Modelling and Passivity-based Control of a Non Isolated DC-DC Converter in a Fuel Cell System

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ABSTRACT

This paper presents the model of a fuel cell and the design and simulation of a cascade of two DC-DC converters. First, a detailed mathematical model of fuel cell is presented and simulated. Then, a nonlinear model of the whole controlled system is developed and a robust nonlinear controller of currents is synthesized using a passivity-based control. A formal analysis based on Lyapunov stability and average theory is developed to describe the control currents loops performances. A classical PI controller is used for the voltages loops. The simulation models have been developed and tested in the Matlab/Simulink. Simulated results are displayed to validate the feasibility and the effectiveness of the proposed strategy.

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1. INTRODUCTION

In recent years, a rapid increase of the population of the world and a significant development of industries are the origine of increase of the demand of electricity. The use of renewable energies such as solar, wind or fuel cell can be a solution to this problem. To meet a part of his energy needs, morocco has developped several solar [1] and wind [2] sites in different regions. It also has an opportunity to develop hydrogen production. The fuel cell is one of the most promising sources of renewable energy. They can be considered as green power because they are environmentally clean and have low emission of greenhouse gases, they can operate with a very low level of noise. In addition, they can provide energy in a controlled way with higher efficiency than conventional power plants.

Fuel cells are electrochemical devices which convert chemical energy into electrical energy directly by oxidizing fuel (hydrogen) without intermediate thermal or mechanical processes [3], [4]. They are efficient and silent devices that can provide power to a wide variety of utilities, from portable electronics to vehicles, to electric grids. They are categorized mainly on the type of electrolyte used, operating conditions or fuel. In this work, the type of fuel cell considered is the Polymer Exchange Membrane Fuel Cell (PEMFC). Obtaining a high voltage is needed in some applications using a fuel cell. The problem can be handled either by using a simple step-up converter with high duty cycle or by using cascaded converters. In this work, a cascaded boost DC-DC converter is used and designed by a nonlinear control strategy such as a passivity-based control.

Passivity-based control is essentially the control of energy. It has been utilized in some applications such as the DC-DC converters [5]-[6], active power filters [7]-[8] and controlled rectifiers [9]-[10]. Using the passivity-based control can bring about good control effects on power electronic converters because it can accelerate the convergence of the energy function to the desired energy function under the precondition of system stability by properly injecting damping [11]. Some previous works have presented a studies of cascaded DC-DC converters in a fuel cell system controlled by a sliding mode strategy [12]-[14].

The paper is organized as follows: in Section 2, the fuel cell model is developed; in section 3 the cascaded boost converter is described and modeled, Section 4 is devoted to designing the inner loop, using the passivity control, and the synthesis of the outer loop. The controller performances are illustrated by simulations in Section 5, a conclusion and a reference list end the paper.

2. FUEL CELL MODEL

Generally, the electrochemical operation principle of a PEM fuel cell is described by two chemical reactions and may be summarized as follows:

- In anode, the oxidation reaction is given by: $H2 \rightarrow 2\ H+ + 2\ e-$
- In the cathode, the reduction reaction is given by: $½O2 + 2\ H+ + 2\ e- \rightarrow H2O$
- The overall reaction is: $H2 + ½O2 \rightarrow H2\ O$

The model of PEM fuel cell proposed in Reference [15] is considered in this paper. The output voltage of a stack is given by (1):

$$V_{FC} = \frac{V_N}{(1+(\frac{i_{FC}}{I_h})^{\sigma}} \quad (1)$$

V_Nis the open stack voltage, V_FC and i_FC are respectively the voltage and current of fuel cell, σ and I_h are two parameters experimentally defined. Using the values in Table 1, the simulation of the PEM fuel cell model has been using Matlab software gives a graph of voltage versus current as shown in Figure 1.

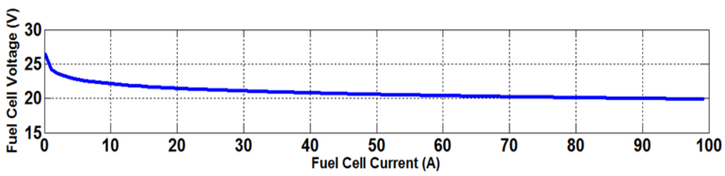

Figure 1. The fuel cell voltage versus current

For the rest of study, it was considered that the energy provided by the fuel cell is in the linear zone “ohmic region”, where the fuel cell deliver a stable power.

