
1	Number cells	400
2	Cell Area	280 cm^2
3	Membrane thickness	125µm
4	Gas channel width/height	1 cm
5	Number of gas channels per cell	8
6	Exchange current density	0.0001 A/cm^2
7	Limiting current density	1.4 A/cm^2
8	Charge transfer coefficient	0.7
9	Overall density of membrane electrode assembly	1800kg/s
10	Overall specific heat	870 J/ kgK
11	Hydrogen tube diameter	0.01m
12	Air tube diameter	0.05m
13	Gas diffusion layer thickness	250µm

2.2 Fuel cell stack system diagram

The PEMFC model was developed in MATLAB version R2021a, the data obtained from MATLAB is needed to simulate the PEMFC in the Simulink software. In order to collect the data, there are a few parameters that will be considered as the input element of the fuel cell stack which is stack number of cells, fuel cell area, membrane thickness, electric load, and channel pressure of oxygen and hydrogen. Current (A), Voltage (V), Power (kW) and stack temperature of the fuel cell system will be recorded. The recorded data consists of input and output data.

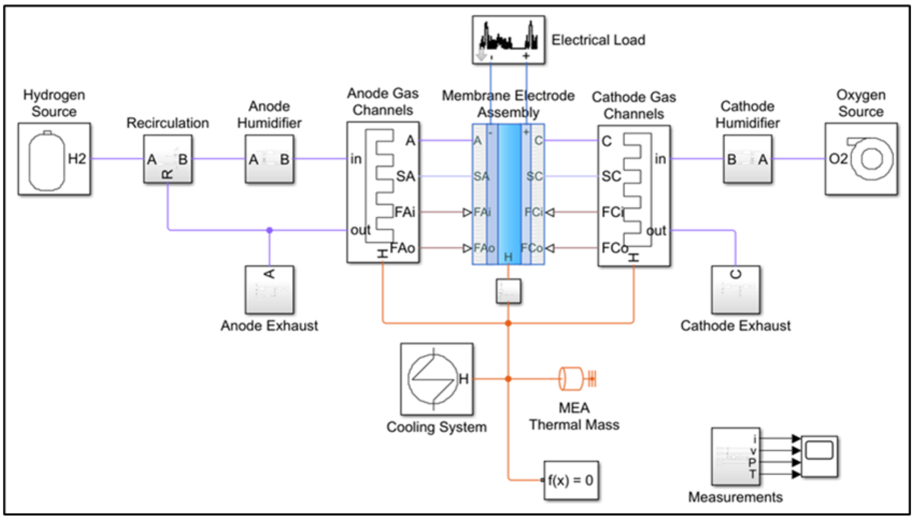

Figure 1:Fuel cell system diagram using drive cycle load

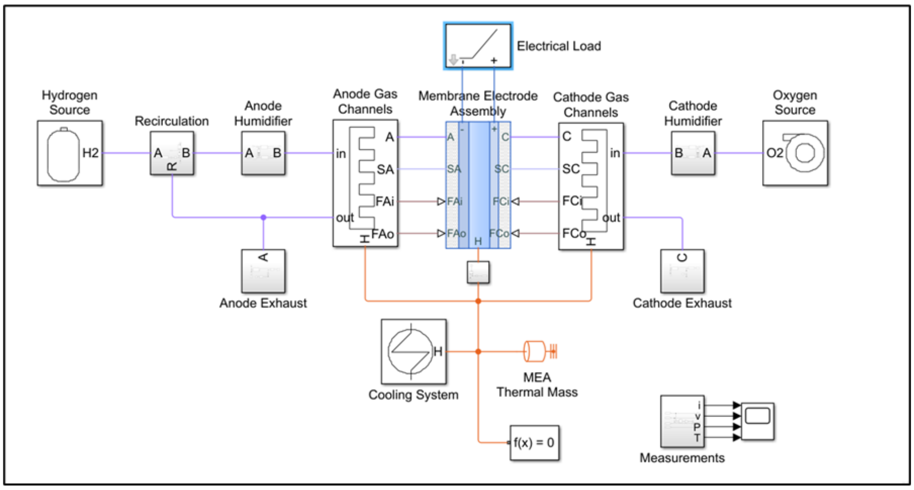

Figure 2:Fuel cell system diagram using ramp load

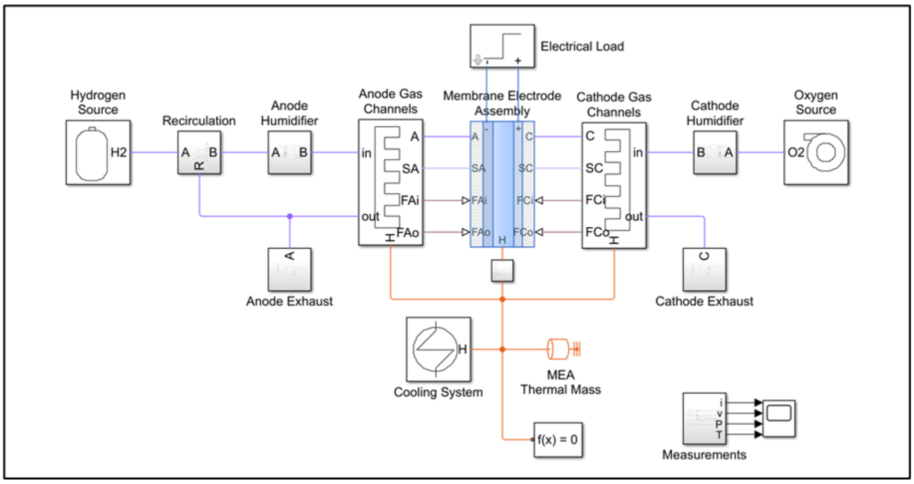

Figure 3: Fuel cell system diagram using step load

Figure 1, Figure 2, Figure 3 above shows the circuit model of the PEMFC stack using different electrical loads in the MATLAB/Simulink software. The PEM fuel cell generates electrical power by consuming hydrogen and oxygen and producing water vapour. The block represents the membrane electrode assembly (MEA) and is connected to two separate moist air networks which is one for the anode gas flow and one for the cathode gas flow.

2.3 System Structure Interaction

Controlling the reactant flow and pressure, as well as the temperature of the stack and the humidity of the membrane, inside the system, is very necessary for the viability, efficiency, and resilience of fuel cell systems.

2.4 Reactant Flow Subsystem

The hydrogen supply and air supply loops make up the reactant flow subsystem of a reaction system. The amount of hydrogen and oxygen available in the fuel cell stack decreases whenever there is a demand on the electrical load. The valve command is used to regulate the hydrogen flow into the anode, while the compressor command is used to regulate airflow into the cathode. The controller's purpose is to guarantee that adequate reactant fluxes are maintained to achieve the appropriate excess ratio, facilitate rapid transient responses, and reduce overall power usage.

