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# Simplified electrical model tuned for actual controlled PEMFC

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**Abstract**—Using fuel cells in combination with other sources as energy elements in transport application is now a reality. Having, at least, two power sources on board, requires an efficient energy management strategy. Most of these energy management strategies are model-based. In order to reduce computation time consumption for such a global simulator, simplified models must be established. Such a simplified physical fuel cell model is thus proposed in this work. A complete model is studied in simulation to derive a simpler model tuned not only with the simulator parameters but also with parameters identification made on an actual fuel cell. Results obtained on current and voltage behaviors, following an actual requested power demand, are accurate enough to use the proposed model in iterative optimization algorithms.

## I. INTRODUCTION

For few years, hybrid and electrical vehicles have attracted lot of researchers. Due to environmental constraints (pollution, noise...) and to the need to find other solutions to replace thermal engines, embedded Fuel Cell (FC) system seems to be an interesting solution. For mid and high power embedded applications (car, bus, tramway, train...) the Proton Exchange Membrane (PEM) technology is foreseen. This is mainly due to the solid state of their electrolyte membrane, their mid operating temperature (which enables fast start-up of the system) and also their easy-to-control behavior. Considering the whole fuel cell system, many ancillaries are needed (pumps, compressor, valves...) to control not only gases supplies (Hydrogen and Oxygen – or Air) but also temperature and humidity. Moreover, it is well-known that the fuel cell design imposes the choice of current density and the mechanical design (pipes and gas distribution, number of cells requested...).

Numerous studies analyze the fuel cell behavior and are based on the development of efficient models to compute its behavior [1-2]. An electro-chemical model can be built but is heavy and computer-time consuming and can not be used in optimization algorithms [3-4]. A complete model must take into account fluid mechanic phenomena linked to gas distribution in non linear pipes, electro-chemical reaction characteristics, and thermal influence and so on. 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 accurate enough to describe main phenomena for current-voltage behavior. In the second part, the simplified model parameters are identified not only in simulation 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 the validity of this model

## II. FUEL CELL MODEL

### A. Base-Cell Model

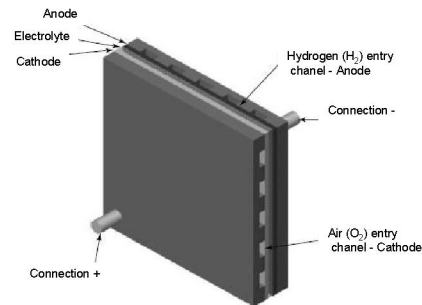


Figure 1: Elementary cell scheme [1]

Anode, cathode, membrane (electrolyte) and electrode elements constitute the base-cell also called elementary-cell. With serial and parallel connections a more powerful fuel cell can be built to have sufficient power needed in transport application (the tramway in precedent works uses a virtual 400kW PEMFC with 586 base-cells – actual recent tests are made on a fuel cell with 20 base-cells to reach 700W). The chemical to electrical behavior starts to be well known for PEMFC and complex model can be found in [1,5]. In a first approach, 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  $\lambda_{H_2O}$ .

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

The output voltage expression is:

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

Where, the reversible voltage  $E_{rev}$  is:

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

$R_m$  is the ohmic resistance,  $j$  the current density.

And the cathode activation over voltage  $\eta_{act}$  is:

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

Where  $c_{O_2}$  is the concentration of dissolved oxygen can be defined by Henry's law (mol/m<sup>3</sup>) 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:  $\alpha_1=1.229$

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

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

To note that the voltage equation neglects the diffusion or concentration over potential which influence is limited to high current density.

### B. 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 controls; a fuel cell system given in Figure 2 is obtained and modeled for simulation in Matlab/Simulink environment.

Moreover, as the PEMFC is here designed for a tram application, the power demand profile has been chosen to represent actual tram course avoiding specific profiles where there is a need of special energy management. The power demand is composed of acceleration and breaking phases linked to the profile slope. So the power profile to be delivered imposes the fuel cell power. The fuel cell design is based on typical PEM polarization curve; in a compromise between current density and efficiency, we chose to work with:

- Low Pressures:  $P_{mO_2} = 1.5 \cdot 10^5 Pa$  ;  $P_{mH_2} = 2.0 \cdot 10^5 Pa$
- Mid-Temperature:  $T_{fc} = 353.15^\circ K$  (80°C)
- Constant oxygen stoichiometry:  $St_{O_2} = 1.6$
- Electrical part:  $Power_{nom} = 400kW$  ,  $Unom_{min} = 375V$

