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ELECTRICAL ANALOGY MODELLING OF PEFC SYSTEM FED BY A COMPRESSOR

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Abstract

The PEFC generator for automotive application is expected to have a low cost, a low weight and a low size, to compete with more and more efficient combustion engine. To reach this aim, the complete system has to be taken into account, not only the stack itself, but also the fluid circuit ancillaries. A model is developed with the aim in view to be integrated in the simulation of an electrical vehicle power train. As many components have to be modelled, a macroscopic approach has been chosen.

A general scheme of the system is proposed, which structure is representative of an embedded generator, i.e. few sensors, few actuators. Gaseous hydrogen is stored in a tank. The anode output is closed by a solenoid valve. It is opened when the fuel cell voltage reaches a minimum threshold, allowing flushes of the channels. Air is provided by a compressor which flow is controlled by the motor speed.

The modelling of the fuel cell electrical response is developed, based on semi-empirical approach. The decrease of the output voltage which can be attributed to the anodic dead end operation is taken into account. The fluidic behaviour of the gas circuits has been dealt through an electrical analogy to facilitate the implementation in a usual electrical engineering software (Matlab/Simulink®). Each component of volume V and fluidic resistance R_f is represented by a RC cell. In a formal approach, the flow is related to the current and the pressure is related to the voltage. The model is validated with experimentations carried out on a low power test bench (100W). Then, it is simulated on a load cycle, compatible with vehicle application dynamics.

1 Introduction

Polymer Electrolyte Fuel Cell is one of the promising technologies under development for embedded power supply. The PEFC generator for automotive application is expected to have a low cost, a low weight and a low size, to compete with more and more efficient combustion engine. To reach this aim, the complete system has to be taken into account, not only the stack itself, but also the fluid circuit ancillaries. The behaviour of the last can have a great impact on the global performance. Moreover, the generator architecture should allow to minimise the sensor number and to optimise the reactant consumption. Simulation is a binding milestone to fulfil these requirements. As many components have to be modelled, a macroscopic approach has been chosen. The model is developed with the aim in view to be integrated in the simulation of an electrical vehicle power train.
In the second section, a general scheme of the system is proposed, which structure could be implemented on board. The modelling of the electrical response is developed, based on a semi-empirical approach. The hydraulic behaviour of the gas circuits has been dealt through an electrical analogy to facilitate the implementation in usual electrical engineering software (Matlab/Simulink® has been used). In the third section, the model is validated with experimentations carried out on a low power test bench, under constant current and also on a load cycle, compatible with vehicle application.

2 Component modelling

2.1 System structure

An embedded fuel cell system has to fulfil several requirements as compactness, low cost, reliability and durability. Then, at least, the system structure should low the number of actuators and sensors, as much as possible, and guarantee anyway an acceptable performance level of the generator. Figure 1 is an example of such an architecture. Gaseous hydrogen is stored in a tank. A mechanical valve limits the pressure up to 1500mbars absolute. The anode output is closed by a solenoid valve. It is opened when the fuel cell voltage reaches a minimum threshold, allowing flushes of the channels. Air is provided by a compressor. The air is saturated by a humidifier.

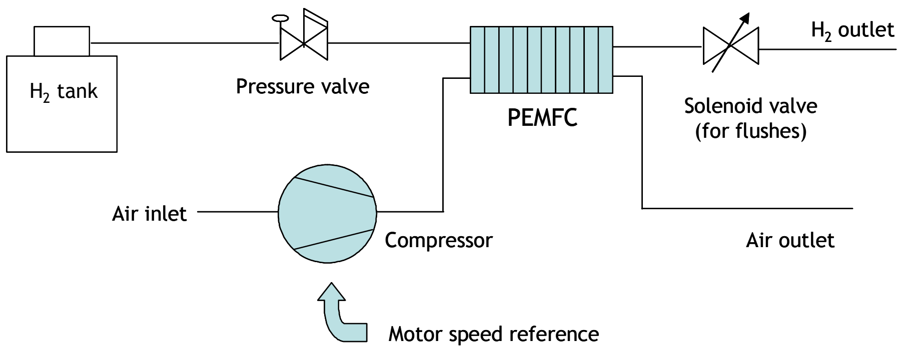

Figure 1 diagram of the setup, consisting of air and hydrogen supplies

The laboratory test bench [1] allows us to carry out measurements useful to characterise such a structure with reservations concerning the compressor, which will be developed in the section 3.

