Fuel Cell Systems for Electrical Vehicles : Solutions, Modelling and Test benches design

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Abstract

This paper presents the modelling of fuel cell (FC) power generator oriented toward the integration into an electrical vehicle simulation. First a brief description of the FC principles as well as the benefits of the Proton Exchange Membrane Fuel Cell (PEMFC) technology for automotive applications are given. Next, the model of the whole fuel cell system that has been implemented in the MATLAB/Simulink environment is described. Finally, after a brief description of a test bench dedicated to PEMFC, experimental results are compared with those obtained using the proposed simulation model.

1 Introduction

Due to the increasing environmental problems caused by the use of automobiles powered by combustion engines, the electrical vehicle has been considered as the alternative solution for keeping and even increasing the level of personal mobility and satisfying the transportation needs of the coming century [1]. Then considerable efforts have been made to reach the goal of producing electric vehicles with satisfactory performance characteristics, but the results obtained so far have been generally disappointing. The main reason can be found in the inability of available rechargeable battery systems to provide the energy and power densities needed to make electric propulsion systems competitive with the range and power output of internal combustion engines operated on fossil fuels. This has caused, in recent years, an ever increasing attention towards fuel cells (FC). Indeed, the electrochemical conversion has a high theoretical efficiency, could lead to high fuel economy, is friendly toward environment, and has an excellent dynamic response. They are then expected to be good candidates for substituting, at least in some applications, more conventional energy conversion systems, in the future.

Thus, auto manufacturers around the world have launched important research programs on FC. In fact, many of them have already demonstrated buses or cars powered by FC (most of them by Proton Exchange Membrane FC). In association with FC manufacturers, great efforts have been done in order to improve the stack performances. However, in most cases, the efficiency of the global power system is still reduced due to the lack of specific and optimised ancillaries. Many hurdles have still to be overcome, particularly in terms of integration, system energetic optimisation and cost reduction. Simulation tools are needed to reach this ambitious goal and find the best structure for the system.

At first, we present the different architectures of hybrid vehicles and how FC systems could take place in these architectures. Then, a modelling of a proton exchange membrane FC stack and its implementation are presented. In a third part, we describe a 500W PEMFC test bench and we discuss different experimental results. Finally, these results are compared to the simulation results.

2 Presentation of Proton Exchange Membrane Fuel Cell systems

A fuel cell is an open converter producing electrochemical power due to the oxidisation of a gas rich in hydrogen on an anode and the reduction of oxygen (generally from air) on a cathode, with an electrolyte among the anode and cathode which enables the exchange of electrical charges (ions). The ion flow through the electrolyte produces an electrical current in an external circuit or load. In normal operating conditions, a simple FC typically presents a voltage from 0,5V to 0,9V. For use in energy generation systems, where a relatively high power is needed, several cells must be connected in series, forming a stack that could supply hundreds of kW.

Among the several types of fuel cells; the PEM (Proton Exchange Membrane or Polymer Electrolyte Membrane) fuel cell is the most promising alternative regarding automotive applications [2]. PEMFC, as long as they are fed with pure hydrogen, produce water as single residue. They operate at low temperatures (80°C) compared to other types of fuel cell, allowing then faster start-up. They use a polymer as the electrolyte, which must be wet to be a good ionic conductor. The solid electrolyte reduces construction, transportation and safety concerns. Their high current density allows a reduction of both weight and size of the stack [3].

Ancillaries have to be added to run properly a PEMFC. Their contribution in terms of integration and efficiency is far from being negligible as they can represent up to 70% of the system size and consume up to 30% of the generated electrical power.

Four circuits have to be considered (fig.1):

- Hydrogen can be produced on board but as reforming needs high temperature, technological problems have still to be solved. The anode can also be supplied with pure hydrogen either stored in high pressure cylinders or absorbed at low pressures on metal hydrides. The circuit is very simple as it consists mainly in an expander. However, the solution to get a sufficient range in a reasonable volume has still to be found.
- Air is usually provided by a compressor, as oxygen partial pressure has a great influence on the fuel cell voltage.
- Gases, more often air, are humidified in order to avoid the drying out of the membrane.
- As the electrochemical reaction is highly exothermic, the fuel cell must be cooled. For very low powers (under 500We), it can be cooled using a fan, but beyond, water should be used.