3. DC-DC CONVERTER MODELLING

The circuit topology of the cascaded boost DC-DC converter is shown in Figure 2. The used parameter values of the present converter are depicted in Table 1.

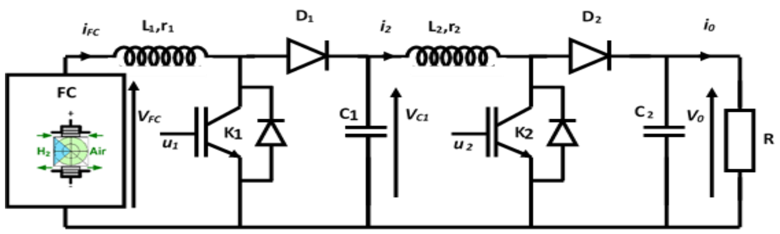

Figure 2. the cascaded boost DC-DC converter scheme

Table 1. The Used Parameter Values for the System

Parameter	Value	Prameter	Value	Prameter	Value	Prameter	Value
σ	0,335	Number of cell	22	*Inductors*	$L_1 = 35\mu H$ $L_2 = 100\mu H$	*Fuel cell voltage*	$V_{FC} = 12V$
I_h	483,2	V_N	26V	*Capacitors*	$C_1 = 4mF$ $C_2 = 600\mu F$	*Load resistor*	$R = 10\Omega$
P_{FC}	1,2kW			*Frequency*	$10kHz$	*Swiches*	IGBT

3.1. Switched model

The cascaded Boost converter can be represented by the following differential equations (2-5).

$$L_1 \frac{di_1}{dt} = V_{FC} - r_1 i_1 - (1-\mu_1)V_{C1} \quad (2)$$

$$C_1 \frac{dV_{C1}}{dt} = (1-\mu_1)i_1 - i_2 \quad (3)$$

$$L_2 \frac{di_2}{dt} = V_{C1} - r_1 i_2 - (1-\mu_2)V_O \quad (4)$$

$$C_2 \frac{dV_O}{dt} = (1-\mu_2)i_2 - \frac{V_0}{R} \quad (5)$$

Where i_1 and i_2 are, respectively, the currents in inductors L_1 and L_2, r_1and r_2are respectively the series resistor of inductors L_1 and L_2, V_c1 denotes the voltage in capacitor C_1and V_O is the output voltage. μ_1 and μ_2 are denoted the duties ratio functions defined by (6-7):

$$\mu_1 = \begin{cases} 1 \ if \ K_1 \ is \ ON \\ 0 \ if \ K_1 is \ OFF \end{cases} \quad (6)$$

$$\mu_2 = \begin{cases} 1 \ if \ K_2 \ is \ ON \\ 0 \ if \ K_2 is \ OFF \end{cases} \quad (7)$$

The averaged model is defined as follows (8-11):

$$\dot{x}_1 = -\frac{r_1}{L_1}x_1 - \frac{1-u_1}{L_1}x_2 + \frac{V_{FC}}{L_1} \quad (8)$$

$$\dot{x}_2 = \frac{1-u_1}{C_1}x_1 - \frac{1}{C_1}x_3 \quad (9)$$

$$\dot{x}_3 = -\frac{r_2}{L_2}x_3 + \frac{1}{L_2}x_2 - \frac{1-u_2}{L_2}x_4 \quad (10)$$

$$\dot{x}_4 = \frac{1-u_2}{C_2}x_3 - \frac{1}{RC_2}x_4 \quad (11)$$

In the above model x1, x2, x3, x4 are denoted, respectively, the averages currents and voltages i1, VC1, i2, VO and (u1,u2) represents the averages duties ratio function (μ1,μ2).

3.2. Establishment of euler lagrange model for DC-DC converter

These equations can be rewritten in Euler-Lagrange (EL) form as shown in (12):

$$\mathcal{D}\dot{x} + \Im x + \mathcal{R}x = \mathcal{E} \quad (12)$$

where x is the system state variable vector, D is the positive definite diagonal matrix, $\Im$ is the anti-symmetric matrix $\Im = -\Im^T$ which reflects the system internal interconnection structure; R is the system dissipation element matrix which reflects the system dissipation characteristics and $\mathcal{E}$ is the system external input vector.

