Analysis and Characterization of PEMFC Power Systems with Bond Graph

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Abstract

This paper addresses the problem of bond graph methodology as a graphical approach for modeling fuel cell systems. The system consists of a Proton Exchange Membrane Fuel Cell (PEMFC) stack, an interleaved boost converter.

Simulation results illustrate the simplified system response obtained using implementation of the governing equations in MATLAB/Simulink or a bond graph implementation in the simulation program 20-sim.

Keywords: *PEM fuel cell, boost, modeling, dynamic, Bond graph, simulation.*

1. Introduction

In recent years, an energetic approach original was set up to model the fuel cell via the tool Bond Graph (BG) [5]. BG to define and model the energy exchanges within a system and any physical realm.

The bond graph formalism is a graphical approach to modeling, based on the concept of power and incorporating ideas from network theory in a general setting [1][2].

Bond graph modeling is a multi-domain approach that has been applied in a variety of disciplines, covering all areas of engineering but also many others such as biological systems [3].

Fuel cells are known to have higher efficiency than conventional power plants [4]. Fuel cells are environmentally friendly (environmentally clean), have extremely low emission and they produce very low noise [4].

Modeling's of fuel cells have become increasingly important. This in order to achieve integration simulates the fuel cell in an electrical system. These models must be comprehensive enough to take into account all the electrochemical phenomena brought into play while being simple enough to allow the simulation of the complete system

In this work we have tried to present the bond graph modeling of the conversion chain. Our goal is first to create a direct model (simulation) having as inputs the molar flow qH_2, qO_2 output power of the system taking into account its environment.

The paper is organized as: the section II discusses the dynamic behavior of H-Tec 1.2W PEM fuel cell model and details out the design of a simple DC/DC boost converter used to provide a regulated voltage for varying loads. The section III evaluates the performance of PEM fuel cell system with DC/DC boost converter using simulink and simulation results is brought out.

2. Modeling of the Power system

The topology of the Fuel cell system is that given in Figure 1.

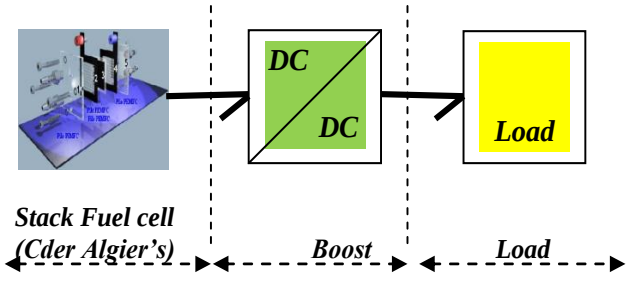


Figure.1.Bond graph à mot of the FC system .

Before starting the modeling of the whole system, we model each component alone.

2.1. Dynamic model of PEMFC

Based on the work presented in [6,7,8], The actual cell potential decreases from its equilibrium potential due to irreversible losses. The output voltage of the

single cell is given by (1) according to the PEMFC output characteristics empirical equation [7].

$$V_{cell} = E_{cell} - \eta_{act} - \eta_{ohm} - \eta_{dif}) \quad (1)$$

Where; V_{cell} fuel cell voltage, E_{cell} Thermodynamic potential of the fuel cell, η_{act}, η_{con}, η_{ohmic} are losses, introduced into the fuel cell.

The ideal performance of a fuel cell is defined by its Nernst equation, in the case of PEMFC:

$$E_N = E_0 + \frac{RT}{2F}\ln\left(\frac{PH_2 PO^{1/2}}{PH_2 O}\right) \quad (2)$$

Many model have been proposed to simulate the fuel cell in the literature [10, 13].This model is built by utilizing the relationship between the output voltage and potential pressure of hydrogen, oxygen.

The relationship between the modular flows of any gas through the valve is proportional to its partial pressure inside the channel [10]. For hydrogen, this relationship can be expressed as follows

$$\frac{qH_2}{pH_2} = \frac{k_{an}}{\sqrt{M_{H_2}}} = k_{H_2} \quad (3)$$

With,pH_2 hydrogen partial pressure (atm),k_{an} anode valve constant (Kmol Kg (atm s)$^{-1}$),

M_{H2} molar mass of hydrogen (kg kmol $^{-1}$),k_{H2} hydrogen valve molar constant (kmol (atm s)$^{-1}$).

