Air Flow Regulation in Fuel Cells: An Efficient Design of Hybrid Fuzzy-PID Control

(Full text in English)

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Abstract

This paper presents a hybrid fuzzy-PID controller for air flow supply on a Proton Exchange Membrane fuel cell (PEMFC) system. The control objective is to adjust the oxygen excess ratio at a given a set-point in order to prevent oxygen starvation and damage of the fuel-cell stack. The proposed control scheme combines a fuzzy logic controller (FLC) and classical PID controller with a view to benefit the advantages of both controllers. The results show that the proposed technique performs significantly better than the classical PID controller and the FLC in terms of several key performances indices such as the Integral Squared Error (ISE), the Integral Absolute Error (IAE) and the Integral Time-weighted Absolute Error (ITAE) for the closed-loop control system.

Keywords: PEM fuel cell system, Fuzzy Logic, Classical PID, Hybrid controller.

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1. Introduction

The serious environmental pollution and energy crisis around the world are driving innovation on new clean energy sources such as solar, wind, geothermal or hydrogen. Among these sources, the hydrogen appears as a energy vector to be used as a combustible for fuel cells to produce electricity, water and heat [1][2].

Among all types of fuel cells, the proton exchange membrane fuel cells (PEMFC), also called solid polymer fuel cells (SPFC), are particularly suitable for use in wide range applications, with advantages of high efficiency, low weight, low pollution and low operation temperature (50°C to 100°C), facts that allow fast starting times. However, short lifetime and high expenses have hundred their vast applicability in real systems so far [3]. As a result, in order to improve the performance, enhance the lifetime and reduce the production costs, effective control systems are required.

Many control strategies for PEMFC systems in the literature, have been proposed considering dynamic feedforward and linear quadratic regulator [4][5], unfalsified control [6], sliding mode control [7][8][9], model predictive control [10], optimal control [11] and Fuzzy logic control [12][13][14]. These control methods are applied to the manipulation of the oxygen excess ratio in PEMFC with certain limitations on the tracking performance.

In order to enhance effectively the tracking accuracy of the oxygen excess ratio, a hybrid fuzzy-PID controller is proposed in this paper. The proposed controller combines a fuzzy logic controller and a classical PID controller, allowing the overall scheme to switch between both strategies by using a simple switching system. The dynamic model used in this paper to validate the proposed controller is a reduced version of the ninth-order state-space model proposed by Pukrushpan et al. [4].

The remainder of the paper is organized in the following way: the mathematical model of the PEMFC air supply system and the control objective are explained in Section 2. In Section 3, the hybrid fuzzy-PID controller design is explained. The designed control strategy is applied to the model of PEMFC system and its simulation results are shown in Section 4. Finally, main conclusions are presented in Section 5.

2. PEMFC System Model

2.1. Nonlinear Model

The PEMFC model considered in this paper is based on a 75 kW PEMFC power system. The PEMFC system includes five main subsystems: the air flow (breathing), the hydrogen flow, the humidifier, the stack electrochemistry and the stack temperature. In [15], it is assumed that the temperature and humidity of input reactant flows are well regulated by dedicated controllers. In addition, it is considered that sufficient compressed hydrogen is available, and therefore the main attention is focused on the air management. Under these assumptions, we present a fourth-order state space model that is a reduced version of the ninth-order model presented in [4]. The model equations and the constants are summarized in Tables A.1 and A.2 in Appendix A, respectively. The details of the model used in this study and the numerical values can be found in [15] and [16].

The nonlinear state equations in Table A.1 in Appendix A have the form

$$\dot{x} = f(x, u, w), \tag{1}$$

where the vector of states $x \in \Re^4$ is associated to the partial pressure of oxygen and nitrogen in the cathode channel, the rotational speed of the motor shaft in the compressor and the air pressure in the supply manifold, respectively.

The control input $u \in \Re$, as shown in Figure 1, is the compressor motor voltage v_{cm}, which allows the manipulation of the air feed and, as a consequence, the oxygen supply to the fuel-cell stack.

