Available online at www.sciencedirect.com
ScienceDirect
Journal of Power Sources 161 (2006) 1062–1068
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

# An improved dynamic model considering effects of temperature and equivalent internal resistance for PEM fuel cell power modules

Zhihao Zhang [a], Xinhong Huang [a], Jin Jiang [a,*], Bin Wu [b]

[a] *Department of Electrical & Computer Engineering, The University of Western Ontario, London, Ont. N6A 5B9, Canada*
[b] *Department of Electrical & Computer Engineering, Ryerson University, Toronto, Ont. M5B 2K3, Canada*

Received 4 April 2006; received in revised form 14 May 2006; accepted 16 May 2006
Available online 5 July 2006

**Abstract**

This paper introduces a semi-empirical dynamic model for PEM fuel cell power modules with potential applications in distributed generation. The proposed model is constructed based on the measurements from a Nexa™ PEM fuel cell power module under different load conditions, and the model has been validated by static as well as dynamic tests. The effects of temperature and variations in the internal impedance under different load conditions have been studied. The results have indicated that the model provides an accurate representation of the dynamic and static behaviors of the fuel cell power module.


*Keywords:* PEM fuel cell; Nexa™ power module; Fuel cell modeling; Equivalent internal resistance

## 1. Introduction

As a clean energy conversion device, fuel cells have recently attracted a great deal of attention with some promising results in applications ranging from powering small cellular phones to large power generation in utilities [1]. There are several different types of fuel cells depending on the type of electrolyte materials used [2]. Each fuel cell type has its own characteristics. To design control systems for fuel cells and to compensate its dynamic interactions with rest of the system, it is necessary to have a reasonably accurate dynamic model. In fact, there are several fuel cell models reported in the literature; some are even commercially available [3]. Generally speaking, the models can be categorized into two types, theoretical models based on physical conservation laws [4–12] and semi-empirical models based on experiments [13,14]. Different models have been developed for different type of fuel cells. For example, the model proposed in [5] is for molten carbonate fuel cells (MCFC) for power generation; the models discussed in [7,9] are for solid oxide fuel cells (SOFC). There are also many papers discussing the models for proton exchange membrane (PEM) fuel cells [4,6,8,10–14]. PEM fuel cells generally operate at lower pressure and lower temperature with higher power density compared to other types of fuel cells. Therefore, they are more suitable for applications in small to medium power levels, such as fuel cell powered automobiles or micro-grid power applications.

To design an adequate fuel cell based distributed power generation system to accommodate different load changes, it is essential to have an accurate dynamic model for the fuel cell system so that adequate control systems can be designed to meet the load demand. In such a situation, the dynamics of the temperature and the internal resistance characterstics of fuel cells have to be considered. Padullés et al. introduces a detailed model for the SOFC simulation in [7]; and El-Sharkh et al. subsequently modifies this model for the simulation of PEM fuel cells in [8]. However, both have assumed the temperature and the internal resistance to be constant. In fact, both the stack temperature and internal resistance will have effects on the static and dynamic characteristics of the fuel cell output. Although such effects may not be so significant in the case of large scale fuel cells, where the large thermal mass may prevent an excessive temperature excursion, however, for smaller fuel cells in the range of a few kW levels, such as the Nexa™ PEM fuel cell power module, it has been observed that both the stack temperature and the equivalent

* Corresponding author. Tel.: +1 519 661 2111x88320; fax: +1 519 8502436.
*E-mail address:* jjiang@eng.uwo.ca (J. Jiang).

0378-7753/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2006.05.030

internal resistance of the power module can change dramatically with different load conditions under different hydrogen pressures, which consequently affect the output characteristics of the fuel cell. This is particularly true if the power module is to be used with a variable load. Therefore, such effects cannot and should not be ignored. This forms the motivation of the work reported herein.

The objectives of the paper are to investigate the effects of the temperature and the equivalent internal resistance on the output characteristics of a PEM power module under different load conditions, and to develop a dynamic model for this module. The current investigation is based on the work reported in [8] by taking into account of the electrochemical and thermal aspects of chemical reactions within the stack as well as the equivalent internal resistance. The developed model has been validated by experiments on a Nexa™ PEM fuel cell power module. The results have confirmed that the dynamic model can indeed represent the static and dynamic characteristics of the fuel cell system.

This paper is organized as follows. In Section 2, the Nexa™ PEM power module will be briefly described. Section 3 provides some experimental details. The dynamic model constructions have been presented in Section 4. The model has been validated in Section 5 followed by the conclusions.