2.2 Electrical response modelling

The electrical response of the fuel cell is modelled by the following equation [2] :

$$U_{pol} = U_0 + aT\ln P_{air} + bT\ln P_{H2} + cT\ln I - rI \qquad (1)$$

With:
P_{air} : the inlet air pressure
P_{H2} : the inlet hydrogen pressure
I : the fuel cell current
U_{pol} : the fuel cell voltage
r : the fuel cell apparent resistance
U_0, a, b, c are parameters to be determined

This expression is used to determine the voltage at the initial time and at the end of the flush. It is defined from a minimal current (because of the logarithmic curve term) below which the voltage is fixed at the value of U0.
When the stack is operated in an anodic dead end mode, the stack voltage decreases with time, even if all the operating parameters and the current are kept constant. This phenomenon can be attributed to the accumulation of water and nitrogen, which have migrated from the cathode. This voltage drop is modelled by an exponent function of time and current u(t, I) (2). [3]

$$\delta u(t,I) = d(\hat{I}) + e(\hat{I})\cdot\exp(-f(\hat{I}).t) \qquad (2)$$

$\hat{I}$: Average value of the fuel cell current.
d, *e* et *f* are parameters to be determined.
According to the relation (1) and (2), the voltage of the FC can be written in the following expression :

$$U_{FC} = U_{pol}\cdot\delta u(t) \qquad (3)$$

2.3 Test bench modelling by electrical analogy

The fluidic behaviour of the gas lines was modelled using an electric analogy, for the integration in Matlab/Simulink®. Each component (pipe, valve, compressor...) of volume V and fluidic resistance R_f is represented by a RC cell (figure 2).

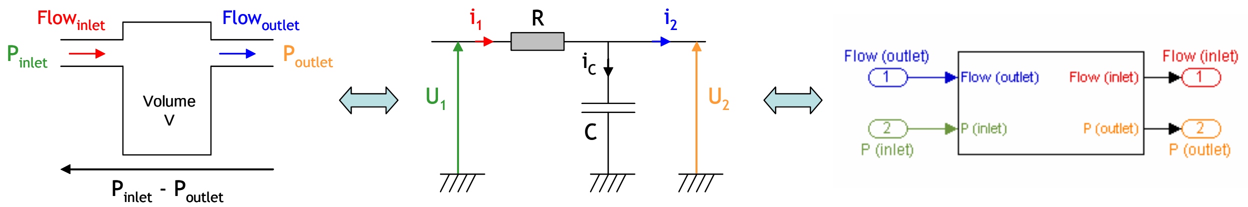

Figure 2 principle of the analogy used between pipe and electric RC cell

The following table illustrates the equations used in the electric-fluidic analogy :

	Electric domain (R and C)	Fluidic domain (R_f and C_f)
Resistance	$\Delta U = R\, i$	$\Delta P = R_f\, F$ with F: molar flow and R_f possibly non linear [4-6]
Capacity	$U = \frac{1}{C}\int i \cdot dt$	$P = \frac{RT}{V} \cdot n = \frac{RT}{V}\int F \cdot dt$

Table1 equations used in the electrical analogy

Such an electric representation allows applying methods of electricity and automation. Figures 3 and 4 justify the choice of RC cell representation. On the 1 kW test bench developed at the laboratory, a statement of the pressure and flow on the air line was made. The FC does not supply any current.
The inlet flow (DeAir) is controlled upstream of the stack by a flow controller. The outlet flow (DsAir) is measured downstream of the stack.

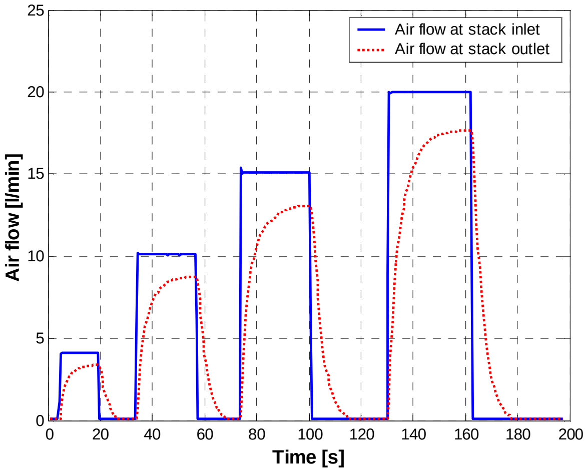

Figure 3 experimental air flows at stack inlet and outlet

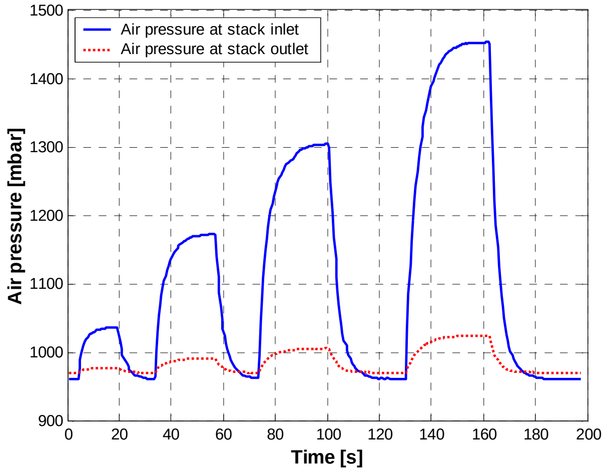

Figure 4 experimental air pressures at stack inlet and outlet

The evolutions of the outlet air flow and air pressures have the typical look of a RC circuit response [7].

