Modeling and Simulation of 1.2 kW Nexa PEM Fuel Cell System

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Abstract

This work concerns the fuel cell systems modeling for their diagnosis. Particularly, we are interested in the systems based on the Nexa 1200W PEM fuel cell. To do this, a dynamic model of this fuel cell taking account of the different physical and chemical phenomena within the stack is presented. It is based principally based on Nerst equation and the use of certain parameters of the Nexa fuel cell provided by the manufacturer. Furthermore, it is accomplished by a certain number of original experimental tests (load modulation method). This model which is designed fortransportation applications contributes to the development offuel cells advanced models because it ensures the decoupling between the different internalphysical phenomena. In fact, to simplify the vehicle motor control, the established model is controlled by an average current at its input. It is especially shown that the membrane of the fuel cell model is solicited by the harmonicsgenerated by the static converters used in the vehicle powertrain powered by the 1.2 kW Nexa fuel cell model. The very important result achieved is that we cantolerate the current harmonics because the double layer capacitor realizes efficient high frequencies harmonic filtering. In this case, the systemstability is noticed. However, the results obtained confirm the use of the Nexa fuel cell system not only in powertrain, but in power electronics generally.

Keywords: Harmonics, Modeling, Nexa, PEM Fuel Cell, Powertrain, Static Converters

1. Introduction

The need of green energies makes the hydrogen one of the energetic vectors that can replace fossil energies in several areas especially in vehicles area. Thus, fuel cells are presently considered the most promising alternative sources of electric power area. In principle, a hydrogen fuel cell operates similar to the battery, producing electricity, which can power an electric motor. Scientists are developing many different types of fuel cells, but the most promising for use in vehicles is the proton exchange membrane fuel cell¹ (PEM fuel cell). Generally, the fuel cells are characterized by the delivery of a high direct current under a voltage generally quite low and difficult to use despite significant efforts to stack in series the largest number of elementary cells². For many applications, this voltage is insufficient and it is not convenient for optimal utilization. It is therefore necessary to place between the battery and the electric load a static converter whose primary role is to decrease or raise the voltage supplied by the fuel cell. In addition, the conversion stage is, essential because of the variation of the output voltage depending on the load that can reach at least 20 % of the nominal voltage¹. This is the most important part of the PEMFCload conversion since load directly affects the lifetime of the fuel cell. Indeed, among the various phenomena affecting the life of fuel cells are the current ripple and the harmonics contained in it³⁻⁴. They are directly related to the architecture of the converter positioned upstream of the fuel cell. This paper is divided into five main sections. Section 1 is an introduction to this work. Section 2 explains the model of each element of the power train system based on Nexa PEM fuel cell. In Section 3 we will present the principal simulations realized while specifying the interactions between the PEM fuel cell and boost converters through our models and we will analyze certain phenomena. Section 4 is the experimental work; it serves firstly to validate the model and also to illustrate

some phenomena that we cannot explain by the modeling. We will finish this paper with the conclusion in section 5.

2. The Power Train Elements Modeling

The electric power train based fuel cell system consists of primarily of the Nexa 1.2 kW fuel cell which is the source of energy, the static converters and a 2 HP electric motor. There are three architectures of vehicles powertrain⁵. The Figure 1 represents the chosen architecture which is generally used when there is no secondary power source.



Figure 1. Block diagram of a PEM fuel cell based electric powertrain.

2.1 The PEM Fuel Cell

PEMFC is the most developed fuel cell offering high power density and low temperature. However, it is necessary to investigate its dynamic characteristics under load variation. Consequently, we developed a PEMFC dynamic model based on electrical circuits to illustrate the electrochemical and thermal phenomena in the PEMFC. The model operates under constant pressure. According to load current, the fuel flow in the fuel cell is regulated in order to keep a constant pressure.

