Oxygen excess ratio control of PEM fuel cell systems with prescribed regulation time

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Jiyuan Kuang, Jianfeng Lv, Wenbo Hao, Xinpo Lin, Dongdong Zhao, Senior Member, IEEE, Imad Matraji, Patrick Muhl, Jianxing Liu*, Senior Member, IEEE.

Abstract

In this paper, we focus on addressing the air supply problem for fuel cells. The air supply system faces a challenge: operating at maximum load consumes a significant amount of power, while insufficient air can lead to oxygen starvation problems in fuel cells. An important metric, the oxygen excess ratio, indicates whether the fuel cell is receiving the appropriate amount of air. Unfortunately, directly measuring this ratio is generally impractical. To overcome this limitation, we propose a fixed-time observer that reconstructs the oxygen excess ratio within a short predetermined period. By utilizing this reconstructed index, we introduce a cascaded double-loop controller. Specifically, both the external and internal loops are regulated using a modified prescribed time control strategy. This approach enables the regulation of the oxygen excess ratio to the optimal value within a prescribed short time. The advantages of our proposed method are validated through hardware in-loop experiments, showcasing its superiority over conventional finite-time control techniques.

Index Terms

Prescribed-time control, Fixed-time observer, Polymer electrolyte membrane fuel cell, Oxygen excess ratio.

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Abstract

In this paper, we focus on addressing the air supply problem for fuel cells. The air supply system faces a challenge: operating at maximum load consumes a significant amount of power, while insufficient air can lead to oxygen starvation problems in fuel cells. An important metric, the oxygen excess ratio, indicates whether the fuel cell is receiving the appropriate amount of air. Unfortunately, directly measuring this ratio is generally impractical. To overcome this limitation, we propose a fixed-time observer that reconstructs the oxygen excess ratio within a short predetermined period. By utilizing this reconstructed index, we introduce a cascaded double-loop controller. Specifically, both the external and internal loops are regulated using a modified prescribed time control strategy. This approach enables the regulation of the oxygen excess ratio to the optimal value within a prescribed short time. The advantages of our proposed method are validated through hardware-in-loop experiments, showcasing its superiority over conventional finite-time control techniques.

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NOMENCLATURE

Abbreviations
PEMFC Proton exchange membrane fuel cell.
OER Oxygen excess ratio.
FXTS Fixed-time stability.
PSTS Prescribed-time stability.

Subscripts
$O_2$ Oxygen.
$N_2$ Nitrogen.
ca Cathode.
atm Atmosphere.
a Air.
st Stack.
cp Compressor.
I. INTRODUCTION

Under the background of carbon neutrality, hydrogen energy is considered a compelling contender due to its characteristic of carbon zero and high energy density [1]. Fuel cells play a pivotal role in converting hydrogen energy into electric energy. Proton exchange membrane fuel cells (PEMFCs) are especially suitable for application in transportation because of their good stability, low operating temperature, rapid startup, and superior power-to-weight ratio. However, the so-called oxygen starvation problem should be solved when PEMFCs operate when loads increase suddenly. Oxygen starvation can impede the chemical reactions within fuel cells and harm membrane surfaces. This requires a sensitive control for air feed systems, which are mainly constructed by a compressor to supply air to the cathode of PEMFCs. While the compressor ensures an adequate reactant supply to PEMFCs, it also consumes power generated by the cells. To maximize the overall net power, numerous experimental findings indicate that the optimal value of oxygen excess ratio (OER) varies from 2 to 2.5 for different loads [2]. When the load changes, the real OER is supposed to track the desired one. However, the OER in the fuel cell stack is usually not measurable in practice. So an OER observer is commonly integrated into the air supply control of PEMFCs [3].

Up to now, numerous methods have been applied in OER control. Intelligent control methods are very popular in OER control for their outstanding performance. The work in [4] revealed the overshoot phenomenon as an inherent control difficulty for systems with nonlinearity, parametric uncertainty, and load disturbances, this overshoot problem is addressed by a data-driven control method. The work in [5] proposed a data-driven PI controller for OER regulation. Simulations show the superiority of robustness, overshoot reduction, and flexibility. The work in [6] adopted an interval type-2 fuzzy logic controller based on a high-gain observer for OER of PEMFC. The work in [7] employed the reinforcement learning algorithm to adjust the PI coefficients of the OER controller. The work in [8] proposed a cascade decoupling controller based on the fuzzy logic technique for the air supply system of a vehicular fuel cell, the simulations confirm the robustness under model uncertainty and external disturbances. The work in [9] applied discrete neural network control to OER regulation to deal with system uncertainty and unknown variables. One drawback of intelligent control methods is the time-consuming offline training process. Moreover, neural networks or fuzzy rule-based control methods lack an explicit model.

The intelligent control methods take a long time to train their networks. In contrast, the model-based methods are more practical. The work in [10] proposed a fractional order PID control based on an unknown input observer. The work in [11] presented a nonlinear three-step controller based on a control-oriented model of a PEMFC, an extended state observer is utilized to estimate the model uncertainty. The work in [12] designed a nonlinear model predictive control (MPC) strategy to regulate the OER. The designed MPC model is based on a second-order Volterra series model. Experimental results show great effect, while the computation is also huge. The work in [13] focuses on the PEMFC working at high altitudes, an extremum search
method is applied to optimize the output power, and an adaptive controller is presented to track the optimal OER value. The work in [14] proposed a high-order sliding mode controller to regulate the OER under system uncertainty and disturbance, its experimental results show great robustness of the sliding mode control.