The detailed expressions of these matrices are listed as shown in (13-17):

$$x = (x_1 \quad x_2 \quad x_3 \quad x_4)^T \quad (13)$$

$$\mathcal{E} = (V_{FC} \quad 0 \quad 0 \quad 0)^T \quad (14)$$

$$\mathcal{D} = \begin{pmatrix} L_1 & 0 & 0 & 0 \\ 0 & C_1 & 0 & 0 \\ 0 & 0 & L_2 & 0 \\ 0 & 0 & 0 & C_2 \end{pmatrix} \quad (15)$$

$$\mathfrak{J} = \begin{pmatrix} 0 & 1-u_1 & 0 & 0 \\ -(1-u_1) & 0 & 1 & 0 \\ 0 & -1 & 0 & 1-u_2 \\ 0 & 0 & -(1-u_2) & 0 \end{pmatrix} \quad (16)$$

$$\mathcal{R} = \begin{pmatrix} r_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & r_2 & 0 \\ 0 & 0 & 0 & 1/R \end{pmatrix} \quad (17)$$

3.2. Equilibrium points

The equilibrium point can be obtained by forcing the time derivative of the state variables of the reduced order model to be null while letting the averages controls inputs u1 and u2 to adopt respectively the constant values U10 and U20. As a result, we obtain a simple linear system of equations for the steady state equilibrium values of the average state variables [16].

Using the average state representation where we take into account that: r_1=r_2=0 and solving the system of equations for the unknowns x10, x20, x30 and x40, we obtain the equilibrium state of the system as shown in (18):

$$\dot{x} = 0 \Rightarrow \begin{cases} x_1^0 = \frac{1}{(1-U_1^0)^2(1-U_2^0)^2}\frac{V_{FC}}{R} \\ x_2^0 = \frac{V_{FC}}{1-U_1^0} \\ x_3^0 = \frac{V_{FC}}{R(1-U_1^0)(1-U_2^0)^2} \\ x_4^0 = \frac{1}{(1-U_1^0)(1-U_2^0)} V_{FC} \end{cases} \quad (18)$$

The equilibrium point is noted by (19-20)

$$X^0 = (x_1^0 \quad x_2^0 \quad x_3^0 \quad x_4^0) = (100 \quad 70 \quad 14 \quad 140) \quad (19)$$

$$U^0 = (U_1^0 \quad U_2^0) = (0.83 \quad 0.5) \quad (20)$$

From the equilibrium point, the output power is equal to the input power and that the input voltage in a boost converter is less than its output voltage.

4. CONTROL DESIGN

There are two operational control objectives:

a. Regulating the output voltage x_4 to a desired value x_4^*.
b. Ensure the global stability of the system.
c. Ensure the robustness of the system.

The control laws are illustred by the Figure 3.

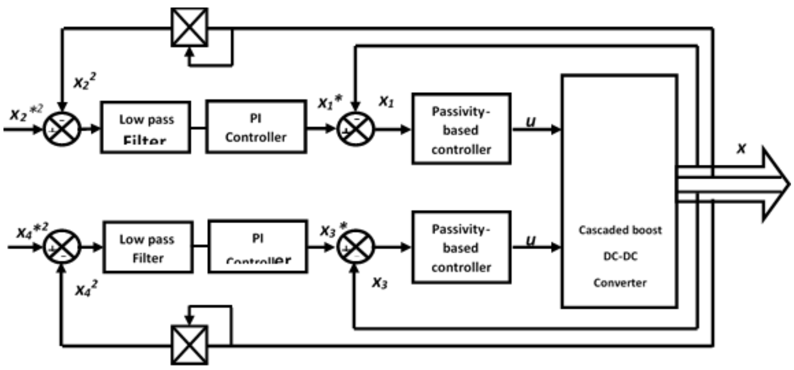

Figure 3. Controllers based structure

4.1. Inner loop

Let z=x-x^* denotes the tracking error matrix and consider the desired error dissipation matrix defined by (21-22):

$$\mathcal{R}_d = \mathcal{R} + \mathcal{R}_a \tag{21}$$

$$\mathcal{R}_a = diag(r_{a1}, r_{a2}, r_{a3}, r_{a4}) \tag{22}$$

where $\mathcal{R}_a$denotes the injected damping and $r_{a1}, r_{a2}, r_{a3}$and r_{a4} are positive constants.

