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SIMPLIFIED FUEL CELL SYSTEM MODEL IDENTIFICATION

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Abstract— The use of fuel cell and supercaps as energy elements in transport application is now a reality. Having two power sources on board allows a certain energy management strategy. In order to reduce computation time consumption, a simplified physical fuel cell model is proposed. An accurate model is studied in simulation to derive a simpler model. The simplified model is used with parameters identification made on an actual fuel cell. Results obtained on current and voltage, with an actual power demand, are sufficient to use the proposed model in iterative optimization algorithms.

Keywords—Circuit Model – Identification – Power management – Optimization

1. INTRODUCTION

Mainly due to pollution regulations, there is a growing interest in using non-conventional and environmental-friendly energy supply in transport applications. Over the last decade, among the different solutions, fuel cell systems have shown considerable promises. Using fuel cell in transport application in the heart of cities has 2 main interests: air pollution reduction (fuel cell only produces water, no CO₂) and allows catenaries suppression (all energy sources and converters are on board). The technology chosen in this study is Proton Exchange Membrane Fuel Cell (PEMFC) working at low pressure (about 2bars or less) and mid-temperature (about 80°C). Supercaps compose the Energy Storage System, added to help the fuel cell supplying the high power demand and to absorb energy providing by the load because the PEMFC is not reversible (Solero2001 and Corgier1997).

Numerous studies analyze the fuel cell behavior and model is requested to compute the behavior of such system (Jemeï2002, Friede2002). The electro-chemical model can be built but is heavy and computer-time consuming. A complete model must take into account fluid mechanic phenomenon linked to gas distribution in non linear pipes, electro-chemical reaction characteristics, and also thermal influence and so one. Based on the physics of the fuel cell this paper proposes in the first part, a simplification approach to obtain a simpler model of the controlled fuel cell system enough accurate to describe main phenomena for current-voltage behavior. In the second part the simplified model parameters are identified not only on the simulator but also on an actual fuel cell. Finally, the simplified model practically tuned is fed with actual power demand and results are compared to the actual fuel cell behavior to verify if the simplified model behavior is quite close to reality.

2. FUEL CELL MODEL

2.1 Based-Cell Model

Anode, cathode, membrane and electrode elements constitute the based-cell also called elementary-cell. With serial and parallel connections a more powerful fuel cell can be build to have different power needed in transport application (the tramway in Lachaize,2003 uses a virtual 400kW PEMFC with 586 based-cell – actual recent tests are made on fuel cells with 3 or 20 based-cell to reach 700W). The chemical to electrical behavior starts to be well known for PEMFC and complex model can be found in: Amphlett1995 and Alstom-CEA-LEEI2002). The FC voltage U_{fc} , depends on the current in the fuel cell I , the partial pressures of hydrogen P_{H_2} and oxygen P_{O_2} , the temperature of the cells T_{fc} , and the hydration of the membrane λ_{H_2O} .

$$U_{fc} = f(I, P_{O_2}, P_{H_2}, T_{fc}, \lambda_{H_2O}) \quad (1)$$

The output voltage expression is:

$$U_{fc} = E_{rev} + \eta_{act} - R_m \cdot j \quad (2)$$

Where, the reversible voltage E_{rev} is:

$$E_{rev} = \alpha_1 + \alpha_2 \cdot (T_{fc} - 298.15) + \alpha_3 \cdot T_{fc} \cdot \left(\frac{1}{2} \cdot \ln P_{O_2} + \ln P_{H_2} \right) \quad (3)$$

The cathode activation over voltage η_{act} is:

$$\eta_{act} = \beta_1 + \beta_2 \cdot T_{fc} + \beta_3 \cdot T_{fc} \cdot \ln(j \cdot 5.10^{-3}) + \beta_4 \cdot T_{fc} \cdot \ln c_{O_2} \quad (4)$$

Where c_{O_2} the concentration of dissolved oxygen, can be defined by henry's law (mol/m³) according to:

$$c_{O_2} = \frac{P_{O_2}}{5.08 \cdot 10^6 \cdot \exp\left(-\frac{498}{T_{fc}}\right)} \quad (5)$$

With parameters extracted from literature: $\alpha_1=1.229$

$$\alpha_2 = -8.5 \cdot 10^{-4} \quad \alpha_3 = 4.3085 \cdot 10^{-5} \quad \beta_1 = -0.9514$$

$$\beta_2 = 3.12 \cdot 10^{-3} \quad \beta_3 = -1.87 \cdot 10^{-4} \quad \beta_4 = 7.4 \cdot 10^{-5}$$

and $R_m = f(T_{fc}, \lambda_{H_2O})$ ohmic resistance (0.097m Ω .m²) and for the fuel cell made with N based-cell, $R_{fc} = R_m \cdot N \cdot S = 0.11 \Omega$; j = current density.