3 Model identification and validation of FC generator

3.1 Structure of test bench

The parameters of the model are identified using experimental measurements on a low power test bench (<1kW) developed in L2ES laboratory [8].
The figure 5 shows the simplified structure of the laboratory test bench :

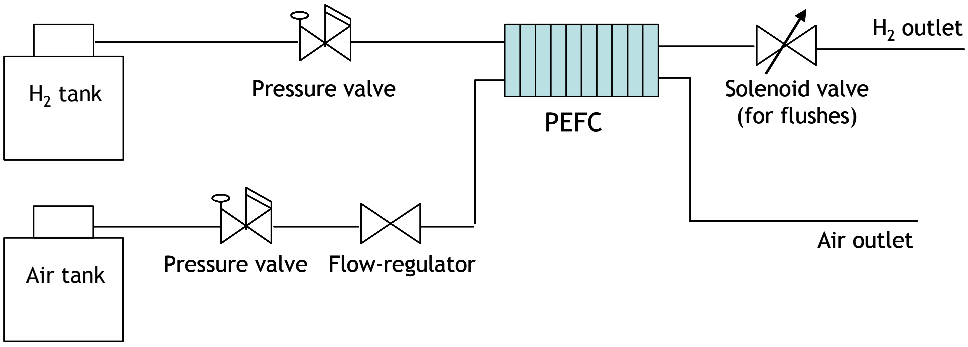

Figure 5 structure of test bench

The figures 6 and 7 show the two models adopted for the gas lines (air and hydrogen).

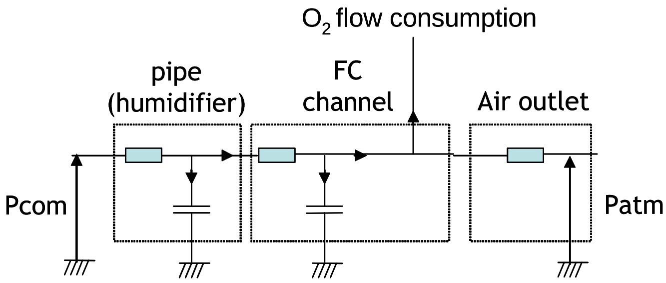

Figure 6 model adopted for the air line

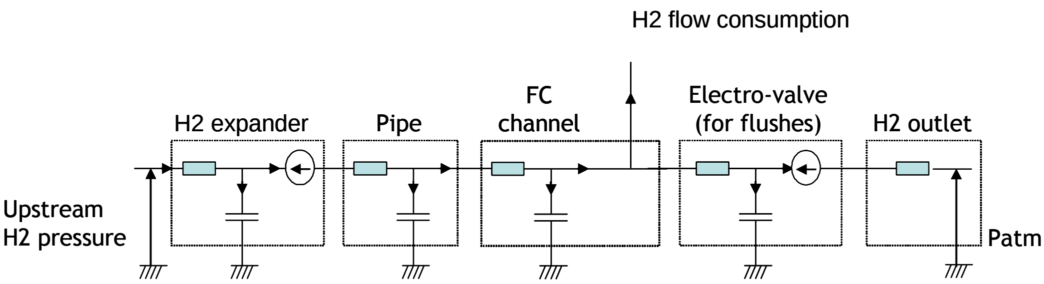

Figure 7 model adopted for the hydrogen line

The identification of each element of the air and hydrogen lines is based on analytical calculations in static and dynamic modes. In statics, resistances are calculated, as in electricity.

In dynamics, by identifying on tests the time-constant RC (and/or also by knowing the volume of each element), the capacities C can be calculated. Two types of current profile were used to identify the model parameters and to validate the results of simulation: a profile of constant current (I=40A) and a standard profile of transport (J227).

