Robust Model of PEMFC for Mobypost Electric Vehicles

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***Abstract*— Fuel Cell Hybrid Electric Vehicles (FCEV) are low emissions. However, these systems are still not very suitable for onboard applications because of their slow dynamic response and complex architecture. Nevertheless, an analytical model can be a suitable solution for improving the utilization of the fuel cells onboard in the electric vehicles. This model can replace the actual system, and thus reduce the instrumentation cost.**

In the present paper, a signal based PEMFC model is proposed which is used to power a post-delivery hybrid electrical vehicle. This model is based on evaluating the variation effect of four parameters: temperature, mass flow, pressure and voltage. The objective of this modelling is to propose a simple identification technique, namely the AutoRegressive model with eXagenous inputs (ARX) and the Wavelet Transform (WT) in order to generalize a voltage variation model for a specific application such as FCHEV post-delivery vehicles. This model is simulated by using actual data. The simulation results are then compared with the experimental data from different vehicles. The results were found to be very promising (less than 2.5% of error) and show the robust model.

***Index Terms*— ARX model, FCHEV, PEMFC, Wavelet Transformer.**

NOMENCLATURE:

FCHEV	Fuel Cell Hybrid Electric Vehicle.
PEMFC	Proton Exchange Membrane Fuel Cell.
ARX	Autoregressive model with exogenous inputs.
OCV	Open Circuit Voltage.

Roman Symbols :

E	The reverse voltage including the effect of gas pressures and temperature (V).
i	Current density (A cm-2).
V	Fuel cell stacks voltage (V).

SUBSCRIPTS AND SUPERSCRIPTS :

V_{act}	Activation polarization (V).
V_{con}	Concentration polarization (V).
V_{ohm}	Ohmic polarization (V).

I. INTRODUCTION

FUEL CELL Hybrid Electric Vehicles (FCHEV) are one of the most promising solutions for reducing pollution and fuel consumption. The fuel cell system uses the hydrogen to produce water, electricity and heat. Such chemical reactions are clean and it is advantageous in comparison with the conventional vehicles [1-3]. Multiple power sources are responsible for powering these vehicles, namely fuel cells, batteries, ultra-capacitors, flywheels, etc…. However, the fuel cell (FC) system is one of the most interesting power sources [4]. However, the FC system suffers from slow dynamic response, load dependent voltage, indirection in the power flow and high costs and consequently such reasons limit the utilization of the FC onboard vehicles. By contrast, the output voltage of the FC is considered as a good parameter which can represent and characterize the FC [5]. It enables indications, performance of the fuel cell and sustainability [6,7]. Hence, an attribution of a robust mathematical model for this voltage can be very useful for simulating, testing and validating any operation on the FC system. This model can replace the actual FC and thus reduce instrumentation costs [8]. Modelling an FC system onboard the vehicles has been an important subject for researchers recently [9,10]. According to the literature, FC model can be classified in three main groups:

1) Analytical models: they are based on physical and chemical reactions and they need accuracy in internal operation. However, they are quite complex since complex equations must be solved to find an accurate model [11,12].
2) Empirical models: they require special equipment with advanced programming knowledge [13-15].
3) Semi empirical models: they need experimental data to find the internal parameters of the FC [16-18].

However, these models require a great number of physiochemical parameters of the FC system, which, in the real electric vehicle FC stack, is a complex task since these parameters are difficult to be evaluated [19,20].

Therefore, it is necessary to have a simple model which

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requires a few number of parameters, with fast execution time and enough accuracy. To reach this aim, identification technology and autoregressive models appear to be good solutions. This model uses an accurate fit of the FC output voltage by taking into account the impacts of a few parameters such as temperature, pressure, mass flow, etc….