## 2. Nexa™ PEM fuel cell power module

PEM fuel cell power modules have many unique features as compared with other fuel cell types, such as relatively low operating temperature, high power density, and high modularity. They can be tailored to different applications, in particular for mobile applications and small-scale power generation [1]. The power generated by fuel cells can provide a viable alternative in areas where noise, vibration or emissions are of concerns. Although it is still more expensive in comparison with bulk power generation, with advances in technologies and reduction in the cost of producing hydrogen, PEM fuel cells can, one day, become more competitive and popular in various applications.

The Nexa™ PEM power module from Ballard Power Systems Inc. is capable of providing 1.2 kW of unregulated dc output. The output voltage level can vary from 43 V at no load to about 26 V at the full load. The designed operating temperature in the stack is around 65 °C at the full load. There are totally 47 cells connected in series in the stack. The fuel is 99.99% hydrogen with no humidification, and the hydrogen pressure to the stack is normally maintained at 5 psig. Oxygen comes from the ambient air. The pressure of the oxidant air is 2.2 psig, and the air is humidified through a built-in humidity exchanger to maintain membrane saturation and prolong the life of the membrane. There is a small compressor supplying excess oxidant air to the fuel cell, and the speed of the compressor can be adjusted to match the power demand from the fuel cell stack. The Nexa™ fuel cell stack is air-cooled; the cooling fan draws air from the ambient surroundings in order to cool the fuel cell stack and regulate the operating temperature [15].

After start-up, the power module will provide all the necessary internal power requirements for operation, such as cooling fan, air compressor, and the control circuit board. Therefore, the output characteristics of the power module can be somewhat different from that of the fuel cell stack itself. Since the power module will be used as a unit and be integrated into a distributed power system, it is necessary to have a complete knowledge of the dynamic characteristics of the entire power module, rather than just that of the fuel cell stack.

## 3. Experimental investigation of the temperature profile and the equivalent internal resistance

### *3.1. Experimental setup*

Through experiments, the characteristics of the stack temperature and the equivalent internal resistance of the Nexa™ power module have been investigated. To study the effect of the change in hydrogen pressures on the output characteristics of the power module, a hydrogen bypass with an adjustable pressure regulator has been installed. The test bed is shown in Fig. 1.

### *3.2. Stack temperature characteristics*

To investigate the change in temperatures for different load conditions, the hydrogen pressure is kept at 5 psig. The load connected to the power module is adjusted by varying load resistances. The results of these tests are shown in Fig. 2. The stack temperature reaches 31 °C from the room temperature (25 °C) in about 5 min when 5 A of the load current is drawn. The temperature reaches 44 °C in about 5 min if the load current is increased to 20 A. If the output current is further increased to 47 A, the temperature will reach to 66.5 °C in about 4 min. Fig. 2 also indicates that as the load changes, the stack current follows immediately with no noticeable time delays. Subsequently, the temperature of the fuel cell stack also changes, and the rate of the change is proportional to the level of the load. It should be noted that there are some variations of the cell temperature along the stacks

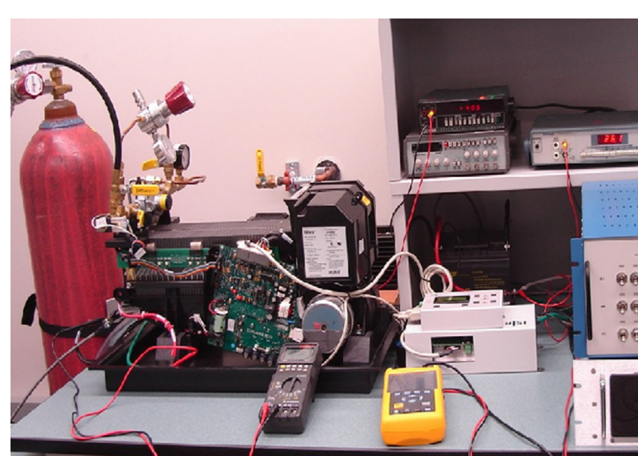

Fig. 1. Experimental setup.

