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An Intelligent Controller for PEM Fuel Cell Power System Based on Double Closed-loop Control

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ABSTRACT

This paper presents a double closed-loop controller for a proton exchange membrane fuel cell (PEMFC) power system, which consists of a PEMFC stack, a controller, an AC-DC and DC-AC converter with the function of uninterruptible power system (UPS). According to the output voltage and current values which are feedback variables in the system, an optimizing fuzzy-PI controller has been designed to mainly control the hydrogen and air/oxygen mass flows, and auxiliary variables, such as the temperature, pressure, humidity of the membrane, and proportion of stoichiometry. Experimental results show that the optimized fuzzy-PI controller can improve the voltage and current performance of the system.

1. INTRODUCTION

In the last decade, the performance of fuel cells has been greatly improved mainly due to the advancements of proton exchange membrane fuel cell (PEMFC), and a large amount of work was conducted by various researchers for predicting the performance, which is a key factor in the development of new applications. Unfortunately, the performance of a PEMFC is extremely difficult to model analytically, so empirical models have been used. Its performance depends on many variables, including temperature, pressure, current density, water content of the membrane, and other factors. Many of these variables that influence the performance depend on each other, yielding non-linearity in the performance models [1]. This makes the study on PEMFC control systems more difficult.

In 1994, Kuwata *et al* [2] described a control method for a new DC-DC converter and its characteristics. The new converter control method can maintain maximum fuel cell output to keep total efficiency high, and can achieve stable fuel cell operation even if the AC power fails or the load varies. In 2003, Ro and Rahman [3] developed a controller for a fuel cell power plant to assist the conventional generators to damp out oscillations. The controller received the grid bus voltage magnitude and system frequency variations, which were taken as the feedback inputs. A power conditioning subsystem fulfilled the DC–AC power conversion by turning on and off switches according to a certain switching scheme. In 2003, Sedghisigarchi [4] analyzed the dynamics of distribution systems that contained fuel cells and the enhancement of the stability of these systems by controlling the fuel cells. The fuel-cell control loops through the power conditioning units were first explained using a one-machine infinite bus system. In 2003 and 2004, Sakhare and Davari [5, 6] adopted a solid oxide fuel cell mathematical model, and a power conditioning unit was designed for this solid oxide fuel cell and for fuel cells in general. The fuzzy logic control strategy was used to design the controllers for DC-AC, and DC-DC. The output was converted to a controlled DC voltage by a control scheme that adjusts the duty ratio of the converter and also protects the fuel cell against sudden load variations and current reversal. In 2003, Iqbal [7, 8] presented the dynamic modeling of various components of an isolated system. The selection of control strategies and design of controllers for the system was described. A software package, SIMNON™, was used for the simulation of this highly nonlinear system. A proportional-integral-differential (PID) type fuel cell controller was used to adjust the fuel inlet and oxygen pressure to maintain a constant stack output voltage. This controller action compensated the drop in the fuel cell stack voltage caused by the load current variations. In the simulation, Iqbal used a PID type controller to control the fuel cell voltage by varying the H_2 and O_2 flow rates. In 2005, Khan and Iqbal [9], based on their previous work, conducted a dynamic modeling and simulation of a small wind–fuel cell hybrid energy system. The system, however, was never implemented.

In summary, although the PID type controllers have been used to control the fuel cell voltage by varying the H_2 and O_2 flow rates, only the simulation studies were conducted, whereas the fuzzy logic controllers only were used in the DC-AC, or AC-DC converters of the power system. The experimental results, however, were not reported in the literature.

In this paper, an intelligent fuzzy logic controller with PI control loops has been designed and implemented to directly control the H_2 and air mass flow in a 100W PEMFC power system. The fuzzy-PI controller is used to automatically fine tune the parameters of a conventional PI controller. Depending on the output voltage and current of the stack, the fuzzy controller constantly interprets the process reaction and calculates the optimal P and I gains. The output voltage of the PI controller directly regulates the flow rate of H_2 and air. The experimental results demonstrate that the fuzzy-PI controller can improve the V-I performance of the PEMFC system, and maintain a constant output voltage of the PEMFC stack over a wide range of load.

