International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 8, No. 1, March 2017, pp. 462~469
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v8i1.pp462-469

Proton Exchange Membrane Fuel Cell Emulator Using PI Controlled Buck Converter

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Article Info

Article history:

Received Nov 03, 2016
Revised Jan 09, 2017
Accepted Jan 19, 2017

Keyword:

DC-DC converter
Emulator
Fuel cell
Hydrogen energy
Proton exchange membrane

ABSTRACT

Alternative energy technologies are being popular for power generation applications nowadays. Among others, Fuel cell (FC) technology is quite popular. However, the FC unit is costly and vulnerable to any disturbances in input parameters. Thus, to perform research and experimentation, Fuel cell emulators (FCE) can be useful. FCEs can replicate actual FC behavior in different operating conditions. Thus, by using it the application area can be determined. In this study, a FCE system is modelled using MATLAB/Simulink®. The FCE system consists of a buck DC-DC converter and a proportional integral (PI) based controller incorporating an electrochemical model of proton exchange membrane fuel cell (PEMFC). The PEMFC model is used to generate reference voltage of the controller which takes the load current as a requirement. The characteristics are compared with Ballard Mark V 5kW PEMFC stack specifications obtained from the datasheet. The results show that the FCE system is a suitable replacement of real PEMFC stack and can be used for research and development purpose.

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1. INTRODUCTION

In recent years, renewable energy based power generations are encouraged to reduce the use of fossil fuel. Among the renewable energy sources, fuel cells are gaining popularity for their wide range of application areas- especially, distributed generation, portable power supply, and transportation. The fuel cell is a device which has the advantages of both engines and batteries, as it converts the chemical energy of fuel into electrical energy like engines and also, it has high efficiency under load condition like batteries. It can be used as a replacement of batteries, as it does not need any extra source to charge. Due to its variety of usage, research on fuel cells is increasing day by day. For research purpose, accurate modelling of power sources is a vital task, as the research outcome mostly depends on the source modelling. The experimental setup of renewable energy sources are costly and complex. Especially, fuel cell system experimental test bench requires auxiliary units, including hydrogen tank full of pure hydrogen, air supply unit, and cooling unit, which need to maintain certain flow rate and standard. Moreover, the safety measures are also a vital issue for initial test benches. Any disruption can lead to hazardous accidents, costing life and money. The perfect replacement for initial test bench is using emulators. The emulators are capable of depicting the actual behavior of corresponding renewable energy sources. Researchers have proposed photovoltaic (PV), wind turbine, and fuel cell emulators in different literatures.

PV emulator system consists of three parts: the PV model, power electronic converter, and the control strategy. For designing PV model most literatures use either single diode PV model or look up table resembling the PV characteristics [1],[2]. Other than buck converters, buck-boost, boost, and push-pull converters are also used for PV emulator implementation [3]-[5]. However, the control strategy becomes complex in case of other converters. Recent works in control strategy development includes using fuzzy-PI controller to determine the operating point [5] and microcontroller based implementation [6]. Wind turbine emulator (WTE) consists of two mechanically connected drives: one works as a motor and another as a generator. The motor emulates the wind torque and the generator produces electricity based on the torque. Majority of Previously proposed WTEs use simulation and digital implementation using MATLAB/Simulink® with dSPACE [7], MathWorks xPC target [8] or LabVIEW with Data *acquisition* board [9]. In order to emulate the inertia torque, some researchers use first order filter [7] or a moving average filter [10] or a PLL [11] to filter the speed derivative term. A few researchers proposed implementation of WTEs using its own specific software and hardware [11],[12]. Similar to other emulators, fuel cell emulators (FCEs) can be constructed using either basic electronic components or digital controllers [13]. Generally, the FCE models are programmed using MATLAB/Simulink® and implemented using DSP controller or dSPACE boards [14]. The emulator is constructed using DC-DC buck converter and the controller, which includes the FC model behavior and the switch driver [15]. The main challenge of FCE system is to emulate the fuel cell characteristics. Several emulators use electrical circuit representation of the FC model, while others use electrochemical model to extract the characteristics of FC [15],[16]. The initial FCEs include only the steady state behaviour [17]. Later, both the steady state and dynamic properties are included in the emulator model [18],[19]. This can be done using either mathematical model or experimental data of the FC.