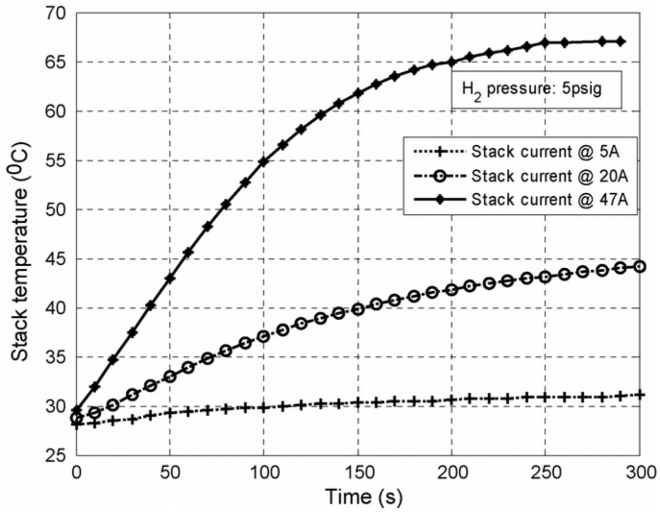


Fig. 2. Temperature profile as a function of stack current.

from the inlet to the outlet as discussed in the literature; however, the Nexa™ fuel cell stack is air-cooled, the cooling fan draws air from the ambient not from the oxidant stream so as to cool the fuel cell stack uniformly [15]. Therefore, those variations can be negligible, and the measured temperature is an average value.

### 3.3. Equivalent internal resistance

As mentioned in Section 2, after start-up, the Nexa™ power module will provide all necessary internal power requirements for sustaining the operation, such as cooling fan, air compressor, and the control circuit board. These devices cannot be separated from the module, therefore, they should be considered as an integral part of the module. As a result, the equivalent internal resistance $R_{\text{int}}$ of the module is different from the internal resistance of fuel cell stacks which is often considered in the literature, even though it may be true that the big part of $R_{\text{int}}$ is due to the internal resistance of the stack. When the power module is used as an energy source, it is more accurate to use $R_{\text{int}}$ to measure the internal resistance. To investigate the characteristics of this equivalent internal resistance $R_{\text{int}}$, a resistive load bank $R_{\text{L}}$ is used, and the periodic current interruption (PCI) mechanism is employed to maintain an isothermal stack temperature [16]. The experimental circuit is shown in Fig. 3. The 0.6 Ω load resistor is frequently switched in and out by the switch S in order to maintain the stack temperature at the desired levels at which the $R_{\text{int}}$ is measured. In Fig. 3, $V_{\text{o}}$ is the open-circuit voltage of the power module. $I_{\text{fc}}$ is the module output current; $V_{\text{L}}$ is the output voltage of the power module when a load is connected. The load is adjusted to obtain different output voltages of the module. $R_{\text{int}}$ can be calculated by (1).

$$R_{\text{int}} = \frac{V_{\text{o}} - V_{\text{L}}}{I_{\text{fc}}} \tag{1}$$

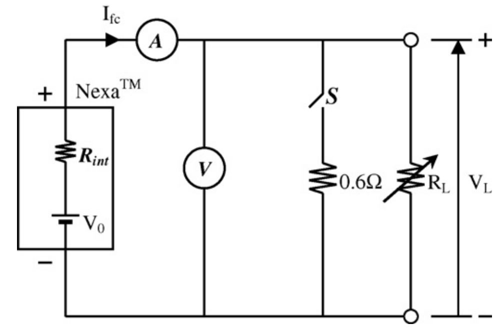


Fig. 3. The measurement circuit for equivalent internal resistance.

The output characteristics of the Nexa™ module at different stack temperatures and different hydrogen pressures have been examined. The relationship between the equivalent internal resistance $R_{\text{int}}$ and the module output current has been recorded and illustrated in Fig. 4.

When a fuel cell is connected to a load, the output voltage is always less than the open-circuit voltage, because there are some voltage drops across the fuel cell caused by the activation loss, ohmic resistance voltage drop, and concentration overpotential. Therefore, there are equivalent activation resistance, equivalent ohmic resistance, and equivalent concentration resistance correspondingly. The total internal resistance of fuel cell stack consists of these resistances, which are current-dependent and temperature-dependent [17], and it mainly determines the equivalent internal resistance of the power module. Fig. 4 clearly shows that when the stack current increases, the equivalent internal resistance dramatically decreases. This is also in part because the conductivity of the membrane is largely affected by the water content and the temperature [18].