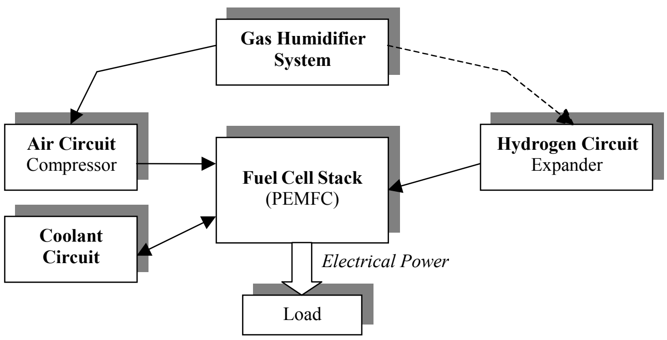

Fig.1: Stack and auxiliaries

3 Hybrid vehicles

Pure battery-electric vehicles have shown their limitations, because of low specific power and the limited range of the vehicle [4]. Adding different power supply in the same vehicle allows taking advantages from their different characteristics. This is the principle of hybridisation. Various sources and various configurations are possible and can be classified for instance from parallel to series hybrid vehicles. Most of the applications involves internal combustion engine, and one or two electric machine(s) with batteries or/and supercapacitors

3.1 Parallel and dual architectures

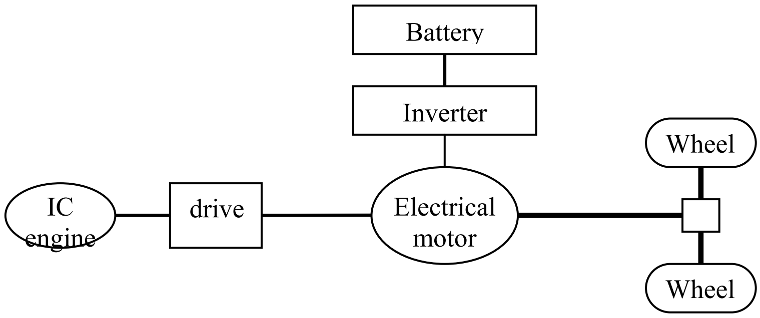

Fig. 2 Example of parallel hybrid vehicle

In these architectures, the internal combustion engine and electric motor(s) are mechanically linked to the. wheels. A wide range of solutions may be encountered, mainly depending on clutch position in the driveline, the main ones being :

- Starter alternator damper (booster) : The electric motor (integrated or not) is located between the engine and the clutch. This solution does not enables electric operation of the vehicle, (Honda Insight available on the market or Citroën Dynalto project),
- Parallel hybrid : The clutch is located between the engine and the electric motor, then enabling pure electric operation of the vehicle (20 km for the Citroën Dynactive project),
- Dual mode hybrid : Using two electric machines enables both parallel and series operations, controlled by a sophisticated software (Toyota Prius, for witch more than 70 000 have already been sold since 1997, and Nissan Tino with 100 vehicles already marketed).

3.2 Series architectures

In the series hybrid configuration, the vehicle propulsion is electrical, the engine being used as an on board generator. Many projects have been carried out in the past, with large engines such as diesel (Peugeot SA VERD) or gas turbine (Peugeot SA and Renault VERT, Volvo bus). More recently, projects involving small engine, as a range extenders, have been launched (Citroën Dynavolt, Renault Kangoo).

In order to have a complete local zero emission vehicle, increase the global efficiency of the powertrain and diversify primary energy use, pure electrical power sources solutions can be also envisaged [5]. The association of a ? engine driving an electrical generator can be replaced by a FC system [6]. Since FC are still expensive, hybridisation with batteries and/or supercapacitors may be considered as an interesting way to minimise the FC size and recover braking energy. The cost of the pure FC system and the cost of the hybridised system have to be compared. Weight and volume have also to be taken into account [7]. Thanks to a hybrid system, dynamic solicitations on the fuel cell are lower : start up delay could be reduced and life span could be improved. Nevertheless, many technical issues have to be solved and the complete system should be considered to reach a real optimisation for commercial purposes. Simulations allow to define the most interesting structures of hybrid vehicles, to optimise component sizing and energy management laws before experimental validations. It is with this aim in view that our fuel cell model is developed.