In this paper, a FCE is designed based on a PEMFC model explained in ref [20]. The parameters are adapted from Ballard Mark V PEMFC model datasheet. The model considers the activation, concentration, and ohmic losses and also depicts the steady state and dynamic behaviors. The basic block diagram of the emulator is shown in the Figure 1. The system includes a buck DC-DC converter, controller, and a DC load. In the controller, PEMFC electrochemical model is included to produce the reference voltage and a PI compensator is used to generate the control signal for the pulse width modulator. MATLAB/Simulink® environment is used for the system simulation. The emulator shows fast response and it is easily scalable and can be applied for other types of FCs. In this paper, the basic of PEMFC is elaborated in section II, the MATLAB modelling of the FCE system is presented in section III, the simulation results and discussion is stated in section IV, and finally, section V discusses the concluding remarks.

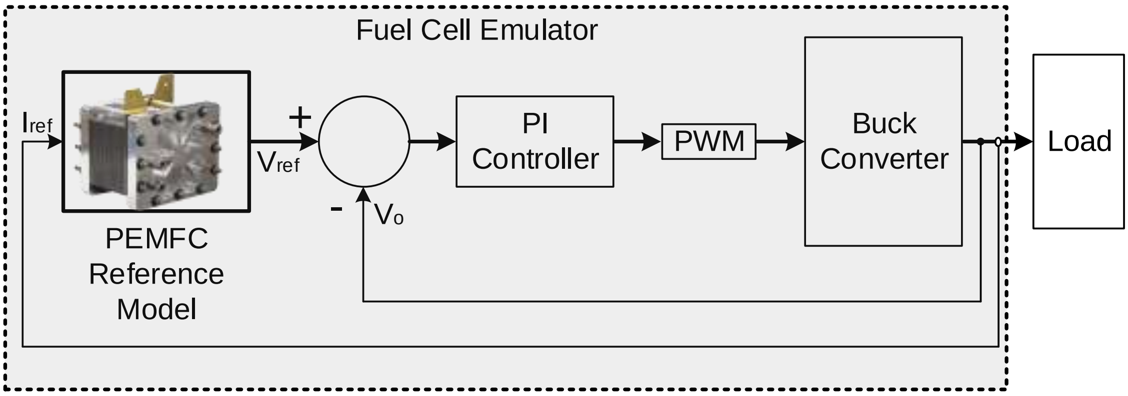

Figure 1. Block diagram of the proposed FC emulator

2. PROTON EXCHANGE MEMBRANE FUEL CELL (PEMFC) MODEL

PEMFC produces electricity through an electrochemical reaction, in which an oxidizer reacts with a fuel to produce electricity, where, water and heat is generated as by-product. The PEMFC construction starts with three parts: two porous electrodes and a solid polymer electrolyte. The electrolyte works as a medium of ion exchange between the electrodes. The main reactant of PEMFC is hydrogen from the fuel and oxygen from the air. At anode, the hydrogen fuel is fed continuously and at cathode, air is supplied. At anode, hydrogen is decomposed into protons and electrons, while at cathode oxygen is reduced to oxide ions and then reacts with protons to form water. The mechanism of a PEMFC is shown in the Figure 2. The anode, cathode, and overall chemical reactions are given in equation (1-3) [21]. Anode reaction:

$$H2 \rightarrow 2H^{+} + 2e^{-} \quad (1)$$

Cathode reaction:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (2)$$

Overall reaction:

$$2H_2(g) + O_2(g) \rightarrow 2H_2O + energy\ (electrical\ power + heat) \quad (3)$$

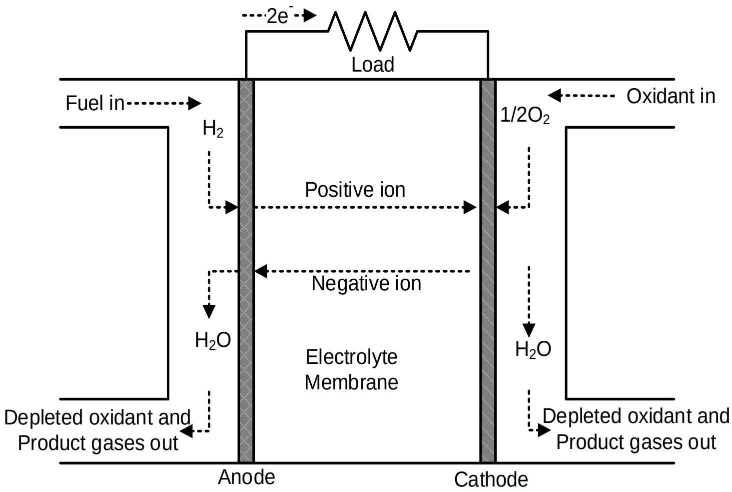

Figure 2. Principle of operation of PEMFC [22]

