TELKOMNIKA, Vol. 11, No. 5, May 2013, pp. 2800~ 2809
ISSN: 2302-4046

Fuzzy Sliding Mode Control for a Fuel Cell System

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Abstract

Fuel cell powered systems have low voltage and high current output characteristics. Therefore, the output voltage of the fuel cell must be stepped up by DC-DC converter. In this paper an integrated mathematical model for proton exchange membrane fuel cell power system with DC-DC converter is described by analyzing the working mechanism of the proton exchange membrane fuel cell and the boost DC-DC converter. Fuzzy sliding mode control scheme is proposed to realize stable output voltage under different loads. Simulation operations are carried out and results are compared with fuzzy control and sliding mode control. It is shown that the use of the proposed fuzzy sliding mode controller can achieve good control effect.

***Keywords**: Fuel Cell, DC-DC Converter, Fuzzy Logic, Sliding Mode Control*

1. Introduction

With the rapid development of the world economy, the global energy crisis is getting ever more acute. Because of economic and ecological problems of fossil fuel power plants, developing renewable energies for generating electrical power attracts many attentions [1-2].

Fuel cells are promising energy sources that produce electrical currents with almost null pollutant emissions. In the recent years there was an increasing interest in fuel cell technology. Proton exchange membrane fuel cells (PEMFCs) are the most popular kind of fuel cells due to theirs quick start-up, low operating temperature, high efficiency, low weight and low electrolyte corrosion [3-5]. They use hydrogen and oxygen as fuels, and water is the only waste. PEMFCs provide the highest power density and specific power among all the other fuel cell types and hence have use in portable devices, transportation and stationary power generation and cogeneration applications. They are acknowledged as most valuable new alternative energy sources [6-7].

However, despite the promising achievements and plausible prospects of PEMFCs, the remaining problems mean that it is still long way before they can successfully and economically replace the various traditional energy systems. Because of amending of PEMFC's performance and increasing safety and reliability, a satisfying control on PEMFC must be done. Traditional controllers couldn't lead to acceptable responses because of time-change, long-hysteresis, uncertainty, strong-coupling and nonlinear characteristics of PEMFCs. So an intelligent or adaptive controller is needed [8].

From the point of view in the system complexity, fuel cells are complex and nonlinear system; they should focus on how to design an appropriate controller to make correct operating conditions when subjected to fast load changes. Sliding mode control (SMC) features such valuable properties as low sensitivity to external disturbances and robustness with respect to plant parameter uncertainties and variations. However, the price being paid for that is an undesirable phenomenon called chattering, which in turns results in the oscillations of the state trajectory around the sliding surface [9]. This drawback of the sliding mode control is well known, and many efforts of the researched were aimed at elimination of chattering or mitigation of its effects. Fuzzy logic control (FC) using linguistic information possesses several advantages such as robustness, model-free, universal approximation theorem and rule-based algorithm. Fuzzy logic control is considered to be a useful tool for non-model based control system design

Received January 10, 2013; Revised March 20, 2013; Accepted March 29, 2013

[10-12]. However, fuzzy control lacks a formal synthesis technique and all fuzzy rules have to be supplied by human experts, and it also has the shortcoming of poor stability precision [13-14].

Fuzzy sliding mode control (FSMC) is a control method to integrate fuzzy control and sliding mode control. It utilizes fuzzy control to enervate chattering caused by sliding mode control, and uses sliding mode control to overcome the effect of fuzzy rules and so that it improves rapidity and stationary of system dynamic response.

A complete PEM fuel cell power system includes DC-DC converter apart from the fuel cell. The DC-DC converter transforms unregulated DC power of the fuel cell to regulated DC bus power. A system consisting of proton exchange membrane fuel cell and DC-DC converter is modeled and constant voltage output of the PEMFC and DC-DC converter system is realized by using fuzzy sliding mode control under the condition of fast load changes. This paper is organized as follows. The mathematical model for proton exchange membrane fuel cell and DC-DC converter system is described in Section 2. Section 3 presents a brief description of designing an adaptive fuzzy sliding mode controller for PEMFC system. Simulation results are presented in section 4 to confirm the effectiveness and the applicability of the proposed method. Finally, our work of this paper is summarized in the last section.

