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Advanced Control of DC Grid-Connected Proton Exchange Membrane Fuel Cell: A Linear Parameter Varying Approach

Amir Afsharinejad, Maryam Dehghani, Mohammad H. Asemani, Navid Vafamand
School of Electrical and Computer Engineering, Shiraz University
Shiraz, Iran
{a.afsharinejad, mdehghani, asemani, n.vafamand}@shirazu.ac.ir

Mohammad S. Javadi
INESC TEC
Porto, Portugal
msjavadi@gmail.com

Fei Wang
North China Electric Power University
Baoding, China
feiwang@ncepu.edu.cn

João P. S. Catalão
FEUP and INESC TEC
Porto, Portugal
catalao@fe.up.pt

***Abstract*—In this paper, an advanced control of a DC Micro Grid (MG)-connected Proton Exchange Membrane (PEM) Fuel Cell connected with a DC/DC boost converter is addressed to achieve an overall appropriate control scheme in the power management system. In this context, a nonlinear PEM Fuel Cell stack, which is the main source of the continuous power to the load, is modelled and controlled by an optimal Linear Parameter Varying (LPV) technique in the presence of uncertainties and variation in its operating parameters i.e. output current and temperature. To this end, a polytopic-LPV model is considered for nonlinear PEM Fuel Cell stack and sufficient conditions for designing a stabilizing continuous time LPV controller based on state feedback controlling law is derived in terms of Linear Matrix Inequality (LMI). On the other hand, a feedback linearization controller is developed simultaneously to control the duty cycle of the DC/DC boost converter, which is connected between the PEM Fuel Cell stack and the load, aiming to regulate the DC output voltage of the grid to an arbitrary and predefined reference value. The performance of the proposed approach and controllers are verified through simulation results.**

***Keywords*—DC Micro Grid connected Proton Exchange Membrane Fuel Cell, Converter control, Optimal controller, Linear Matrix Inequality, Linear Parameter Varying model.**

NOMENCLATURE

PEM Fuel Cell modelling parameters

V_{act}	Activation voltage drop
P_{H_2}	Partial pressure of hydrogen at the anode
P_{O_2}	Partial pressure of oxygen at the cathode
I_{fc}	Output current
T	Operating temperature
$\dot{m}_{H_{2,in}}$	Hydrogen input flowrate
$\dot{m}_{O_{2,in}}$	Oxygen input flowrate
y,V_{fc},V_{stack}	Stack voltage

Boost converter

i_L	Inductor current
V_c	Boost converter output voltage
V_c^*	Desired boost converter output voltage

I. INTRODUCTION

A. Motivation and background

The utilization of new energies is received more and more attention due to declining fossil fuel reserves and particular sensitivity to the problem of global warming. Fuel Cells are also placed in the category of new energies and have attracted much research attention since they benefit from high efficiency, process cleanliness, a wide range of consumable fuels, and generate heat and water as secondary products. Fuel Cells can operate stand-alone or grid-connected. The grid-connected form attracts more attention since the produced water and heat can be utilized in the grid.

Fuel Cells are divided into various types by the type of their electrolyte. Among the various types, the Proton Exchange Membrane Fuel Cell (PEMFC) is an appropriate choice to be hired in electric vehicles and MGs due to its low operating temperature.

Exploiting Fuel Cells for various applications requires its optimal power management and control. This significant issue motivates this study for designing appropriate controllers for DC grid-connected Fuel Cells.

B. Relevant literature

As important as a system is, the need to model and control that system will be doubly important. Therefore, the nonlinear dynamics of Fuel Cells in both stand-alone and grid-connected form were modelled and controlled in many references. As a few examples, in [1] a Fuel Cell in a DC MG is considered and a controller for the boost converter is suggested. The experimental results verify the robustness and efficacy of the proposed approach.

Reference [2] considers the control of power electronic interfaces of a grid-connected Fuel Cell power plant, where a PID controller is hired to regulate the output DC voltage to a desired reference quantity through controlling the boost converter. Moreover, an LPV robust controller is hired to control the inverter to fulfill the arbitrary real and reactive power requirement of the grid. In this work, the grid impedance is uncertain and the load is time-varying. In addition, a predefined disturbance attenuation level is assured by using an H_∞ approach via pole placement consideration.