The molar flow of hydrogen that reacts can be found from the basic electrochemical relationship between hydrogen flow and the fuel cell system current [9]

$$qH_2^r = \frac{NI}{2F} = 2K_r I \quad (4)$$

The hydrogen partial pressure can be obtained by applying Laplace transform on (3) and (4) [9],

$$pH_2 = \frac{1/K_{H_2}}{(1+\tau_{H_2}^S)}(q_{H_2}^{in} - 2K_r I) \quad (5)$$

Where:

$$\tau_{H_2} = \frac{V_{an}}{RTK_{H_2}} \quad (6)$$

With, K_{H2} Valve molar constant for hydrogen (kmol/s atm), τ_{H2} Response time for hydrogen (s),similar operation can be done oxygen partial pressure.

Based on Eqs.(1) to (5), the developed model for fuel cell is shown Figure.2.

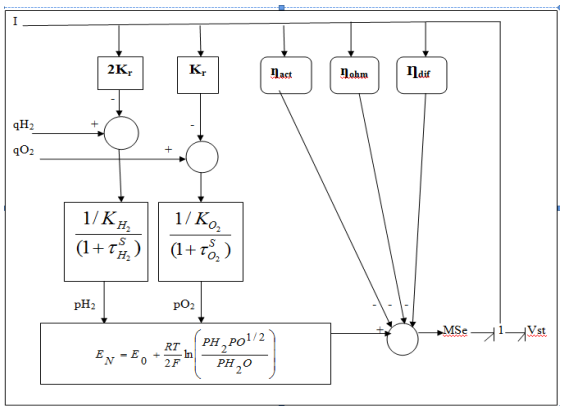


Figure.2. Dynamic model of the FC system [8].

2.2. Dynamic Boost converter model

A boost dc/dc converter can be used to convert the fuel cell output voltage to the desired dc bus voltage.

The boost converter is given in Figure.3 with a switching period T and a duty cycle α. Again, assuming continuous conduction mode of operation, the state space equations when the main switch is ON And when the switch is OFF [11].

During the on state, switch S is closed, which makes the input voltage (V_i) appear across the inductor, which in turns results in change in inductor current (iL) during a time interval Δt. Rate of change of current is given by [14]:

$$V_i = L\frac{di_L}{d_t} \quad (7)$$

At the end of the on-state the increase in inductor current is given by [14] :

$$\Delta I_{Lon} = \int_0^{\alpha T} dI_L = \frac{V_i \alpha T}{L} \quad (8)$$

During the off-state, the switch s is open, so the inductor current flows through the load, the evolution of iL assuming voltage drop across diode is zero and a large capacitor is:

$$V_i - V_0 = L\frac{di_L}{d_t} \quad (9)$$

Variation of iL during the Off-period is:

$$\Delta I_{Loff} = \int_0^{(\alpha-1)T} dI_L = \frac{(V_i - V_0)(\alpha-1)T}{L} \quad (10)$$

The energy stored in each component at the end of commutation cycle T is the equal to that at the beginning of the cycle. That means overall change in current is zero [14]:

$$\Delta I_{L\,on} + \Delta I_{L_{off}} = 0 \qquad (11)$$

This can be written as [11, 14]:

$$\frac{V_0}{V_i} = \frac{1}{1-\alpha} \qquad (12)$$

The above equation reveals that the output voltage will be always greater than input voltage.

$$\frac{V_0}{V_i} = \frac{1}{1-\alpha} = m \qquad (13)$$

With the equation (13), we can modeled the converter by Bond graph, supposed is transformer (TF).

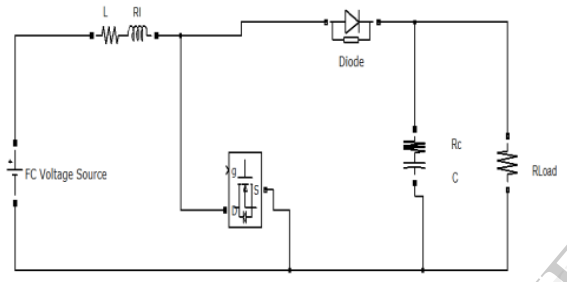


Figure.3.a: DC-DC Boost Converter.