2. SYSTEM DESCRIPTION

2.1 STRUCTURE OF PEMFC POWER SYSTEM

Figure 1 illustrates schematically the structure of our PEMFC power system, which consists of a PEMFC stack and its control subsystem, an uninterruptible power

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2. SYSTEM DESCRIPTION

2.1 STRUCTURE OF PEMFC POWER SYSTEM

Figure 1 illustrates schematically the structure of our PEMFC power system, which consists of a PEMFC stack and its control subsystem, an uninterruptible power system (UPS), a lead-acid battery and LabVIEW™ control software package. The UPS system supplies the load with the required and uninterruptible AC power through the inverter. The PEMFC stack operates on pure hydrogen and air. Because of the slow start-up, which takes several seconds, the battery is required for UPS applications. Another option with higher cost is to use supercapacitors.

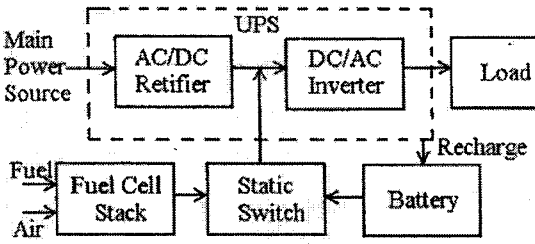


Figure 1: UPS with back-up fuel cell and battery

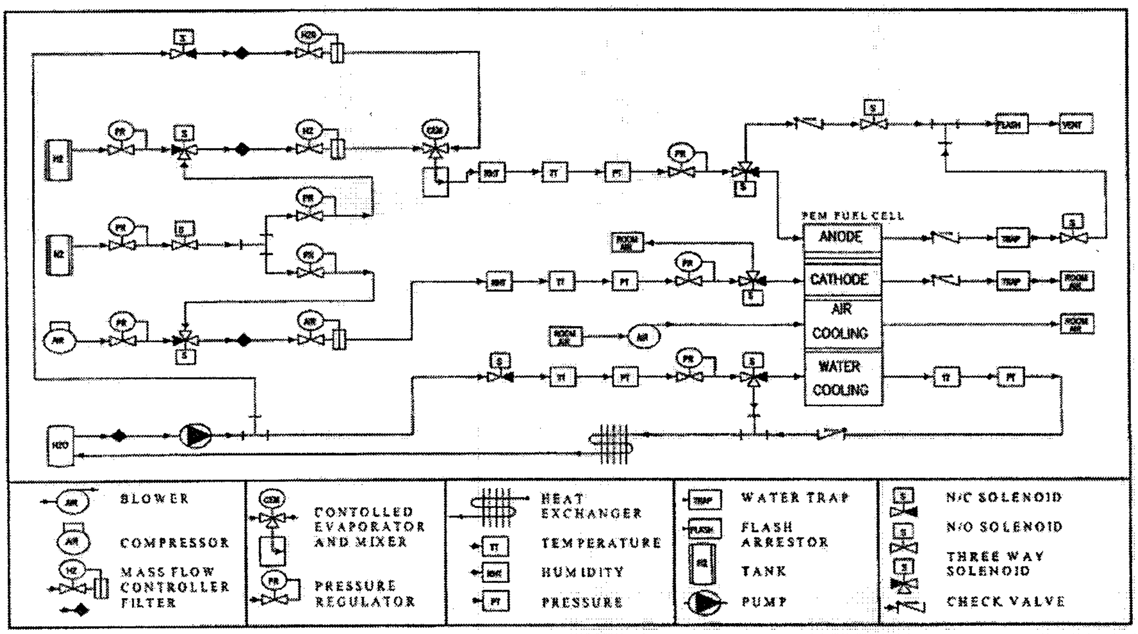


Figure 2: Schematic Diagram of PEM Fuel Cell System

2.2 STRUCTURE OF PEMFC TEST SYSTEM

Figure 2 illustrates the 100W PEMFC test system [10], which consists of a PEMFC stack, water-cooling components, air-cooling, H_2 humidifying and filtering, and temperature and pressure monitoring. Three types of gases, hydrogen, nitrogen and air/oxygen, are used in the system. A LabVIEW™ software package is used to control the whole process.

