Liping FAN[1], Yi LIU[2]

Shenyang University of Chemical Technology, China (1), North Heavy Industry Group Co., Ltd , China (2)

Fuzzy Logic Based Constant Power Control of a Proton Exchange Membrane Fuel Cell

***Abstract**. Proton exchange membrane fuel cells have been receiving more and more attention these recent years. Maintaining a fuel cell system in correct operating conditions requires good system control. The mathematical model of proton exchange membrane fuel cells is described in this paper and a simulation platform is set up, and then the fuzzy logic controller is designed for the proton exchange membrane fuel cell to realize constant power output. Simulation results show that the use of the proposed fuzzy controllers can get good control effects.*

***Streszczenie.** Przedstawiono możliwości modelowania baterii wykorzystujących membranę z wymianą protonową. Zastosowano kontroler wykorzystujący logikę rozmytą dla sterowania mocą wyjściową. (Sterowanie baterią z membraną o wymianie protonowej z wykorzystaniem logiki rozmytej)*

Keywords: fuel cell; fuzzy control; constant power
Słowa kluczowe: logika rozmyta, baterie protonowe

Introduction

The world is facing an energy crisis as well as significant environmental problems. It is well known that fossil fuels such as petroleum, natural gas and coal are the main resources for generating electricity. However, they also have been major contributors to environmental problems. Major efforts to reduce greenhouse gas emission have increased the demand for pollution-free energy sources. Renewable bioenergy is viewed as one of the ways to alleviate the current global warming crisis. Major efforts are devoted to developing alternative electricity production methods [1, 2].

Fuel cells are promising energy sources that produce electrical currents with almost null pollutant emissions. Fuel cell technology plays an important role in the development of alternative energy. In the recent years there was an increasing interest in fuel cell technology. One of the most interesting fuel cells types is the proton exchange membrane fuel cell (PEMFC) due to its high efficiency [3], and it is one of the promising technologies for power generation in future [4].

The fuel cells are replacing the batteries and in the current trend are becoming the most widely used resources. Fuel cells are finding use in every aspect because of their clean and efficient way of supplying electric power. PEMFCs can serve as an emergency source of energy in the event of a long-term power outage. The PEMFCs are used in the standalone purposes at homes, hospitals, industries and now are finding their use in numerous vehicles.

The performance of PEMFC, being important and getting more and more attention in recent years, is known to be influenced by many parameters such as operating temperatures both fuel cell and humidifiers, pressure, flow rates and relative humidity of fuel and oxidant gases [5]. Significant improvements in proton exchange membrane (PEM) fuel cell technology have been achieved over the past decade. However, the performance, stability, reliability, and cost for the present fuel cell technology are not enough to replace internal combustion engines. A number of fundamental problems must be overcome to improve their performances and reduce their cost [6].

Maintaining a fuel cell system in correct operating conditions when subjected to fast load changes requires good system control. The complex and nonlinear dynamics of the fuel cell make it a difficult task to design a good control system. Fuzzy logic can capture the continuous nature of human decision processes and as such is a definite improvement over methods based on binary logic [7]. Fuzzy control 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 [8]. The techniques of fuzzy logic control have been used in many applications successfully [9, 10]. It is an effective method to solve complex industrial process control.

Constant power sources are needed on many occasions. So, making a PEMFC output a constant power during a run is sometimes necessary. A single proton exchange membrane fuel cell model was built in this paper and a fuzzy logic controller for PEMFC was designed to control the PEMFC to resist load disturbance and maintain a constant output voltage.

This paper is organized as follows. The mathematical model for a typical proton exchange membrane fuel cell is described in Section 2. Section 3 presents a brief description of designing a fuzzy logic power controller for PEMFC. 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.

Model of PEM fuel cell

Mathematical models and simulation are needed as tools for design optimization of fuel cells. In system studies, it is important to have an adequate model to estimate overall performance of a PEM fuel cell in terms of operating conditions without extensive calculations [11].

