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Adaptive Fuzzy Control of a Fuel Cell/DC-DC Convertor System

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Abstract: Maintaining a fuel cell system in a correct operating status requires good system control. An adaptive fuzzy control scheme is proposed in this study for the fuel cell/DC-DC converter system to realize constant voltage output under different loads. PID controller and fuzzy controller are used to compare with the proposed adaptive fuzzy controller. Simulation results show that the adaptive fuzzy controller can provide attractive control effects such as faster response characteristic and better steady-state behavior.

Key words: Fuel cells, DC-DC converter, adaptive, fuzzy control, constant voltage

INTRODUCTION

Energy resources are significant foundation for human existence and development (Zhao, 2008; Kilic, 2011). It is well known that conventional fossil fuels are gradually exhausted. Furthermore, the negative impacts brought on by fossil fuels are immeasurable. Hence, major efforts are devoted to the discovery of alternative energy resources and to the solution of energy shortage and environmental pollution (Frumkin *et al.*, 2009; Logan, 2010).

Fuel cells are new-type electricity production systems with high effective utilization rate that produce electrical currents with almost null pollutant emissions (Gencoglu and Ural, 2009). Proton exchange membrane fuel cell (PEMFC) is one of the most interesting fuel cells types due to its low operating temperature, high efficiency and low electrolyte corrosion and it attracts more and more attention currently (Kunusch *et al.*, 2009; He and Jin, 2012).

Fuel cell systems couldn't be leaded to acceptable responses by using traditional controllers as a result of its time-change, uncertainty, strong-coupling and nonlinear characteristics. So an intelligent or adaptive controller is needed (Williams *et al.*, 2008). Fuzzy logic control features such valuable merits as universal approximation theorem, rule-based algorithm and robustness with respect to plant parameter uncertainties (Galzina *et al.*, 2008; Corcau, *et al.*, 2007). However, the price being paid for that of an undesirable phenomenon called steady-state error and it relies on experience excessively. Adaptive control is considered to be a useful tool for reducing steady-state error because of its capability of seeking the optimal control parameters automatically to resist load disturbance. Adaptive fuzzy control utilizes fuzzy control to overcome the influence of plant parameter uncertainties and utilizes adaptive control to decrease steady-state error caused by fuzzy control. Therefore it improves rapidity and stationary in dynamic response of the system and it is an effective method to solve complex industrial process control

In this study, an adaptive fuzzy controller was designed for a fuel cell system to achieve constant voltage output.

DYNAMIC MODEL OF THE SYSTEM

Electrochemical process of PEMFC starts on the anode side where H_2 molecules are brought by flow plate channels. On the anode, hydrogen divides into hydrogen protons H^+ and electrons e^- by anode catalyst. Proton H^+ travel to cathode through membrane while electron e^- travel to cathode over external electrical circuit. On the cathode, hydrogen proton H^+ and electron e^- combine with oxygen O_2 attached on the cathode surface by use of catalyst, to form water H_2O and heat. Described reactions can be expressed by the following equations (Carnes and Djilali, 2005; Moreira and da Silva, 2009; Youssef *et al.*, 2010).

$$H2 \rightarrow 2H^+ 2e^- (\text{Anode}) \tag{1}$$

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

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{heat} + \text{electricity} \quad (\text{Total}) \tag{3}$$

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The output voltage V_{fc} of a single cell can be described as:

$$V_{fc} = E_{nernst} - V_{act} - V_{ohmic} - V_{con} \tag{4}$$

where, E_{nernst} is the thermodynamic potential of fuel cell representing its reversible voltage and its expression is:

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

where, P_{H2} and P_{O2} (atm) are pressures of hydrogen and oxygen, respectively and T_{fc}(k) is the operating temperature of fuel cells. V_{act} in Eq. 4 is the voltage drop due to the activation of the anode and the cathode which can be described as:

$$V_{act} = 0.9514 - 3.12\times10^{-3}T_{fc} - 7.4\times10^{-5} T_{fc}\ln(C_{O_2}) + 1.87\times10^{-4}T_{fc}\ln(i) \tag{6}$$

where, i(A) is the electrical current of fuel cell and C_{O2} is the oxygen concentration. V_{ohmic} in Eq. 4 is the ohmic voltage drop associated with the conduction of protons through the solid electrolyte and electrons through the internal electronic resistance and this is given by:

$$V_{ohmic} = i(R_M + R_C) \tag{7}$$

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

$$R_M = \frac{\rho_M \cdot l}{A},\qquad \rho_M = \frac{181.6\left[1 + 0.03\left(\frac{i}{A}\right) + 0.062\left(\frac{T_{fc}}{303}\right)^2\left(\frac{i}{A}\right)^{2.5}\right]}{\left[\psi - 0.634 - 3\left(\frac{i}{A}\right)\right]\exp\left[4.18\left(\frac{T_{fc}\text{-}303}{T_{fc}}\right)\right]} \tag{8}$$

where, $\rho_M(\Omega.cm)$ is the membrane specific resistivity for electron flow, l(cm) is the thickness of membrane, A (cm^2) is the active area of membrane, ψ is the specific coefficient for every type of membrane. V_{con} in Eq. 4 references the voltage drop resulting from the mass transportation effects which affects the concentration of the reacting gases and can be calculated by the following expression:

$$V_{con} = \text{-}B\ln\left(1 - \frac{i}{i_{max}}\right) \tag{9}$$

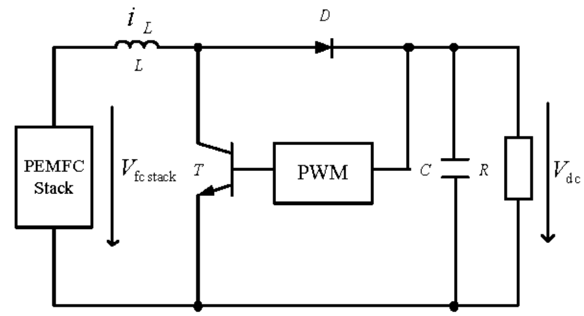

Fig. 1: Fuel cell stack/DC-DC converter system

where, B (V) is a parametric coefficient depending on the type of fuel cell, i_{max} is the maximum electrical current. To obtain the desired amount of electrical power, individual PEM fuel cells are combined to form a PEMFC stack. Based on the mathematical model of a single fuel cell, a PEMFC stack can be set up and its output voltage can be described as:

$$V_{fc\ stack} = n_{fc}\, V_{fc} \tag{10}$$

where, n_{fc} is the number of the single fuel cell in the PEMFC stack. According to the above described mathematical model, a simulation model of PEMFC based on MATLAB/SIMULINK can be set up (Fan, 2012).

A circuit model of the fuel cell system consisting of fuel cell stack and DC-DC converter is shown in Fig. 1.

The output voltage of the fuel cell stack is $V_{fc\ stack}$ and the output voltage of the boost DC-DC converter is V_{dc}. The dynamics of the boost DC-DC converter can be calculated by the following system of bilinear differential equations (Suh and Stefanopoulou, 2005):

$$\begin{aligned} \frac{dV_{dc}}{dt} &= \frac{1-d}{C}i_L - \frac{V_{dc}}{RC} \\ \frac{di_L}{dt} &= \frac{V_{fc\ stack}}{L} - \frac{1-d}{L}V_{dc} \end{aligned} \tag{11}$$

where, d is the duty ratio of the switch T.

Simulation model of a boost DC-DC converter can be set up and integrated with the simulation model of the fuel cell stack based on the above described mathematical model.

DESIGN AN ADAPTIVE FUZZY CONTROLLER

The structure of the closed-loop adaptive fuzzy control system is designed as shown in Fig. 2. In order

