HIGH-GAIN OBSERVER IN FUEL CELL AND CASCADED DC-DC BOOST CONVERTER SYSTEM

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Abstract. In this study, we propose using a high-gain observer (HGO) in fuel cell systems and the FC-cascade boost converter to achieve precise state estimation and improve control accuracy. The HGO offers significant advantages, including robustness to disturbances, simplicity of design, and reduced dependency on costly sensors, thereby enhancing system performance and reducing operational costs. Our results demonstrate the superior accuracy and reliability of this approach, confirming its potential as a promising solution for fuel cell applications.

Keywords— Fuel cell electric vehicles (FCEVs), DC-DC boost cascade converter,high-gain observer

1 Introduction

Fuel cells (FC) represent a promising technology to address current energy challenges[1], [2], offering clean and efficient energy production from renewable sources such as hydrogen. However, integrating FCs into electrical systems requires efficient and robust power converters[3]. Among these converters, the cascade DC-DC boost converter plays a crucial role, stepping up the FC voltage to an appropriate level, typically ranging from 400V to 700V[4], especially for Fuel Cell Electric Vehicles (FCEVs), as illustrated in Figure 1.

The control and supervision of the FC-cascade boost converter system are essential to ensure its stable and efficient operation. A key element of this supervision is the accurate estimation of the system's internal state, including the FC voltage and converter current. This estimation is particularly important in the presence of disturbances and nonlinearities, as it enables the implementation of adaptive and robust control strategies.The use of observers in nonlinear systems offers several advantages[5]. One of the main benefits is the improvement in control accuracy. Better state estimation allows for a better system response and more precise control because the control is based on the estimates provided by the observer rather than on direct and potentially[6], [7] noisy measurements.Even for values measured using sensors, it is possible to estimate them using the observer. This allows, firstly, to reduce the number of sensors, which represents an economic gain. As mentioned previously, it also improves accuracy by reducing the number of sensors used.By monitoring the discrepancies between actual measurements and the estimates provided by the observer, it is possible to detect

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anomalies and diagnose potential faults. This improves the safety and reliability of industrial systems, as early detection of anomalies and faults can prevent serious failures and reduce downtime.

In this article, we propose the use of a high-gain observer (HGO) as an effective solution for estimating the states of the FC-cascade boost converter system. HGOs offer several advantages over other estimation techniques, such as the Kalman filter, including simplicity of design and robustness to system disturbances. Compared to classical observers such as the Kalman filter or the Luenberger observer, the high-gain observer (HGO) offers a simpler structure and better robustness against disturbances, making it an ideal solution for applications with a limited number of sensors[8], [9]

The use of a high-gain observer in the FC-cascade boost converter system is motivated by several factors:

Simplicity of design: HGOs have a simple and easy-to-implement structure, making them attractive for real-time applications.
Robustness to disturbances: HGOs are robust to system disturbances, such as load variations and measurement noise.
Fast convergence: HGOs ensure rapid convergence of state estimates to real values, which is crucial for effective system control.

The article will be structured as follows: Section 2 will delve into the equivalent model of the FC DC-DC cascade boost converter, focusing on operational dynamics. Section 3 will design a high-gain observer for the FC DC-DC cascade boost system to enhance observability and control. Section 4 will present simulation results, offering insights into performance. Finally, the article will conclude with a discussion of results.