2.5 Heat and Temperature Subsystem

Cooling system reactants of fuel cell stack temperature system are both heat and temperature subsystems. Within the fuel cell, heat is produced whenever electricity is extracted from it. The internal combustion engine presents a more significant challenge than the fuel cell stack in heat control. Instead of an efficient coolant fluid, the stack utilizes deionized water as its coolant. This decision was made in order to save money. Second, the PEM fuel cell is intended to work best at around 80 degrees Celsius. Therefore, the exhaust gas from the internal combustion engine (ICE) has a greater capacity to transport away heat than the exhaust air expelled from the stack, which has a temperature of just around 80 degrees Celsius. The cooling system is responsible for the heat rejection required for the fuel cell stack. In addition, the heat transfer from the stack to the water coolant is not as efficient as it might be because of the relatively small temperature differential between the two. In order to accomplish this goal, active cooling through the reactant flow rate and the cooling system is required. The temperature of the stack is also affected by the temperature of the input reactant air, the flow velocity of the water coolant and the temperature of the water itself.

2.6 Water management subsystem

The task of the water management system is to maintain the hydration of the polymer membrane and to balance water usage or consumption in the system. The amount of reactant flow and the water injected into the anode and cathode flow streams effect.

3. Result and Discussion

This section will present the results and findings of this study. The MATLAB program was used to do simulations, and the results and findings were based on those simulations. In order to collect input and output, the PEMFC system will need to be designed and modelled in MATLAB during the portion of the simulation that involves it. In this chapter, we will compare the results obtained with three different electrical loads. In this project, the results will be compared in terms of the power generated, thermal efficiency, temperature, and hydrogen that the fuel cell system used.