Above all, the main difficulties in OER control are summarized as follows. First, unmodeled system dynamics and disturbance of PEMFC should be considered to ensure robustness [15]. Second, the OER is usually not measurable or expensive to be measured in most applications [3]. Therefore, an observer is needed to reconstruct the OER. Last but not least, the OER regulation should be accomplished timely. Although finite-time control methods such as super twisting sliding mode control can ensure high accuracy and finite convergence time, the exact upper bound of the convergence time is unknown [16]. Therefore, it is difficult to know whether the OER can track its optimal value in the required time. To address this problem, the following new control methods proposed in this decade are necessary to be introduced. The fixed-time stability (FXTS) ensures the settling time $T(x_0)$ satisfies $T(x_0) \leq T_f, \forall x_0 \in \mathbb{R}^n$, where $T_f$ is a function of several controller parameters but is independent of the initial value of systems $x_0$ [17], [18]. As a comparison, the prescribed-time stability (PSTS) introduces time-varying gain into the controller so that $T(x_0) \leq T_p, \forall x_0 \in \mathbb{R}^n$, where $T_p$ is an independent parameter explicit in the controller [19]. Although the aforementioned methods have been widely applied, their studies on OER control are very limited.

In this work, a fixed-time observer is presented so that the OER can be estimated in a fixed short time. Then, the cascade control structure is utilized to adjust the OER. Specifically, both the outer and inner loops are controlled by the prescribed-time control method. By using these new methods, the OER regulation can be accomplished in a physically possible predetermined time. In other words, it is guaranteed by mathematical results that after a preassigned time, the OER will surely be regulated to the optimal value. Then, a hardware-in-loop experiment will be presented to validate our desired effect. As a comparison, the Kalman filter and traditional finite-time control are also demonstrated to show the characteristics of our proposed method.

This paper is structured as follows. A control-oriented model of the PEMFC air-feed system based on [20] is presented in Section II. Section III gives the fixed-time observer, and the modified prescribed-time controller, which is then applied to both external and internal loops. Section IV presents the detailed controller design. In Section V, the hardware-in-loop experiment results demonstrate the desired performance of our OER control method. Finally, Section VI concludes the paper.

II. SYSTEM MODELING AND PROBLEM STATEMENT

A. Control Oriented Model of the PEMFC Air-feed System

A brief sketch of the PEMFC system is given in Fig. 1. It is noted that the humidity and temperature management subsystems are simplified since they are regulated independently and their behavior is much slower. For the hydrogen supply subsystem, the hydrogen is supplied by a high-pressure tank followed by an injector valve. The hydrogen to the anode is rapidly adjusted by an electronic valve and is considered adequate. The main problem, therefore, is to control the air supply system, which is constructed from an air compressor and a supply manifold.

There are many mathematical models available in the existing literature to describe the dynamic of PEMFC air-feed systems. For example, the nine-state model established in [2] is widely verified to describe the dynamics of the air supply system with high accuracy, but it is too complex to be utilized in the controller design. Suh et al. [21] decoupled the air-supply system from
the PEMFC model, and the nine-order model is simplified to a four-order model. Moreover, a simplification of the third-order model is then proposed by Talj et al. [22]. Some other models serve analytical purposes such as the 1-D power density model and multidimensional models were developed in [23], [24]. To balance the model accuracy and feasibility, we consider the PEMFC model derived from [16] and [20]. The dynamic model contains the following four states:

\[ x = [p_{O_2}, p_{N_2}, w_{cp}, p_{sm}], \]  

where \( p_{O_2}, p_{N_2}, w_{cp}, \) and \( p_{sm} \) are the oxygen partial pressure, nitrogen partial pressure, compressor speed, and supply manifold pressure, respectively. Assume that air contains 21\% part of oxygen and 79\% part of nitrogen.

(1) The derivatives of the oxygen and nitrogen partial pressure models are given as follows:

\[ \frac{dp_{O_2}}{dt} = \frac{RT}{V_{ca} M_{O_2}} (W_{O_2,in} - W_{O_2,out} - W_{O_2,react}), \]  

\[ \frac{dp_{N_2}}{dt} = \frac{RT}{V_{ca} M_{N_2}} (W_{N_2,in} - W_{N_2,out}), \]

where \( M_{O_2} \) and \( M_{N_2} \) are the molar masses of oxygen and nitrogen, respectively. \( V_{ca} \) is the cathode volume, \( R \) is the universal gas constant, and \( T_{fc} \) is the fuel cell temperature. \( W_{O_2,in}, W_{N_2,in}, W_{O_2,out}, \) and \( W_{N_2,out} \) are the inlet and outlet flow rates of oxygen and nitrogen, correspondingly, and \( W_{O_2,react} \) is the oxygen reacted mass flow rate. The inlet mass flow rates of different gases are given by,

\[ W_{O_2,in} = x_{O_2} W_{ca,in}, \]

\[ W_{N_2,in} = (1 - x_{O_2}) W_{ca,in}, \]

\[ W_{ca,in} = \frac{1}{1 + w_{atm}} k_{ca,in} (p_{sm} - p_{ca}), \]

with

\[ w_{atm} = \frac{M_a \Phi_{atm} p_{atm}(T_{atm})}{M_a p_{atm} - \Phi_{atm} p_{atm}(T_{atm})}, \]
where $x_{O_2}$ is the oxygen ratio of air, $\phi_{atm}$ is the relative humidity, $p_{atm}$ is the atmospheric pressure and $p_{sat}$ is the saturation pressure. $k_{ca,in}$ is the cathode inlet orifice constant. The cathode pressure $p_{ca}$ is given by

$$p_{ca} = p_{O_2} + p_{N_2} + p_{sat}. \quad (8)$$

The outlet mass flow rates of different gas are calculated by,

$$W_{O_2,\text{out}} = M_{O_2}p_{O_2}W_{ca,\text{out}}, \quad (9)$$

$$W_{N_2,\text{out}} = M_{N_2}p_{N_2}W_{ca,\text{out}}, \quad (10)$$

where the cathode outlet mass flow rate $W_{ca,\text{out}}$ is

$$W_{ca,\text{out}} = k_{ca,\text{out}}\sqrt{p_{ca} - p_{atm}}, \quad (11)$$

where $k_{ca,\text{out}}$ is the cathode outlet orifice constant. The oxygen reacting rate is calculated by the principle of charge conservation,

$$W_{O_2,\text{react}} = M_{O_2}nI_{st}/4F, \quad (12)$$

where $F$ is the Faraday number, $n$ is the number of cells, and $I_{st}$ is the stack current.

