Research Article

Survey on $H_\infty$ Robust Control of the Solid Oxide Fuel Cell

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Received 22 November 2020; Revised 1 February 2021; Accepted 27 February 2021; Published 18 March 2021

Academic Editor: Chaolong Zhang

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Excessive use of fuel or being underutilized will make the actual performance of solid oxide fuel cells (SOFCs) affected by a lot, and at the same time, in order to meet the demands of DC load voltage, a controller of the SOFC that is subjected to small varying loads is proposed on the basis of $H_\infty$ control theory. For the controller design, a state-space representation of the SOFC by using small-signal linearization is derived. To evaluate the control performance, the presented $H_\infty$ controller is tested on the SOFC stack with various load disturbances. The results show that the obtained $H_\infty$ controller can mitigate the voltage oscillations and deviations and can keep fuel utilization constant at varying loads.

1. Introduction

Fuel cells (FCs) have notable potential for power generation in stationary, portable, and transport applications [1]. As one of the most promising types of FC, the solid oxide fuel cell (SOFC) has a high energy conversion efficiency from 60% to 80%. Furthermore, high-quality exhaust energy makes it suitable for distributed generation (DG).

Fuel utilization is the most critical constraint for the SOFC system safety [2]. An oversused fuel condition (fuel utilization $> 0.9$), which can lead to fuel starvation and then irreversible decay of the fuel cell, should be strictly avoided. However, it is a great waste under a low fuel utilization when there is no cycling of the anode gas flow, thus causing a low generation efficiency and the increased fuel cost. By far, constant fuel utilization is a primary mode of operation of SOFCs [3, 4]. So, it is essential to design control strategies for transient control of fuel utilization.

The stability of the voltage is very important for the power quality of the converted electricity. In order to mitigate the voltage fluctuation and to improve the load-following capability, different voltage control strategies have been proposed. Moreover, an aggressive control action may cause some potential risks in violating the safety range of the fuel utilization [5, 6].

To control the utilization and the terminal voltage of the SOFC, Li et al. designed two control loops, i.e., the inner current feedback used in the constant fuel utilization control and the PI-type controller for keeping the terminal voltage constant [7]. Huo et al. also designed two control loops to maintain the fuel utilization and the output voltage of the SOFC at their desired values, respectively. In particular, the nonlinear model predictive controller (MPC) based on the Hammerstein model was developed to control the output voltage of the SOFC [8]. However, the utilization and the output voltage cannot be kept constant simultaneously. To solve the above problem, Sendjaja and Kariwala designed a decentralized PI controller as the terminal voltage and the fuel utilization of the SOFC were selected as controlled variables (CVs). Simulation results demonstrated that the proposed decentralized PI controller can closely meet the control objectives of the SOFC [9]. Nevertheless, due to considering the interactions between manipulated variables (MVs) and CVs, a centralized controller has a more optimal and comprehensive nature than a decentralized controller.

So far, different centralized control approaches have been proposed for controlling the output voltage and the fuel utilization of the SOFC. The recent studies have shown that the control of the SOFC is challenging due to its slow...
response and tight operation constraints [10]. Thus, the
model predictive control (MPC) is the most appropriate
approach for centralized control implementation. Wang
et al. applied a data-driven predictive control approach via
the subspace approach for the SOFC system to solve the
above control problem [11]. Bhattacharyya et al. designed
a nonlinear model predictive controller (NMPC) to meet the
requirement of the multiple input multiple output (MIMO)
control of power and the fuel utilization [12]. However, the
MPC suffers from several drawbacks in practical industrial
processes. First, its calculation cost is quite large, and
second, it is hard to obtain the stability analysis of the
MPC [13–15]. As a result, Sedghisigarchi et al. designed a
controller using $H_\infty$ control strategy [16]. The results
demonstrated the potential of $H_\infty$ control to achieve fast
load following, while satisfying constant utilization of op-
terational constraint. However, the detailed design process of
the $H_\infty$ controller was not described, and only the fuel
utilization was kept constant.

In this paper, for the controller design, the state-space
description of the SOFC based on small-signal linearization is
derived for the first time. OQ_hen, a robust $H_\infty$ controller for
constant fuel utilization and output voltage control of the SOFC
was proposed. For this control design, the controlled variables
include the fuel utilization and the output voltage of the SOFC,
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scription of the SOFC based on small-signal linearization is
derived for the first time. Then, a robust $H_\infty$ controller for
constant fuel utilization and output voltage control of the SOFC
is proposed. For this control design, the controlled variables
include the fuel utilization and the output voltage of the SOFC,
the current is taken as a disturbance, and the fuel and oxygen
flow rates are employed as the manipulated variables.