The results of the experiments have indicated that both the stack temperature and the equivalent internal resistance change dramatically with the change in the load currents. Consequently, the assumption of a constant stack temperature and internal resistance would not be adequate in the case of a Nexa™ PEM power

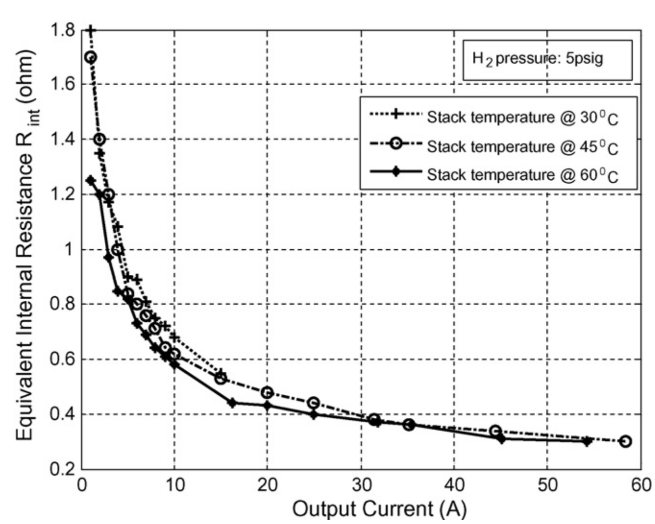


Fig. 4. The relationship between $R_{\text{int}}$ and the module output current.

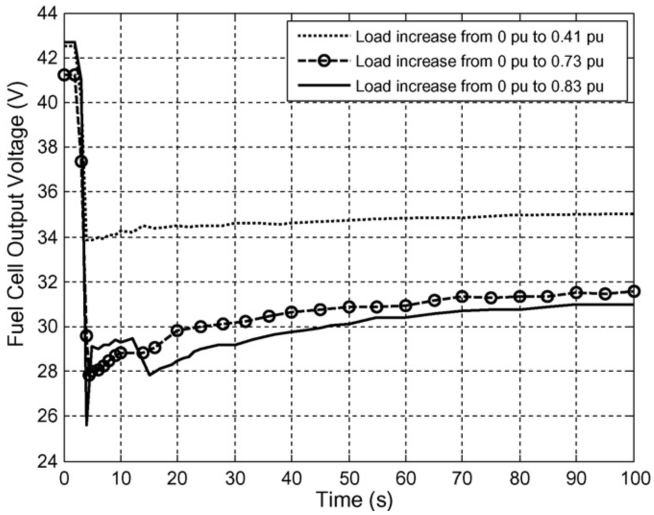


Fig. 5. Voltage profile under sudden load increase.

module. Such changes have to be taken into consideration when constructing a dynamic model.

*3.4. Dynamic responses of the power module*

To investigate the dynamic response of the Nexa™ power module, the output voltage is measured when the module is subject to load increases from 0 per unit (pu) to 0.41, 0.73, and 0.88 pu, respectively, and also to load decreases from 0.41, 0.73, and 0.88 to 0 pu, respectively, under the nominal hydrogen pressure of 5 psig (1 pu = 1.2 kW, i.e. the full capability of the system). The results are illustrated in Figs. 5 and 6 for both cases. It can be seen that the output voltage changes almost instantaneously when the load changes, but it takes more than 1.5 min for the output to reach a new steady state. These observations suggest that some kind of independent energy sources such as batteries may be needed to supply the instantaneous power demand so as to improve the transient performance of the overall system.

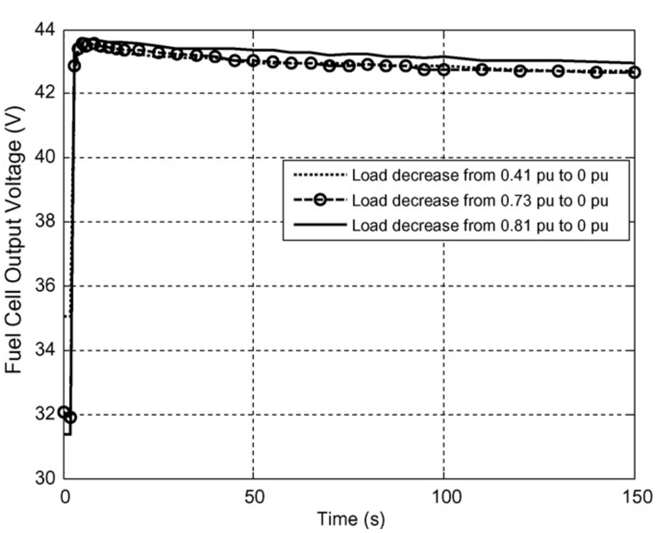


Fig. 6. Voltage profile under sudden load decrease.