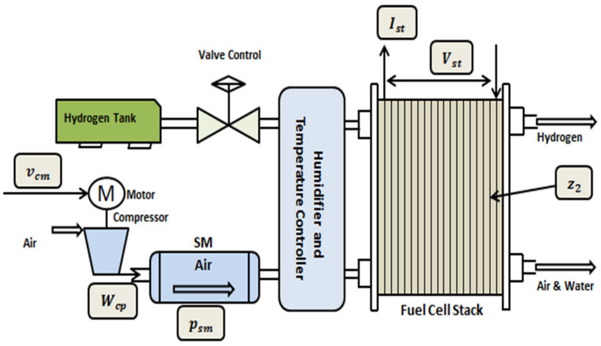

Figure 1. Fuel Cell System showing control inputs and outputs

The measurable disturbance input $w \in \Re$ is the stack current I_{st}. The system output $h_y \in \Re^3$, as illustrated also in Figure 1, is the stack voltage $h_{y_1} = v_{st}$, the supply manifold pressure $h_{y_2} = x_4$ and the air flow rate through the compressor $h_{y_3} = W_{cp}$, respectively. For further details about the functions h_{y_1} and h_{y_3}, see [16] and [17]. The performance variables $z \in \Re^2$, with z_1 as the net power and z_2 as the oxygen excess ratio, are also outlined in Table A.1. in Appendix A.

2.2. Control Objective

The main control objective for the PEMFC system is to regulate the oxygen excess ratio z_2, which is defined by the amount of oxygen provided $W_{O_2,in}$ and the amount of oxygen reacted $W_{O_2,rct}$, which is described as

$$z_2 = \frac{W_{O_2,in}}{W_{O_2,rct}} \tag{2}$$

If the value of z_2 is quite low, even though higher than 1, it is likely to cause Oxygen starvation. This phenomenon can cause a short circuit and hot spot on the surface of membrane cell. On the other hand, a higher value of z_2 will drive the auxiliary system to consume more power. Therefore, the system efficiency then decreases. Consequently, it is necessary to use efficient control methods to regulate the oxygen excess ratio around an optimal value.

The oxygen excess ratio was analysed for different stack current and temperature in [18]. The results show that the optimal value of z_2 depends strongly on the stack current. Hence, we choose $z_{2,opt} = 2.05$, which corresponds to maximum PEMFC net power z_1 for the nominal stack current [3].

3. Control Design

This section presents the design of the hybrid fuzzy-PID controller based on simple switching system to regulate the oxygen excess ratio at its optimal value. Firstly, we design the PID controller and the fuzzy logic controller, and then we combine them to obtain the hybrid controller. The switching method depends on the state of the system response.

3.1. PID Controller

The PID-controller-based scheme, shown in Figure 2, is widely used in industrial process control due to its simple structure and robust performance for both linear and nonlinear systems.

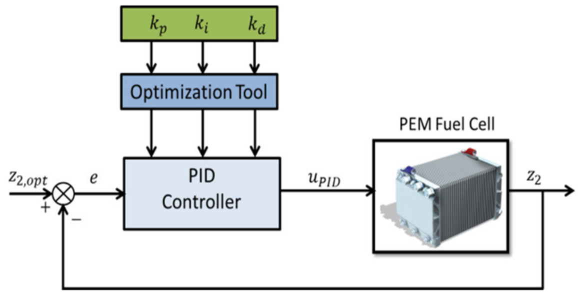

Figure 2. Structure of PID-controller-based scheme

The mathematical expression of this controller is given by

$$u_{PID}(t) = k_p\, e(t) + k_i \int e(t)dt + k_d \frac{de(t)}{dt} \tag{3}$$

where e is the feedback error defined in the case of this paper as the difference between the current value of z_2 and its set-point value, i.e.

$$e(t) = z_2(t) - z_{2,opt} \tag{4}$$

Besides, the parameters k_p, k_i and k_d are known as proportional gain, integral gain and derivative gain, respectively.

Gains k_p, k_i and k_d may be computed by using optimization methods [19], among other traditional strategies.

3.2. Fuzzy Logic Controller (FLC)

Fuzzy logic is one of the most versatile control techniques due to its simplicity, efficiency and robustness against the system dynamics variation. The FLC has several advantages such as it does not require the precise information about the process dynamics [20].

There are three main parts in the FLC, as shown in Figure 3 (*infra*):

- Fuzzification interface: Converts a crisp input to a fuzzy value by using fuzzy sets,
- Rule base and inference system: Generates a result for each suitable rule, then combines the results of the rules,
- Defuzzification interface: Converts the combined result back into a specific control output value.