2. Model of the System

2.1. Model of PEMFC

As a tool for the optimization of the design of the fuel cell, the mathematical model and simulation is necessary. It is important to have an appropriate model to estimate the overall performance of proton exchange membrane fuel cell operating conditions [15].

Fuel cells are electrochemical devices that convert the chemical energy of a fuel (hydrogen) and an oxidizer (oxygen) directly into electricity. The fuel cell consists of an electrolyte between two electrodes. The electrolyte allows the positive ions (protons) to pass through while blocking the electrons. Hydrogen gas passes over one electrode (anode), and with the help of a catalyst, separates into electrons and hydrogen protons. A graphic representation of a PEM fuel cell structure is given in Figure 1 [16].

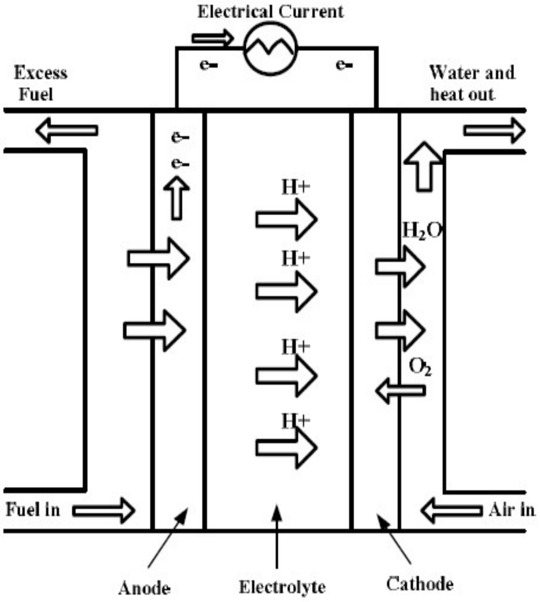


Figure 1. Schematic diagram of PEMFC

PEM fuel cell electrochemical process starts on the anode side where H_2 molecules are brought by flow plate channels. Anode catalyst divides hydrogen on protons H^+ that travel to cathode through membrane and electrons e^- that travel to cathode over external electrical circuit. At the cathode hydrogen protons H^+ and electrons e^- combine with oxygen O_2 by use of catalyst, to form water H_2O and heat. Described reactions can be expressed by the following equations [17-18]:

$$\mathrm{H_2 \rightarrow 2H^+ + 2e^-} \quad \text{(Anode)} \tag{1}$$

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

The output voltage V_{fc} of a single fuel cell can be represented by the following formula

$$V_{\mathrm{fc}} = E_{\mathrm{nernst}} - V_{\mathrm{act}} - V_{\mathrm{ohmic}} - V_{\mathrm{con}} \tag{3}$$

in which E_{nernst} is the thermodynamic potential of the cell representing its reversible voltage, and

$$E_{\mathrm{nernst}} = 1.229 - 0.85\times10^{-3}(T_{\mathrm{fc}} - 298.15) + 4.31\times10^{-5} T_{\mathrm{fc}}\left[\ln(P_{H_2}) + \frac{1}{2}\ln(P_{O_2})\right] \tag{4}$$

where P_{H_2} and P_{O_2} (atm) are the hydrogen and oxygen pressures, respectively, and T_{fc} (K) is the operating temperature. V_{act} is the voltage drop due to the activation of the anode and the cathode:

$$V_{\mathrm{act}} = 0.9514 - 3.12\times10^{-3} T_{\mathrm{fc}} - 7.4\times10^{-5} T_{\mathrm{fc}}\ln(C_{\mathrm{O_2}}) + 1.87\times10^{-4} T_{\mathrm{fc}}\ln(i) \tag{5}$$

where i (A) is the electrical current, and $C_{\mathrm{O_2}}$ is the oxygen concentration. V_{ohmic} is the ohmic voltage drop associated with the conduction of protons through the solid electrolyte, and electrons through the internal electronic resistance:

