Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 70 (2023) 213–217

Transportation Research Procedia

www.elsevier.com/locate/procedia

8th International Electric Vehicle Conference (EVC 2023)

Feedback Linearization Controller Design for Solid Oxide Fuel Cells

Donggil Kim[a], Jaehoon Kim[b], Jisoo Kim[b] And Dongik Lee[b]*

[a]*Kyungil University, Gyeongsan-si 38428, South Korea*
[b]*Kyungpook National University, Daegu 41566, South Korea*

Abstract

Electric vehicles have attracted the attention of users because they do not burn fossil fuels and emit zero greenhouse gas emissions. Fuel cells have shown their potential to power vehicles as well. The most common fuel cell types as power sources for automobiles are i) Proton exchange membrane fuel cell (PEMFC) and ii) Solid oxide fuel cell (SOFC). Normally, the PEMFC is considered main propulsion system. On the other side, the SOFC is generally not considered for propulsion system but considered for auxiliary power unit (APU). In this paper, feedback linearization controller for solid oxide fuel cells is proposed. And the performance of proposed controller is simulated under current disturbances operation condition through Matlab simulation.

Keywords: Feedback Linearzation Controlm, PEMFC, SOFC,

1. Introduction

Electric vehicles have attracted the attention of users because they do not burn fossil fuels and emit zero greenhouse gas emissions. Just as many electric vehicles around the world use batteries as their primary power source, fuel cells have shown their potential to power vehicles as well. The most common fuel cell types as power sources for automobiles are i) Proton exchange membrane fuel cell (PEMFC) and ii) Solid oxide fuel cell (SOFC). Normally, the PEMFC is considered main propulsion system. PEMFC-powered electric vehicles have several advantages over battery-powered electric vehicles. i) PEMFC electric vehicles do not need battery charging and can refuel in less than 5 minutes, increasing operational efficiency. ii) PEMFC electric vehicles can distribute hydrogen refueling stations around a central storage tank, saving space compared to charging pile parking lots. iii) PEMFC electric vehicles can maintain a constant voltage regardless of usage period or weather, unlike batteries that show a significant voltage drop

* Corresponding author. Tel.: +82-53-950-7564.
E-mail address: dilee@ee.knu.ac.kr

10.1016/j.trpro.2023.11.021

(Liu, 2016). On the other side, the high operating temperature of SOFCs results in a long startup time and so SOFC is generally not considered for propulsion system but considered for auxiliary power unit (APU). SOFCs for APUs are being developed since reformed gasoline and diesel can be used in these systems without construction of hydrogen supply infrastructures(Rechberger, 2016; Barelli, 2020).

In SOFC, the reaction takes place at the anode and cathode. The ceramic electrolyte will be a good conductor for oxygen ions, not electrons. At the SOFC anode, hydrogen binds with the migrated oxygen ions. It makes water and releases electrons.

SOFC is increasingly gaining traction due to some advantages: (Abdalla, 2018; Fernandes, 2018) i) SOFC have flexible fuel selection and can directly use hydrocarbons. This is a huge advantage over PEMFCs, which can only be supplied with pure hydrogen. ii) The SOFC's high-temperature working environment is compatible with the reforming of hydrocarbons to produce hydrogen-rich gases, providing more possibilities for heat recovery, system efficiency improvement and system modernization. iii) SOFC is mainly composed of ceramic materials and does not use precious metals, so there is a high possibility of cost reduction in large-scale application.

The trend in SOFC control is towards developing more efficient, reliable, and cost-effective solutions to meet the challenges of controlling and regulating the output of SOFC stack. This includes developing advanced control systems that can monitor and adjust cell operating conditions in real time to optimize performance. This involves using advanced algorithms and sensors to detect changes in fuel cell environmental and operating conditions and automatically adjust cell performance accordingly. In addition, new technologies are being developed to improve fuel cell durability and life as well as improve efficiency and performance. SOFC control research trends including PID, model predictive control, H-infinity control, fault-tolerant control can be found in Peng et. al. (2021) and Yang et. al. (2022).

In this paper, feedback linearization controller for solid oxide fuel cells is proposed. And the performance of proposed controller is simulated under current disturbances operation condition.