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 [12, 13, 14]:

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

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

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

The output voltage V_{fc} of a single cell can be defined as the result of the following expression:

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

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

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

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

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

where i (A) is the electrical current, and C_{O2} 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, and its expression can be written as:

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

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

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

where ρ_M ($\Omega\cdot\text{cm}$) 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:

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

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

$$P_{fc} = V_{fc} i \tag{10}$$

A generally accepted dynamic model of the PEM fuel cell is modified and shown in Fig.1, in which q_{H_2} is the input molar flow of hydrogen, q_{O_2} is the input molar flow of oxygen, K_{H2} is the hydrogen valve molar constant, and K_{O2} is the oxygen valve molar constant, K_r is a transformation constant [15, 16].

Based on the above described mathematical model, a Matlab/Simulink simulation model of the PEMFC can be set up [17]. Parameters of the Ballard Mark V fuel cell [18] are used in the simulation model.

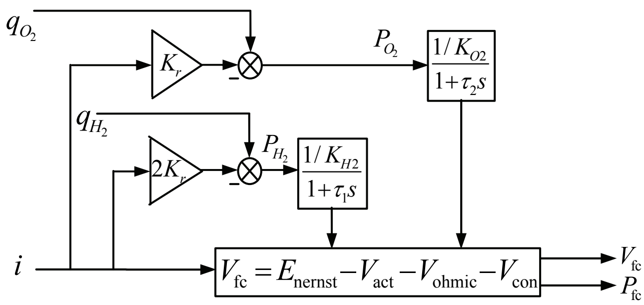

Fig.1. PEMFC dynamic model

Design of a fuzzy logic controller

On many occasions, constant power source are needed. So, control a fuel cell output a constant power is necessary. In order to make the PEM fuel cell keep constant power output, a fuzzy logic controller for constant power output is designed.

Fig.2 shows the structure of the closed-loop fuzzy control system. A fuzzy control system with dual inputs is used to control the output power of the fuel cell, where P_{fc}^* is the set point value of the output power. The error $e(k)$, the change in error $ec(k)$ and the control output $u(k)$ of the fuzzy controller are given as:

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

$$ec(k) = e(k) - e(k-1) \tag{12}$$

$$u(k) = u(k-1) + \Delta u(k) \tag{13}$$

Here $\Delta u(t)$ is the inferred change of duty ratio by fuzzy controller.

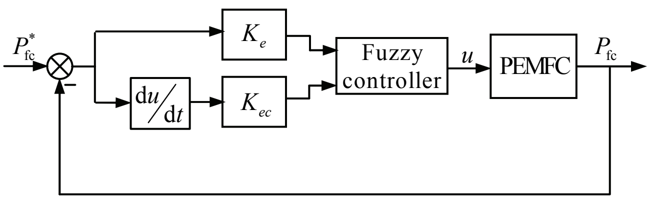

Fig.2. The closed-loop fuzzy control system

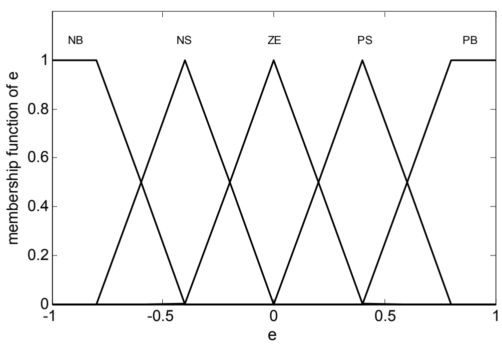

Fig.3. Membership function of the error e

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 u is [1, 10]. The fuzzy set for e is {NB, NS, ZE, PS, PB}, and for ec and u is {NB, NM, NS, ZE, PS, PM, PB}. The membership functions for input error e, change of error ec and output control u are shown in Fig.3 to Fig.5.