2.2 Fuel Cell System

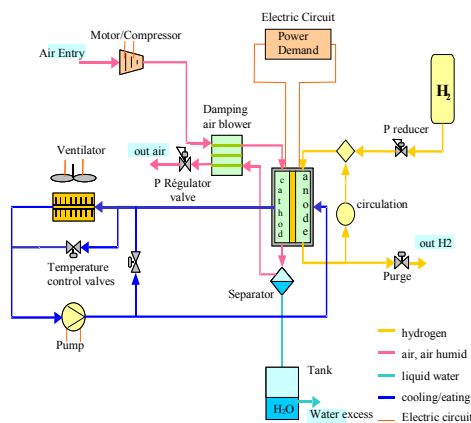


Fig 1. Complete Fuel Cell System

Fuel cell needs also some ancillaries to control the different gas loops and different important values as: pressure, flow and temperature. So adding compressor, pump, radiator and valves with their own control a fuel cell system given in Fig 1 is obtained and modeled for simulation in Matlab/Simulink. In the hydrogen loop there is no special control because an ideal source of hydrogen is considered represented by only an infinite tank and a passive reducer to fix the 2bar absolute pressure in this compartment whatever the flow is. In the cooling water loop a pump assures a constant flow and a cooling radiator and 2 valves assure the temperature regulation with a suitable decoupling and compensating control structure. The temperature is regulated around the optimal temperature defined (80°C). So the most difficult compartment to model is the cathode (oxygen) compartment where a compressor and a valve must provide the desired flow under the 1.5bar absolute pressure fixed. All controls have been studied and validated in simulation in Lachaize2004 and considered to be effectives. So, a simplified model can be extracted considering the controllers acting and keeping the fuel cell in their own settings.

2.3 Controlled fuel cell assumptions

The main phenomena represented in the model provide the fuel cell voltage behavior taking into account the most significant dynamics in the loops. The simplified model is based on the quasi static Amphlett model used to predict the voltage response of the cell as a function of the derived current, the temperature and partial pressures of the reactive gazes. Whereas the precedent eq (2) is on an elementary cell scale, expansion to a stack of multiple cells scale is made possible by multiplying the potential of a cell by the number of cells (N_{cell}):

$$U = N_{cell} \cdot (E + \eta_{act} + \eta_{ohmic}) \quad (6)$$

To obtain this expression some assumption are made:

- For control purpose and simplified modelling, a uniform current density is considered in the stack.
- A uniform temperature equal to the temperature of the outlet cooling water is considered. Moreover, with an effective control law being established, this temperature is maintained constant during the work of the fuel cell.
- Non significant anodic activation voltage during the transfer is assumed.
- The damping air-blower unit that recuperates water and ensures that the air has a high humidity level, has been designed and modelled ideally. The humidity is adequate, saturation in water vapour thus a relative humidity of 100 % is ensured in the cathode compartment, while the anode is supposed to be supplied with dry hydrogen.

- The partial pressures of gases are considered constants inside the stack and this, by neglecting the pressure drop in the gas distribution channels due to the gas / membrane and gas / gas interactions whereas the pressures used in the Amphlett equations are on the interface electrode / gas level.
- Same as temperature, the pressure at the entry of the anode and cathode compartments is supposed to be controlled and maintained constant.
- The pure delays related to the progress of gases in the distribution channels are considered to be negligible compared to the system time-constants.
- The inlet air flow is controlled and in particular a cathode stoichiometric ratio is maintained constant.
- The flooding phenomenon of the membrane due to water excess is not taken into consideration.
- The migration of oxygen and nitrogen molecules from the cathode towards the anode throughout the membrane is supposed to be negligible.

3. FUEL CELL SIMPLIFIED MODEL

3.1 Simulation based approach

To compute voltage behavior U , the current I and pressures P_{O_2} and P_{H_2} behaviors under current solicitation must be known.

