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Dynamic modeling of an open cathode PEM fuel cell for automotive energy management applications

Nada Rifai[1,2], Jalal Sabor[1], Chakib Alaoui[2], Raffaele Petrone[3], Hamid Gualous[3]
[1]LSMI Laboratory, ENSAM, Moulay Ismail University, Meknes, Morocco
[2]Insa Euro-Méditerranée, Euromed University, Fes, Morocco
[3]LUSAC Laboratory, University of Caen Normandie, Cherbourg-en-Cotentin, Caen, France

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ABSTRACT

Among the different clean energy conversion devices, fuel cells systems are largely employed due to their high-power densities and efficiencies. Several models are available in literature to characterize their functioning, both for stationary and dynamic behaviors. Vehicular application of a fuel cell requires a model that is accurate enough, and simple enough for quick computations for real-time reporting. To meet these constraints, the model of the different sources must be simple and efficient as they are used in the energy management strategy block to estimate the power references to be requested from the sources. The objective of this paper is then to develop a fuel cell model that is both efficient at representing the dynamic and static behavior of the fuel cell, and low consuming in terms of storage space and computation time. The aim is to have a suitable model for use in online simulations for vehicle energy management applications. The proposed model is compared to a representative dynamic model, and the results approve the performance of the model. An experimental test bench is performed to evaluate and validate the proposed model. The model shows good agreement with the experimental data.

Corresponding Author:

Nada Rifai
LSMI Laboratory, ENSAM, Moulay Ismail University
Marjane 2, BP: 298، Meknes 50050, Morocco
Email: n.rifai@ueuromed.org

1. INTRODUCTION

Among the different fuel cells technologies, proton exchange membrane fuel cells (PEMFC) has attracted a lot of interest due to their balance of plant (BoP) simplicity, their efficiency, and low operating temperature range [1]. Several studies have focused on modelling the static behavior of the PEMFC, considering its electrochemical characteristics [2]-[5]. For example, in his study on modeling, control and implementation of the maximum power point tracking (MPPT) control system of the fuel cell with a DC converter, Maaspaliza *et al*. [2] based his study only on a static model of the fuel cell defined by the electrochemical equations. This one, indeed, allows to represent the overall behavior of the fuel cell but does not really describe the variations which occur in a dynamic regime. However, for non-stationary applications, such as for transportation, the dynamic behavior of the cell remains an open issue. Several models have been developed in the literature to describe the fuel cell dynamics. Shekhar Das set up a dynamic model [3] of the fuel cell FC that includes the double-layer charging effect, which is due to the two charged layers of opposite polarity formed between the membrane and the cathode. These layers behave like supercapacitors and are known as electrochemical double layer. The characteristics of the PEMFC were then modeled in MATLAB/Simulink® incorporating temperature, partial gas pressure, and the effects of the double layer capacitor. Rabbani and Rokni [4] proposed a dynamic model suitable to investigate the behavior and transient

response of fuel cell for automotive domain. According to the authors, the PEMFC dynamic is influenced by reactant flows, heat management and water content in the streams and in the fuel cell itself. Thus, the Rabbani's model is composed of electrochemical, thermal, feed flow and water transportation models. However, incorporating all the phenomena and auxiliaries of the fuel cell system results in several mathematical models and multiple equations to be implemented, which considerably increases the complexity and computational burden of the model, not to mention the significant number of assumptions introduced in the modelling.

The model presented by Ferrero [5] is based on the Randles circuit. He has linearized the Tafel equation which describes the activation drops around an equilibrium current point to omit the nonlinear behavior of the activation source. The originality of his approach was to use the simple configuration of the Randles circuit, which assumes a dielectric relaxation of the material, which can be expected for a material over the entire frequencies range due to the conventional processes of electrical polarization and conduction. However, dielectric material relaxation is interesting to consider in the case of very high frequency applications (above Ghz). For applications in the µHz-MHz range (such as transportation), there is no need to consider it, since it makes the model more complex.

Lechartier proposed in a PEMFC model [6] suitable for prognostics. It is composed of a static part and dynamic part that are independent. The static part is based on the Butlere Volmer law. The dynamic part is an electrical representation of the physical phenomenon based on the Warburg impedance, the same dynamic electrical model was used by Ganier [7]. The problem of these models is that the Warburg impedance cannot easly be implemented on MATLAB/Simulink [8]. In addition, identification of parameters is based on electrochemical impedance spectroscopy, which is not always available. Papadopoulos *et al*. [9] proposes an improvement of the model proposed in [10]. The transfer function proposed in [10] is adapted to describe the slow dynamics of the PEMFC, however Papadopoulos presented an enhanced model by adding a second order transfer function to describe the transient dynamics of fuel cell. The model was evaluated using experimental results.

The selection of an appropriate model for the online parameter identification process, in different applications, especially, automotive ones is crucial because the number of parameters and sensors required, as measurement inputs to the model, has a meaningful impact on the computation time the accuracy of the model, The different models and studies presented in this review and in the literature in general, involve different complex physical phenomena such as transport of water, electrochemical reactions, heat exchange of the PEMFC, ice creation in the cathodic catalytic layer. The parameters number in the fuel cell model is critical for real-time and online operations, as many parameters would significantly delay the process and a small number of parameters would result in a lack of accuracy for control [11].

The aim of this article is to propose a simplified dynamic model of PEM fuel cell. The model must be easy to be implemented and identified and suitable for vehicular energy management applications. The proposed model is formulated in two parts: a static part based on electrochemical equations of the fuel cell, and a dynamic part represented by transfer functions.

The remaining of this paper will detail the different steps of this study, it is structured as follows. Section 2 describes the model developed in this work. Followed by the process carried out for parameters identification in section 3. The test bench built for experimentation, the characterization thereafter. And the model evaluation and validation are given in section 4. A presentation of the results and discussions are detailed in section 5. The paper ends with a general conclusion in section 6.