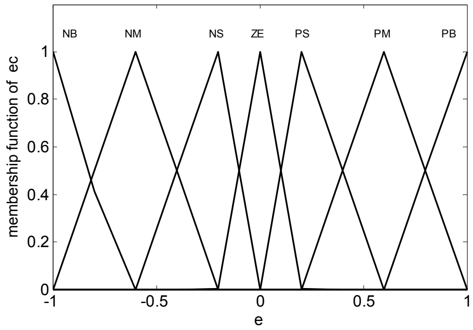

Fig.4. Membership function of the change of error ec

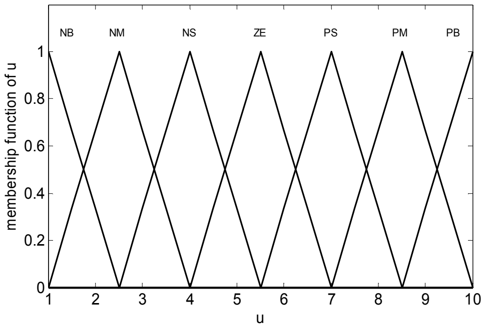

Fig.5. Membership function of the control u

In this paper, the output control u of the fuzzy controller is designed as q_{O_2}, that is the input molar flow of oxygen of the PEM fuel cell. The fuzzy control rule base is shown in Table.1, and the 3-dimensional representation of control variable u for fuzzy variables (e, ec) is shown in Fig. 6.

Table.1. Fuzzy control rules

u		*e*				
		NB	NS	ZE	PS	PB
ec	NB	ZE	ZE	NB	ZE	ZE
	NM	ZE	ZE	NM	ZE	ZE
	NS	ZE	ZE	NS	ZE	ZE
	ZE	NB	NS	ZE	PS	PB
	PS	ZE	ZE	PS	ZE	ZE
	PM	ZE	ZE	PM	ZE	ZE
	PB	ZE	ZE	PB	ZE	ZE

Simulation and results

In order to verify the validity of the proposed fuzzy controller, simulation operation was carried out in the MATLAB simulation platform. The main parameters of the PEMFC used in the simulation are shown in Table.2.

Table.2. Main parameters of the PEMFC

B [V]	A [cm^2]	T_{fc} [k]	P_{H2} [atm]	R_c [Ω]	l [cm]	ψ
0.016	50.6	343	1	0.0003	0.0178	23

The controller was designed to control the output power of the PEMFC by adjusting the oxygen flow. The reference setting output power of the fuel cell is 0.5W. The load changes from 5Ω to 6Ω at the time of 25s. In order to diminish the influence caused by load disturbance, a self-acting selector is applied to pick different quantifying factors according to the condition of loading. Simulation results are shown in Fig.7 to Fig.8. When the load is 5Ω, the quantifying factors are K_e=0.5, K_{ec}=0.001, K_u=0.9; and when the load turns to 6Ω, the quantifying factors are switched to K_e=10, K_{ec}=0.001, K_u=70.

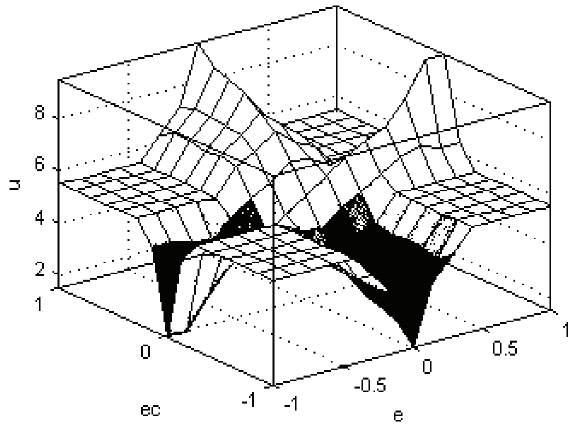

Fig.6. 3-dimensional representation of control variable u for fuzzy variables (e, ec)