Each PEMFC cell produces output voltage of 1.23 V theoretically, although in practice the voltage achieved is approximately 0.6 V ~ 0.7 V. The FC cell has several loss factors, such as activation, ohmic, and mass transportation loss, which results in decrement in output voltage and increment in current [23]. The characteristics curve of PEMFC cell is shown in the Figure 3 [24]. The I-V curve depicts that there are three operating regions namely, ohmic, activation, and concentration. At the warming up stage, PEMFC operates at the activation region as there is less current density, resulting in high terminal voltage. Again, when the current density is very high, the opearting state reaches to concentration polarization, where the voltage drops due to the gas transport effeciency reduction. In between the two states, there is ohmic region where the loss is due to internal resistance and the current density as well as voltage change is linear. The ideal operating region of the PEMFC is ohmic region, due to having minimum loss, good health, and maintaing stable operation.

As a single FC cell output voltage and current is not sufficient for practical applications, multiple cells are arranged in series and parallel combinations to build the FC stack. The number of cells in series defines the output voltage and parallel combination gives the output current. The commercial fuel cell stacks have certain voltage and current rating. Also, the fuel and oxidant flow rate and coolant specifications are also defined. In order to apply the FC stack in power generation, the regulation of the pressure and flow rate of all these streams are required. Moreover, the operating temperature and gas humidification are also needed to follow up. For all these features, a complete system should include FC unit, fuel storage, fuel delivery system, cooling system, air supply system, and a humidification system. Also, proper alarms and safety equipemnts should be included to prevent any malfunction hazard. Electrical control systems perform the controlling and monitoring of the different subsections.

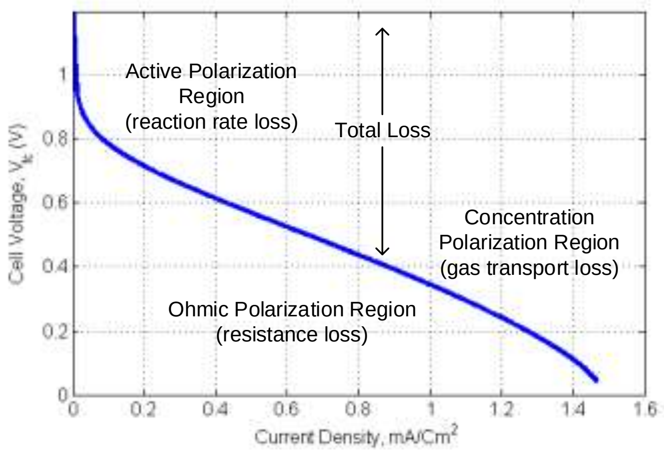

Figure 3. Typical fuel cell I-V curve

2.1. Dynamic model of PEMFC

The redox reaction of equation (3) produces the electrical power in a single FC cell. The voltage of a single cell is given by the Nernst equation described in equation (4)

$$E_{Cell} = E_0 + \frac{RT}{2F} \ln \frac{P_{H_2}\sqrt{P_{O_2}}}{P_{H_2O}} \tag{4}$$

Here, E_0 (1.23V) is the standard potential of redox reaction and R, T, and F are the universal gas constant, absolute temperature, and Farady's constant respectively. P denotes the partial pressures of the gases and water. The voltage obtained from equation (4) is open circuit voltage and the normal operative voltage gets reduced from that due to the activation (V_{act}), concentration (V_{con}) and resistive (V_{ohm}) losses of the FC. Thus, the output voltage (V_{stack}) can be expressed as equation (5) [16].

$$V_{Stack} = N_{Cell} \times E_{Cell} = E - V_{act} - V_{conc} - V_{ohm} \tag{5}$$

The voltage losses can be represented by the equation (6) to represent the output current (I_{stack}) and voltage (V_{stack}) relation.

$$V_{Stack} = E - AT \ln\left(\frac{I_{stack}}{I_0}\right) - BT \ln\left(\frac{I_L - I_{stack}}{I_L}\right) - I_{stack} R_{int} \tag{6}$$

Here, E is the open circuit voltage, I_0 and I_L are the exchange and limiting currents, R_{int} is the internal resistance, A and B are the activation and concentration coefficients.