1 - If temperature T_{fc} and hydrogen pressure P_{H_2} are constant (inside pressure is constant because input pressure is fixed and T_{fc} fixes the saturated pressure in the cell), a constant source U_0 representing the constant voltage of the fuel cell is computed by:

$$U_0 = \alpha_1 + \alpha_2 \cdot (T_{fc} - 298.15) + \alpha_3 \cdot T_{fc} \cdot \ln P_{H_2} + \beta_1 + \beta_2 \cdot T_{fc} \quad (7)$$

2 - The fuel cell voltage depends on the current delivered I_{fc} , so a varying voltage source U_1 can be detailed by writing:

$$U_1 = \beta_2 \cdot T_{fc} \cdot \ln \left(\frac{I_{fc}}{S} \cdot 5 \cdot 10^{-3} \right) \quad (8)$$

3 - The last voltage source corresponds to the voltage due to the fuel cell parameters and the oxygen pressure P_{O_2} and the temperature of the fuel cell T_{fc} , so, U_{o_2} is written as:

$$U_{o_2} = \alpha_3 \cdot T_{fc} \cdot \frac{\ln P_{O_2}}{2} + \beta_4 \cdot T_{fc} \cdot \ln \left(\frac{P_{O_2}}{5.08 \cdot 10^{-6} \exp(-498/T_{fc})} \right) \quad (9)$$

α_i and β_i coefficients are the same defined above. The current needed for ancillaries (compressor, pump...) is consumed before providing the usable current to its exit to feed the converter ($I_{elec} = I_{fc} - I_{aux}$). This consumption is represented by a varying resistance R_{aux} . Resistance of the Fuel Cell is represented by r . r , R_{aux} and P_{O_2} must be computed to have an accurate representation of the controlled fuel cell system behavior.

$$r = N \cdot (\rho \cdot e / S)$$

With $N=586$ the number of based-cell used, $e=50\mu\text{m}$ width of the membrane, $S=0,1956\text{m}^2$ the equivalent surface and ρ depends on air humidity injected and

temperature (if both are regulated $\rho = 72.4\text{m}\Omega\cdot\text{m}$)
 - $R_{aux} = U_{fc}^2 / P_{comp}$. P_{comp} is computed with the compressor characteristics depending on its velocity and the P_{O_2} pressure. The air pressure is fixed to 1.5bar so the compressor map can be read to obtain the equivalent P_{comp} to deliver the current I_{fc} . In real time U_{fc} is the previous computed voltage value. If no compressor is used R_{aux} disappears and U_{O_2} law can be a little different. The electrical model is shown on Fig2.

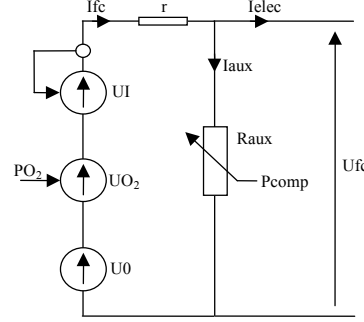


Fig 2. Simplified Fuel Cell Model

P_{O_2} also varies and depends on the fuel cell behavior, so identification is first made with the complete physical fuel cell model provided by our partner (CEA).

The oxygen partial pressure is computed by the number of mole presents inside the compartment, so the calculus is made in 3 steps:

* The flow in the controlled loop can be seen as a second order transfer function:

$$F_{o_2}(s) = \left(\frac{1}{(1 + \tau_{bf} s)^2} - 1 \right) X_{o_2\text{air}} \cdot F_{ref}(s) \quad (10)$$

with : s =Laplace operator, τ_{bf} the flow time constant fixed in the closed loop controller ($\tau_{bf}=0.02\text{s}$), $X_{o_2\text{air}}=21\%$ the oxygen ration in ambient air at the beginning and F_{ref} computed by faraday's law $F_{ref} = \frac{NI_{fc}}{4F}$ and I_{fc} is known using the power reference: $I_{fc} = P_{ref} / U_{fc}$

* So number of mole is known by integration:

$$n_{o_2}(s) = \frac{1}{p} F_{o_2}(s) \quad \text{with initial condition } IC,$$

adjusted after a first simulation using the complete model to track the fuel cell behavior. Initial Condition depends on the fuel cell characteristics, using prefect gaz law:

$$IC = P_{cath} V_{cath} / R \cdot T_{fc} \cdot X_{o_2\text{init}}$$

With: $X_{o_2\text{init}}=8.21\%$ oxygen ratio in the cathode; $P_{cath}=2\text{bar}$; $V_{cath}=0.11\text{m}^3$; $R=8.1\text{J/K/mol}$; $T_{fc}=298^\circ\text{K}$