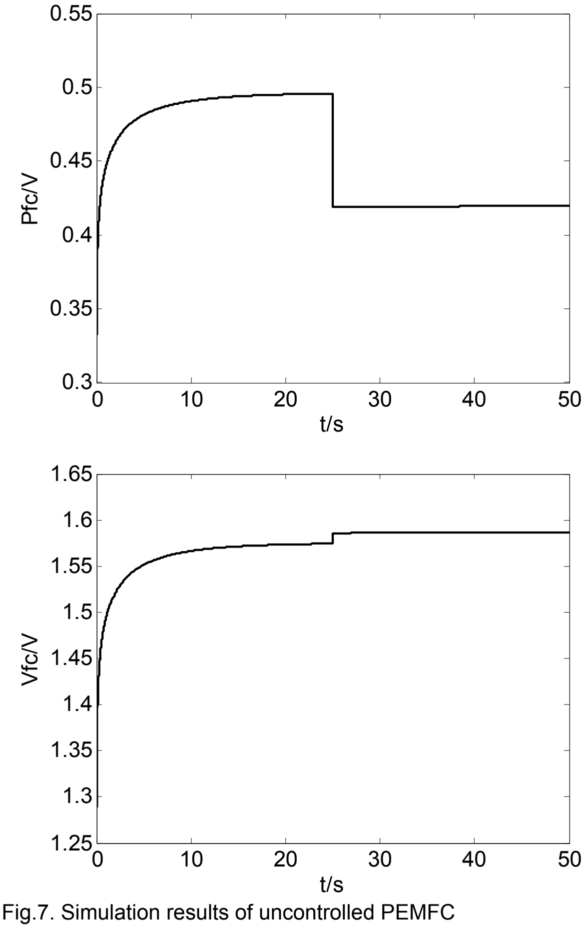

Fig.7. Simulation results of uncontrolled PEMFC

In the normal condition of no controller exists in its system, the PEMFC cannot output constant power, and this can be seen from Fig.7. When the load changed from 5Ω to 6Ω, the output power jumped obviously. While if the fuzzy control is applied to the PEMFC, the output power can keep constant well, and this can be seen from Fig.8. The steady tracking error approaches zero. Fuzzy control can make the fuel cell track setting power well.

Conclusions

Proton exchange membrane fuel cells which need to keep the output power invariable require good control systems. By using fuzzy logic controller, the fuel cell can not only have fast response characteristic, but also have good steady-state behavior and strong robustness. The suitable fuzzy logic control schemes can get satisfactory results in tracking a given power and guarantee that the fuel cells have constant power outputs.

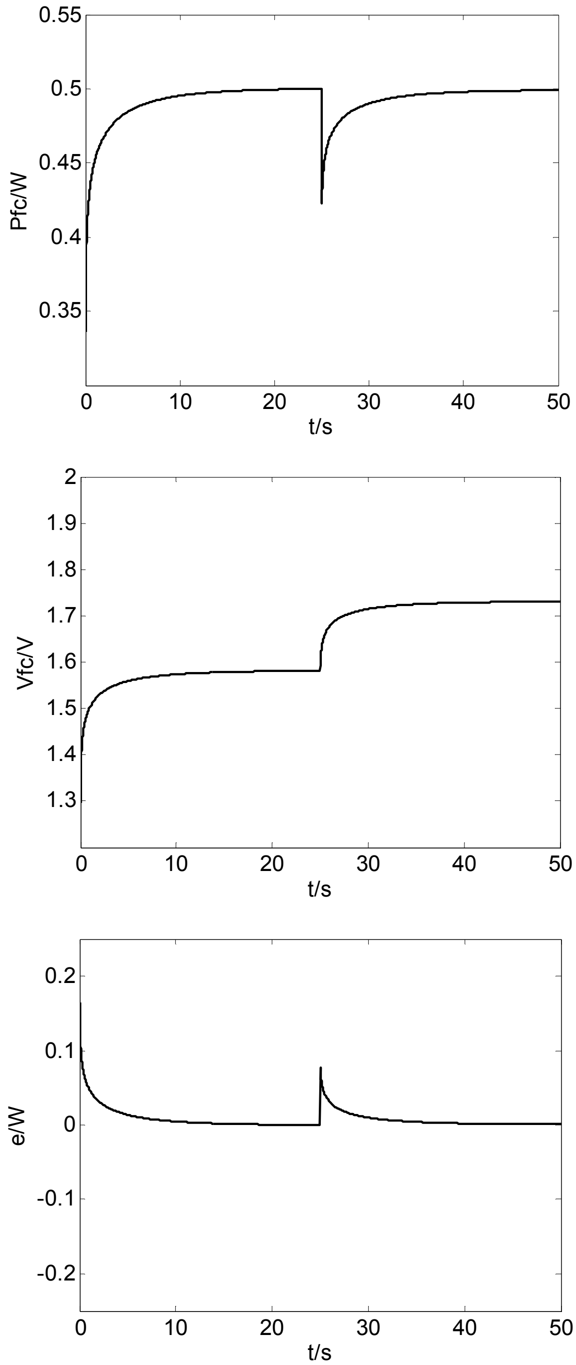

Fig.8. Simulation results of Fuzzy Control PEMFC

Acknowledgments

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

REFERENCES

[1] Das S., Mangwani N., Recent Development Of Microbial Fuel Cell: a Review. Journal of Scientific & Industrial Research, 69 (2010), 727-731