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Reference [3] takes action to decentralized control of energy storage apparatuses joint with a DC MG. In this paper, a decentralized charge controller is designed to regulate the bus voltage in the grid and make storage apparatuses (two batteries and a Fuel Cell), to operate optimally. Additionally, the power, the current and the voltage of the storage system are controlled by a PI controller, where the controller design process is carried out based on a represented mathematical model included in the paper. Reference [4] represents a two-port converter attached to Fuel Cell and battery sources, where the converter benefits from multiple output in series to obtain a high-voltage output. Reference [5] deals with energy management for PV-Fuel Cell-battery-based DC MG and reference [6] utilizes an adaptive controller for a converter connected to the Fuel Cell to stabilize the DC bus.

In another study [7], the frequency and the voltage of a MG are taken into account from controlling aspect. Parallel inverters and a PEMFC are included in the system under study, where the control strategy established on fuzzy logic and adaptive droop control. In addition, the proposed control scheme alleviates power losses of the MG. Reference [8] considers a strategy to control the transient response of a solid-oxide Fuel Cell in a MG. The proposed approach is lying on an adaptive feedback linearization embedded structure. This study benefits from a fully recurrent Neuro Fuzzy Laguerre wavelet control to appraise unknown functions of feedback linearization control.

C. *Paper innovation*

In this study, advanced control of a DC grid-connected PEMFC is considered. Since the continuous power to the load is provided by the PEMFC, the authors focus on the investigation of the modelling and controlling the PEMFC stack, precisely. Firstly, inspired from [9], all admissible variations of the uncertainties in PEMFC's operating parameters are considered as a convex polytope and a polytopic-LPV model with four vertices is derived.

Afterward, the optimal control of the mentioned model is considered by solving an optimization problem involving some LMIs. In addition, a feedback linearization controller is proposed simultaneously to control the duty cycle of a DC/DC boost converter which is located between the PEMFC stack and the load with the goal of regulating the output DC voltage of the DC MG to an arbitrary reference value.

D. *Paper organization*

The paper is structured as follows; in section II, the whole structure of the DC MG connected Fuel Cell is studied, where the PEMFC dynamics and mathematical model for boost converter are presented. In section III, the controller designs for the PEMFC stack and the DC/DC boost converter are proposed. Simulation results are considered in section IV and the conclusion and future works are brought in section V.

II. DC MG-CONNECTED FUEL CELL

In this section, the considered DC MG, which comprises a PEMFC, boost converter, and load is presented. The PEMFC benefits from the electrochemical reaction between oxygen and hydrogen to produce electricity from the chemical energy and is an undertaking solution to generate high power density in low operating temperature with no pollutants [10], [11].

A practical PEMFC comprises several components such as compressor/motor, water pump/tank/separator, cooling fan/humidifier/radiator, and hydrogen and oxygen tank and valve [12], each of which should be controlled properly for generating electricity. Due to high nonlinearity of the PEMFC stack dynamics, its control is more difficult compared to the other components. Thereby, only the control of PEMFC stack is investigated. While the PEMFC provides the continuous power to the load, a boost converter is considered to block current reverse flow and increase the PEMFC output voltage so that it regulates the DC MG bus voltage and supplies the loads.