$$V_{\mathrm{ohmic}} = i(R_M + R_C) \tag{6}$$

where $R_C\,(\Omega)$ is the contact resistance to electron flow, and $R_M\,(\Omega)$ is the resistance to proton transfer through the membrane, which can be described as

$$R_M = \frac{\rho_M \cdot l}{A}, \qquad \rho_{\mathrm{M}} = \frac{181.6\left[1 + 0.03\left(\frac{i}{A}\right) + 0.062\left(\frac{T_{\mathrm{fc}}}{303}\right)^2\left(\frac{i}{A}\right)^{2.5}\right]}{\left[\psi - 0.634 - 3\left(\frac{i}{A}\right)\right]\exp\left[4.18\left(\frac{T_{\mathrm{fc}}\text{-}303}{T_{\mathrm{fc}}}\right)\right]} \tag{7}$$

where ρ_{M} $(\Omega\cdot\mathrm{cm})$ is the membrane specific resistivity, l (cm) is the membrane thickness, A (cm^2) is the membrane active area, and ψ is a specific coefficient for every type of membrane; V_{con} represents the voltage drop resulting from the mass transportation effects, which affects the concentration of the reacting gases and can be described by the following expression:

$$V_{\mathrm{con}} = -B\ln\left(1 - \frac{i}{i_{\mathrm{max}}}\right) \tag{8}$$

where B (V) is a constant depending on the type of fuel cell, $i_{\max}$ is the maximum electrical current. The output power of the single fuel cell is

$$P_{\mathrm{fc}} = V_{\mathrm{fc}} i \tag{9}$$

An accepted dynamic model of the PEMFC is shown in Figure 2. Based on the above described mathematical model, a Matlab/simulink simulation model of the PEMFC can be set up [19]. Parameters of the Ballard Mark V fuel cell [20] are used in the simulation model.

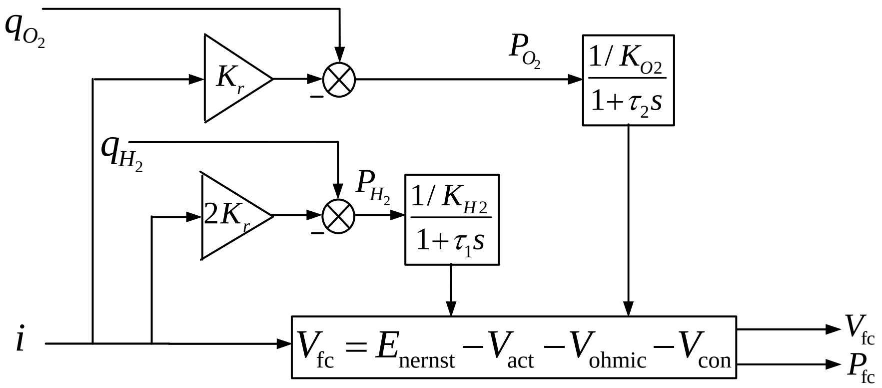


Figure 2. PEMFC dynamic model

2.2. Integration of PEMFC Model with a Boost DC-DC Converter

A circuit model of fuel cell and DC-DC converter system is shown in Figure 3. The output voltage of the fuel cell is V_{fc}. The output voltage of the boost DC-DC converter is V_{dc}. The dynamics of the boost DC-DC converter are governed by the following system of bilinear differential equations [21]:

$$\frac{\mathrm{d}V_{\mathrm{dc}}}{\mathrm{d}t} = \frac{1-d}{C} i_L - \frac{V_{\mathrm{dc}}}{RC} \tag{10}$$

$$\frac{\mathrm{d}i_L}{\mathrm{d}t} = \frac{V_{\mathrm{fc}}}{L} - \frac{1-d}{L} V_{\mathrm{dc}} \tag{11}$$

where d is the duty ratio of the switch T.

Based on this above mathematic model, a simulation model of a boost DC-DC converter can be set up and integrated with the fuel cell simulation model.