2. The dynamic of air compressor speed is modeled as follows:

$$\frac{dw_{cp}}{dt} = \frac{1}{J_{cp}}(\tau_{cm} - \tau_{cp} - \tau_f), \quad (13)$$

where $J_{cp}$ is the inertia of the compressor motor, $\tau_{cm}$, $\tau_{cp}$, and $\tau_f$ represent the compressor motor torque, compressor load torque, and the friction torque, respectively.

$$\tau_{cm} = \eta_{cm}k_tI_q, \quad (14)$$

$$\tau_f = f w_{cp}, \quad (15)$$

$$\tau_{cp} = C_p T_{atm} \left( \frac{p_{sm}}{p_{atm}} \right)^{\gamma - 1} W_{cp}, \quad (16)$$

where $I_q$ is the quadratic current, $k_t$ is the motor constant, $\eta_{cp}$ is the efficiency of the compressor, $f$ is the motor friction, $\eta_{cm}$ is the mechanical efficiency of the motor, $\gamma$ is the air ratio of heat, and $C_p$ is the heat capacity of air. The detailed compressor mass flow rate $W_{cp}$ can be expressed as:

$$W_{cp} = \frac{1}{2\pi} \eta_{v-c} V_{cp}/\rho_{atm} w_{cp} = a_{21} w_{cp}, \quad (17)$$

where $\eta_{v-c}$ is the volumetric efficiency.

3. The dynamics of supply manifold air pressure are:

$$\frac{dp_{sm}}{dt} = \frac{RT_{cp} \cdot 1}{M_a V_{sm}} \left[ W_{cp} - k_{ca,in}(p_{sm} - p_{atm}) \right], \quad (18)$$
where \( V_{sm} \) is the supply manifold volume, \( T_{cp} \) is the compressor outlet gas temperature,
\[
T_{cp} = T_{am} + \frac{T_{am}}{\eta_{kp}} \left( \frac{p_{am}}{p_{sm}} \right)^{\frac{\gamma}{\gamma - 1}} - 1,
\]
where \( W_{cp}, p_{ca}, \) and \( T_{am} \) are the compressor mass flow rate, cathode pressure, and ambient temperature, \( V_{sm}, k_{ca,in}, \) and \( \eta_{kp} \) are the supply manifold volume, cathode inlet orifice constant, and compressor efficiency, respectively. The nominal values of the model parameters are listed in Table 1.

### Table 1: Emulated PEMFC system parameters [16].

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
<td>Number of cells in stack</td>
<td>45</td>
</tr>
<tr>
<td>( R )</td>
<td>Universal gas constant</td>
<td>8.314 J/(mol·K)</td>
</tr>
<tr>
<td>( R_a )</td>
<td>Air gas constant</td>
<td>286.9 J/(kg·K)</td>
</tr>
<tr>
<td>( T_{fc} )</td>
<td>Temperature of the fuel cell</td>
<td>353.15 K</td>
</tr>
<tr>
<td>( F )</td>
<td>Faraday constant</td>
<td>96485 C/mol</td>
</tr>
<tr>
<td>( p_{am} )</td>
<td>Atmospheric pressure</td>
<td>( 1.01325 \times 10^5 ) Pa</td>
</tr>
<tr>
<td>( T_{am} )</td>
<td>Atmospheric temperature</td>
<td>298.15 K</td>
</tr>
<tr>
<td>( V_{ca} )</td>
<td>Cathode volume</td>
<td>0.0015 m³</td>
</tr>
<tr>
<td>( V_{sm} )</td>
<td>Supply manifold volume</td>
<td>0.003 m³</td>
</tr>
<tr>
<td>( k_{ca,in} )</td>
<td>Cathode inlet constant</td>
<td>0.3629 kg/(Pa·s)</td>
</tr>
<tr>
<td>( k_{ca,out} )</td>
<td>Cathode outlet constant</td>
<td>0.3629 kg/(Pa·s)</td>
</tr>
<tr>
<td>( x_{O_2,ca,in} )</td>
<td>Oxygen mass fraction</td>
<td>0.23</td>
</tr>
<tr>
<td>( M_a )</td>
<td>Air molar mass</td>
<td>28.9644 × 10⁻³ kg/mol</td>
</tr>
<tr>
<td>( M_{O_2} )</td>
<td>Oxygen molar mass</td>
<td>32.×10⁻³ kg/mol</td>
</tr>
<tr>
<td>( M_{N_2} )</td>
<td>Nitrogen mass</td>
<td>28×10⁻³ kg/mol</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>Ratio of specific heats of air</td>
<td>1.4</td>
</tr>
<tr>
<td>( C_p )</td>
<td>Specific heat capacity of air</td>
<td>1004 J/(kg·K)</td>
</tr>
<tr>
<td>( J_p )</td>
<td>Compressor inertia</td>
<td>671.9 × 10⁻⁵ kg·m²</td>
</tr>
<tr>
<td>( \eta_{cp} )</td>
<td>Compressor efficiency</td>
<td>80%</td>
</tr>
<tr>
<td>( \eta_{me} )</td>
<td>Motor mechanical efficiency</td>
<td>90%</td>
</tr>
<tr>
<td>( k_t )</td>
<td>Motor constant</td>
<td>0.31 N·m/A</td>
</tr>
<tr>
<td>( f )</td>
<td>Motor friction</td>
<td>0.00136 V/(rad/s)</td>
</tr>
<tr>
<td>( V_{cp/tr} )</td>
<td>Compressor volume per turn</td>
<td>( 5 \times 10^{-4} ) m³/rev</td>
</tr>
<tr>
<td>( \rho_0 )</td>
<td>Air density</td>
<td>1.293 kg/m³</td>
</tr>
</tbody>
</table>