2. PROPOSED MODEL

In this section, a new model of fuel cell is proposed. The model is designed specifically for vehicular energy management applications. The objective is to have a model that reproduces the overall behavior of the fuel cell under stationary as well as dynamic conditions. The steady state behavior is considered according to the electrochemical equations of the fuel cell. Temperature is one of the most critical parameters influencing the performance of proton exchange membrane fuel cells [12], so it is not appropriate to consider it constant. However, for applications such as energy management, it is not necessary to consider the heavy and complex thermodynamic equations, a simple model is sufficient to introduce the variations of temperature into the fuel cell model [9]. Based on the experimental characterization the temperature increases when the current increases and drops when the current decreases. It is assumed that the temperature changes linearly with the current. The dynamics of the PEMFC can be classified into rapid and slow dynamics.

The fast and rapid dynamics occurs as a result of the mass balance equations. On the other hand, the slow dynamics is caused by the energy balance equations. The solution of these equations requires a thorough knowledge of all the construction parameters of the fuel cell, which are not easy to obtain. The dynamic modeling of the fuel cell is often complex and cumbersome due to the complexity of these equations. This paper proposes a method to correctly describe the fast and slow dynamics of the fuel cell while avoiding the complexity of these equations. For this purpose, a voltage corrector is integrated into the fuel cell model, based on transfer functions. This approach will allow to characterize the slow and fast dynamics of the PEMFC, and

to cover the overshoots and undershoots that occur in transient mode. One of the main advantages of this model is its simplicity which makes it suitable for numerical simulations and implementation on an embedded controller with limited storage space. Moreover, the model is easy to identify, the identification of the parameters can be carried out using few data, only from a polarization curve and a dynamic profile.

2.1. Electrochemical static model

Starting from the standard thermodynamic potential (which theorically should be 1.23 V under the normal conditions of temperature and pressure based on the datasheet of the fuel cell manufacturer), this value is reduced depending on the different losses that affect the FC during its operation causing the voltage decreases with increasing current draw [13]. The effect of the operating temperature is also considered with the model. This voltage drop is due to the different electrochemical phenomena that occur in the electrodes, the membrane and at their exchange interfaces, and are usually classified as ohmic drops, activation drops, and concentration drops [14]. The fuel cell static voltage of is represented by the electrical circuit shown in Figure 1 and described by in (1).

$$V_{cell} = E_0 - V_{ohm} - V_{act} - |V_{conc}| \quad (1)$$

Where E_0 is the open circuit voltage, which is generally calculated from the Nerst equation. However, to simplify the model and considering the fact that using the present test bench the partial pressures of oxygen, hydrogen cannot be measured. E_0 will be assumed constant since the variation due to temperature and pressures is negligible.

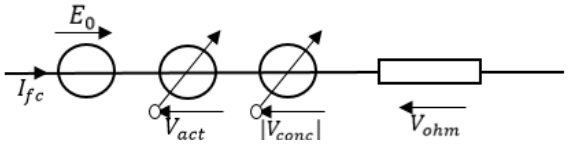

Figure 1. Electrical circuit of fuel cell static model

V_{ohm} is the ohmic loss is due to the resistance of the polymer electrolyte membrane to the ions and the resistance of imperfect electrodes [15]. The voltage drop in the fuel cell is approximately linear to current in this region. It can be described in (2).

$$V_{ohm} = I_{fc}\, R_{ohm} \quad (2)$$

V_{act} is the activation losses that are related to the electrochemical reaction activation and speed. In fact, due to slowness of the reactions on the surface of the electrodes, the catalyst helps to accelerate the reaction [2], which causes a loss in the generated voltage . The activation voltage drop is expressed by the Tafel in (3).

$$V_{act} = \frac{RT}{\alpha z F} \ln\left(\frac{I_{fc}+i_n}{i_0}\right) \quad (3)$$

Where α is the transfer coefficient, z is the number of electrons involved in the reaction, i_0 is the exchange current and i_n is the internal current which represents the undesired flow of electrons from the anode onto the cathode through the electrolyte, and the undesired flow of fuel from the anode to the cathode, through the electrolyte [16]. V_{conc} is the concentration losses that are due to a lack of reactants at the electrode caused by mass transfer phenomena. At highest power demand, the gas diffusion become not fast enough to maintain the reaction [9]. The flow channel floods the phenomene ocuurs when the accumulation of liquid water becomes excessive in a PEMFC, in this case water columns form inside the flow channels, which clog the gas flow [9]. All these reasons leads to a voltage drop, which is called concentration voltage drop. It can be described by (4).

$$V_{conc} = \frac{RT}{\beta z F} . \ln\left(1 - \frac{I_{fc}}{i_L}\right) \quad (4)$$

Where i_L is the limiting current and β diffusive phenomena coefficient. The total static output voltage of the fuel cell is then calculated in (5).

$$V_{FC,static} = N_{cell} . V_{cell} \quad (5)$$

In order to adjust the classical electrochemical equations to the fuel cell used in this paper, the following assumptions were made to simplify the static model:

- All the cells are homogeneous. Ion and heat transfer are supposed to be identical in the cells. The electro-active exchange surface is also assumed identical for all cells.
- The reversible potential is assumed constant, since the losses due to the temperature and to the variation of the partial pressures of oxygen and hydrogen are considered negligible.
- The only resistance considered as equivalent internal resistance is the membrane resistance, and it is assumed constant.

2.2. Temperature characteristics

PEMFC's operations are strictly related to the operating temperature, and the stack temperature is related to its operations as well. An increase in load demand generate heat to be dissipated in order to avoid any excessive rise in the cell's temperature rise [17], the cooling system, will dissipate the heat production regulating the stack temperature. Most often, the temperature is modelled thanks to the energy balance of the thermodynamics by using Gibbs free energy, electrical output power, the latent heat absorbed during the process and the heat loss [9], as given by in (6).

$$M_{FC} C_{FC} \frac{dT}{dt} = \dot{q}_{net} \quad (6)$$

Where M_{FC} is the total mass of the fuel cell, C_{FC} is its overall specific heat capacity and q_{net} is the net heat generated inside the fuel cell. Other more simplified models have been proposed, especially model using only current as input [18]. Temperature variation model was given using current polynomial model as described by (7).

$$T = T_0 + (T_0 - T_{rt} + T_{ic} I_{fc})(1 - e^{-\frac{t}{\tau}}) \quad (7)$$

Where τ is time constant and T_0, T_{rt}, T_{ic} are are the empirical parameters.