For the PEMFC modeling, we choose a macroscopic representation based on Nerstequation⁴. So, the output voltage V_{FC} can be written as follows⁵:

 $V_{FC} = E - V_{con} - V_{act} - V_{ohm}(1)$ Where:

E is the theoretical potential of the stack.

 V_{con} is the voltage loss due to the gazes concentration

$$V_{con} = -\frac{R.T}{2.F} ln \left(1 - \frac{Id}{I_{dMax}}\right)$$

- R is the perfect gas constant equal to 8,314 J/K/ mol.
- T is the operating temperature
- F is Faraday constant equal to 96485 C/mol.

- $I_{d Max}$ is the current maximal density (A/cm²).
- I_d is the current nominal density (A/cm²)
- V_{act} is the voltage loss due to the rate of reactions on the electrodes surface⁶:

 $V_{act} = \left[\xi_1 + \xi_2 T + \xi_3 T . \ln(C_{O2}) + \xi_4 T . \ln(I)\right](3)$

- C₀₂: Concentration of the oxygen at the interface of the catalytic surface of the cathode.
- $\xi_1, \xi_2, \xi_3, \xi_4$: Parametric coefficients defined on the basis of kinetic phenomena, thermodynamics and electrochemical.

 $\rm V_{_{ohm}}$ is the ohmic voltage losses.

 $V_{ohm} = R_m, I$

• I is the fuel cell current

$$R_{ohm} = \frac{\rho_M . l}{A}$$

- *l* : the membrane thickness (cm) ;
- A : the active surface of the membrane (cm^2) ;

The Figure2 shows the equivalent electric circuit of PEMFC illustrating the previous phenomena and implemented in Matla/simulink.



Figure 2. Electric circuit of the PEMFC.

where, R_{act} , R_{conc} and R_{ohmic} are respectively the activation resistor, the concentration resistor and the ohmic resistances. C represents the double –layer capacitor and I is the fuel cell current.

2.2 The Boost Chopper

For an electric power train, always the DC bus V_{BUS} is higher than the fuel cell output voltage V_{FC} . In this case

we can use a boost converter in order to increase the fuel cell voltage. The Figure3 shows the boost converter composed of an inductance L, an output capacitance C, a diode D and a principal switch S_1 (MOS transistor) and an auxiliary MOS transistor (switch S_2). The circuit is powered by a fuel cell; the output is loaded with a resistance R and supplies a current i



Figure 3. Scheme of the Boost chopper.

where:

- C and $R_{\rm C}$ are respectively the capacity and the series resistance of the output filter

- L and R_L are respectively the inductance and the series resistance of the input inductance

- $\rm R_{_M}$ is the resistance of the MOS power transistors in the conductive state

- V_D the voltage drop of the diode

- V_{FC} and V_{BUS} respectively the input and output voltages

of the converter

 $-i_{FC}$ the current in the input inductor

 $-V_{C}$ the capacitive component of the voltage across the

output filter.

The voltages ratio is related to the duty cycle α by the

following relation7.

 $\frac{V_{BUSS}}{V_{FC}} = \frac{1}{1 - \alpha}$

This relationship assumes that we neglect the losses in the different elements of the circuit8.

Let X is the state vector defined as:

 $X(t) = {}^{t} \left[i_{FC}(t)v_{c}(t) \right]$ Then the equations controlling the converter operation can be written, on the sequence of the switch conduction for the time interval $[0, \alpha T]$ as follows:

(7)

$$\begin{cases} \frac{dt_{FC}}{dt} = \frac{1}{L} \left[V_{FC} - (R_L + R_M) . i_{FC} \right] \\ \frac{dV_c}{dt} = -\frac{V_C}{(R_C + R_{CH})} \end{cases}$$

on the sequence of the diode conduction, the time interval $[\alpha T, T]$

$$\frac{dt_{FC}}{dt} = \frac{1}{L} \left[-\left(R_L + R_D + \frac{R_C + R_{CH}}{R_C + R_{CH}}\right) \cdot i_{FC} - \frac{R_{CH}}{R_C + R_{CH}} + V_{FC} - V_D \right]$$
$$\frac{dV_c}{dt} = -\frac{1}{C} \cdot \frac{R_{CH}}{R_{CH} + R_C} \cdot i_{FC} - \frac{1}{C \cdot (R_C + R_{CH})} \cdot V_C$$

