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Designing Controller for Joined Dynamic Nonlinear PEMFC and Buck Converter System

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ABSTRACT

Designing controller for a class of dynamical nonlinear model for Polymer Electrolyte Membrane Fuel Cell (PEMFC) is discussed in this paper inwhich the PEMFC system is used for powering a Notebook PC (Processing Computer). The power requirement of a Notebook PC varies significantly under different operational conditions. The proposed feedback controller is applied for the buck dc/dc converter to stabilize the load voltage at a desirable level under various operational conditions. The simulation results show the promising performance of the proposed controller at the different operating conditions.

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1. INTRODUCTION

The inseparable part of human life is a need for reliable power source. This seems more necessary in developing countries as the main infrastructure. In many countries, this need is neglected due to existence of fossil fuel sources but these fossil fuel sources are limited. It should be noted that the dependence of a country in terms of energy supply can lead to other sequential dependence on the owners [5]. Because of the current environmental problems and air pollution, we need to reach clean sources of energy is urgent [5]. Nowadays access to clean and renewable sources of energy is vital. Renewable energy sources, such as fuel cells, wind, solar and hydro power are essential for an environment-friendly energy supply. The Fuel cell technology has attracted much attention because of inherent properties and potentials in its technology. This technology is under development for more than a decade, optimizing the efficiency and reducing costs are still in progress.

The fuel cells are electrochemical devices that convert the chemical energy of both the energy carrier and the oxidizer-typically oxygen-directly into the electricity and the heat [12]. The power output of fuel cells can range from a few watts to several megawatts. It has been hypothesized that fuel cells are well-poised to meet the power requirements of various applications of the 21st century ranging from electrical vehicles [2], high voltage distributed generator (DC-AC) [4], Industrial dynamic loads [3], Uninterruptible Power Supply (UPS) and ect.Unlike conventional energy sources, fuel cell is a clean energy source with significantly low emissions and low noise [7], [8], [18]. These attractive features of fuel cells have engendered interest in DC power generation using fuel cells and their subsequent commerciallization for various applications.

There are different types of fuel cells with own characteristics. For portable applications, the fuel cell should be small and able to operate at ambient conditions. Among the available fuel cells, Proton Exchange Membrane or Polymer Electrolyte Membrane Fuel Cell (PEMFC) is becoming increasingly popular because of its attractive features such as high power density, solid electrolyte, low operating temperature, fast start-up, low sensitivity to orientation, favorable power-to-weight ratio, long cell and stack life, and low corrosion [10]. Hence, it is now well understood that the Proton Exchange Membrane (PEM) fuel cell is the primary choice for developing distributed generation power systems, hybrid electric vehicles and for many other emerging applications of fuel cells. The core component of a PEMFC consists of a five layered structure called the Membrane Electrode Assembly (MEA), which is formed by a PEM with a thin layer of catalyst on both sides, and a porous Gas Diffusion Layer (GDL) in contact with each of the catalyst layers [14]. It is important that detailed dynamic models and high-performance control algorithms be developed for the PEMFC in order to facilitate its successful use in these applications. Block diagram of the proposed system for a notebook PC (processing computer) is shown in Figure 1.

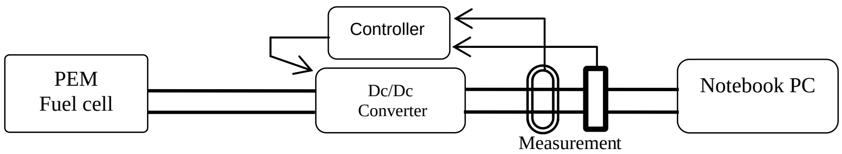

Figure 1. Diagram of the proposed system for a notebook PC

In this paper we concentrate on the dynamic model of a PEMFC system for portable applications. Creating a control-oriented dynamic model of the overall system is an essential first step, not only for the understanding of the system behavior, but also for the development and design of model-based control methodologies. There are several dynamic fuel cell models reported in the literature [7], [8]. The purpose of this paper is to present a 100 W PEMFC system for powering a notebook PC. The power requirement of a notebook PC varies significantly under different operational conditions.