The temperature is measured by means of thermocouples at the fans exit. In fact, it is the heat of the air that is measured. The stack will have a slightly higher temperature. However, as in the examined fuel cell system, the temperature measurement is not integrated, it is assumed that the fuel cell temperature is equal to the air heat at the exit of the fans. Considering the temperature profile and given the fact that the time factor is not considered in the measurement of temperature, The thermodynamic model would be too complex to describe the temperature variation, a polynomial model would be sufficient to describe the behavior of the temperature during voltage stabilization. So, in this paper, we modeled the temperature variations using a second order equation of the current as in (8).

$$T = T_i + k_T . I_{fc} + \gamma I_{fc}^2 \quad (8)$$

In (8) is then integrated into the electrochemical model to take into account the impact of temperature in system operations.

2.3. Dynamic model

In (1) to (5) and (8) define a PMEFC model that is suitable for stationary applications while considering the temperature variations. To use this model in power management applications, the fuel cell's dynamic behavior should be included. In the proposed model, the dynamic behavior is considered using transfer functions. The simplification of the dynamic model of the fuel cell using transfer functions has already been proposed by Papadopoulos in [9]. His model is given by (9).

$$V_{cell} = E_{\text{nerst}} - V_{ohm} - V_{act} - V_{conc} - \lambda_e \frac{\tau_e s}{\tau_e s + 1} \frac{d}{as^2 + bs + 1} \quad (9)$$

In this model, the dynamic behavior is considered as a voltage that was subtracted from the electrochemical equations. The author has carried out the parameters identification using MATLAB/Simulink estimation toolbox and then by tuning manually these parameters following a guideline that it has established.

Unlike what is proposed by Papadopoulos, in this paper, the dynamics are considered by applying an open-loop corrector to the static model coupled with the temperature function described above (in (1) to (5) and (8)). Based on this approach, the dynamics are considered. First the identification of the parameters of the temperature model, then the parameters of the electrochemical equations. The output of the static model will be used as input to determine the parameters of the transfer functions.

Fuel cell dynamics are mainly influenced by the mass balance and energy balance equations. However, the solution of these equations requires a detailed knowledge of the fuel cell parameters as well as

the auxiliary systems of the fuel cell, which are not always easily accessible. Therefore, modelling based on transfer functions can be used to characterize both high and low dynamics as in Figure 2. The FC stack voltage is expressed in (10).

$$V_{FC} = H_1(s).H_2(s).V_{FC,static} \quad (10)$$

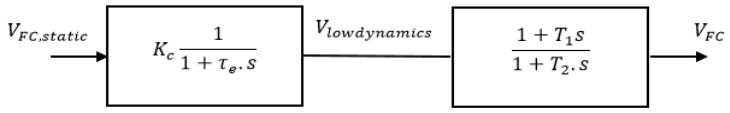

Figure 2. Block diagram of the dynamic representation of the fuel cell

The dynamic characteristics of the fuel cell is represented with transfer functions. A first-order transfer function to define the capacitive character of the fuel cell (11), and phase-advance corrector (12), to represent the fast dynamics and describe the rapid overshoots and undershoots caused by changes in the mass flows.

$$H_1(s) = K_c \frac{1}{1+\tau_e.s} \quad (11)$$

$$H_2(s) = \frac{1+T_1 s}{1+T_2.s} \quad (12)$$

Where τ_e, K_c, T_1 and T_2 are empirical parameters that will be identified in next sections, using expemimental data. The following section is dedicated to the identification of the model parameters.

3. IDENTIFICATION METHOD USING THE PSO (PARTICLE SWARM OPTIMIZATION) ALGORITHM

The parameters identification is done using particle swarm optimization algorithm. The implementation of the algorithm has been implemented on Matlab. PSO is a stochastic optimization technique that imitates the social behavior of a swarm of animals, such as birds and fish. By initializing the PSO with a random population and an iterative procedure based on movement and intelligence processes in a scalable system, the algorithm succeeds in finding an optimal global solution [19]. Several methods have been used for fuel cell parameter identification in the literature, such as the genetic algorithm [20]-[21], the teaching-learning based optimization algorithm [22] and quantum-based optimization algorithm [11], [19], [23]-[25]. In this paper, the particle swarm optimization (PSO) approach is used to identify the mathematical parameters of each part of the model since it has been proven to be an accurate technique for identifying the parameters of PEM fuel cell models, even in the presence of measurement noise [24]. Figure 3 illustrates the flow of the PSO algorithm.

In PSO, each particle represents a potential solution. To each particle, the velocity v_i and the position x_i with dimension N are assigned. For each particle, a fitness function is used to measure all the particles in the swarm. In this paper, the root mean square error (RMSE) described by (10) is used to evaluate the fitness of the particle.

$$f_{obj} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_{obs}(i) - x_{model}(i))^2} \quad (10)$$

The velocity of each particle is updated by tracking the two best positions: p_{best} is the best position a particle has traveled so far, and g_{best} is the position of the particle that have the best fitness value of all particles. Velocity and Position are updated according to in (11) and (12):

$$v_i = \mathrm{w} \times v_i + y_1 \times u_1 . \times (p_{best} - x_i) + y_2 \times u_2 . \times (g_{best} - x_i) \quad (11)$$

$$x_i = x_i + v_i \quad (12)$$

Where w is the inertia weight, y_1 and y are positive constants and work as acceleration coefficients, and u_1 and u_2 denote random variables within [0,1]. If any parameter of the particle is outside a limit, this one is set equal to that limit. The algorithm stops when number of iterations reaches its maximum or when the fitness function reaches a set minimum.