* Inside pressure behavior can be described by transfer function (11) after parameters identification:

$$P_{O_2}(s) = (n_{O_2}(s) \cdot \frac{RT_{fc}}{P_{cath} V_{cath}}) (P_{cath} - K_{int} F_{comp}(s)) \quad (11)$$

With K_{int} a coefficient describing the fuel cell behavior which must be identified by measures made with our simulator to compute the ratio from entry and interne pressure on the compressor flow:

$$K_{int} = Ka \cdot F_{comp} + Kb \quad (12)$$

And after simulation: $Kb=996.2$ and $Ka=-0.28$

This simple model is compared to the complete model which takes into account all electro-mechano-chemical phenomena (fluid behavior, chemical reaction, gas propagation, direct and reverse flow see Bird1960). This simplified model generates little relative error but is 100 times faster (Lacheize2005) and details are also in section 4.

3.2 Experimental approach

Two types of tests were used, namely a set of static tests on a 20 cells stack with an active surface of 100cm² and a nominal power of 700W and dynamic tests on a 3 cells stack of the German manufacturer ZSW with a membrane GORE MESGA Primea Series 5510. During the dynamic test, the fuel cell is subjected to a specific current/time profile resulting from measurements of speed recovered on the course of a vehicle in urban environment and after having carried out a homothety on the power in order to make it compatible with the tested fuel cell stack. An example of the polarization curve of the 20-cells stack is given on Figure 3, in addition dynamic current profile tests of 3-cell stack are provided on Figure 4.

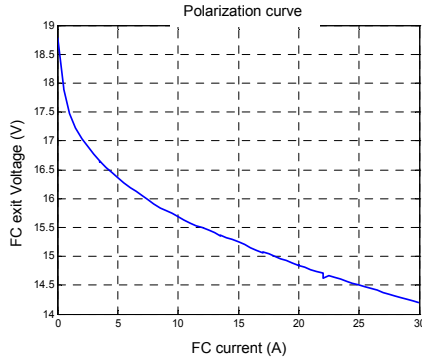


Fig 3. Polarization curve measured on the actual 20based-cell fuel cell at Belfort.

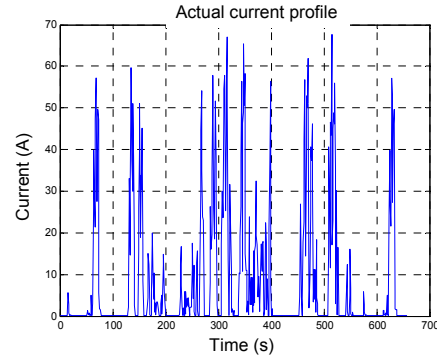


Fig 4. Actual current demand measured and used for current demand.

Due to experimental constraints adaptations, some expression have been made to be representative of the experimental setup and to adapt the formulation with the available sensors. Constant voltage source in the system corresponds to the oxydo-reduction principle and did not change, the ohmic relation not at all and can be measured. But the relation providing η_{act} must be identified replacing β_i by experimentally identified coefficient ξ_i .

$$\eta_{act} = \xi_1 + \xi_2 \cdot T_{fc} + \xi_3 \cdot T_{fc} \cdot \ln(C_{O_2}) + \xi_4 \cdot T_{fc} \cdot \ln(I_{fc}) \quad (13)$$

No problem to compute I_{fc} : With the fuel cell stack feeding its own ancillaries, in particular the compressor, the current output I_{fc} will be the sum of the current consumed by these auxiliaries I_{aux} and the load current (the static converter for example) I_{cvs} . The reference air flow is calculated according to Faraday's law as a function of reference current I_{ref} and stoichiometric ratio St_{O_2} .

No problem to compute P_{H_2} : For the anode compartment and using the simplification hypothesis stated before, P_{H_2} can be expressed as:

$$P_{H_2}(t) = P_{anode}(t) - P_{H_2O_{sat}}(T_{fc}) \quad (14)$$

$$P_{H_2O_{sat}}(T_{fc}) = \exp\left(23.1961 - \frac{3816.44}{T_{fc} - 46.13}\right) \quad (15)$$

With $P_{H_2O_{sat}}(T_{fc})$ is the saturation pressure of water vapour (in Pascal), P_{anode} the pressure of the anodic compartment considered to be constant (in Pascal).