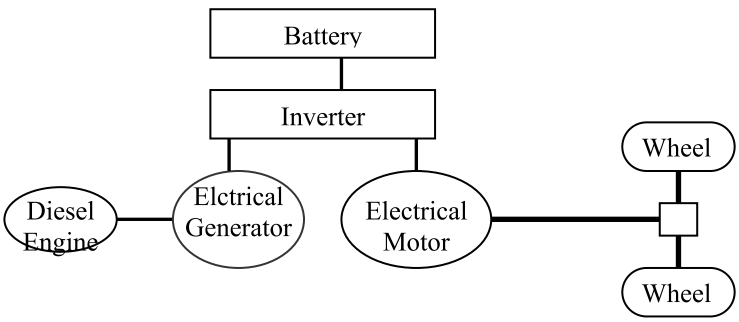

Fig. 3 Example of series hybrid vehicle

4 Presentation of the Model

The stack is submitted to many different kinds of complex physical phenomena: electrochemical, thermodynamic, thermal… On one hand, the desired simulation model must be accurate enough to take into account the influence of input parameters as gas pressures, flows, temperatures on the electrical characteristics. On the other hand, the final aim of this work is the integration in a larger software, able to simulate the entire vehicle powertrain. Therefore, the fuel cell generator model must be rather simple for two reasons. First, calculation time must be as low as possible. Second, parameters of the model must be identified with as little experiments and as few informations about the internal structure of the stack as possible (this is usually confidential property of the stack manufacturers).

4.1 Modelling structure

The model is structured in separated modulus, interacting each other with output and input data. The cells are supposed to be identical and to have the same behaviour; the stack is then modelled as a unique cell. The temperature of the stack is supposed to be constant and equal to the outlet temperature of the coolant water. This assumption can be done considering the thermal time response of the stack, which is much higher than the electrical time response, in case of limited load solicitations. The load is taken into account as the evolution of current versus time is imposed to the stack. Hydrogen and air flow references are calculated according to the Faraday low (1-2).

$$q_{H_2} = F_{SA} \frac{NI}{2F} \tag{1}$$

$$q_{O_2} = F_{SC} \frac{NI}{4F} \tag{2}$$

where: q_{H_2} is the incoming hydrogen flow ($mols^{-1}$), q_{O_2} the incoming oxygen flow ($mols^{-1}$), N the number of cells, F the Faraday constant. F_{SA} and F_{SC} are the stoichiometry factors of the anode and cathode respectively. They are greater than 1 in order to be sure that there is a sufficient amount of reactants to provide the required current. Each gas passes through an expander and a mass-flow controller.

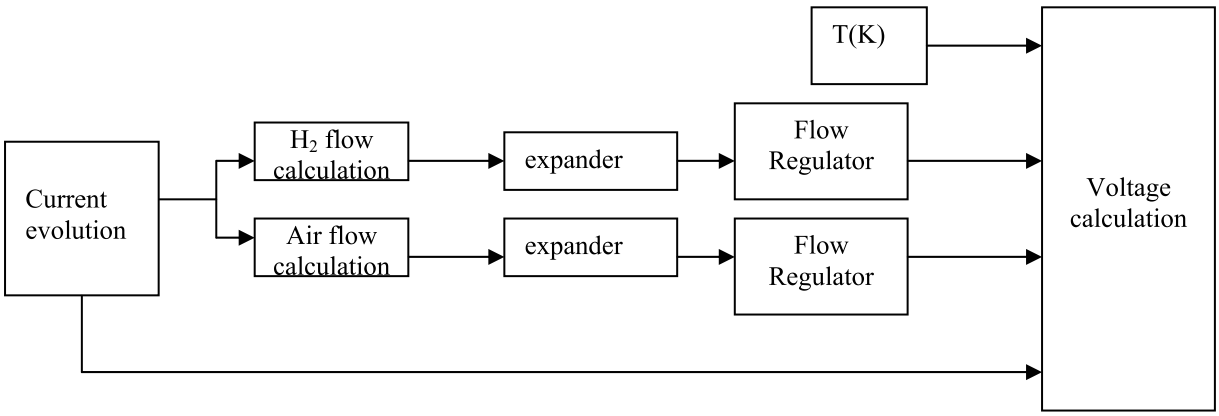

Fig.4: General architecture of the simulated system.

4.2 Voltage calculation

The output voltage depends on the current, the temperature and the logarithms of hydrogen and oxygen partial pressures on the catalytic sites of the electrochemical reactions [8]. As the modelling is at a macroscopic level, we consider instead of these partial pressures, the input gas partial pressures in anode and cathode compartments.

The output voltage can be expressed as:

$$U = U_0 + \alpha T \ln(P_{O_2}) + \beta T \ln(P_{H_2}) + \gamma T + \delta T \ln(I) + rI \qquad (3)$$

where : I: output current(A)

P_x : input partial pressure of the gas x

U_0, α, β, γ, δ, et r : coefficients identified from an experimental test.

Coefficients are identified from experiments by a least square method. Due to the natural logarithm on current I, this relation cannot be used for very low currents. The voltage is then maintained equal tto the value of the open circuit voltage until the current has reached to 20mA.