Several fuel cell models have been investigated based on the identification technology. For instance, C. Raga et al [21] investigated a black box model of a commercial Proton Exchange Membrane Fuel Cell (PEMFC) to reproduce the behaviors of the FC in static and dynamic response. The validation of the model resulted a less than 4% error. In [22] Hou et al, the authors have presented a dynamic voltage model for a PEMFC. In their study, the effect of hydrogen purge has been considered and the results revealed that there exists a linear relationship between the output voltage and the purge hydrogen. To analyze time-frequency domains for the PEMFC, Cheng et al in [22] proposes a nonlinear autoregressive moving average with exogenous inputs (NARMAX) model. The model was tested and found to be consistent to ensure accurate predictions.

Moreover, identification technology has been used in [22], that proposed a dynamic modeling of the solid oxide fuel cell (SOFC) stack based on the autoregressive with exogenous inputs (ARX) algorithm. The simulation results showed that such model can be established for the SOFC, with high accuracy.

Nevertheless, the identification technology methods developed in the literature are still computationally costly and depend on a many parameters in the fuel cell. Additionally, very few have studies focused on modelling a FC system onboard in the electric vehicles.

In this paper, an identification technology method is proposed, namely the AutoRegressive with eXogenous inputs (ARX) to provide an accurate and simple model of a PEMFC. The aim of this study relies on two steps: Firstly, the data are collected from an actual vehicle, then the Wavelet Transform (WT) technique is used to remove the noise incorporating data. The ARX is applied to give a model of the voltage with taking into account the effect of a few number of parameters such as the pressure, the temperature and the mass flow. This model is obtained, with enough accuracy that will be compared with the experimental data of multiple vehicles in order to get a generalization of the model. This model can afterward be used for multiple application like controlling, energy management and degradation of the PEMFC in the electric vehicles.

The paper is organized as following: Section 2 gives a general introduction of the Mobypost project. Section 3 describes the ARX and the Wavelet Transform with some analytical formulations. The experimental data and the test bench are detailed in section 4, followed by a numerical application of the proposed model, the results and a discussion in section 5; and finally section 6 is a general conclusion of the present work.

II. MOBYPOST PROJECT

Mobypost is a European project which aims to develop and design post-delivery hybrid electrical fuel cell vehicles powered by renewable hydrogen produced locally [24-26]. Ten vehicles quadric cycles can carry up to 1000 kg of postal mails. The vehicles are powered by a PEMFCs that recharges the batteries. They are composed by very low-pressure hydrogen tanks.

Fig. 1 depicts an Mobypost vehicle. In this vehicle, the batteries provided the energy necessary for two motor in the rears wheel. The latter are charged by an air cooler, and the PEMFC is fed by an embedded hydrogen tank.

Fig1. Mobypost Vehicle.

III. ARX MODELS AND WAVELET TRANSFORM

A. ARX model

The AutoRegressive with eXagenous inputs (ARX) model is one of the simplest model that it integrating the dynamic signals. The ARX model can be represented as following:

Let A (z) and B (z) be two polynomials defined by:

$$A(z) = 1 + a_1.z^{-1} + ... + a_r z^{-r} \tag{1}$$

$$B(z) = b_0 + b_1.z^{-1} + ... + b_{s-1} z^{-(s-1)} \tag{2}$$

Where r and s are respectively the order of A and B, z is the variable and z^(-1) the backward shift operator. The ARX model of A and B can be obtained by:

$$A(z) * y(k) = B(z) * u(k-n) + e(t) \tag{3}$$

Where e is the system disturbance or noise and n is the delay. z^(-1) is the backward shift operator, that makes :

$$z^{-n} u(k) = u(k-n) \tag{4}$$

Where u is the input system. In the time domain the equation (4) can be written in simplest form:

$$\begin{aligned} y(k) + a_1 y(k-1) + ... + a_r y(k-r) = b_0 u(k-n) + \\ b_1 u(n-m-1) + ... + b_{s-1} u(k-n-s+1) + e(k) \end{aligned} \tag{5}$$

With y is the system output [27].