### B. State-Space Representation

The abovementioned model in the last subsection is further simplified by regrouping the constant parameters. The state-space model is presented as follows:
\[
\begin{align*}
\dot{x}_1 &= a_{11} x_1 + a_{12} x_1 x_2 + a_{13} x_1 x_4 - a_{14} x_1 x_3 + a_{15} x_1^2 + x_2 + a_2 - a_11 - a_17 I_s, \\
\dot{x}_2 &= a_{8} x_1 + a_{82} x_1 x_2 + \frac{a_{83}}{a_{11}} x_1^2 + x_2 + a_2 - a_{11}, \\
\dot{x}_3 &= -a_9 x_3 - a_{10} \left( \frac{x_4}{a_{11}} \right)^{a_{12}} - 1 + a_{13} u, \\
\dot{x}_4 &= a_{14} \left( 1 + a_{15} \left( \frac{x_4}{a_{11}} \right)^{a_{12}} - 1 \right) (a_{21} x_3 - a_{16} x_4),
\end{align*}
\]
where \( \kappa = x_4 - x_1 - x_2 - a_2, x_1, x_2, x_3, \) and \( x_4 \) are given in equation (1). \( I_s \) represents the stack current and is considered as the system load. \( u = I_s \) is considered the system control input. The details of parameters \( a_i \) are shown in Table 2. The outputs are defined as:
\[
y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} V_{st} \\ p_{am} \end{bmatrix},
\]
(21)
where $V_{st}$ is the stack voltage, and $p_{sm}$ is the supply manifold pressure.

| Table 2: The details of parameters $a_i$. |
|------------------|------------------|
| $a_1 = \frac{RT_{in}k_{in}}{w_{atm}}x_{O_2}$ | $a_2 = p_{atm}$ |
| $a_3 = \frac{RT_{in}}{w_{atm}}$ | $a_4 = M_{O_2}$ |
| $a_5 = M_{N_2}$ | $a_6 = M_Np_{atm}$ |
| $a_7 = \frac{RT_{in}}{w_{atm}}$ | $a_8 = \frac{RT_{in}k_{in}}{w_{atm}}\frac{1-x_{O_2}}{V_{st}M_{O_2} \pm w_{atm}}$ |
| $a_9 = \frac{L_{in}}{p_{atm}}$ | $a_{10} = \frac{C_p T_{atm}}{\tau_{cm} \tau_{cp}} \frac{1}{\eta_{t-c}}V_{cpr}p_0$ |
| $a_{11} = p_{lim}$ | $a_{12} = \frac{\gamma - 1}{\gamma}$ |
| $a_{13} = w_{in}k_{t}$ | $a_{14} = \frac{RT_{in}}{M_NV_{in}}$ |
| $a_{15} = \frac{1}{w_{in}}$ | $a_{16} = k_{in}$ |
| $a_{17} = k_{in}$ | $a_{18} = \eta_{cm}k_4$ |
| $a_{19} = \frac{k_{in}x_{O_2}}{\tau_{in}w_{atm}}$ | $a_{20} = \frac{\mu M_{O_2}}{4\pi}$ |
| $a_{21} = \frac{1}{2}\eta_{t-c}V_{cpr}p_0$ |

### C. Control Objective

The compressor consumes a large amount of power generated by the fuel cell. Therefore, the power transferred to the net can be calculated as:

$$P_{net} = P_{st} - P_{cp}, \quad (22)$$

where $P_{st}$ is the power produced by PEMFC, $P_{cp}$ is the power consumed by the compressor, i.e.,

$$P_{st} = V_{st}I_{st}, \quad (23)$$

$$P_{cp} = \tau_{cm}w_{cp}. \quad (24)$$

The ratio of the supplied and consumed oxygen in the cathode is called the Oxygen Excess Ratio (OER), which is calculated as:

$$\lambda_{O_2} = \frac{W_{in}}{W_{O_2,react}} = \frac{a_{19}}{a_{20}}I_{t-c}(x_4 - p_{atm}). \quad (25)$$

Note that the functions of $P_{net}$ and $\lambda_{O_2}$ both contain $I_{st}$, so a balance point between $P_{net}$ and $\lambda_{O_2}$ is desired.

For a given load (stack current), the output power of the fuel cell is determined by the OER. When the OER is large, i.e., superfluous air is fed into the fuel cell, this means a lot of power is consumed by the air-feed system and the fuel cell output power will decrease. When the OER is small, less power is consumed by the air-feed system but the shortage of air will reduce the power delivered by the fuel cell. As a result, the output power of the fuel cell will decrease. According to [2], this
optimization problem is equivalent to keeping $\lambda_{O2}$ at the optimal value $\lambda_{O2,\text{ref}}$. The optimal value lies between 2 and 2.5 in connection with the current $I_d$ [20]. This relationship is fitted by a polynomial.

$$\lambda_{O2,\text{ref}} = 5 \times 10^{-8} I_d^3 - 2.87 \times 10^{-5} I_d^2 + 2.23 \times 10^{-3} I_d + 2.5. \quad (26)$$

### III. Fixed-time and Prescribed-time Stability

Consider the following system:

$$\dot{x} = f(x, \eta), \quad x(t_0) = x_0.$$ \quad (27)

where $x \in \mathbb{R}^n$ is the state, $\eta \in \mathbb{R}^l$ is the parameters.

**Definition 1:** The origin of the system (27) is said to be

1. finite-time stable (FNTS), if it is globally asymptotically stable and the solution $\Phi(t, x_0, \eta)$ converges to the origin in some finite time, i.e., $\Phi(t, x_0, \eta) = 0, \forall t \geq t_0 + T(x_0, \eta)$, where $T(x_0, \eta)$ is the settling time function.

2. fixed-time stable (FTS) [18], if it is finite-time stable and the settling-time function is bounded, i.e., $\exists 0 < T_f < \infty$ such that $T(x_0, \eta) \leq T_f(\eta), \forall x_0 \in \mathbb{R}^n$.