4.3 Gas circuits

4.3.1 Expander

The inlet flow of the expander comes from a high pressure cylinder. The outlet pressure depends on the expander reference which is determined by the user and decreases linearly with the volumic flow requested by the fuel cell. Its slope depends on the reference value and is determined experimentally. The outlet pressure is equal to the pressure reference for a zero flow.

4.3.2 Mass flow regulator

The gas flow reference calculated according to the current is the real gas flow but the regulator, modelled by a first order transfer function, is supposed to respond with a 1second delay. The pressure drop across the regulator has been supposed to vary linearly with the inlet pressure and the volumic flow. Abacus has been determined experimentally.

5 Experimental results and simulation validation

5.1 Description of the test bench

A fuel cell test bench has been developed at the L2ES (Fig. 5). The stack can be operated with pure or reformed hydrogen on the anode side and with air on the cathode side. It is made up of 20 cells (area 100 cm²) and is able to supply an electrical power up to 500W under about 12 V. The nominal operating temperature has been limited to 55°C since we are providing dry air to the stack. The stack must be operated with an air pressure between atmospheric pressure and 1,5 bars. Additional to the anode and cathode gas circuits, a coolant deionized water circuit is used to extract the calories from the stack.

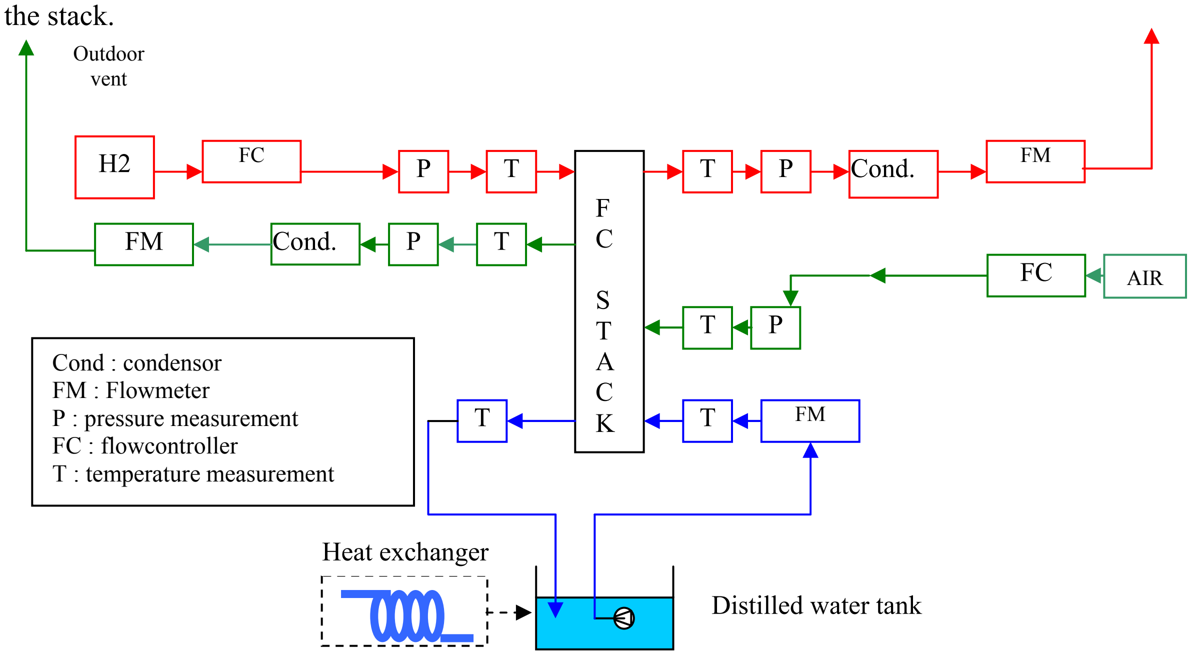

Fig. 5 Test Bench

Air and hydrogen are here stored under 150 bars and 200 bars cylinders respectively. After having gone through a pressure reducing valve, a gas mass-flow controller is used to regulate the fuel-cell gas supply. At the output of the stack, a mass flow meter is available. Therefore, a condenser has been placed before the gas exhaust which is also dedicated to the quantification of the produced water.

The stoichiometry factors are fixed through the mass-flow controllers. The gas pressure is reduced from the high pressure in the storage cylinders to a value between 1 and 1,5 bars.

5.2 Experimental results

Experimental tests on the bench have been carried out. The influence of the current, the operating temperature and the stoichiometry factors on the output voltage has been investigated.