The dynamic model of FC includes the double layer charging effect, which is due to the two opposite polarity charged layers formed across the membrane and the cathode. The layers behave like super capacitors and is known as electrochemical double layer. The PEMFC characteristics can be modeled in MATLAB/Simulink® incorporating the temperature, partial pressure of gases, and the double layer capacitor effects as shown in Figure 4.

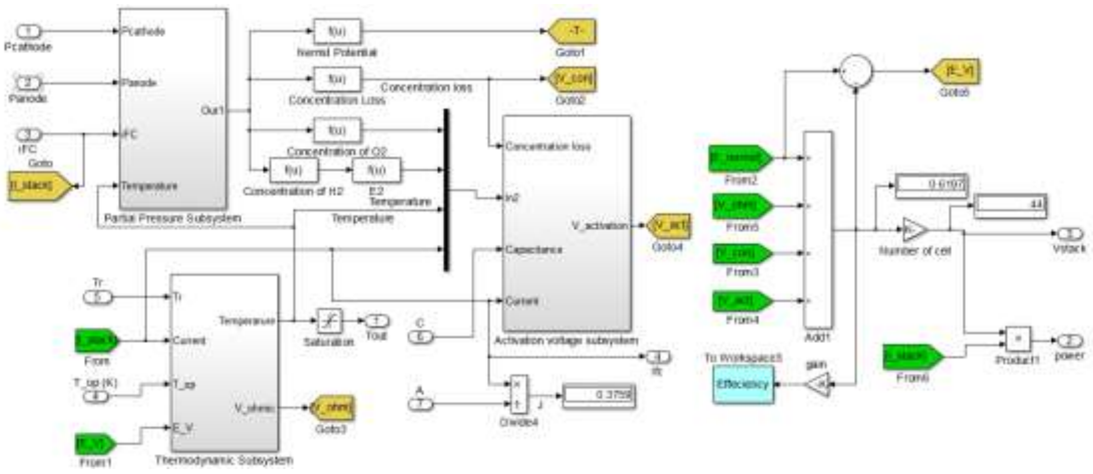

Figure 4. Electrochemical simulation model of PEMFC

3. SIMULATION OF PEMFC EMULATOR

The simulation diagram of PEMFC emulator is shown in the Figure 5. The emulator has three parts: the FC model for reference voltage generation, the DC-DC converter, and the controller for emulating the fuel cell voltage. FC model is developed based on the mathematical equations and simulated using the Simulink blocks. The FC model demonstrates both static and dynamic characteristics of a PEMFC stack. The parameters used in the model is given in Table 1. The FC model takes the load current as reference and provides reference voltage of the emulator controller. The maximum power of the reference model is 5.7 kW. The voltage-current relationship of the model is shown in the Figure 6. From the figure, it can be observed that, the ohmic region lies approximately between 50 V and 20 V stack voltage. The maximum power is at 28 V where the current is 200 A. The power curve is similar to the characteristics of Ballard Mark V PEMFC stack [20].

The buck converter is used to emulate the fuel cell characteristics into the load. The input voltage is considered 100 V, which is higher than the reference FC model maximum voltage (80 V). The inductor and capacitor values are defined using the standard buck converter formulae and the voltage and current range considered for the modelling is the FC ohmic operating region. The switching speed of the converter is considered 20 kHz due to convenience of hardware implementation. Also, internal resistance of the passive elements are considered in the simulation. In order to control the buck converter, PI compensator based controller is simulated. A voltage loop controller is designed, which compares the output voltage with the FC reference voltage and produces control signal for the pulse width modulator (PWM). The PWM generates the gate signal pulses of the MOSFET switch. Table 2 demonstrates the Buck converter components and proportional and integral compensator values.