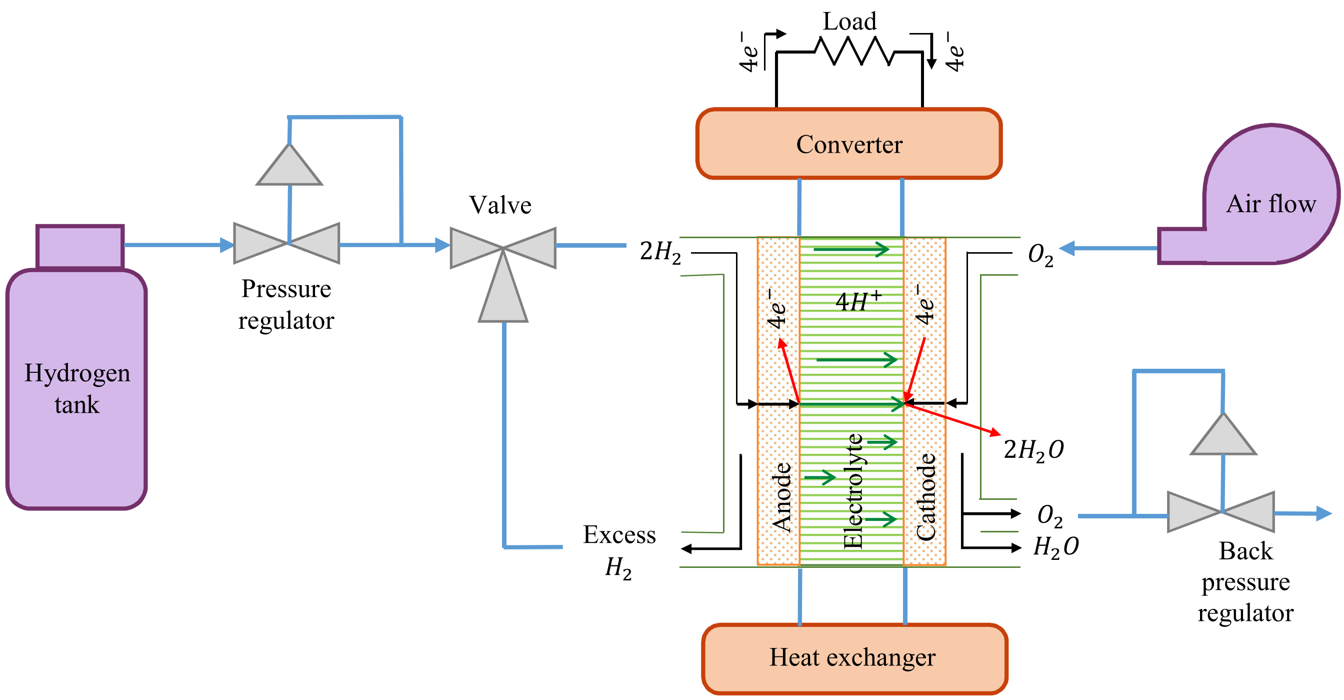

Fig. 1. The structure of PEMFC connected to a DC MG.

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A. PEMFC Dynamics with Time-varying Parameters

The PEMFC utilizes oxygen and hydrogen to generate electricity, water and heat. This action in the PEMFC stack is represented by three dynamics, given in (1)-(3) [9]:

$$\frac{dV_{act}}{dt} = \frac{V_{act} I_{fc}}{\eta_{act} C_{dl}} + \frac{I_{fc}}{C_{dl}}, \quad (1)$$

$$\frac{dP_{H_2}}{dt} = \frac{RT}{V_{an}}\left(\dot{m}_{H_{2,in}} - k_{an}\left(P_{H_2} - P_{H_{2,in}}\right) - \frac{NI_{fc}}{2F}\right), \quad (2)$$

$$\frac{dP_{O_2}}{dt} = \frac{RT}{V_{ca}}\left(\dot{m}_{O_{2,in}} - k_{ca}\left(P_{O_2} - P_{O_{2,out}}\right) - \frac{NI_{fc}}{4F}\right), \quad (3)$$

where activation voltage drop is represented by V_{act} and partial pressures of hydrogen and oxygen are represented by P_{H_2} and P_{O_2}, respectively. Moreover, the inlet flow rates of hydrogen and oxygen are represented by $\dot{m}_{H_{2,in}}$ and $\dot{m}_{O_{2,in}}$ respectively.

In addition,

$$\begin{aligned} \eta_{act} &= -0.948 + T\Big[0.00286 + 0.0002\ln(A_{cell}) \\ &+ 4.3 \times 10^{-5} \ln\left(9.174 \times 10^{-7} P_{H_2} e^{\frac{-77}{T}}\right)\Big] \\ &+ 7.6 \times 10^{-5} T ln\left(1.97 \times 10^{-7} P_{O_2} e^{\frac{-498}{T}}\right) \\ &- 1.93 \times 10^{-4} T ln\left(I_{fc}\right). \end{aligned} \quad (4)$$