The dynamic model associated to the systems (7) and (8) can be defined by the following system:

$$\begin{aligned} \frac{dt_{FC}}{dt} &= \frac{1}{L} \bigg[- \bigg[R_L + d.R_M + (1+d) \bigg[R_D \frac{R_C \cdot R_{CH}}{R_C + R_{CH}} \bigg] j_{FC} + (d-1) \frac{R_{CH}}{R_C + R_{CH}} \cdot V_C + V_{FC} + (d-1) V_D \bigg] \\ & \frac{dV_c}{dt} = -\frac{1}{C} \cdot \bigg[(1-d) \frac{R_{CH}}{R_{CH} + R_C} \cdot j_{FC} - \frac{1}{(R_C + R_{CH})} \cdot V_C \bigg] \end{aligned}$$

After the establishment of the boost converter status equations, the model was implemented in Matlab Simulink. The Figure 4 and the Figure 5 show respectively the Simulink model of the fuel cell current i_{FC} and the Simulink model of the fuel cell voltage V_{BUS} .



Figure 4. Simulink model of the cell current .



Figure 5. Simulink model of the voltage VBUS.

2.3 The Motor-inverter

In the electric drive the three-phase inverter is the last stage. It is widely cited in the bibliography stage since it is directly related to the three-phase motor, ensuring the drive of the vehicle operating in all conditions with good performance. This engine is chosen for its advantages such as low cost, robustness. It should be an asynchronous motor of 2 HP nominal power. The three-phase two-level inverter-motor is illustrated by the power circuit of the Figure6. Detailed modeling of the motor-inverter has been the subject of several studies and it is strongly related to the control part 9-10.



Figure 6. Thethree phase inverter scheme.

The phase voltages are given by the following equations:

VAB=VAN+VNB=VAN-VBN=(S1-S2)VBus(10) VBC=VBN+VNC=VBN-VCN=(S2-S3)VBus(11) VCA=VCN+VNA=VCN-VAN=(S3-S1)VBus(12)

The Simulink diagram of a voltage inverter with a PWM controlis shown in the Figure 7.



Figure 7. Simulink model of the voltage VBUS.

The control of the machine is made in the two-phase reference Park. That is why we used Park transformation

to pass from three dimenssional refernce (a,b,c) to two dimenssional rotating reference (d,q). The outputs of the controller are transformed back to the three-dimensional stationary reference plane using the inverse of the Park transformation (transformationdenoted "3/2" and "2/3"). In fact, the control section will be discussed in further work and is not the subject of this study

3. The Simulations and Discussion

3.1 The Fuel Cell Model

The Figure 8 shows the 1.2 k WPEMFC dynamic model voltage versus current curve obtained by simulation where the gas pressure (for both the hydrogen and the oxygen) is P = 2 bars at the temperature $T = 65^{\circ}$ C. The parameters of the stack model are those of a Nexa stack of 47 cells Electrochem technology who's physical and geometrical parameters are given by the Nexa fuel cell constructer¹¹.



Figure 8. Voltage versus current curve of the 1.2 kW PEMFC dynamic model.

3.2 Open-loop Simulation of the Boost Converter Supplied by the PEMFC Model

We will compare the simulation results of the boost converter supplied by the established fuel cell model and generating the voltage V_{FC} then by a classic generator or battery delivering the voltage V_{Gen} . The conditions are the following:

 $V_{_{FC}}{=}V_{_{Gen}}{=}12V$; $R_{_{CH}}{=}500~\Omega$; L= 10 μH ;C=100 μF and f=20 kHz.

The Figure 9 represents the V_{BUS} voltages for a duty cycle of 0.7.