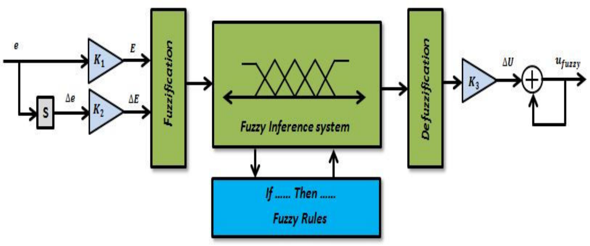

Figure 3. Structure of the FLC

In Figure 3, the variables $e, \Delta e; E$ and ΔE indicate error, derivative of error, normalized error and normalized derivative of error, respectively, while the parameters k_1, k_2 and k_3 are input and output scaling factors. In Table 1, the fuzzy linguistic variables NB, N, Z, P and PB represent negative big, negative, zero, positive and positive big, respectively.

The membership functions of the FLC inputs and output are respectively shown in Figures 4 and 5.

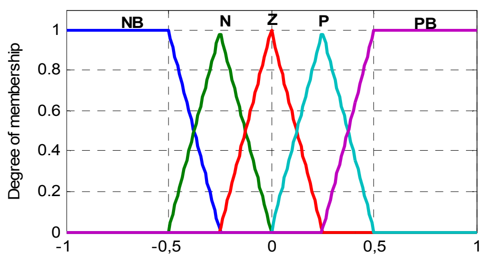

Figure 4. Membership functions of inputs $(e, \Delta e)$

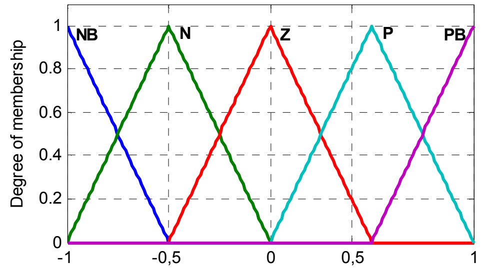

Figure 5. Membership functions of output (Δu)

Table 1. Linear rule base for FLC

ΔU		E				
		NB	N	Z	P	PB
	NB	NB	NB	N	N	Z
	N	NB	N	N	Z	P
	Z	N	N	Z	P	P
ΔE	P	N	Z	P	P	PB
	PB	Z	P	P	PB	PB

3.3. Hybrid Fuzzy-PID Controller

While the fundamental difficulty with PID control is that it is sensitive to variations of the system parameters, FLC does not need precise information about the system variables in order to be effective. However, PID control is more able to reduce the steady-state error of the system [21]. Therefore, a hybrid system, as shown in Figure 6, is required in order to regulate the dynamic and steady-state performance of the oxygen excess ratio.

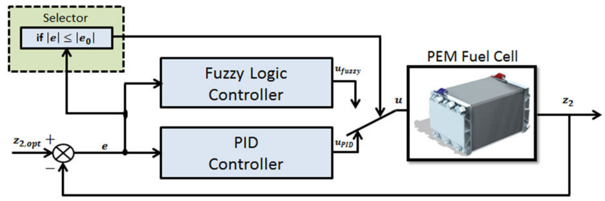

Figure 6. Structure of the hybrid Fuzzy-PID controller

Figure 6 shows the switching mechanism between the FLC and the PID controller, where the position of the switch depends on the error between the actual value of oxygen excess ratio and its optimal value.

If the output value is far away from the set-point, the FLC has the greatest effect on the control system. Similarly, when the output value is near the set-point value, the PID controller has the greatest effect over the system rather than the FLC. The output of the hybrid fuzzy-PID controller can be expressed as

$$u(t) = \begin{cases} u_{fuzzy}(t) & if \ |e| > |e_0| \\ u_{PID}(t) & if \ |e| \le |e_0| \end{cases} \qquad (5)$$

where e_0 is the threshold value.

4. Simulation results

The hybrid fuzzy-PID control scheme is applied to the PEMFC system model in (1) The control input is computed such as it is defined a compressor motor input voltage v_{cm} in order to maintain the oxygen excess ratio at 2.05 and thus, minimizing the parasitic power consumption. For this purpose, rapid variations of stack current are applied, as shown in Figure 7, in order to illustrate the air supply regulation in a wide range of operation points.

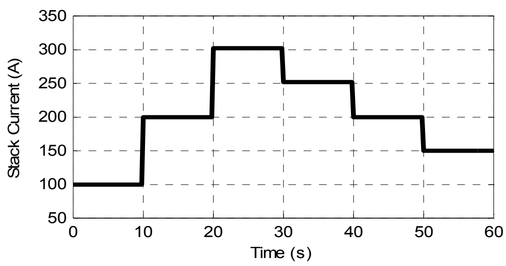

Figure 7. Stack current variation

It can be seen from Figure 8 that all the applied control strategies adjust z_2 at the setpoint with a satisfactory tracking performance.

