Research Journal of Applied Sciences, Engineering and Technology 5(20): 4884-4889, 2013
DOI:10.19026/rjaset.5.4336
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: September 27, 2012 Accepted: November 11, 2012 Published: May 15, 2013

Research Article

Constant Power Control of a Proton Exchange Membrane Fuel Cell through Adaptive Fuzzy Sliding Mode

Minxiu Yan and Liping Fan
College of Information, Shenyang University of Chemical Technology, Shenyang 110142, China

Abstract: Fuel cell is a device that converts the chemical energy from a fuel into electricity through a chemical reaction with oxygen or another oxidizing agent. The paper describes a mathematical model of proton exchange membrane fuel cells by analyzing the working mechanism of the proton exchange membrane fuel cell. Furthermore, an adaptive fuzzy sliding mode controller is designed for the constant power output of PEMFC system. Simulation results prove that adaptive fuzzy sliding mode control has better control effect than conventional fuzzy sliding mode control.

Keywords: Adaptive fuzzy sliding mode control, constant power, dynamic model, proton exchange membrane fuel cells

INTRODUCTION

Due to the environmental problems and energy crisis, fuel cells as pollution-free energy sources have been receiving more and more attention in the recent years. The Proton Exchange Membrane Fuel Cell (PEMFC) as one of the most popular kind of fuel cells has a wide scope of applications such as emergency power supply and small mobile power supply for outdoors power supply and high reliable and high stable power supply (Logan *et al*., 2010; Hatziadoniu *et al.*, 2002; Padulles *et al.*, 2000). PEMFC has many advantages including low temperature, low electrolyte corrosion, high efficiency (Pukrushpan *et al.*, 2004).

Controller design is the main part in PEMFC as well as the major objectives is stability and robustness. One of the significant challenges in control algorithms is that many parameters such as operating temperatures, pressure and flow rates of fuel and oxidant gases and so on influence the performance of PEMFC (Kaytakoglu and Akyalm, 2007). Many research studies have been carried out on proton exchange membrane fuel cell technology. To date, many linear controllers are designed for PEMFC. The controllers can be implemented easily but it is hard to maintaining a fuel cell system in correct operating conditions when subjected to fast load changes (Riascos and Pereira, 2010).

Adaptive fuzzy sliding mode control Presented in this paper is a method of design by combining adaptive control, fuzzy control and sliding mode control (Mammar and Chaker, 2009; Kunusch *et al.*, 2009).

The method can utilize fuzzy control to overcome the effect of mode inaccuracy and utilize adaptive control to enervate buffeting and overshoot caused by sliding mode control so that it has rapider response characteristic and better steady-state behavior than conventional fuzzy sliding mode control.

MATHEMATICAL MODEL OF PEMFC

Fuel cells are made up of three adjacent segments: The anode, the electrolyte and the cathode. They transform chemical energy on the anode side into electric and thermal energy on the cathode side. Two chemical reactions occur at the interfaces of the three different segments (Liu *et al.*, 2006; Zhang *et al.*, 2008; Wei *et al.*, 2010; Zhou *et al.*, 2011). Figure 1 shows the basic structure of a single cell.
In PEMFC the following chemical reaction exists:

$$H_2 + 1/2O_2 \rightarrow H_2O\text{+heat+electrical energy} \quad (1)$$

In this electrochemical process hydrogen molecules are carried by flow plate channels on the anode side. Anode catalyst divides hydrogen on protons H^+ and electrons e^-. At the cathode hydrogen protons H^+ and electrons e^- combine with oxygen to form water and heat. The semi reactions on both electrodes can be expressed by the following equations (Carnes and Djilal, 2005; Moreira and Da Silva, 2009; Rezazadeh *et al.*, 2010):

$$H_2 \rightarrow 2H^+ + 2e^- \qquad \text{anode} \quad (2)$$

Corresponding Author: Minxiu Yan, College of Information, Shenyang University of Chemical Technology, Shenyang 110142, China

