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Oxygen Excess Ratio Controller Design of PEM Fuel Cell

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Abstract: The work of this paper focuses on oxygen excess ratio control, for the oxygen excess ratio has a great influence on the performance of the proton exchange membrane (PEM) fuel cell. To model dynamics of air supply system and oxygen excess ratio, a validated three-order model is used for controller design. Because the pressure of the cathode is unmeasurable in the actual system, a state observer is designed to observe the cathode pressure based on the third-order model. A controller combining with feedforward control and feedback control based on LQR method and map that can output the equilibrium state, feedforward control signal and feedback gain calculated off-line at different equilibrium points through the input of the expected oxygen excess ratio and load current is then designed. At last, oxygen excess ratio control strategy under different working conditions is realized and the simulation results verify the effectiveness of the proposed controller.

Keywords: PEM fuel cell, State observer, Oxygen excess ratio, LQR method.

1. INTRODUCTION

Energy consuming reduction and environmental protection against pollutants and greenhouse gas emission have become the core propulsion of sustainable energy development in recent years. Among the ongoing efforts and solutions, fuel cells are considered as the best solution to environmental pollution and energy problems. In many types of fuel cell systems, PEM fuel cell which is a kind of complex device (Carrette et al. (2001)) that converts the chemical energy of hydrogen and oxygen directly into electrical energy through electrochemical reactions, is thought to be the most promising choice because of its advantages of clean, high efficiency, low working temperature (Beheshti et al. (2015), Kunusch et al. (2008), Hall and Kerr (2003)). Especially in the field of transportation, PEM fuel cell engine vehicle has become the main battlefield of major automobile manufacturers such as Toyota Motor Corporation, Honda Motor Corporation and Hyundai Motor Corporation. In PEM fuel cell, air supply system has great influence on the performance which the optimal oxygen excess ratio is determined to minimize the voltage drop, undershoot, and voltage fluctuation under the load change (Kim et al. (2015)). On the one hand, since the air supply flow is controlled by the air compressor, system efficiency will reduce without changing the air supply flow when the load is reduced. On the other hand, because of the dynamic process of the compressor and the time delay of the air supply system, electrochemical reaction rate will accelerate when the current load increase, leading to acceleration of oxygen consumption rate, which can cause oxygen starvation (Suh (2006)). Improper air supply control can reduce the output power and shorten service life of the fuel cell stack (Pukrushpan et al. (2004)). Therefore, it is very important to control oxygen excess ratio so that adequate but necessary oxygen can be supplied to cathode channel to ensure high efficiency of fuel cell system.

For the above mentioned problems, many researchers have carried out a large number of researches and experiments on the model and control of PEM fuel cell air supply subsystem. Several different control models are proposed for various purposes. A nine-order nonlinear model based on gas dynamics, thermal dynamics proposed by Pukrushpan (2003) is widely used and verified. In this model,the dynamic process of the air supply system is described in detail, but the complexity of the model is too high to be used for control of the system. Through reasonable assumption, nine-order nonlinear model can approximately simplified as four-order model, including four states: the speed of compressor, supply manifold pressure, nitrogen gas pressure and oxygen pressure inside the cathode, see Pukrushpan et al. (2004). As further simplification, the fourth-order model is transformed into a third-order model by Talj et al. (2010), then model based air supply control becomes reasonable and feasible.

In the past decade, different effective control strategies have been proposed to control oxygen excess ratio. Through linearizing the model, the LQR controller to control oxygen excess ratio is designed by Pukrushpan (2003).

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However, due to the measurement error and system error in high model order, it is difficult to guarantee the performance of the system. A feedback linearization controller to track variable optimal oxygen excess ratio is proposed by Chen et al. (2017) which is based on the experimental data to build the polynomial of air compressor flow about pressure ratio and the angular velocity. On this basis, the control of oxygen ratio is realized and the stability is proved by lyapunov method. A second-order sliding model control is proposed by Kunusch et al. (2008). Although sliding control has a good effect on system uncertainty, the fluctuation is generated near the equilibrium point which is harmful for the system. By optimization, MPC control method is used in the control of oxygen excess ratio (Gruber et al. (2012)), however, it is difficult to ensure real-time performance in such a fast dynamic engineering application.