2. NONLINEAR PEMFC STACK SYSTEM

The following assumptions are applied to construct the simplified dynamic model for PEMFC [19]. The gases are ideal, The effect of Nitrogen in the cathode is not considered because of using reformer, the oxygen flow rate is determined by Hydrogen oxygen flow ratio from the reformer, the stack temperature is regulated at 80^{oC} by using an independent cooling system [15], the Nernst's equation is applied [11], [20], [21]. The nonlinear dynamic model developed in this paper is based on the fuel cell models provided by the Department of Energy (DOE) [17]. A PEM fuel cell consists of a polymer electrolyte membrane sandwiched between two electrodes (anode and cathode). The FC system model parameters used in this model are shown in Table 1.

Table 1. Parameters Description

Parameter	Description	Parameter	Description
Vfc	Stack Output Voltage	In	The Internal Current Density To Internal Current Losses
Va	Volume of anode	A, B	constants
Vc	Volume of cathode	I	The Output Current Density
Ac	Cell active area	R	Gas Constant
N	Number of Cells in the Stack	α	Charge transfer coefficient
V0	Cell Open Circuit Voltage	r	FC internal resistance
T	Operating Temperature	p_{sat}	The Standard Pressure
L	Voltage Losses	F	Faraday's Constant
pH_2, pO_2, pH_2O	The Partial Pressures Of Each Gas Inside Cell	Io	The Exchange Current Density Related To Activation Losses

In the electrolyte, only ions can exit and electrons are not allowed to pass through. Therefore, the flow of electrons needs a path like an external circuit from the anode to the cathode to create electricity because of a potential difference between the anode and cathode.The overall electrochemical reactions for a PEM fuel cell fed with an oxygen-containing cathode gas and a hydrogen-containing anode gas are as follows:

$$\begin{aligned} \text{Anode}: & \ 2H_2 \Leftrightarrow 4H^+ + 4e^- \\ \text{Cathode}: & \ O_2 + 4H^+ + 4e^- \Leftrightarrow 2H_2O \\ \text{Overall}: & \ 2H_2 + O_2 \Leftrightarrow 2H_2O + \text{electricity} + \text{heat} \end{aligned} \tag{1}$$

2.1. PEMFC Output Voltage Equation

According to the Nernst's equation and Ohm's law, the cell voltage equation is given as;

$$V_{fc} = E_{Nernst} - V_{ohmic} - V_{activation} - V_{concetration} \tag{2}$$

In the Equation (2), E_{Nernst} is the thermodynamic potential of the cell or reversible voltage based on the Nernst equation [16], V_{ohmic} is the ohmic voltage drop from the resistances of proton flow in the electrolyte, $V_{activation}$ is the voltage loss due to the rate of reactions on the surface of the electrodes, and $V_{concetration}$ is the voltage loss from the reduction in concentration gases or the transport of mass of oxygen and hydrogen. Their equations are given as follows:

$$E_{Nernst} = No\left(Vo + \left(RT/2F \right) Ln\left(\frac{P_{H_2}\sqrt{P_{O_2}}}{P_{H_2O}} \right) \right) \tag{3}$$

$$V_{ohmic} = NI_{fc}r \tag{4}$$

$$V_{activation} = N\frac{RT}{2\alpha F}Ln\left(\frac{I_{fc} + I_n}{I_O} \right) \tag{5}$$

$$V_{concetration} = Nm \ \ e^{(nI_{fc})} \tag{6}$$

2.2. State Equations

The partial pressures of hydrogen, oxygen, and water on the cathode side are defined as the state variables of the system, and the relationship between inlet gases and outlet gases is described in Figure 2.

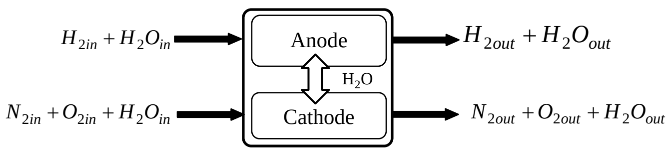

Figure 2. Illustration of gas flows of the PEMFC

From the ideal gas law, we know that the partial pressure of each gas is proportional to the amount of the gas in the cell, which are three relevant contributions depending on the gas inlet flow rate, gas consumption and gas outlet flow rate [7], [16]. Thus, the state equations become;

$$\frac{dpH_2}{dt} = \frac{RT}{V_A} H_{2\_in} - \frac{RT}{V_A} H_{2\_used} - \frac{RT}{V_A} H_{2\_out}$$
$$\frac{dpO_2}{dt} = \frac{RT}{V_C} O_{2\_in} - \frac{RT}{V_C} O_{2\_used} - \frac{RT}{V_C} O_{2\_out} \quad (7)$$
$$\frac{dpH_2O}{dt} = \frac{RT}{V_C} H_2O_{c\_in} - \frac{RT}{V_C} H_2O_{c\_produced} - \frac{RT}{V_C} H_2O_{c\_out}$$