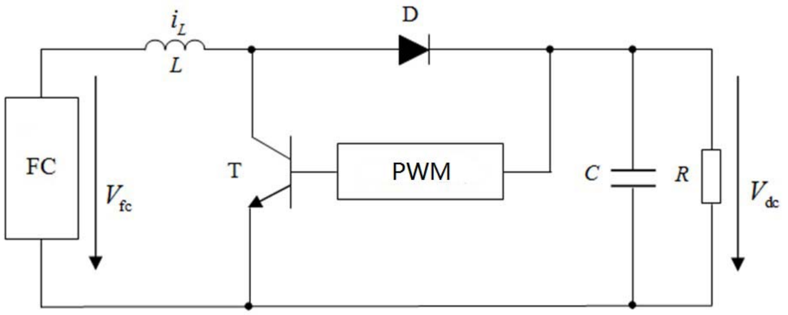


Figure 3. The PEMFC/DC-DC converter system

3. Design of a Fuzzy Sliding Mode Controller

A fuzzy sliding mode controller is designed for the PEMFC. The structure of the closed-loop fuzzy sliding mode control system is shown in Figure 4. In the aspect of control methods, fuzzy control and sliding mode control are different from conventional control theory, and each of them has its advantages and disadvantages. Fuzzy control needs not an accurate mathematical model of object creation and has good robustness. However, once control rule and coefficient are fixed, fuzzy control cannot adapt condition change well. Sliding mode control has the advantage of fast response characteristic, and it is not sensitive to parameter variation and fast load changes. In traditional SMC, the structure of the controller is decided by the switching function, it is sensitive to external disturbances in the approaching process, and it is easy to bring about chattering. Combining fuzzy control with sliding mode control can lighten or eliminate chattering caused by sliding mode control.

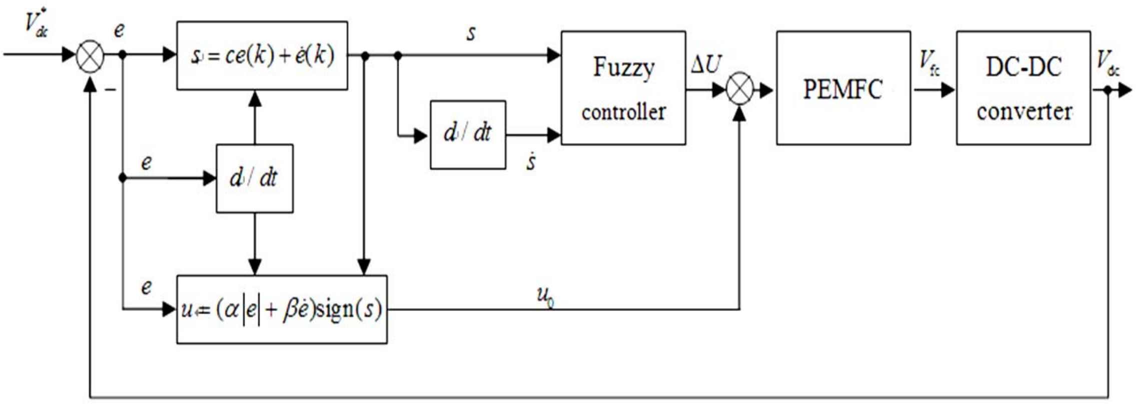


Figure 4. The closed-loop fuzzy sliding mode control system

In consideration of the control aim of keeping the output voltage in a given constant value, the output error the its change are defined as

$$e(k) = V_{\text{dc}}^* - V_{\text{dc}}(k) \tag{12}$$

$$\dot{e}(k) = e(k) - e(k-1) \tag{13}$$

The switching function of SMC and the control output *u*(*k*) of are given as follows:

$$s = ce(k) + \dot{e}(k) \tag{14}$$

$$\dot{s} = s(k) - s(k-1) \tag{15}$$

$$u(k) = u(k-1) + \Delta U(k) \tag{16}$$

The sliding mode control variable *u* is designed by fuzzy control law directly. A 2-D fuzzy controller is applied. The two inputs of the fuzzy controller are chosen as *s* and $\dot{s}$. The fuzzy set for s is {NB, NS, ZO, PS, PB}, and for $\dot{s}$ and Δ*U* are {NB, NM, NS, ZO, PS, PM, PB}. 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 rules are shown in Table 1.