As for the calculation of the inlet hydrogen flow in the compartment, $F_{H_2}(t)$, we have :

$$F_{H_2}(t) = (F_{H_2})_{cons} + (F_{H_2})_{purge}(t) \quad (16)$$

$$(F_{H_2})_{cons} = \frac{N_{cell} \cdot I_{fc}}{2 \cdot F} \quad (17)$$

Where $(F_{H_2})_{cons}$ is the hydrogen flow consumed by the chemical reaction of oxydo reduction (mol/s) and $(F_{H_2})_{purge}(t)$ the flow of the purge valve (mol/s).

The valve is controlled in order to ensure on one hand the elimination of liquid water and nitrogen

which can stratify in the bottom of the compartment, and on the other hand to verify a constant hydrogen stoichiometric ratio.

Special P_{O_2} computation: Let $F_{O_2,ref}$ be the oxygen reference flow, as air is a constant mixture of oxygen and nitrogen ($X_{O_2}=21\%$) reference flow is:

$$F_{ref} = \frac{N_{cell} \cdot I_{ref} \cdot S_{t_{O_2}}}{X_{O_2} \cdot 4 \cdot F} \quad (18)$$

The term n_{cath} corresponds to the total number of moles in the cathodic compartment at pressure P_{cath} :

$$\eta_{cath} = \frac{P_{cath} V_{cath}}{R \cdot T_{fc}} \quad \text{and the number of } O_2 \text{ moles is}$$

$$\text{under varying } I_{ref}: n_{O_2}(s) = \frac{F_{ref}(s)}{s} + IC$$

where 's' is the Laplace operator and IC the initial condition in the compartment and $F_{O_2}=F_{O_2ref}$ with an accurate control tracking (depending on compressor dynamic if present).

On experimental device, P_{O_2} can be computed as: $P_{O_2} = \frac{n_{O_2}(s)}{n_{cath}} P_{cath}$. By taking into consideration the

evolution of pressure inside the compartment, therefore of pressure drops related to diffusion between gases and to load losses inside the channels, a pressure correction is envisaged by replacing P_{cath} with term $P_{int,erne}$. This value is then simplified by the following formulation:

$$P_{int} = P_{cath} - K_{int} \cdot F_{comp} \quad (19)$$

As the test is held while the outlet pressure ($P_{s,Air}$) is the atmospheric pressure thus known, the pressure is expressed inside the fuel cell system ($P_{cathode}$)

according to $P_{s,Air}$ and the outlet air flow (F). The Darcy - Weisbach equation is regarded as a good experimental formula to determine the relation between fluid pressure losses and flow inside a pipe.

In this study $\Delta P = K_{int} \cdot F^2$ is considered, as the different coefficients in the Darcy's equation are constant values for a given system ignoring furthermore the influence of the Reynolds' number variation or other element not easy to measure. Therefore more practically:

$$P_{cath} - P_{sair} = K_{int} \cdot F^2 \quad (20)$$

$$F = F_{e,Air} - F_{O_2,cons}$$

where : F is the outlet air flow (in moles/s), F_e is the inlet flow and F_{cons} is the consumed oxygen flow. Consequently, the value of K_{int} has to be experimentally identified.

Using simple mean square algorithm fed with different actual measurements, the ζ_i coefficients are identified and given in table I.

ζ_1	ζ_2	ζ_3	ζ_4	K_{int}
-1.2668	9.7 e-3	4.4558 e-4	-8.763 e-5	3.1 e-3

Table I : Parameters identified

4. EXPERIMENTAL VALIDATION AND COMPARISON

To test the behavior of the proposed model, actual measurements have been used to prove the accuracy of the computed behavior on actual working points. The full 400kW power is used in simulation and an artificial repetition of 54s of a most varying tramway profile is used. An urban cycle is used for actual tests and simple homothetic coefficient provides reachable values.

4.1 Results in simulation

The complete accurate simulator is used in parallel with the proposed three-voltage-sources model and the two voltage behaviors are given on Fig 5.

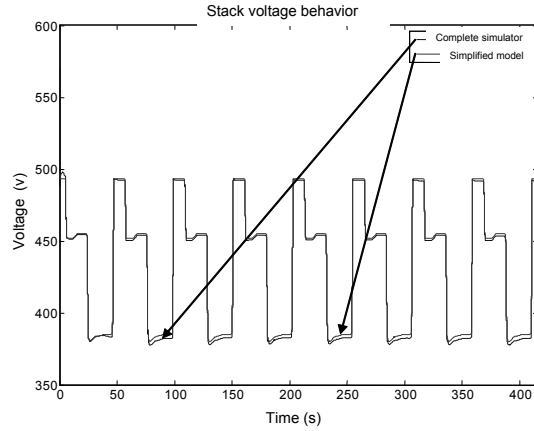


Fig 5. Simplified model tuned with simulation parameters knowledge compared to complete simulated model.