3.2 Constant current (I=40A)

A load current of 40A was applied to a 3 cell stack, with a current density of 0.4A/cm2. The hydrogen line operates in dead end mode and using the valve placed at the FC outlet, periodic flushes are carried out. The air line is operated in open mode. The FC temperature is maintained constant at 58℃. Figures 8-12 show the results of simulation and experimental tests :

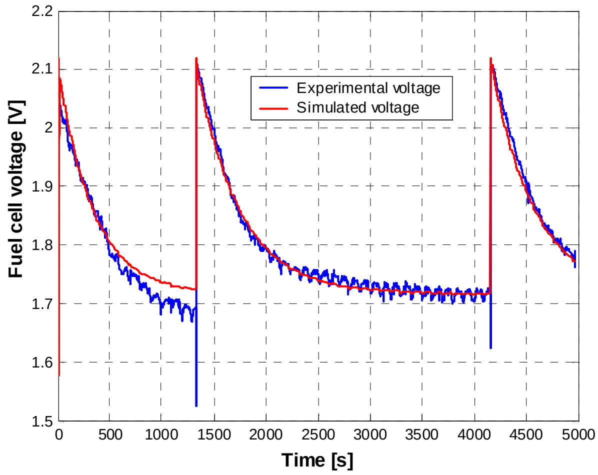

Figure 8 experimental and simulation fuel cell voltages

The voltage change with time is well reproduced by the exponential function (2). In the simulation, flushes have not been started on voltage threshold. The reason why is that in the first phase of the experiment, the stack voltage curve is not repeatable from one flush to an other as long as the membrane hydration is not stabilised, so a time delay between simulation and experiment cannot be avoided. Then the simulation flush starts have been synchronised on the experimental times.

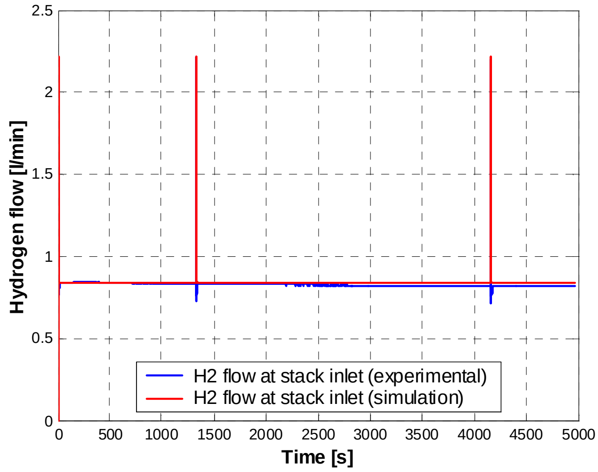

Figure 9 experimental and simulation hydrogen flows at stack inlet

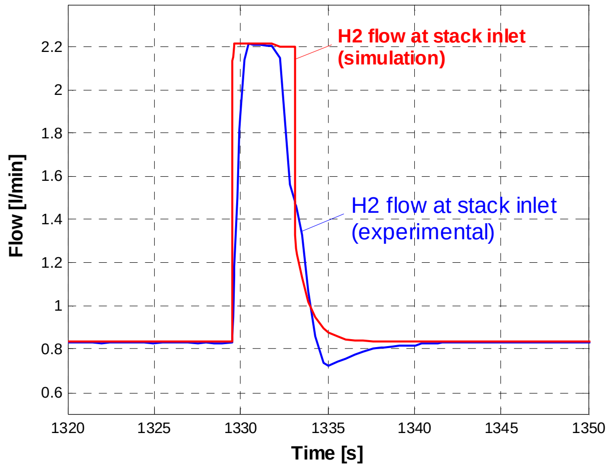

Figure 10 zoom - experimental and simulation hydrogen flows at stack inlet

The simulated inlet hydrogen flow is in very good agreement with the experiment. Between two flushes, hydrogen flow is of course constant as it depends directly on the produced current. During the flush, it evolves dynamically, and the simulation reproduces well the fuel surplus, which is consumed because of the flush.

