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Cathode Pressure Control of Air Supply System for PEMFC ⋆

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Abstract: This paper proposes a backstepping method controller for the polymer electrolyte membrane fuel cell (PEMFC)air supply system. The control objective is adjusting the cathode pressure to its reference value quickly, in order to solve the problem of excessive extreme pressure difference between anode and cathode in practice. Considering model uncertainty and some disturbances, we design an extend state observer (ESO) to estimate disturbances. Next, a backstepping method is proposed to adjust control law. Finally, the experiment results demonstrate the effectiveness and robustness of the control strategy.

Keywords: PEMFC, Air supply system, Cathode pressure tracking control, ESO, Backstepping method.

1. INTRODUCTION

In recent decades, full cell technologies have received much attention due to the emission of Green House Gases Wang et al. (2011), Wu (2016). Among the different types of fuel cells, the PEMFC ,which plays a key role in vehicle field owing to low operating temperature, zero emissions, high power density, high efficiency, and excellent dynamic characteristics, is an electrochemical device that converts chemical energy to electrical energy by combining oxygen and hydrogen Pukrushpan et al. (2004), Jung et al. (2012), Alaefour et al. (2012), Hillstrom et al. (2013).

However, because PEMFC has a strong nonlinear characteristic, accurate control scheme is required. The air feed systems have great influence on the performance of PEMFC. Extreme pressure difference between cathode and anode will damage proton exchange membrane (PEM). Besides, if the oxygen is insufficient in the cathode, it will lead to oxygen starvation and cut the life of PEMFC Ma et al. (2020). Inversely, excessive oxygen will generate the parasitic power to decrease operating efficiency for PEMFC. Therefore, in order to avoid above problems, it is necessary to propose a reasonable control strategy to realize better air flow rates and pressures.

In the past, many models have been proposed for air supply systems. A classic ninth-order nonlinear model was proposed in Pukrushpan (2003) to describe air feed system. However, since high order model is so complex, it is not suited to the design of control strategies. Hence, many control-oriented models simplified were proposed. Neglecting humidity and temperature dynamics, the ninth-order model was simplified to the fourth-order model in Ref Suh (2006). Furthermore, through replacing the partial pressure of oxygen and nitrogen with the cathode pressure, the above model order was reduced from four to three states in Ref Talj et al. (2009) . The third-order model is widely applied to air supply system control owing to a better description of the control problem.

Many researchers have proposed several linear and nonlinear control strategies for the air supply system of PEMFC. A linear quadratic Gaussian controller was proposed to realize cathode pressure tracking control Bao et al. (2006). In this control strategy, although the steady state performance is guaranteed by the action of integrator when operating is far from linear point, strong integration will make the system unstable. In Gruber et al. (2009), J. K. Gruber et al. present a linear model predictive control(MPC) to realize the control of oxygen excess ratio. However, since linear controllers are dependent on model and can not be controlled with high precision, many nonlinear control schemes are proposed. Zhao et al. (2013) design a decentralized sliding-mode controller (DSMC)based on super twisting algorithms to realize to control flow and pressure separately. Although DSMC has the ability to avoid model uncertainties, it generates tremors due to the rate of control passing through the sliding surface. Research Ouyang et al. (2017) proposed a nonlinear model predictive control (NMPC) to control the air feed system

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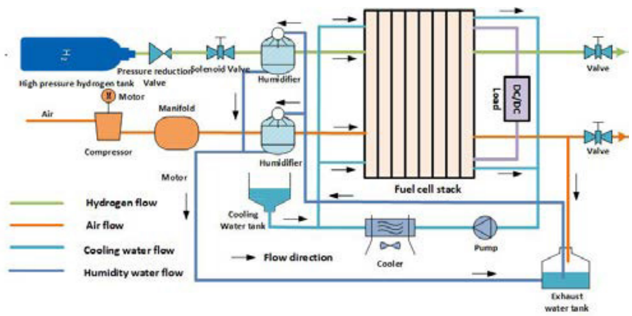

Fig. 1. PEMFC system structure schematic

in order to ensure an adequate oxygen supply. The above control strategies have their own advantages in their respective applications.