Where H_{2_in}, O_{2_in} and shows the inlet flow rates of hydrogen, oxygen, and water of the cathode. H_{2_Out} O_{2_Out} and $H_2O_{2\_out}$ are the outlet flow rates of each gas. H_{2_used}, O_{2_used} and $H_2O_{\_produced}$ are usage and production of the gases. Based on the basic electrochemical relationships, usage and production of the gases are related to output current I by;

$$H_{2\_used} = 2O_{2\_used} = 2KI = 2KA_C i \quad (8)$$

Where $K = N / (4F)$, Ac is the cell active area, and i is the cell current density. Based on the inlet flow rates and output current, the outlet flow rates can be defined as:

$$H_{2\_out} = (Anode_{in} - 2K_r I) F_{H_2}$$
$$O_{2\_out} = (Cath_{in} - K_r I) F_{O_2} \quad (9)$$
$$H_{2\_out} = (Cath_{in} + 2K_r I) F_{H_2O_c}$$

Where $H_{2\_in} = Anode_{in}$ and $O_{2\_in} + N_{2\_in} = Cath_{in}$. F_H, F_{O_2} and F_{H_2O} are the pressures fraction of each gas inside the fuel cell as follows:

$$F_{H_2} = \frac{pH_2}{P_{op}}, F_{O_2} = \frac{pO_2}{P_{op}}, F_{H_2O_c} = \frac{pH_2O_c}{P_{op}} \quad (10)$$

By substituting (9) and (10) in (7), we obtain:

$$\frac{d}{dt} pH_2 = \frac{RT}{V_A}(H_{2\_in} - 2K_r A_C i - (Anode_{in} - 2K_r A_C i)\frac{pH_2}{P_{op}})$$
$$\frac{d}{dt} pO_2 = \frac{RT}{V_C}(O_{2\_in} - K_r A_C i - (Cath_{in} - K_r A_C i)\frac{pO_2}{P_{op}}) \quad (11)$$
$$\frac{d}{dt} pH_2O_C = \frac{RT}{V_C}(H_2O_{C\_in} + 2K_r A_C i - (Cath_{in} + 2K_r A_C i)\frac{pH_2O_C}{P_{op}})$$

To simplify (11), we substitute $Anode_{in}$ and $Cath_{in}$ in the above equations and reconstruct the equation (11) as (12). Due to the small portion of $H_2O_{C\_in}$ on the Cathode side, this element is ignored in the following equation and during the control law development;

$$\frac{d}{dt} pH_2 = \frac{RT}{V_A}(H_{2\_in} - 2K_r A_C i - (H_{2\_in} - 2K_r A_C i)\frac{pH_2}{P_{op}})$$
$$\frac{d}{dt} pO_2 = \frac{RT}{V_C}(O_{2\_in} - K_r A_C i - (O_{2\_in} - K_r A_C i)\frac{pO_2}{P_{op}}) \quad (12)$$
$$\frac{d}{dt} pH_2O_C = \frac{RT}{V_C}(H_2O_{C\_in} + 2K_r A_C i - (O_{2\_in} + 2K_r A_C i)\frac{pH_2O_C}{P_{op}})$$

Consider the following multiple-input single-output (MISO) nonlinear system:

$$\dot{x} = f(x) + \sum_{i=1}^{m} Gi(x)ui, i = 1,2,...., m$$
$$y = h(x) \quad (13)$$