2. Methodology

The dynamic model of SOFC which is widely accepted as a benchmark model is used to verify the proposed control method. As shown in equation (1), SOFC system have nonlinearity due to the Nernst`s equation(Li, 2005; Padullés 2000):

$$V_0 = N_0\left[E_0 + \frac{R_0 T_0}{2F_0}\ln\frac{p_{H_2}(p_{O2}/101325)^{0.5}}{p_{H_2O}}\right] \tag{1}$$

where, the partial pressures can be approximately expressed as the following transfer functions:

$$p_{H_2} = \frac{1/K_{H_2}}{1+\tau_{H_2}s}\left(\frac{1}{1+\tau_f s}q_f - 2K_r I\right),\ p_{O_2} = \frac{1/K_{O_2}}{1+\tau_{O_2}s}\left(\frac{1/\tau_{H-O}}{1+\tau_f s}q_f - K_r I\right),\ p_{H_2O} = \frac{1/K_{H_2O}}{1+\tau_{H_2O}s}2K_r I. \tag{2}$$

The system output V_o denote stack output voltage which is main control object. The manipulate input is q_f which denote natural gas flow(mol/s). I represent current load(A). the partial pressure of hydrogen, oxygen, and steam in the cell are denoted as p_{H_2}, p_{O_2}, and p_{H_2O}, respectively. And other parameters are summarized in Table 1. The block diagram of SOFC model is shown in Fig 1 in order to improve understanding.

The real output voltage may be reduced due to ohmic loss, activation loss, and concentration loss as follows:

$$V_{dc} = V_o - \eta_{act} - \eta_{ohmic} - \eta_{conc} \tag{3}$$

where,

$$\eta_{act} = \alpha - \beta I,\ \eta_{ohmic} = Ir \text{ and } \ \eta_{conc} = \frac{R_0 T_0}{2F_0} ln\left(1 - \frac{I}{I_L}\right) \tag{4}$$

Table 1. Parameters in the SOFC system.

Parameters	Value	Unit	Representation
T_o	1273	K	Absolute temperature
F_o	96,485	C mol-1	Faraday's constant
R_o	8.314	J mol-1 K-1	Universal gas constant
E_o	1.18	V	Ideal standard potential
N_o	384	-	Ideal standard potential
K_r	0.996 * 10^{-3}	mol s-1 A-1	
K_{H_2}	8.32 * 10^{-6}	mol s-1 Pa-1	Valve molar constant for hydrogen
K_{H_2O}	2.77 * 10^{-6}	mol s-1 Pa-1	Valve molar constant for water
K_{O_2}	2.49 * 10^{-5}	mol s-1 Pa-1	Valve molar constant for oxygen
τ_{H_2}	26.1	s	Response time of hydrogen flow
τ_{H_2O}	78.3	s	Response time of hydrogen flow
τ_{O_2}	2.91	s	Response time of hydrogen flow
τ_{H-O}	1.145	-	Ratio of hydrogen to oxygen
r	0.126	Ω	Ohmic loss
τ_f	5	s	Time constant of the fuel processor
α	0.05	-	Tafel constant
β	0.11	-	Tafel slope
I_L	800	A	Limiting current density