Aiming at the control of oxygen excess ratio , this paper puts forward a control method based on map graph, combining feedforward and feedback, which is more suitable for practical engineering problems. First, equilibrium points of air supply system at desired operating conditions are calculated based on the model, then the model is linearized for feedback controller design. Second, based on the operating conditions dependent linearized model, LQR approach is used to synthesize controller gain of feedback channel. In order to apply the proposed method, both equilibrium points and feedback controller gain are stored as map at last, so that little calculation complexity is demanded in implementation.

2. AIR SUPPLY SYSTEM MODEL FOR CONTROLLER DESIGN

In this paper, we focus on controlling the air supply system. A key variable that has a significant impact on the performance of PEM fuel cell is oxygen excess ratio λ_{O_2}, which is the ratio of the amount of oxygen entering the cathode to the amount of oxygen consumed by the electrochemical reaction, see Kim et al. (2015), Arce et al. (2010) and Chen et al. (2017). The formula of λ_{O_2} is shown below.

$$\lambda_{O_2} = \frac{W_{O_2,in}}{W_{O_2,rect}} \tag{1}$$

where $W_{O_2,in}$ represents the flow of oxygen into the cathode which is the proportional function of pressure difference between the supply manifold pressure and the cathode pressure. $W_{O_2,rect}$ represents the oxygen consumption of electrochemical reaction which is proportional function of the load current. Two variables can be represented by the following formula.

$$\begin{aligned} W_{O_2,in} &= K_{sm,out} \times \omega_{O_2}(P_{sm} - P_{ca}) \\ W_{O_2,rect} &= \frac{nM_{O_2}I_{st}}{4F} \end{aligned} \tag{2}$$

where $K_{sm,out}$ is the supply manifold outlet orifice constant, ω_{O_2} is the oxygen mass fraction, P_{sm} is the internal pressure of the supply manifold, and P_{ca} is the cathode pressure, I_{st} is the load current. n is the number of cells in the stack, M_{O_2} is the oxygen molar mass, F is the Faraday number.

Because the oxygen excess ratio is a function of the P_{sm} and P_{ca}, the dynamics of these two variables should be considered. In this paper, a simplified three-order model given by Talj et al. (2010) that contains cathode pressure and air supply manifold pressure, is used to describe the air supply system. The model is given as follows.

$$\begin{aligned} \dot{x_1} &= -c_6x_1 - \frac{c_7}{x_1}[(\frac{x_2}{c_8})^{c_9} - 1]f(x_1,x_2) + c_{10}u \\ \dot{x_2} &= c_{11}[1 + c_{12}[(\frac{x_2}{c_8})^{c_9} - 1]] \times [f(x_1,x_2) - c_{13}(x_2 - x_3)] \\ \dot{x_3} &= (c_1 + c_5)(x_2 - x_3) - \frac{c_3(x_3 - c_2)\varphi(x_3)}{c_{14}x_3} - c_4I_{st} \end{aligned} \tag{3}$$

and

$$\lambda_{O_2} = \frac{W_{O_2,in}}{W_{O_2,rect}} = \frac{c_{15}(x_2 - x_3)}{c_{16}I_{st}}$$

where $x_1 = \omega_{cp}$ represents the angular velocity of the air compressor, $x_2 = P_{sm}$ is the pressure of the supply manifold and both x_1, x_2 can be measured by external sensors, $x_3 = P_{ca}$ represents the pressure inside cathode but is unmeasured. The air supply subsystem control input u is the compressor voltage, the load current I_{st} can be regarded as a known disturbance here. $f(x_1, x_2)$ represents the flow rate of the gas outlet of the air compressor, which is a function of the speed of the air compressor and supply manifold pressure. $\psi(x_3)$ represents the outlet flow rate of the cathode which is shown below.

$$\psi(x_3) = \frac{C_DA_Tx_3}{(\bar{R}T_{st})^{0.5}}\gamma^{\frac{1}{2}}(\frac{2}{\gamma+1})^{\frac{\gamma+1}{2(\gamma-1)}}. \tag{4}$$

where C_D and A_T represent throttle discharge coefficient and throttle area respectively. $\bar{R}$ is gas constant. T_{st} and λ represent the cathode temperature and ratio of specific heat of air. c_i(i=1,2,3......15), as well as parameters in Eq. (4) are all known parameters that can be calculated according to the data in Talj et al. (2010), as seen in Table 1.