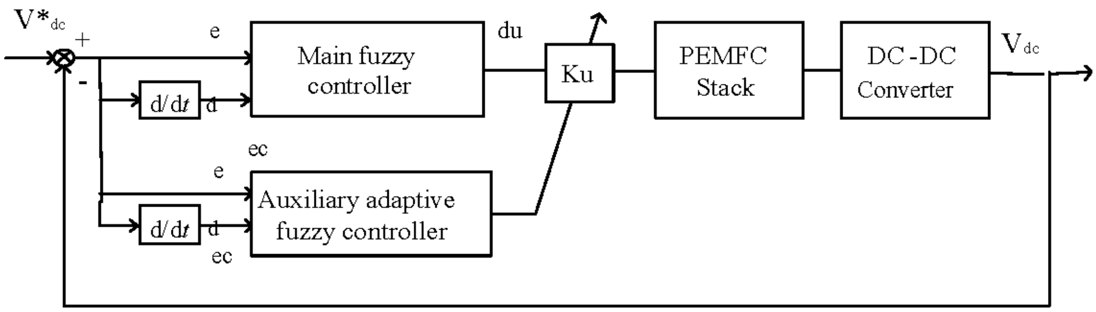

Fig. 2: Closed-loop adaptive fuzzy control system

to make the boost DC-DC converter keep constant voltage output with fast response characteristic and good steady-state behavior when subjected to fast load changes, the control input is adjusted by using a main fuzzy controller according to the error and the change of the error and an auxiliary adaptive fuzzy controller is applied to adjust the proportionality factor of the main fuzzy controller to weaken the steady-state error caused by the fuzzy control method.

The control purpose is to keep the output voltage V_{dc} equal to the given output voltage V^*_{dc}. In order to obtain the satisfactory control effect, the error e(k) and the change of error ec(k) are used as the dual input of the main fuzzy controller. e(k), ec(k) and the control output u(k) of the main fuzzy controller are given as:

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

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

$$u(k) = u(k-1)+du(k) \tag{14}$$

Here, du(k) is the inferred change of duty ratio given by the main fuzzy controller.

The triangular type membership functions are chosen for the error, the change of the error and the change of the output control. The fuzzy domain for e, ec is [-1, 1] and for du is [0, 10]. The fuzzy set for e is {NB, NS, ZE, PS, PB} and for ec and du is {NB, NM, NS, ZE, PS, PM, PB}. The output control u of the main fuzzy controller is designed as q_{O2}, the fuzzy control rule base of the main fuzzy controller is shown in Table 1.

For the purpose of reducing the steady-state error caused by the main fuzzy controller, an auxiliary adaptive fuzzy controller with dual inputs is designed to adjust the proportionality factor K_u of the main fuzzy controller. The inputs of the auxiliary adaptive fuzzy controller are still e and ec, the control output K_u of the auxiliary adaptive fuzzy controller is given as:

Table 1: Rules of main fuzzy controller

		e						
du		NB	ZM	NM M S	ZE	PS	PM	PB
ec	NB	ZE	ZE	ZE	NB	ZE	ZE	ZE
	NS	ZE	ZE	ZE	NS	ZE	ZE	ZE
	ZE	NB	NM	NS	ZE	PS	PM	PB
	PS	ZE	ZE	ZE	PS	ZE	ZE	ZE
	PB	ZE	ZE	ZE	PB	ZE	ZE	ZE

Table 2: Rules of auxiliary fuzzy controller

		e						
dK_u		NB	NM	NS	ZE	PS	PM	PB
ec	NB	NB	NB	NB	NB	NM	NS	ZE
	NM	NB	NB	NB	NM	NS	ZE	PS
	NS	NB	NB	NM	NS	ZE	PS	PM
	ZE	NB	NM	NS	ZE	PS	PM	PB
	PS	NM	NS	ZE	PS	PM	PB	PB
	PM	NS	ZE	PS	PM	PB	PB	PB
	PB	ZE	PS	PM	PB	PB	PB	PB

$$K_u(k) = K_u(k-1) + dK_u(k) \tag{15}$$

and dK_u is the inferred change of duty ratio given by the auxiliary adaptive fuzzy controller.

The triangular type membership function is chosen for the change of the output control variable. The fuzzy domain for dK_u is [-1, 1]. The fuzzy set for dK_u is {NB, NM, NS, ZE, PS, PM, PB}. The fuzzy control rule base of the auxiliary adaptive fuzzy controller is shown in Table 2.

SIMULATION AND ANALYSIS

In order to verify the control effect of the designed control scheme, simulation based on the above mentioned model was implemented in the simulation platform of Matlab/simulink. The reference setting output voltage of the DC-DC converter is 120 V. The load changes from 20-30Ω at the time of 5 sec.

The output of the fuel cell system cannot maintain a constant voltage without control and this can be seen from Fig. 3. The output voltage deviates from the reference setting steady value markedly.