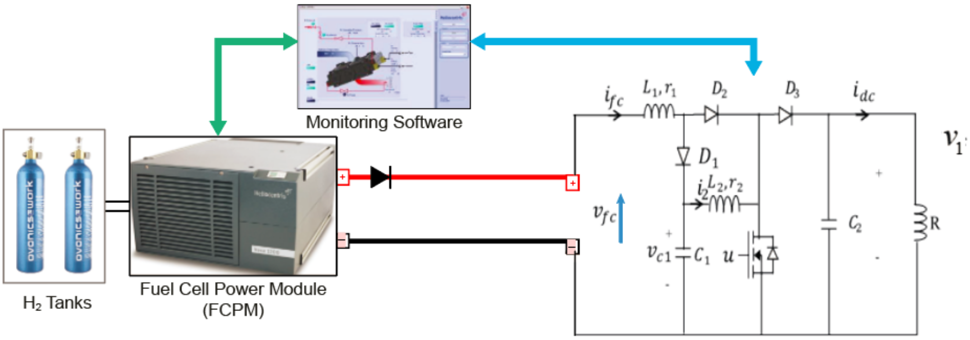


Fig. 1. Fuel Cell and Cascaded DC-DC Boost Converter System

2 Equivalent model of FC DC-DC cascade boost converter

To validate our experimental approach, we designed a setup comprising a fuel cell, a cascaded DC-DC boost converter[7], [8], [9], which includes three diodes (D1, D2, D3), two inductors (L1, L2), a MOSFET transistor, and two capacitors (C1, C2).The input voltage for our converter is provided by a Nexa® 1200 PEM (Proton Exchange Membrane) fuel cell. This fuel cell consists of 36 cells and has an output voltage of 24V with a power output of 1200W. The static characteristic of the PEMFC includes three distinct regions: the reduction region, the ohmic polarization region, and the overvoltage region, as illustrated in Figure 2 [10].

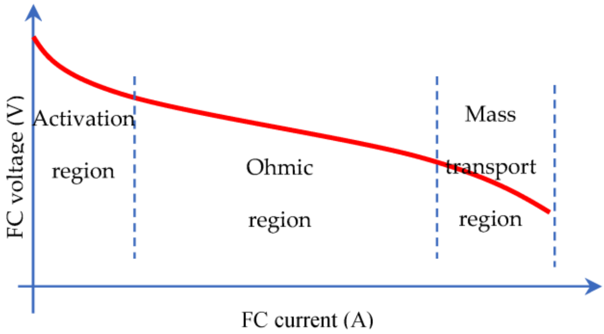


Fig. 2. Caractéristique statique de la PEMFC

The diagram of the cascaded DC-DC boost converter is illustrated in Figure 2. The gain of this converter is determined by the following equation:

$$v_1 = v_{fc}\left(1+\frac{\mu}{1-\mu}\right)^2 \tag{1}$$

where v_1 is the output voltage, v_{fc} is the input voltage, and μ is the duty cycle of the converter.

By using the average values of the following variables, which are as follows $x_1 =< v_1 >$, $x_2 =< i_2 >, x_3 =< v_{C1} >, x_4 =< i_{fc} >$, $x_5 =< v_{fc} >$ which are respectively the output voltage, the current, the voltage across capacitor C1, and the current and voltage at the output of the fuel cell, we obtain the following equations, which are defined as follows[10]:

$$\frac{dx_1}{dt} = \frac{(1-\mu)}{C_2}x_2 - \frac{1}{C_2}i_{dc} \tag{2}$$

$$\frac{dx_2}{dt} = -\frac{(1-\mu)}{L_2}x_1 - \frac{r_2}{L_2}x_2 + \frac{1}{L_2}x_3 \tag{3}$$

$$\frac{dx_3}{dt} = -\frac{1}{C_1}x_2 + \frac{(1-\mu)}{C_1}x_4 \tag{4}$$

$$\frac{dx_4}{dt} = -\frac{(1-\mu)}{L_1}x_3 - \frac{r_1}{L_1}x_4 + \frac{1}{L_1}v_{fc} \tag{5}$$

3 High-Gain Observer in Fuel Cell and Cascaded DC-DC Boost Converter System

In our system, consisting of a fuel cell and a cascaded DC-DC boost converter, we employ a high-gain observer to estimate the ²states of the system using only two measured variables. This significantly simplifies the sensor requirements and enhances the overall system performance. A high-gain observer is designed to estimate state variables with high accuracy and rapid convergence by utilizing the system's dynamic model. In our case, the input voltage from the fuel cell and the output current of the boost converter are used to estimate the inductor currents, capacitor voltages, and the duty cycle.