3.1 Simulation result

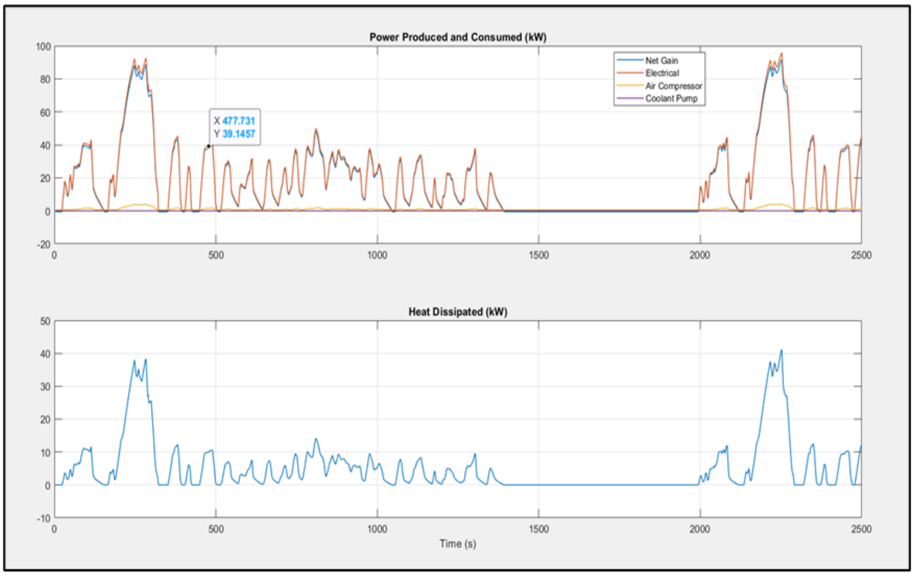

Figure 4: Graph power produced and heat dissipated by fuel cell system using drive cycle load

Figure *4* above shows the electrical power produced and heat dissipated by the fuel cell stack using the drive cycle electrical load. When the power produced and consumed by the fuel cell is increased, the heat generates by the fuel cell also increases. The graph above shows inconsistency in power produced and consume and heat dissipated by the fuel cell.

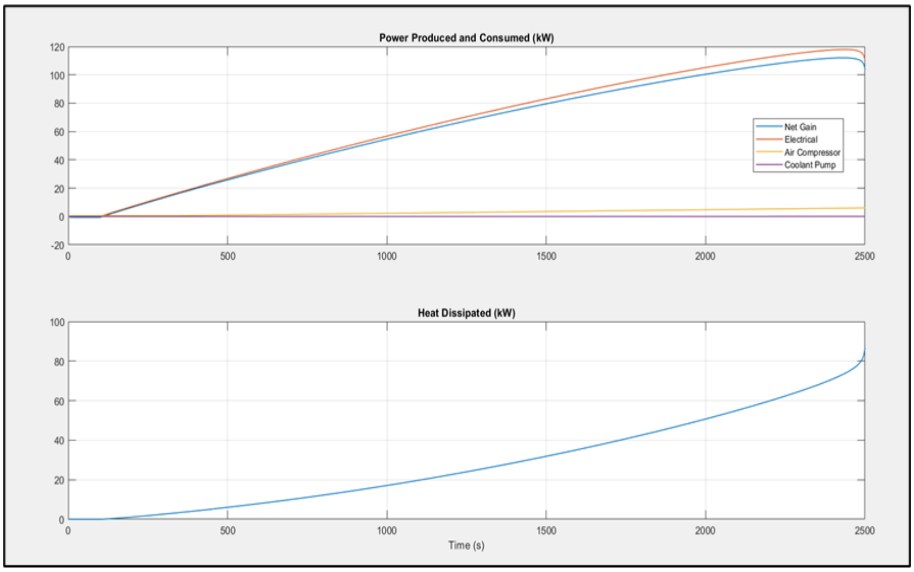

Figure 5:Graph Power produced and heat dissipated by fuel cell system using ramp load

Figure 5 above shows the electrical power produced and heat dissipated by the fuel cell stack using the ramp electrical load. The power produced and consumed by the fuel cell is increasing directly proportional. While the heat dissipated by the fuel cell increase gradually lower from the power produced.

Figure *6* shows, the electrical power produced and heat dissipated by the fuel cell stack using step electrical load. The power produced and consumed by the fuel cell is increasing at time 500s and constant at power 80kW. The heat dissipated also increased following the power produced.