To acquire optimal performance, cathode pressure control is the focus of our research. Hence, we propose a closed-loop control strategy based on backstepping method. First, a control-oriented model is established and a second order model is obtained. Second, ESO is introduced to estimate model uncertainty and external disturbances. Finally, a backstepping method is proposed to design control law for cathode pressure tracking the reference value, and the control scheme has the strong robustness.

The remainder of this paper is organized as follows: A control-oriented model is established in section 2. In section 3, we design an ESO to estimate unknown disturbances and propose a backstepping method to track the reference trajectory. Experimental verification and analysis results are given in section 4. Finally, the conclusions are proposed in section 5.

2. SYSTEM DESCRIPTION AND MODELING

2.1 System Description and Problem Statement

A schematic diagram of a PEMFC is shown in Figure 1, which includes four auxiliary subsystems Pukrushpan (2003): the hydrogen supply subsystem, the air supply subsystem, the humidity and thermal management subsystem and the energy management subsystem. For hydrogen supply subsystem, the hydrogen is stored in a high-pressure hydrogen tank and supply to the anode through a pressure release valve and ejector. For air supply system, the air is compressed by compressor which supplies to cathode. For humidity and thermal subsystem, it is mainly the humidification of the gas entering the stack and reduce the system temperature. For energy subsystem, it draw the power from PEMFC to deliver to electrical device.

In this paper, we mainly focus on the control of air supply subsystem. The main control objective is to realize cathode pressure tracking the reference value. Hence, a control-oriented model of air supply system is built and design a reasonable control strategy for the model.

2.2 Modeling of System

Modeling of the cathode. The dynamics of the cathode includes thermodynamics properties, ideal gas equilibrium properties and electrochemical properties, which describes the change of air flows and pressure. The dynamic equation of the cathode can be expressed as equation (1):

$$\frac{\mathrm{d}p_{ca}}{\mathrm{d}t} = \frac{R_a T_{st}}{V_{ca}}(W_{cp} - W_{ca,out}) - \frac{R_{O_2} T_{st}}{V_{ca}} W_{O_2,react}. \tag{1}$$

where R_a and R_{O_2} denote air gas constant and oxygen gas constant, V_{ca} is the volume of the cathode, T_{st} is the operating temperature of the cathode and can be measured in real time. The flow rate W_{cp} can be measured. The oxygen consumption rate $W_{O_{2,react}}$ is related to load current I_{st} in equation (2):

$$W_{O_{2,react}} = \frac{n_{cell} M_{O_2}}{4F} I_{st}. \tag{2}$$

where n_{cell} is the number of PEMFC cells, M_{O_2} is the oxygen molar mass, and F is the Faraday constant.

The outlet air flow rate $W_{ca,out}$ is represented by cathode pressure p_{ca} and throttle opening angle θ :

$$W_{ca,out} = f\left(p_{ca}, \theta\right) \tag{3}$$

the analytic form is not given due to the great difference between the actual system and it.

Modeling of the throttle. The throttle is located at the cathode outlet and is connected to the exhaust port. We control the throttle opening angle to adjust proper pressure in the cathode. The dynamic equation of the throttle can be described in equation (4):

$$\dot{\theta} = \frac{1}{T_{tr}}\left(-\theta + \theta^*\right) \tag{4}$$

where T_{tr} denote the response time constant of the throttle, and θ^* is the throttle opening angle command.

According to equation from (1) to (4), a space-state equation is gained:

$$\begin{aligned} \dot{x}_1 &= -a_1 f\left(p_{ca}, \theta\right) + a_1 W_{cp} - a_2 I_{st} \\ \dot{x}_2 &= \frac{1}{a_3}\left(-x_2 + u\right) \end{aligned} \tag{5}$$

where the state of the system is $x = [x_1 \quad x_2]^T = [p_{ca} \quad \theta]^T$, $u = \theta^*$ is the control input. The parameters are given in Table 1.