This approach offers several advantages. Firstly, by reducing the number of sensors, we lower system complexity and cost while increasing reliability by minimizing points of potential failure. Fewer sensors also mean less susceptibility to noise, which enhances measurement accuracy. Accurate state estimation allows for improved control performance, enabling precise control actions that enhance the efficiency and stability of the fuel cell and DC-DC converter system. The scalability of this approach makes it suitable for more complex systems without a proportional increase in sensor count, offering versatility for various applications.To design our observer, we must represent our system in a specific form [11], [12], [13]. Let's start by defining the following variabl $X = \begin{pmatrix} x_1 & x_2 & x_3 & x_4 & x_5 \end{pmatrix}^T$

Equations (2) to (5) can be written in the following form(6):

$$\dot{X} = F(x)X + G(x,\mu,i_{dc}) + \bar{\xi}(t) \tag{6}$$

$$Y = CX = x_1$$

With

$$F(x) = \begin{pmatrix} 0 & F_1 & 0 & 0 & 0 \\ 0 & 0 & F_2 & 0 & 0 \\ 0 & 0 & 0 & F_3 & 0 \\ 0 & 0 & 0 & 0 & F_4 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}; \tag{6.1}$$

$$F_1 = \frac{1}{C_2}, F_2 = \frac{1}{L_2}, F_3 = \frac{1}{C_1}, F_4 = \frac{1}{L_1}$$

$$G(x,\mu,i_{dc})=\begin{pmatrix} -\frac{\mu}{C_2}x_2-\frac{1}{C_2}i_{dc} \\ -\frac{1-\mu}{L_2}x_1-\frac{r_2}{L_2}x_2 \\ -\frac{1}{C_1}x_2-\frac{\mu}{C_1}x_4 \\ -\frac{(1-\mu)}{L_1}x_3-\frac{r_1}{L_1}x_4 \\ 0 \end{pmatrix} \qquad (6.2)$$

$$\bar{\xi}=\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \xi(t) \end{pmatrix} \quad (6.3) \qquad C=\begin{pmatrix} 1 & 0 & 0 & 0 & 0 \end{pmatrix} \quad (6.4)$$

For the high-gain system described in equation (6), it is necessary to verify three assumptions before proceeding with the design of our observer. The first two conditions, $\xi(t)$ and i_{dc} , are both bounded. Specifically, $\xi(t)$ is bounded because $\frac{dv_1}{dt}$ is bounded, since the chemical reactions at the fuel cell terminals are limited and do not diverge. Additionally, the current i_{dc} and its derivative are also bounded. Hence, the first two assumptions are verified. As for the third assumption, it is demonstrated as follows:

Let α and β two positive constants, where $\forall k \in 1,...,q-1, \forall x \in \Re^n$ In our case, $q=5$ The condition $0\langle \alpha^2 \le F_K(x)^T F_K(x) \le \beta^2$ (7) nk represents the dimension of each state variable x_n , In our system, all variables have a dimension equal to 1, thus $n_1=n_2=n_3=n_4=n_5=1$ $I_{n_{K+1}}$ is the $(n_{K+1})\times(n_{K+1})$ identity matrix.And (7) becomes $0\langle \alpha^2 I_{n_{K+1}} \le F_K(x)^T F_K(x) \le \beta^2 I_{n_{K+1}}$ which means that this condition is satisfied

After verifying the three hypotheses, we move on to designing the observer. Consider the following diagonal matrices used in the creation process,

$$\Delta_\theta = diag(1,\frac{1}{\theta},\frac{1}{\theta^2},\frac{1}{\theta^3},\frac{1}{\theta^4}) \qquad (8)$$

$$\Delta_\theta = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{\theta} & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{\theta^2} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{\theta^3} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\theta^4} \end{pmatrix} \qquad (8.1)$$

With θ parameter for adjusting the observer, which must be sufficiently large.

$$\Lambda = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{C_2 L_2} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{C_2 L_2 C_1} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{L_1 L_2 C_1 C_2} \end{pmatrix} \qquad (9)$$

Let the matrix be defined as follows ;

$$S^{-1}C^T = \begin{pmatrix} C_5^1 \\ C_5^2 \\ C_5^3 \\ C_5^4 \\ C_5^5 \end{pmatrix} \qquad (10)$$

After determining the matrices, the design of the observer to estimate the variables starts with the initial term given in equation (6) and adds an additional term, the complete form of which is given in the following equation (11).