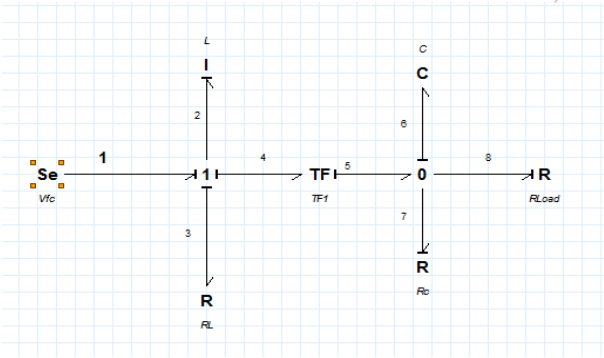


Figure.3 b. Bond graph of Boost converter.

This bond graph model has allowed us to ask analytically all equations of the system without reducing the causal path:

Table.1. Boost converter equations

Jonction1	*Jonction0*
$f_1 = f_2 = f_3 = f_4$ $e_2 = e_1 - e_3 - e_4$	$f_6 = f_5 - f_7 - f_8$ $e_6 = e_5 = e_7 = e_8$
Elément I : L $f_2 = \frac{p_2}{L}$	*Elément I:C* $e_6 = \frac{q_6}{C}$
Elément R : R_L $e_3 = R_L . f_3$	*Elément TF* $e_4 = m.e_5$ $f_5 = m.f_4$
Elément R : R_c $e_7 = R_c . f_7$	*Elément R : R_{Ld}* $e_8 = R_{Ld} . f_8$

After rearrangement we can write the equations as state variable.

$$\frac{d}{dt}\begin{bmatrix} p_2 \\ q_6 \end{bmatrix} = \begin{bmatrix} -\frac{R_L}{L} \cdots \frac{-(1-\alpha)}{c} \\ \frac{1-\alpha}{L} \cdots -\left(\frac{1}{R_c C} + \frac{1}{R_{ld} C}\right) \end{bmatrix} \begin{bmatrix} P_2 \\ q_6 \end{bmatrix} + V_{fc} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad (14)$$

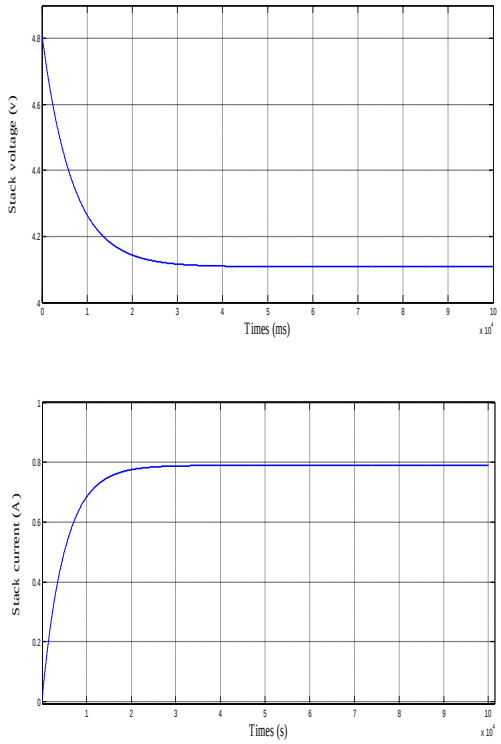
3. Simulation results

When we have constructed the model by means of Bond Graph, The mathematical expressions for the fuel cell system and power converters were simulated in environment Matlab- simulink [16].

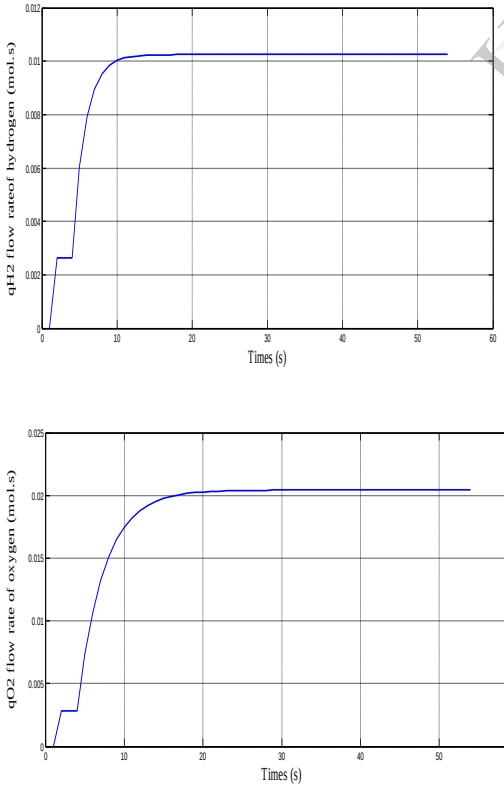
3.1. Simulation of PEMFC subsystem

Figure.4 shows changes in fuel cell voltage and current for varying loads. The equivalent capacitor will basically change the stack electrical constant, then, it will change the time response. As observed in Figure, the fuel cell voltage and current takes about 3ms for the base parameter (C = 3 F).