Also, the output of the cell is defined as

$$y = V_{fc} = V_{stack} = N\left(E_{cell} - V_{act} - I_{fc}\frac{r_m l_m}{A_{cell}}\right), \quad (5)$$

where N is the number of PEMFC, and

$$\begin{aligned} E_{cell} &= 1.229 - 8.5 \times 10^{-4}(T - 298.15) \\ &+ \left(\frac{RT}{2F}\right)\ln\left(P_{H_2}\sqrt{P_{O_2}}\right), \end{aligned} \quad (6)$$

$$r_m = \frac{18.16\left[1 + \frac{0.03 I_{fc}}{A_{cell}} + 0.062\left(\frac{I_{fc}}{303}\right)^2\left(\frac{I_{fc}}{A_{cell}}\right)^{2.5}\right]}{11.866 - 3\left(\frac{I_{fc}}{A_{cell}}\right)\exp\left(4.18\left(\frac{T-303}{T}\right)\right)}. \quad (7)$$

B. Mathematical model for boost converter

Fig. 2, depicts the circuit diagram of boost converter. It comprises a high frequency inductor (L), a diode, and a capacitor (C). The state-space representation of the boost converter is as follows [13]:

$$\frac{dI_{fc}}{dt} = -(1-u)\frac{V_C}{L} + \frac{V_{fc}}{L}, \quad (8)$$

$$\frac{dV_C}{dt} = (1-u)\frac{I_{fc}}{C} - \frac{V_C}{RC}, \quad (9)$$

where $i_L = I_{fc}$ represents inductor current, V_C stands for the boost converter output voltage and V_{fc} is the PEMFC stack voltage.

The goal is to regulate the PEMFC and boost converter to supply the load and keep the DC bus voltage at the desired value.

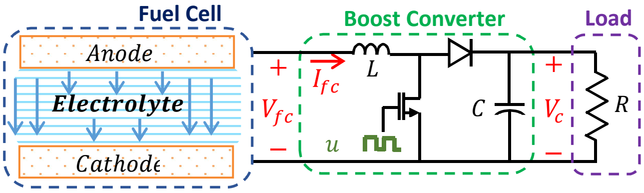

Fig. 2. The circuit diagram of the boost converter.

III. Proposed Controller Design

In this section, two separate controllers are designed to achieve an overall control on the power management system. As can be seen in Fig. 3, a stabilizing continuous time LPV controller based on state feedback controlling law is designed to assure closed-loop stability of the nonlinear PEMFC stack in the presence of its uncertain and varying operating parameters I and T. It will be a challenging task since the current variation will end to impact on the lots of parameters as the load demand changes. For instance, reactant's pressure, stack's voltage and input flowrate of reactant gasses [14].

A. Optimal control of the PEMFC stack

This subsection devotes to optimal control of the PEMFC model. Since the PEMFC stack model is nonlinear, the LPV representation of the stack is derived and then an optimal controller is designed for the LPV model of the stack. The rationale behind the LPV model is to use the polytopic LPV representation of the original nonlinear system. In the polytopic-LPV representation, linear systems comprise the model vertices and controlling goals can be achieved just based on these vertices [15]. Inspired by [16], for the region $\mathcal{R}: \{I_{fc} \in [0,350]\ \&\ T \in [70,100]\}$, the dynamics (1)-(3) result in the following polytopic-LPV model:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{4} \rho_i(t)\{A_i \tilde{x}(t) + B_i \tilde{u}(t)\}. \quad (10)$$

where the details and values of the parameters $\rho_i(t)$, A_i, B_i, $\tilde{x}$, and $\tilde{u}$ can be found in [16]. Assume that the optimal controller is in the following form:

$$\tilde{u}(t) = K\tilde{x}(t), \quad (11)$$

where K represents the controller gain. Therefore, the closed-loop PEMFC stack is formulated as follows:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{4} \rho_i(t)\,(A_i + B_i K)\tilde{x}(t) \quad (12)$$

To design the controller gain K optimally, in the following, Theorem 1 is given to guarantee the optimal controller gain for the closed-loop model of the PEMFC stack.

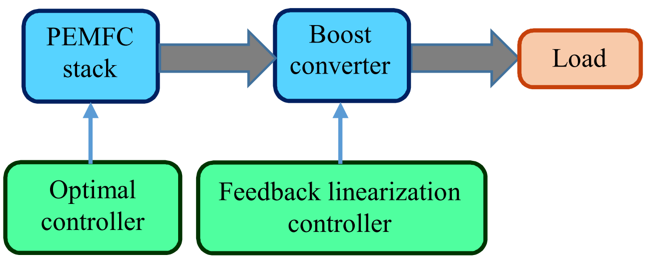

Fig. 3. The control action of the grid-connected PEMFC.