Table 1. Fuzzy control rules

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

Table 2. Main parameters of PEMFC

Parameters	Units	Values
B	V	0.016
A	cm^2	50.6
T_{fc}	K	343
P_{H_2}	atm	1
R_c	Ω	0.0003
l	cm	0.0178
ψ	/	23
L	mH	0.0005
C	μF	0.0005
V_{dc}^*	V	5

4. Simulation and Results

In order to verify the validity of the proposed fuzzy sliding mode controller, simulation operations are carried out in MATLAB/Simulink simulation platform, based on the above-mentioned simulation model. The parameter values of the PEMFC and the boost DC-DC converter used in the simulation process are shown in Table 2.

For investigating the performance and accuracy of the fuzzy sliding mode control method, simulation results of fuzzy sliding mode control are compared with the results of sliding mode control and fuzzy control. The controllers are designed to keep the output voltage of the DC-DC converter at a constant value. The reference setting output voltage of the DC-DC converter is 5V. For purpose of testing the capacity of resisting disturbance, load disturbance is considered. The load is set to change from 5Ω to 10Ω at the time of 2s.

The simulation results corresponding to fuzzy control, sliding mode control and fuzzy sliding mode control are shown in Figure 5, Figure 6 and Figure 7 respectively.

By comparing these figures with each other, it is clearly shown to us that the fuzzy sliding mode controller proposed in this paper has the predomination of a faster time response and higher precision than the fuzzy controller and the sliding mode controllers.

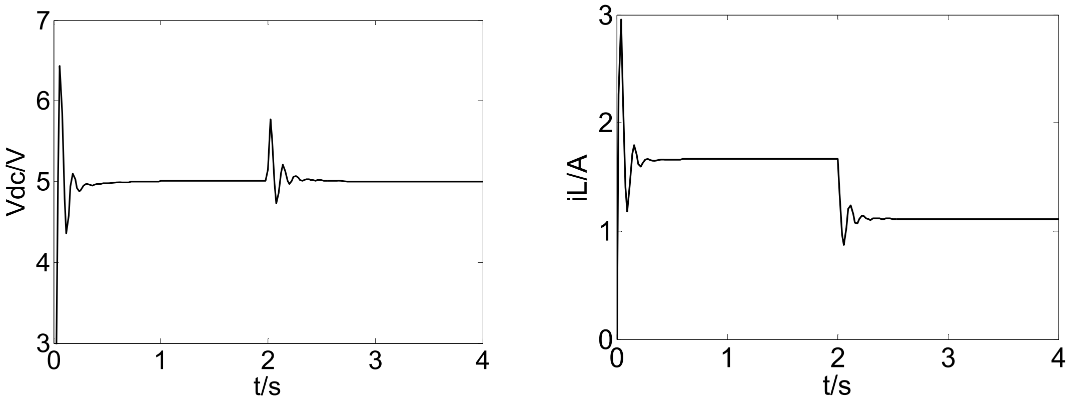


Figure 5. Simulation curves corresponding to fuzzy control

The fuzzy controller can achieve the control objective basically, but it has a big overshoot in the output voltage and has a long control period in initialization phase, and these can be seen from Figure 5. Speaking from the design level, the control effect of a fuzzy controller relies on the experiential knowledge of experts highly. The fuzzy rules and the fuzzy coefficients need to be adjusted over and over so as to reach a good status, based on expertise. It is a fussy cut-and-try work to choose the appropriate fuzzy rules and fuzzy coefficients to achieve a relatively satisfactory control effect.

The sliding mode controller can also reach the control objective mainly, but it has longer control period and more visible undulation than fuzzy control, and these can be seen from Figure 6.

