Research Journal of Applied Sciences, Engineering and Technology 5(3): 1059-1063, 2013
DOI:10.19026/rjaset.5.5063
ISSN: 2040-7459; E-ISSN: 2040-7467

Submitted: June 29, 2012 Accepted: July 24, 2012 Published: January 21, 2013

Research Article

Fuzzy Sliding Mode Control with Constant Power Control for a Proton Exchange Membrane Fuel Cell

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Abstract: Proton exchange membrane fuel cells have been causing attention because of theirs many advantages. In order to maintain good working condition good controller is required. In this study, the mathematical model for proton exchange membrane fuel cell is developed. Then combining the characteristics of fuzzy control and sliding mode control fuzzy sliding mode controller is designed. The controller can realize constant power output and improve stability by fuzzy reasoning to control the amount of output variation that effectively reduces chattering. Simulation results show that the proposed controllers can obtain better control effect compared with fuzzy controller.

Keywords: Constant power, fuel cell, fuzzy control, sliding mode control

INTRODUCTION

Fuel cell is a device capable of converting chemical energy from a fuel into electrical energy through a chemical reaction with oxygen or another oxidizing agent. In recent years, as one of the most popular kind of fuel cells the Proton Exchange Membrane Fuel Cell (PEMFC) has many 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.*, 2002; Hatziadoniu *et al.*, 2002; Padulles *et al.*, 2000). Unlike conventional fuel cells, PEMFC has many advantages including low temperature, low electrolyte corrosion, high efficiency (Pukrushpan *et al.*, 2004).

The PEMFC needs to be controlled rapidly and efficiently in correct operating conditions. 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 affect the performance of PEMFC (Riascos and Pereira, 2010). Many research studies such as many linear controllers have been carried out on proton exchange membrane fuel cell technology. However, the complex and nonlinear dynamics of PEMFC make it hard to maintaining a fuel cell system in correct operating conditions when subjected to fast load changes (Kaytakoglu and Akyalm, 2007).

Variable structure control with sliding mode as one of the effective nonlinear robust control approaches was first introduced in the 1950s. It can yield a closed loop system with an invariance property to uncertainties when the system states are on the sliding mode (Edwards and Spurgeon, 1998; Kaynak *et al.*, 2001). Sliding mode controller has been used in wide range areas. However, several disadvantages exist for pure sliding mode controller. One is chattering problem which caused the high frequency oscillation in the controller output. Another is that controller design depends on the dynamic equation.

Fuzzy logic can express the amount of ambiguity in human thinking and possess several advantages such as robustness, model-free, universal approximation theorem (Poursamad and Montazeri, 2007; Nhivekar *et al.*, 2011; Corcau and Stoenescu, 2007; Horiuchi and Kishimoto, 2002). In the past several decades, fuzzy control has been used in many applications. However, the huge amounts of fuzzy rules for a high-order system make the analysis complex. At the same time, the fuzzy controller parameters must go through repeated attempts to determine and be the lack of the stability analysis.

In many cases constant power sources are needed. Therefore keeping a PEMFC output a constant power during work process should be sometimes necessary. The mathematical model for a typical proton exchange membrane fuel cell is described in this study and a fuzzy sliding mode controller for PEMFC is designed to maintain a constant power of PEMFC under load disturbance.

MODEL OF PEM FUEL CELL

PEM fuel cells transform chemical energy on the anode side into electric and thermal energy on the cathode side. Figure 1 shows the basic structure of a single cell.

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In PEM fuel cell the following chemical reaction exists:

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

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 *et al.*, 2005; Moreira and Silva, 2009; Rezazadeh *et al.*, 2010; Youssef *et al.*, 2010):

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

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

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.

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

$$V_{FC} = E_{Nernst} - V_{act} - V_{ohmic} - V_{con} \quad (4)$$

where, E_{Nernst} is the thermodynamic potential of the cell and represents its reversible voltage:

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

In which 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:

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

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:

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

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

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

Here R_c (Ω) is the resistance to electron flow and R_m (Ω) is the resistance to proton transfer through the membrane.

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

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

where, B(V) is a parametric coefficient depending on the cell, J(A/cm^2) is the actual current density of the cell (Rezazadeh *et al.*, 2011).

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

$$P_{FC} = V_{FC}I_{stack} \quad (10)$$

Fuel cell dynamic model can be set up based on the above described mathematical model (Fan, 2012; Correa *et al.*, 2004). An accepted dynamic model of the PEM fuel cell is shown in Fig. 2. q_{O2} is the input molar flow of hydrogen, q_{H2} is the input molar flow of oxygen, K_{H2} is the hydrogen valve molar constant and K_{O2} is oxygen valve molar constant.