Table 1. Parameters in Eqs. (3) and (4)

$c_1 = 8.554$	$c_2 = 47200$
$c_3 = 293501$	$c_4 = 289.745$
$c_5 = 28.166$	$c_6 = 5.62275$
$c_7 = 7483565000$	$c_8 = 101325$
$c_9 = 0.285714$	$c_{10} = 367.5$
$c_{11} = 4277032.738$	$c_{12} = 1.25$
$c_{13} = 0.000003625$	$c_{14} = 0.02585$
$c_{15} = 0.0000008455$	$c_{16} = 0.00003159$
$T_{st} = 353$	$C_D = 0.0124$
$A_T = 0.002$	$\gamma = 1.4$
$\bar{R} = 8.3145$	

3. STATE OBSERVER

Because the cathode pressure x_3 in Eq. (3) is not measurable, in order to control oxygen excess ratio, it is necessary to design a state observer to online estimate the cathode pressure so that oxygen excess ratio is able to be calculated based on Eqs. (1) and (2) for feedback control. According to the observer designed in Zhao et al. (2014), the system is reformed as follows:

$$\begin{aligned} \dot{x_2} &= \lambda \times [f(x_1,x_2) - c_{13}(x_2 - x_3)] \\ \dot{x_3} &= (c_1 + c_5)(x_2 - x_3) - \frac{c_3(x_3 - c_2)\varphi(x_3)}{c_{14}x_3} - c_4I_{st} \end{aligned} \tag{5}$$

where

$$\lambda = c_{11}[1 + c_{12}[(\frac{x_2}{c_8})^{c_9} - 1]]$$

and $f(x_1, x_2)$ are measurable variables. According to the design principle of Luenberger observer, the design method of state observer is as follows.

$$\begin{aligned} \dot{\hat{x}}_2 &= \lambda \times [f(x_1, x_2) \; - c_{13}(\hat{x}_2 - \hat{x}_3)] + l_2(x_2 - \hat{x}_2) \\ \dot{\hat{x}}_3 &= (c_1 + c_5)(\hat{x}_2 - \hat{x}_3) - \frac{c_3(\hat{x}_3 - c_2)\varphi(\hat{x}_3)}{c_{14}\hat{x}_3} \\ &\quad - c_4 I_{st} + l_3(x_2 - \hat{x}_2) \end{aligned} \tag{6}$$

where the gain l_2, l_3 are designed observer gains. Define the error between the observed value $\hat{x}$ and the actual value x as

$$[\, e_2 \;\; e_3 \,]^T = [\, \hat{x}_2 - x_2 \;\; \hat{x}_3 - x_3 \,]^T$$

According to Eq. (4), introduce a constant

$$c_{17} = \frac{\psi(x_3)}{x_3} = \frac{C_D A_T}{(\bar{R}T_{st})^{0.5}} \gamma^{\frac{1}{2}} (\frac{2}{\gamma + 1})^{\frac{\gamma+1}{2(\gamma-1)}}$$

then the error vector is calculated as follows.

$$\begin{aligned} \begin{bmatrix} \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} &= \begin{bmatrix} -c_{13}\lambda - l_2 & c_{13}\lambda \\ (c_1 + c_5) - l_3 & -(c_1 + c_5 + \dfrac{c_3 c_{17}}{c_{14}}) \end{bmatrix} \\ &\times \begin{bmatrix} e_2 \\ e_3 \end{bmatrix} \end{aligned} \tag{7}$$

Based on error dynamics of Eq. (7), observer gain can be easily fixed by poles placement method, and $\hat{x}_3$ converges to its real value x_3.

Through the design of the above state observer and the analysis of the convergence conditions, we select $l_2 = 25, l_3 = 90$, and the verification was carried out in Simulink. It can be seen from the curves in Fig. 1, the error of the observer is within one percent and negligible. Thus, based on this observer, we can design the controller for the air supply system, assuming that λ_{O_2} and all states are known.