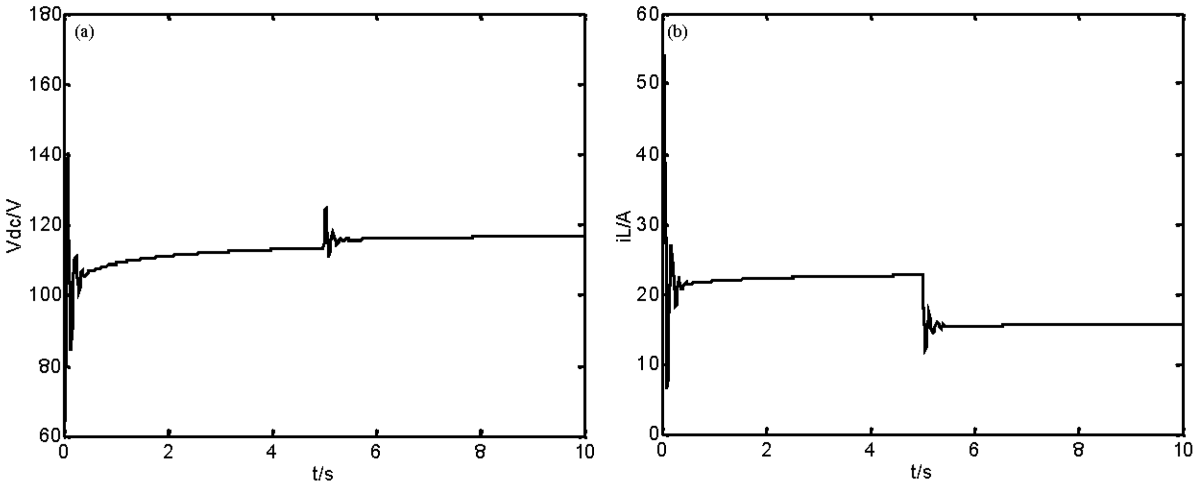

Fig. 3(a-b): Simulation results of uncontrolled system

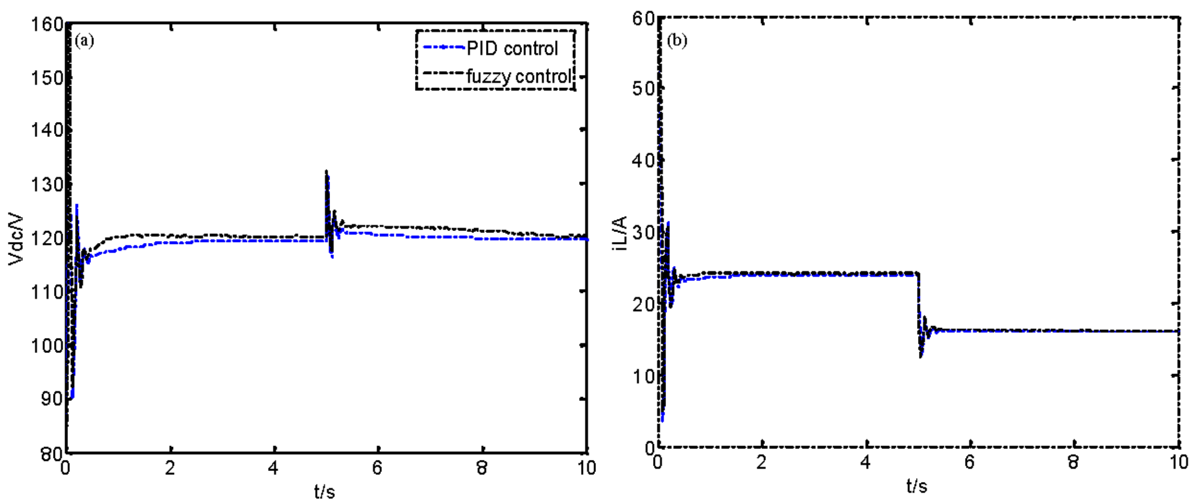

Fig. 4(a-b): Simulation results compared fuzzy control with PID control

For assessing the performance and accuracy of the adaptive fuzzy control method, three kinds of controllers, including PID control, fuzzy control and adaptive fuzzy control, are designed and compared. For the PID control scheme, the quantifying factors are $K_P = 800$, $K_I = 0.1$ and $K_D = 2$. For the fuzzy control scheme, the quantifying factors are $K_e = 1000$, $K_{ec} = 0.001$ and $K_u = 10$. For the adaptive fuzzy control scheme, the quantifying factors of the main fuzzy controller are $K_e = 1000$, $K_{ec} = 0.001$ and K_u is adjusted by the auxiliary adaptive fuzzy controller online. The factors of the auxiliary fuzzy controller change along with the load. When the load is 20 Ω, $K_e = 10$, $K_{ec} = 0.01$, $K_u = 40$; when the load turns to 30 Ω, $K_e = 10$, $K_{ec} = 0.01$, $K_u= 420$. Simulation results compared between these three control schemes are shown in Fig. 4-5.

PID controller can make system output a constant voltage basically, but it gives a long control period and these can be seen from Fig. 4. Also, it is an uphill work to determine the suitable PID parameters.