The output $y = p_{ca}$ as shown by equation (6):

$$y = x_1 \tag{6}$$

Table 1. The value of parameters

R_a	$8.314J/(mol*k)$
V_{ca}	$0.0061m^3$
R_{O_2}	$8.313J/(mol*k)$
n_{cell}	180
F	96485
M_{O_2}	$0.032kg/mol$
T_{tr}	10

3. BACKSTEPPING CONTROLLER DESIGN

In order to solve the control problem in section 2.1, it is necessary for the system to propose a effective control scheme. An ESO is proposed to estimate the cathode pressure. The control input u is obtained by backstepping controller.

3.1 Disturbance Observation

The model uncertainties and external disturbances will have great influences on the stability and tracking performance of the controller. Hence, the ESO is designed to estimate all disturbances. According to the study of ESO is introduced in ref Liu et al. (2018), the equation (5) can be rewritten as follows:

$$\dot{x}_1 = -a_1 f(p_{ca}, \theta) + a_1 W_{cp} - a_2 I_{st} + d \tag{7}$$

where d is disturbance. And an ESO for equation (8) is constructed:

$$\begin{aligned} \dot{\hat{x}}_1 &= -a_1 f(p_{ca}, \theta) + a_1 W_{cp} - a_2 I_{st} + \hat{d} + \beta_{01}(\hat{x}_1 - x_1) \\ \dot{\hat{d}} &= \beta_{02}(\hat{x}_1 - x_1) \end{aligned} \tag{8}$$

where β_{01}=$2\omega_0$ and β_{02}=ω_0^2 are the observer gains and ω_0 denote the observer bandwidth.

Define the extend observer error $e = \hat{x}_1 - x_1$ and $e_d = \hat{d} - d$. Then, a error state space equation can be written as:

$$\begin{bmatrix} \dot{e} \\ \dot{e}_d \end{bmatrix} = \begin{bmatrix} \beta_{01} & 1 \\ \beta_{02} & 0 \end{bmatrix} \begin{bmatrix} e \\ e_d \end{bmatrix} \tag{9}$$

hence, proper values of $\beta_{0i}, i = 0, 1$ are selected to make the above equation stable, and then Equation (8) is the extend state observer for the system.

3.2 Controller Design

In order to satisfy the needs of fast and accurate tracking cathode pressure, a back-stepping method is proposed in ref Davila (2013). The backstepping method is suitable for nonlinear systems through designing Lyapunov function and virtual control input to set control law. The details are given as follows.

Step 1: Defining desired pressure x_{1d} and introducing a tracking error e_1 as shown by equation (10):

$$e_1 = x_{1d} - x_1 \tag{10}$$

A Lyapunov function is selected as:

$$V_1 = \frac{1}{2} e_1^2 \tag{11}$$

then, differentiating the above equation obtain:

$$\begin{aligned} \dot{V}_1 &= e_1 \dot{e}_1 \\ &= e_1 (\dot{x}_{1d} - \dot{x}_1) \\ &= e_1 (\dot{x}_{1d} + a_1 f(p_{ca}, \theta) - a_1 W_{cp} + a_2 I_{st} - d) \end{aligned} \tag{12}$$

Obviously, when $\dot{x}_{1d} + a_1 f(p_{ca}, \theta) - a_1 W_{cp} + a_2 I_{st} - d = -k_1 e_1$, the $\dot{V}_1 = -k_1 e_1^2 \leq 0$ where k_1 is a positive constant. Therefore, we can obtain:

$$f(p_{ca}, \theta) = \frac{-k_1 e_1 - \dot{x}_{1d} + a_1 W_{cp} - a_2 I_{st} + d}{a_1} \tag{13}$$

Since the pressure can be measured, we get the virtual input θ by reverse lookup table.