An illustration of this model is given in Fig. 2.

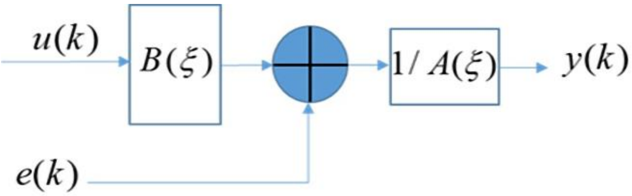


Fig2. The structure of the ARX model.

Before data want to use for construction the ARX model the data should be pre-proceed. Because the data are incorporated with a lot of noise coming from the measurement instruments. Therefore, the data should be passed by a suitable filter in order to remove useless noises. Hence, the Wavelet Transform is one of the most powerful methods to detect, identify, localize and remove useless noises in 1-D signals [28].

B. *Wavelet Transform*

In summary, the continuous wavelet transform is defined as equation:

$$W_{a,b}(t)=\int_{-\infty}^{+\infty}x(t)\varphi^{*}{}_{a,b}(t)dt \qquad a\in R^{*+}, b\in R \tag{6}$$

Where * indicate the complex conjugate, a and b are representing the scale and parameter position respectively, x (t) is the signal to be transformed and

$$\varphi^{*}{}_{a,b}(t)=\frac{1}{\sqrt{a}}\varphi(\frac{t-b}{a}) \tag{7}$$

φ being a zero-mean pass band function, called mother wavelet.

The WT decomposes x (t) into multiple components at different times and frequency bands. For more details about the wavelet transform, refer to [28-29].

IV. EXPERIMENTAL DATA AND TEST BENCH DESCRIPTION

The PEMFC has been used in the Mobypost electric vehicle). Because of the suitable feature of PEMFC (e.g. Low operating temperature/pressure ranges, solid state polymer electrolyte etc). Figure 3 shows the series architecture which have been chosen for Mobypost vehicle. In this architecture, PEMFC is applied as second source of energy in order to charge the battery when State of Charge (SoC) of the batteries is close to 20%.

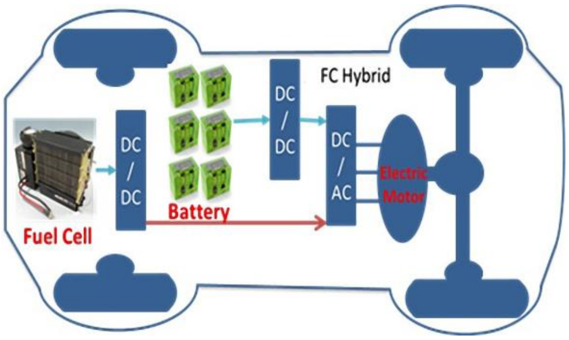


Fig3. the architecture of Mobypost vehicles.

A commercial PEMFC from the MES company is considered in this work. This fuel cell includes 45 cell in series to provide voltage of stack. The selected FC generates at nominal power 1kW. Table I is a description of the MES FC operating conditions.

The data collection (current, pressure, mass flow and voltage, see next section) is carried out with a sampling interval. The experimental period on each day is between 2 and 3 hours that the data collected in each second.

TABLE I. DESCRIPTION OF THE MES SINGLE CELL

Nominal power:	about 1000 W
Unregulated DC output voltage range:	0.5 – 0.95 V
Nominal cell voltage	0.6 V
Nominal cell current:	42 A (max 55 A)
Active area:	62 cm^2
Minimum cell voltage:	0.5 V
Nominal cell temperature	58-60°C
Ambient temperature range:	> 0 °C up to + 35 °C
Ambient relative humidity range	30 – 80 %
Hydrogen supply minimum flow rate	0.5 Nlt/min (at the nominal power and pressure)

A. *Voltage of the PEMFC*

The PEMCS is one the most interesting FCs that have being used in electric vehicles. The output voltage of fuel cell can be obtained as the equation bellow [30]:

$$V=E-\Delta V_{act}-\Delta V_{ohm}-\Delta V_{con} \tag{8}$$

E is the reversible open circuit voltage, second part is related to activation part, third parts indicate ohmic losses and last part is mass transport or concentration losses [31].