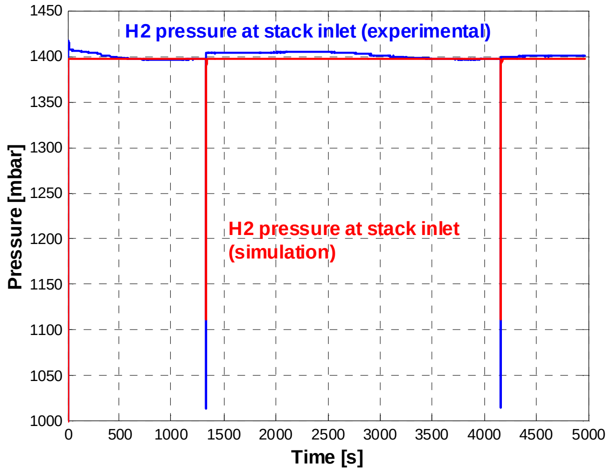

Figure 11 experimental and simulation hydrogen pressures at stack inlet

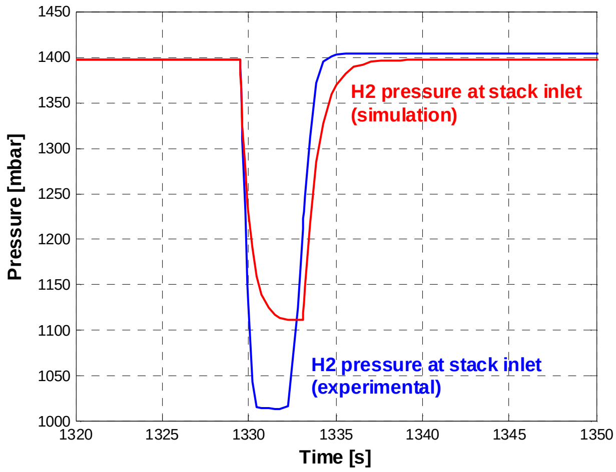

Figure 12 zoom - experimental and simulation hydrogen pressures at stack inlet

The inlet hydrogen pressure is constant in the normal operating mode as the flow is constant; it drops when the solenoid valve is opened, and then recovers after the valve shutting. This trend can be seen well on the simulated curve; however there is an error on the pressure level reached during the flush. It can be easily explained as fluidic resistances are taken constant in the model despite the possible strong non-linearity of such a phenomenon. As during the flush, the flow is much higher than during the constant operating point, the linear model resistance cannot take into account the pressure drop anymore. It could have been possible to introduce a non linear resistance but the final accuracy gain is not high enough to justify the complexity raise of the model. The air flow circuit is constant and allows the tuning of fluidic resistances.
The air pressure upstream is maintained constant with 1350mbars. Using the flow-regulator, the air flow was controlled with 10.1Nl/min.

3.3 Transportation current profile (J227)

A standard speed-time profile for personal vehicle (J227) has been used to define a current profile for our 3 cell stack. It has been calculated on the basis of a software developed by the Laboratory on Transportation and Environment (INRETS LTE).
In order to run the stack in the best conditions, the air flow is kept constant at a value corresponding to the maximum current value.

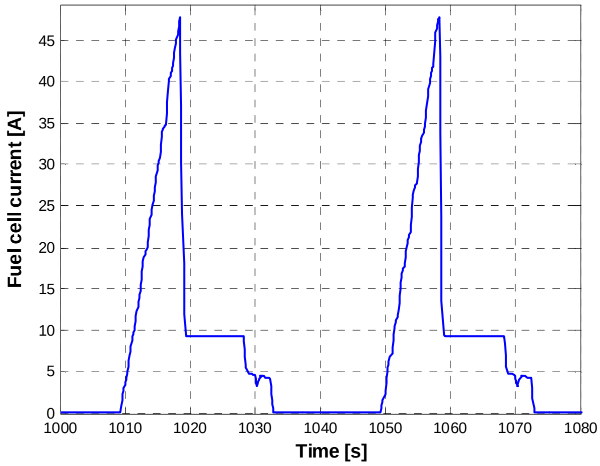

Figure 13 fuel cell current (J227 current profile)

The results of simulation are represented in figures 14-16.

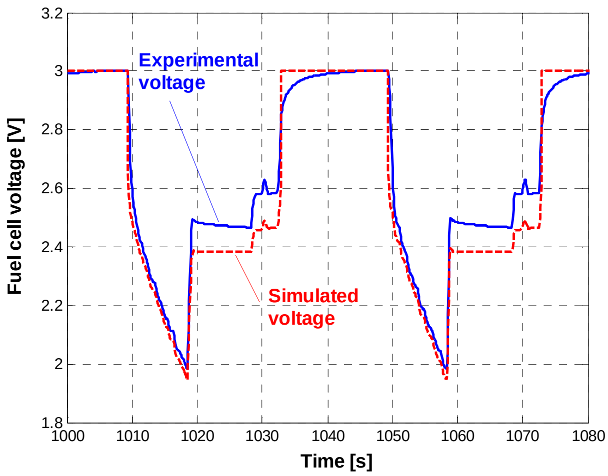

Figure 14 experimental and simulation fuel cell voltages (J227 current profile)

For low currents near to zero, the open circuit value is considered. So, in the simulation, the voltage reaches instantaneously the open circuit value (3V), but the experimental one exhibits a relaxation time.
The discrepancy between the simulated and the measured voltages around the 9A plateau is mainly due to the polarisation resistance error. This voltage is extremely sensitive to this parameter. It has been tuned for a 40A value and kept constant. In a further study, a more accurate resistance mode will be developed to improve this point, particularly for low current. During transient phase, the voltage simulation is very satisfying.
The simulated hydrogen pressure and flow are in very good agreement with the experiment (fig. 15 and 16).