The fuzzy controller can achieve an elementary control effect and this can be seen from Fig. 4. Before the disturbance emerges, the fuzzy controller can make the system track the given voltage quickly and the tracking error is small. However, when disturbance appears, the output voltage shows obvious deviation. The simple fuzzy controller does not have the ability of self-adapting and anti-interference.

For the purpose of reaching a satisfactory control effect, the fuzzy coefficients need to be adjusted along with load. Adaptive fuzzy control can overcome the

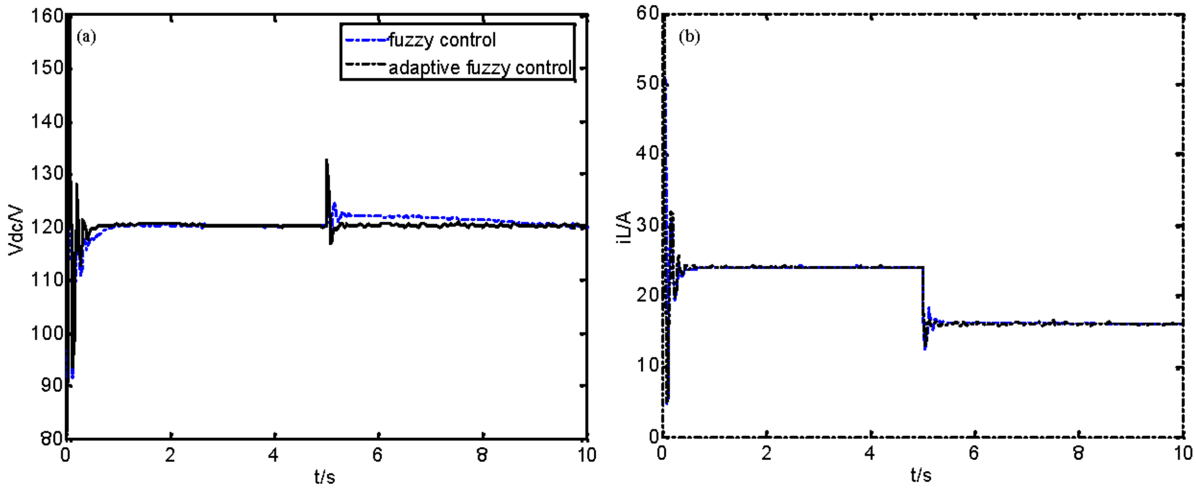

Fig. 5(a-b): Simulation results compared adaptive fuzzy control with fuzzy control

drawback of fuzzy control, so the better steady-state behavior can be integrated with the faster response characteristic and this can be seen from Fig. 5. The output voltage shows faster response speed, tinier fluctuation and less steady error. Adaptive fuzzy control can make the fuel cell stack/DC-DC converter system track setting output voltage well.

CONCLUSION

The adaptive fuzzy controller for the fuel cell system presented in this study can make the system keep the constant voltage output even in the condition of load disturbance. The adaptive fuzzy controller is able to adapt the fuzzy parameters for strong robustness and insensitive to variations in external disturbances and is superior to PID controller and fuzzy controller in response characteristic and steady-state behavior. In the next work, the adaptive fuzzy controller will be carried out in a real fuel cell system.

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