The equation above is based on the empirical equation modified as :

$$V=E-a.\ln(i)-r(i)-b.\exp\ (ci) \tag{9}$$

Where the values of the A, r, m and n are obtained experimental with respect to polarization curve with different current as shown in Fig.4. These values summarized in table II.

TABLE II . PARAMETRIC OF VOLTAGE OF MES FUEL CELL

Parameters	Value
E	40.0079
a (V)	0.372
r(KΩ/cm^2)	0.254
b(V)	3.09e^{-6}
c(cm^2/mA)	0.1881

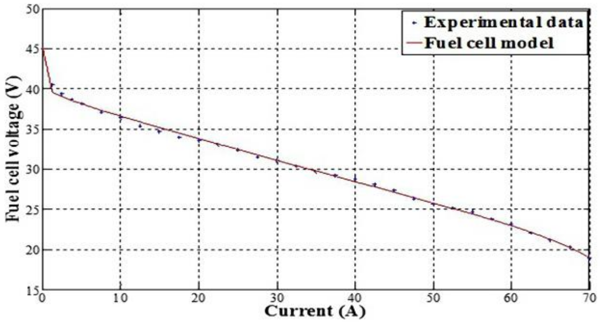


Fig4. The comparison polarization curve between experimental and model.

B. Thermal model of PEMFC

One of the most effective input parameters on the model is the temperature of FC stack. In order to obtain the impact of the temperature on the FC the thermodynamic of the model is obtained by empirical nonlinear equation as bellow:

$$T_{stack} = a \cdot e^{b \cdot i} + c \cdot e^{d \cdot i} \tag{10}$$

Where a=38.27, b=0.01032, c=-11.93, d=-0.1782

To obtain the thermodynamic terms, the PEMFC tested in the climatic chamber as shown in Fig. 5.

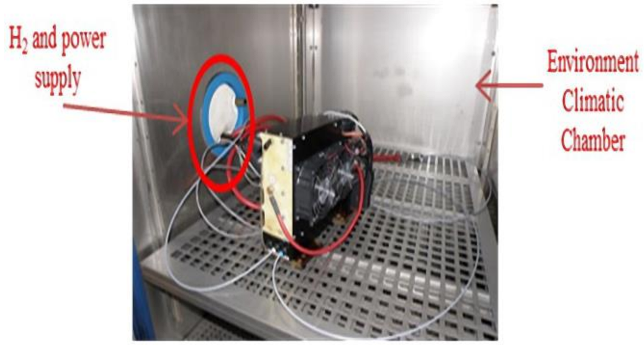


Fig5. Test bench of experimental tests on the FC in climatic chamber.

Fig.6 shows the difference between temperatures measured in the stack FC and temperature obtained by thermodynamic model. The result shows that the measurement temperature are not suitable parameter for modeling. However, thermodynamic can be modeled using the current of FC. This model is suitable for tracking the short circuit and purging phenomena that happened in the FC (Fig.6).

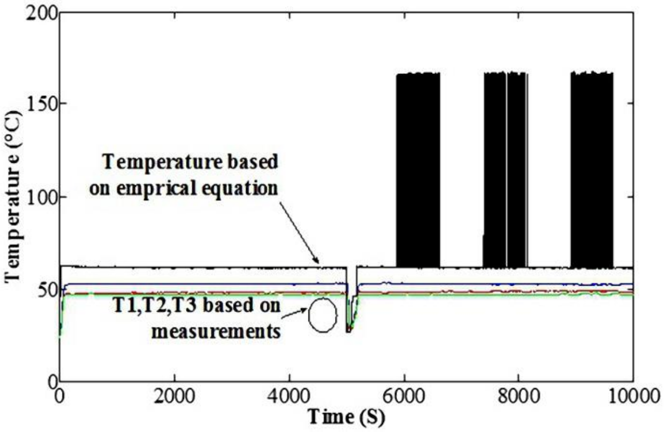


Fig6. The comparison of thermodynamic model with sensor measurements.