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It is important to mention that before applying the theorem, the state equations in (1)-(3) are divided by the temperature (T) to assure that the matrix B_i which is the coefficient of the control signals is constant.

***Theorem 1*:** To assure that the controller gain (11) stabilizes the closed-loop PEMFC stack model and the following performance function is optimal:

$$J = \int_0^\infty (\tilde{x}^T Q \tilde{x} + \tilde{u}^T R \tilde{u}) \qquad (13)$$

where Q and R are positive definite matrices, it is needed to find the solution of the optimization problem in (14) for all vertices of the LPV model in (10).

$$\begin{aligned} &Min\ \sigma \\ &Such\ that: \\ &\begin{bmatrix} -\sigma & \tilde{x}_0^T \\ \tilde{x}_0 & -S \end{bmatrix} < 0 \\ &\begin{bmatrix} SA_i^T + A_i S - BR^{-1}B^T & S \\ S & -Q^{-1} \end{bmatrix} < 0 \\ &S > 0 \end{aligned} \qquad (14)$$

Then, the optimal controller gain can be calculated using $K = -R^{-1}B^T S^{-1}$.

***Proof*:** The optimal controller can be guaranteed by the following Riccati inequality:

$$A_i^T P + PA_i - PBR^{-1}B^T P + Q < 0 \qquad (15)$$

where $P > 0$. By utilizing the congruence lemma [17] and letting $S = P^{-1}$, (15) leads to the second LMI constraint in (14). The third LMI in (14) needs to have $P > 0$.

By considering the performance index in (13) and taking into account some mathematical simplification, one concludes that the optimal performance index is as given in (16) [17]:

$$J_{opt} = \tilde{x}_0^T P \tilde{x}_0 \qquad (16)$$

The optimal performance in (16) is achieved by solving the following problem

$$\begin{aligned} &Min\ \sigma \\ &Such\ that: \\ &\tilde{x}_0^T P \tilde{x}_0 < \sigma \end{aligned} \qquad (17)$$

By utilizing the Schur lemma [17], (17) leads to the optimization function and the first LMI in (14). This completes the proof. ■

B. Feedback linearization control of the boost converter

To control the boost converter output voltage, the dynamic (9) is considered to design the duty cycle of the boost converter so that the V_c is kept to the desired value V_c^*. Define the regulation error $e = V_C - V_C^*$. Therefore,

$$\dot{e} = \dot{V}_C - \dot{V}_C^* = (1-u)\frac{I_{fc}}{C} - \frac{V_C}{RC}. \qquad (18)$$

Choose the control input as follows:

$$u = 1 - \frac{C}{I_{fc}}\left(-\gamma e + \frac{V_C}{RC}\right). \qquad (19)$$

The error dynamic (18) will then be:

$$\dot{e} = -\gamma e. \qquad (20)$$

According to (20), the regulation error e asymptotically converges to zero. Therefore, the controller (19) stabilizes the boost converter.

IV. Simulation Results

In this section, the overall performance of the developed approach is evaluated. It should be pointed out that all simulations are carried out on Matlab/Simulink. The parameters of the boost converter and sample 5 kW PEMFC are given in Table I and Table II respectively.

Moreover, the initial conditions of PEMFC stack state trajectories are chosen as $X^T(0) = [0.8251 \quad 3 \quad 3.5582]$. In addition, the initial conditions of the state trajectories of the boost converter are chosen as $X^T(0) = [0.1 \quad 5]$.

The changing profile of the PEMFC stack's operating temperature is depicted in Fig. 4. This profile is considered in such a way that, I) It covers a wide range of the predefined operating regions for PEMFC's varying parameters. II) Being close to the actual and practical behavior of a PEMFC.

TABLE I. Boost converter parameters [13].

Parameter	Description	Value	Unit
L	High frequency inductor	9	mH
C	Capacitor	20	μF
R	Load	5	Ω

TABLE II. PEMFC stack parameters [9].