2.3 STRUCTURE OF FUZZY-PI CONTROLLER

There are many different ways to use fuzzy controllers in closed-loop control applications. The most basic structure uses the sensor signals from the process as the input signals for the fuzzy controller and the outputs as the command values to drive the actuators for process control. A PEMFC stack control loop structure is shown in Figure 3.

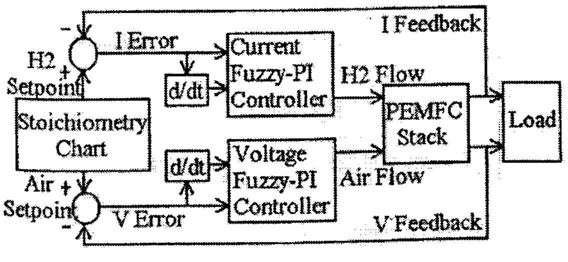


Figure 3: Structure with Fuzzy-PI Controller

This paper presents the employment of the concept of double closed-loop control for PEMFC. According to the output voltage and current values which are feedback variables in the system, two intelligent fuzzy-PI controllers have been designed to mainly control the hydrogen and air/oxygen mass flows.

3. DESIGN OF FUZZY LOGIC CONTROLLER

3.1 MODEL OF PEMFC SYSTEM

The PEMFC model used in this paper was developed by Balkin, Holland and Zhu [11] in 2002. In this model, the fuel cell stack terminal voltage, V_{stack}, is determined by subtracting the various voltage losses from the reversible voltage as the following

$$V_{stack} = V_{reversible} - V_{ohmLOSS} - V_{actLOSS} - V_{conLOSS} \tag{1}$$

where $V_{reversible}$, $V_{ohmLOSS}$, $V_{actLOSS}$ and $V_{conLOSS}$ are maximum theoretical voltage, ohmic voltage loss, activation voltage loss and concentration voltage loss, respectively.

Incorporated in these voltage loss terms is an internal current. These voltage losses result in an operating voltage that is less than the reversible voltage as shown in the typical polarisation curve in Figure 4.

The reversible voltage at varying temperature and pressure can be expressed as

$$V_{reversible} = \mathrm{N}_{cell}V^0 + \frac{RT}{2F}\ln\left[\frac{\dot{p}_{H_2}\left(\dot{p}_{O_2}\right)^{\frac{1}{2}}}{\dot{p}_{H_2 0}} \times \left(\frac{1}{P_0}\right)^{\frac{1}{2}}\right] \quad (2)$$

$$- \mathrm{N}_{cell}\frac{\Delta \bar{s}_{298.15K}}{2F}(T - 298.15)$$

where N_{cell}, V^0, R, T, F, P_0, $\Delta \bar{s}_{298.15K}$, and p^*_m are the number of cells in the PEMFC stack, reversible fuel cell voltage at STP, universal gas constant, temperature of the fuel cell stack in K, Faraday's constant, standard pressure in pressure units used, change in the molar entropy at STP, and partial pressure of species m, respectively.

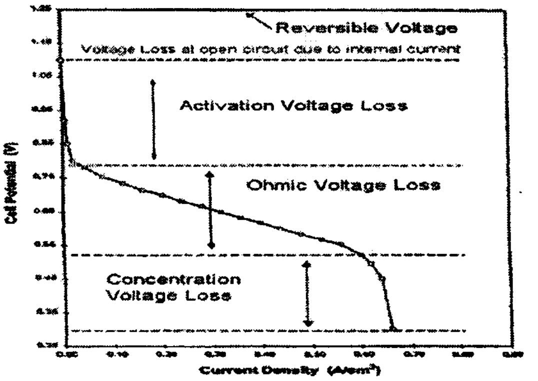


Figure 4: Typical polarisation curve [11]

With the pressure in atmosphere and using the standard values for the constants in (2), the reversible voltage is reduced to

$$V_{reversible} = N_{cell} \times 1.229 + \left(4.308 \times 10^{-5}\right)T \times \ln\left[\dot{p}_{H_2}\left(\dot{p}_{O_2}\right)^{\frac{1}{2}}\right] \quad (3)$$

$$- N_{cell} \times \left(8.453 \times 10^{-4}\right)\left(T - 298.15\right)$$

3.2 DESIGN OF FUZZY-PI CONTROLLER

3.2.1 DESIGN CONCEPT

The fuzzy-PI controller, as shown in Figure 3, uses the error signal and its change from the measured feedback data step as inputs [12]. If the output signal describes the necessary difference toward the voltage and current output values, an intelligent fuzzy reasoning device is needed to build up the command variable value. That is to say, although the fuzzy-PI controller does not have a special operating point, the controller rules evaluate the difference between the measured values of voltage and current and the setting values, which is the error signal, and also evaluate the tendency of the error signal to determine whether to increase or decrease the control output variable. The absolute value of the command output variable is not influenced.