$$\dot{\hat{X}} = F\left(\hat{x}\right)\hat{X} + G\left(\hat{x}, \mu, i_{dc}\right) - \theta\Lambda^{+}\Delta_\theta^{-1}S^{-1}C^T C(\hat{x} - x) \qquad (11)$$

Expanding equation (11) leads to the estimated values of the desired variables, which are given by the following equations.

$$\dot{\hat{x}}_1 = \frac{1}{C_2}\hat{x}_2 - \frac{\mu}{C_2}\hat{x}_2 - \frac{1}{C_2}i_{dc} - 5\theta(\hat{x}_1 - x_1) \tag{11.1}$$

$$\dot{\hat{x}}_2 = \frac{1}{L_2}\hat{x}_3 - \frac{1-\mu}{L_2}\hat{x}_1 - \frac{r_2}{L_2}\hat{x}_2 - 10\theta^2 C_2(\hat{x}_1 - x_1) \tag{11.2}$$

$$\dot{\hat{x}}_3 = \frac{1}{C_1}\hat{x}_4 - \frac{1}{C_1}\hat{x}_2 - \frac{\mu}{C_1}\hat{x}_4 - 10\theta^3 C_2 L_2(\hat{x}_1 - x_1) \tag{11.3}$$

$$\dot{\hat{x}}_4 = \frac{1}{L_1}\hat{x}_5 - \frac{(1-\mu)}{L_1}\hat{x}_3 - \frac{r_1}{L_1}\hat{x}_4 - 5\theta^4 C_2 L_2 C_1(\hat{x}_1 - x_1) \tag{11.4}$$

$$\hat{x}_5 = \hat{x}_5 - \theta^5 C_1 C_2 L_1 L_2(\hat{x}_1 - x_1) \tag{11.5}$$

4 Simulation results

To validate our observer, we conducted a validation on MATLAB Simulink of our system representing a fuel cell and a cascaded DC-DC boost converter. This system presents a challenge due to its non-minimum phase characteristic and nonlinear nature, represented by equations (2) to (5). Additionally, the high-gain observer is described by equations (11.1) to (11.5) to estimate the variables using only two measurements to estimate five variables.

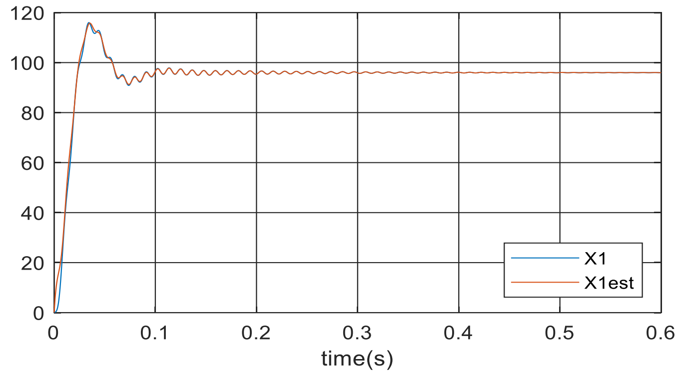
Using the values described in Table 1 below to validate our simulation, we obtained the results presented in Figure 3.

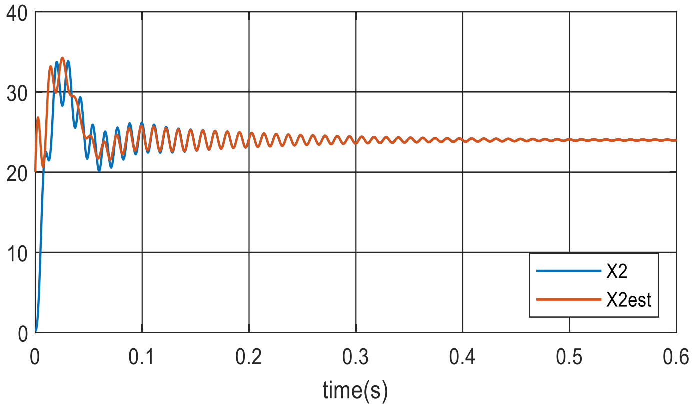
Table 1: Fuel Cell and the Cascaded DC-DC Boost Converter parameters

