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# Bond graph modeling approach development for fuel cell PEMFC systems

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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, battery pack connected via a buck converter.

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



## Introduction

In near future, fuel cells could provide an attractive value proposition, particularly for economic and environmental reasons. They are highly efficient, low fuel consumption, produce minimal or no harmful emissions very low noise and have relatively low maintenance requirements [1]. In the past few years, an advanced effort through international research and development activities on fuel cell systems technologies for various applications has dramatically been increased [2]. In the same vein, the polymer electrolyte membrane fuel cell (PEMFC) has been regarded as a promising power source, especially for transportation and stationary cogeneration applications due to its high efficiency conversion, low-temperature operation, high power density, fast startup, and system robustness [3].

However, on the other hand, due to several factors contribute to the complexity of the fuel cell stack [4], in which several disciplinary fields are concerned: hydraulics, chemical, thermal and electric [5]. Use of bond graph tool as a multidisciplinary approach is well suited for modeling of such process. Since their official birth on April 24, 1959, were devised by Professor Henry Martyn Paynter at the Massachusetts Institute of Technology (MIT) [6,7], bond graphs (some refer it as Bondgraph), or BG's for short, evolved to become one of the most effective, powerful and elegant tools used for dynamic system modeling, simulation and designing. The unifying attitude of bond graphs [8], as an interdisciplinary graphical description language, towards systems enables model builders to connect system components from different physical domains using the same set of bond graphic elements [9] and can support communication between experts from different engineering disciplines [10–12]. In addition, the

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bond graph approach is therefore used when developing the component library. The component library consists of selected power producers like diesel and gas engines, fuel cell and synchronous generator, and power consumers like asynchronous motor with voltage source converter and generic load used for hotel and auxiliary loads [13,14].

It was this unifying attitude that furnished the impetus for appearance of various works that investigates the possibility of applying the BG multifunctional approach, which could be used as a unifying approach to PEM fuel cell systems. Among the contributions that are relevant to this paper, we find the work of S. Benbouzid and G. Dauphin et al. (2003; 2004; 2006) who proposed a control approach with Bond Graph to optimize the Fuel Cell system efficiency for vehicle traction [15–17]. Saïsset (2004) has presented in his doctoral thesis a contribution to the systemic study of energetic systems including electrochemical devices with the Bond Graph formalism applied to modeling fuel cells, lithium-ion batteries and sun-racer [18,19]. Hung et al. (2007) in their paper they presented the modeling technique and dynamic simulation results of fuel cell and engine Hybrid Electric Scooters using the bond graph approach [20]. Agbli et al. (2011) they used Bond Graph approach to describe the reversibility between a PEM fuel cell/electrolyser and to model both devices [21]. In 2013, Robin et al., they have presented according to the Bond Graph representation an approach allowing connecting two numerical models for the simulation of the structure of PEMFC/System Model [22], and Chatti (2013) has developed a new graphical formalism for dynamic system modeling, this formalism is emanating from the BG methodology and it is called Signed Bond Graph (SBG), his proposed methodology is validated by two different systems namely a proton exchange membrane fuel cell and an electromechanical system of an electric vehicle [23–25]. Chatti (2013) is referred to the work of Peraza et al. (2008) [26], however, the authors demonstrated in their work that the dynamic behavior of a fuel cell can be finely studied by the simplified Bond Graph approach using 20-Sim software package suited for bond graph modeling of mechatronic systems. The authors concluded that "The model can also be improved in order to deal with the dynamic behavior of PEMFC and analyze its performance."

Even, Ould Bouamama (2013) [27] has presented the specifics of the bond graph software (20-SIM):

✓ Modeling and simulation program that runs under Windows,
✓ Advanced modeling and simulation package for dynamic systems that supports iconic diagrams, bond graphs, block diagrams, equation models or any combination of these allows interaction with SIMULINK,
✓ Good product recommended for modeling of small to medium sized systems. The graphics and hard copy output quality is poor,
✓ Not control analysis support.