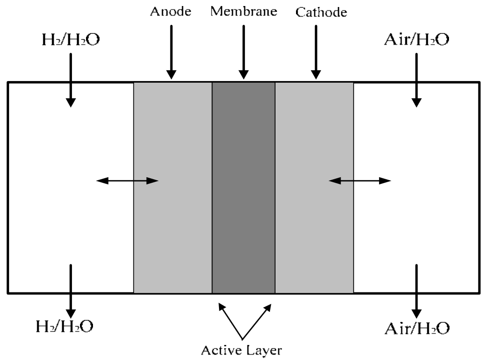

Fig. 1: A typical PEM fuel cell

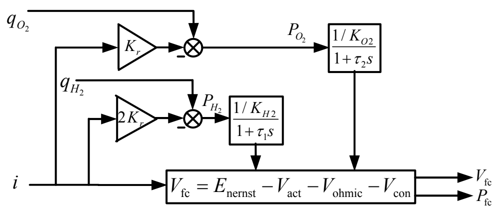

Fig. 2: PEMFC dynamic model

$$\frac{1}{2}O_2 + H^+ + 2e^- \rightarrow H_2O \quad \text{Cathode} \tag{3}$$

Modeling of fuel cells is needed as powerful fuel cell stacks are getting available and have to be integrated into power systems. An adequate model can estimate overall performance of a fuel cell according to operating conditions.

The output voltage of a single cell can be defined as the following expression (Mammar and Chaker, 2009):

$$V_{FC} = E_{Nernst} - V_{act} - V_{ohmic} - V_{con} \tag{4}$$

where,

E_{Nermst} = The thermodynamic potential of the cell and represents its reversible voltage:

$$E_{Nernst} = 1.229 - 0.85\times10^{-3}(T - 298.15) + 4.31\times10^{-5}T[\ln(p_{H2}) + \frac{1}{2}\ln(p_{O2})] \tag{5}$$

where, p_{H2} and p_{o2} are the partial pressures of hydrogen and oxygen, respectively and variable T denotes the operating temperature. V_{act} is the voltage drop due to the activation of the anode and cathode:

$$V_{act} = 0.9514 - 3.12\times10^{-3}T - 7.4\times10^{-5}T\ln(c_{O2}) + 1.87\times10^{-4}T\ln(I_{stack}) \tag{6}$$

where, I_{stack} (A) is the electrical current and c_{o2} (mol/cm) represents the oxygen concentration in the catalytic interface of the cathode, determined by:

$$c_{O2} = \frac{p_{O2}}{5.08\times10^6 e^{-498/T}} \tag{7}$$

V_{ohmic} = The ohmic voltage drop results from the conduction of protons through the solid electrolyte and electrons through the internal electronic resistance:

$$V_{ohmic} = I_{stack}(R_m + R_c) \tag{8}$$

where,

R_c (Ω) = The resistance to electron flow

R_m (Ω) = The resistance to proton transfer through the membrane

V_{con} = The voltage drop due to the mass transport which can be described by the following expression:

$$V_{con} = -B\ln(1 - \frac{J}{J_{max}}) \tag{9}$$

where,

(V) = A parametric coefficient depending on the cell

J(A/cm^2) = The actual current density of the cell

The output power of the single fuel cell can be written as:

$$P_{FC} = V_{FC} I_{stack} \tag{10}$$

Fuel cell dynamic model can be set up based on the above described mathematical model. This model can reflect the relationship between the output voltage and current and pressure of hydrogen, oxygen (Rezazadeh *et al.*, 2011; Fan *et al.*, 2012).

An accepted dynamic model of the PEMFC is shown in Fig. 2.

DESIGN OF AN ADAPTIVE FUZZY SLIDING MODE CONTROLLER

In order to overcome the parameter uncertainty and external disturbance, an adaptive fuzzy sliding mode control is presented for constant power output.

In the aspect of control methods, fuzzy control and sliding mode control are different from conventional control theory. Each of them has its advantages and disadvantages.

Fuzzy control can express the amount of ambiguity in human thinking and possess several advantages such as model-free, universal approximation theorem. However, once control rule and coefficient are fixed, fuzzy control cannot well adapt to the change of conditions.

Sliding mode control can yield a closed loop system with an invariance property to uncertainties

Table 1: Fuzzy control rules

		S				
Δu		PB	PS	ZO	NS	NB
$\dot{s}$	PB	ZO	ZO	PB	ZO	ZO
	PM	ZO	ZO	PM	ZO	ZO
	PS	ZO	ZO	PS	ZO	ZO
	ZO	PB	PS	ZO	NS	NB
	NS	ZO	ZO	NS	ZO	ZO
	NM	ZO	ZO	NM	ZO	ZO
	NB	ZO	ZO	NB	ZO	ZO

when the system states are in the sliding mode. But sliding mode control can cause the high frequency when fastening the response of the system.