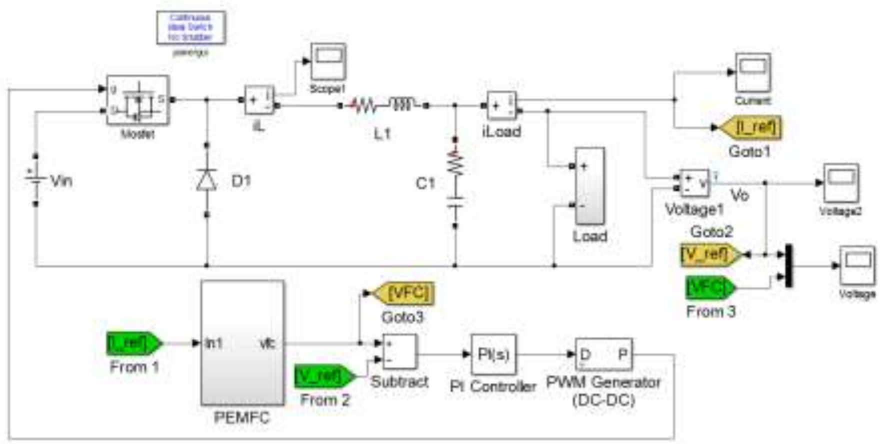

Figure 5. MATLAB/Simulink® diagram of fuel cell emulator

Table 1. Model parameters of PEMFC stack [20]

Parameters	Values
Anode Partial Pressure (Pa)	2.3816
Cathode Partial Pressure (Pc)	2.3816
Thickness of FC (L)	178e-4
Concentration loss coefficient (B)	0.016
Membrane resistance (Rc)	0.0003
Parametric coefficients (E1)	-0.948
Parametric coefficients (E3)	7.6e-5
Parametric coefficients (E4)	-1.93e-4
Maximum current density (Jmax)	1.5
Initial current density (Jn)	0.1
FC area (A)	232
Adjustable Parameter (Y)	18

Table 2. Buck converter and controller parameters

Parameters	Values
Input Voltage (Vin)	100 V
Inductor (L)	200 µH
Capacitor (B)	250 µF
Switching frequency (Rc)	20000 Hz
Proportional compensator (Kp)	0.004
Integral compensator (Ki)	5

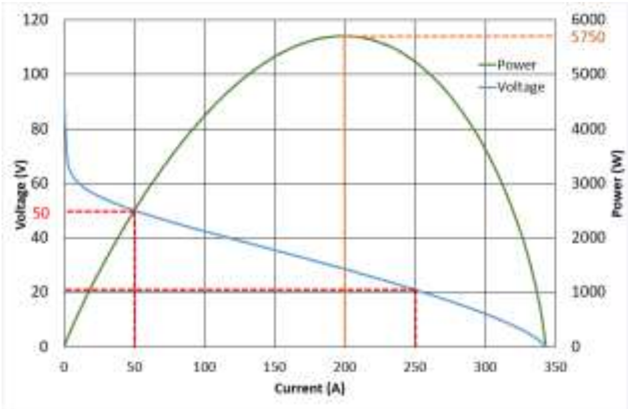

Figure 6. Voltage and Power curve of PEMFC stack model

4. SIMULATION RESULTS AND ANALYSIS

The FCE model has been simulated with both static and dynamic load to assess the characteristics. The results show that the emulator model replicates the behaviour of actual PEMFC stack. In Figure 7, the voltage and current response of the FCE system with resistive load is presented. It can be seen that, the FC reference voltage and load voltage have some ripples. Otherwise, the voltage is constant at 31V, whereas the load current is .180 A. Figure 8 presents the voltage and current response of the FCE with changes in resistive load. With the change of load resistance, the load current and voltage should change linearly. However, there is overshoot and undershoot in both voltage and current responses. When the load resistance increases, the load current drops and the voltage increases. However, at the moment of change, there is a spike on load voltage as well as undershoot on load current response. The reason behind the effect is the slow dynamic of the FC model. The model needs time to increase or decrease the current flow. Similar incident takes place while the load resistance drops.

