Multivariable System Identification and Robust Control of a Proton Exchange Membrane Fuel Cell System

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Abstract—This paper develops a multivariable robust controller for a proton exchange membrane fuel cell (PEMFC) system. To give a perspective of the system, a PEMFC can be simplified as a two-input-two-output model, where the inputs are air and hydrogen flow rates, while the outputs are cell voltage and current. By fixing the output resistance, we aim to control the cell voltage output by regulating the air and hydrogen flow rates. Due to the nonlinear characteristics of this system, a multivariable robust controller is designed to provide robust performance and to reduce hydrogen consumption. The study is carried out in three parts. First, the system transfer functions are experimentally identified. Secondly, robust control algorithms are adopted to design a 2-by-1 H_∞ controller to deal with the system uncertainty and performance requirements. Finally, the designed H_∞ controller is implemented to control the air and hydrogen flow rates. From the experimental results, the multivariable robust control is deemed effective.

I. INTRODUCTION

DUE to the fact that, in recent years the greenhouse effect has become more serious and fossil fuel decreases are considered necessary, people pay more attention to alternative energy resources. One of the best alternative energy resources for transport systems is the PEMFC. This is because of the advantageous features of PEMFC systems, such as functioning in low operation temperatures, quick power responses, high power density, no air pollution, and high system efficiency. With the increasing use of PEMFC, the control of the systems has become critical. However, most of the current fuel-cell systems still make use of the traditional control methodologies, such as process control. Owing to the nonlinear characteristics of PEMFC, these methods cannot fully satisfy the complex loading variations for many applications, and may cause instability problems. On the other hand, DC/DC converters are normally implemented with PEMFC to guarantee steady voltage output. Nevertheless, the system performance might be degraded by the structure in terms of power efficiency and loading effects, e.t.c. Therefore,

more elegant control strategies, such as robust control, should be applied to fulfill the requirement for robustness and performance.

Rodatz et al. [1] presented a dynamic model of air supply and developed an LQG regulator for a PEMFC system, in which the pressure trace was successfully decoupled from the mass flow trace, and a faster response time was also achieved. Pukrushpan et al. [2] developed an observer-based feedback controller to protect the fuel-cell stack from oxygen starvation during changes in current commands, while the linear quadratic technique was employed based on the linearised state-space model. Sedghisigarchi and Feliachi [3] developed an H_∞ controller to regulate the system's output voltage under small load variations. In their simulations, the output voltage variation was kept below 5% by controlling the hydrogen flow rate. Caux et al. [4] were able to control the air supply of a PEMFC system under varying current loadings. Those simulations proposed a species balance model to maintain constant pressure on the cathode (oxygen) compartment and to follow a desired air flow-rate. Takeuchi et al. [5] emphasized the power management of fuel-cell systems interconnected with a utility grid, while successfully introducing typical topologies of fuel-cell based distributed generation systems. Jurado and Saenz [6] developed an adaptive controller of a fuel-cell micro-turbine hybrid power plant. Considering time-varying dynamics of the model and the plant disturbances, the adaptive controller designed at a fixed operating point was utilized to stabilize the system under different operating conditions. Because a steady power source is important for electrical equipment, robust control methodologies are selected in this paper in order to provide a steady voltage or current when the operating conditions change. Robust control is well known for its capability of dealing with system uncertainties and disturbances [7-9]. Wang et al. [10-12] applied robust control to a single-input-single-output (SISO) PEMFC system, in order to provide steady voltage output by tuning the oxygen flow rate. The experimental results demonstrated that robust controllers can achieve splendid performance and cope with system perturbations.

This paper extends the robust control strategies to a multi-input fuel-cell system. The multivariable robust controller was shown to be better than the SISO controller in terms of hydrogen consumption. This paper is arranged as

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follows: in section II the fuel-cell dynamics is described and modeled as a MIMO system. In section III the PWM theory is introduced and applied to control the hydrogen valve. In section IV robust control strategies are introduced and applied to design a multivariable H_∞ robust controller. In section V the designed controller is implemented to verify the performance. Finally we draw some conclusions in section VI.

II. SYSTEM IDENTIFICATION OF THE FUEL CELL SYSTEM

In this section, the dynamics of the fuel cell system is described and modeled by identification techniques. The linear models will then be used for the controller designs in the next section.