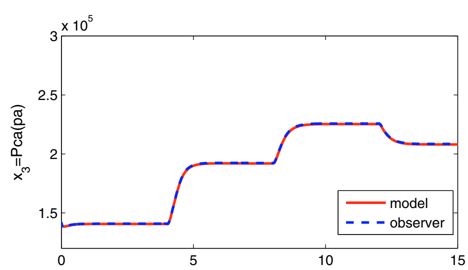


Fig. 1. Comparison of cathode pressure between model and observer

4. CONTROLLER DESIGN

The control goal of the air supply system is to maximize the net power output of the fuel cell, and avoid the occurrence of oxygen starvation. In general, the appropriate value of the oxygen excess ratio can reflect the optimal operation state of the electrochemical reaction.

In Pukrushpan (2003), the value of optimal oxygen excess ratio is considered to be 2.0. In practical applications, the optimal oxygen excess ratio of the PEM fuel cell system may not be 2.0 due to difference of structure and parameters. In Chen et al. (2017), the optimal value of the oxygen excess ratio is the function of the load current calculated through the fitting of data. In this paper, we control the oxygen excess ratio at set point that is given between 1.6 to 2.1 with different load currents.

According to the definition of oxygen excess ratio in Eq. (1), the pressure difference of the supply air manifold pressure and cathode pressure $x = x_2 - x_3$, is introduced as a new state variable, which is proportional to controlled variable λ_{O_2}, then the new state space equation is obtained.

$$\begin{aligned} \dot{x} &= c_{11}[1 + c_{12}[(\frac{x_2}{c_8})^{c_9} - 1]] \times [f(x_1, x_2) - c_{13}x] \\ &\quad -((c_1 + c_5)x - \frac{c_3(x_2 - x - c_2)\varphi(x_2 - x)}{k(x_2 - x)} - c_4 I_{st}) \\ \dot{x}_2 &= c_{11}[1 + c_{12}[(\frac{x_2}{c_8})^{c_9} - 1]] \times [f(x_1, x_2) - c_{13}x] \\ \dot{x}_1 &= -c_6 x_1 - \frac{c_7}{x_1}[(\frac{x_2}{c_8})^{c_9} - 1] f(x_1, x_2) + c_{10}u \end{aligned} \tag{8}$$

with all the states measurable. From the above Eq. (8), it is known that the model is highly nonlinear so that it is challenging to design oxygen excess ration controller based on this complicated model directly. To make controller synthesis easier and track given oxygen excess ratio quickly, a combination of feedforward control and feedback control is constructed and implemented using looking-up table method. The control block diagram is shown in Fig. 2. According to the load current I_{st} and desired oxygen excess ratio $\lambda_{O_2,ref}$, stable input U_0 can be calculated in feedforward channel. At the same time, feedback controller is designed based on linearized model and LQR method, which is also obtained offline and stored as map for online quick implementation. In addition, an integrator is added in the feedback controller design to eliminate the steady state error caused by disturbance or model uncertainty.

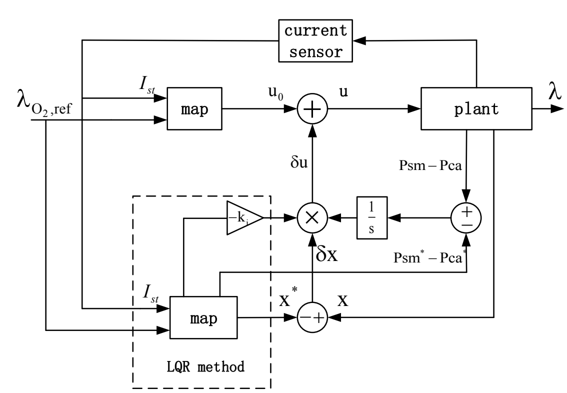


Fig. 2. Control block diagram of oxygen excess ratio

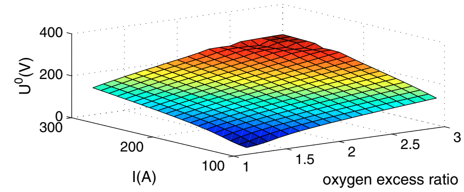
In order to design the feedforward controller of the system, we first calculate the equilibrium point of the system with the given load current I_{st} and oxygen excess ratio set point $\lambda_{O_2,ref}$. For simplicity, Eq. (8) is verified to

$$[\, \dot{x} \;\; \dot{x}_2 \;\; \dot{x}_1 \,]^T = F\,(x, x_1, x_2, u, I_{st})$$