V. NUMERICAL APPLICATION OF THE PROPOSED MODEL, THE RESULTS AND A DISCUSSION

In order to construct the model using the ARX, the inputs are set to be: The H_2 pressure, the H_2 mass flow, the temperature and the current. The output of the model is the desired FC voltage. These parameters are selected based on the application and measurement technique. The model is simulated with Matlab/Simulink.

As mentioned before, the Wavelet Transform is used in this work in order to filter the noise coming from the measurement instruments. Fig. 7 and 8 present the inputs with noise and after applying the Wavelet Transform.

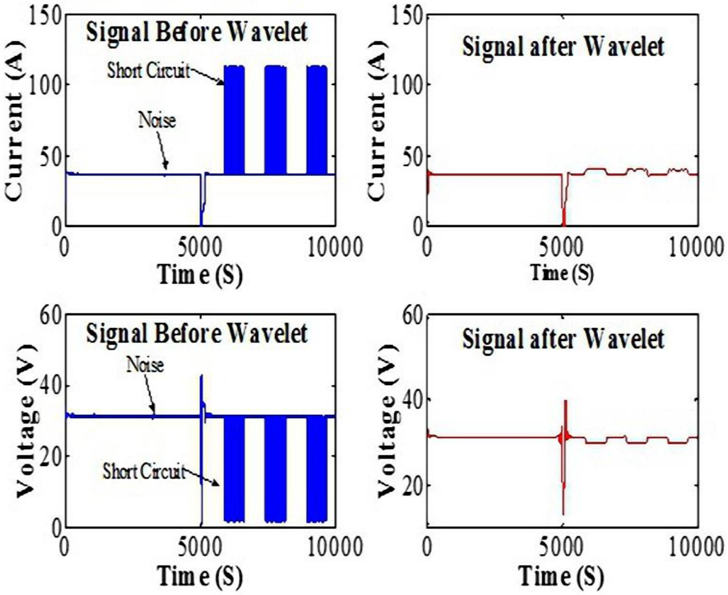


Fig7. The effect wavelet transformer on current and voltage signals.

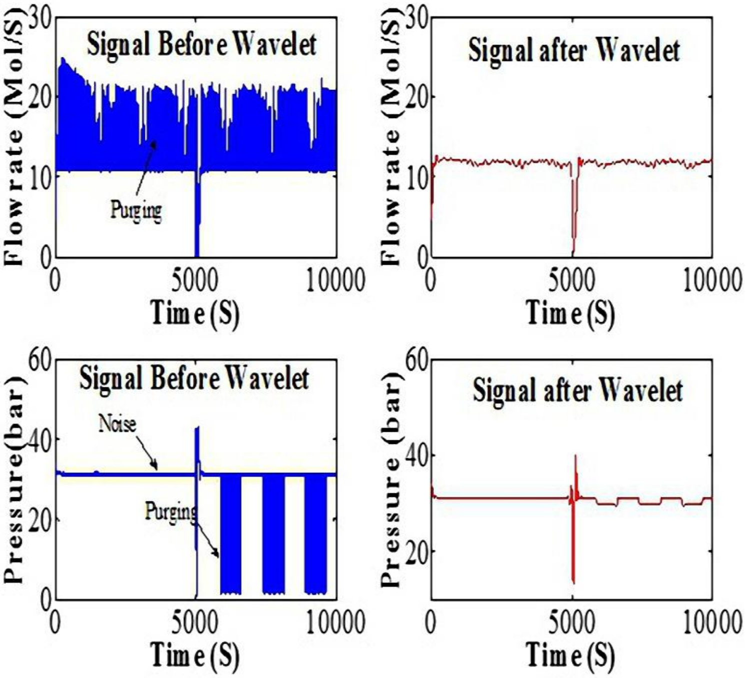


Fig8. The effect wavelet transformer on pressure and flow rate of H_2.