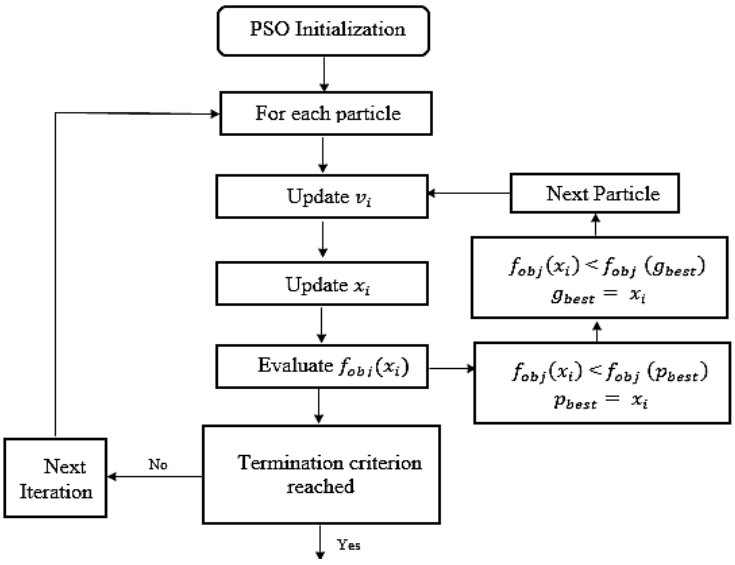

Figure 3. The flowchart of the PSO algorithm

The identification is performed in three parts. First, the identification of the temperature equation parameters T_i, k_T, γ. Then, the identification of the polarization curve parametres $E_0, i_0, i_n, \alpha, \beta, i_L, R_{ohm}$. Finally, the identification of K_c, τ_e, T_1, T_2, the parameters of the dynamic part of the model. For the temperature identification $x_i = [T_i, k_T, \gamma]$. For the polarization curve, the position x_i is equal to $[E_0, i_0, i_n, \alpha, \beta, i_L, R_{ohm}.]$ and finally $x_i = [K_c, \tau_e, T_1, T_2.]$. For each identification part, the size of the swarm is taken equal to 10 times the number of variables, and the maximum number of iterations is equal to 200 times the number of variables.

4. TEST BENCH AND EXPERIMENTAL STUDY

4.1. Experimental setup

The main objective of this study is to propose a simplified model that consider both the FC's steady state behavior as well as its dynamics. The purpose of the experimental study is to characterize the performance of the PMEFC in different operation conditions, and to validate the proposed model using experimental real data. For this, a commercial $AIRCELL^{TM}$ fuel cell system from H2SYS compagny is employed. The system is mainly composed by an open cathode fuel cell, hydrogen suply line, electronics to manage electrical fluxes within the system and the controller to manage actions and safety operations as shown in Figure 1. The system is air cooled using three fans and self-humidified. The 1 kW fuel cell system cell is a series assembly of 28 cells. According to the manufacturer's datasheet, the voltage range is 18V-28V, the maximum current is 65A and the maximum supported current variation is 15A/s. The ambient operating temperature ranges is from 5 °C to 45 °C. The photograph of experimental setup and the synoptic of the test bench are presented in Figure 4. Measurements of current, output voltage and fuel cell temperature were captured using a control unit that recorded the data with a sampling frequency of 1 Hz and 10 Hz, while safety checks and data display were done via a dedicated HMI. A programmable electronic load was used to sink several current values. The output voltage was recorded using a voltage divider bridge with a factor of 0.23, and the current signal was captured by a current clamp. Temperature was measured at the output of the controller using three thermocouples at different points of the fuel cell system. In the employed PEMFC, The cooling is done using blow fan setting, in this case the center area temperature is always higher than the exit area temperature [15]. So, in order cell to get the best approximation of the system temperature, two thermocouples were placed on the output of the fuel cell fans and a third one was placed in the center of the fuel. The temperature measurements are done once the voltage is stabilized, by averaging the measurements of the three thermocouples connected to the fuel cell. The polarization curve is deduced by considering stabilized values of voltage and current.

4.2. Fuel cell caracterization

In compliance with the specifications imposed by the manufacturer for safety reasons, and to avoid damaging the fuel cell, the maximum current applied to the fuel cell will be less than the limit imposed by the manufacturer which is 65A and current variations will not exceed 15A per second. A current profile in steps, as shown in Figure 5(a), has been applied to the fuel cell for characterization of the behavior of the fuel cell as

well as the parameters identification. The current was decreased from 50 A to 0 A, then increased from 0 A to 60 A in 10 A steps.

The temperature profile as a function of the current is presented in Figure 5(b) where it has been noticed that for every 10A step, the temperature has a quasi-linear behavior. The steady state characteristics of Aircell 1 kW fuel cell system is given by the polarization curve shown in Figure 5(c). It is deducted from the data obtained from the test described below, considering the current and voltage values when the system stabilizes. As will be described in Section 3" Electrochemical static model", the different loss regions can be clearly seen in the polarization curve. From 0 A to 10 A, the voltage drop is due to activation losses, from 10 A to 52 A, the polarization curve is quazi-linear, the voltage drop in this region is due to ohmic losses. Finally, above 52A, the concentration losses causes the voltage drop. Since the density of the current accelerates the reaction process and the heat production in the fuel cell is proportional to the speed of the reaction process, it is expected that an increase in current will lead to an elevation in temperature. As for the polarization curve, the temperature is considered when the system is stable, i.e. all the characteristics of the fuel cell have stabilized at a constant value after the variation of the current, it is expected that the variation of the temperature will only be dependent on the current.

Finally, to understand the dynamic behavior of the studied PEMFC, a zoom from the 600th second to the 1800th second is characterized in Figure 5(d). It can be noticed that when the current load is increased , an undershoot occurs during the transient, and an overdershoot occurs while decreasing the current. One of the main objectives of the proposed model is to be able to describe as well as possible the behavior of the fuel cell during transitions.