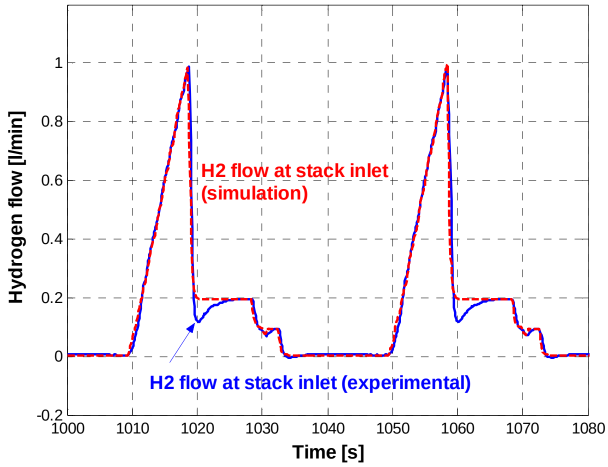

Figure 15 experimental and simulation hydrogen flows at stack inlet (J227 current profile)

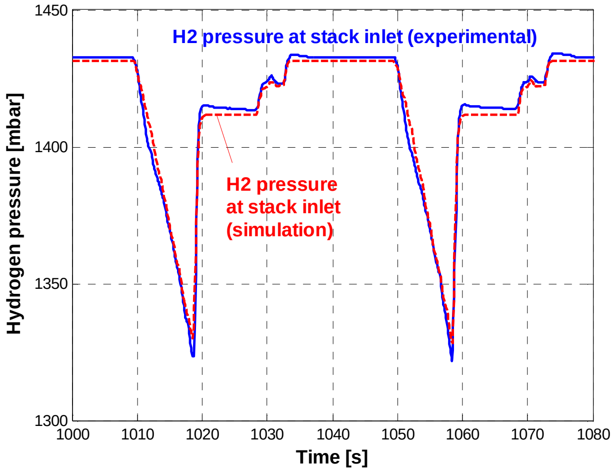

Figure16 experimental and simulation hydrogen pressures at stack inlet (J227 current profile)

3.4 Motor-compressor modelling

The air supply circuit based on a motor-compressor group is the most power hungry. It represents up to 80% of the overall ancillary consumption. Consequently, in order to perform both the energy optimization and the energy control of an embedded fuel cell system, a simple model of the motor-compressor has been developed.
The choice of each compressor depends on its outlet pressure and the range of power of the fuel cell. A pallet compressor has been chosen (simple construction and lower cost).
A permanent magnet synchronous motor is used for the drive of the pallet compressor.

3.4.1 The permanent magnet synchronous motor

The speed regulation of the motor drive is done by varying the I_q with I_d=0 [9].
The following table give the equations of the permanent magnet synchronous motor :

Driving torque	$C_m = \sqrt{\frac{3}{2}} \cdot p \cdot I_q \cdot \Phi$
Load torque	$C_r = \frac{P_c}{\omega}$
Mechanical equation	$C_m - C_r = J \cdot \theta^{\bullet\bullet} + f \cdot \theta^{\bullet}$
Motor speed	$\omega = \frac{d\theta}{dt} = \theta^{\bullet}$
Electrical power	$P_{elec} = K_{phi} \cdot I_q \cdot \omega$

Tableau 1 mechanical equations of permanent magnet synchronous motor

The inputs of this model are the current I_q and the compressor load torque. The outputs of this model are the consumed electrical power, the mechanical power and the motor-compressor group rotational speed.

3.4.2 Compressor modeling

In the work presented in [9], an accurate model of compressor has been developed, for the study of optimized control laws. It has been validated on an experimental bench. This modelling was used as reference for the identification of our simple model. The compressor being element of the chain, it is modelled in the same manner as the other components of the system (on the principle of a cell RC) by a simple first order transfer function.

3.4.3 Results of simulation of the fuel cell generator

A- Constant current (I=40A)

The simulation of the fuel cell generator (motor-compressor /stack/ hydrogen supply) is based on the same tests as in the case of the test bench structure (without compressor). Figures 17-18 show the results simulation with constant current solicitation :

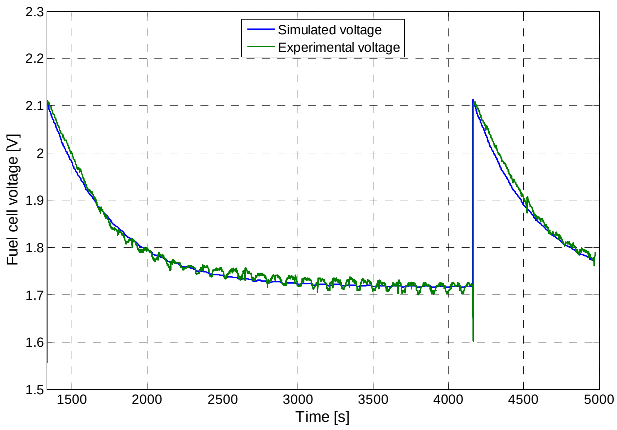

Figure 17 experimental and simulation fuel cell voltages

The fuel cell voltage has not changed compared to the model where an air expander and a flow-regulator are used, since the air pressure is maintained constant by the compressor.