Shows the input molar flow of fed hydrogen after gas processing response and this hydrogen flow will be fed to PEM stack unit. From Figure 5, we can see that the gas reaction process requires a short time of delay to response.



Figures.4.Transient state of load current and output voltage.



Figures.5.Hydrogen, oxygen gases input flow qH_2, qO_2.

3.2 Simulation of power converter subsystem

The output voltages and output currents for 5Vto12V (Boost) dc-dc converter during a load constant are shown in Figures.6.a to 6.b, respectively.

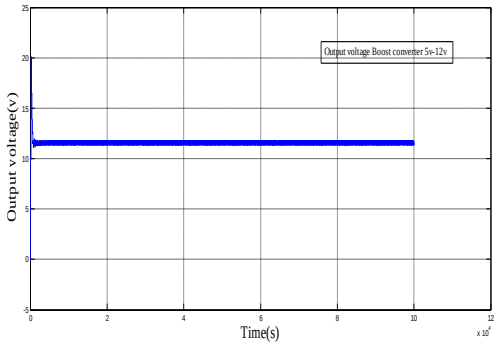


Figure.6.a) Output voltage of the Boost converter.

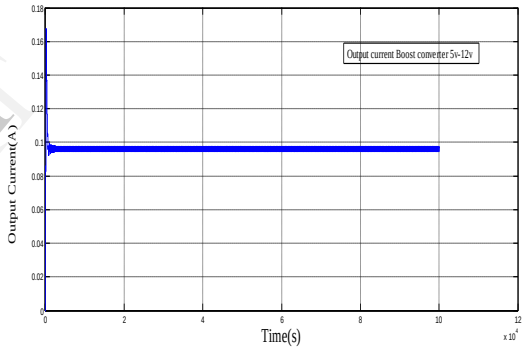


Figure.6.b) Output current of the Boost converter.

Table.2. PEMFC Parameters [7], [this model].

Parameters	Value	Unit	Parameters	Value	Unit
T	298,15	K	R_m	0,126	S
F	96487	C/mol	C	3F	Ω
R	8,314	J/(kmol K)	Rc	0,0003	Ω
E^o	1,229	V	B	0,016	V
N	4		r_{H-O}	1,168	/
Kr	$1,0364 \times 10^{-5}$	kmol/(s A)	L	230	µm
U_{opt}	0,85		$\xi 1_{théorique}$	- 0,949	V
K_{H2}	$4,22 \times 10^{-5}$		$\xi 1_{experimental}$	- 1,053	V
K_{O2}	$2,11 \times 10^{-5}$	kmol/(s atm)	ξ_2	$0,02866 ln(A) + 4,3.10^{-5} ln(CH_2)$	
τ_{H2}	3,37	kmol/(s atm)	ξ_3	$7,6 \times 10^{-5}$	
$\tau O2$	6,74	S	ξ_4	$1,93 \times 10^{-4}$	
τf	0,8	S	J_{lim}	0,0496	A/cm^2
C	3F	Ω			

Table.3. Parameters of Boost converter

Boost Parameters	Value	Unit
L	75	µH
RL	80	mΩ
RC	5	mΩ
C	1.68	µF
Fs	100	kHz
Vfc	5	v
Load resistance	120	Ω
Reference voltage	12	v
Duty cycle	0.6	

5. Conclusion

This paper presents a study of dynamic behavior of 1.2W PEM fuel cell. The dynamic limitations of the stack fuel cell model are analyzed based on their dynamic behavior of characteristic curves. To regulate the fuel cell terminal voltages a simple DC/DC boost converter is interfaced with PEM fuel cell system. It is observed that the design of simple DC/DC boost converter gives better performance.

The future developments will consist in connecting buck converter, a battery to the system and proposed the control structure.

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