Step 2. Defining a tracking error as:

$$e_2 = x_{2d} - x_2 \tag{14}$$

and its Lyapunov function can be defined as:

$$V_2 = \frac{1}{2} e_2^2 \tag{15}$$

Fig. 2. PEMFC Engine System

by differentiating equation (15):

$$\begin{aligned} \dot{V}_2 &= e_2 \dot{e}_2 \\ &= e_2 (\dot{x}_{2d} - \dot{x}_2) \\ &= e_2 \left(\dot{x}_{2d} + \frac{1}{a_3} x_2 - \frac{1}{a_3} u \right) \end{aligned} \tag{16}$$

let $\dot{x}_{2d} + \frac{1}{a_3} x_2 - \frac{1}{a_3} u = -k_2 e_2$, the $\dot{V}_2 = -k_2 e_2^2 \leq 0$.Where k_2 is positive constant. Hence, we can obtain:

$$u = a_3 k_2 e_2 + a_3 \dot{x}_{2d} + x_2 \tag{17}$$

We define a Lyapunov function:

$$\begin{aligned} V &= V_1 + V_2 \\ &= \frac{1}{2} e_1^2 + \frac{1}{2} e_2^2 \end{aligned} \tag{18}$$

then, differentiating the equation(18):

$$\begin{aligned} \dot{V} &= \dot{V}_1 + \dot{V}_2 \\ &= e_1 \dot{e}_1 + e_2 \dot{e}_2 \\ &= -k_1 e_1^2 - k_2 e_2^2 \leq 0 \end{aligned} \tag{19}$$

where $\dot{V} = 0$ is satisfied only occurs when $\dot{V}_1, \dot{V}_2$ less than or equal zero. Therefore, the closed-loop system is asymptotically stable.

4. EXPERIMENTAL VERIFICATION

To validate the effectiveness of the backstepping controller based on ESO , detailed experiments and analysis are performed. And we propose the controller to conduct on a real PEMFC system.

4.1 Experimental environment

The experiments have been conducted on the real system as shown in Figure 2. And Figure 2 shows air supply system. The system includes some components, which are consist of a screw compressor, 30KW stack and throttle. Moreover, the dspace is implemented the control strategy.

Experiments and results Through a series of experiments, the parameters of the controller are selected as follows