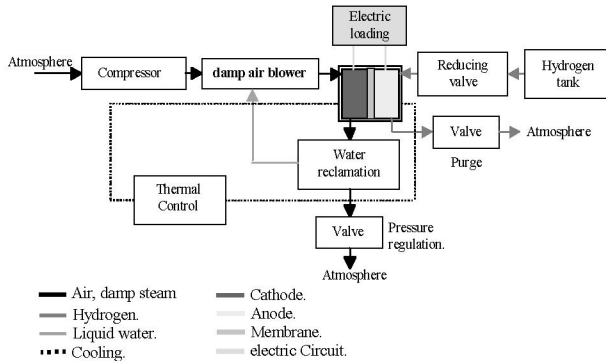


Figure 2: Complete Fuel Cell System

In the Oxygen loop, different elements can be found: from atmosphere – a compressor element fixes air flow – then an air humidifier (blower) fixes 100% air humidity – then the fuel cell cathode compartment consumes some air

– then an exit backpressure valve fixes 1.5bar absolute operating pressure and reject air – to atmosphere.

For Hydrogen loop elements: Hydrogen tank starts the loop and is considered as an infinite hydrogen source – a passive mechanical pressure reducer is introduced to fix 2bar absolute pressure in this loop – the anodic compartment receives the hydrogen - a valve is added for periodic purge – to atmosphere.

The third loop is a thermal loop that constitutes a separated water cooling control circuit. It is constituted with a controlled pump and valves to maintain the FC temperature around 80°C.

Assumptions to focus our attention in the air loop circuit:

- Thermal control loop is not described here but can be found in [6]. This control is of paramount importance and considered effective here and has no influence in the air loop.
- Air blower element is a humidifier and is designed to insure 100% humidity.

In the hydrogen loop, there is no special control because an ideal source of hydrogen is considered. 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 fixed pressure. All controls have been studied and validated in simulation in [7] and considered to be effective. So, a simplified model can be extracted considering the controllers effectively keeping the fuel cell in its desired settings.

### C. Controlled fuel cell assumptions

The main phenomena represented in the model describe the fuel cell voltage behaviour taking into account the most significant dynamics in the loops. The simplified model is based on the quasi static Amphlett model [8] 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 equation (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 assumptions are made:

- For control purpose and simplified modelling, a uniform current density is considered in the stack.
- No behavioural deviation between the different single cells is considered.
- 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 humidifying 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; there is 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 time 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.

### III. FUEL CELL SIMPLIFIED MODEL

#### A. Simulation based approach

To compute voltage behavior  $U_{fc}$ , the current  $I_{fc}$  and partial pressures inside the cathodic and anodic compartment,  $P_{O_2}$  and  $P_{H_2}$ , behaviors under current solicitation must be known. Our simplified model is composed of three virtual voltage sources:

Source 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:

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

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

$$U_1 = \beta_2 \cdot T_{fc} \cdot \ln \left( \frac{I_{fc}}{S} \cdot 5.10^{-3} \right) \quad (8)$$

Where  $I_{fc}/S$  replace current density  $j$  used in (2).

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

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

$\alpha_i$  and  $\beta_i$  coefficients are the same defined above.

Part of the current produced by the fuel cell is consumed by its ancillaries (compressor, pumps...), so the load current is equal to:

$$I_{elec} = I_{fc} - I_{aux} \quad (10)$$

This consumption is represented by a varying resistance  $R_{aux}$ . The fuel cell resistance is  $r$ .

$r$ ,  $R_{aux}$  and  $P_{O_2}$  must be computed to have an accurate representation of the controlled fuel cell system behavior.

$$r = N_{cell} \times \left( \frac{\rho \cdot e}{S} \right) \quad (11)$$

With the physical parameters set in our simulator to :  $N_{cell}=586$  the number of base-cell used ,  $e=50\mu m$  the width of the membrane,  $S=0,1956m^2$  the equivalent surface and  $\rho$  the resistivity which depends on air humidity injected and temperature (if both are regulated  $\rho = 72.4m\Omega \cdot m$ ).

-  $R_{aux}=U_{fc}^2/P_{comp}$ .  $P_{comp}$  is computed with the compressor characteristics depending on its velocity and the  $P_{O_2}$  partial 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.