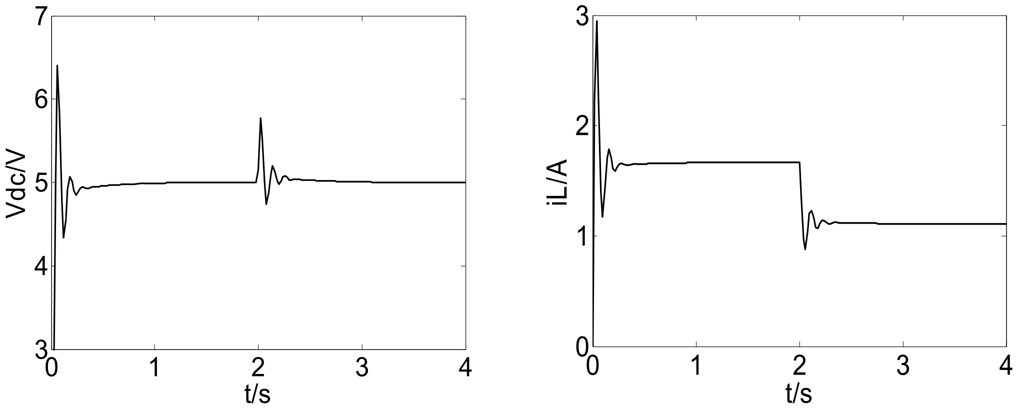


Figure 6. Simulation curves corresponding to SMC

Fuzzy sliding mode control can overcome the drawback of fuzzy control and sliding mode control meanwhile bring their predominance into play, so fuzzy SMC can give a more satisfied control effect, and this can be seen from Figure 7.

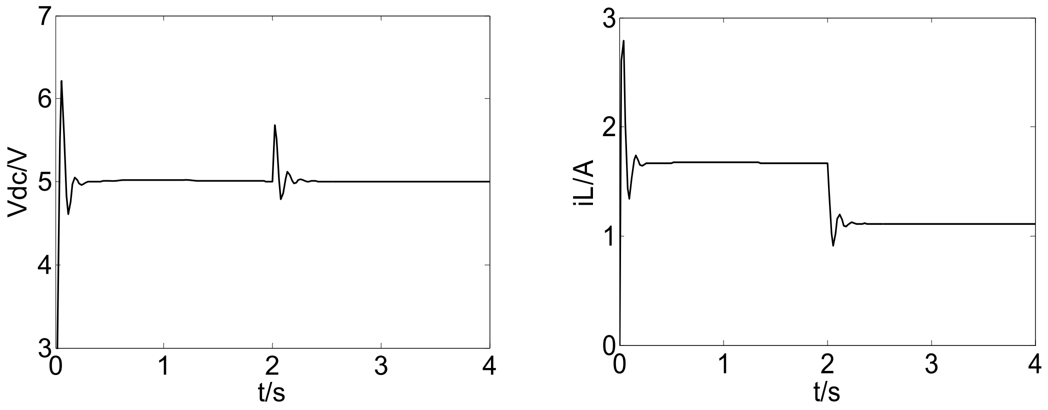
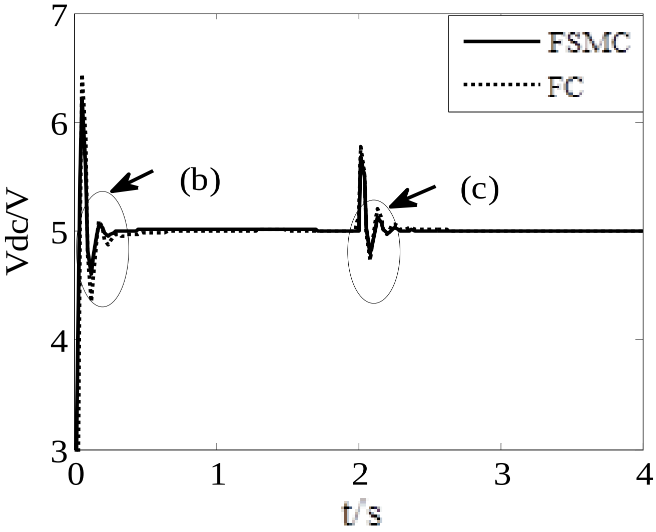