Fig. 9 shows the comparison of the ARX model with the experimental data for one single day. Fig. 10 shows the results for six days of driving cycles of vehicle one. In this figure, the errors of the model and experimental are calculated (in the left rectangle of figure 10).

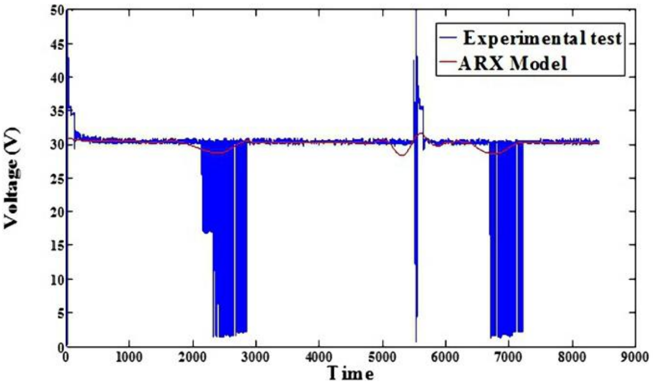


Fig9. The comparison between model and experimental for vehicle one.

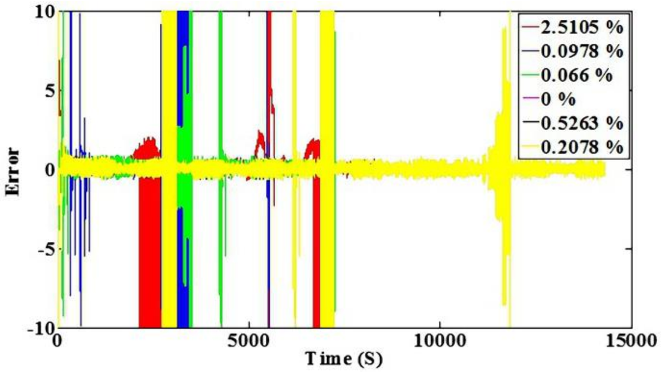


Fig10. The error between model and experimental in different day of vehicle one.

In this figure, the comparison between the model and the experimental data proves the robust of the proposed model. The maximum of the error was found about 2.5%. Therefore, the model is reliable in different condition of vehicle one.

It should be noted that, each day, the proposed model shows a high reliability for the normal condition as well as for the dynamic condition. The obtained model is compared with different experimental data with different vehicles. In view of the result obtained the proposed model of the FC can be generalized for the vehicles. The results are figured in Fig. 11.