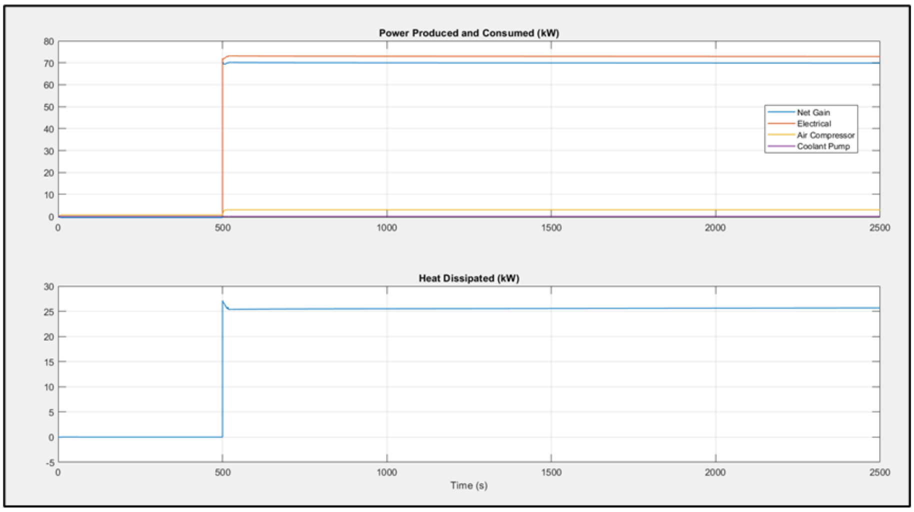

Figure 6: Graph Power produced and heat dissipated by fuel cell system using step load

So, the figure shows the electrical power produced by the fuel cell stack as well as the power consumed by the cathode air compressor and the coolant pump to maintain stability and efficient system operation. This model assumes an isentropic compressor. Accounting for compressor efficiency would decrease net power gain by another couple of per cent.

The plot also shows the excess heat generated by the fuel cell stack, which must be removed by the cooling system. The maximum power produced by the fuel cell stack is 80kW based on the graph.

3.2 Activation loss

The need to produce electron transport and create chemical bonds in the anode and cathode contributes to the activation loss, which may also be called activation overvoltage. The driving of the chemical process that transfers electrons from the electrodes consumes some of the available energy, but it does not use all of it. An activation overvoltage occurs at both the fuel cell's anode and cathode electrodes simultaneously. However, the oxidation of hydrogen at the anode happens exceptionally quickly, but the reduction of oxygen at the cathode happens much more slowly. Because of this, the cathode reaction conditions have a significant impact on the voltage decreases that are caused by the activation loss.

3.3 Ohmic Loss

The resistance of the polymer membrane to the transfer of protons is responsible for the ohmic loss. In contrast, the resistance of the electrode and the collector plate to the transfer of electrons is responsible for the ohmic loss. Where Rohm is the internal electrical resistance and has units of Ω cm2, the voltage drop corresponding to the ohmic loss is proportional to the current density. The wetness of the membrane and the cell's temperature both significantly impact the resistance. Whereas the ohmic resistance is a function of the membrane conductivity in the situation where the thickness of the membrane and the membrane conductivity is a function of the membrane water content and the temperature of the fuel cell, the ohmic resistance is a function of the membrane water content.

4. Conclusion

A well-designed system is needed to provide fast and consistent transient behavior of the fuel cell system. The system consists of four main subsystems: reactant supply, heat and temperature, water management and power management. System dynamic analysis and control design are carried out using the model-based linear control approach. The models of the fuel cell system are developed using physical principles such as chemical reaction, electrochemistry, thermodynamics, and mechanics.

The stack voltage is analyzed based on time-varying electrical load current, cell temperature, air pressure, oxygen and hydrogen pressure, and membrane humidity. The fuel cell voltage is determined using a polarization curve, activation losses, ohmic losses, and concentration losses. Electrochemical relations were used to analyze changes in the pressure and humidity of the gas in the fuel cell stack flow channels.

In this study, a proportional controller for the hydrogen flow for the humidifier is into the Fuel Cell system. The hydrogen flow control ensures a minimum pressure difference between the anode and the cathode channels, while the humidifier control ensures the humidity of the air entering the stack. The performance variable is the oxygen excess ratio, defined as the ratio between oxygen supplied to the cathode and oxygen used in the reaction.

The system operates at maximum optimal value, and net power is achieved when using a drive cycle electrical load with low heat dissipated.

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