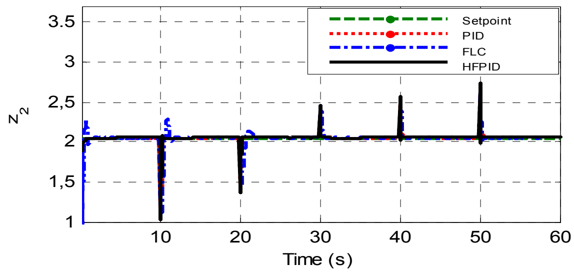

Figure 8. Response of oxygen excess ratio for different control strategies

Figures 9 and 10 present the zoomed plot of z_2 when the stack current is increased from 200 A to 300 A (at t=20 s) and when the stack current is decreased from 250 A to 200 A (at t=40 s), respectively.

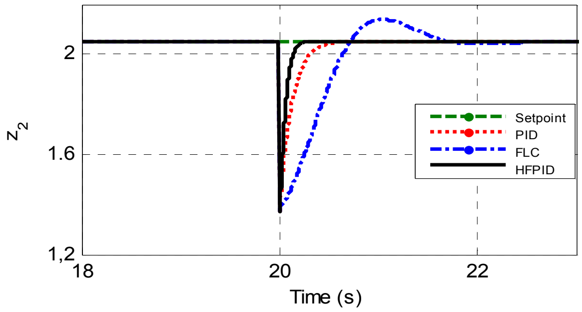

Figure 9. The magnified plot of oxygen excess ratio variation at t=20s

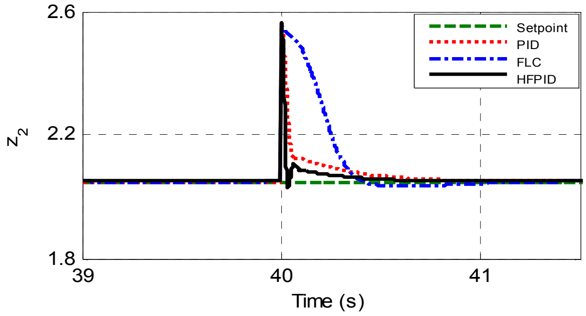

Figure 10. The magnified plot of oxygen excess ratio variation at t=40 s

In the former case, the oxygen excess ratio decreases, as shown in Figure 9, due to the depletion of the oxygen at the cathode side. This fact caused an important drop of the stack voltage, as shown in Figure 11 and Table 2.

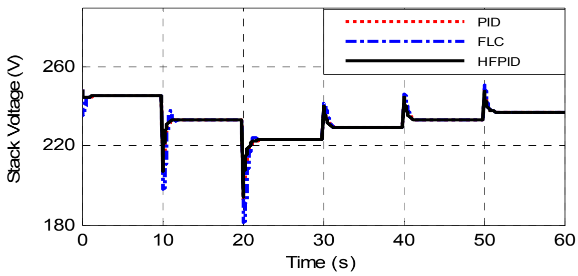

Figure 11. Stack voltage variation

Table 2: Performance index comparison and time domain specifications

Controller	ISE	IAE	ITAE	Rise Time	Settling Time
PID	0.1094	0.3763	7.5115	0.19	0.11
FLC	0.6736	1.3346	23.6383	0.38	0.77
HFPID	0.0606	0.2041	4.1203	0.075	0.061

Table 2 shows the obtained results in terms of several performance indices including the Integral Squared Error (ISE), the Integral Absolute Error (IAE) and the Integral Time-weighted Absolute Error (ITAE). Those indices allow to show that the proposed control strategy performs much better than the PID and FLC control strategies in separate fashion.

An inverse case is shown in Figure 10 at t=40 s. According to the zoomed plot of z_2 (Figures 9 and 10), the HFPID controller exhibits a faster time response compared to the remainder control strategies.

As seen in Figure 11 and Table 2, the HFPID controller reduces the rise time and the settling time of z_2 during the transient step changes of w with respect to the PID and FLC controllers separately.

5. Conclusions

In this study, a reduced PEMFC system model is explained, which presents cathode mass flow transients. Based on this model, a hybrid fuzzy-PID controller is designed to regulate the oxygen excess ratio in order to avoid oxygen starvation when the stack current suddenly changes. The proposed controller combines a FLC and classical PID controller, which can be switched between them by using a simple switching system. The simulation results show that the hybrid fuzzy-PID control has the better control effect than the classical PID and the FLC.

However, for better results, it is advisable to use a variable optimal oxygen excess ratio expression as a function of the PEMFC stack current.