Figure 9. Voltages VBUS: (1) the supply source is the fuel cell model (2) the supply source is a generator.

By comparing the results obtained by the model of the boost converter connected to the battery with those found by the same model of the Boost connected to the generator, it was noted that these results are very close, which validates well the established fuel cell model and that of the Boost. Furthermore, the FC output voltage VBUSFC and VBUS GEN are almost constant and the difference between these two voltages has not exceeded 1V (<3.2%). Indeed, an inductive phenomenon is found in the voltage VBUS (for both the battery or the generator) which presents ripples. These ripples are function of the current generated by the source and the adding of a 10 mH inductor to the boost model can eliminate them8-9. We also noticed that more the switching frequency increases, more these ripples are reduced.

3.3 Closed-loop Simulation of the Boost Converter Supplied by the PEMFC Model

The control used for the boost converter is a linear control based on the use of a PID controller. The control principle diagram is shown in the Figure 10.



Figure 10. The Boost converter control scheme.

 $V_{_{Bus \, Ref}}$ is the desired voltage at the output bus. Indeed, the purpose of the use of the regulator is to maintain the output voltage of the DC bus at a constant value regardless of variations in the load. Note that this converter is controlled by a PWM signal to eliminate low order harmonics. The control loop is implemented in Simulink. It is represented as follows (Figure 11):



Figure 11. Simulink model of the voltage control closed loop VBUS.

In order to validate the operation of the boost chopper in a closed loop, we simulated the assembly to a desired voltage bus $V_{Bus Ref}$ =20 V at different switching frequencies. This voltage corresponds to the full load operation. The simulation parameters used are the same as in open loop. The simulation parameters used are the same as in open loop. However, the coefficients of the PID controller are attached to values Kp = 10⁻⁸, Ki = 10⁻³ and-Kd = 10⁻² which represent respectively the proportional gain, the integral gain and the derivative gain. These coefficients are determined mainly using the method of Ziegler and Nichols¹². The Figure 12 represents the boost converter simulation results in closed loop for a switching frequency of 50 kHz.



Figure 12. The response of the boost converter in closed loop for f= 50 kHz.

For the different switching frequency values used and even changing the consign, it was found that the bus voltage tracks much the value of the imposed cosign. Note only the appearance of small fluctuations which appear at the beginning of the response

3.4 The Inverter Simulation

We used atriangular carrier frequency of 12kHz. The frequency of the reference voltage is taken equal to 1200Hz, the DC bus voltage is equal to 60V, that of the engine. The Figure13 represents the phase voltage at the output of the inverter.



Figure 13. VAB phase voltage generated by the voltage inverter.

We noted that for the inverter which is supplied by the PEM fuel cell model through the boost converter generates a pulse width modulated voltage (PWM) whose low order harmonics are eliminated. This potential is generated when the duty cycle of boost chopper is 0.7.

3.5 The High Frequencies Current Harmonics Study

We will study the behavior of a stack element that is connected to boost converter without filter and that in principle generating current harmonics. The simulations of the boost converter were conducted for a current average of 15 A, a current average modeled at two different frequencies of switching: 20 kHz and 100 kHz. At the frequency of 20 kHz, it appears in the faradic current a very low ripple, however for the experience established by Guillaume La Fontès³, it appears on the faradic current a ripple of 0.8 A (5.33 % of the average current). This result difference is due to the limit of the simulation system for quantification of certain sizes and also to the simplifications made determining the results. It also appears a ripple voltage approximately of 0.12V (about 21 % of the cell average voltage). Naturally, the faradic ripple current decreases as the frequency increases. At the frequency of 100 kHz we have obtained a waveless constant current. The Figure 14 represents the internal currents of the fuel cell at frequency of 20 kHz.



Figure 14. Currents of the fuel cell stack connected to the boost model converter for I=15 A and f=20 kHz.