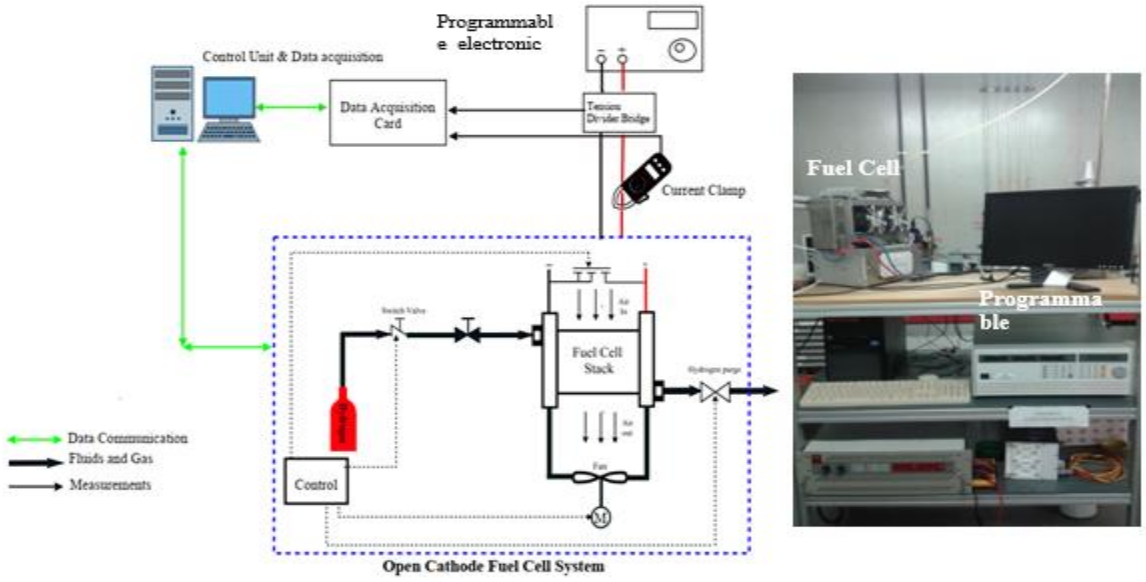

Figure 4. Experimental set up

4.3. Identification results

The current profile used for identification is the same as for the characterization. It is presented in Figure 5(a). This current profile allows to evaluate the behavior of the fuel cell during an increase in power demand which is equivalent to an acceleration and also during a decrease in power demand, as well as during resting or stopping by means of a zero current. The test lasts 1 hour to ensure that the fuel cell has enough time to stabilize after each current variation. The acquisition frequency of current and voltage was set to 10 Hz in order to have an accurate representation of fuel cell voltage.

Based on PSO algorithm, the identification of temperature parameters is accomplished at first. Table. 1 presents the values of these parameters. The algorithm was set to $\gamma = 0$, which means that the temperature is considered linear to the current. As shown in Figure 6, this approximation fit well with the experimental data. At the end of the identification, the RMSE was 0.0442%. The parameters of the polarization curve are presented in Table. 1. The comparison between experimental data and the polarization curve using identified parameters is presented in Figure 5(b). As can be noticed, the static model describes well the steady-state behavior of PEMFC, and the RMSE between the experimental data and the static model is about 2.01%, which is a

relatively small error. The parameters of the dynamic model are given in Table. 1 using PSO algorithm. The comparison between the model and the experimental data is shown in Figure 5(d) and the zoom on the voltage data on the interval [600s 1800s]. In addition to the small RMSE, the identified parameters give suitable results, since the data and the model fit well and the overshootand undershoots th at appear during the current transition are detected in the model too, and well represented.

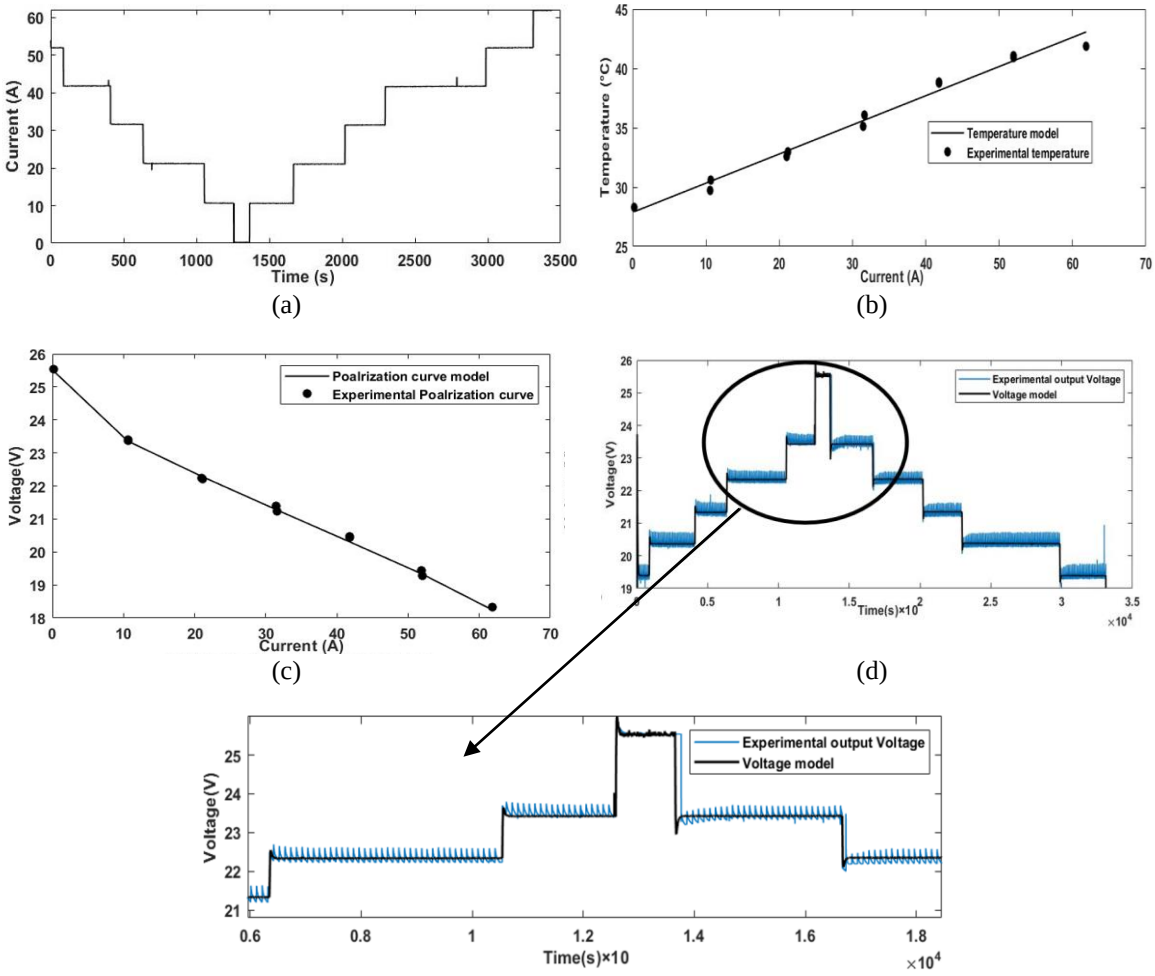

Figure 5. Identification results, (a) current profile for parameter, (b) temperature identification, (c) polarization curve identification, and (d) PEMFC dynamics identification