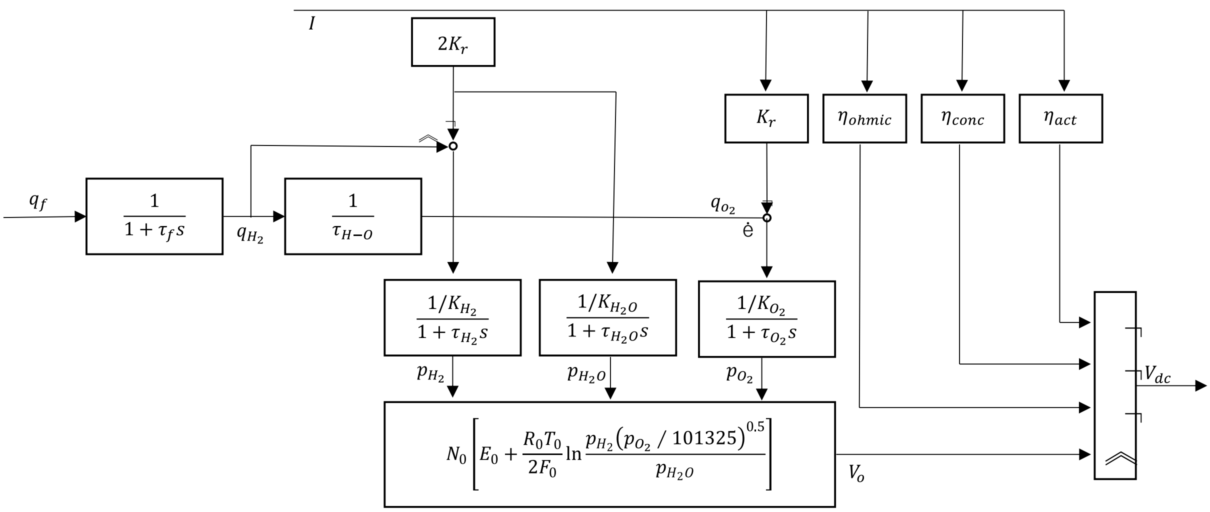


Fig. 1: Illustrative block diagram of SOFC model

In SOFC, the reaction takes place at the anode and cathode. The ceramic electrolyte will be a good conductor for oxygen ions, not electrons. At the SOFC anode, hydrogen binds with the migrated oxygen ions. It makes water and releases electrons. Based on benchmark model, feedback linearization controller is designed to regulate SOFC output voltage with current disturbance meanwhile fuel utilization maintains safe range from 0.7 to 0.9 as far as possible (Fig. 2). The control object is to maintain the output voltage as small as possible under 1) external current load change, 2) complex system nonlinearity, and 3) strict input limitation of nature gas flow rate.

The SOFC system is defined with state variable $x = [q_{H_2} \quad p_{H_2} \quad p_{H_2O} \quad p_{O_2}]$, the output variable $y = V_{dc}$ and input variable $u = q_f$. The control error is defined as followings:

$$e = (\ddot{V}_{dc,ref} - \ddot{V}_{dc}). \tag{5}$$

Then, control error dynamics and control gain are designed as followings (Kim, 2021):

$$(\ddot{V}_{dc,ref} - \ddot{V}_{dc}) + K_1(\dot{V}_{dc,ref} - \dot{V}_{dc}) + K_0(V_{dc,ref} - V_{dc}) = 0, K_1 = 4,\ K_2 = 4. \tag{6}$$

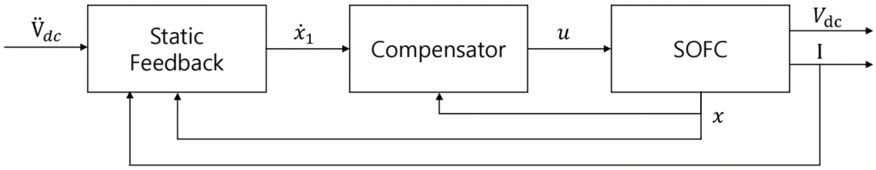
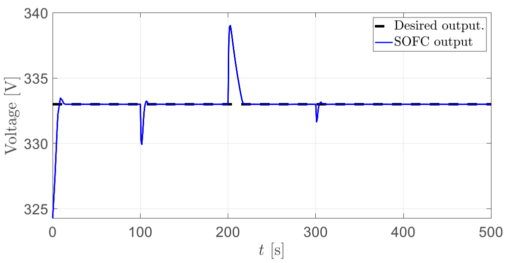


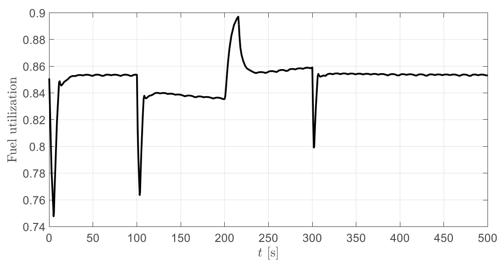
Fig. 2: Designed feedback linearization control diagram

3. Results and Discussion

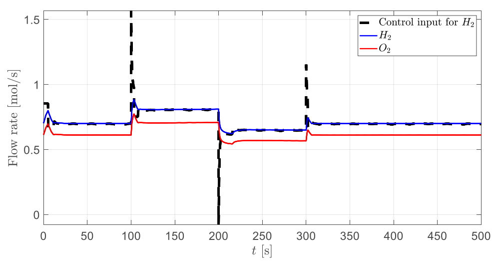
To illustrate the effectiveness of the proposed feedback linearization controller, Matlab simulation was examined. In simulation scenario, we assume that a current disturbance causes step changes at t=100s, t=200s, and t=300s, respectively. The simulation results are shown in through Fig. 3(a) ~ 3(d). The output voltage has converged quickly enough to respond to current fluctuations at t=100s, t=200, and t=300. At same time, it has been confirmed that fuel utilization is maintained within the allowable ranges.