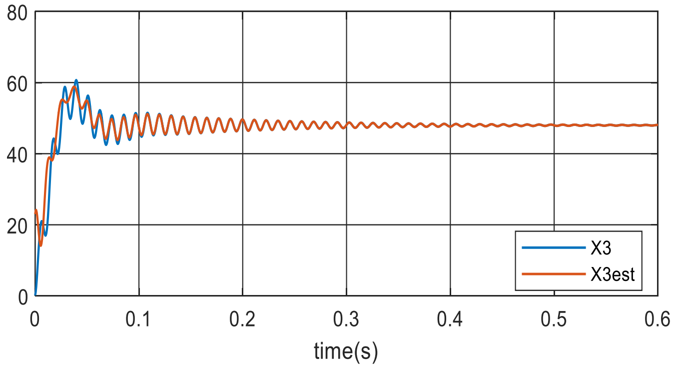
	Designation	Value
Fuel Cell Power Module	FC open circuit voltage	$E = 28.3\ V$
	FC internal capacitor	$C_{fc} = 130\ F$
	Activation resistances	$R_a = 0.155\ \Omega$
	Ohmic resistance	$R_r = 2.89\ m\Omega$
DC-DC Boost Cascade converter	Inductance	$L_1 = L_2 = 4mH$
	Capacitor	$C_1 = C_2 = 1200\mu F$
	ESR of the inductance	$r_1 = 0.64\Omega$ $r_2 = 0.56\Omega$

For the observer parameter, we used the value $\theta = 120$.

Based on the figures, it is clear that the estimated values using the observer closely follow the measured values and even represent values that are more precise than those measured.







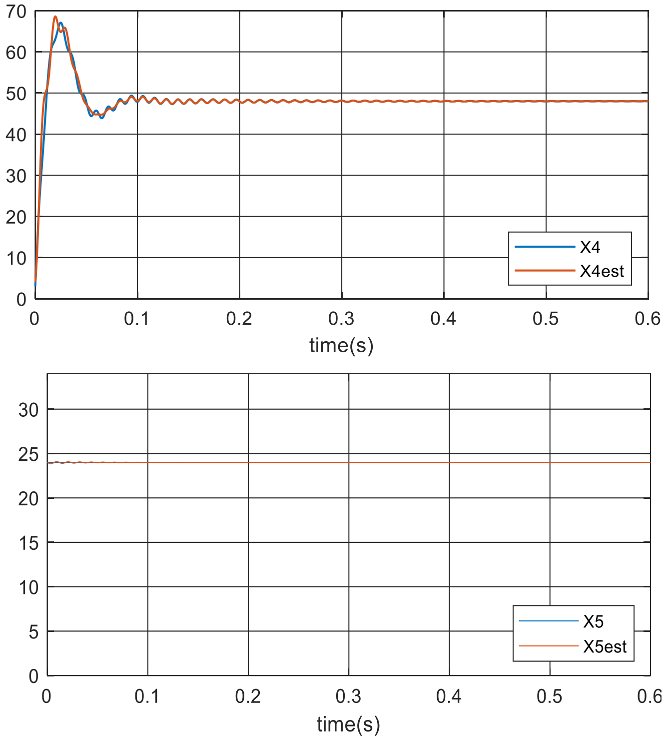


Fig.3. Estimation of variables from x_1 to x_5

5 Results Discussion

The application of the high-gain observer in fuel cell systems represents a significant advancement, allowing for precise estimation of state variables through advanced control and signal processing techniques. The results obtained clearly demonstrate that the values estimated by the observer closely track actual measurements, often with superior accuracy, thus highlighting the reliability and effectiveness of this approach.

This heightened precision is crucial in environments where minor errors can have major implications. It facilitates finer process management, optimizes energy efficiency, and extends component lifespan. Moreover, by reducing dependence on costly and failure-prone physical sensors, the high-gain observer offers substantial economic benefits both initially and over the long term.

In summary, this study confirms that the high-gain observer is a promising solution for enhancing the performance of fuel cell systems, not only in terms of measurement accuracy but also in reducing operational costs.

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