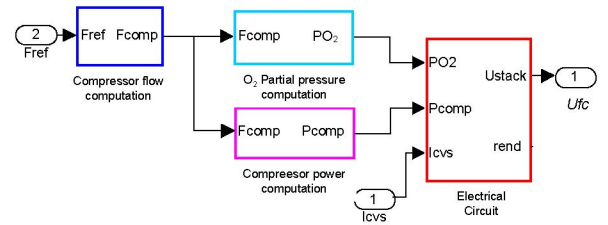


Figure 3: Simplified Fuel Cell Simulink blocs

The electrical model is shown on Fig4.

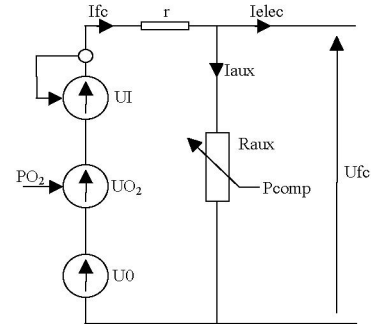


Fig 4: Simplified Fuel Cell Model

The oxygen partial pressure  $P_{O_2}$  is computed as follows:

In a first step, oxygen flow in the controlled cathodic loop can be seen as a second order transfer function:

$$F_{O_2}(s) = \left( \frac{1}{(1 + \tau_{bf} s)^2} - 1 \right) X_{O_2air} \cdot F_{ref}(s) \quad (12)$$

with  $s$  the Laplace operator,  $\tau_{bf}$  the flow time constant fixed in the closed loop controller ( $\tau_{bf}=0.02s$ ),  $X_{O_2air}=21\%$  the oxygen ratio in ambient air at the beginning and  $F_{ref}$  computed by Faraday's law as:

$$F_{ref} = \frac{N I_{fc}}{4F} \quad (13)$$

where  $I_{fc}$  is known using the power reference:

$$I_{fc} = \frac{P_{ref}}{U_{fc}} \quad (14)$$

The next step is to calculate the number of oxygen moles present in the cathodic compartment and this by means of flow integration:

$$n_{O_2}(s) = \frac{1}{p} F_{O_2}(s) + IC \quad (15)$$

Where the Initial Condition IC depends on the fuel cell characteristics, using perfect gas law:

$$IC = \frac{P_{cath} V_{cath}}{RT_{fc}} \times X_{O_2,init} \quad (16)$$

With:  $X_{O_2,init}$  (=8.21%) is the initial oxygen ratio in the cathode identified using the complete model and  $P_{cath}=2\text{bar}$ ;  $V_{cath}=0.11\text{m}^3$ ;  $R=8.1\text{J/K/mol}$ ;  $T_{fc}=298^\circ\text{K}$

Finally, the oxygen partial pressure is described by transfer function (17) after parameters identification:

$$P_{O_2}(s) = (n_{O_2}(s) \cdot \frac{RT_{fc}}{P_{cath} V_{cath}}) (P_{cath} - K_{int} F_{comp}(s)) \quad (17)$$

Where  $K_{int}$  is a corrective coefficient describing the relation between the compressor flow and the pressure drop inside the fuel cell.  $K_{int}$  was identified using the complete model:

$$K_{int} = K_a F_{comp} + K_b \quad (18)$$

And after simulation:  $K_a = 996.2$  and  $K_b = -0.28$ .

This simple model is compared in section IV to the complete model which takes into account all electro-mechanical-chemical phenomena (fluid behavior, chemical reaction, and gas propagation, direct and reverse flow [9-10]).

### B. Experimental approach

Two types of tests were used, namely a set of static tests on a 20-cell stack with an active surface of  $100\text{cm}^2$  and a nominal power of  $700\text{W}$  and dynamic tests on a 3-cell stack of the German manufacturer ZSW with a membrane GORE MESA Primea Series 5510. During the dynamic test, the fuel cell is subject 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. Dynamic current profile tests of 3-cell stack are provided on Figure 5.

Due to experimental constraints, some modifications on expressions have been made to be representative of the experimental setup and to adapt the formulation with the available sensors. The reversible voltage equation (3) is relative to the oxydo-reduction reaction and thus considered invariable. As for the ohmic resistance and the activation over voltage expression, it is considered to be specific to each kind of cell.

Thus the relation providing  $\eta_{act}$  must be identified replacing  $\beta_i$  by experimentally identified coefficient  $\xi_i$ :

$$\eta_{act} = \xi_1 + \xi_2 T_{fc} + \xi_3 T_{fc} \cdot \ln(C_{O_2}) + \xi_4 T_{fc} \cdot \ln(I_{fc}) \quad (19)$$

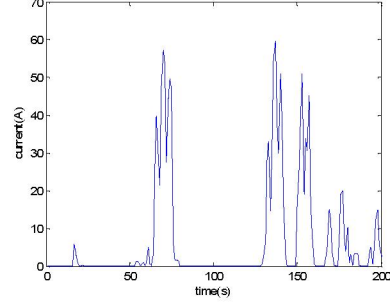


Fig 5: Actual current demand

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  $I_{aux}$  (known using lookup table corresponding to the compressor behaviour mapped) and the load current  $I_{cvs}$ . The reference air flow is calculated according to Faraday's law as a function of reference current  $I_{ref}$  and stoichiometric ratio  $St_{O_2}$ .