If only simply combining fuzzy control with sliding mode control, chattering brought with sliding mode control can be reduced to some extent. However, this method is still based on experiences; controller parameters do not possess adaptive and self-leaning ability. In addition, overshoot from fast response of the system easily occurs. Motivated by this, an adaptive fuzzy sliding mode controller is proposed.

Construction of the fuzzy sliding mode controller: The fuzzy sliding mode controller can make the PEM fuel cell keep constant power out put P_{fc}^{*}. The error *e(k)*, the change in error *de(k)* are given as follows:

$$e(k) = P_{fc}^{*} - P_{fc} \tag{11}$$

$$de(k) = \frac{e(k) - e(k-1)}{T} \tag{12}$$

A switching function $s(k)$ is designed as following:

$$s(k) = ce(k) + de(k) \quad c > 0 \tag{13}$$

$$ds(k) = s(k) - s(k-1) \tag{14}$$

Here we use the proportion switching control method to design controller which meets the conditions for the existence of sliding mode. Controller is designed as:

$$u = (\alpha |e| + \beta \dot{e}) \operatorname{sgn}(s) \tag{15}$$

Using a two-dimensional fuzzy controller, sliding mode control u is designed by fuzzy control rule directly. The fuzzy controller input s and $\dot{s}$ respectively denote fuzzy variables of $s(k)$ and $ds(k)$. The fuzzy controller output ΔU is fuzzy variables of Δu. According to fuzzy control theory, the fuzzy sets are shown as following:

$$s = \{\text{NB,NS,ZO,PS,PB}\}$$
$$\dot{s} = \{\text{NB,NM,NS,ZO,PS,PM,PB}\}$$
$$\Delta u = \{\text{NB,NM,NS,ZO,PS,PM,PB}\}$$

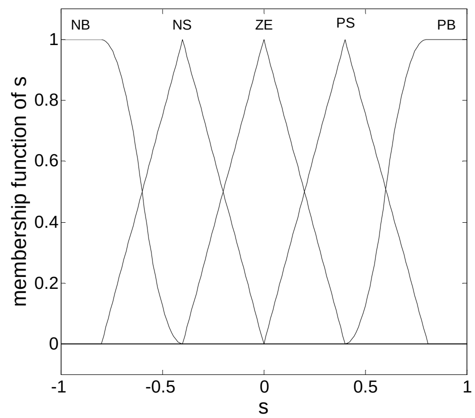

Fig. 3: Membership function of s in the main fuzzy controller

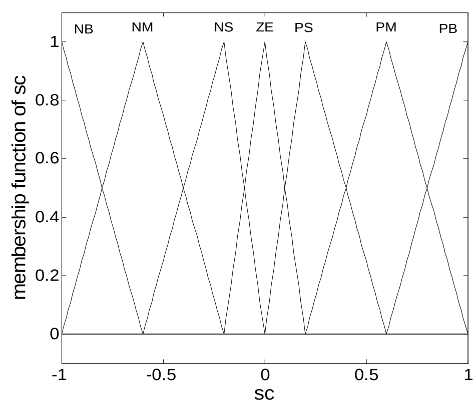

Fig. 4: Membership function of s*c* in the main fuzzy controller

The fuzzy domain for s, $\dot{s}$ and Δu is [-1, 1]. The triangular type membership function is chosen for the above fuzzy variables. Fuzzy control rule base is shown in Table 1.

In Fig. 3-5, the membership functions for input s, $\dot{s}$ and output control Δu in the main fuzzy controller are shown.

In this paper, the output control *u* of the main fuzzy controller is designed as q_{O2}, which is the input molar flow of oxygen of the PEMFC. It shows the 3-dimensional representation of control variable *u* for fuzzy variable (s, $\dot{s}$) is shown in Fig. 6.

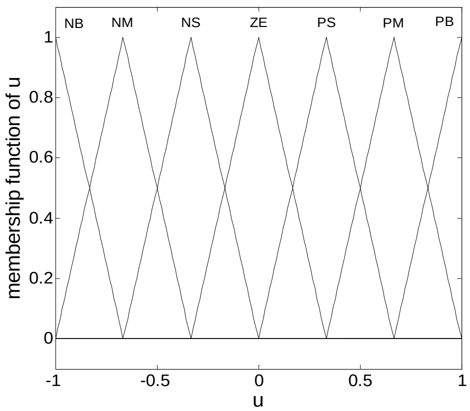

Fig. 5: Membership function of *u* in the main fuzzy controller

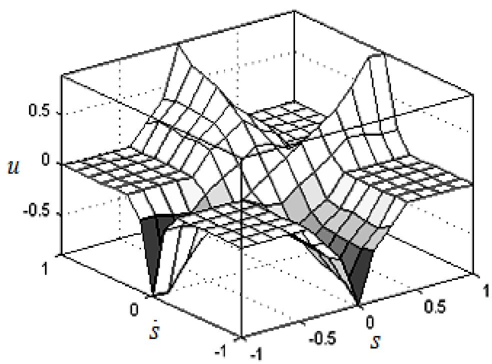

Fig. 6: 3-dimensional representation of control variable u for fuzzy variables (s, $\dot{s}$) of the main fuzzy controller