Da Fonseca et al., (2014) presented a non linear control strategy based on a simplified control model and using the differential flatness control theory, the approach used to describe the transport phenomena and heat transfer in each cell of the stack is based on the bond graph theory [28].

In line with this, in this paper, we have modeled the behavior of the conversion energy systems by consolidating the two methods, the average model computation using the bond graph and modeling instantaneous events of the electrical circuit. This study illustrates the importance of using simplified bond graph model properly account for the reduce simulation time in comparison with the available software package. We deducted, as will be presented in the following text, that the using of simplified equivalent Bond Graph Model, is only possible if the switching period of the converter is very small when compared with the time constants of the passive elements of the converter, as is usually the case in power electronics.

## Modeling

We are interested 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 conversion system includes a PEMFC. The system of fuel cell stack comprises studied, a DC-DC converter (boost) for adapting the low value of the voltage of the fuel cell to the bus 12 V, and battery connected via a converter Buck [29].

The topology of the production system is that given in Fig. 1.

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

### Dynamic model of PEMFC

Based on the work presented in [30,31], 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 [31].

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

where; $V_{cell}$ fuel cell voltage, $E_{cell}$ Thermodynamic potential of the fuel cell, $\eta_{act}$, $\eta_{dif}$, $\eta_{ohm}$ are losses, introduced into the fuel cell.

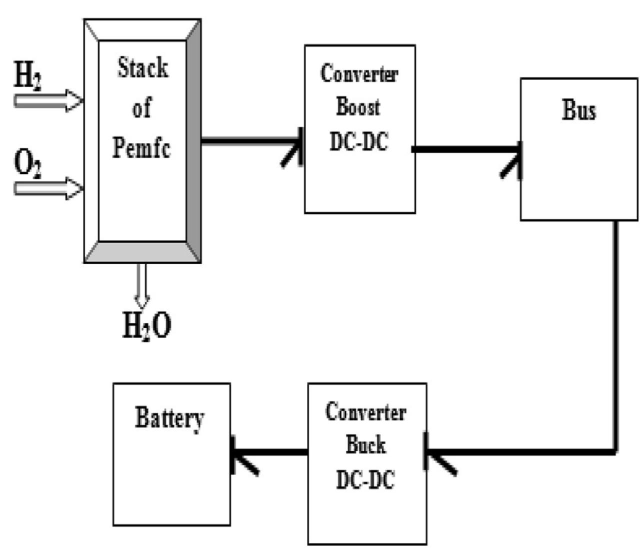


**Fig. 1 – Topology of the production system.**

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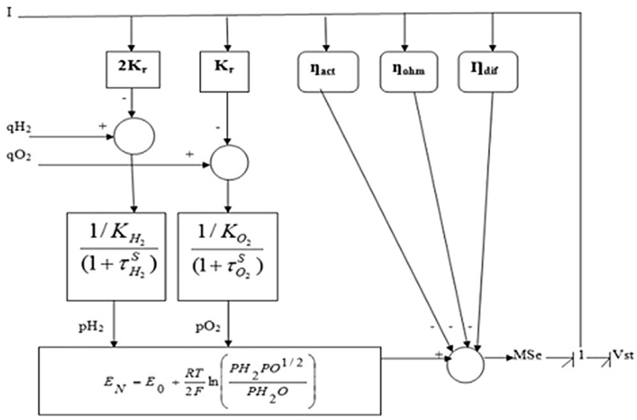


Fig. 2 – BG Dynamic model of the FC system.

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

$$E_N = E_0 + \frac{RT}{2F}\ln\left(\frac{PH_2PO^{1/2}}{PH_2O}\right) \quad (2)$$

A model for 1.2 W PEMFC Table 3 is developed. The fuel cell model that is used in this paper is developed in MATLAB & Simulink.