This paper is structured as follows: in Section 2, the
nonlinear dynamic physical model of the SOFC is simply
introduced, and the description of $H_\infty$ control theory is
presented in Section 3, whereas Section 4 focuses on the
derivation of an accurate state-space representation of the
SOFC and $H_\infty$ control synthesis. Furthermore, the valida-
tion of the $H_\infty$ controller and the simulation results are
reported. Finally, some conclusions are provided.

2. Nonlinear Dynamic Model of the SOFC

To develop the model-based controller, a nonlinear model
proposed in the study by Ault et al. [17] is adopted in this
paper. The schematic of the model is shown in Figure 1, and
the specifications of the SOFC stack are given in Table 1.

The variables of the SOFC can be classified as controlled
variables, manipulated variables, and disturbance variables.
In this study, the controlled variables are the output voltage
and fuel utilization.

2.1. Output Voltage of the SOFC. Nernst’s equation and
Ohm’s law determine the average voltage magnitude of the
fuel cell stack. So, applying Nernst’s equation and Ohm’s law
(taking ohmic losses into account), the output voltage of the
SOFC can be modeled as follows:

$$V_{dc} = E - rI,$$

(1)

$$E = N_oE_0 + \frac{N_oRT}{2F} \ln \frac{P_{H_2}P_{O_2}^{0.5}}{P_{H_2O}},$$

(2)

where

$$P_{H_2}(s) = \frac{1}{1 + \tau_{H_2}s}(q_{H_2}^\in - 2K_1I).$$

(3)

$$P_{O_2}(s) = \frac{1}{1 + \tau_{O_2}s}(q_{O_2}^\in - K_2I),$$

$$P_{H_2O}(s) = \frac{1}{1 + \tau_{H_2O}s}2K_1I.$$

2.2. Fuel Utilization. Fuel utilization is one of the most
important variables affecting the performance of the FC and
is defined as

$$u_c = \frac{\dot{q}_{H_2} - \dot{q}_{H_2}^\text{out}}{\dot{q}_{H_2}^\text{in}} = \frac{\dot{q}_{H_2} - N_oI}{2Fq_{H_2}^\text{in}}.$$  

(4)

where $\dot{q}_{H_2}^\text{in}$ is the hydrogen-reacted flow rate. Generally, large
variations of fuel utilization can cause uneven voltage and
temperature distributions in the SOFC [18]. So, fuel utili-
zation is selected as a controlled variable in this paper.

3. $H_\infty$ Control Theory

Robust control theory has been successfully applied to
control system designs that require robustness against
possible disturbances such as parameter uncertainties, plant
and measurement noises, and external disturbances. During
the past two decades, the robust $H_\infty$ control problem has
attracted great attention from both the academic and in-
dustrial communities [19, 20].

Figure 2 shows a classical block diagram for the $H_\infty$
control problem. In Figure 2, $P(s)$ is a linear time-invariant
system, and its state-space description is

$$\dot{x} = Ax + B_1w + B_2u,$$

$$z_\infty = C_1x + D_{11}w + D_{12}u,$$

$$y = C_2x + D_{21}w + D_{22}u,$$

where $x$ denotes the state vector, $u$ is the control input, $w$ is
an exogenous input vector which includes disturbances,
measured noise (not considered here), and tracking signals,$y$ is the measured output, and $z_\infty$ is a vector of output to be
controlled or minimized.

Assuming $(A, B_2)$ is stabilizable, $(C_2, A)$ is detectable,
and $D_{22} = 0$. Define the closed-loop transfer function from $w$ to $z_\infty$
for a dynamical output feedback law $u = K(s)y$ to be $T_{wz_\infty}(s)$.
The design aim of the $H_\infty$ controller is to ensure that the $H_\infty$ norm
of the plant transfer function is bounded within limits, i.e.,

$$\| T_{wz_\infty}(s) \| \leq \gamma,$$

(6)

where $\gamma$ is a given value defined as guaranteed robust
performance.