Performing a damping injection ensures the desired asymptotic behavior of the output error dynamics. Using the equations (3) and (5), and replacing x by $(z + x^*)$ the error dynamics with desired damping become (23):

$$\mathcal{D}\dot{z} + \Im z + \mathcal{R}_d z = \mathcal{E} - (\mathcal{D}\dot{x^*} + \Im x^* + \mathcal{R}x^* - \mathcal{R}_a z) \tag{23}$$

The control laws will be define by the following expression (24):

$$\mathcal{E} - (\mathcal{D}\dot{x^*} + \Im x^* + \mathcal{R}x^* - \mathcal{R}_a z) = 0 \tag{24}$$

In this case the error dynamics is defined by (25):

$$\mathcal{D}\dot{z} + \Im z + \mathcal{R}_d z = 0 \tag{25}$$

We define the total energy as a Lyapunov function for equation (25) as follows (26):

$$H = \frac{1}{2} z^T \mathcal{D} z \tag{26}$$

To get a stabilizing control laws, the time-derivative H ̇ must be a negative definite function of z. Then H ̇ is chosen as shown in (27):

$$\dot{H} = -z^T \mathcal{R}_d z < 0, \text{ for } z \neq 0 \tag{27}$$

Consider the expression (24) as shown in (28):

$$\mathcal{E} = \mathcal{D}\dot{x^*} + \Im x^* + \mathcal{R}x^* - \mathcal{R}_a z \tag{28}$$

which corresponds to the following scalar differential equations (29):

$$\begin{cases} L_1 \dot{x}_1^* + (1-u_1)x_2^* + r_1 x_1^* - r_{a1} z_1 = V_{FC} \\ L_2 \dot{x}_3^* - x_2^* + (1-u_2)x_4^* + r_2 x_3^* - r_{a3} z_3 = 0 \end{cases} \tag{29}$$

Then, the control laws to satisfy a stabilization are defined by (30):

$$\begin{cases} u_1 = 1 + \frac{1}{x_2^*} (L_1 \dot{x}_1^* + r_1 x_1^* - r_{a1} z_1 - V_{FC}) \\ u_2 = 1 + \frac{1}{x_4^*} (L_2 \dot{x}_3^* + r_2 x_3^* - r_{a3} z_3 - x_2^*) \end{cases} \tag{30}$$

4.2. Voltage outer loop control

The aim is to design tuning laws for the $x_1{}^*$ and $x_3{}^*$. We consider: $y_2 = x_2^2$ and $y_4 = x_4^2$. Using the equations (8-11) we can establish the following relations as shown in (31-32):

$$\dot{y}_2 = \frac{2E}{C_1} x_1^* + \frac{2z_1 k_1}{C_1} x_1^* - \frac{L_1}{C_1} \frac{d}{dt}(x_1^{*2}) - \frac{2z_1}{C_1} \dot{x}_1^* + F(x,t) \tag{31}$$

$$\dot{y}_4 = \frac{2}{C_2} \left[(k_3 z_3 + x_2 - L_2 \dot{x}_3^*) \left(\frac{z_3}{L_2} + x_3^* \right) - \frac{2}{R} y_4 \right] \tag{32}$$

We must use a low pass filter for the first derivative $\dot{x}_1^*$ (respectively $\dot{x}_3^*$) of the reference x_1^* (respectively x_3^*) exists, we obtain finally (33-34):

$$x_1^* = \frac{b}{s+b}\left(k_{p2}z_2 + k_{i2}z_{22}\right) \tag{33}$$

$$x_3^* = \frac{b\prime}{s+b\prime}\left(k_{p4}z_4 + k_{i4}z_{44}\right) \tag{34}$$

With (35-37):

$$F(x,t) = \frac{1}{C_1}\left(-2\sqrt{y_2}x_3^* + \frac{2k_1}{L_1}z_1^2 + \frac{2E}{L_1}z_1 - \frac{2z_3}{L_2}\sqrt{y_2}\right) \tag{35}$$

$$\begin{cases} z_2 = y_2^* - y_2 \\ z_{22} = \int z_2 dt \end{cases} \tag{36}$$

$$\begin{cases} z_4 = y_4^* - y_4 \\ z_{44} = \int z_4 dt \end{cases} \tag{37}$$

5. RESULTS AND ANALYSIS

In this section, the performances of the controller will be illustrated by simulations in the Matlab/Simulink environment. The controlled DC/DC converter has the following characteristics: r_a1=r_a2=40Ω; b=b'=3; k_p2=k_p4=2; k_i2=k_i4=4. The converter has been simulated to check the previous stability conditions. The Figure 4 shows the fuel cell voltage. The output voltage of converter and his reference that having two values: 70V and 140V are shown in Figure 5. We observe that the tracking is satisfied and the stability is guaranteed.