**Definition 2:** [19] The origin of nonautonomous system (28) is said to be prescribed-time stable (PSTS), if it is finite-time stable, and $\forall x_0 \in \mathbb{R}^n$, there exist a constant $T_p$, s.t.,

$$\Phi(t, x_0, \eta) = 0, \quad \forall t \geq t_0 + T_p.$$ \quad (28)

### A. Fixed-time Observer

Consider the following dynamic system,

$$\dot{\hat{z}}_1 = f_0(z_1) + z_2,$$

$$\dot{\hat{z}}_2 = h(t),$$ \quad (29)

where $f_0(z_1)$ is a known function of $z_1$. Moreover, $z_2$ and $h$ are unknown but bounded, $h(t) \leq L_1$. Suppose $z_1$ is the system state that can be measured. Then, $\hat{z}_2$ is observable because it can directly affect the derivative of $z_1$.

Design the fixed-time observer (FTTO) as follows:

$$\dot{\hat{z}}_1 = f_0 + \hat{z}_2 + k_1 \left( [\hat{z}_1 - \hat{z}_1]^4 + k_3^2 [\hat{z}_1 - \hat{z}_1]^2 \right),$$

$$\dot{\hat{z}}_2 = k_2 \left( [\hat{z}_1 - \hat{z}_1]^0 + 4k_3^2 (\hat{z}_1 - \hat{z}_1) + 3k_3^4 [\hat{z}_1 - \hat{z}_1]^2 \right),$$ \quad (30)

where $\hat{z}_i$ is the estimation of $z_i$, $k_1$, $k_2$ and $k_3$ should satisfy

$$k_1 = \sqrt{8\gamma}, \quad k_2 = \gamma, \quad k_3 = \frac{6.9\sqrt{\gamma}}{T_f(\gamma - L_1)},$$ \quad (31)
where \( \gamma > L_1 \) and \( T_f \) is the upper bound of the convergence time. In this fixed-time observer, \( T_f \) is a single parameter, which is different from that in [17, 18]. Define \( \hat{z}_i = z_i - \hat{z}_i \), we have
\[
\dot{\hat{z}}_1 = \dot{\hat{z}}_2 - k_1 \left( \left[ \dot{\hat{z}}_1 \right]^2 + k_2^2 \left[ \dot{\hat{z}}_1 \right]^2 \right),
\]
\[
\dot{\hat{z}}_2 = -k_2 \left( \left[ \dot{\hat{z}}_1 \right]^0 + 4k_2^2 \dot{\hat{z}}_1 + 3k_2^4 \left[ \dot{\hat{z}}_1 \right]^2 \right) + h(t).
\]
(32)

According to Theorem 4.8 and Remark 4.10 in [25], the following lemma is presented.

**Lemma 1:** Consider the system (29) with FXTD (30), the observation error of \( |z_1 - \hat{z}_1| \) and \( |z_2 - \hat{z}_2| \) will converge to a neighborhood of the origin in fixed time \( T_f \).

**B. Prescribed-time Control**

**Lemma 2:** Consider the following first-order system:
\[
\frac{dx}{dt} = u(x, t) + \delta(t), \ |\delta(t)| \leq L_2,
\]
(33)

with the control given by:
\[
u(x, t) = -\frac{cx}{T_p + t_0 - t},
\]
(34)

where \( T_p \) and \( c \) are positive constants and \( c > 1 \). Then \( x \) will converge to zero within \( T_p \).

**Proof:** By introducing a time transformation \( \tau = -\ln(1 - \frac{t - t_0}{T_p}) \) with its inverse mapping \( t = T_p(1 - e^{-\tau}) + t_0 \), one can obtain,
\[
\frac{d\tau}{dt} = \frac{c}{T_p + t_0 - t}.
\]
(35)

Define the time-varying gain as:
\[
k(t - t_0) = \frac{c}{T_p + t_0 - t}.
\]
(36)

Then the transformed system is given by,
\[
\frac{dx}{d\tau} = \frac{dx}{dt} \cdot \frac{dt}{d\tau} = u(x, \tau) + \pi(\tau),
\]
(37)

where \( u(x, \tau) = u(x, t)k(t - t_0)^{-1}\left|_{t=T_p(1-e^{-\tau})+t_0} \right. \) and \( \pi(\tau) = \delta(t)k(t - t_0)^{-1}\left|_{t=T_p(1-e^{-\tau})+t_0} \right. \).

Since \( |\delta(t)| \leq L_2, \forall t \geq t_0 \), and \( k(t - t_0)^{-1}\left|_{t=T_p(1-e^{-\tau})+t_0} \right. = \frac{T_p e^{-\tau} - \tau}{\tau} \), then \( |\pi(\tau)| \leq \frac{T_p e^{-\tau}}{\tau} \) and \( \pi(\tau) \to 0 \) as \( \tau \to +\infty \).

According to Theorem 1 of [26], if the system (37) is asymptotically stable with \( T(x_0) \), then (33) converges the origin at
\[
T(x_0, t_0) = \lim_{\tau \to T(x_0)} T_p(1 - e^{-\tau}) \leq T_p.
\]
(38)

If we choose \( v = -x \), it is easy to conclude the conclusion that the system in (37) is asymptotically stable. In other words, the control in equation (34) ensures the state of the system in (33) converges to zero within \( T_p \).
Theorem 1: Consider the system in (33) with the control given by:

\[
u(x, t) = \begin{cases} 
- \frac{cx}{T_p + t_0 - t} + u_{STA}(x), & t_0 \leq t < t_0 + T_p, \\
u_{STA}(x), & \text{otherwise}, 
\end{cases}
\]  

(39)

\[
u_{STA}(x) = -\alpha |x|^{\frac{1}{2}} \text{sign}(x) - \beta \int_{t_0}^{t} \text{sign}(x) dt,
\]  

(40)

where \(u_{STA}(x)\) is the Super Twisting Algorithm (STA), \(\alpha\) and \(\beta\) are positive parameters. Then, \(x\) is prescribed-time stable with \(T_p\).