We suppose the controller $K(s)$ has the following state-
space representation:
\[ \dot{x} = A_{Koo} x + B_{Koo} y, \]
\[ u = C_{Koo} x + D_{Koo} y, \]  
where \( x \in \mathbb{R}^K \) is the state vector of the controller. Combining equations (5) and (7), we can obtain the closed-loop expression as
\[ T_{\text{LCO}}: \begin{bmatrix} \dot{\mathbf{x}} \\ \dot{\mathbf{z}} \end{bmatrix} = \begin{bmatrix} A + B_2 D_{KCO} C_2 & B_2 C_{KCO} \\ B_{KCO} C_2 & A_{KCO} \end{bmatrix} \begin{bmatrix} \mathbf{x} \\ \mathbf{w} \end{bmatrix} + \begin{bmatrix} B_1 + B_2 D_{KCO} D_{21} \\ D_{11} + D_{12} D_{KCO} D_{21} \end{bmatrix} \begin{bmatrix} \Delta \mathbf{H}_2 \\ \Delta \mathbf{H}_O \end{bmatrix}. \] 

Denoting the closed-loop system states \( \mathbf{x}_C = \begin{bmatrix} \mathbf{x} \\ \mathbf{x} \end{bmatrix} \), we can write equation (8) as

\[ T_{\text{LCO}}: \begin{bmatrix} \dot{\mathbf{x}}_C \\ \dot{\mathbf{z}} \end{bmatrix} = \begin{bmatrix} A_C & B_C \\ C_C & D_C \end{bmatrix} \begin{bmatrix} \mathbf{x}_C \\ \mathbf{w} \end{bmatrix}, \] (9)

where

\[ A_C = \begin{bmatrix} A + B_2 D_{KCO} C_2 & B_2 C_{KCO} \\ B_{KCO} C_2 & A_{KCO} \end{bmatrix}, \]
\[ B_C = \begin{bmatrix} B_1 + B_2 D_{KCO} D_{21} \\ D_{11} + D_{12} D_{KCO} D_{21} \end{bmatrix}, \]
\[ C_C = \begin{bmatrix} C_1 + D_{12} D_{KCO} C_2 \\ D_{12} C_{KCO} \end{bmatrix}, \]
\[ D_C = [D_{11} + D_{12} D_{KCO} D_{21}]. \] (10)

As a result, the closed-loop transfer function \( T_{\text{LCO}}(s) \) can be written as

\[ T_{\text{LCO}}(s) = C_C (sI - A_C)^{-1} B_C + D_C. \] (11)

4. **H_\infty** Controller Design for the SOFC

4.1. State-Space Representation of the SOFC. When the working point fluctuates near the stable point within a small scale, the linear control theory is powerful and has been widely used in nonlinear systems [1]. To facilitate the \( H_\infty \) controller design, the nonlinear dynamic model of the SOFC is first linearized at its nominal state on the basis of small signal linearization. Because it is impossible to know the load in advance, any load change is treated as a disturbance to the controller [21]. In this study, the SOFC current is taken as a disturbance. Furthermore, the fuel and oxygen flow rates are chosen as the control inputs.

After linearization, the state-space model of the SOFC can be expressed as a function of the state vector \( \mathbf{x}(t) \), the control input \( q_{H_2}^{in}(t) \), and the disturbance \( I(t) \):

\[ \Delta \dot{\mathbf{x}} = \mathbf{A} \cdot \Delta \mathbf{x} + \mathbf{B}_1 \cdot \Delta I + \mathbf{B}_2 \cdot \Delta q_{H_2}^{in}, \] (12)

where

\[ \Delta \mathbf{x} = \begin{bmatrix} \Delta \mathbf{P}_{H_2} \\ \Delta \mathbf{P}_{H,O} \\ \Delta \mathbf{P}_{O_2} \end{bmatrix}, \]

\[ A = \begin{bmatrix} 1 - \frac{1}{\tau_{H_2}} & 0 & 0 \\ 0 & -\frac{1}{\tau_{H,O}} & 0 \\ 0 & 0 & -\frac{1}{\tau_{O_2}} \end{bmatrix}, \]

\[ B_1 = \begin{bmatrix} 2K_{H_2} \tau_{H_2} \\ 2K_{H,O} \tau_{H,O} \\ K_{O_2} \tau_{O_2} \end{bmatrix}, \]

\[ \mathbf{B}_2 = \begin{bmatrix} 1 - K_{H_2} \tau_{H_2} \\ 0 \\ 1 - K_{H,O} \tau_{H,O} \end{bmatrix}. \] (13)

Herein, the nominal operating trajectory is denoted by \( \mathbf{x}_0(t) \), which corresponds to the nominal input \( q_{H_2}^{in}(t) \) and \( I_0(t) \). So,

\[ \Delta \mathbf{x}_i = \begin{bmatrix} \Delta \mathbf{x}_i \\ \Delta \mathbf{x}_i \end{bmatrix}, \]
\[ i = H_2, O_2, H_2O. \] (14)