With an accurate knowledge of the fuel cell parameters the main phenomena extracted and the parameters computed for the simplified model did not affect the current and voltage behavior. Non significant error is obtained and the simplified model is about 100 times faster.

4.2 Experimental Results

Using an actual 700W fuel cell, and the simplified model parameters identified Table I, the fig 6 shows the results of the 2 voltage behavior. The simplified model is close to reality.

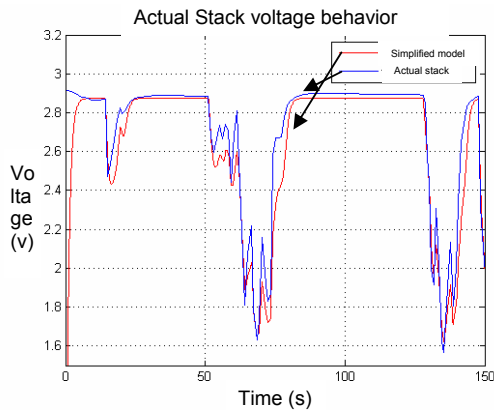


Fig 6. Simplified model exit voltage tuned after parameters identification compared to actual fuel cell voltage behavior measured.

There is some difference but not so important. Some amelioration in parameters identification can be quickly made. For example the profile used has working points not taken into account in the simplified model attract parameters to different values. That concerns point at very low current or when part of the actual cell is down.

5. CONCLUSIONS

A simplified fuel cell model is established to have an accurate voltage behavior without prohibitive simulation time. The model is based on physical main phenomena in the different controlled loops which compose the Fuel Cell System. In the three voltage sources model-circuit proposed, there are little calculus to make and few parameters to identify.

The simplified model obtained is under some classical assumptions, but all the actual current demand used did not always respect these assumptions. To have a better direct identification points out our model range must be canceled. During biggest varying phases, simplified model dynamic is faster than the real one, a filter or the influence of double layer capacitance can be easily added and not considered in the proposed simplified model.

ACKNOWLEDGEMENT

The complete model used in simulation is close to a real fuel cell and has been built in collaboration with CEA (partner of a precedent project named COPPACE involving Alstom-CEA and ADEME). Practical tests and actual fuel cell identification have been possible using the national fuel cell test bench available at Belfort

REFERENCES

- Alstom-CEA-LEEI: "Interest of using Fuel Cells in bus, tramways, shunting loco.", FDFC 2002 – october 7-10 2002 – Forbach - France.
- J. C. Amphlett, R. M. Baumert and al. : "Performance Modeling of the Ballard Mark IV Solid Polymer Electrolyte Fuel Cell", Jour. Electrochemical Society, Vol. 142, No. 1, pp1-8, 1995.
- Bird, Stewart, Lightfoot: book, "Transport Phenomena" p481, Wiley international edition 1960, ISBN: 0-471-07395-4
- D. Corgier: "Hydrogen air fuel cell vehicle technology FEVER demonstration project", proceedings of EVS 14 – Orlando, Florida – 1997.
- W. Friede, S Raël, B Davat: "PEM fuel cell models for supply of an electric load", proceedings of Electrimacs 2002, August 18-19, Canada.
- S. Jemeï, D. Hissel and al: "Black-box modeling of Proton Exchange Membrane Fuel Cell Generators.", proceedings of 28th Int Conf on Ind. Electronics, IECON 2002, 10-5/8 Sevilla-Spain.
- J. Lachaize, M. Fadel, S. Caux and al: "Energy Management of Fuel Cell System and Supercaps Elements", proceedings of IFAC 2005, power plant and power system, 4-8 july- Prague – Techeque Republic .
- J. Lachaize, S. Caux, M. Fadel, P. Shott, L. Nicod : "Pressure, Flow and Thermal control of a Fuel Cell system for Electrical Rail Transport.", proceedings of International Symposium Industrial Electronics ISIE 2004- Ajaccio - France- 05-4/7 2004
- L. Solero, A. Di Napoli, and al. : "Fuel cell HEV's assisted by ultracapacitor and battery storage system", FISITA-Helsinki, Finland – June 2-7 2001.