On the other hand, according to the results obtained by La Fontés, the fardic current ripple is less than 0.2 A (1.3% of the average current)³, however, the voltage ripple does not decrease much due to the membrane¹³.

4. The Experimental Work

To validate by experiments, the established model, we used Nexa PEM fuel cell system. Indeed, the experimental validation was performed on the PEM fuel cell Nexa system which is composed of a stack of 47 cells coupled in series, this system delivers a nominal power of 1200 W at an output voltage equal to 26 V. The fuel cell operating temperature is 338.15°K, the hydrogen and oxygen pressures are both equal to 5 bars [11]. For testing, we used an electronic load carrying a current of 47 A¹⁴. The Figure15 shows the test bench allowing to plot the polarization curve by the measures. The principle of this test is to measure simultaneously the current and the voltage delivered by the fuel cell by means of the electronic load and the other measuring devices.



Figure 15. Test bench and measuring photo of the Nexa PEM stack.

4.1 Validation of the Fuel Cell Model

The objective is to observe and evaluate the behavior and the performance of the proposed PEM stack model. The. Simulation results presented in the Figure 16 obtained using Matlab/Simulink The numerical values of parameters used in the simulation are given by¹¹. This figure compares the simulated polarization curve of the cell Nexa with that obtained experimentally.



Figure 16. Simulated and experimental curves of PEM Nexa 1.2 kW stack.

It is observed in the region of ohmic losses, from about 3.5 to 23 A, the agreement between the experimental results and that found by simulation is very good. A difference between experimental and simulated data appears clearly at low currents (<3 A) as well as high current (> 24 A). This difference is explained by the non-consideration of the electrodes porosity, the cell water absorption and the management of gas inside the fuel cell, the microstructural characteristics are not well taken into account in this modeling. The concentration losses appear only for high power³.

4.2. TheCurrent Sinusoidal Modulation

To study the current harmonics generated by the converters we impose a sinusoidal current modulation on the fuel cell. These sinusoidal perturbations were performed with a controlled current active load.

The current modulation is meant as a perturbation which depends on two parameters:

- the injected perturbation frequency

- the injected perturbation amplitude

This dynamic performance is achieved by connecting the fuel cell to a dynamic nature electronic load (current source) and stimulating the load current with the perturbation signal of frequency f and amplitude ΔI .

The Figure 17 shows the variation in cell voltage versus current stack for various amplitudes of perturbation at a typical frequency in power electronics (10 kHz). We noted that the variation in voltage is very low and even negligible compared to that of the current which confirms the use of the fuel cell as a dynamic voltage source.



Figure 17. $.\Delta I$ influence on the stack model for f=10 kHz.

In the lastfigure we see that the order of succession of curves for different ripples ΔI is respected by taking as a classification criterion the current ripple amplitude. It is the same for the experimental results obtained by La Fontés[3], the difference is reflected in the variation of the power which decreases with the decrease of the ripple due to the dynamics of the fuel cell (example the dynamic of double layer capacitor). This observation is important because it seems that the polarization point of the cell voltage increases with the imposed amplitude. However, it remains difficult to interpret in a reliable manner this phenomenon that models cannot predict until now⁵.

5. Summary and Conclusion

The objective of this work was the study and the modeling of the principal elements of the 1.2 kW Nexa PEM fuel cell system in order to use them in a powertrain. From there, it was necessary to make a PEM fuel cell model taking into account the parasites of the stack and its main physical effects. In order to develop an appropriate modeling, we tried to identify the main physico-chemical phenomena in a PEM stack which may be solicited by the perturbations generated by static converters. It is noted that models were developed in Matlab-Simulink. In fact we became interested in the modeling of the boost converter for which we have established the state equations that control its operation. In a second step we studied the responses of our model in open loop then in closed loop. The achieved results confirm our models and the use of the fuel cell as a voltage source. We have also found that the control system is characterized by design simplicity and robustness. More harmonics are eliminated naturally by the double layer capacitor. All these results are confirmed by experiments and measurements.

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