$\omega_0 = 50$,$k_1 = 5$, and $k_2 = 1$

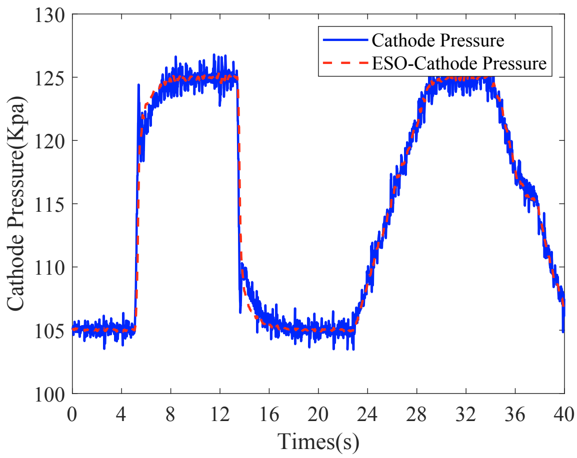

Fig. 3. Comparison between the Plant and ESO for Cathode Pressure

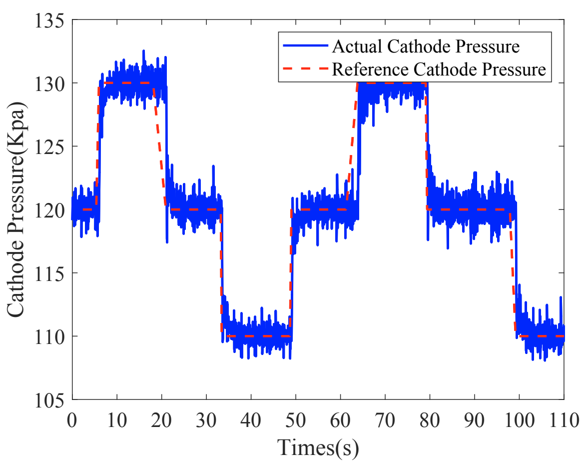

Fig. 4. Tracking of Cathode Pressure

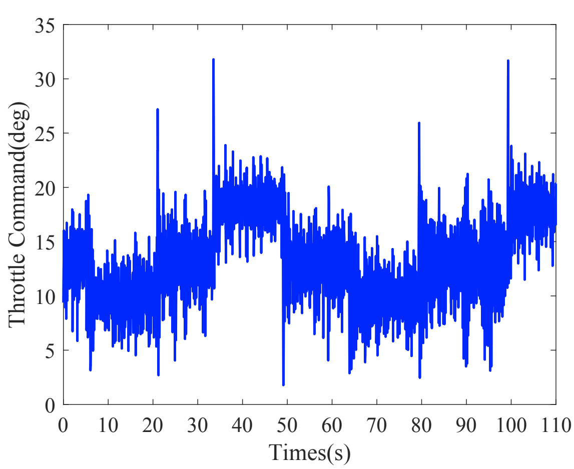

Fig. 5. Throttle Opening Angle Command

In the following, we conduct three experiments to verify the effectiveness of the controller.

In Figure 3, the blue line represents actual cathode pressure and the red line represents estimate cathode pressure. According to this figure, the value of estimate

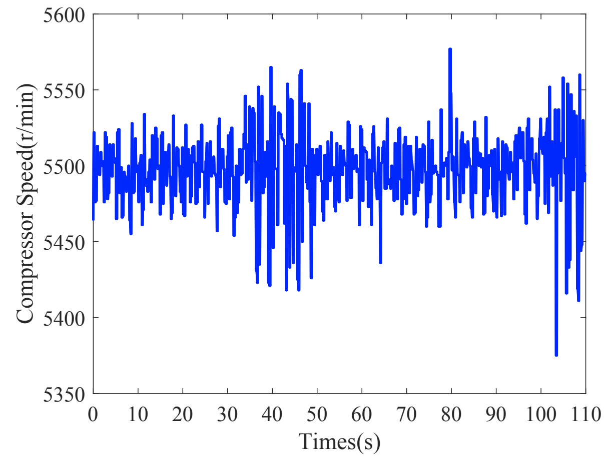

Fig. 6. Compressor Speed

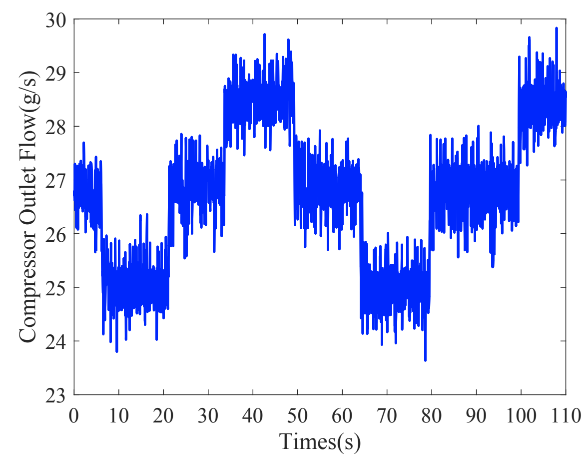

Fig. 7. Compressor Outlet Flow

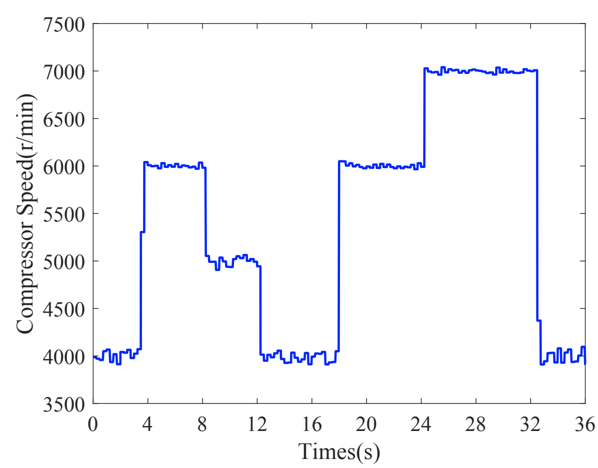

Fig. 8. Compressor Speed

can track the actual value. The result indicates that the model can properly describe the dynamic characteristic of air supply system and overcome the disturbances.