Parameter	Description	Value	Unit
A_{cell}	Cell active area	232	cm^2
C_{dl}	Double-layer capacitance	8.12	F
F	Faraday constant	96487	c/mol
k_{an}	Anode flow constant	0.065	$mol/(s.atm)$
k_{ca}	Cathode flow constant	0.065	$mol/(s.atm)$
N	Number of cells	35	$-$
$P_{H_{2,tank}}$	Hydrogen tank pressure	3	atm
$P_{O_{2,BP}}$	Oxygen back pressure	3	atm
R	Universal gas constant	8.31	$J/(mol.k)$
V_{an}	Anode volume	0.005	m^3
V_{ca}	Cathode volume	0.01	m^3
l_m	Membrane thickness	178×10^{-4}	cm

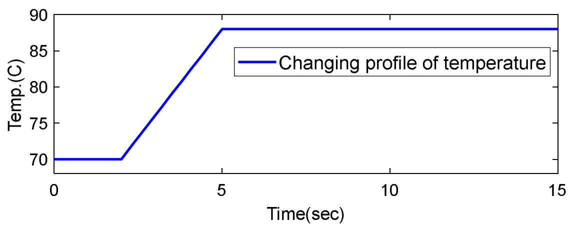

Fig. 4. The PEMFC stack operating temperature (T)

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By applying the proposed theorem on the system dynamics, the controller gain (K) is obtained as follows:

$$K = 10^3 \times \begin{bmatrix} 0.0120 & -0.0357 & -0.1183 \\ 0.1407 & -0.0563 & -1.4277 \end{bmatrix} \tag{21}$$

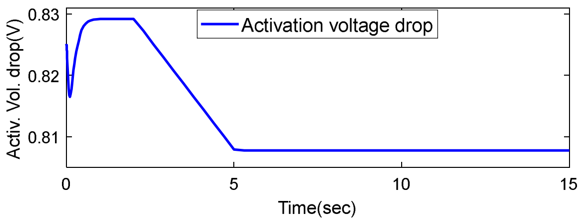
Afterward, the developed optimal controller is applied to the nonlinear PEMFC stack. According to Fig. 5, the system state trajectories converge to their equilibrium points. Its worthy to note that the developed controller is applied to the nonlinear PEMFC stack dynamics (1)-(3), not like [18] to the LPV model, which extracted from the nonlinear dynamics.

Since the PEMFC stack is exploited as the primary source of energy in the power management system under review, it has to provide the continuous power to the load. Input flow rates of hydrogen and oxygen, which are the controlling signals at the anode and the cathode of the PEMFC respectively, are changed due to the load demand. Controlling signals of PEMFC are demonstrated in Fig. 6.

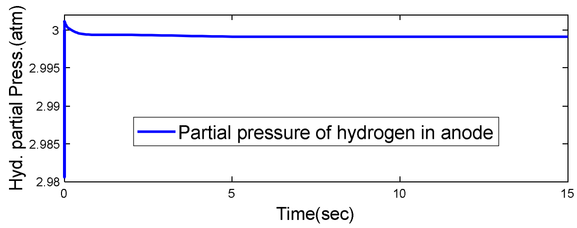
The output voltage of PEMFC stack is depicted in Fig. 7. This figure demonstrates that the PEMFC stack provides constant voltage to the boost converter.

In the next step, the performance of the developed feedback linearization controller for the boost converter is evaluated. The state trajectories of the controlled DC/DC boost converter are shown in Fig. 8.

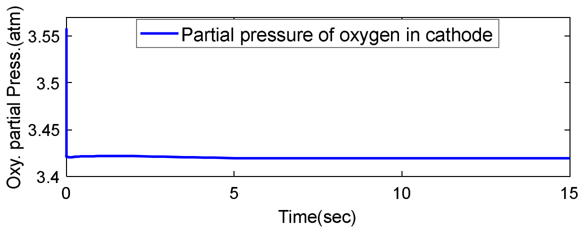
As it can be seen, the controlled converter provides a constant desired DC voltage to the load. The controlling signal of the feedback linearization controller is also depicted in Fig. 9.