Table 1. Fuel cell identified parameters

Temperature parameters	Value	Static Model Parameters	Value	Variable	Speed (rpm)
T_i	27.8764	E_0 (V)	0.9074	K_C	1.0029
K_T	0.2456	I_0 (A)	0.2676	T_1	35.0001
γ	0.0012	I_n (A)	0.0020	T_2	23.4203
		α	0.1	τ	6.0011
		β	0.5831		
		i_L (A)	63.0747		
		R_{ohm} (Ohm)	0.0023		

4.4. Model validation

Once all fuel cell's parameters have been identified, the validation of the complete model was realized based on experimental data from different tests carried out on the test bench. Two current profiles were applied to Aircell 1 kW fuel cell system. First, the current profil employed for validation is shown in Figure 6(a). This profil was obtained by applying a current profile starting with the current limit of the fuel cell, which is 62 A, and decreases by steps of 5A every 5 min. Once the 0 A value is attained, the current increases in steps and in the same way, up to 62 A the maximum allowable current for this fuel cell. The acquisition frequency has been

lowered to 1 Hz , since this frequency still allows to have a proper data base and this is a validation test, so there is no need for a very large database to evaluate the model. Figure 6(b) shows a comparaison between the Simulink implementation of the proposed model using identified parameters and experimental output PEMFC voltage. The RMSE is of only 0.88%. However, an error is observed in the first measurements of the test. In fact, at the beginning of the tests, the fuel cell is supposed to be switched off and therefore cold. When the gases are injected without drawing current, the voltage of the cell will spike for as long as the cell heats up. However, the tests presented in this study were done when the fuell cell is already running and therefore the voltage peak is not observed. The proposed model considers this aspect of the fuel cell and therefore shows the voltage peaks at the moment zero.

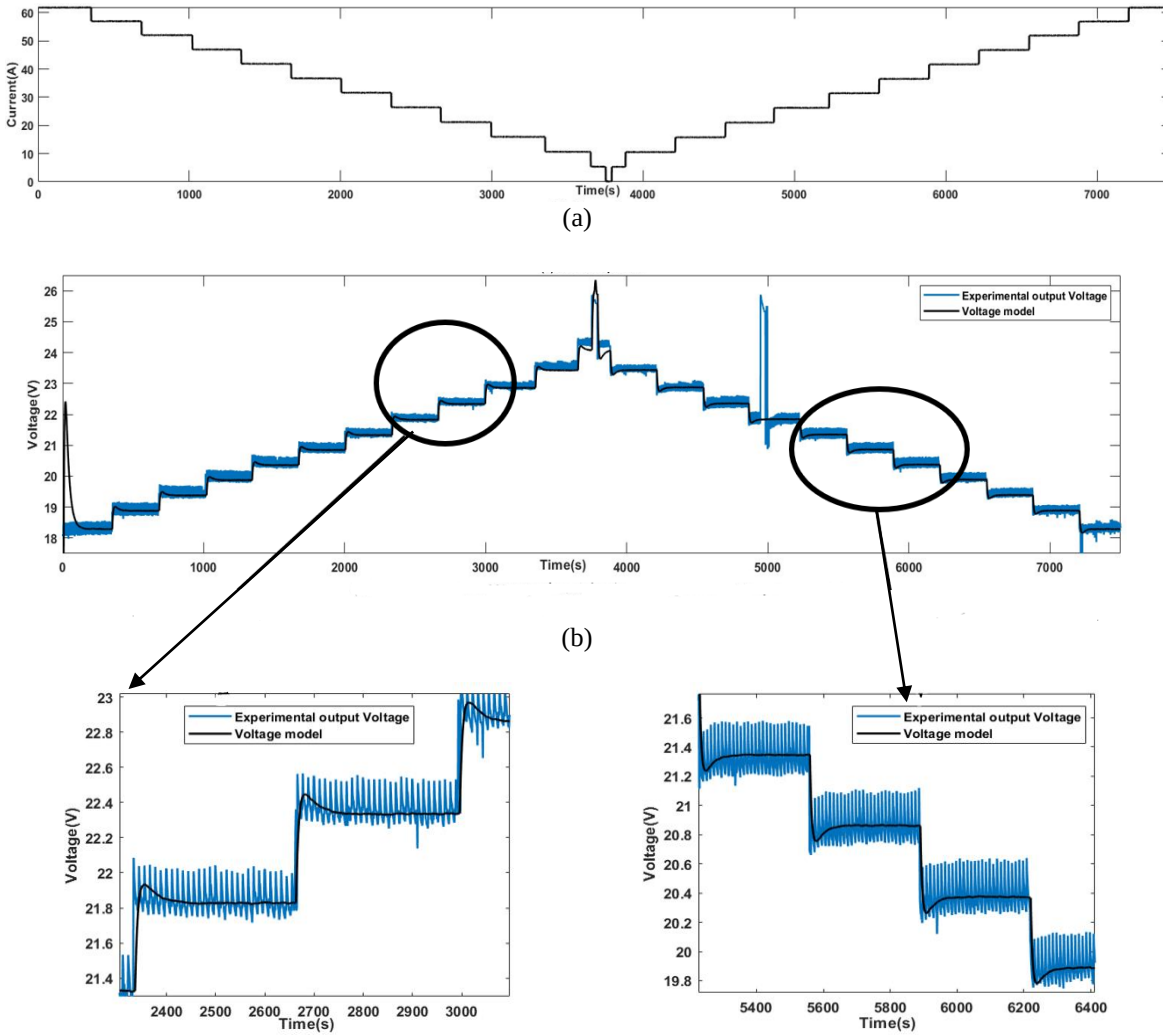

Figure 6. Results of the first validation test for (a) current profile and (b) comparison between experimental output voltage and the proposed model

A final validation test was performed on the fuel cell. In this test, the current load is applied in a more random way than in the previous profiles, with different variations of amplitudes 5 A, 8 A, 10 A, 12 A and 13 A and varying time steps in order to simulate the driving demands of a vehicle. The current and voltage profiles resulting from this test are shown in Figure 7(a). The purpose of this test is to validate the model proposed in this paper, with a current profile different from the one used for the identification as the current variations are different from a step to another. This allows to validate its performance on different current profile. As shown in Figure 7(b), the developped model describes the behavior of the fuel cell very accurately, both statically and in the transitions.