5.2.1 Effect of temperature

Measurements are carried out with constant stoichiometry factors and different operating temperatures (i.e. outlet coolant water temperature). Temperatures have been taken from 22°C to 50°C and currents from 2 to 10A. Experimental results indicates that the fuel cell voltage increases as the temperature increases (fig.6). On one hand, mass transport limitations are reduced at higher temperatures. On the other hand, high temperature contributes to the membrane's susceptibility to dehydration and the subsequent loss of ionic conductivity [9]. Nevertheless, it appears that the overall result is an improvement in cell performance with temperature increase.

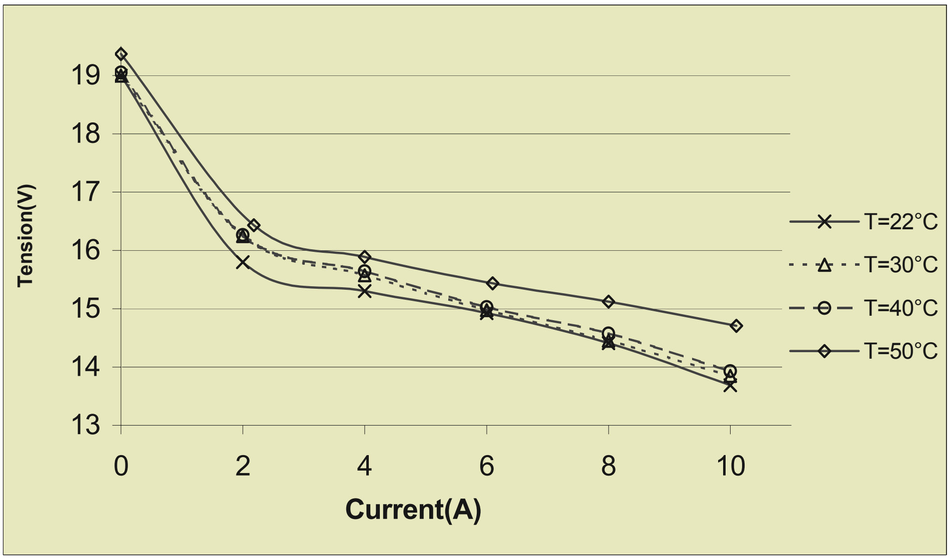

Fig 6: Static electrical characteristics for different temperatures.

5.2.2 Effect of the stoichiometry on PEMFC performances

In this experiment, temperature is kept constant at 50 °C. Voltage is measured for various stoichiometric factors and current varies from 2A to 10A. The influence of stoichiometry on the performance of a PEMFC at 50°C is illustrated on fig 7 (F_{SA} = 2 and F_{SC} = 5 is noted (2_5)). It can be noticed that the voltage increases when the F_{SC} (in keeping F_{SA} constant) increases and on the contrary increasing F_{SA} (in keeping F_{SC} constant) degrades the performances of the fuel cell.
As the oxygen partial pressure increases linearly with F_{SC}, these results demonstrate that an increase in the pressure of oxygen results in a significant reduction in polarisation at the cathode. At this high temperature, the effect of the increasing hydrogen partial pressure must be hidden by the drying of the membrane as no water is produced on the anode side. As a matter of fact, at low temperature increasing F_{SA} improves the electrical characteristic.