To analyze the robustness capability of the proposed controller, a new experiment will be performed. It consists in changing the fuel cell voltage according to Figure 6. Except for this change, the rest of the converter characteristics are the same as previously. The Figure 7 shows that the effect of fuel cell voltage change is well compensated by the controller.

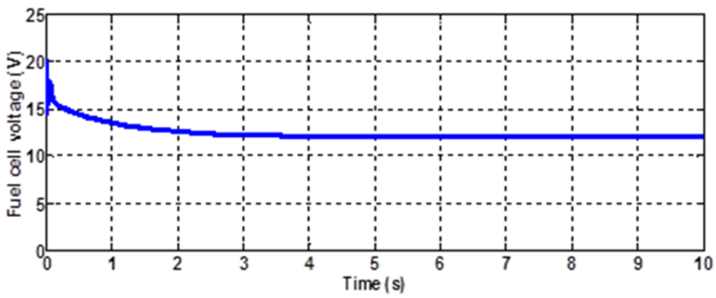

Figure 4. Fuel cell voltage versus time

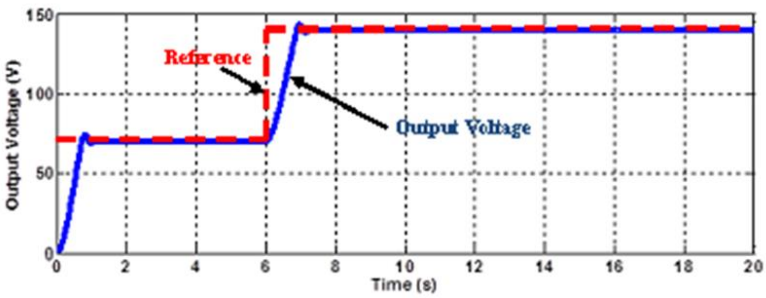

Figure 5. Output voltage with traking

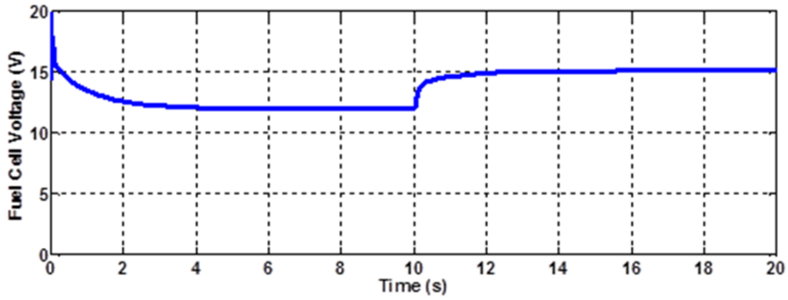

Figure 6. Fuel cell voltage versus time

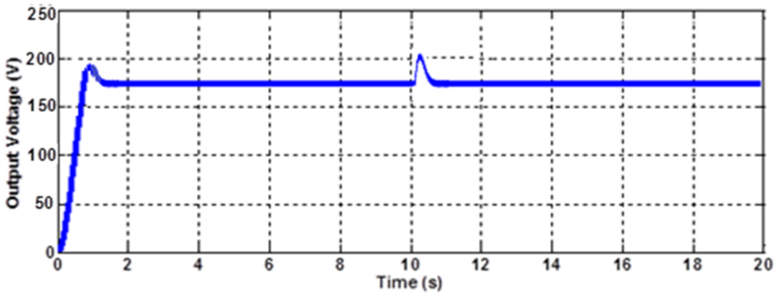

Figure 7. Output voltage with disturbance

6. CONCLUSION

The analysis and study of the insertion of fuel cell in power system is important in order to increase the competitiveness of this source. A nonlinear controller is proposed for DC/DC cascaded boost converter to achieve voltage output regulation. It is developed in two steps. First, an inner-loop is designed, based on the passivity technique. The inner-loop regulator generates the duties cycle μ_1 and μ_2. The second step consists in developing an outer-loop that generates the reference currents so that the squared output voltages $V_{C1}(x_2)$ and $V_O(x_4)$ follows a given reference signals x_2^* and x_4^*. The synthesis of this loop involves a linearizing variable change, a signal filtering to cope with model time-varying and controllability issues and a loop mode separation. A formal analysis and a simulation study prove that the proposed controllers actually meet its objectives: tracking, stability and robustness guarantied. The results obtained are similar to those of the sliding mode controller.

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