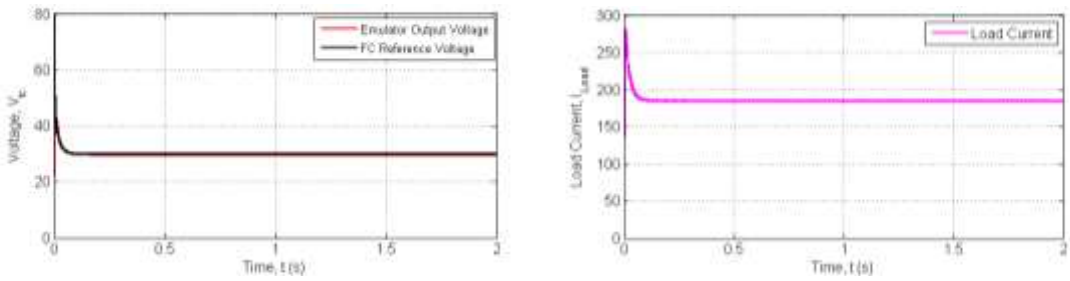

Figure 7. Output voltage and current response of the FCE with fixed load

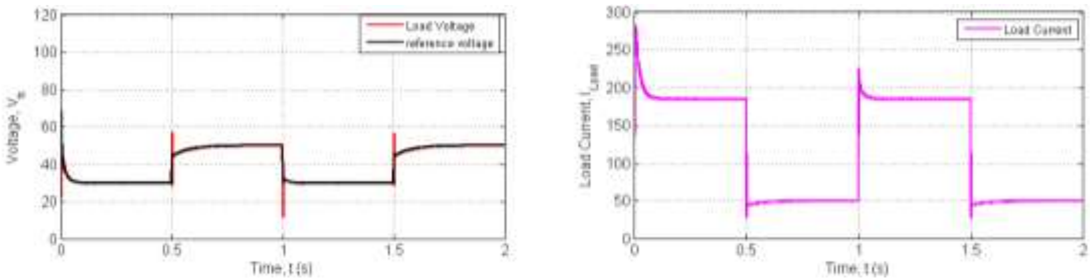

Figure 8. Output voltage and current response of the FCE with changing load

The FCE system is simulated with different sizes of load to determine the accuracy of the emulator in different regions. In Figure 9, the comparison of V-I graphs of the reference PEMFC model and the FC emulator is presented. In this figure, the deviation of the FCE system from the reference model can be observed in the concentration polarization region. For very small loads, the system is not fully consistent with the ideal FC response. The current flow is less than the reference model at the minimum load. For the ohmic region and activation region, the FCE is fully consistent with the FC characteristics curve. In the figure, the blue line represents the reference FC characteristics and the red line represents the FCE output characteristics. The dots represent the simulation points where the values are taken. From the simulation, the load resistance values for each region is determined. For activation region, the values are more than 1.8 Ω, ohmic region loads are between 1.8 Ω and 0.08 Ω, and concentration region load resistances are less than 0.08 Ω. The simulation points at the resistance values are marked on the figure.

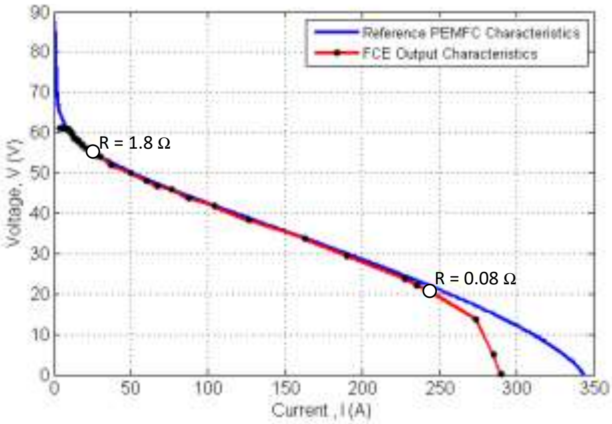

Figure 9. Characteristics curve comparison of the FCE and reference PEMFC model

5. CONCLUSION

The modeling and simulation of PEMFC based FCE is presented in this paper. The FCE system includes a DC-DC buck converter and controller. The buck converter is used because it allows to emulate the behavior of any FCs. Thus, if the current and power rating in the characteristics curve is same, other types of FCs can also be emulated using this system, provided that the switching control law is modified. The controller designed in this study consists of an electrochemical PEMFC model, a PI compensator and a PWM generator. It uses voltage control method for controlling the output and output current as reference to produce the PEMFC voltage. A 5 kW Ballard mark V PEMFC model parameters are used in this study to model the PEMFC. The results show that the FCE can emulate the characteristics of the real PEMFC with acceptable accuracy. As the FCE is a high power system, it can be used for power system application research. Moreover, the simulated system can be implemented in hardware using DSP and other power electronics, which will enable the system to contribute in testing the FC applicability in distributed generation, portable power supply, and in transportation.

ACKNOWLEDGEMENTS

The authors would like to pay gratitude to Universiti Teknologi Malaysia (UTM) for supporting with lab and library facilities. In addition, the authors would like to express their appreciation to the Ministry of Higher Education, Malaysia (MOHE). They also acknowledge funding provided by fundamental research grant scheme (FRGS) under vote 4F596, Universiti Teknologi Malaysia (UTM). Lastly, thanks to those colleagues who have either directly or indirectly contributed to the completion of this work.

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