A. System Description

The fuel-cell system demonstrated in this paper is designed and manufactured by CSIST (Chung Shan Institute of Science and Technology) and integrated by DELTA ElectronicsTM. The inputs of the system are hydrogen and air, while the outputs are cell voltage and current. It consists of 15 cells with the active area of 50 cm² on each. The cells are connected with a pre-treated membrane – Nafion[®] 112 – by hot press for optimum conditions. Platinum loading is about 0.2 mg/cm² at anode and 0.4 mg/cm² at cathode. The maximum efficiency of the fuel cell stack is 37% (LHV) under dry H₂/air and humidification-free conditions.

Figure 1. The dynamics of the PEMFC system. [11]

The system dynamics is non-linear and time varying and is influenced by many factors, including the diffusion dynamic, the Nernst equation, proton concentration dynamics and cathode kinetics as follows:

$$\text{Diffusion Equation: } R_{ohm} = R_{ref} + \alpha_T (T - T_{ref}), \quad (1)$$

$$\text{Nernst Equation: } E = E_{ref} + \frac{dE}{dT} (T - T_{ref}) + k \frac{RT}{2F} \ln(P_{H_2} P_{O_2}^{1/2}), \quad (2)$$

Proton Concentration Dynamics:

$$u \left(-\frac{\partial C_{H^+}}{\partial t} \right) \cdot \frac{\partial C_{H^+}}{\partial t} + \frac{C_{H^+}}{\tau_{H^+}} = \frac{1 + \alpha_{H^+} \cdot j^3}{\tau_{H^+}}, \quad (3)$$

$$\text{Cathodic Kinetics: } \eta = b \ln \left\{ \frac{p_{10}}{p_1} \left[\frac{H^+}{H^+} \right]_0 \left(1 + \frac{j_r}{j_0 A_r} \right) \right\}, \quad (4)$$

as shown in Figure 1. Therefore, when the current load is changed, the cell voltage varies substantially from 12V to 7.5V, using the on-board controller, as illustrated in Figure 2.

Figure 2. The voltage variation as the loading current is changed.

From the system point of view, the fuel-cell can be represented as a MIMO system, as depicted in Figure 3, with the following relation [13]:

$$I_{cell} = G_1 N_{Air} + G_3 N_{H_2}, \quad (5)$$

$$V_{cell} = G_2 N_{Air} + G_4 N_{H_2} - R \cdot I_{cell}, \quad (6)$$

in which $G_1 \sim G_4$ represent the input-output relation of the system. By fixing the output resistance, we can either control the cell voltage or current output by tuning the air (N_{air}) and hydrogen (N_{H_2}) flow rates. Since most electrical equipment requires constant voltage supply, in this paper we aim to control the cell voltage output.

Figure 3. The block diagrams of the fuel cell system. [11]

B. System Identification

To describe a system, we can measure the given input signals and the corresponding output signals, and then, using MatlabTM, identify the system by the subspace system identification skills. The function *n4sid* is utilized to estimate the models in the state-space form, as in following: [14]

$$x(k+1) = Ax(k) + bu(k) + k\omega(k), \quad (7)$$

$$y(k) = c^T x(k) + du(k) + \omega(k), \quad (8)$$

in which $x(k)$ is the state vector, while $u(k)$ and $y(k)$ are the input and output, respectively, and $\omega(k)$ is the noise in the system. To employ the subspace system identification methods, the transfer function of the system can be presented as:

$$G(q) = c^T (qI - A)^{-1} b + d, \quad (9)$$

with the noise model as follows:

$$H(q) = c^T (qI - A)^{-1} k + 1, \quad (10)$$

For the experiments, a chirp signal and a PRBS signal were generated as input signals to drive the air pump and the hydrogen valve of the PEMFC system, respectively, and the corresponding output voltage was recorded, as shown in Figure 4. The bandwidth of the chirp signal and the PRBS signal were between 0.01 Hz and 10 Hz. Due to the nonlinear properties, we selected three operating points, namely 2A, 3A, 4A, and repeated the experiments three times at each operating point to take the system variations into account. As shown in Figure 5, the PEMFC system was regarded as a multi-input-single-output (MISO) system. The experimental setup is depicted in Figure 6 with the operating conditions illustrated in Table 1.

Figure 4. The input and output signals of the system.

Figure 5. The MISO block structure of the PEMFC system.

(a). The fuel cell system.

(b). The notebook with a DAQ card

(c). The load meter.

Figure 6. The experimental setup for system identification.