## 4. Dynamic model construction

*4.1. Thermal dynamics*

Using a curve fitting technique with the experimental data of Fig. 2, the dynamic characteristics of the temperature change can be approximated by Eqs. (2) and (3).

$$T_{\rm m} = T_0 + (T_0 - T_{\rm rt} + T_{\rm ic}I_{\rm fc})(1 - {\rm e}^{-t/\tau_T}) \quad (2)$$

where the time constant can be expressed as:

$$\tau_T = \frac{T_{\rm it}}{I_{\rm fc}} \quad (3)$$

and $T_{\rm m}$ is the measured temperature of the fuel cell stack (°C), $I_{\rm fc}$ is the stack current (A), $T_0$, $T_{\rm rt}$, $T_{\rm ic}$, and $T_{\rm it}$ are the empirical parameters.

For this particular power module, the best match occurs with $T_0 = 28\,°{\rm C}$, $T_{\rm rt} = 20$, $T_{\rm ic} = 0.7$, and $T_{\rm it} = 4000$ at different stack currents (5, 20, and 47 A). The results are shown in Fig. 7.

By taking the Laplace transform, the transfer function of the temperature change with respect to the load current can be expressed in Eq. (4).

$$T(s) = T_0 + \frac{T_0 - T_{\rm rt} + T_{\rm ic}I_{\rm fc}}{\tau_T s + 1} \quad (4)$$

*4.2. Characteristics of the equivalent internal resistance*

The load characteristics of the module are investigated under different stack temperatures. Based on the experimental results as shown in Fig. 4, the equivalent internal resistance of the power module can best be described by:

$$R_{\rm int} = A_{\rm R} + R_0 \exp\left(\frac{-I_{\rm fc}}{\tau_{\rm R}}\right) - B_{\rm R}\ln(I_{\rm fc}) \quad (5)$$

where $R_{\rm int}$ is the equivalent internal resistance, $A_{\rm R}$, $B_{\rm R}$, $R_0$, $\tau_{\rm R}$ are all empirical parameters.

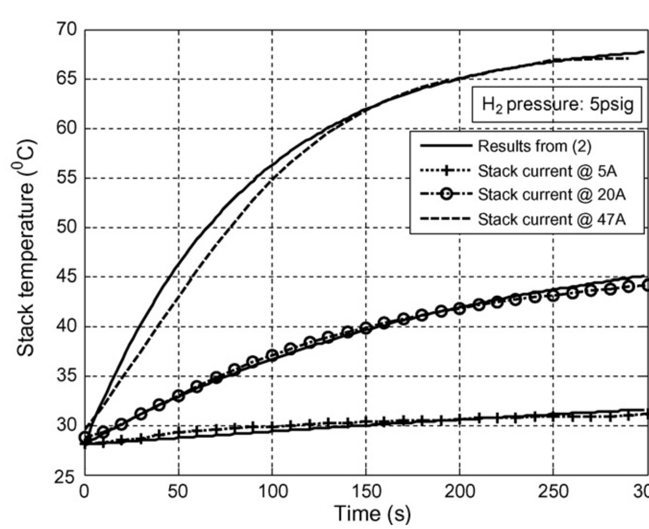


Fig. 7. Comparison of the measured and the computed stack temperatures from the proposed model.

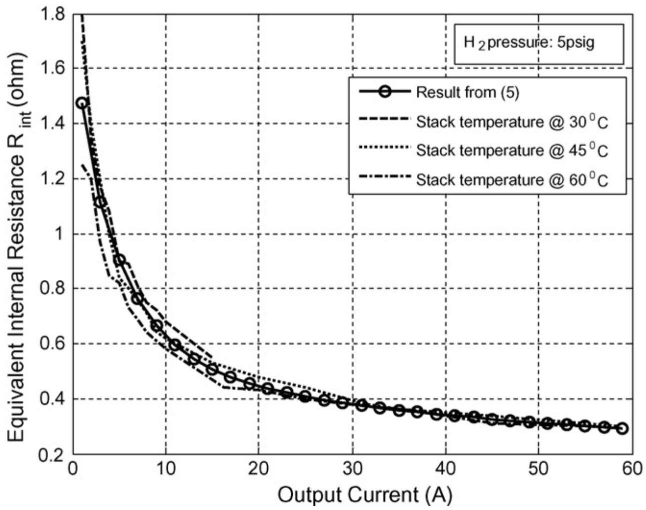


Fig. 8. Comparison of the computed equivalent internal resistance and the measured $R_{\rm int}$.