Furthermore, linearizing equations (1) and (4) results in

\[ \mathbf{z}_\infty = \mathbf{C}_1 \cdot \Delta \mathbf{x} + D_{11} \cdot \Delta I + D_{12} \Delta q_{H_2}^{in}, \]
\[ \mathbf{y} = C_2 \cdot \Delta \mathbf{x} + D_{21} \cdot \Delta I + D_{22} \Delta q_{H_2}^{in}, \] (15)

where
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\[ z_{\infty} = \left[ \frac{\Delta V_{dc}}{\Delta u_c} \right] \]  

(16)

\[ y = \Delta V_{dc}, \]  

(17)

\[ C_1 = \left[ \begin{array}{c} \frac{\partial V_{dc}}{\partial P_{H_1}} \\ \frac{\partial V_{dc}}{\partial P_{H_2}} \\ \frac{\partial V_{dc}}{\partial P_{O_2}} \end{array} \right] \left|_{k_{d_i}J_{g_i}f_{i}^{\infty},o} \right. \]  

(18)

\[ D_{11} = \left[ \begin{array}{c} \frac{\partial V_{dc}}{\partial t} \\ \frac{\partial u_c}{\partial t} \end{array} \right] \left|_{k_{d_i}J_{g_i}f_{i}^{\infty},o} \right. \]  

(19)

\[ D_{12} = \left[ \begin{array}{c} \frac{\partial V_{dc}}{\partial P_{H_1}} \\ \frac{\partial V_{dc}}{\partial P_{H_2}} \\ \frac{\partial V_{dc}}{\partial P_{O_2}} \end{array} \right] \left|_{k_{d_i}J_{g_i}f_{i}^{\infty},o} \right. \]  

(20)

\[ D_{21} = \frac{\partial V_{dc}}{\partial t} \left|_{k_{d_i}J_{g_i}f_{i}^{\infty},o} \right. \]  

(21)

\[ D_{22} = \frac{\partial V_{dc}}{\partial P_{H_1}} \left|_{k_{d_i}J_{g_i}f_{i}^{\infty},o} \right. \]  

(22)

\[ D_{22} = \frac{\partial V_{dc}}{\partial P_{H_1}} \left|_{k_{d_i}J_{g_i}f_{i}^{\infty},o} \right. \]  

(23)

Specifically, we have the following formulas:

\[ \frac{\partial V_{dc}}{\partial P_{H_1}} = \frac{N_{o}RT}{2Fp_{H_1,0}} \]  

(24)

\[ \frac{\partial V_{dc}}{\partial P_{H_2}} = \frac{-N_{o}RT}{2Fp_{H_2,0}} \]  

\[ \frac{\partial V_{dc}}{\partial P_{O_2}} = \frac{N_{o}RT}{4Fp_{O_2,0}} \]  

\[ \frac{\partial V_{dc}}{\partial t} = -r, \]  

\[ \frac{\partial u_c}{\partial t} = \frac{N_{o}I_{0}}{2Fp_{H_1,0}} \]  

\[ \frac{\partial u_c}{\partial P_{H_1}} = \frac{-N_{o}I_{0}}{2Fp_{H_1,0}} \]  

Here, \( r_{H_1} \) is the ratio of hydrogen to oxygen. In general, excess oxygen is expected to make sure that hydrogen reacts with oxygen more completely. In our study, \( r_{H_1} \) is held around 1.145, as in \([11, 13]\).

4.2. \( H_{\infty} \) Control Synthesis and Simulation. Because solver of the linear matrix inequality (LMI) control toolbox is faster and more powerful than classical convex optimization solvers [22], in this study, the \( H_{\infty} \) controller is synthesized by using the LMI control toolbox. To control the voltage and the fuel utilization of the SOFC, the controlled variables \( z_{\infty} \), as described in equation (16), are chosen to formulate the objectives in an \( H_{\infty} \) control. In this study, the test system is a 100 kW SOFC connected to a resistive load, and its steady state data are given in Table 2.

Based on the state-space representation of the SOFC in Section 4.1, the \( H_{\infty} \) control problem can be directly solved by using the LMI control toolbox. To control the voltage and the fuel utilization of the SOFC, the controlled variables \( z_{\infty} \), as described in equation (16), are chosen to formulate the objectives in an \( H_{\infty} \) control. In this study, the test system is a 100 kW SOFC connected to a resistive load, and its steady state data are given in Table 2.

\[ A_{K_{\infty}} = \begin{bmatrix} -0.0133 & 0.0027 & -0.2422 \\ 0.0201 & -0.2952 & -20.7093 \\ 1.5474 & -62.6332 & -8771.8 \end{bmatrix} \]  

(25)

\[ B_{K_{\infty}} = \begin{bmatrix} -0.0015 \\ -0.0053 \\ 2.9262 \end{bmatrix} \]  

\[ C_{K_{\infty}} = \begin{bmatrix} 0.0002 \\ 0.2654 \\ 113.8685 \end{bmatrix} \]  

\[ D_{K_{\infty}} = -0.0202. \]

Afterwards, the proposed \( H_{\infty} \) controller is tested with various load disturbances by simulation in order to evaluate its performance.