The advantage of a fuzzy-PI controller over a conventional PI controller is that it can implement nonlinear control strategies and that it uses linguistic rules. It is possible to consider only the error tendency when the error becomes small.

In this paper, in order to avoid the difficulty caused by that a large number of variables have effects on the performance of the PEMFC system, and the use of a complex model, a fuzzy-PI controller rule-based PEMFC expert knowledge base is proposed. The fuzzy-PI controller can result in a much better performance than that of a conventional PID one.

The fuzzy-PI controller consists of five different steps and parts, including definition of input-output variables of the controller, fuzzification, designing of fuzzy control rules, inference and defuzzification [13-16].

3.2.2 DEFINITION OF INPUT-OUTPUT VARIABLES

The air flow control loop is used as an example to show the design process of the fuzzy-PI controller as follows.

The fuzzy-PI controller input variable are the voltage error *e(k)*, and the change of error *c(k)*. The output variables of the controller are the optimal *P* and *I* gains of a subsequent PI controller device, one of them gives the proportional part *K* as a function of *e(k)* and *c(k)*, and the other gives the increment *ΔT*, which is then integrated to provide the integral term *T* of the PI controller. The error *e(k)*, change of error *c(k)* and the output variable *u(k)* of the controller are given as follows:

$$e(k) = V_{setpoint} - V_{stack} \quad (4)$$

$$c(k) = e(k) - e(k-1) \quad (5)$$

$$u(k) = u(k-1) + K\{e(k) + \frac{1}{T}\sum_{i=1}^{k}[\frac{e(i) + e(i-1)}{2}]\Delta t\} \quad (6)$$

3.2.3 FUZZIFICATION AND MEMBERSHIP FUNCTION

The triangular type membership function is chosen because of its linearity. The collections of the reference fuzzy sets for the error, the change of error, and the control input are the same, but their scale factors have little difference. As shown in Figure 5, seven fuzzy subsets, i.e. positive big (PB), positive medium (PM), positive small (PS), zero (ZE), negative small (NS), negative medium (NM), and negative big (NB), have been selected for the input and output variables *e(k)*, *c(k)*, *K* and *T*.

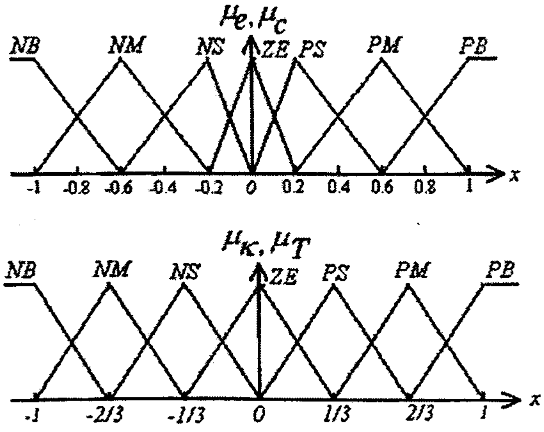


Figure 5: Membership function for *e(k)*, *c(k)*, *K* and *T*

3.2.4 DESIGN OF FUZZY CONTROL RULES

Fuzzy control rules are obtained from the behaviour analysis of the PEMFC system. Because the rule-base represents the intelligence of the controller, the formulations must be carefully considered. Correct use of control laws according to the operating conditions can greatly improve the system stability. A fast response with a small overshoot for the PEMFC system can be achieved with proper handling of the proportional and integral part. It is the cause that the fuzzy-PI controller is more advantageous than a standard PI controller.