For the anode compartment and using the simplification hypothesis stated before,  $P_{H_2}$  can be expressed as:

$$P_{H_2}(t) = P_{anode}(t) - P_{H_2O,sat}(T_{fc}) \quad (20)$$

$$P_{H_2O,sat}(T_{fc}) = \exp\left(23.1961 - \frac{3816.44}{T_{fc} - 46.13}\right) \quad (21)$$

With  $P_{H_2O,sat}(T_{fc})$  is the saturation pressure of water vapor (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:

$$F_{H_2}(t) = F_{H_2,cons}(t) + F_{H_2,purge}(t) \quad (22)$$

$$F_{H_2,cons}(t) = \frac{N_{cell} \cdot I_{fc}}{2 \cdot F} \quad (23)$$

Where  $F_{H_2,cons}(t)$  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.

As for the  $P_{O_2}$  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:

$$F_{O_2,ref} = \frac{N_{cell} \cdot I_{ref} \cdot St_{O_2}}{X_{O_2} \cdot 4 \cdot F} \quad (24)$$

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

$$\eta_{cath} = \frac{P_{cath} V_{cath}}{RT_{fc}} \quad (25)$$

and the number of O<sub>2</sub> moles is under varying  $I_{ref}$ :

$$n_{O_2}(s) = \frac{F_{O_2}(s)}{s} + IC \quad (26)$$

where 's' is the Laplace operator and IC the initial condition in the compartment and  $F_{O_2} = F_{O_2ref} - F_{O_2cons}$  with an accurate control tracking  $F_{O_2}$  is little (depending on compressor dynamic if present).

On experimental device,  $P_{O_2}$  can be computed as:

$$P_{O_2} = \frac{n_{O_2}(s)}{n_{cath}} P_{cath} \quad (27)$$

As the test is held while the outlet pressure ( $P_{sAir}$ ) is the atmospheric pressure, thus known, the pressure is expressed inside the fuel cell system ( $P_{cath}$ ) according to  $P_{sAir}$  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:

$$P_{cath} - P_{sair} = K_{int} \cdot F^2 \quad (28)$$

$$F = F_{eAir} - F_{O_2cons} \quad (29)$$

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 a simple mean square algorithm fed with different actual measurements,  $K_{int}$  along with the  $\xi_i$  coefficients and the internal resistance  $R_{int}$ , are experimentally identified and given in table I.  $R_{int}$  is estimated to 0.0031Ω.

Table I : Parameters identified

$\xi_1$	$\xi_2$	$\xi_3$	$\xi_4$	$K_{int}(Pas^2/mol^2)$
-1.2668	9.7 e-3	4.4558 e-4	-8.763 e-5	9.26 e <sup>6</sup>

#### IV. EXPERIMENTAL VALIDATION AND COMPARISON

##### A. First comparison in simulation

To test the behavior of the proposed model, actual power measurements have been used to prove the accuracy of the computed behavior on actual working points. An artificial repetition of a 54s urban cycle tramway profile of 400kW maximal power is used in simulation (Fig 6). The complete accurate simulator is used in parallel with the proposed three-voltage-sources model and the two voltage behaviors are given on Fig 7.

The comparison between the complete CEA model and the simplified one shows a similar behavior with an average relative error between the two voltages

estimation of about 0.41% and this while the latter is 100 times faster.

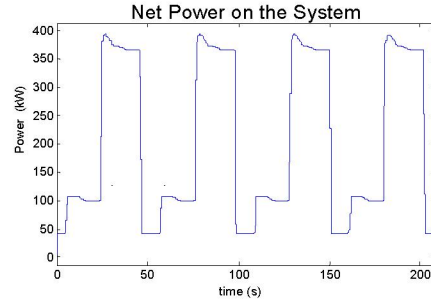


Figure 6: desired fuel cell power profile

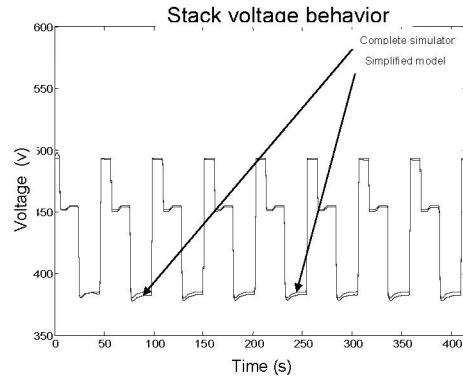


Fig 7: Voltage computed with the complete simulator and with the simplified model tuned with simulators parameters