The relationship between the modular flows of any gas through the valve is proportional to its partial pressure inside the channel [32]. For hydrogen, this relationship can be expressed as follows

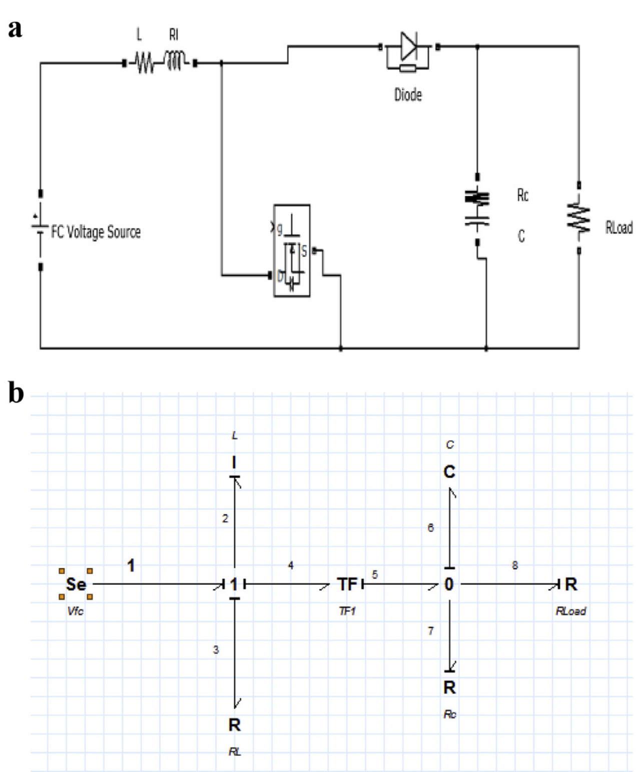


Fig. 3 – (a) DC–DC Boost Converter. (b) Bond graph of Boost converter.

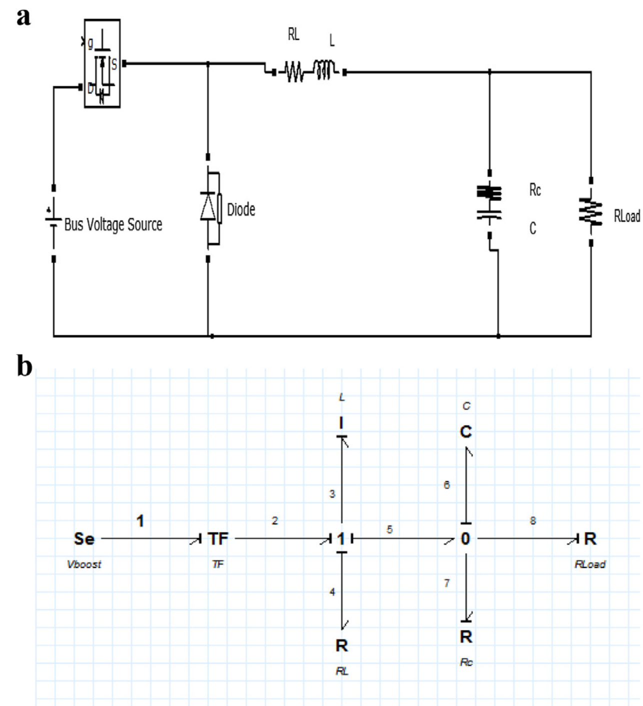


Fig. 4 – (a) DC–DC Buck Converter. (b) Bond graph of Buck converter.

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

With, $pH_2$ hydrogen partial pressure (atm), $k_{an}$ anode valve constant (kmol kg(atm s)$^{-1}$), $M_{H_2}$ molar mass of hydrogen (kg kmol$^{-1}$), $k_{H_2}$ 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 [33]

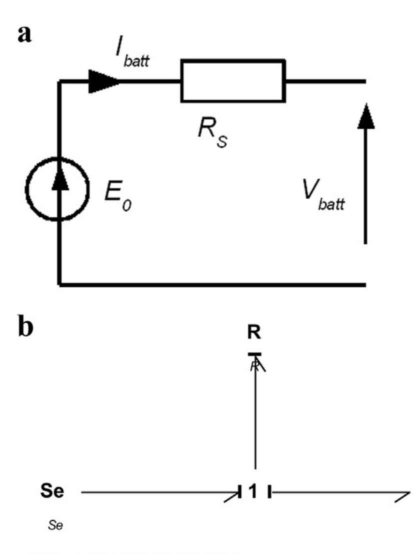


Fig. 5 – (a) Battery model. (b) Bond graph of battery.