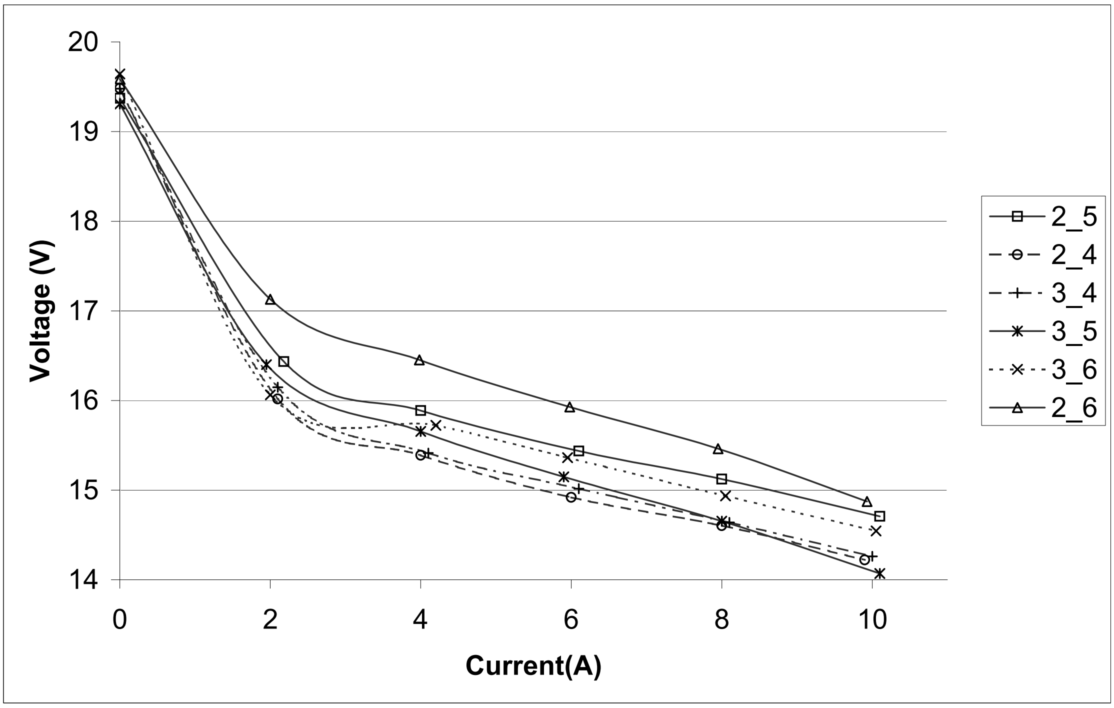

Fig 7: Static electrical characteristics for different stoichiometry factors.

6 Model validation and simulation results

6.1 Model validation

Fig. 8 to10 show comparisons between experiment and simulation for various parameters. The error on the voltage is less than 8%. The error on the identification of the electrical law U(I) is responsible for a minor part of this gap, the error is mostly due to the error on partial pressures calculation. The maximum error on the evaluation of the pressure drop in the regulator is 7%, and it induces a difference of 2% on the inlet air pressure. Results on the hydrogen circuit are better (less than 0.5% on the inlet gas pressure) as the flow range is smaller.

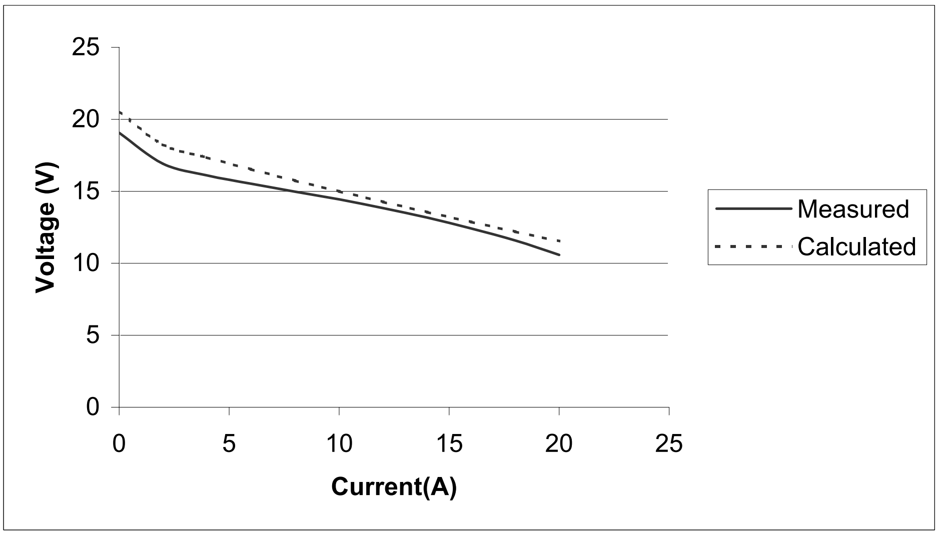

Fig 8: Comparison between experimental and calculated electrical characteristics at 45°C, (F_{SA}, F_{SC})=(2,5), relative expander pressure references (H_2, air) = (1bar, 1,4bars).