(a)



(b)



(c)

Fig. 5. PEMFC stack closed-loop state trajectories. a) Activation voltage drop, b) Partial pressure of hydrogen, c) Partial pressure of oxygen

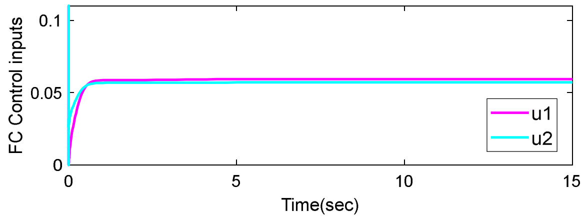


Fig. 6. Input flow rates of hydrogen (u_1) and oxygen (u_2) as PEMFC control inputs

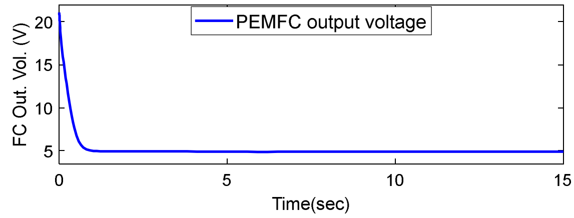
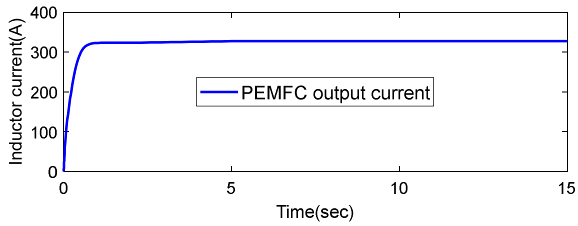
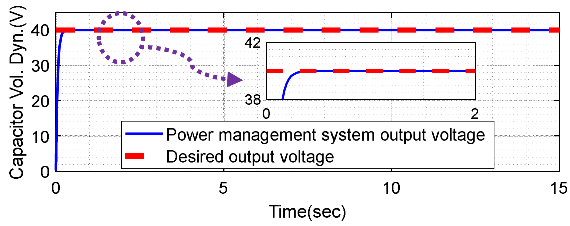


Fig. 7. The output voltage of the PEMFC stack



(a)



(b)

Fig. 8. Controlled boost converter state trajectories. a) Inductor current dynamic (PEMFC stack output current), b) Capacitor voltage dynamic (power management system outlet voltage)

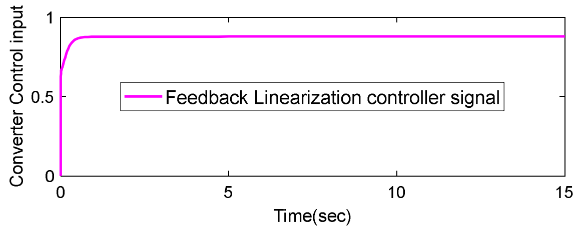


Fig. 9. Control input for DC/DC boost converter

V. Conclusion

Due to the importance of a DC MG-connected PEM Fuel Cell, this paper proposes suitable controllers for controlling the PMEFC and the DC/DC boost converter to achieve an overall appropriate control scheme in the power management system. The nonlinear PEMFC stack is modelled and controlled by the LPV technique, where the variations in the PEMFC operating parameters, which are output current and temperature, are treated as time varying uncertainties. Additionally, a feedback linearization controller is developed to determine the duty cycle of the DC/DC boost converter that

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is located between the PEMFC stack and the load and its aim is to regulate the DC output voltage of the grid to a predefined reference value. The performance of the proposed approach and controllers is verified through simulation results. Briefly, this study demonstrates the importance of designing appropriate controllers for PEMFC and the boost converter. The proposed approach designs two separate controllers for the PEMFC and its boost converter. The PEMFC is equipped with an optimal LPV controller to deal with all uncertainties seen in the model, while the controller of the converter is a feedback linearization one and its goal is to regulate the output power given to the load.

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REFERENCES

[1] Thounthong, P., Mungporn, P., Pierfederici, S., Guilbert, D., Takorabet, N., Nahid-Mobarakeh, B., ... & Burikham, P. (2021). Robust Hamiltonian-Energy Control Based on Lyapunov Function for Four-Phase Parallel Fuel Cell Boost Converter for DC Microgrid Applications. *IEEE Transactions on Sustainable Energy*.