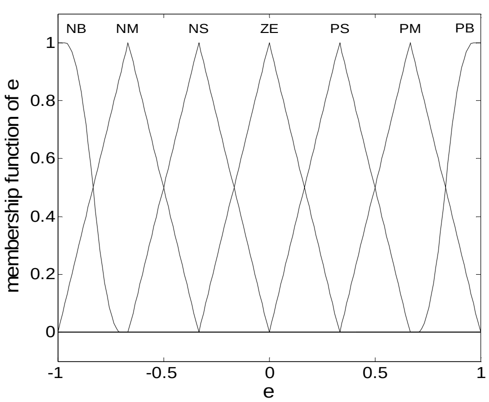

Fig. 7: Membership function of e in the auxiliary adaptive fuzzy controller

Construction of the auxiliary adaptive fuzzy controller: Using conventional fuzzy sliding mode control can realize constant power output of PEMFC; however, this control method brings about overshoot when fastening the response of the system. At the same time, the parameters of the controller don't have adaptive and self-learning ability in the process of control.

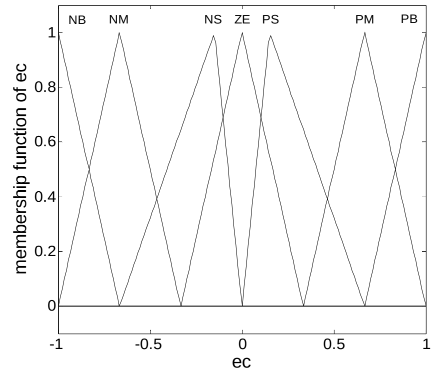

Fig. 8: Membership function of *ec*

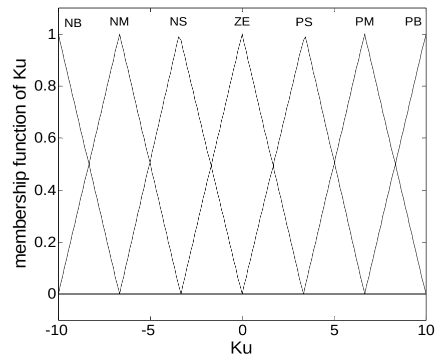

Fig. 9: Membership function of K_u

Hence, an auxiliary adaptive fuzzy controller with dual inputs is designed to adjust the proportionality factor K_u of the main fuzzy controller in order to obtain faster response characteristic and better steady-state behavior, where P_{fc}^* is the set point of the output power. The error $e(k)$, the change of error $ec(k)$ and the control output $K_u(k)$ of the auxiliary adaptive fuzzy controller are given as:

$$e(k) = P_{fc}^* - P_{fc} \tag{16}$$

$$ec(k) = e(k) - e(k-1) \tag{17}$$

$$K_u(k) = K_u(k-1) + \Delta K_u(k) \tag{18}$$

Here $\Delta K_u(k)$ is the inferred change of duty ratio by the auxiliary adaptive fuzzy controller.

The triangular type membership function is chosen for error, change of error and output control variable. The fuzzy domain for *e*, *ec* is [-1, 1] and for K_u is [-10, 10]. The fuzzy set for *e*, *ec* and K_u is {NB, NM, NS, ZE, PS, PM, PB}. The membership functions for input error *e*, change of error *ec* and output control K_u of the auxiliary adaptive fuzzy controller are shown in Fig. 7 to 9.