To achieve reasonably accurate representation, the following values have been selected: $A_{\rm R} = 0.82$, $B_{\rm R} = 0.13$, $R_0 = 0.8$, and $\tau_{\rm R} = 5$. The synthesized curves and the measurement data are shown in Fig. 8. These curves indicate a good match between the computed values based on the proposed models and the experimental data. According to Eq. (5), a resistance dynamic block of the Nexa$^{\rm TM}$ module has been developed, and integrated into the proposed dynamic model.

### *4.3. Dynamic model of the fuel cell module*

For hydrogen, the derivative of the partial pressure can be expressed as follows [7–9]:

$$\frac{{\rm d}p_{\rm H_2}}{{\rm d}t} = \frac{RT}{V_{\rm an}}(q_{\rm H_2}^{\rm in} - q_{\rm H_2}^{\rm out} - q_{\rm H_2}^{\rm r}) \tag{6}$$

where $R$ is the universal gas constant (1 atm (kmol K)$^{-1}$); $T$ is the absolute temperature (K); $V_{\rm an}$ is the volume of the anode (l); $p_{\rm H_2}$ is the hydrogen partial pressure (atm); $q_{\rm H_2}^{\rm in}$ is the hydrogen input flow (kmol s$^{-1}$); $q_{\rm H_2}^{\rm r}$ is the hydrogen flow that reacts inside the stack (kmol s$^{-1}$); and $q_{\rm H_2}^{\rm out}$ is the hydrogen output flow (kmol s$^{-1}$). In small size PEM fuel cell power modules such as the Nexa$^{\rm TM}$ module, $q_{\rm H_2}^{\rm out}$ can be set to zero, because the channel of the anode is usually a dead-end.

According to the fundamental electrochemical relationship, the reacting hydrogen flow can be calculated as:

$$q_{\rm H_2}^{\rm r} = \frac{N_0 I_{\rm fc}}{2F} = 2\ \ K_{\rm r} I_{\rm fc} \tag{7}$$

$$K_{\rm r} = \frac{N_0}{4F} \tag{8}$$

where $F$ is the Faraday's constant (C (kmol)$^{-1}$); $K_{\rm r}$ is the modeling constant (kmol (s A)$^{-1}$); and $N_0$ is the number of the cells connected in series in the stack, which is 47 for the Nexa$^{\rm TM}$ module.

Isolating the hydrogen partial pressure and taking the Laplace transform, the dynamic characteristics of the fuel cell can be written as:

$$p_{\rm H_2}(s) = \frac{1/K_{\rm H_2}}{1 + \tau_{\rm H_2^s}}(q_{\rm H_2}^{\rm in} - 2K_{\rm r} I_{\rm fc}) \tag{9}$$

and

$$\tau_{\rm H_2} = \frac{V_{\rm an}}{K_{\rm H_2} RT} \tag{10}$$

where $K_{\rm H_2}$ is the hydrogen valve molar constant (kmol (atm s)$^{-1}$).

The partial pressure of the other reactants and products can be derived in a similar way. Applying Nernst's equation and Ohm's law, the output voltage of the fuel cell can be expressed in Eq. (11).

$$V_{\rm fc} = N_0 \left[E_0 + \frac{RT}{2F}\ln\left(\frac{p_{\rm H_2} p_{\rm O_2}^{0.5}}{p_{\rm H_2O}}\right)\right] - \frac{RT}{2\alpha F}\ln\left(\frac{I_{\rm fc}}{i_0}\right) + \frac{RT}{2\beta F}\ln\left(1 - \frac{I_{\rm fc}}{i_{\rm L}}\right) - R_{\rm int} I_{\rm fc} \tag{11}$$

Based on the above equations, a dynamic model of the Nexa$^{\rm TM}$ power module, which includes the effects of temperature and internal resistance variations, has been developed and validated with the experiments.