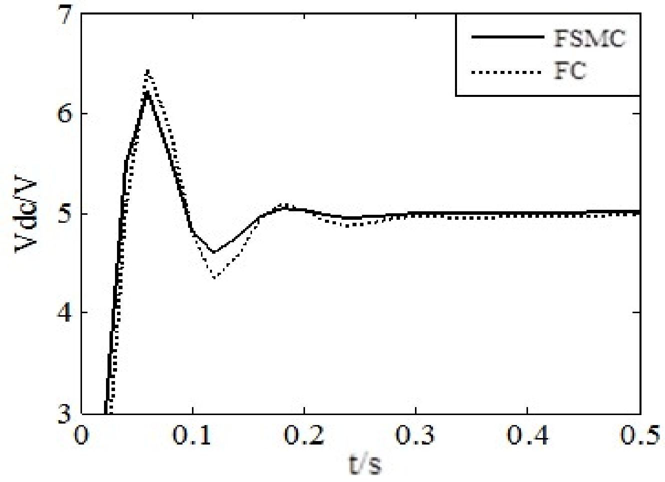
Figure 7. Simulation curves corresponding to fuzzy SMC

To show a more intuitionistic contradistinction, compared curves between fuzzy control and fuzzy sliding mode control are given in Figure 8, in which (a) shows the curves of the output voltage compared fuzzy control with fuzzy SMC, (b) and (c) shows the curves of the output voltage in the initialization phase and in the disturbance stage separately.

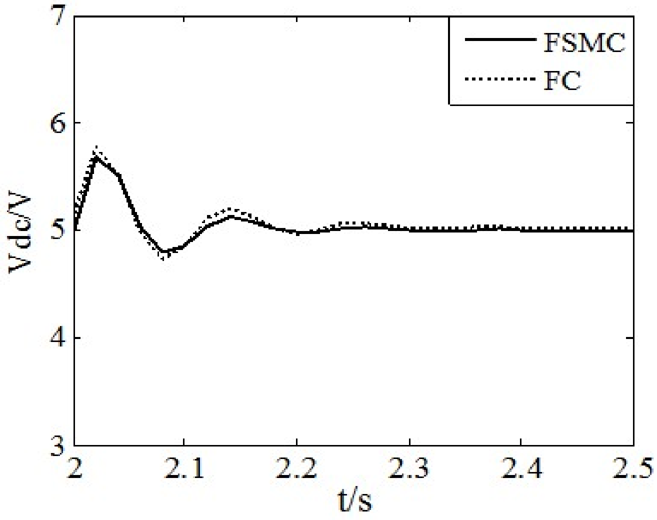
Table 3 shows some compared performance indexes of fuzzy control and fuzzy sliding mode control. Both setting time and overshoot are compared. The comparison shows that fuzzy sliding mode control is superior to fuzzy control in setting time and overshoot.



(a) output voltage



(b) voltage in initialization phase



(c) voltage in disturbance stage

Figure 8. Compared curves between fuzzy control and fuzzy SMC

Table 3. Comparison of FC and FSMC

Control Method	R=5 Ω		R=10 Ω	
	Setting time(s)	Overshoot(%)	Setting time(s)	Overshoot(%)
FC	0.5	20	0.4	10
FSMC	0.3	10	0.2	8

5. Conclusion

A Fuel Cell/DC-DC Converter System is a promising renewable electrical power source for both stationary and mobile applications. The fuzzy sliding mode control proposed in this paper can not only have fast response characteristic, but also have good steady-state behavior and strong robustness. The suitable control scheme for the integrated system of fuel cell and boost DC-DC converter can get satisfactory results in tracking a given voltage and make the fuel cell system integrated DC-DC converter output a required constant voltage.

Acknowledgements

This work was supported by the National Natural Science Foundation of China under Grant 61143007, the National Key Technology Research and Development Program of China under Grant 2012BAF09B01, and the Science and Technology Research Project of Liaoning Education Department of China under Grant L2012140.