This test was also used to compare the proposed model with the model developed by Papadopoulos, which is also based on transfer functions [9]. Indeed, as for the identification of the parameters of the proposed

model, the identification of the parameters of the Papadopoulos model was done on the data of the identification test presented in Figure 7(b). Firstly, the PSO algorithm was applied as described above, and then the parameters were manually tuned following the procedure presented by Papadopoulis [9]. As can be noticed in Figure 7(b) in the zoom done on the voltage profile, both models correctly represent the behavior of the fuel cell. However in terms of complexity the Papadopoulos model remains more complex, in the dynamic part, the model contains 6 parameters to be identified compared to 4 parameters for the proposed model. Also, regarding H2 transfer function form, which is a second order, the identification algorithm tended to stumble on singularity points. It is therefore necessary to define the limits well, which means having enough knowledge of each parameter and to reduce the step time which led to a higher time for the identification of the parameters.

Finally, the proposed model allows to improve the dynamic behavior at the transient. Indeed, the duration and amplitude of the overshoot and undershoot are more appropriate to the data of the studied fuel cell. Finally, the proposed model allows to improve the dynamic behavior at the transient. Indeed, the duration and amplitude of the overshoot and undershoot are more appropriate to the data of the studied fuel cell. The model proposed by Papadopoulos [9] is likely to reduce the overshoot (undershoot) time and therefore the response time of the fuel cell. As explained below, for the previous test, the model defined in this article has a spike at the beginning of the test, unlike the Papadopoulos model which will directly consider the current profile applied, and does not consider that the fuel cell is cold at the beginning of the test. So, the RMSE was calculated for both models once the voltage is stabilized, i.e. after the instant t=170s, the RMSE between the Papadopoulos and the data was 0.094 compared to an RMSE of 0.073 for the proposed model.

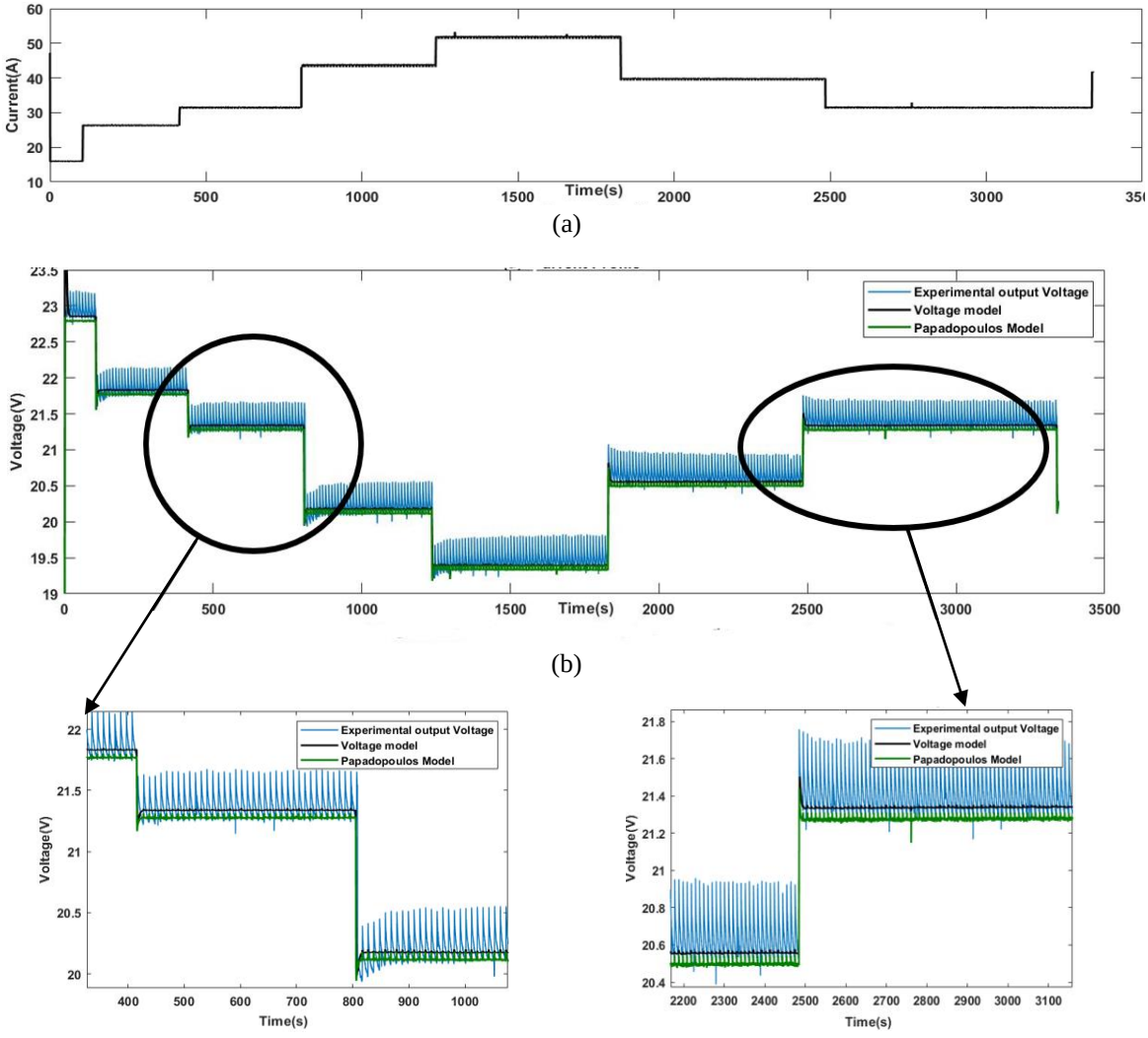

Figure 7. Results of the second validation test and comparison with Papadopoulos model for (a) current profile and (b) comparison between proposed model and experiment output data