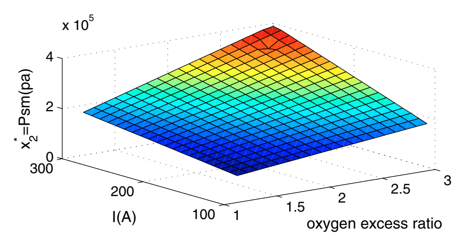
where $F\,(x, x_1, x_2, u, I_{st})$ is equal to the right side of Eq. (8). If the system works at the point $(I_{st}, \lambda_{O_2,ref})$ steadily, the following equation should be held.

$$\left[\,\dot{x}^* \;\, \dot{x}_2^* \;\, \dot{x}_1^*\,\right]^T = F\left(x^*, x_1^*, x_2^*, u^*, I_{st}\right) = 0$$

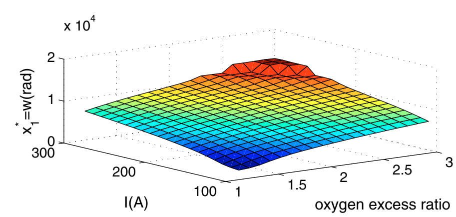
where x^* is determined by $\lambda_{O_2,ref}$, $x^* = \frac{c_{16}}{c_{15}} I_{st} \lambda_{O_2,ref}$, while x_1^*, x_2^* and u^* are the elements of equilibrium point holding the above equality. Especially, u^* at the corresponding equilibrium point can be regarded as the feedback control input U_0 in Fig. 2. Without loss of generality, the values of equilibrium state of x^* can be calculated with different I_{st} and $\lambda_{O_2,ref}$. Then, $x1^*$, $x2^*$ and u^* can be calculated by "fsolve" function in MATLAB. In this paper, desired oxygen excess ratio is changed from 1.6 to 2.1 with 0.1 intervals, and the value of load current ranges from 120 to 270 with 10 intervals. The values of each state and input at different equilibrium points are given by Figs. 3.



(a) Feedforward output u_0



(b) State x_2^* of equilibrium point



(c) State x_1^* of equilibrium point

Fig. 3. x_2^*,x_1^*,u_0 at different I_{st} and $\lambda_{O_2,ref}$

Based on the designed feedforward controller, the steady state of air supply system will converge to the desired oxygen excess ratio $\lambda_{O_2,ref}$ if the system dynamics perfectly matches the model used for equilibrium point calculation. However, feedforward control cannot ensure the transient performance when $\lambda_{O_2,ref}$ or I_{st} is changed, even the steady state tracking error is indispensable when there are some disturbance or model mismatches. To overcome this problem and simplify the feedback controller design process, the nonlinear model given by Eq. (8) is first linearized around equilibrium point, then LQR method is used to design feedback controller.

Suppose system is working around equilibrium point i with $x_{1,i}^*$, $x_{2,i}^*$ and u_i^*, the linear model of tracking error using Taylor expansion can be obtained by

$$\delta\dot{X} = A\left(x_i^*, x_{2,i}^*, x_{1,i}^*\right)\delta X + B\delta u \tag{9}$$

where

$$\delta X = \left[\,x \;\, x_2 \;\, x_1\,\right]^T - \left[\,x^* \;\, x_2^* \;\, x_1^*\,\right]^T, \;\; \delta u = u - u^*$$

and

$$A\left(x_i^*, x_{2,i}^*, x_{1,i}^*\right) = \left.\begin{bmatrix} \dfrac{\partial \dot{x}}{\partial x} & \dfrac{\partial \dot{x}}{\partial x_2} & \dfrac{\partial \dot{x}}{\partial x_1} \\[2ex] \dfrac{\partial \dot{x}_2}{\partial x} & \dfrac{\partial \dot{x}_2}{\partial x_2} & \dfrac{\partial \dot{x}_2}{\partial x1} \\[2ex] \dfrac{\partial \dot{x}_1}{\partial x} & \dfrac{\partial \dot{x}_1}{\partial x_2} & \dfrac{\partial \dot{x}_1}{\partial x_1} \end{bmatrix}\right|_{\substack{x = x_i^* \\ x_2 = x_{2,i}^* \\ x_1 = x_{1,i}^*}},$$

$$B = \left[\,0 \;\, 0 \;\, c_{10}\,\right]^T$$

In order to eliminate steady state tracking error, integral of δx is added to Eq. (9). So we have a fourth-order linear system, it yields

$$\bar{X} = \left[\int \delta x dt \quad \delta X\right]^T$$

and

$$\dot{\bar{X}} = \bar{A}_i \bar{X} + \bar{B}\delta u \tag{10}$$

where

$$\bar{A}_i = \left[\begin{array}{c|c} 0 & 1\;0\;0 \\ \hline 0_{3\times 1} & A\left(x_i^*, x_{2,i}^*, x_{1,i}^*\right) \end{array}\right], \;\; \bar{B} = \begin{bmatrix} 0 \\ B \end{bmatrix}$$