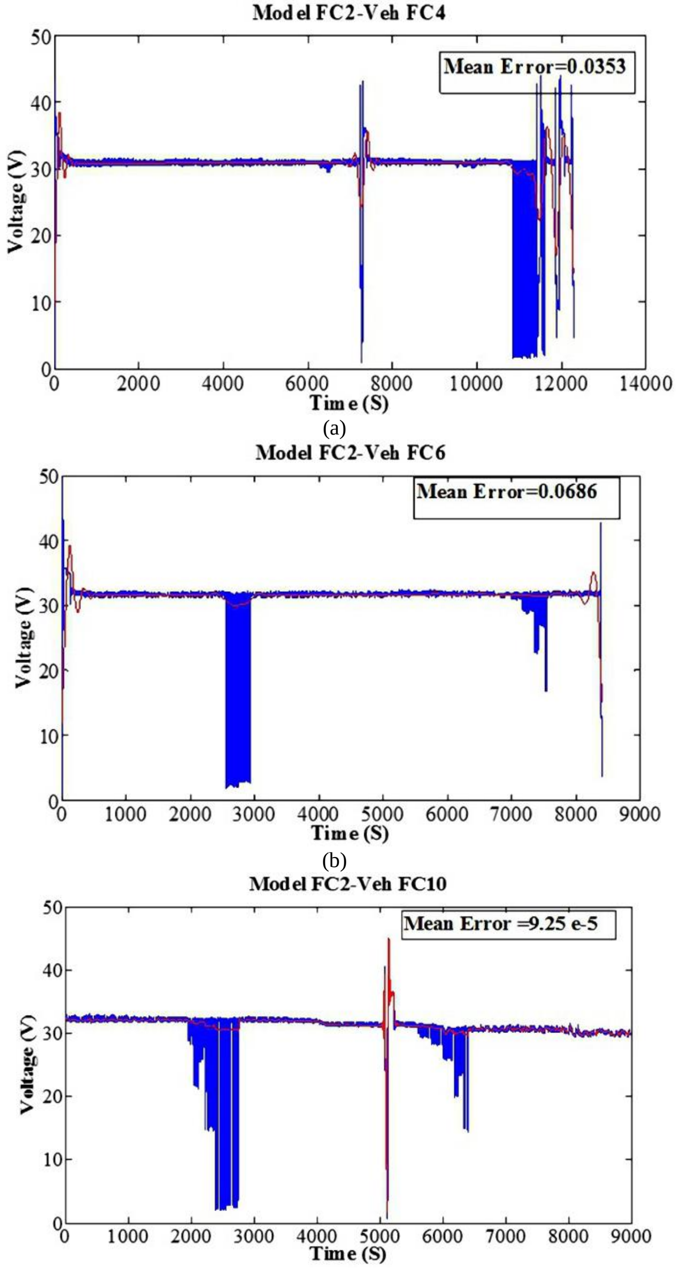
In this figure, the quality of the fitting between the model and the experimental data, is measured by the mean error, defined by:

$$E = \frac{1}{n}\sum_1^n |y_i - \hat{y}_i| \qquad (11)$$

Where n is the total number of observation, y_i is the observation and $\hat{y}_i$ is the model at time i.

Three different FC of three different vehicles are used to validate the ARX model. As shown in this figure, the error is very minimal, less than 0.06, or 6%. The results show a good accuracy of the ARX model for fuel cell systems in the Mobypost electric vehicles.

In addition, in this figure, some short circuit happened, and being presented: between 7020 and 7030 s for Vehicle 4, between 8030 and 8040 s for vehicle 6 and between 5000 and 5010 s for vehicle 10. The ARX model (in red line) are able to fit and follow these variations, which can be a very interesting result. The model can also follow sharp variation and fast transient in the voltage signal.



(a)

(b)

(c)

Fig11. Comparison model FC two with other FCs data.

VI. CONCLUSIONS

This work is focuses on constructing a robust model for a PEMFC onboard a hybrid electric vehicle designed for Mobypost vehicles. The model is based on the identification technology, namely the ARX model. The inputs for this model are: current, mass flow, temperature and pressure, whereas the output is the voltage. After removing the noises from the input data by using the Wavelet Transform technique. The ARX model was found to be robust enough to provide a fit of the voltage with very low error, in both steady state and dynamic conditions. The model firstly was tested using data from one vehicle in one day, then the same model was applied by using different data from different vehicles and different days, with variable weather and operating condition. The model shows an accurate fitting for these data as well.

The present work will be used for a degradation model of the PEMFC in hybrid electrical vehicles application. To reach this aim, a robust and reliable model of voltage presented in this article. To continue the next step, this model will be used in order to predict the degradation in the fuel cell. Using the ARX model, the Remaining Useful Lifetime (RUL) of the PEMFC could be predicted.

ACKNOWLEDGMENTS

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