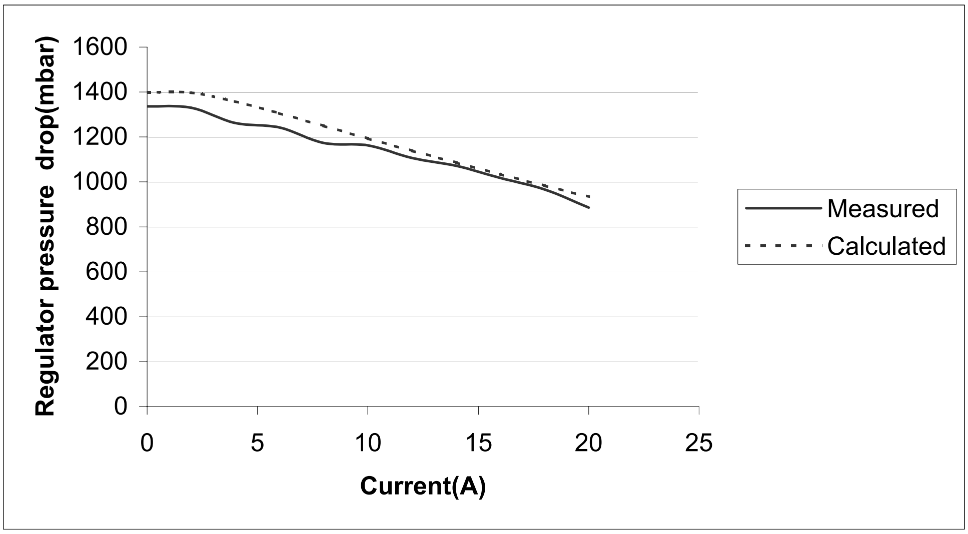

Fig 9: Comparison between experimental and calculated regulator pressure drops at 45°C, (F_{SA}, F_{SC})=(2,5), relative expander pressure references (H_2, air) = (1bar, 1,4bars).

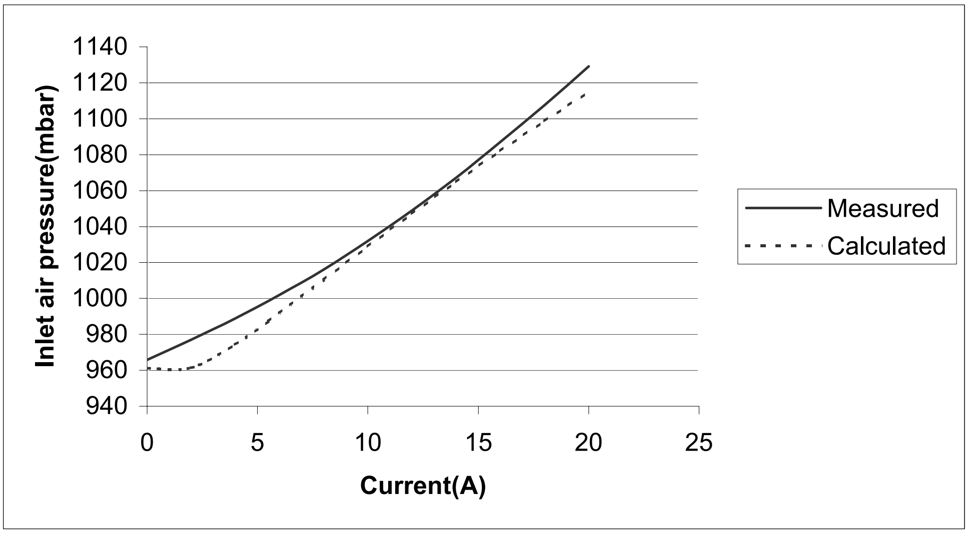

Fig 10: Comparison between experimental and simulated inlet air pressures at 45°C, (F_{SA}, F_{SC})=(2,5), relative expander pressure references (H_2, air) = (1bar, 1,4bars).

6.2 Simulation results

Fig 11 shows simulation results on the whole fuel cell system. The running temperature is 50°C, stoichiometry factors are (2_5). The reference of relative pressure on the hydrogen expander is 1 bar, on the air expander 1.4 bars. The current is supposed to be imposed by the load according to the first figure. The current has been limited under 20A to stay within the experimental ranges. The load current variation is rather low as the stack model is quasi-static. The voltage decreases when the current demand increases, with a delay due to the response of the flow regulators. The inlet pressure increases with the current as keeping stoichiometry factors constant implies an increase of the flow regulator references.

7 Conclusion

Fuel cell technology is an attractive alternative for the development of low fossil fuel consuming, quiet and environment respectful vehicles. Among the different technologies, the proton exchange membrane fuel cell is the most appropriate to transportation constraints, as the electrolyte is solid, the dynamic is high and the start-up time is reduced. However, the fuel cell generator and the electrical power train need further improvements before being competitive with conventional IC engine.

Moreover, the structure and the hybridization rate able to optimize the energy management have still to be investigated. Simulation is an important milestone to reach this aim. A simple and efficient model of the stack and afferent gas circuit has been presented. The influence of the actuators controlling the gas distribution on the electrical response has also been taken into account. A test bench has been built in order to carry out experiments. It has allowed to identify the model parameters and to validate the proposed simulation. Notice that the number of parameters, which have to be identified, has been reduced as much as possible. Simulation and experimentation results are in good agreement as the difference remains under 8% on the voltage.