Where $x \in X \subset R^n$ is the state, $u \in U \subset R^m$ is the input or control vector, and $y \in Y \subset R^P$ is the output vector of the system. Equations (2) and (12) imply the following nonlinear dynamic system model of PEMFCs:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} \frac{RT}{V_A}(1-\frac{x_1}{P_{op}}) \\ 0 \\ 0 \end{bmatrix} u_1 + \begin{bmatrix} 0 \\ \frac{RT}{V_C}(1-\frac{x_2}{P_{op}}) \\ \frac{RT}{V_C P_{op}} x_3 \end{bmatrix} u_2 + \begin{bmatrix} \frac{RT}{V_A P_{op}}(-2K_r A_C + 2K_r A_C x_1) \\ \frac{RT}{V_C P_{op}}(-K_r A_C + K_r A_C x_2) \\ \frac{RT}{V_C P_{op}}(2K_r A_C - 2K_r A_C x_3) \end{bmatrix} u_3 \quad (14)$$

$$Y = V_{fc} = E_{Nernst} - V_{ohmic} - V_{activation} - V_{concetration}$$

Where;

$$\begin{aligned} x &= [pH_2, pO_2, pH_2O_C]^T \\ u &= [H_{2\_in}, O_{2\_in}, i]^T \\ y &= V_{fc} \end{aligned} \quad (15)$$

In the aforementioned nonlinear model, because the number of outputs is less than that of the inputs, which means that the decoupling matrix for exact linearization is not square, the exact linearization approach for MIMO systems cannot be directly applied. In other words, additional states and outputs are chosen and added in such a way that a square system appears and that the decoupling matrix is nonsingular.

2.3. Reformer Model

The fuel cell system consumes hydrogen, according to power demand and the reformer continuously generates hydrogen for stack operation. The mathematical form of the reformer model can be expressed as [9]:

$$\frac{H_{2\_in}}{methan_{in}} = \frac{2}{4S^2 + 4S + 1} \quad (16)$$

During operational conditions, to control the hydrogen flow rate according to the output power of the FC system, a PID control system is used. To achieve this feedback control, FC current from the output is taken back to the input while converting the hydrogen into molar form [13]. The amount of hydrogen available from the reformer can be used to control the methane flow rate by using a PID controller.

3. THE BUCK DC/DC CONVERTER

The buck dc/dc converter is used to adjust output voltage of the PEM fuel cell to 19 V. The proposed buck dc/dc converter is demonstrated in Figure 3.

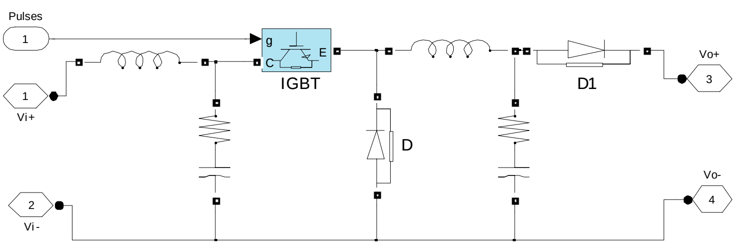

Figure 3. A buck dc/dc converter for a notebook PC

4. THE LOAD: NOTEBOOK PC

The output voltage and current of AC adapter of ASUS K43S are 19 V and 4.75 A respectively. The dc power consumptions of ASUS K43S have been measured using a power quality analyzer. Figure 4 shows the change of dc power demand of the notebook PC. It is obvious from Figure 3 that the dc power consumption of the notebook PC may vary from 22.8 W to 81.68W.

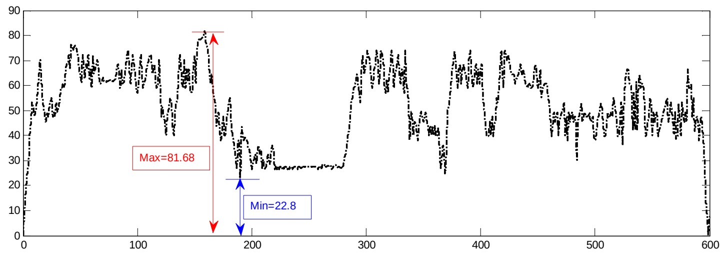

Figure 4. Power demand under different operation conditions

5. PID CONTROLLER

A PID controller is a generic control loop feedback mechanism and regarded as the standard control structures of the classical control theory. PID control has prominent advantages and it is widely used as an effective control scheme such as simple controller structure and easier parameter adjusting. PID is the most commonly used feedback controller, literally everywhere in industrial applications [1]. To stabilize the fuel cell voltage using PID control, the equations of PID control are given as following:

$$u(t) = K_P e(t) + K_i \int_0^t e(\tau)d\tau + K_d N_p \frac{de(t)}{dt} e^{-N_p e(t)} \quad (17)$$

The gate pulses of the buck dc/dc converter are produced by a feedback controller based on a discrete PID controller [6]. The block diagram of the feedback controller is illustrated in Figure 5. In the controller, the output voltage is compared with the reference voltage and the difference between them is used as the input of the discrete PID controller.