Table 2: Control rules of the auxiliary adaptive fuzzy controller

		Ec						
k_u		NB	NM	NS	ZE	PS	PM	PB
e	NB	NB	NB	NB	NB	NM	NS	ZE
	NM	NB	NB	NM	NM	NS	ZE	PS
	NS	NB	NM	NM	NS	ZE	PS	PM
	ZE	NB	NM	NS	ZE	PS	PM	PB
	PS	NM	NS	ZE	PS	PM	PM	PB
	PM	NS	ZE	PS	PM	PM	PB	PB
	PB	ZE	PS	PM	PB	PB	PB	PB

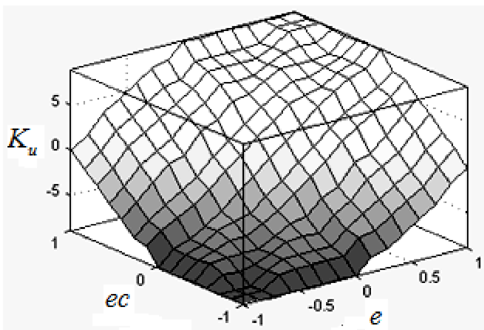

Fig. 10: 3-dimensional representation of control variable K_u for fuzzy variable (*e*, *ec*)

The output control K_u of the auxiliary adaptive fuzzy controller is the value of proportionality factor in the main fuzzy controller. The fuzzy control rule base of the auxiliary adaptive fuzzy controller is shown in Table 2 and the 3-dimensional representation of control variable K_u for fuzzy variables (*e*, *ec*) is shown in Fig. 10.

SIMULATION AND RESULTS

In order to verify the validity of the proposed adaptive fuzzy sliding mode controller, simulation operation is implemented in the MATLAB simulation platform. The main parameters of the PEMFC used in the simulation are shown in Table 3.

Simulation results of control schemes are presented in this section. Output power is controlled by adjusting the oxygen flow. The reference output power of the fuel cell is 0.5W. There is a change in the load from 5 Ω to6 Ω at the time of 25s. The quantifying factors of the main fuzzy sliding mode controller are $K_e = 1$ and $K_{ec} = 0.0003$ and the proportionality factor K_u is revised by the auxiliary adaptive fuzzy sliding mode controller. In the auxiliary adaptive fuzzy controller, When the load is 5Ω, the quantifying factors are $Ke^* = 8$ and $Kec^* = 0.001$, the proportionality factor is $K_u = 1$ and when the load changes to 6Ω, the quantifying factors are changed to $Ke^* = 600$ and $Kec^* = 0.001$, the proportionality factor is adjusted to $K_u = 30$. Simulation results are shown in Fig. 11 and 12 under no control.

Table 3: Main parameters of the PEMFC

B	A	T_{fc}	P_{H2}	R_c	l	ψ
0.016	50.6	343	1	0.0003	0.0178	23

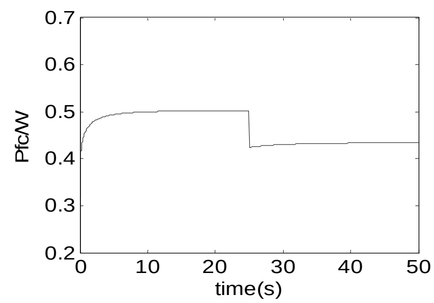

Fig. 11: Output power under no control

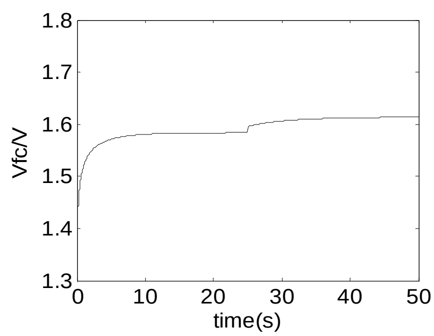

Fig. 12: Output voltage under no control

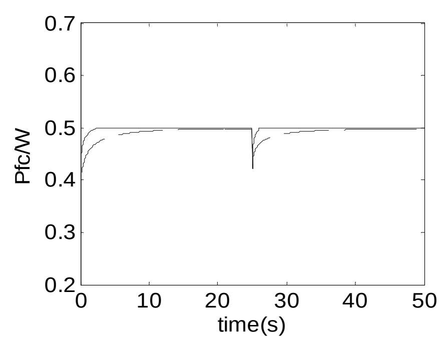

Fig. 13: Output power controlled by adjusting oxygen flow

In the Fig. 13 and 14 the solid line represents the adaptive fuzzy sliding mode control and the dotted line represents the fuzzy sliding mode control.

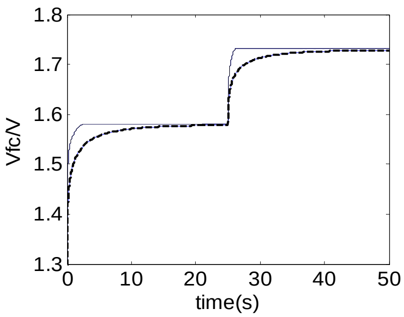

Fig. 14: Output power controlled by adjusting oxygen flow

It can be seen from these figures that the fuzzy sliding mode controller can modify the oxygen flow to realize constant power output under varying load. The adaptive fuzzy sliding mode controller is characterized by a faster time response and higher precision compared to the fuzzy sliding mode controller.