It is apparent that Eq. (10) represents the augmented model around equilibrium point i, and the model parameters depends on x_i^*, $x_{1,i}^*$ and $x_{2,i}^*$. In order to obtain the optimal state feedback control law, the LQR state regulator is adopted in this paper. Define the optimal performance indicators as

$$J = \int (\bar{X}^T Q \bar{X} + \delta u R \delta u) dt$$

where Q and R are nonnegative definite matrices that balances the weights on states and input. Feedback control input obtained by state feedback can be described by

$$\delta u = -K_i \bar{X}$$

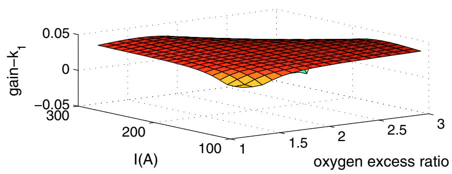
where K_i is the controller gain vector described as

$$K_i = \left[\,k_1 \;\, k_2 \;\, k_3 \;\, k_4\,\right]$$

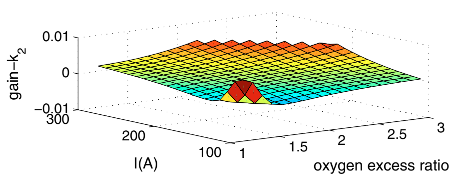
around equilibrium point i. When the desired oxygen excess ratio $\lambda_{O_2,ref}$ and current load I_{st} are changed, the system parameters of Eq. (10) must change as well, resulting in the variation of feedback controller gain by LQR method. In the paper, we first deduce the equilibrium point dependent model based on Eq. (10), then the corresponding control gain K_i can be obtained and stored as lookup table. The optimal oxygen excess ratio and the measured load current are regarded as input to the lookup Table module, and the corresponding gain K_i is the output. In the study, LQR method can obtain the optimal variable control law by adjusting the weight of Q and R matrices, which is easy to form the optimal control of closed-loop. Here, weighting matrices Q, R are set constant and tuned at all equilibrium point, finally are chosen as

$$R = 300, Q = diag\{0.2, 3, 0.01, 0.01\}$$

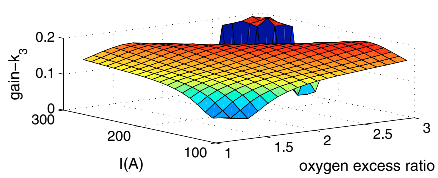
The optimal state feedback gain at different equilibrium points are given in Figs. 4.



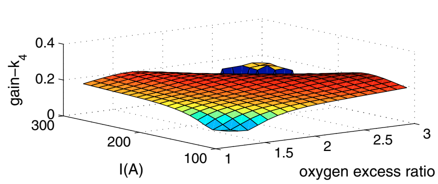
(a) Gain k_1 of feedback controller



(b) Gain k_2 of feedback controller



(c) Gain k_3 of feedback controller



(d) Gain k_4 of feedback controller

Fig. 4. feedback gain of optimal state feedback law using LQR method

5. SIMULATION RESULTS

Based on the research given by Talj et al. (2010), the simulation model in this paper was built in MATLAB/simulink environment. The parameters in the model are derived from Talj et al. (2010) and Pukrushpan (2003). In order to verify the effectiveness of the controller, simulations with different desired oxygen excess ratio and current load I_{st} are carried out.