By the aforementioned identification techniques, the corresponding transfer functions are illustrated in Table 2 which will be utilized to design a robust controller.

Table 1. The operating conditions.

Input Load	Hydrogen valve control signal	Air pump control signal
2A	10mHz~5Hz , PBRs signal	10mHz~10Hz , Chirp signal
3A	1.2(LPM)	(Level:2V, Offset:5V)
4A	7(psi)	

Table 2. Transfer functions at the operation points.

	2A		3A		4A	
Transfer function	Air pump	Hydrogen valve	Air pump	Hydrogen Valve	Air pump	Hydrogen Valve
1	$G_{11} = \frac{[-0.151s - 6.488]}{[s^2 + 4.436s + 14.23]} \frac{0.141s - 3.426}{s^2 + 4.436s + 14.23}$		$G_{12} = \frac{[-0.116s - 6.942]}{[s^2 + 12s + 110.2]} \frac{0.252s - 1.611}{s^2 + 12s + 110.2}$		$G_{13} = \frac{[-0.135s - 4.212]}{[s^2 + 12.56s + 58.38]} \frac{0.285s - 2.099}{s^2 + 12.56s + 58.38}$	
2	$G_{21} = \frac{[-0.085s - 6.784]}{[s^2 + 12.59s + 13.82]} \frac{0.204s - 2.963}{s^2 + 12.59s + 13.82}$		$G_{22} = \frac{[-0.12s - 6.367]}{[s^2 + 10.7s + 75.94]} \frac{0.236s - 2.124}{s^2 + 10.7s + 75.94}$		$G_{23} = \frac{[-0.139s - 5.118]}{[s^2 + 10.93s + 51.40]} \frac{0.253s - 2.13}{s^2 + 10.93s + 51.40}$	
3	$G_{31} = \frac{[-0.102s - 8.148]}{[s^2 + 13.09s + 18.38]} \frac{0.245s - 3.016}{s^2 + 13.09s + 18.38}$		$G_{32} = \frac{[-0.1s - 6.236]}{[s^2 + 13.32s + 74.77]} \frac{0.263s - 2.05}{s^2 + 13.32s + 74.77}$		$G_{33} = \frac{[-0.131s - 5.203]}{[s^2 + 13.9s + 73.3]} \frac{0.288s - 2.284}{s^2 + 13.9s + 73.3}$	

III. PULSE WIDTH MODULATION THEORY

In this section, the PWM theory will be briefly introduced. In recent years, the combination of PWM and fast-switch valves has been widely used in the control field, especially for pneumatic and fluid control [15]. Because the hydrogen flow rate is controlled by an electrical valve, we can tune the exact hydrogen flow rate by applying PWM theory. PWM is a modulation technique that uses a sinusoidal signal or a frequency pulse signal to generate variable-width pulses in order to represent the amplitude of an analog input signal, as illustrated in Figure 7.

Figure 7. Illustration of Pulse Width Modulation.

The saw-tooth signal in the figure is called a “carry signal” and is applied to modulate the input signal. The period of the modulated output signal is the same as the period of carry signal, T_c . The duty ratio τ is defined as:

$$\tau = T_{on} / T_c, \quad (11)$$

which is the operating time of the valve, and depends on T_{on} . With an increase in operating time, the PEMFC system gets more hydrogen. In general, the frequency and the amplitude of carry signals must be higher and wider than those of input signals. For the experiments, we employed a 2/2-way valve as the hydrogen control valve with a switch frequency of about 1K Hz and a maximum power consumption of 5.4 W.

IV. ROBUST CONTROLLER DESIGN

From the analysis of gap metrics and coprime factorization, a robust controller will be designed to provide the maximum stability bound for the fuel cell system. The resulting controller which combines PWM with Robust control methodologies will then be applied to experiments to verify the effect.

Theorem 1 (Small Gain Theorem) [7]:

Suppose $M \in RH_\infty$ and let $\gamma > 0$. Then the interconnected system shown in Figure 8 is well posed and internally stable for all $\Delta(s) \in RH_\infty$ with (a) $\|\Delta\|_\infty \leq 1/\gamma$ if and only if $\|M(s)\|_\infty \leq \gamma$; (b) $\|\Delta\|_\infty < 1/\gamma$ if and only if $\|M(s)\|_\infty < \gamma$, where $\|G\|_\infty$ is the ∞ norm of system G .