## 5. Model validation and discussion

### *5.1. Static output characteristics*

The comparison of fuel cell characteristics based on the work in [8], static output characteristics based on Eq. (11), and the measured data have been carried out. The results are presented in Fig. 9. The dashed line marked as 'Result from [8]' is from [8], which assumes a constant temperature and a

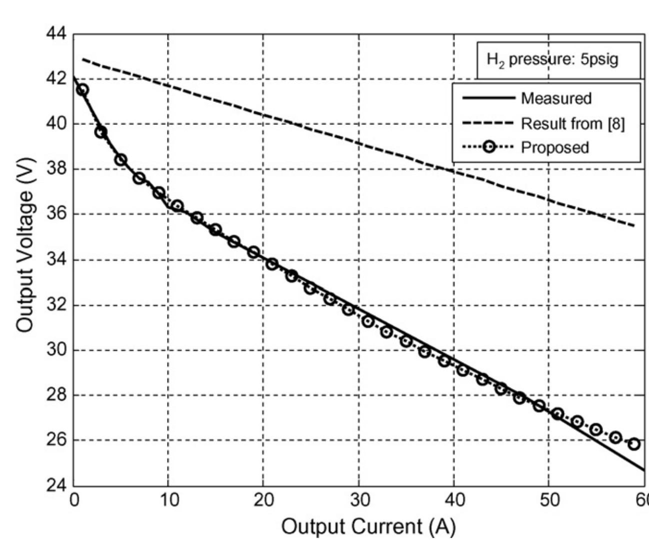


Fig. 9. Comparison of the static output characteristics.

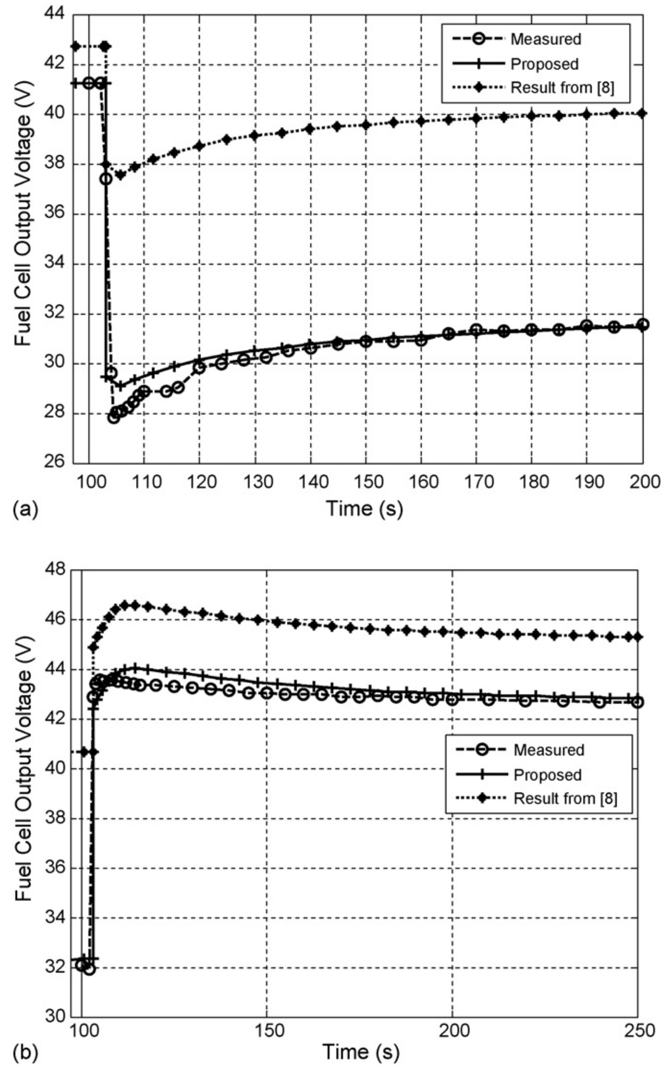


Fig. 10. Comparison of dynamic responses subject to step load changes: (a) a step load increase and (b) a step load decrease.

constant internal resistance. The solid line is traced from the experimental data, while the dotted line with circles is computed from the model, where effects of temperature and variations in the equivalent internal resistance have been considered. The results clearly show that the developed model matches significantly better than that from the model proposed in [8] with the assumptions of constant temperature and the internal resistance.

### 5.2. Dynamic output characteristics

To validate the dynamic characteristics of the output voltage with respect to load changes, a step load increase from 0 to 0.73 pu and a step load decrease from 0.73 to 0 pu have been carried out. The results of both the model of [8] and the developed model are shown in Fig. 10. The comparisons of experimental data with these models are also included in these figures. Clearly, a good agreement between the predicted response from the developed model and the measured data has been established. The results also indicate that there is a significant discrepancy between the model proposed in [8] and the experimental data.