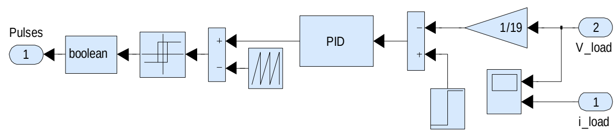

Figure 5. Feedback controller for the buck dc/dc converter

6. SIMULATION RESULTS

Table 2. Parameters Value

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
Va	6.495 cm2	r	0.00303ohm	L_b	1*10^-3H	C_b	1500*10^-6F
Vc	12.96 cm2	A	136*10^-4	methane	15*10^-3	N_P	100
Ac	136.7 cm2	B	478*10^-4	p_{op}	101*10^3 Pa	$rH-O$	1.1168
N	35	K_P _buck	1	p_{sat}	101325 Pa	K_D _Ref	100
Vo	0.6 V	K_I _buck	1	F	96439 C/M	K_I _Ref	2.5
T	338.5 K	K_D _buck	1*10^-3	R	8.3144	K_P _Ref	10

To demonstrate the performance of the proposed control law, the system is simulated using the simplified models connected to a laptop through a dc/dc converter and also is applied disturbance to input voltage of the converter (Figure 8). A Proportional Integral Derivative (PID) controller is used for stabilize the fuel cell voltage using PID control. The PEM fuel cell used in this paper is a dc power source with an unregulated 28 V dc-power output and the 100 watts dc nominal power rating. The parameters of the PEMFC system are given in Table 2.

The modeling and simulation of the PEMFC system are verified using MATLAB, Simulink and SIMPOWER Systems Block set Simulation of the PEMFC system is illustrated in Figure 6.

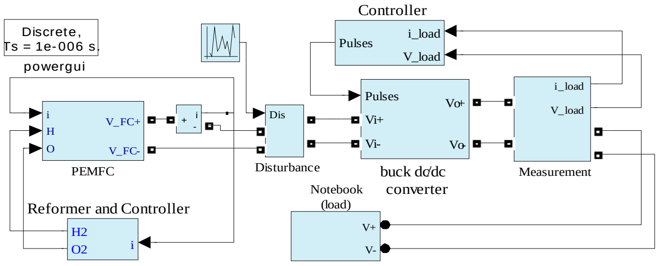

Figure 6. General Diagram of the proposed system for a notebook PC

The load currents of the notebook PC vary significantly under different operation conditions. Figure 7 shows the change of load currents of the notebook PC. The PEM fuel cell provides adequate power to the laptop computer during different operation conditions. The load currents fluctuate between 1.4 A and 4.3 A. The dc power consumptions of the laptop are varied between 22.8 W and 81.68 W, presented in Figure 7.

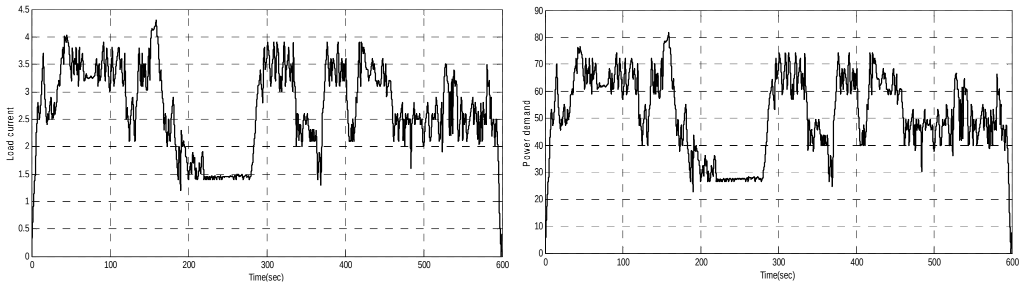

Figure 7. Load current and Power demand under different operation conditions

The hydrogen flow rate and the oxygen flow rate under different operation conditions shown are Figure 8.