5. RESULTS DESCUSSION

Based on the results of both tests, the model proposed in this article represents accurately the FC's behaviour in both the transient and steady-state regimes, as the model fits well the experimental data, and the provides a more precision and accuracy compared to the Papadopoulos model. As shown in Figure 6 and Figure 7 during transitions, the open-cathode fuel cell system shows an overflow. The model proposed in this paper correctly reproduces the overshoot as the load increases and the undershoot as the current load lowers. In addition, this model respects the FC's response time. Furthermore, the model stabilizes around the average value of the actual fuel cell voltage once the current load is in a stable state.

However, the small fluctuations that appear in the experimental data and that are due to the purging and short circuit of the fuel cell are not taken into account. In fact, the voltage studied in this paper is the voltage at the output of the fuel cell, however the fuel cell will be coupled to a converter and a bus. The voltage at the output of the global system will be automatically smoothed thanks to the converter. The fluctuations due to the purges and especially to the short circuit would be removed.

The model developed in this paper involves electrochemical equations that describe the FC's static behavior and an open loop corrector based on a first order transfer function and a phase advance corrector which represents the fuel cell dynamics. All experimental results were in good agreement with simulations. The error between the model and the experimental data is very low, a maximum of 0.88% RMSE has been noticed. The model provides a accurate characterization of an open cathode fuel cell behaviour, both statically and dynamically. The strength of this model is its simplicity, only current and temperature are considered as inputs. And the identification of the model can be done by simple profiles of current. The model demonstrated its efficiency and robustness represented the fuel cell behavior, which has been validated experimentally and by comparaison to an existing dynamic model.

6. CONCLUSION

A simple PEM fuel cell model, suitable for automotive applications, especially for online power management applications, has been presented. In fact, the dynamic behavior of a fuel cell is a very complex phenomenon, and its modeling requires a lot of computation time and storage space. The objective of this work was therefore to provide a complete fuel cell model, accurate to describe its static behavior as well as and its dynamic behavior and easily implementable on an on-board system of a vehicle.

The model is composed of a static model based on semi-empirical equations, several assumptions have been considered in order to simplify these equations, and a dynamic model represented by two transfer functions which summarize and represent correctly the slow and fast dynamics of the fuel cell. The major simplification of this model is that the mass and energy balance equations are not represented in detail, thus simplifying the model considerably without negatively impacting the overall performance.

The model was experimentally validated on a 1 kW PEM Aircell fuel cell. The model has proven to be effective in reproducing correctly and perfectly the stable and dynamic behavior of a PEMFC. Moreover, the improvements proposed in this study also enhanced the accuracy of the model. Indeed, when conducting a comparison of the proposed model in this paper with the Papadopoulos model, the RMSE decreased, as we obtained an RMSE of 0.094 between the Papadopoulos model and the experimental data and we obtained an RMSE of 0.073 for the proposed model. The proposed model has proven to be more efficient and accurate in describing the behavior of the fuel cell.

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BIOGRAPHIES OF AUTHORS

Nada Rifai was born in Morocco in 1995. She received the engineering degree in Electronics from the ENSEIRB-MATMECA, Bordeaux France, in 2018. She is currently a PhD student at Ecole Nationale Supérieure d'Arts and Métiers, Meknès, Morocco since 2019. Her research interests include energy storage and energy management, more specifically for fuel cells and supercapacitors. She can be contacted at email: n.rifai@ueuromed.org.

Jalal Sabor received the Ph.D. degree in engineering science from the Institut National des Sciences Appliquées de Rouen, Rouen, France, in 1995. He is currently a Professor of industrial computer science at the Ecole Nationale Supérieure d'Arts et Métiers, Université Moulay Ismail, Meknès, Morocco. He is a member of the LSMI Laboratory, as well as the Research Team Control Steering and Supervision Systems Head. His research interests include intelligent management of energy, smart grid, control and supervision systems, architecture based on multiagent systems, and fuzzy logic. He can be contacted at email: j.sabor@ensam.umi.ac.ma.

Chakib Alaoui received the Ph.D. degree in electrical and computer engineering from the University of Massachusetts at Lowell, Lowell, MA, USA in 2001. He is currently with the faculty of INSA Euro-Méditerranée at EUROMED University in Fes, Morocco. His current research interests include energy conversion and management for vehicular and smart grid applications. He can be contacted at email: c.alaoui@insa.ueuromed.org.

Raffaele Petrone received the Ph.D. degree in co-direction between the University of Franche-Comté (UFC) and the University of Salerno (UNISA), in March 2014. He received the PhD on Industrial Engineering (UNISA) and Electrical Engineering (UFC). From April 2014 to August 2019, he was a Postdoctoral Research Fellow at the FCLAB Research Federation (UFR-STGI/FEMTO-ST), Belfort (France), working on Hydrogen and Hybrid Vehicle domains, monitoring & diagnosis, accelerated stress tests, prognostic & health management. Since September 2019 he is Associate Professor at the University of Caen Normandie (UNICAEN), where he joined the LUSAC laboratory to work in renewable Energy, Hydrogen and Hybrid Vehicle domains, and energy management. He can be contacted at email: raffaele.petrone@unicaen.fr.

Hamid Gualous (Member, IEEE) received the Ph.D. degree in electronics from the University of Paris—XI, Orsay, France, in 1994. From 1996 to 2009, he was an Associate Professor with the University of Franche-Comte in FEMTO-ST Laboratory, France. Since then, he has been a Full Professor with the University of Caen-Basse Normandie and the Director of LUSAC Laboratory. His main research activities include energy storage device, marine renewable energies, and energy management systems for smart grids. He can be contacted at email: hamid.gualous@unicaen.fr.