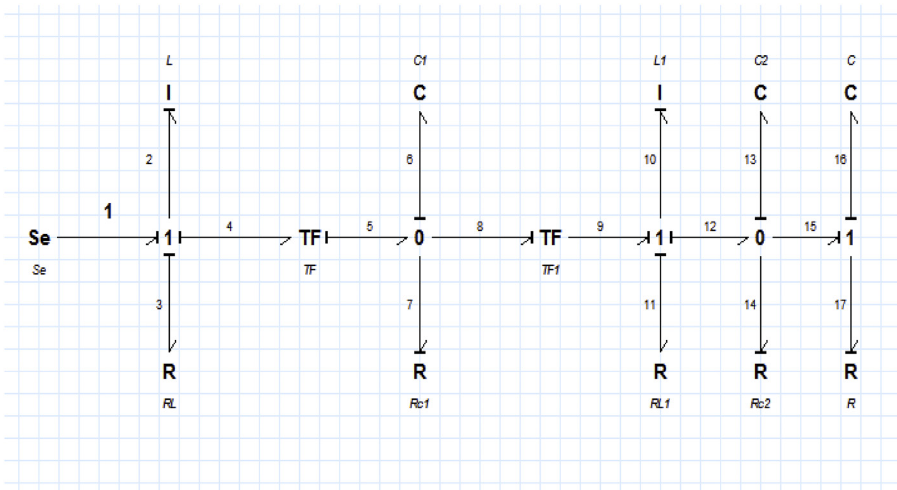


**Fig. 6 – Bond graph of fuel cell system traction.**

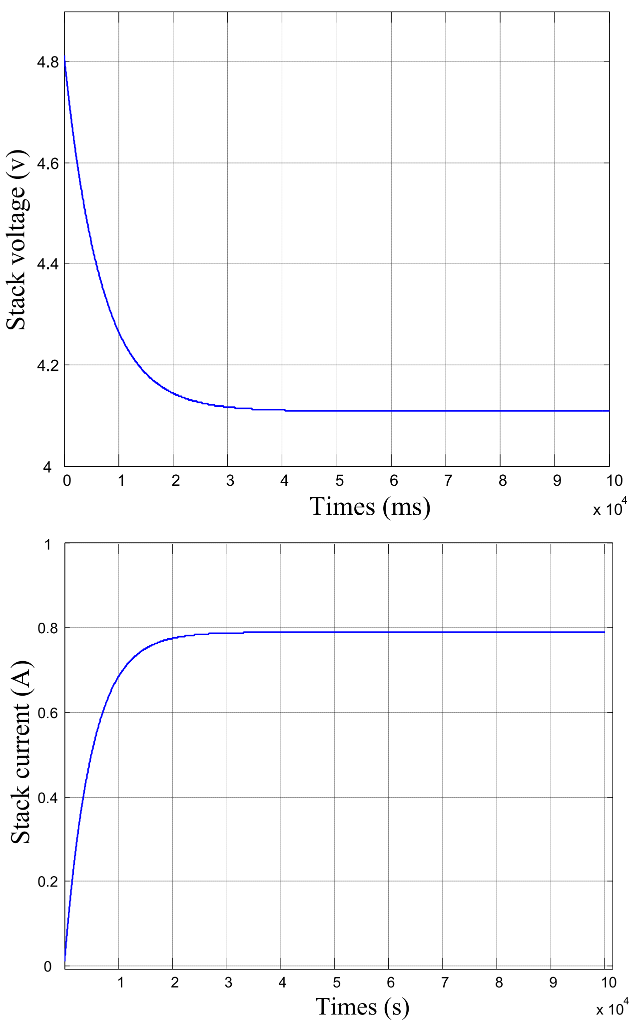


**Fig. 7 – Transient state of load current and output voltage.**

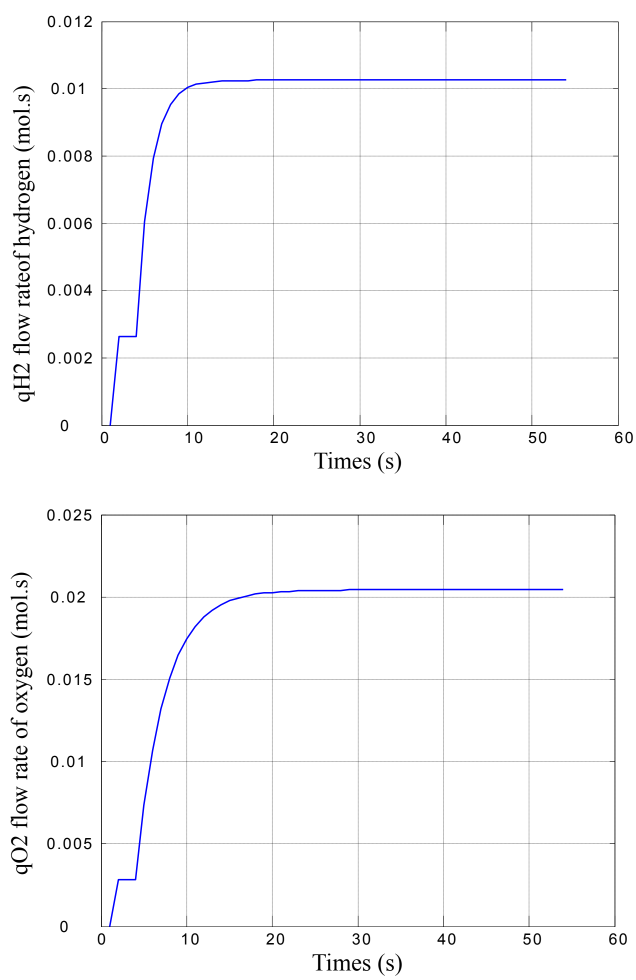


**Fig. 8 – Hydrogen, oxygen gases input flow $qH_2$, $qO_2$.**

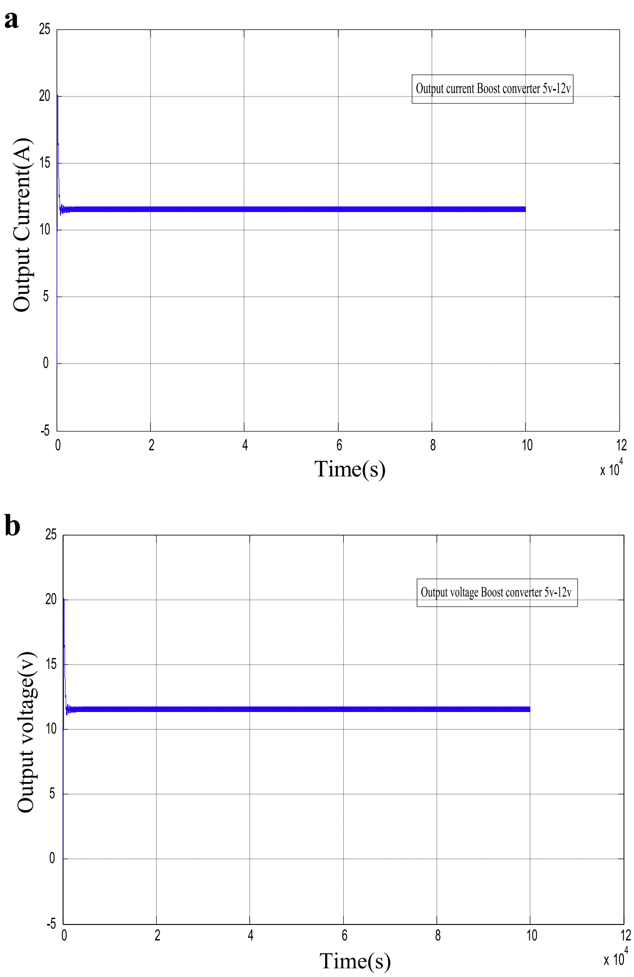