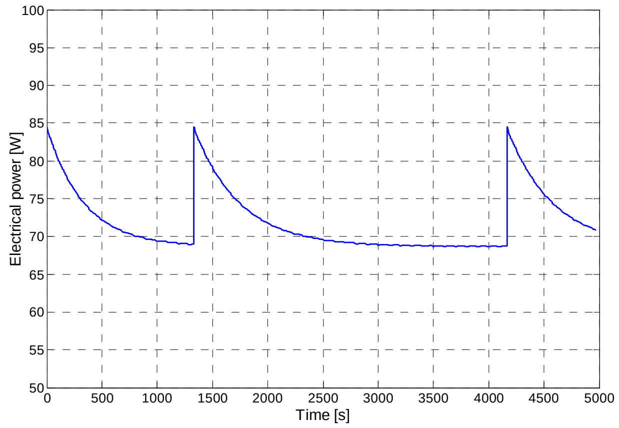

Figure 18 instantaneous electrical power of the fuel cell (constant current)

For a constant current (I=40A), the consumption of the motor-compressor is approximately 20% of the power provided by the fuel cell.

B- Transport current profile (J227)

Figures 19-20 show the results with transportation current profile :

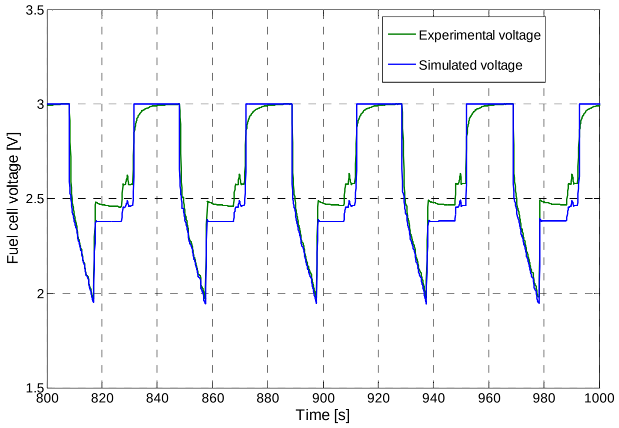

Figure 19 experimental and simulated fuel cell voltages (J227 current profile)

The strategy of air supply applied in the case of the test bench (constant air flow) is not viable for a real application (the fuel cell does not even provide the sufficient power to feed its own auxiliaries). In this simulation, the motor speed is controlled in order to have a variable flow and to keep a constant air stoichiometry.

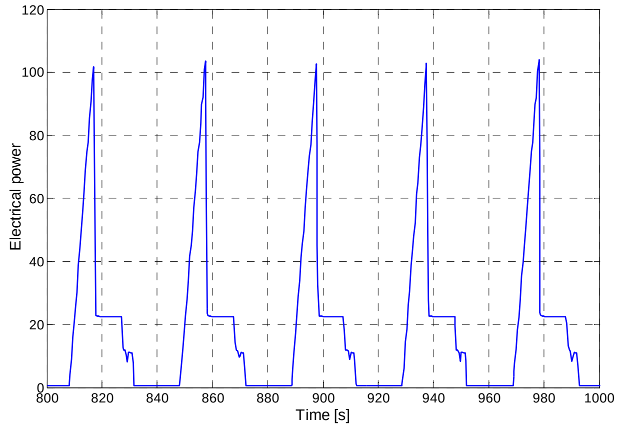

Figure 20 instantaneous electrical power of the fuel cell (J227 current profile)

The motor-compressor consumes 16.5% of the power of the fuel cell, by neglecting the consumption of the other ancillaries.

C- Electrical efficiency of the generator (stack and motor-compressor)

The hydrogen flow is often measured in standard litres per minute (slpm). If this is the case the electrical efficiency should be derived as follows :

$$\eta_{el} = \frac{U_{stack} \times I_{stack} - P_{elec(motor-compressor)}}{\dot{n}_{hydrogen,supplied} \times \Delta H_f^0 (H_2O(g))} \quad (4)$$

$$\eta_{el} = \frac{U_{cell} \times n_{cell} \times I_{stack} - P_{elec(motor-compressor)}}{\frac{\dot{V}_{slpm,hydrogen}}{1000 \times 60} \times \frac{p}{R \times T_{273}} \Delta H_f^0 (H_2O(g))} \quad (5)$$

Where p=101325Pa, R=8.3145(J/mol K), T_{273}=273K, $\Delta H_f^{\circ} (H_2O(g)) = 241.82 \times 10^3$ J/mol (at 298 K and 1atm) and $\dot{V}_{slpm,hydrogen}$ is the hydrogen flow in slpm.