[2] Erfanmanesh, T., & Dehghani, M. (2015). Performance improvement in grid-connected fuel cell power plant: an LPV robust control approach. *International Journal of Electrical Power & Energy Systems*, *67*, 306-314.

[3] Chowdhury, N. U. R., Al Hadi, A., & Mann, M. (2018, April). Design and analysis of a standalone dc microgrid with battery and fuel cell energy storage penetration for different load characteristic. In *2018 International Conference on Power Energy, Environment and Intelligent Control (PEEIC)* (pp. 425-429). IEEE.

[4] Lai, C. M., Yang, M. J., Lin, Y. J., Lin, Y. C., & Lin, Y. Y. (2016, March). Study of a high-gain two-port power converter with fuel cell/battery sources and stacked output for hybrid electric vehicle and dc-microgrid. In *2016 IEEE International Conference on Industrial Technology (ICIT)* (pp. 366-371). IEEE.

[5] Han, Y., Chen, W., Li, Q., Yang, H., Zare, F., & Zheng, Y. (2019). Two-level energy management strategy for PV-Fuel cell-battery-based DC microgrid. *International Journal of Hydrogen Energy*, *44*(35), 19395-19404.

[6] Thounthong, P., Mungporn, P., Pierfederici, S., Guilbert, D., & Bizon, N. (2020). Adaptive Control of Fuel Cell Converter Based on a New Hamiltonian Energy Function for Stabilizing the DC Bus in DC Microgrid Applications. *Mathematics*, *8*(11), 2035.

[7] Shafiee Roudbari, E., Beheshti, M. T. H., & Rakhtala, S. M. (2020). Voltage and frequency regulation in an islanded microgrid with PEM fuel cell based on a fuzzy logic voltage control and adaptive droop control. *IET Power Electronics*, *13*(1), 78-85.

[8] Awais, M., Khan, L., Ahmad, S., & Jamil, M. (2021). Feedback-Linearization-Based Fuel-Cell Adaptive-Control Paradigm in a Microgrid Using a Wavelet-Entrenched NeuroFuzzy Framework. *Energies*, *14*(7), 1850.

[9] Chen, P. C. (2013). Robust voltage tracking control for proton exchange membrane fuel cells. *Energy conversion and management*, *65*, 408-419.

[10] Nehrir, M. H., & Wang, C. (2009). *Modeling and control of fuel cells: distributed generation applications* (Vol. 41). John Wiley & Sons.

[11] Hayati, M. R., Khayatian, A., & Dehghani, M. (2016). Simultaneous optimization of net power and enhancement of PEM fuel cell lifespan using extremum seeking and sliding mode control techniques. *IEEE Transactions on Energy Conversion*, *31*(2), 688-696.

[12] Yuan, H., Dai, H., Wei, X., & Ming, P. (2020). Model-based observers for internal states estimation and control of proton exchange membrane fuel cell system: A review. *Journal of Power Sources*, *468*, 228376.

[13] Sharma, H., Jaga, O. P., & Maurya, S. K. (2016, July). Sliding mode control strategies for fuel cell system. In *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)* (pp. 1-4). IEEE.

[14] Na, W. K., Gou, B., & Diong, B. (2007). Nonlinear control of PEM fuel cells by exact linearization. *IEEE Transactions on Industry Applications*, *43*(6), 1426-1433.

[15] Javanmardi, H., Dehghani, M., Mohammadi, M., & Vafamand, N. (2020). Bilinear matrix inequality-based nonquadratic controller design for polytopic-linear parameter varying systems. *International Journal of Robust and Nonlinear Control*, *30*(17), 7655-7669.

[16] Afsharinejad, A., Asemani, M. H., & Dehghani, M. (2020, August). Optimal Linear Parameter Varying Controller Design for Proton Exchange Membrane Fuel Cell Using LMI Techniques. In *2020 28th Iranian Conference on Electrical Engineering (ICEE)* (pp. 1-5). IEEE.

[17] Herrmann, G., Turner, M. C., & Postlethwaite, I. (2007). Linear matrix inequalities in control. In *Mathematical methods for robust and nonlinear control* (pp. 123-142). Springer, London.

[18] Chen, P. C. (2011). The dynamics analysis and controller design for the PEM fuel cell under gas flowrate constraints. *International Journal of Hydrogen Energy*, *36*(4), 3110-3122.

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