Fig. 9 – (a) Output voltage of the Boost converter. (b) Output current of the Boost converter.

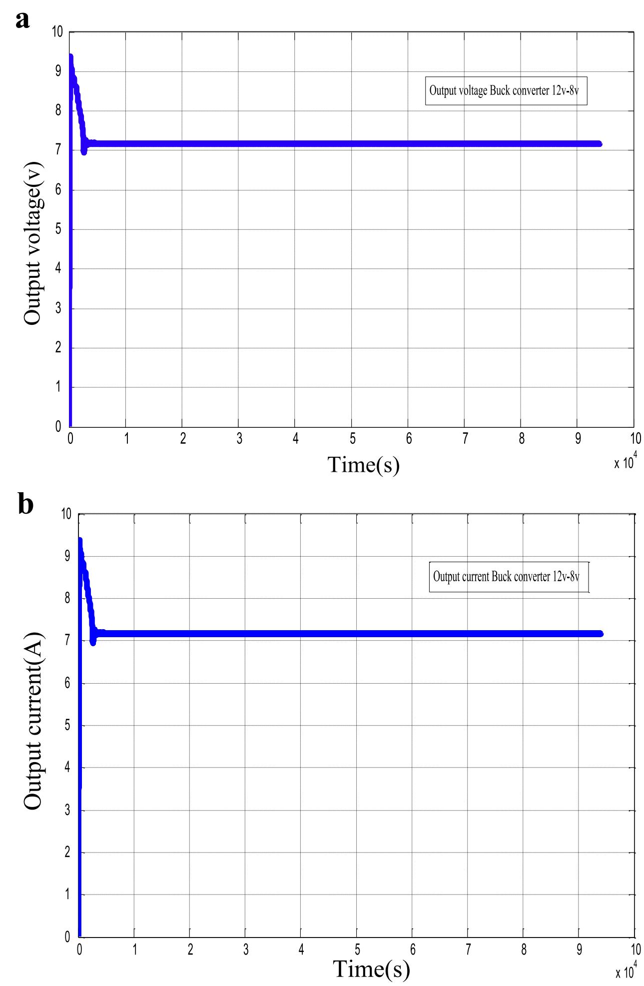


Fig. 10 – (a) Output voltage of the Buck converter. (b) Output current of the Buck converter.

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

The hydrogen partial pressure can be obtained by applying Laplace transform on (3) and (4) [5].

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

where:

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

Similar operation can be done oxygen partial pressure.

Based on Eqs. (1)–(5), the developed model for fuel cell is shown Fig. 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 Fig. 3 with a switching period $T$ and a duty cycle $\alpha$. Again, assuming continuous-

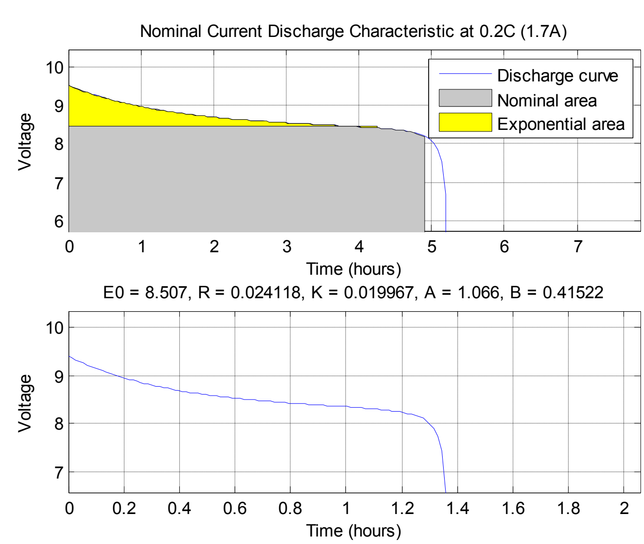


Fig. 11 – Discharge characteristics.