## 6. Conclusions

Through experiments, this paper conclusively show that both the stack temperature and the equivalent internal resistance of the Nexa$^{TM}$ PEM power module have significant effects on the static as well as dynamic characteristics of the fuel cell output. Consequently, they should not be ignored. A semi-empirical dynamic model for a Nexa$^{TM}$ PEM power module considering the characteristics of the temperature and the equivalent internal resistance has been developed in the paper. This developed model has been validated using the experimental data. The results have convincingly shown that the developed model can accurately represent the Nexa$^{TM}$ PEM power module in a wide range of load conditions. Consequently, this model is more suitable for applications in which the load is not a constant.

## Acknowledgments

The authors would like to sincerely acknowledge the support from NSERC, MMO and Mr. Srdjan Stevandic of MVA Engineering Group for the work reported in this paper.

## References

[1] G. Hoogers, Fuel Cell Technology Handbook, CRC Press, 2003.
[2] J. Larminie, A. Dicks, Fuel Cell Systems Explained, second ed., John Wiley & Sons, 2003.
[3] K. Haraldsson, K. Wipke, Evaluating PEM fuel cell system models, J. Power Sources 126 (February 1/2) (2004) 88–97.
[4] A. Rowe, X. Li, Mathematical modeling of proton exchange membrane fuel cells, J. Power Sources 102 (December 1/2) (2001) 82–96.
[5] M.D. Lukas, K.Y. Lee, H.G. Ayagh, Development of a stack simulation model for control study on direct reforming molten carbonate fuel cell power plant, IEEE Trans. Energy Convers. 14 (December 4) (1999) 1651–1657.
[6] G. Maggio, V. Recupero, L. Pino, Modeling polymer electrolyte fuel cells: an innovative approach, J. Power Sources 101 (October 2) (2001) 275–286.
[7] J. Padullés, G.W. Ault, J.R. McDonald, An integrated SOFC plant dynamic model for power systems simulation, J. Power Sources 86 (March 1/2) (2000) 495–500.
[8] M.Y. El-Sharkh, A. Rahman, M.S. Alam, P.C. Byrne, A.A. Sakla, T. Thomas, A dynamic model for a stand-alone PEM fuel cell power plant for residential applications, J. Power Sources 138 (November 1/2) (2004) 199–204.
[9] K. Sedghisigarchi, A. Feliachi, Dynamic and transient analysis of power distribution systems with fuel cells. Part I. Fuel cell dynamic model, IEEE Trans. Energy Convers. 19 (June 2) (2004) 423–428.
[10] J.T. Pukrushpan, A.G. Stefanopoulou, H. Peng, Control of Fuel Cell Power Systems, Springer, 2004.
[11] J.C. Amphlett, R.M. Baumert, R.F. Mann, B.A. Peppley, P.R. Roberge, T.J. Harris, Performance modeling of the Ballard Mark IV solid polymer electrolyte fuel cell. I. Mechanistic model development, J. Electrochem. Soc. 142 (1995) 1–8.
[12] B.R. Sivertsen, N. Djilali, CFD-based modelling of proton exchange membrane fuel cells, J. Power Sources 141 (February 1) (2005) 65–78.

[13] J.C. Amphlett, R.M. Baumert, R.F. Mann, B.A. Peppley, P.R. Roberge, T.J. Harris, Performance modeling of the Ballard Mark IV solid polymer electrolyte fuel cell. II. Empirical model development, J. Electrochem. Soc. 142 (1995) 9–15.

[14] R.F. Mann, J.C. Amphlett, M.A. Hooper, H.M. Jeasen, B.A. Peppley, P.R. Roberge, Development and application of a generalised steady-state electrochemical model for a PEM fuel cell, J. Power Sources 86 (March 1/2) (2000) 173–180.

[15] Nexa™ (310-0027) Power Module User's Manual, Ballard Power Systems Inc., 2003.

[16] W.H. Zhu, R.U. Payne, D.R. Cahela, B.J. Tatarchuk, Uniformity analysis at MEA and stack levels for a Nexa PEM fuel cell system, J. Power Sources 128 (April 1) (2004) 231–238.

[17] C. Wang, M.H. Nehrir, S.R. Shaw, Dynamic models and model validation for PEM fuel cells using electrical circuits, IEEE Trans. Energy Convers. 20 (June2) (2005) 442–451.

[18] F. Barbir, H. Gorgun, X. Wang, Relationship between pressure drop and cell resistance as a diagnostic tool for PEM fuel cells, J. Power Sources 141 (February 1) (2005) 96–101.