4.2.1. Case 1. To evaluate the control performance of the proposed control strategy, we choose the current disturbance as a multiple step signal which reduces from 372.5 A to 342.5 A at 200 s and goes back to 372.5 A after 650 s, and the profile related to the current is shown in Figure 3. Under this circumstance, the control effect of the output voltage and the fuel utilization of the SOFC are depicted in Figures 4 and 5.

When the load current decreases suddenly, the regulation time of output voltage is 175 s, the maximum overshoot is 0.0044%, the regulation time of fuel utilization is 231 s, and the maximum overshoot is 62.05%. While the load current increases, the regulation time is 173 s and 235 s for the output voltage and the fuel utilization, respectively.

4.2.2. Case 2. Due to power demand variation, multiple step changes occur in the disturbance \( I_1 \), as shown in Figure 6. The current suddenly increases from 372.5 A to 402.5 A at 200 s and goes back to 372.5 A at 650 s. The controlled outputs for the output voltage and the fuel utilization using closed-loop simulations are shown in Figures 7 and 8.

As can be seen from Figures 7 and 8, the proposed \( H_{\infty} \) controller ensures that the output voltage and the fuel
Table 2: Steady state data of the SOFC.

| Parameters | Value       |
|------------|-------------|
| $q_{H_2,0}$ | 0.95 mol/s  |
| $I_0$      | 372.5 A     |
| $V_{dc,0}$ | 244.55 V    |
| $u_{c,0}$  | 0.7803      |
| $T_0$      | 1273 K      |

Figure 3: The profile of the current for case 1.

Figure 4: Voltage control of the SOFC using the $H_\infty$ controller for case 1.
Figure 5: Fuel utilization control of the SOFC using the $H_\infty$ controller for case 1.

Figure 6: The profile of the current for case 2.
utilization from the SOFC, respectively, followed their reference values accurately. This clearly demonstrates the excellent performance of the $H_\infty$ controller.

5. Conclusion

To mitigate the voltage oscillations and deviations and keep fuel utilization constant at varying loads, the state-space representation of the SOFC is first derived for the controller design. Then, the $H_\infty$ robust controller for the SOFC is proposed. Simulation results demonstrate its superiority in controlling the output voltage during power requirements’ change as well as its capability of controlling fuel utilization for the SOFC system safety.

As a future work, the authors would like to design intelligent control strategies for the SOFC considering temperature variations.

Abbreviations

$V_{dc}$: Stack output voltage (V)

$E$: Open-circuit reversible potential (V)
I: Stack current (A)

$E_0$: Ideal standard potential (V)

$N_0$: Number of series cells in the stack

$P_{H_2}$: Hydrogen partial pressure (atm)

$P_O_2$: Oxygen partial pressure (atm)

$P_{H_2O}$: Water vapor partial pressure (atm)

$T$: Stack operating temperature (K)

$F$: Faraday’s constant (96485 C/mol)

$R$: Ideal gas constant (8.314 J/(mol K))

$H$: Hydrogen valve molar constant (mol/(atm s))

$H_{O_2}$: Oxygen valve molar constant (mol/(atm s))

$\tau_{H_2}$: Hydrogen flow response time (s)

$\tau_{H_2O}$: Water flow response time (s)

$\tau_{O_2}$: Oxygen flow response time (s)

$q_{H_2}^i$: Hydrogen input flow (mol/s)

$q_{O_2}^i$: Oxygen input flow (mol/s)

$q_{H_2:}$: Hydrogen reacted flow (mol/s)

$K_c$: Constant with the value of $(N_0/4F)$ (mol/(s·A))

$u_c$: Fuel utilization.

**Data Availability**

The data (specifications for the SOFC stack) supporting this nonlinear dynamic model of the SOFC are from previously reported studies. These studies are cited at relevant places within this paper as references 17 and 7.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

**Acknowledgments**

This work was supported by Young Eastern Scholar Program at Shanghai Institutes of Higher Learning, Special Funding for the Development of Science and Technology of Shanghai Ocean University (no. A2-2006-00-200211), Shanghai Pujiang Program (no. 18PJ1404200), and Shanghai Engineering Research Center of Marine Renewable Energy (no. 19DZ2254800).

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