As can be seen in Fig. 5, this paper selects 120A load current while desired oxygen excess ratio $\lambda_{O_2,ref}$ is changed between 1.6 and 2.1. In this case, if oxygen excess ratio can be controlled to track its reference, it means the proposed method is effective even though the set point of oxygen excess ratio is not constant. Feedforward control signal and feedback control signal are shown in

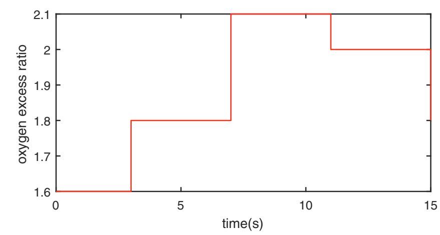


Fig. 5. Desired oxygen excess ratio in simulation

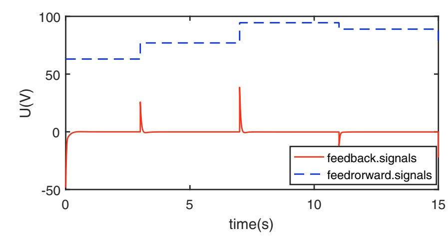


Fig. 6. Feedforward control signal and feedback control signal under different desired oxygen excess ratio

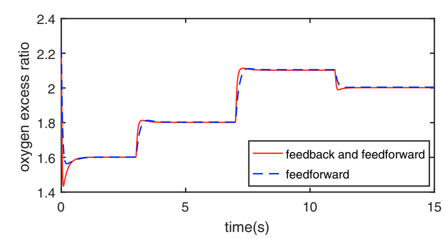


Fig. 7. Effect comparison of two control methods with 120A load current

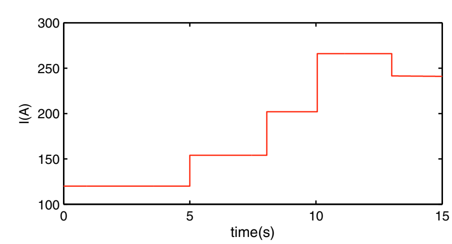


Fig. 8. Current load in simulation

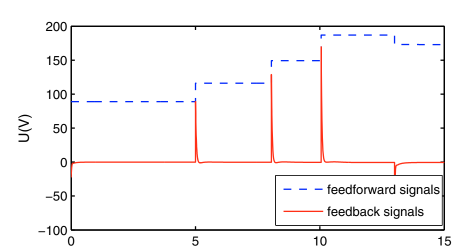


Fig. 9. Feedforward control signal and feedback control signal under different load current

Fig. 6. Obviously, when the desired oxygen excess ratio changes, the feedforward control signal acts on the system as a steady constant control quantity, and the feedback control signal can accelerate the dynamic process of the system. Fig. 7 presents the oxygen excess ratio control performance where $\lambda_{O_2,ref}$ is set to the curve shown in

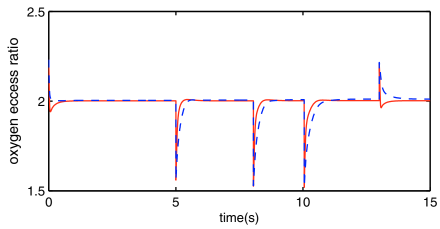


Fig. 10. Effect comparison of two control methods when desired oxygen excess ratio is 2

Fig. 5. Both feedforward control and feedforward control combining with feedback channel are used for comparison. It shows that the feedforward control is enable to track the given oxygen excess ratio, however, the dynamic response time is slower than the result when using feedforward and feedback control.

Constant set point tracking performance with variable current load are shown in Figs. 8 and 10. Current load changes between 120A and 270A in the simulation. If oxygen excess ratio can be controlled to track its set point, it means the proposed method is effective even though the load of PEM fuel cell varies a lot. Feedforward control signal and feedback control signal are shown in Fig. 9. When the current load changes, feedforward control signal combining with feedback control signal control system together. Fig. 10 shows the effect of the tracking fixed oxygen excess ratio when the load changes. In detail, when the system load current rises at 5s, both two controller can track given oxygen excess ratio, but the dynamic response of system with feedforward plus feedback control is faster than that feedforward control only. According to the above simulations, it concludes that the proposed control can control oxygen excess ratio to its set point effectively no mater current load of system is constant or variable.

6. CONCLUSION

Based on the simplified three-order model and state observer, a controller combined with feedback control and feedforward control is proposed. The feedforward control based on map can make the system quickly track the given oxygen excess ratio and the variable feedback control law based on LQR state regulation is used to ensure the dynamic performance of the system.Finally, the simulation results verify the effectiveness of the controller designed in this paper.

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