CONCLUSION

Fuel cells need constant power output when load changes. The adaptive fuzzy sliding mode control described in this paper can not only have fast response characteristic, but also have good steady-state behavior and strong robustness compared with fuzzy sliding mode control. Simulation results indicate that the adaptive fuzzy sliding mode controller is very effective in tracking a given power and guarantees that the fuel cells have constant power output.

ACKNOWLEDGMENT

This study is supported by the National Key Technology Research and Development Program of China under grant 2012BAF09B01 and the National Natural Science Foundation of China under grant 61143007.

REFERENCES

Carnes, B. and N. Djilal, 2005. Systematic parameter estimation for PEM fuel cell models. J. Power Sources, 144(1): 83-93.

Fan, L.P., 2012. Simulation study on the influence factors of generated output of proton exchange membrane fuel cell. Appl. Mech. Mater., 121-126: 2887-2891.

Hatziadoniu, C.J., A.A. Lobo and F.M. Pourboghrat Daneshdoost, 2002. A simplified dynamic model of grid-connected fuel-cell generators. IEEE Trans. Power Deliv., 17(2): 467-473.

Kaytakoglu, S. and L. Akyalm, 2007. Optimization of parametric performance of a PEMFC. Int. J. Hydrog. Energy, 32: 4418-4423.

Kunusch, C., P.F. Puleston, M.A. Mayosky and J. Riera, 2009. Sliding mode strategy for PEM fuel cells stacks breathing control using a super-twisting algorithm. IEEE Trans. Cont. Syst. Technol., 17(1): 167-174.

Liu, G.D., W.S. Yu and Z.S. Tu, 2006. Power management for alleviation of the impact on PEM fuel cell due to load fluctuation. Proceeding of 6th International Conference on Intelligent Systems Design and Applications, pp: 1104-1110.

Logan, B.E., R.V. Kulkarni and D. Stroud, 2010. Microbial fuel cells and other bioelectrochemical systems. Appl. Microbiol. Biotechnol., 85(6): 1665-1671.

Mammar, K. and A. Chaker, 2009. Fuzzy logic control of fuel cell system for residential power generation. J. Electr. Eng., 60(6): 328-334.

Moreira, M.V. and G.E. Da Silva, 2009. A practical model for evaluating the performance of proton exchange membrane fuel cells. Renewab. Energy, 34(7): 1734-1741.

Padulles, J., G.W. Ault and J.R. McDonald, 2000. An integrated SOFC plant dynamic model for power systems simulation. J. Power Sources, 86(1-2): 495-500.

Pukrushpan, J., A. Stefanopoulou and H. Peng, 2004. Control of fuel cell breathing. IEEE Cont. Syst., 24(2): 30-46.

Rezazadeh, A., M. Sedighizadeh and M. Karimi, 2010. Proton exchange membrane fuel cell control using a predictive control based on neural network. Int. J. Comput. Electr. Eng., 2(1): 81-85.

Rezazadeh, A., A. Askarzadeh and M. Sedighizadeh, 2011. Adaptive inverse control of proton exchange membrane fuel cell using RBF neural network. Int. J. Electrochem. Sci., 6: 3105-3117.

Riascos, L.A.M. and D.D. Pereira, 2010. Controlling operating temperature in PEM fuel cells. ABCM Symp. Series Mechatron., 4: 137-146.

Wei, G.A., S.H. Quan, Q.H. Chen, L.Y. Zhang and L. Su, 2010. Neural-PID control of air pressure in fuel cells. International Conference on Electrical and Control Engineering, pp: 5353-5356.

Zhang, Y.Y., J.C. Sun, L.B. Du and Y. Zhang, 2008. An intelligent control strategy for power and voltage of PEMFC generator. Proceeding of 4th International Conference on Natural Computation, pp: 458-462.

Zhou, W.H., L.C. Wang and L.B. Wang, 2011. A new model enforcing water mass balance of proton exchange membrane fuel cell. International Conference on Computer Distributed Control and Intelligent Environmental Monitoring, Sch. of Environ. and Municipal Eng., Lanzhou Jiaotong Univ., Lanzhou, China, pp: 377-380.