The selected control rules or laws are described as follows:

1) Far from the voltage set point: When the output voltage is far from the set point (*e(k)* is PB or NB), the corrective action must be strong; this means that *K* should be NB (or PB) while *T* should be zero (ZE), in order to prevent the continuous increase (or decrease) of integral term that would cause overshoots. In this case, the change of error plays little part.

The basic control rules are:
If *e(k)* is PB, then *K* is PB and *T* is ZE;
If *e(k)* is NB, then *K* is NB and *T* is ZE.

2) Close to the voltage set point: In this region, the change of error must be properly taken into account in order to ensure stability and speed of response. The goal of the fuzzy controller is to achieve a satisfactory dynamic performance with small sensitivity to parameter variations.

The control rules are:
If both *e(k)* and *c(k)* are ZE, then *K* and *T* are ZE ;
If both *e(k)* and *c(k)* is negative, *K* and *T* are negative;
If both *e(k)* and *c(k)* is positive, *K* and *T* are positives.

According to these criteria, the rule sets shown in Tables I and II are derived.

TABLE I
RULE TABLE FOR *P*

e(k) c(k)	NB	NM	NS	ZE	PS	PM	PB
PB	NB	PS	PM	PM	PB	PB	PB
PM	NB	ZE	PS	PM	PM	PB	PB
PS	NB	NS	ZE	PS	PM	PB	PB
ZE	NB	NM	NS	ZE	PS	PM	PB
NS	NB	NB	NM	NS	ZE	PS	PB
NM	NB	NB	NM	NM	NS	ZE	PB
NB	NB	NB	NB	NM	NM	NS	PB

TABLE II
RULE TABLE FOR *T*

e(k) c(k)	NB	NM	NS	ZE	PS	PM	PB
PB	ZE	ZE	PM	PB	PM	ZE	ZE
PM	ZE	ZE	PS	PM	PS	ZE	ZE
PS	ZE	NS	ZE	PS	PM	ZE	ZE
ZE	ZE	NM	NS	ZE	PS	PM	ZE
NS	ZE	ZE	NM	NS	ZE	PS	ZE
NM	ZE	ZE	NS	NM	NS	ZE	ZE
NB	ZE	ZE	NM	NB	NM	ZE	ZE

3.2.5 INFERENCE

There are various ways in which the observed input values can be used to identify which rules should be used to infer an appropriate fuzzy control action. The commonly used fuzzy inference methods are MAX-MIN fuzzy inference reasoning, MAX-PRODUCT inference reasoning, and SUM-PRODUCT fuzzy reasoning.

A basic and simple inference method, MAX-MIN fuzzy inference is employed in this paper. One of rules is expressed below:

Rule *i*: If *e* is *Ei* and *c* is *Ci*, then *P* (or *T*) is *Pi* (or *Ti*), *i*= 1, 2, …, *n*.

The membership of the inferred consequence *P* (or *T*) is point-wise, given by

$$\mu_P(z) = \vee_{i=1}^{n}((\mu_{E_i}(e) \wedge \mu_{C_i}(c)) \wedge \mu_{P_i}(e,c)) \tag{7}$$

where *Ei*, *Ci* and *Pi* are the input or output fuzzy variables corresponding to the *i*-th rule.

3.2.6 DEFUZZIFICATION

Defuzzification is the process of mapping from a space of inferred fuzzy control actions to a space of non-fuzzy control actions. A defuzzification strategy aims to produce a non-fuzzy control action that best represents the possibility distribution of the inferred fuzzy control actions. In real-time implementation of fuzzy logic control, the commonly used defuzzification strategies are the mean of maximum (MOM), the centre of Maximum (COM), the centre of area (COA) and the center of Gravity (COG).

The centre of area (COA) is selected for the defuzzification process in this paper. With these choices, the inferred values *P** (or *T**) of the control action in correspondence to the values *e(k)* and *c(k)* is

$$P^* = \frac{\sum_{i=1}^{n} \mu_P(P_i)P_i}{\sum_{i=1}^{n} \mu_P(P_i)} \tag{8}$$

where *Pi* is the singleton value of the fuzzy output variable using the *i*-th rule.

4. EXPERIMENTAL RESULTS

The proposed fuzzy-PI logic controller is implemented in the 100W PEMFC power system available in our laboratory. Based on the control software LabVIEW™, the control interface is shown in Figure 6.