Proof: The candidate Lyapunov function is chosen as \(V = |x|\). When \(t \in (t_0, t_0 + T_p)\),

\[
\dot{V} = \dot{x} \text{sign}(x) \\
= - \frac{c|x|}{T_p + t_0 - t} - \alpha |x|^{\frac{1}{2}} \text{sign}(x) \int_{t_0}^{t} \text{sign}(x) dt \\
\leq -\alpha V^{\frac{1}{2}} + M.
\]  

(41)

It is obvious that \(V = |x|\) is bound so that \(u_{STA}(x)\) is bound. So \(u_{STA}(x)\) can be lumped into \(\delta(t)\). Then the proof is the same as that of Lemma 2. When \(t \in (t_0 + T_p, +\infty)\), the stability is ensured by STA [27].

Remark 1: In applications, one problem of this kind of time-varying prescribed-time controller is that \(u\) may go to infinity as \(t\) tends to \(t_0 + T_p\). One practical solution to this problem is taking over the control a little earlier than \(t_0 + T_p\), which sacrifices the accuracy [19]. The corresponding control is:

\[
u(x, t) = \begin{cases} 
- \frac{cx}{T_p + t_0 - t} + u_{STA}(x), & t_0 \leq t < t_0 + T_p - \Delta t, \\
u_{STA}(x), & \text{otherwise}.
\end{cases}
\]  

(42)

It will be shown in simulations that bringing in \(u_{STA}(x)\) is qualified enough to make compensation.

IV. CONTROL DESIGN

According to equations (20) and (25), \(\lambda_{O_2}\) is related to \(u\) by \(x_3\). Therefore, the double-loop control structure is utilized. As presented in Fig. 2, the stack current \(I_{st}\) can be considered as the system load. Its change leads to the change in PEMFC operation conditions including OER. As the real OER is difficult to measure, we present an FXTO to estimate it in a fixed time. Therefore, the separation principle is automatically satisfied so that the controller and observer can be designed separately. Moreover, each specific \(I_{st}\) corresponds to its optimal, this relationship is fitted as equation (26). By comparing the real OER and the observed one, the double-loop control structure comes into play.

A. Oxygen Excess Ratio Estimation

Given (25), the main difficulty in estimating the OER is that the cathode pressure \(p_{ca}\) is usually not measurable. Considering the cost of sensors and the measuring difficulty, we propose an FXTO to reconstruct the stoichiometry \(\lambda_{O_2}\).
As shown in (20), the dynamic of manifold pressure is
\[
\dot{x}_4 = a_{14} \left( 1 + a_{15} \left[ \frac{x_4}{a_{11}} \right]^{n_{12}} - 1 \right) (W_{cp} - a_{16} \kappa)
\]
\[
= f_1(x_4) W_{cp} - f_1(x_4) a_{16} \kappa,
\]
where \( f_1(x_4) = a_{14} \left( 1 + a_{15} \left[ \frac{x_4}{a_{11}} \right]^{n_{12}} - 1 \right) \). Denote \( z_1 := x_4, z_2 := f_1(z_1) a_{16} \kappa, h := \dot{z}_2 \). We have
\[
\dot{z}_1 = f_1(z_1) W_{cp} + z_2,
\]
\[
\dot{z}_2 = h,
\]
where \( z_2 \) and \( h \) are unknown but assumed to be bounded. The FXTO is constructed as follows:
\[
\begin{align*}
\dot{\hat{z}}_1 &= f_1(z_1) W_{cp} + \hat{z}_2 + k_1 \left( [z_1 - \hat{z}_1]^{\frac{n_{12}}{2}} + k_3 [z_1 - \hat{z}_1]^{\frac{3}{2}} \right), \\
\dot{\hat{z}}_2 &= k_2 \left( [z_1 - \hat{z}_1]^6 + 4k_2 [z_1 - \hat{z}_1] + 3k_4 [z_1 - \hat{z}_1]^2 \right).
\end{align*}
\]
According to Lemma 1, there exists a small constant \( \Delta \) and a fixed time \( T_f \) such that \( |z_i - \hat{z}_i| \leq \Delta, \forall t \geq T_f \geq 0 \). Since \( f_1 \) and \( a_{16} \) are positive in the operation range, the estimation of \( \kappa \) can be obtained by:
\[
\hat{\kappa} = f_1(z_1)^{-1} a_{16}^{-1} \hat{z}_2.
\]
Due to the definition of \( \kappa \) and (8), the estimation of \( p_{ca} \) is:
\[
\hat{p}_{ca} = x_4 - \hat{\kappa}.
\]
Hence, the estimation of OER is reconstructed as:
\[
\hat{\lambda}_{O_2} = \frac{a_{19}}{a_{20} a_d} (x_4 - \hat{p}_{ca}).
\]
For satisfactory performance, parameters such as \( k_1, k_2, \) and \( k_3 \) should be carefully adjusted.
B. External Loop

The tracking error of OER is denoted as:

\[ e_1 = \hat{\lambda}_{O2} - \lambda_{O2,ref} = \frac{a_{19}}{a_{20}}(x_4 - \hat{p}_{ca}) - \lambda_{O2,ref}. \]  

(49)

The first-order derivative of \( e_1 \) is calculated as:

\[ \dot{e}_1 = \frac{a_{19}}{a_{20}T_d}[f_1 \cdot (W_{cp} - a_{16}\dot{k}) - \dot{\hat{p}}_{ca}], \]

(50)

where the signal \( \dot{\hat{p}}_{ca} \) can be approximated by a numerical differentiator \( \frac{\Delta u}{\Delta t} \). Since the derivative of \( e_1 \) is manipulated by the compressor flow rate \( W_{cp} \), the feedback linearization of the dynamic in (50) can be rewritten as:

\[ \dot{\hat{e}}_1 = g_{10}W_{cp} + \phi_{10}, \]

(51)

where \( g_{10} = a_{19}a_{20}\frac{I_{st}}{f_1} \) and \( \phi_{10} = -a_{19}a_{20}\frac{I_{st}}{f_1}(f_1 \cdot a_{16}\hat{\kappa} + \dot{\hat{p}}_{ca}) \).