[2] Logan B. E., Scaling up Microbial Fuel Cells and Other Bioelectrochemical Systems. Applied Microbiology and Biotechnology, 85 (2010), No. 6. 1665–1671.

[3] Pukrushpan J., Stefanopoulou A., Peng H., Control of fuel cell breathing. IEEE Control Systems, 24 (2004), No. 2, 30-46

[4] Kunusch C., Puleston P. F., Mayosky M. A., Riera J., Sliding Mode Strategy for PEM Fuel Cells Stacks Breathing Control Using a Super-Twisting Algorithm. IEEE Transactions on Control Systems Technology, 17 (2009), No. 1, 167-174

[5] Kaytakoglu S., Akyalm L., Optimization of Parametric Performance of a PEMFC. International Journal of Hydrogen Energy, 32 (2007), No. 17, 4418-4423

[6] Riascos L. A. M., Pereira D. D., Controlling Operating Temperature in PEM fuel cells. ABCM Symposium Series in Mechatronics, 4 (2010), 137-146

[7] Sala A., Guerra T., Babuska R., Perspectives of Fuzzy Systems and Control. Fuzzy Sets and Systems, 156 (2005), No. 3, 432-444

[8] Nhivekar G.S., Nirmale S.S., Mudholker R.R., Implementation of Fuzzy Logic Control Algorithm in Embedded Microcomputers for Dedicated Application. International Journal of Engineering, Science and Technology, 3 (2011), No. 4, 276-283

[9] Corcau J. I., Stoenescu E., Fuzzy Logic Controller as a Power System Stabilizer. International Journal of Circuits, Systems and Signal Processing, 3 (2007), No. 1, 266-272

[10] Horiuchi J., Kishimoto M., Application of Fuzzy Control to Industrial Bioprocesses in Japan. Fuzzy Sets and Systems, , 128 (2002), No. 1, 117-124

[11] Carnes B., Djilal N., Systematic Parameter Estimation for PEM Fuel Cell Models. Journal of Power Sources, 144 (2005), No. 1, 83–93

[12] Moreira M. V., Silva G. E., A Practical Model for Evaluating the Performance of Proton Exchange Membrane Fuel Cells. Renewable Energy, 34 (2009), No. 7, 1734-1741

[13] 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, 2 (2010), No. 1, 81-85

[14] Youssef M. E., Nadi K. E., Khalil M. H., Lumped Model for Proton Exchange Membrane Fuel Cell (PEMFC). International Journal of Electrochemical Science, 5 (2010), 267-277

[15] Mammar K., Chaker A., Fuzzy Logic Control of Fuel Cell System for Residential Power Generation. Journal of Electrical Engineering, 60 (2009), No. 6, 328-334

[16] Rezazadeh A., Askarzadeh A., Sedighizadeh M., Adaptive Inverse Control of Proton Exchange Membrane Fuel Cell Using RBF Neural Network. International Journal of Electrochemical Science, 6 (2011), 3105 - 3117

[17] Fan L. P., Simulation Study on the Influence Factors of Generated Output of Proton Exchange Membrane Fuel Cell. Applied Mechanics and Materials, 121 (2012), 2887-2891

[18] Correa J. M., Farret F. A., Canha L. N., Simoes M. G., An Electrochemical-based Fuel-Cell Model Suitable for Electrical Engineering Automation Approach. IEEE Transactions on Industrial Electronics, 51 (2004), No. 5, 1103-1112

***Authors:** Prof. Dr. Liping Fan, Shenyang University of Chemical Technology, No.11 St., Economical and Technological Development Zone, Shenyang 110142, China, E-mail: flpsd@163.com. Prof. Yi Liu, E-mail: ly18ly28@163.com.*