**Table 1 – Boost converter equations.**

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

conduction mode of operation, the state space equations when the main switch is ON And when the switch is OFF [34].

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 [37]:

$$V_i = L\frac{di_L}{d_t} \tag{7}$$

At the end of the on-state the increase in inductor current is given by [35]:

$$\Delta I_{L_{on}} = \int_0^{\alpha T} dI_L = \frac{V_i \alpha T}{L} \tag{8}$$

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:

$$V_i - V_0 = L\frac{di_L}{d_t} \tag{9}$$

Variation of iL during the Off-period is:

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

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 [36]:

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} = 0 \tag{11}$$

This can be written as [7,10]:

$$\frac{V_0}{V_i} = \frac{1}{1-\alpha} \tag{12}$$

**Table 2 – Buck converter equations.**

| | |
|---|---|
| Jonction1 | Jonction0 |
| $f_2 = f_3 = f_4 = f_5$ | $f_6 = f_5 - f_7 - f_8$ |
| $e_3 = e_2 - e_4 - e_5$ | $e_6 = e_5 = e_7 = e_8$ |
| Element I: L | Element I: C |
| $f_3 = \frac{p_3}{L}$ | $e_6 = \frac{q_6}{C}$ |
| Element R: $R_L$ | Element TF |
| $e_4 = R_L \cdot f_4$ | $e_4 = \alpha \cdot e_5$ |
| | $f_5 = \alpha \cdot f_4$ |
| Element R: $R_c$ | Element R: $R_{Ld}$ |
| $e_7 = R_c \cdot f_7$ | $e_8 = R_{Ld} \cdot f_8$ |

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

$$\frac{V_0}{V_i} = \frac{1}{1-\alpha} = m \tag{13}$$

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

This bond graph model has allowed us to ask analytically all equations of the system without reducing the causal path Table 1:

After rearrangement we can write the equations as state variable.

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

### Dynamic buck converter

A buck converter operates in continuous mode if current through inductor never falls to zero, during the commutation cycle. Its operating principle is described by the Fig. 4. When the switch shown above is closed, the voltage across the inductor is $V_L = V_i\text{-}V_O$ .The current through inductor rises linearly. As the diode is reverse biased by the voltage source, no current flows through it [35,37]

$$\frac{V_0}{V_i} = \frac{I_i}{I_0} = \alpha \tag{15}$$

This bond graph model has allowed us to ask analytically all equations of the system without reducing the causal path Table 2:

After rearrangement we can write the equations as state variable.

$$\frac{d}{dt}\begin{bmatrix} p_3 \\ q_6 \end{bmatrix} = \begin{bmatrix} -\frac{1}{L} \cdots\cdots \frac{-1}{c} \\ \frac{1-\alpha}{L} \cdots -\left(\frac{1}{R_c C} + \frac{1}{R_{ld} C}\right) \end{bmatrix} \begin{bmatrix} P_3 \\ q_6 \end{bmatrix} + V_{fc}\begin{bmatrix} \frac{1}{\alpha} \\ 0 \end{bmatrix} \tag{16}$$

### Battery model

Storage devices are used as energy storing in the hybrid power sources [38,39]. The batteries store energy in the electrochemical form. Li-ion batteries are preferable to other types of batteries because they have high energy density, high operating voltage levels and long cycle life [40].