6. References

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7. Appendix A

Equations, Constants of the PEMFC system

Table A.1: Fourth-order state-space model of the PEMFC system.

$$\dot{x}_1 = c_1(x_4-\chi) - \frac{c_3 x_1 \alpha(x_1,x_2)}{c_4 x_1 + c_5 x_2 + c_6} - c_7 w$$

$$\dot{x}_2 = c_8(x_4-\chi) - \frac{c_3 x_2 \alpha(x_1,x_2)}{c_4 x_1 + c_5 x_2 + c_6}$$

$$\dot{x}_3 = -c_9 x_3 - \frac{c_{10}}{x_3}\left(\left(\frac{x_4}{c_{11}}\right)^{c_{12}} - 1\right)\cdot h_{y3}(x_3,x_4) + c_{13} u$$

$$\dot{x}_4 = c_{14}\left(1 + c_{15}\left(\left(\frac{x_4}{c_{11}}\right)^{c_{12}} - 1\right)\right)\cdot\left(h_{y3}(x_3,x_4) - c_{16}(x_4-\chi)\right)$$

$$\chi = x_1 + x_2 + c_2$$

$$\alpha = c_{17}\chi\left(\frac{c_{11}}{\chi}\right)^{c_{18}}\sqrt{1-\left(\frac{c_{11}}{\chi}\right)^{c_{12}}},$$

$$z_1 = h_{y1}(x_1,x_2)w - c_{21}u(u - c_{22}x_3)$$

$$z_2 = \frac{c_{23}(x_4-\chi)}{c_{24} w}$$

Table A.2: Constants of the PEMFC system model.

$c_1 = \frac{RT_{st}k_{ca,in}}{M_{O_2}V_{ca}}\left(\frac{x_{O_2,atm}}{1+\omega_{atm}}\right)$	$c_{15} = \frac{1}{\eta_{cp}}$
$c_2 = p_{sat}$	$c_{16} = k_{ca,in}$
$c_3 = \frac{RT_{st}}{V_{ca}}$	$c_{17} = \frac{C_D A_T}{\sqrt{RT_{st}}}\sqrt{\frac{2\gamma}{\gamma-1}}$
$c_4 = M_{O_2}$	$c_{18} = \frac{1}{\gamma}$
$c_5 = M_{N_2}$	
$c_6 = M_v p_{sat}$	
$c_7 = \frac{RT_{st}n}{4FV_{ca}}$	$c_{19} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$
$c_8 = \frac{RT_{st}k_{ca,in}}{M_{N_2}V_{ca}}\left(\frac{1-x_{O_2,atm}}{1+\omega_{atm}}\right)$	$c_{20} = \frac{C_D A_T}{\sqrt{RT_{st}}}\gamma^{1/2}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2\gamma-2}}$
$c_9 = \frac{\eta_{cm}k_t k_v}{J_{cp}R_{cm}}$	$c_{21} = \frac{1}{R_{cm}}$
$c_{10} = \frac{C_p T_{atm}}{J_{cp}\eta_{cp}}$	$c_{22} = k_v$
$c_{11} = p_{atm}$	$c_{23} = k_{ca,in}\frac{x_{O_2,atm}}{1+\omega_{atm}}$
$c_{12} = \frac{\gamma-1}{\gamma}$	$c_{24} = \frac{nM_{O_2}}{4F}$
$c_{13} = \frac{\eta_{cm}k_t}{J_{cp}R_{cm}}$	$x_{O_2,atm} = \frac{y_{O_2,atm}M_{O_2}}{M_{a,atm}}$
$c_{14} = \frac{RT_{atm}\gamma}{M_{a,atm}V_{sm}}$	$\omega_{atm} = \frac{M_v}{M_{a,atm}}\frac{\phi_{atm}p_{sat}}{p_{atm}-\phi_{atm}p_{sat}}$

Biographies

Zakaria BAROUD was born on 21 April 1990 in Laghouat/Algeria. He earned his License degree in Electro-technology (2010) and his Master degree in Automatic (2012) from the university of Amar Telidji.

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In 2007-2008, he held a postdoctoral position at University of Newcastle (Australia) and, afterwards (2008-2011) at the Spanish Research Council (CSIC), Institut de Robòtica i Informàtica Industrial (IRI), CSIC-UPC. Currently, he is Associate Professor at UPC, Automatic Control Department. Since 2014, he is also Deputy Director of IRI. His research interests include constrained predictive control, large-scale systems and industrial applications (mainly in water and energy).

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