References

[1] Frumkin H, Hess J, Vindigni S. Energy and Public Health: The Challenge of Peak Petroleum. *Public Health Reports*. 2009; 124(1): 5–19.
[2] Logan BE. Scaling up Microbial Fuel Cells and Other Bioelectrochemical Systems. *Applied Microbiology and Biotechnology.* 2010; 85(6): 1665–1671.
[3] Fan LP, Liu Y, Li C. Fuzzy Logic based Constant Voltage Control of PEM Fuel Cells, *TELKOMNIKA.* 2012; 10(4): 612–618.
[4] Gencoglu MT, Ural Z. Design of a PEM fuel cell system for residential application. *International Journal of Hydrogen Energy.* 2009; 34(12): 5242–5248.
[5] Peighambardoust SJ, Rowshanzamir S, Amjadi M. Review of the proton exchange membranes for fuel cell applications. *International Journal of Hydrogen Energy.* 2010; 35(17): 9349–9384.
[6] Wee JH. Applications of proton exchange membrane fuel cell systems. *Renewable and Sustainable Energy Reviews*. 2007; 11(8): 1720–1738.
[7] Kirubakaran A, Jain S, Nema RK. A review on fuel cells echnologies and power electronic interface. *Renewable and Sustainable Energy Reviews.* 2009; 13(9): 2430–2440.
[8] Rezazadeh A, Sedighizadeh M, Karimi M. Proton Exchange Membrane Fuel Cell Control Using a Predictive Control Based on Neural Network. *International Journal of Computer and Electrical Engineering.* 2010*;* 2(1): 81–85.
[9] Boiko IM. *Analysis of Chattering in Sliding Mode Control Systems with Continuous Boundary Layer Approximation of Discontinuous Control*. 2011 American Control Conference*.* San Francisco. 2011: 757-762.
[10] Sala A, Guerra T, Babuska R. Perspectives of Fuzzy Systems and Control. *Fuzzy Sets and Systems.* 2005; 156(3): 432–444.
[11] Nhivekar GS, Nirmale SS, Mudholker RR. Implementation of fuzzy Logic Control Algorithm in Embedded Microcomputers for Dedicated Application. *International Journal of Engineering, Science and Technology.* 2011; 3(4): 276–283.
[12] Atia DM, Fahmy FH, Ahmed NM, Dorrah HT. Modeling and Control PV-Wind Hybrid System Based On Fuzzy Logic Control Technique. *TELKOMNIKA*. 2012; 10(3): 431-441.
[13] Han H, Su CY. Robust fuzzy control of nonlinear systems using shape-adaptive radial basis functions. *Fuzzy Sets and Systems.* 2002; 125(1): 23–38.
[14] Guo J, Chiu FC, Huang CC. Design of a sliding mode fuzzy controller for the guidance and control of an autonomous underwater vehicle. *Ocean Engineering.* 2003; 30(16): 2137–2155.
[15] Carnes B, Djilal N. Systematic Parameter Estimation for PEM Fuel Cell Models. *Journal of Power Sources.* 2005; 144(1): 83–93.
[16] Abdous F. Fuel Cell/DC-DC Convertor Control by Sliding Mode Method. *World Academy of Science, Engineering and Technology.* 2009; 25: 1012–1017.

[17] Moreira MV, Silva GE. A Practical Model for Evaluating the Performance of Proton Exchange Membrane Fuel Cells. *Renewable Energy.* 2009; 34(7): 1734–1741.

[18] Youssef ME, Nadi KE, Khalil MH. Lumped Model for Proton Exchange Membrane Fuel Cell (PEMFC). *International Journal of Electrochemical Science*. 2010; *5*: 267–277.

[19] Fan LP. Simulation Study on the Influence Factors of Generated Output of Proton Exchange Membrane Fuel Cell. *Applied Mechanics and Materials*. 2012; 121-126: 2887–2891.

[20] Correa JM, Farret FA, Canha LN, Simoes MG. An Electrochemical-Based Fuel-Cell Model Suitable for Electrical Engineering Automation Approach. *IEEE Transactions on Industrial Electronics*. 2004; 51(5): 1103–1112.

[21] Suh KW, Stefanopoulou AG. Coordination of converter and fuel cell controllers. International Journal of Energy Research. 2005; 29(12): 1167–1189.