(52)

while \( \delta g_{10} \) and \( \delta \phi_{10} \) are the uncertainties of the unknown part of the parameters. To guarantee that the solution \( e_1 \) is unique, assuming that \( \delta g_{10}, \delta \phi_{10} \), and its first derivative are bounded, \( g_{10} \) and \( \phi_{10} \) are smooth enough [28]. Then, the desired \( W_{cp} \) is denoted by \( W_{cp}^{*} \), which is designed as:

\[ W_{cp}^{*} = \frac{1}{g_{10}}[v_1(e_1, t) - \phi_{10}]. \]

(53)

According to [29], as long as \( v_1 \) is bounded, the dynamic of \( e_1 \) can be rewritten as:

\[ \dot{e}_1 = (1 + \frac{\delta g_{10}}{g_{10}})v_1(e_1, t) + \delta \phi_1 - \frac{\delta g_{10}}{g_{10}}\phi_{10} = v_1(e_1, t) + \delta_1(t). \]

(54)

It is noted that the term \( \delta_1 \) is bounded. The control \( v(e_1, t) \) is designed as given in equation (42), i.e.,

\[ v_1(e_1, t) = \begin{cases} \frac{e_1(t)}{r_{1e} + \Delta t_1} + u_{STA}(e_1), & t_0 \leq t < t_0 + T_{p1} - \Delta t_1, \\ u_{STA}(e_1), & otherwise. \end{cases} \]

(55)

To provide a smooth reference for the internal loop, the external loop controller (53) is followed by a first-order linear filter [30]:

\[ \mu W_{cp,ref} = W_{cp}^{*} - W_{cp,ref}. \]

(56)

where \( W_{cp,ref} \) is the actual reference compressor flow rate given to the internal loop.
C. Internal Loop

The internal loop will drive the real compressor flow rate $W_{cp}$ to track the desired $W_{cp,ref}$ by regulating the compressor quadratic current $u = I_q$. The tracking error is defined as:

$$e_2 = W_{cp} - W_{cp,ref}. \tag{57}$$

The first time derivative of $e_2$ is given as:

$$\dot{e}_2 = a_{21} \{ - a_9 x_3 - a_{10} \left( \frac{x_4}{a_{11}} \right)^{a_{12}} - 1 \} + a_{13} u - W_{cp,ref} \tag{58}$$

with

$$g_2 = g_{20} + \delta g_{20}, \tag{59}$$

$$\phi_2 = \phi_{20} + \delta \phi_{20}, \tag{60}$$

where $g_{20}, \phi_{20}$ are the known functions, while $\delta g_{20}, \delta \phi_{20}$ are the uncertainties of the unknown part of parameters. Assuming that $\delta g_{20}, \delta \phi_{20}$, and their first derivatives are bounded, $g_2$ and $\phi_2$ are smooth enough.

**Remark 2:** It is reasonable to assume that all functions of known system states are bounded except the first-time derivative of $W_{cp}^*$, according to (40), if the external controller $W_{cp}^*$ is given directly to the internal loop, $\dot{W}_{cp}$ may be unbounded at the origin. This is another reason for introducing a smoothing filter (56). The stability of the cascade control with a smoothing filter has been proven in [30].

Then, $u$ is designed as follows:

$$u = \frac{1}{g_{20}} [v_2(e_2, t) - \phi_{20} + W_{cp,ref}], \tag{61}$$

where $W_{cp,ref}$ can be calculated from (56). The first derivative of $e_2$ is given by:

$$\dot{e}_2 = (1 + \frac{\delta g_{20}}{g_{20}}) v_2(e_2, t) + \delta \phi_2 + \frac{\delta g_{20}}{g_{20}}(\dot{W}_{cp,ref} - \phi_{20}) \tag{62}$$

where $\delta$ is bounded and

$$v_2(e_2, t) = \begin{cases} - \frac{e_{cp}}{T_{id} + \Delta t} + u_{STA}(e_2), & t_0 \leq t < T_{id} + t_0 - \Delta t, \\ u_{STA}(e_2), & otherwise. \end{cases} \tag{63}$$

The control parameters are selected in Table 3.

V. HARDWARE-IN-LOOP VALIDATION

In this section, to validate the effectiveness of the fixed-time observer and the prescribed-time control method, the Kalman filter (KF) and sub-optimal control algorithm are presented as comparisons. All these methods are validated by hardware-in-loop (HIL) test, as presented in Fig. 3. The real PEMFC is replaced by a PEMFC emulator, which is modeled in dSPACE 1202.
The detailed model was presented in Section II. The emulated PEMFC is a 12 kW unit containing 45 cells in series. The manifold pressure $p_{sm}$ is an output of the PEMFC and is available. In addition, the compressor motor speed $w_{cp}$ is measurable. According to the compressor map constructed by experimental data of the compressor speed $w_{cp}$, manifold pressure $p_{sm}$, and mass flow $W_{cp}$, we can obtain the air mass flow $W_{cp}$ in the virtual PEMFC supply manifold [31]. To simulate the model uncertainty, the exact model parameters for the controller are not known, parameter uncertainties are given in Table 4.