The output voltage and current values are set according to the stoichiometry chart of the PEMFC stack. Some experimental results are given in Figures 7(a)-(d).

The experimental results reveal that while the PEMFC stack works in open-loop state, according to the stoichiometry chart, after the H_2 and air flow values have been set, the output voltage and current values will change when load and other conditions change. In other words, the open-loop controller has no functions of the automatic tuning when load changes, as shown in Figure 7(a). Once the close-loop controller is added to the PEMFC power system, the voltage and current output characteristics could be adjusted to the desired states. The response time of the fuzzy-PI controller is shorter than that of a standard (conventional) PI one, as shown in Figure 7(b). Furthermore, the fuzzy-PI controller can offer good performance with relatively fast response and small overshoot, as shown in Figures 7(c) and (d). It makes the V-I performance of PEMFC stack become harder, i.e. the output voltage and current are maintained constant for a wide range of load.

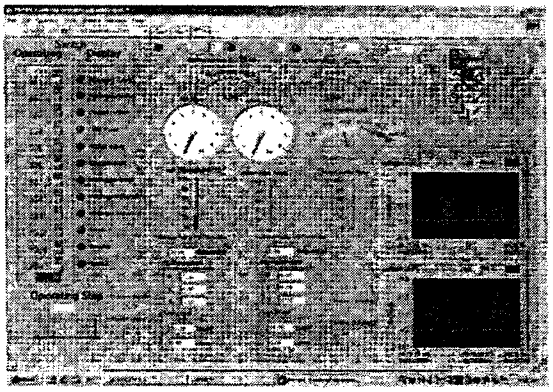
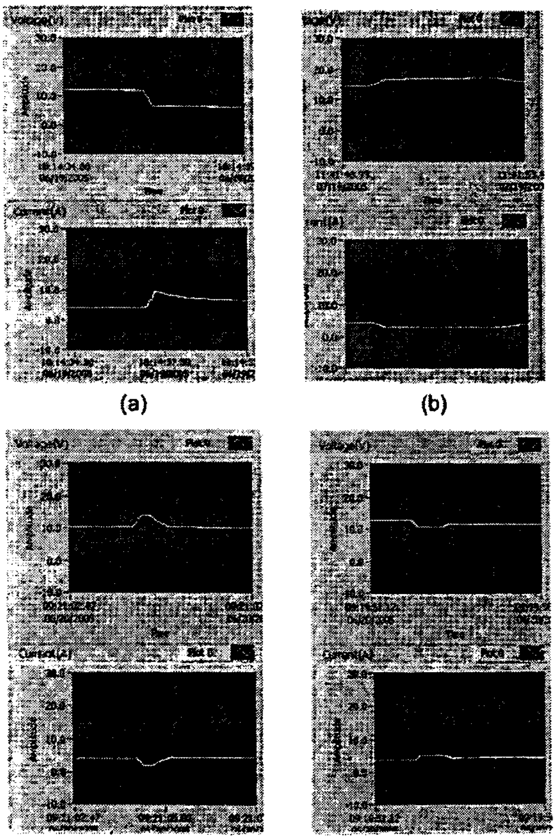


Figure 6: Control interface of the PEMFC system



(a) (b) (c) (d)

Figure 7: Experimental results of output voltage and current when load changes: (a) Open-loop dynamic response; (b) Closed-loop standard PI control response; (c) and (d) Closed-loop fuzzy-PI control dynamic response when the load varies

5. CONCLUSIONS

A fuzzy-PI controller for PEMFC power systems based on double closed-loop control is presented. Compared to the open-loop and standard PI control, the new controller can improve significantly the load performance of the fuel cell stack. Both the theoretical and experimental results have proved that the fuzzy control scheme can work well without using an accurate mathematical model. A major advantage of the fuzzy-PI controller over a conventional PI controller is its capability to implement nonlinear control strategies and obtain good output performencs by using linguistic rules. It is possible to consider only the error tendency when the error becomes small. With fuzzy logic controllers, the experience and the knowledge obtained by the supervising operators can be used to form fuzzy rules, which are important in developing a fuzzy logic controller. The effectiveness of the proposed intelligent fuzzy controller has been verified by experimental results of a PEMFC power system.

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