##### B. Comparison on actual fuel cell

Using an actual 700W fuel cell and the simplified model parameters identified (Table I), the fig 8 shows the results of the 2 voltage behaviors. The simplified model is close to reality.

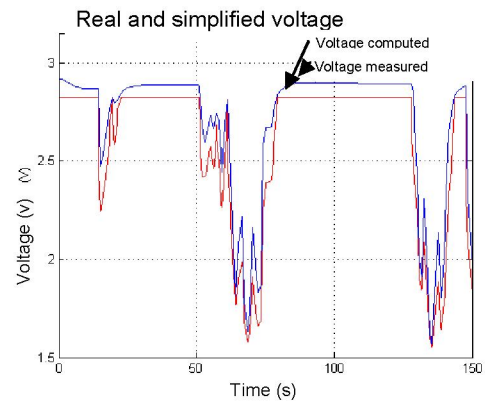


Figure 8: Simplified model exit voltage tuned after parameters identification compared to actual fuel cell voltage behavior

There is some difference yet but results remain very acceptable. Main differences are on the static voltage level and on low to high voltage variation. The simulated voltage is always lower (offset to be compensated) and has a higher dynamic as the actual fuel cell (to be limited).

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

The proposed model is so simple that some errors mainly in  $P_{O_2}$  computation are compensated only by adding 10% to the proposed computation (this delivers a sufficient offset voltage). The voltage dynamics has been smoothed by use of a first order filter with a relatively big time constant (1s) modeling the double layer capacitance phenomenon among other system delays. With adding only these two modifications, better results are obtained in Figure 9.

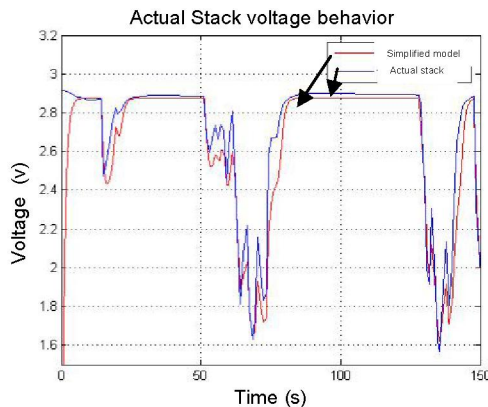


Figure 9: Simplified model voltage tuned after parameters identification and correction compared to actual fuel cell voltage behavior measured

## V. CONCLUSIONS

A fuel cell system is so complex that all phenomena present can not be exactly described without heavy computer time processing. There is different level dynamics and some reactions can be neglected for a global behavior point of view. Under some assumptions based on the fuel cell principle, construction and controls, a simplified fuel cell model is established. This model provides 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. Three voltage sources and two resistances are proposed to compose a model-circuit. This model-circuit needs only little computational time and few parameters to identify.

The simplified model obtained is under some classical assumptions, but the actual current demands used did not always respect these assumptions. To have a better direct identification, points outside our model range must be canceled. The influence of the charge double layer capacitance was considered in a global manner and a more precise study is to be done.

The simplified electrical model represents an accurate controlled fuel cell electrical behaviour because comparison on actual fuel cell using actual current demand in transport application has shown promises. The

proposed model can also compute a global fuel cell efficiency not presented here to be used in optimization algorithms [4,11]. In the continuation of this work, a global model combining the fuel cell system coupled to a storage element by means of an inverter is to be finalized to study global efficiency. This model, being accurate enough while little computer time consuming, could be used in iterative algorithms to test different energy management strategies in order to minimize the vehicle size or gas consumption.

## VI. AKNOWLEDGMENT

This work has been made in the Coppace project, a PACo label from the French Research Ministry-CNRS. Collaboration with the fuel cell laboratory of the French Atomic Energy Center (CEA) allowed using an accurate fuel cell simulator. Alstom transport provided its industrial constraints and actual measurements. Part of this project has been also financed by the Agency for the Environment and Energy Management (ADEME).

Practical tests and actual fuel cell identification have been made possible using the French national fuel cell test platform available in Belfort.

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