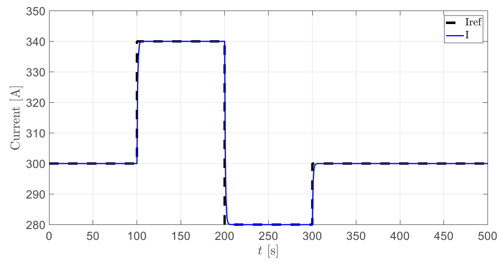
(a) output voltage



(b) fuel utilization



(c) flow rate



(d) load current

Fig. 3: Simulation results of the feedback linearization control

4. Conclusion

The most common types of fuel cells to power source of vehicles are i) proton exchange membrane fuel cells (PEMFC) and ii) solid oxide fuel cells (SOFC). Generally, PEMFC is considered main propulsion system and SOFC is considered for auxiliary power unit. SOFC is increasingly gaining traction due to some advantages including fuel efficiency, flexibility of fuel selection and large scale application. The recent trend of SOFC control is towards developing more efficient, reliable, and cost-effective solutions to meet the challenges of controlling and regulating the output of SOFC stack.

In this paper, we have proposed a feedback linearization controller for solid oxide fuel cells. The simulation results on the benchmark SOFC system have illustrated that the proposed method can successfully dela with not only output voltage regulate but also fuel utilization under step current disturbance. However, it is necessary to study additional research on controller performance comparison by referring to other control methods such as PID, MPC and SMC.

Acknowledgements

This work was supported under the framework of international cooperation program managed by National Research Foundation of Korea(NRF-2021K1A3A1A78097970).

References

Abdalla, A. M., S. Hossain, A. T. Azad, P. M. I. Petra, F. Begum, S. G. Eriksson, and A. K. Azad., "Nanomaterials for solid oxide fuel cells: A review", *Renewable and Sustainable Energy Reviews*, vol.82, 2018, 353-368.

Barelli, L., Bidini, G., Ciupgeanu, D., Pianese, C., Polverino, P. and Sorrentino, M., "Stochastic power management approach for a hybrid solid oxide fuel cell/battery auxiliary power unit for heavy duty vehicle applications", *Energy Conversion and Management*, vol.221, 2020, 113-197.

Fernandes, M. D., V. N. Bistritzki, R. M. Fonseca, L. G. Zacarias, H. N. C. Gonçalves, A. F. de Castro, R. Z. Domingues, and T. Matencio, "SOFC-APU systems for aircraft: A review", *International Journal of Hydrogen Energy*, vol.43, no.33, 2018, 16311-16333.

Li, Y. H., Choi, S. S., and Rajakaruna, S., "An Analysis of the Control and Operation of a Solid Oxide Fuel-Cell Power Plant in an Isolated System", *IEEE Transactions on Energy Conversion*, vol. 20, no. 2, 2005, 381-387.

Liu, Y., Lehnert, W., Janßen, H., Samsun, R. and Stolten, D. "A review of hightemperature polymer electrolyte membrane fuel-cell (HT-PEMFC)-based auxiliary power units for diesel-powered road vehicles", *Journal of Power Sources*, vol.311, 2016, 91-102.

Peng, J., Huang, J., Wu, X., Xu, Y., Chen, H., and Li, X., "Solid oxide fuel cell (SOFC) performance evaluation, fault diagnosis and health control: A review", Journal of Power Sources, vol.505, 2021, 230058.

Padullés, J., Ault, G. W., McDonald, J. R., "An integrated SOFC plant dynamic model for power systems simulation", *Journal of Power Sources*, vol. 86, no. 1-2, 2000, 495-500.

Kim, J., Kiss, B., Kim, D. and Lee, D. "Tracking Control of Overhead Crane Using Output Feedback with Adaptive Unscented Kalman Filter and Condition-Based Selective Scaling", *IEEE Access*, vol.9. 2021, 108628-108639.

Rechberger, J., Kaupert, A., Hagerskans, J. and Blum, L., "Demonstration of the first European SOFC APU on a heavy duty truck", *Transportation Research Procedia*, vol.14, 2016, 3676–3685.

Yang, B., Li, Y., Li, J., Shu, H., Zhao, X., Ren, Y. and Li, Q., "Comprehensive summary of solid oxide fuel cell control: a state-of-the-art review", *Protection and Control of Modern Power Systems*, vol.7, no. 36, 2022.