Figure 8. Small Gain Theorem.

Suppose that a nominal plant G_0 can be expressed as $G_0 = M^{-1}N$, where (1) $M, N \in RH_\infty$ and (2) $MM^* + NN^* = I$, $\forall \omega$. This is called a normalized left coprime factorisation of G_0 . Suppose that a perturbed system G_Δ with the block diagram of Figure 9 is expressed as:

$$G_\Delta = (M + \Delta_m)^{-1}(N + \Delta_N), \quad (12)$$

with $\|[\Delta_M, \Delta_N]\|_\infty < \varepsilon$, $\Delta_M, \Delta_N \in RH_\infty$, the system transfer functions can be simplified as follows:

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} K \\ I \end{bmatrix} (I - GK)^{-1} M^{-1} \omega = \begin{bmatrix} K \\ I \end{bmatrix} (I - GK)^{-1} [I \quad G] \omega, \quad (13)$$

Thus, from Theorem 1, the closed-loop system remains internally stable for all $\|[\Delta_M, \Delta_N]\|_\infty < \varepsilon$ if and only if

$$\left\| \begin{bmatrix} K \\ I \end{bmatrix} (I - GK)^{-1} M^{-1} \right\|_\infty \leq \frac{1}{\varepsilon},$$

or equivalently

$$\left\| \begin{bmatrix} K \\ I \end{bmatrix} (I - GK)^{-1} [I \quad G] \right\|_\infty \leq \frac{1}{\varepsilon}. \quad (14)$$

Definition 1: Stability Margin:

The stability margin $b(G, K)$ of the closed-loop system is defined as follows:

$$b(G, K) \equiv \left\| \begin{bmatrix} K \\ I \end{bmatrix} (I - GK)^{-1} [I \quad G] \right\|_\infty^{-1}, \quad (15)$$

Thus from Theorem 1 the closed-loop system is internally stable for all $\|[\Delta_M, \Delta_N]\|_\infty < \varepsilon$ if and only if $b(G, K) \geq \varepsilon$.

Figure 9. The block diagram of G_Δ with a feedback controller K .

It is further noted that the coprime factorisation of a system is not unique. That is, there is more than one expression for G_0 and G_Δ . Therefore, the gap between two systems G_0 and G_Δ can be defined as:

Definition 2: Gap Metric [7]:

The smallest value of $\|[\Delta_M, \Delta_N]\|_\infty$ which perturbs G_0 into G_Δ , is called the gap between G_0 and G_Δ , and is denoted as $\delta(G_0, G_\Delta)$.

Thus, $b(G, K)$ gives the radius (in terms of the distance in the gap metric) of the largest ball of plants stabilized by the controller K . Therefore, the design goal is to derive a suitable

controller K from a nominal plant G_0 , such that all perturbed plants G_i located inside the gap $\delta(G_0, G_i) < \varepsilon$ will satisfy $b(G, K) \geq \varepsilon$ and the closed-loop system remains internally stable.

From the identification results of Section II, the gap between all plants are illustrated in Table 3.

Table 3. The gap between plants.

	G_{i1}	G_{i2}	G_{i3}	G_{i4}	G_{i5}	G_{i6}	G_{i7}	G_{i8}	G_{i9}
G_{i1}	0	0.2956	0.2702	0.4293	0.4078	0.4068	0.4107	0.3883	0.4146
G_{i2}	0.2956	0	0.0605	0.4156	0.3932	0.3941	0.4	0.3756	0.4029
G_{i3}	0.2702	0.0605	0	0.3649	0.3424	0.3434	0.3502	0.3249	0.3532
G_{i4}	0.4293	0.4156	0.3649	0	0.0283	0.0263	0.0341	0.0468	0.0263
G_{i5}	0.4078	0.3932	0.3424	0.0283	0	0.0195	0.0361	0.0273	0.0293
G_{i6}	0.4068	0.3941	0.3434	0.0263	0.0195	0	0.0185	0.0215	0.0137
G_{i7}	0.4107	0.4	0.3502	0.0341	0.0361	0.0185	0	0.0283	0.0088
G_{i8}	0.3883	0.3756	0.3249	0.0468	0.0273	0.0215	0.0283	0	0.0302
G_{i9}	0.4146	0.4029	0.3532	0.0263	0.0293	0.0137	0.0088	0.0302	0
max	0.4293	0.4156	0.3649	0.4293	0.4078	0.4068	0.4107	0.3883	0.4146