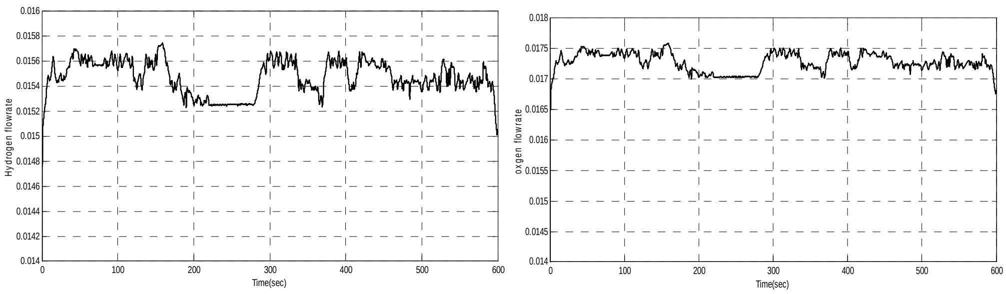

Figure 8. Hydrogen flow rate and Oxygen flow rate under different operation conditions

When the laptop is operated at standby state, operation software (Windows seven), fully loaded state and close software, it is clearly seen from Figure 4 that power consumptions of the laptop computer varies significantly. The PEMFC stack voltages with disturbance and without disturbance are illustrated in Figure 9.

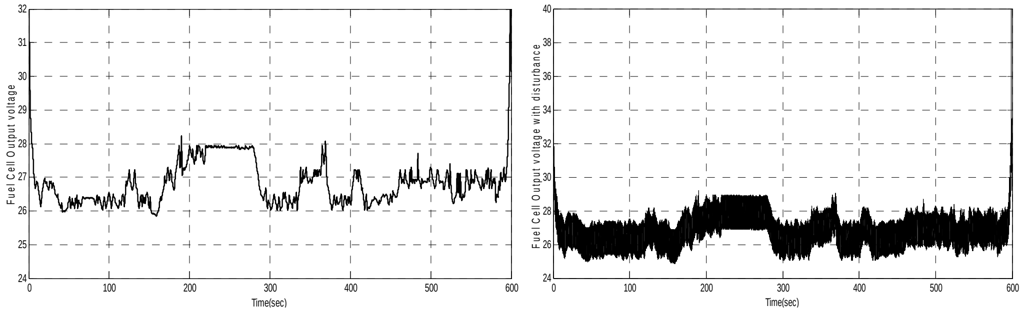

Figure 9. Fuel Cell Output voltages without disturbance and with disturbance

Figure 10 shows the load voltage of the notebook PC.

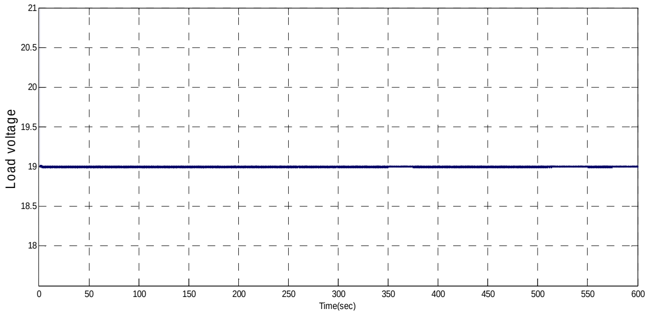

Figure 10. Load voltage under different operation conditions

As shown in Figure 10, it is obvious that the controlled output voltage remains stable under the load change disturbances. The feedback control system keeps the load voltage at a desirable level, 19 V under various operation conditions.

7. CONCLUSION

In paper, we consider the nonlinear dynamic equations for Polymer Electrolyte Membrane Fuel Cell (PEMFC). The PEMFC system is used for supplying a Notebook PC (processing computer). In order to stabilize the load voltage at a desirable level under various operational conditions, we used the feedback controller in the buck dc/dc converter. The simulation results show that PEMFC Provides Notebook required Power at different operating conditions.

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