The figures 21-22 show the global efficiency of generator (stack and motor-compressor) for a constant current (I=40A).

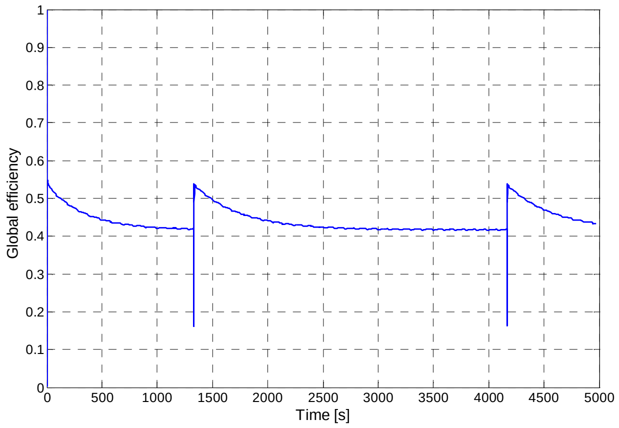

Figure 21 instantaneous global efficiency of generator (I=40A)

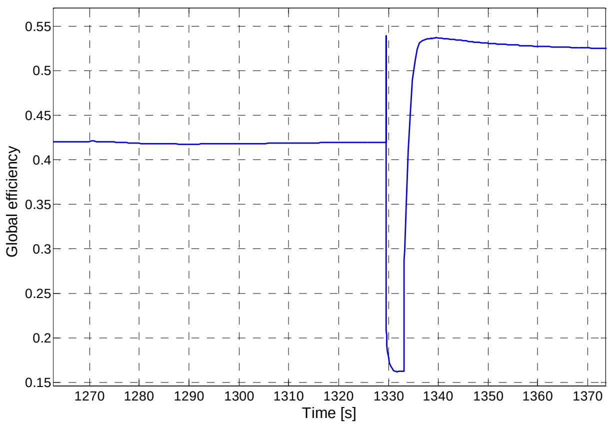

Figure 22 zoom-instantaneous global efficiency of generator (I=40A)

The average global efficiency of the generator is approximately 45%.

For transport current profile (J227), the instantaneous global efficiency is periodic and for a null current the global efficiency cannot be calculated, so figure 23 shows one period of generator efficiency with fuel cell current :

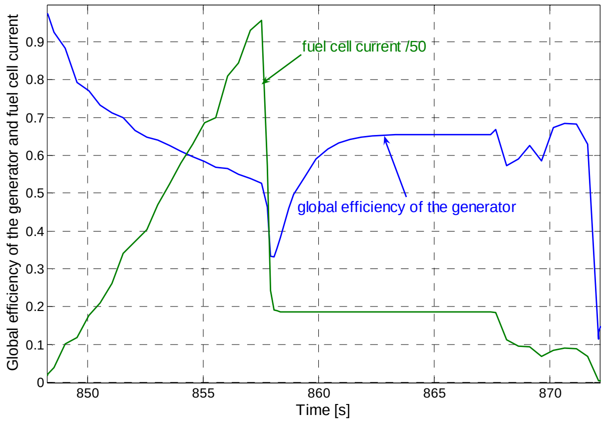

Figure 23 instantaneous global efficiency of the generator (J227 current profile)

The average global efficiency of the generator is approximately 60%. This is an upper limit as the consumption of the other ancillaries (mainly the humidifier) has not been taken into account. Furthermore, the average current is rather low so that hydrogen flushes have not been performed.

4 Conclusion

PEFC generator is a promising technology for the future of electrical vehicles. Simulation is a binding milestone to evaluate the potential interest for propulsion or auxiliary power unit. The whole system has to be taken into account, that includes the stack and the ancillaries needed to manage the fluid feeding of the stack. The proposed model is based on a homogeneous approach of the system components, from the fluidic point of view. As it is based on an electrical analogy, it can be easily implemented in electric engineering softwares, particularly if the whole power train (converter, motorisation and electrical buffers) has to be considered. The model parameters have been tuned around a nominal operating point and linearity has been assumed around this point. It is clear that it reduces its validity area, however simplicity has been favoured and it is very efficient in the first step of the system sizing. Further improvements will be investigated, concerning mainly two aspects: first a better model of polarisation resistance, and the modelling of the humidifier consumption.

5 References

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