The selection of the nominal plants $G_0(s)$ was based on the calculation of system gaps between the nominal plants and the perturbed plants such that the maximum gap is minimized as:

$$\min_{G_0} \max_{G_i} \delta(G_0, G_i), \quad (16)$$

Therefore,

$$G_{13} = \left[\frac{-0.102s - 8.148}{s^2 + 13.09s + 18.58} \quad \frac{0.245s - 3.016}{s^2 + 13.09s + 18.58} \right], \quad (17)$$

was chosen as the nominal plant because the maximum gap between G_{13} and other plants is 0.3649, which is the minimum for all systems (see Table 3). In order to balance the requirements between stability and performance [9, 11], we added the weighting function

$$W_1(s) = \begin{bmatrix} \frac{s+1}{s} & 0 \\ 0 & 1 \end{bmatrix}, \quad (18)$$

to eliminate the steady-state errors. The H_∞ robust controller for the shaped plant $G_{13}W_1$ is designed as follows:

$$K_{13}(s) = \left[\frac{0.9372s^2 + 13.18s^2 + 29.08s + 16.84}{s^3 + 14.02s^2 + 15.79s} \quad \frac{0.1091s^2 + 1.407s + 1.794}{s^2 + 14.02s + 15.79} \right], \quad (19)$$

with a stability bound of $b(G_{13}W_1, K_{13}) = 0.7273$, which is greater than the maximum plant perturbation (0.3649). Therefore, system stability and performance can be guaranteed by the proposed controller.

V. EXPERIMENTAL RESULTS

In order to implement the controller, the controller $K_{13}(s)$ was transferred to z -domain (with sampling time of 0.01 second) as follows:

$$K_{13}(z) = \left[\frac{0.9372z^3 - 2.687z^2 + 2.564z - 0.8149}{z^3 - 2.868z^2 + 2.737z - 0.8692} \quad \frac{0.1091z^2 - 0.205z + 0.09602}{z^2 - 1.868z + 0.8692} \right]. \quad (20)$$

The block diagram of the controller structure in the MatlabTM is illustrated in Figure 10.

Figure 10. The implemented controller structure.

Following implementation of the designed controller, the experimental results are shown in Figures 11-13, with the output voltage set as 9V. Figure 11 shows the output responses at fixed loadings of 2A, 3A and 4A, respectively. The voltage output and air-pump variations are shown in Figure 12, where the loading conditions vary as 2A→3A→4A→3A→2A. Figure 13 shows the responses of output voltage, when the loading current is set as 3A and the command voltage varies as 7v→8v→9v→8v→7v. It is shown that the closed-loop system remained internally stable under system perturbations, and that the steady-state error was zero because of the integral factor of the weighting function.

Figure 11. Output voltage responses for loadings 2A, 3A and 4A.

Figure 12. The output voltage as the loading current varies 2A→3A→4A→3A→2A

Figure 13. Output voltage to references: 7v→8v→9v→8v→7v, (loading current set as 3A)

Table 4 describes the root mean square error of the output voltage, average operation voltage of the air-pump, and average duty ratio of the hydrogen valve, taken from Figure 11 in the interval of $t \in [10, 200]$ sec. It is shown that the multi-variable H_∞ robust controller can help reduce hydrogen consumption from 100 % (with the original on-board controller) to about 16-17%. In addition, the controller also demonstrated its excellent tracking ability when the reference voltage varies, which is more efficient than the DC/DC converter.

Table 4. Stochastic data from Figure 11

Set volt 9v, from 10s->200s	2A	3A	4A
RMS of output voltage error	0.0268	0.021	0.025
Air pump average voltage (V)	2.661	3.29	3.954
Average duty ration of hydrogen	0.163	0.167	0.162

Although the present study has demonstrated the practical applications, it is noted that the limitation of this design is the external power supply. That is, at this moment, the controller circuit consumes power from an external power source, and is implemented in a notebook. Therefore, future research should be carried out to integrate the robust controller with the PEMFC system as an SOC (system on chip).

VI. CONCLUSION

In this paper, the dynamics of the PEMFC was described and modeled as a MIMO system. By fixing the output resistance, we aimed to control the output voltage by tuning the hydrogen and air flow rates through a multivariable robust controller. From the experimental results, the proposed robust controller was deemed to achieve robust performance and to reduce hydrogen consumption of the system.

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