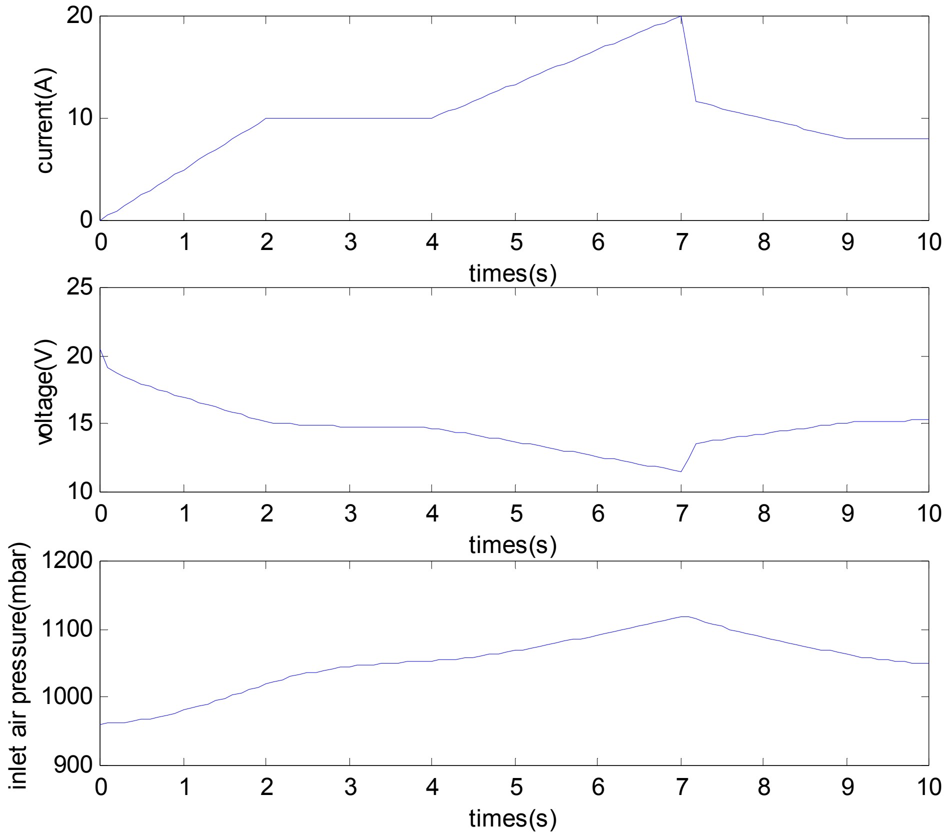

Fig 11: Simulation results for an imposed evolution of fuel cell current versus time.

8 References

1. K. Kordesh, G. Simader, *Fuel Cell applications.* VCH. pp. 251-279, 1996.
2. M.Ceraolo, R. Giglioli, C. Miulli, A.Pozio, "A dynamical model of a proton exchange membrane fuel cell", *EVS 18*, Berlin, 2001.
3. J. Corrêa, F. Farret, L. Canha, "An analysis of the dynamic performance of proton exchange membrane fuel cells using an electrochimical model", *Industrial Electronics Conference IECON'01*, pp. 141-146, 2001.
4. M.C. Péra, D. Hissel, X. François, J.M. Kauffmann, P.Baurens, "Modelling of a proton exchange membrane fuel cell power generator device for transportation", *IEEE VTS NEWS*, vol. 49 No.1 p 9-14, February 2002.
5. P. Van den Bossche, "Power sources for hybrid buses: comparative evaluation of the state of art", *J. of Power Sources*, vol.80, pp. 213-216, 1999.
6. A. Djerdir, H. Gualous, D. Bouquain, A. Berthon, M.Y. Ayad, I. Rasoanavivo, S. Rael, B Davat, "Utilisation de supercondensateurs dans la motorisation de véhicules électriques à pile à combustible", *Conference on Fuel Cells and Interfaces for Transportation Applications*, pp 117-124, Belfort, France, 2000
7. D. Candusso, E. Rullière, S. Bacha. "Modelling of a Fuel Cell Hybrid Power Source for a small Electric Vehicle", *EVS 18,* Berlin 2001
8. J.C. Amphlett, R.M. Baumert, R.F. Mahn, B.A. Peppley, P.R. Roberge, T.J.Harris, "Performance Modelling of the Ballard Mark IV Solid Polymer Electrolyte Fuel Cell", *J.Electrochem. Soc.*, vol. 142, n°1, pp.1-8, 1995.
9. U.S. Department of Energy EG&G Services, *Fuel Cell Handbook*, Parsons, October 2000.