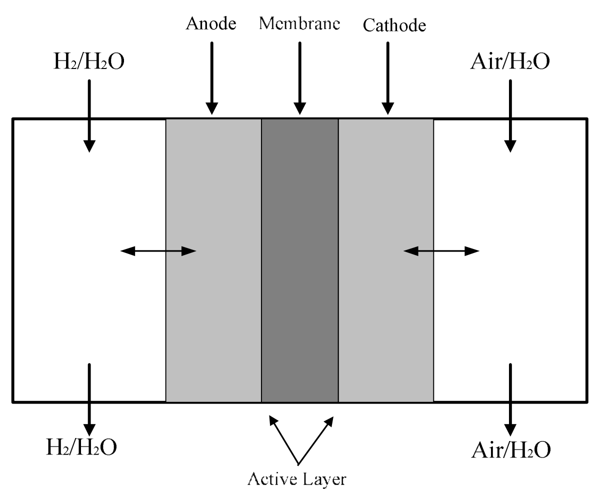

Fig.1: A typical PEM fuel cell

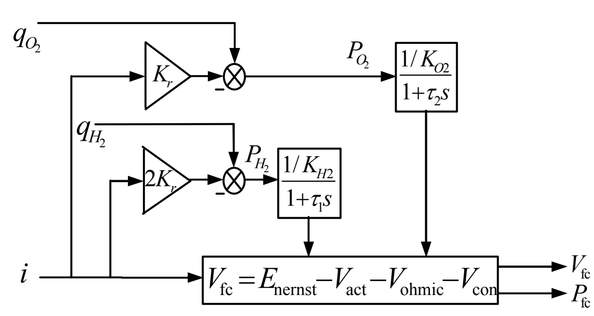

Fig. 2: PEMFC dynamic model

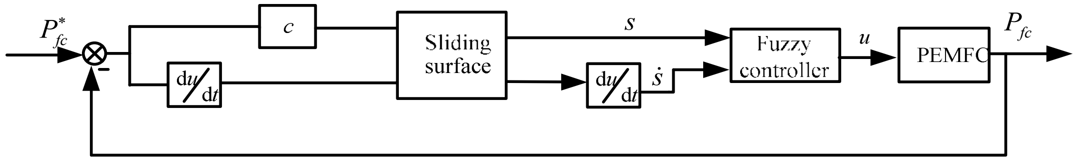

Fig. 3: The closed-loop fuzzy control system

DESIGN OF FUZZY SLIDING MODE CONTROLLE

In order to overcome the parameter uncertainty and external disturbance, a fuzzy sliding mode control is presented. The algorithm adjusts the control of variable size by fuzzy control rules based on the previous experience. The fuzzy control in the algorithm can lessen the chattering problem of sliding mode control. The configuration of a closed-loop fuzzy sliding mode controller is shown in Fig. 3. The proposed controller can make the PEM fuel cell keep constant power output 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:

$$s = \{NB, NS, ZO, PS, PB\}$$

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

Table 1: Fuzzy control rules

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

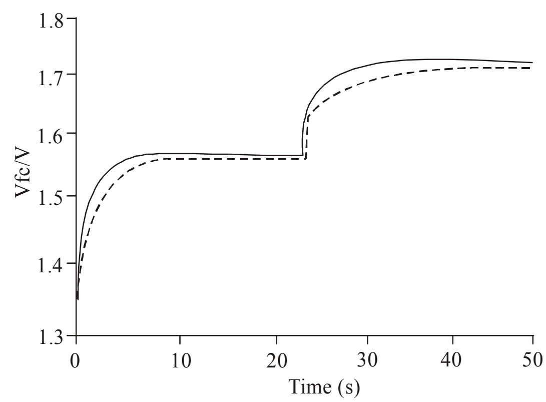

Fig. 4: Output voltage controlled by adjusting oxygen flow

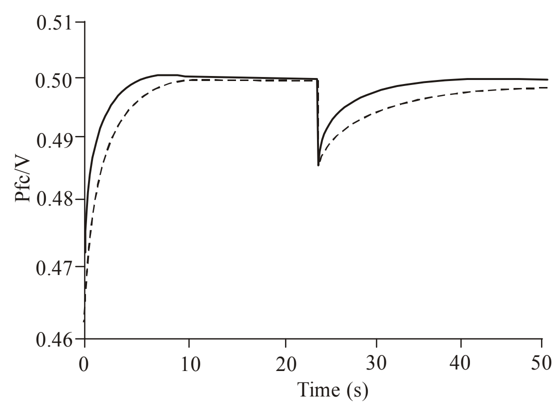

Fig. 5: Output power controlled by adjusting oxygen flow

$$\Delta U = \{NB, NM, NS, ZO, PS, PM, PB\}$$

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 rule base is shown in Table 1.

SIMULATION RESULTS

In order to verify the validity of the proposed fuzzy sliding mode controller, simulation results have been carried out. Output power is controlled by adjusting the oxygen flow. The reference output power of the fuel cell is 0.5 W. There is a change in the load from 5 Ω to 6 Ω at the time of 25s. Simulation results are shown in Fig. 4 and 5. In the following figures the solid line represents the fuzzy sliding mode control and the dotted line represents the fuzzy control proposed in Fan (2012).

It can be seen from Fig. 4: when the load is 5, fuzzy control with a rise time of 11.8s reaches 1.58v and fuzzy sliding mode control with the 6s reaches 1.58v. When the load changes into 6, fuzzy control with a rise time of 19s reaches 1.72v and fuzzy sliding mode control with the 14.4s reaches 1.73v.

In Fig. 5, output power of fuzzy control is about 0.5 W in 11s and output power of fuzzy sliding mode control reaches 0.5 W in about 5.1s. When the load changes, output power is about 9s to steady state under fuzzy control while it is about 24s to steady state using fuzzy sliding mode control. At the same time using fuzzy mode control there is a smaller overshoot and system reaches final value more quickly than that using the fuzzy control.

Obviously, simulations validate that the fuzzy sliding mode controller is characterized by a faster time response and higher precision compared to the fuzzy controllers.

CONCLUSION

Fuel cells need constant power output when load changes. The fuzzy sliding mode control proposed in this study can not only have fast response characteristic, but also have good steady-state behavior and strong robustness compared with fuzzy control, Simulation results indicate that the fuzzy sliding mode controller is very effective to realize constant power output.

ACKNOWLEDGMENT

This study is supported by the National Natural Science Foundation of China (No. 61143007) and the National Science and Technology Support Projects of China (No. 2012BAF09B01).

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