Then, we verify tracking performance. In Figure 4, the blue line is actual cathode pressure and the red line is reference cathode line. The result indicates that

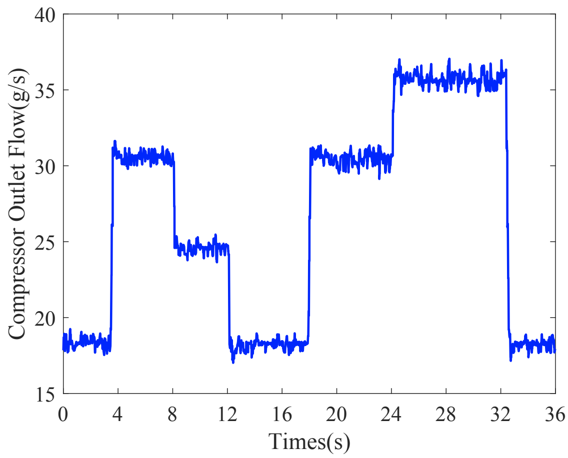

Fig. 9. Compressor Outlet Flow

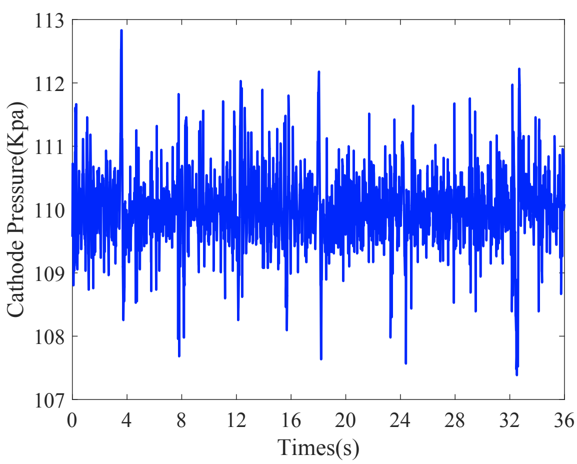

Fig. 10. Cathode Pressure

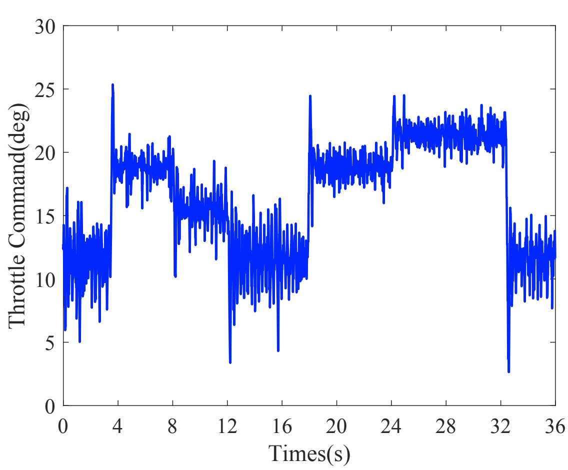

Fig. 11. Throttle Opening Angle Command

when the reference input produces a rising edge, the cathode pressure can quickly track the reference pressure. Similarly, when produces a falling edge, the tracking performance also is acceptable. According to Figure 4 and Figure 6, when keep the compressor speed unchanged, we increase the reference pressure. Owing to increasing pressure, the throttle command will decrease in a moment, corresponding to increasing the resistance of air flow in Figure 5. And the compressor outlet flow also decrease in Figure 7.

In a final pair of experiments, we keep the pressure unchanged to adjust compressor speed in Figure 10. In Figure 8 and Figure 9, giving a rising or falling edge for compressor speed, the compressor outlet flow will increase or decrease. As shown in Figure 9 and Figure 11, when the compressor speed is increased, the throttle command is increased to keep pressure stable at the moment. Similarly, when the compressor speed is decreased, the control effect is satisfactory. Therefore, the controller is proved to have effectiveness by experiments.

5. CONCLUSION

This paper designs a backstepping controller to adjust cathode pressure. A second order nonlinear model of air supply system is built. Then we propose a ESO to estimate and compensate disturbances and the controller is designed by backstepping method. To verify the effectiveness of the controller, different experiments are conducted. The experimental results indicate that the controller is capable of excellent traceability in some disturbances and model uncertainties. In addition, there are some issues to be solved in the following work. The high measurement noise of the system has a certain influence on the control effect.

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