We find in the literature other end models but for our applications, this model Fig. 5 is sufficient Table 5. Considering all models Bond graphs energy devices (energy converters (Boost, Buck), and battery), we can deduce the Bond graph of the system under study. Fig. 6.

## Results and discussion

After the construct of the model by means of Bond Graph, we can make the simulation of the system. For that, we select the 20-sim software [41,42] and the Matlab SIMULINK™ [43]

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**Table 3 – PEMFC parameters [4], [this model].**

| Parameters | Value | Unit | Parameters | Value | Unit |
|---|---|---|---|---|---|
| T | 298.15 | K | $R_m$ | 0.126 | S |
| F | 96,487 | 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 |
| $K_{H_2}$ | $4.22 \times 10^{-5}$ | | $\xi 1_{experimental}$ | −1.053 | V |
| $K_{O_2}$ | $2.11 \times 10^{-5}$ | kmol/(satm) | $\xi_2$ | $0.02866\ln(A) + 4.3 \times 10^{-5} \ln(CH_2)$ | |
| $\tau_{H_2}$ | 3.37 | kmol/(satm) | $\xi_3$ | $7.6 \times 10^{-5}$ | |
| $\tau_{O_2}$ | 6.74 | S | $\xi_4$ | $1.93 \times 10^{-4}$ | |
| $\tau f$ | 0.8 | S | $J_{lim}$ | 0.0496 | A/cm² |
| C | 3F | Ω | | | |

**Table 4 – Parameters of Boost and Buck converters.**

| Boost parameters | Value | Unit | Buck parameters | Value | Unit |
|---|---|---|---|---|---|
| L | 75 | μH | Source voltage | 12 | v |
| $R_L$ | 80 | mΩ | Reference voltage | 8 | v |
| $R_C$ | 5 | mΩ | L | 4.1 | μH |
| C | 1.68 | μF | $R_L$ | 3e-4 | Ω |
| Fs | 100 | kHz | C | 300 | μF |
| $V_{fc}$ | 5 | v | $R_C$ | 5e-3 | Ω |
| Load resistance | 120 | Ω | *fs* | 100 | kHz |
| Reference voltage | 12 | v | Load resistance | 1 | Ω |
| Duty cycle | 0.6 | | Duty cycle | 0.66 | |

environments, although other algorithms also have given good results.

Fig. 7 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 3 ms for the base parameter (C = 3 F).

Fig. 8 shows the input molar flow of fed hydrogen after gas processing response and this hydrogen flow will be fed to PEM stack unit. From Fig. 8, we can see that the gas reaction process requires a short time of delay to response.

The output voltages and output currents for 5 V–12 V (Boost), and 12V–8 V (Buck) dc–dc converters Table 4 during a load constant are shown in Figs. 9a–10b, respectively.

A discharge curve is composed of three sections, as shown in the Fig. 11: The first section represents the exponential voltage drop when the battery is charged. Depending on the battery type, this area is more or less wide. The second section represents the charge that can be extracted from the battery until the voltage drops below the battery nominal voltage. Finally, the third section represents the total discharge of the battery, when the voltage drops rapidly.

**Table 5 – Parameters of Li-ion battery.**

| Battery parameters | Value | Unit |
|---|---|---|
| Nominal voltage | 8.2 | V |
| Rated capacity | 8.5 | Ah |
| Initial state of charge | 100 | % |

## Conclusions and perspectives

This paper assesses modeling of the conversion system by the graphical approach “Bond graph” which was simulated by the software “20-sim” and that achieved in the environment “Matlab Simulink” allowed us to confirm the validation of the model system.

The PEMFC model includes the double-layer charging effect, gases diffusion in the electrodes and the thermodynamic characteristic while the operation of PWM dc–dc converter assumes to be in continuous-conduction mode.

From these results, we find that the bond graph approach is very reliable in the field of modeling because it is simple and does not take account of mathematical equations sometimes unknown and mostly it saves a lot of time.

The future developments will consist in connecting active loads to the system, such as a synchronous machine and will proposed the control structure.

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