![Diagram of the HIL test bench](image)

### Table 3: Control parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$c_1$</td>
<td>5</td>
</tr>
<tr>
<td>$c_2$</td>
<td>3</td>
</tr>
<tr>
<td>$T_{p1}$</td>
<td>0.7s</td>
</tr>
<tr>
<td>$T_{p2}$</td>
<td>0.6s</td>
</tr>
<tr>
<td>$T_f$</td>
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</tr>
<tr>
<td>$\Delta t_1$</td>
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</tr>
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<td>$\Delta t_2$</td>
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<tr>
<td>$\beta_1$</td>
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<tr>
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<tr>
<td>$\mu$</td>
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<td>$k_2$</td>
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<tr>
<td>$k_3$</td>
<td>260</td>
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</tbody>
</table>

### Table 4: Variations of system parameter

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_a$</td>
<td>Stack temperature, °C</td>
<td>+5%</td>
</tr>
<tr>
<td>$V_{ca}$</td>
<td>Cathode volume, m³</td>
<td>+5%</td>
</tr>
<tr>
<td>$V_{sm}$</td>
<td>Supply manifold volume, m³</td>
<td>−10%</td>
</tr>
<tr>
<td>$T_{atm}$</td>
<td>Atmosphere temperature, °C</td>
<td>+5%</td>
</tr>
<tr>
<td>$k_{ca,in}$</td>
<td>Cathode inlet orifice constant, kg/(Pa·s)</td>
<td>+5%</td>
</tr>
<tr>
<td>$k_{ca,out}$</td>
<td>Cathode outlet orifice constant, kg/(Pa·s)</td>
<td>+5%</td>
</tr>
<tr>
<td>$k_I$</td>
<td>Motor constant, N·m/A</td>
<td>−10%</td>
</tr>
<tr>
<td>$J_{cp}$</td>
<td>Compressor inertia, kg·m²</td>
<td>+10%</td>
</tr>
</tbody>
</table>
Set the step load (Ist) sequence varies from 150 to 280(A), see Fig. 4. Meanwhile, the corresponding dynamic response of the stack voltage varies between 31V and 32V, see Fig. 5. As presented in Fig. 3, when the load Ist changes, the corresponding reference OER $\lambda_{O_2, \text{ref}}$ can be derived from (26). The estimated OER $\hat{\lambda}_{O_2}$ obtained by an observer is compared with $\lambda_{O_2, \text{ref}}$. The error $e_1 = \lambda_{O_2} - \hat{\lambda}_{O_2, \text{ref}}$ is sent to the external loop and derives a reference compressor flow rate. Then, the reference compressor rate is sent to the inner loop. The performance of the inner loop under our proposed control method is presented in Fig. 6 and Fig. 7. It is shown that the tracking error drops in a small neighborhood of zero in the prescribed time $T_{c2} = 0.6s$. This result accords with the theoretical analysis in Theorem 1 very well. So the internal loop is considered to be qualified and no redundant discussion will be presented.

The control input $I_q$ (motor quadratic current) is modulated by SVPWM, and the corresponding controller is set by default to the PI control method. As presented in Fig. 8, the quadratic current varies between $-3$ and $9A$. To track $W_{cp, \text{ref}}$, a large value of $I_q$ occurs at $t = 5s$ so $W_{cp}$ increases quickly. A negative value of $I_q$ occurs at $t = 15s$ to slow down the motor, so $W_{cp}$ decreases faster than that under normal conditions. After a sharp regulation, the motor current always tends to be stable within the desired time. Only the intrinsic chatter of the sliding mode control is presented after $t = 0.6s$.

The control result of the outer loop is presented in Fig. 9 (a). According to the variation of stack current, a load increase (from 150A to 230A) occurred at $t = 5s$. The OER regulation under our proposed controller is rapid enough (no longer than
Fig. 6. Real and reference compressor flow rate.

Fig. 7. Compressor flow rate tracking error.

Fig. 8. Variations of motor quadratic current.
$T_{p1} = 0.7\, s$ so that oxygen starvation is avoided. Note that the real OER is not available to the controller, so its value is observed by a fixed-time observer and a Kalman filter. The observer errors of these two techniques are given in Fig. 10. It can be seen that both the tracking errors of FXTO and KF converge to a small neighborhood of zero in a short time. However, the response speed of FXTO is faster. In particular, the error of FXTO never exceeds 0.1. In contrast, the observer error of KF achieves 0.6 at $t = 5\, s$. This difference can be magnified because of the cascade control structure of this paper. Moreover, the FXTO can provide a fixed upper bound of the settling time, which supports the theoretical result of this paper. Therefore, the FXTO rather than KF is utilized to estimate the OER in this paper.

![Fig. 9](image-url) Oxygen excess ratio regulation results with (a) the proposed controller and (b) the sub-optimal sliding mode algorithm.
VI. CONCLUSIONS

This paper introduces a cascade control method for regulating the oxygen excess ratio (OER) in a PEMFC within a prescribed-time frame. The control strategy comprises an OER tracking (external) loop and a compressor flow rate tracking (internal) loop, both employing prescribed-time stability techniques. To address the difficulty in directly measuring the OER, a fixed-time observer is developed to estimate the actual OER value accurately within a short duration. Through hardware-in-loop experiments, the proposed method demonstrates strong robustness against system uncertainties and disturbances. Notably, the OER observation process is characterized by its short duration and minimal errors, in contrast to the relatively slower response of the Kalman filter. Particularly, the OER under the proposed controller converges to the desired value within the prescribed time, while no apparent convergence time limit exists under sub-optimal sliding mode control. This work demonstrates the fixed-time and prescribed-time control application on the PEMFC OER regulation problem. Besides, these methods can also
be utilized in other systems which are sensitive to regulation times and disturbance. Future research endeavors will focus on investigating the states and input limitations associated with the PEMFC air feed system.

REFERENCES


**State of Contributions**

The main contributions of this paper are summarized below:

1. The controller ensures the oxygen excess ratio is regulated in a prescribed time.
2. The oxygen excess ratio isn’t measurable, so we reconstruct it by a Fixed-time observer.
3. A comparison with finite-time control is presented in a hardware-in-loop experiment.
4. The proposed method shows robustness against disturbance and parameter uncertainties.
Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: