Energy Management and Performance Evaluation of Fuel Cell Battery Based Electric Vehicle

Ahmed Khadhraoui[1], **Tarek SELMI**[2], and **Adnene Cherif**[3]
Ahmed.khadhraoui@fst.utm.tn
Analysis and treatment of electrical and energy signals and systems (ATSSEE) Laboratory,
Faculty of Sciences of Tunis, Tunis Al-Manar University, 2092- Tunisia.

Abstract
Plug-in Hybrid electric vehicles (PHEV) show great potential to reduce gas emission, improve fuel efficiency and offer more driving range flexibility. Moreover, PHEV help to preserve the eco-system, climate changes and reduce the high demand for fossil fuels. To address this; some basic components and energy resources have been used, such as batteries and proton exchange membrane (PEM) fuel cells (FCs). However, the FC remains unsatisfactory in terms of power density and response. In light of the above, an electric storage system (ESS) seems to be a promising solution to resolve this issue, especially when it comes to the transient phase. In addition to the FC, a storage system made-up of an ultra-battery UB is proposed within this paper. The association of the FC and the UB lead to the so-called Fuel Cell Battery Electric Vehicle (FCBEV). The energy consumption model of a FCBEV has been built considering the power losses of the fuel cell, electric motor, the state of charge (SOC) of the battery, and brakes. To do so, the implementing a reinforcement-learning energy management strategy (EMS) has been carried out and the fuel cell efficiency has been optimized while minimizing the hydrogen fuel consummation per 100km. Within this paper the adopted approach over numerous driving cycles of the FCBEV has shown promising results.

Keywords:
Fuel cell; Electric vehicle; Eco-driving; Speed profile optimization.

1. Introduction

Hybrid Electric Vehicles (HEV) are vehicles using electric motors instead of internal combustion engine motors (ICE) [1]. In fact, Electric Vehicles (EVs) relying on electric motors, although the power source varies according to the user's expected efficiency [2]. The EV has numerous advantages listed next: high speed, zero-emission, and high efficiency. The main challenge remains the low battery capacity in terms of charging cycles [3]. to get rid of the above-mentioned issue, researchers are continuously trying to develop battery technologies such as the lion technologies characterized by their high energy storage capacity, their low weight and size, and their quiet long lifetime compared to other competitors. The FCEV has higher autonomy and lasts longer in terms of distance, respectively, compared to the BEV. When it comes to refueling, the FCEV takes only 5 minutes unlike the BEV that needs around seven hours to be fully charged [4]. However, and due to the lack of refueling stations worldwide, it seems compulsory to add an alternative source of energy to the FC. This is to say an extra battery and the entire system becomes the so-called Fuel-Cell-Battery-Electric-Vehicle (FCBEV) [5]. Likewise, the authors of [6], have come with a promising solution that consists of replacing the battery with a supercapacitor SCAP thanks to the performance of the later compared to a conventional battery. For the sake of better energy sustainability, it has been proposed in [7] and [8] a solution consisting of a system made up of the FC, the Battery, and the SC. Although the later system seems to be promising, it is bulky, expensive, and hard to troubleshoot. In light of the above, this paper considers the FCBEV in terms of energy management. In fact, a novel algorithm of energy management has been developed and tested taking into account a virtual road called FTP-75. Accordingly, an Energy Management System (EMS) has been carried out to control the vehicle's power by feeding a portion of the output to the input. The proposed algorithm shows encouraging real-time responses and it considers the load carried by the vehicle.

2. The FCBEV configuration

The FCBEV shown in Figure 1 is made up of a FC along with a battery. if the output current of the FC is not stable at a fixed level, a DC-DC converter is inserted between the FC and the DC-AC inverter that feeds the permanent magnet Synchronous motor PMSM. The Battery, considered as the alternative energy source, is connected to a bidirectional converter, as shown in figure 1. The EMS explained above controls the entire systems in terms of energy exploitation.

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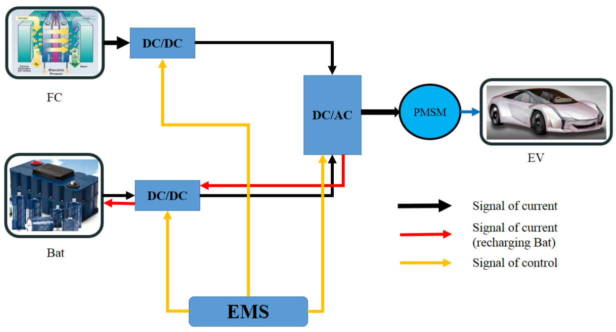

Fig 1: The main structure of the FCBEV.

2.1 Fuel Cell Modeling

Nowadays, proton exchange membrane fuel cells, also known as electrolyte polymer membrane fuel cells (PEMFC: Proton Exchange Membrane Fuel Cells or Polymer Electrolyte Membrane Fuel Cells) are the most common batteries in mobility applications [9]. its configuration and working principle are explained next

The PEMFC considered is made up of three parts: a cathode and an anode, which act as electrolytes, and the membrane. The block diagram of a conventional FC is shown in Figure 2.

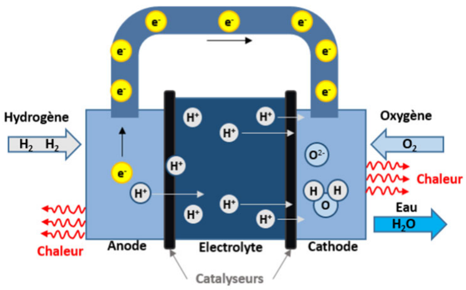

Fig 2: Fuel Cell Schematic

The PEMFC is integrated into the electric vehicle system with auxiliary components such as the electric control unit and the cooling fan to ensure better operation in terms of electricity production [10]. At the anode, the hydrogen molecules are divided into electrons and protons according to the hydrogen oxidation reaction, given below:

$$H_2 \rightarrow 2H^+ + 2e^- \qquad (1)$$

As shown in Figure 3, the electrical diagram, is made up of a voltage source connected to a resistor after which a current sensor is inserted. The sensed current is fed to the control block and compared to the vacuum voltage (E_{nernst}). The FC voltage is therefore calculated. By subtracting losses from the open-circuit voltage of the FC, the potential of the FC could be found:

$$\{V_{stack} = N_{cell}.V_{cell}\ V_{stack} = N_{cell}.(E_{nernst} - V_{act} - V_{ohm} - V_{com}) \qquad (2)$$

Where (E) is generator voltage as shown in Figure 3 and equation (3):

$$E = E^0 + \frac{RT}{F} Ln\left(\frac{PH_2PO_2^{0.5}}{PH_2O}\right) \qquad (3)$$

The activation voltage depends on the Kinematic phenomena and the oxygen concentration given in equation (4).

$$V_{act} = [\xi_1 + \xi_2.T + \xi_3.T.Ln(C_{O_2}) + \xi_4.T.Ln(I)]\ C_{O_2} = \frac{P_{O_2}}{5.08 * 10^6 e^{\frac{-498}{T}}} \qquad (4)$$

$$V_{ohm} = R_m.I \qquad (5)$$

$$R_m = \frac{\rho_m.l}{A} \qquad (6)$$

$$E_{Nernst} = 1.229 - 0.85 * 10^{-3}(T - 298.15) + 4.3085 * 10^{-5}T[ln\ ln\ (P_{H_2}) + 0.5 * ln(P_{O_2})] \qquad (7)$$

$$V_{ohm} = R_m.I \qquad (8)$$

$$V_{com} = -B\left(1 - \left(\frac{I}{J_{max}}\right)\right) \qquad (9)$$

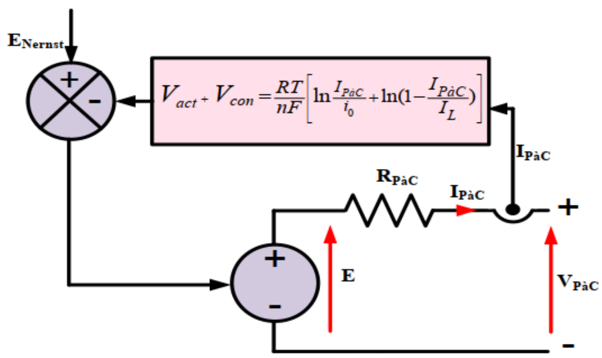

Fig 3: Equivalent model of the Fuel Cell Electrical

2.2 Battery Modeling

Although lot of modeling techniques are available to describe the behavior of the battery, its electric model remains the most accurate one. In fact, models based on equivalent electrical diagrams (based on ideal voltage generators, resistors, capacitors, etc.) provide better accuracy in terms of battery's electrical behavior [11]. The equivalent electrical model of the battery considered within this paper is given in Figure 4. Its diagram consists of a voltage source connected in series to a resistor. The elements the diagram of Figure 4 (V_{oc} vacuum voltage and R_{int} load and discharge internal resistor) depend on the state of charge of the battery referred to as Battery SOC.

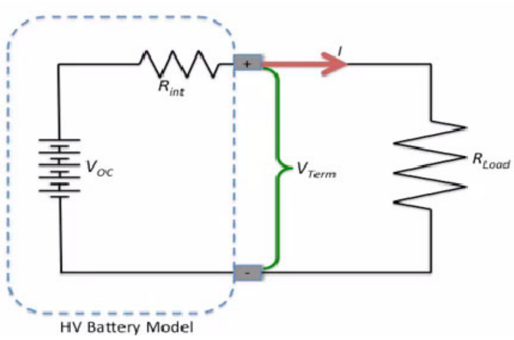

Fig 4: Equivalent Battery model

The current of the battery is given by equation (10):

$$I = V_{oc} - \sqrt{\frac{V_{oc}^2 - 4R_{int}P_{actual}}{2R_{int}}} \quad (10)$$

$$V_{term} = V_{oc} - IR_{int} \quad (11)$$

The new state of charge "SOC_{new}" is given based on the previous state of charge, "SOC_{old}" as presented in equation (12):

$$SOC_{new} = SOC_{old} + 100\left(\frac{dE_{int}}{E}\right) \quad (12)$$

The ideal power "P_{ideal}" is given next:

$$P_{ideal} = P_{actual} + P_{loss} \quad (13)$$

$$P_{loss} = I^2R_{int} \quad (14)$$

$$P_{ideal} = IV_{OC} \quad (15)$$

$$P_{actual} = IV_{OC} - I^2R_{int} \quad (16)$$

2.3 Vehicle Modeling

Commonly speaking, EVs require certain energy called $E_v$which is given by equation (17). Moreover, the dynamic behavior of the car is in general described by the classical equations of mechanics given in equations (18) and (19), respectively [12].

$$E_v = \int_0^t P_v dt \quad (17)$$

The power P_v is expressed as function of the total traction torque, C_T, and the wheel speed, Ω_r, as follows:

$$P_v = C_T\,\Omega_r \quad (18)$$

$$C_T = F_T.r\,;\ \Omega_r = \frac{v}{r} \quad (19)$$

Where F_T presents the tractive force exerted on the vehicle at the contact level between the tires of the driving wheels and the road surface enabling the vehicle to be run forward, v and r are respectively, the vehicle's speed and wheel radius.

Consequently, according to Newton's second law, the acceleration of the vehicle, α , can be expressed by.

$$\alpha = \frac{F_{tr} - (F_{aero} + F_{grade} + F_{rr})}{m_i} \quad (20)$$

As shown in Figure 5, the traction force used within the mathematical model is the algebraic sum of the inertial force, F_i , the aerodynamic drag, F_{aero} , the rolling resistance, F_{rr} , and the grade force, F_{grade} , respectively. Such force is given in (21):

$$F_T = F_{aero} + F_i + F_{grade} + F_{rr} \quad (21)$$

F_{aero} is the aerodynamic drag is the air resistance against the vehicle direction. It depends on the air density, the frontal surface A_F , the air penetration coefficient C_d of the vehicle and the vehicle speed V as expressed next:

$$F_{aero} = \frac{1}{2}\rho C_d A_f V^2 \quad (22)$$

F_{rr} is the rolling resistance of the vehicle, that acts at the contact point between the tires and the roadway and it behaves against the free movement of the vehicle.

$$F_{rr} = mgC_{rr} \quad (23)$$

F_{grade} is the resistance force of hill climb, also called gravity force of the vehicle. It is function of the slope inclination as well as the vehicle's weight as given in (24). :

$$F_{grade} = mgsin\,(\theta) \quad (24)$$

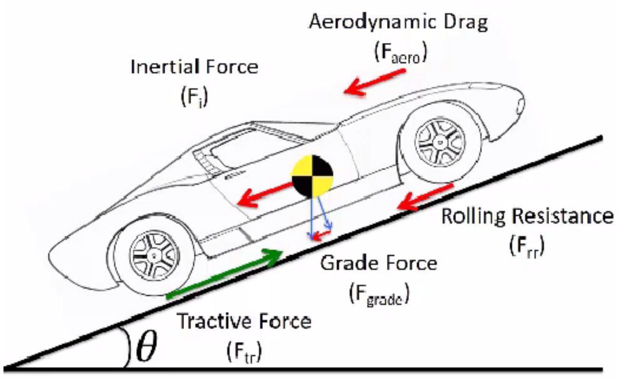

Fig 5: All tractive force of vehicle

3. ENERGY MANAGEMENT (EM)

3.1 Types of EM

The energy management system controls the compatibility of the required power/energy and the required vehicle's speed. It acts as a smart calculator in charge of the ratio speed to fuel consumption for the sake of energy optimisation. With this in mind, three principal methods of energy optimization could be addressed:

- Dynamic programming methods: Such methods considers initial and final conditions along with a predefined riding cycle. This method is no longer used due to its low efficiency in terms of energy optimisation [13].
- Optimal control methods: Although this method is not universal, it has proven higher efficiency and it acts in real-time mode. [14]. A major drawback of this method is that it takes long calculation times.
- Intelligent techniques: This method neural network-based and it showed certain superiority other the two method previously discussed [15]. The major drawback of such method is that it needs high performance and fast digital signal processors (DSP).

3.2 Proposed energy management system

Figure 6 shows the basic components of the proposed EM.

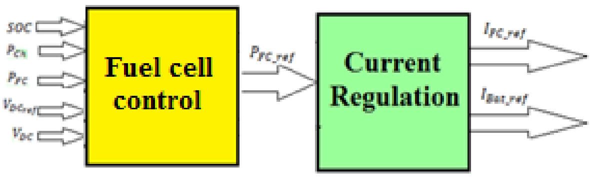

Fig 6: Global structure using a rule-based algorithm.

The EMS is made up of fuel cell control subsystem feeding a current regulator. Their is described in every single detail in the algorithm of Figure 8. Within the proposed EMS, the main source is the FC, and the battery is the secondary one. For better understanding of the EMS and its configuration one can distinguish three possible operation modes, which are denoted P_{Ch}, namely the "stop" mode, the "traction" mode, and the "braking" mode, respectively. These modes are defined by the sign of the vehicle's power, as shown by the flowchart given in Figure 7. This is to say a positive sign defines the power supplied at the traction phase by the energy storage system (ESS) while the recovered power is considered, by convention, negative [16].

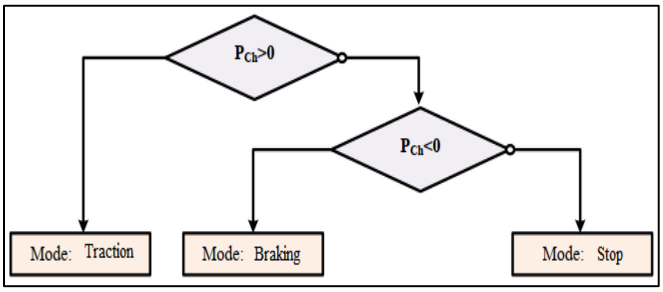

Fig 7: Operating modes of a FCBEV

To optimise the hydrogen consumption, the proposed algorithm of Figure 8 seems to have promising effects at the expense of the FC power, denoted P_{FC}. As shown in Figure 6, a number of six parameters are fed to the EMS to output the desired level of the FC power. . On the other hand, the battery capacity is limited and may not handle all the power suggested by the EMS. To overcome such incompatibility that could take place, the EMS draws its necessary power directly from the FC. One can be aware that the full charge and the deep discharge situations should be avoided for security reasons. Such phenomenon is highlighted in equation (25):

$$P_{Ch} = P_{FC} + P_{Bat} \qquad (25)$$

To improve the EMS, the upper and lower charge levels $SOC_{Bat_{max}}$,SOC_{Bat_min} respectively have been defined with regards to the P_{Ch},

$$V_{Bat\_min} < V_{Bat} < V_{Bat\_max} \qquad (26)$$

The algorithm adopted uses regulation blocks making it possible to control the converters used to interface the sources. The references of the powers of the FC and of the battery are obtained from the algorithm presented in Figure 8.

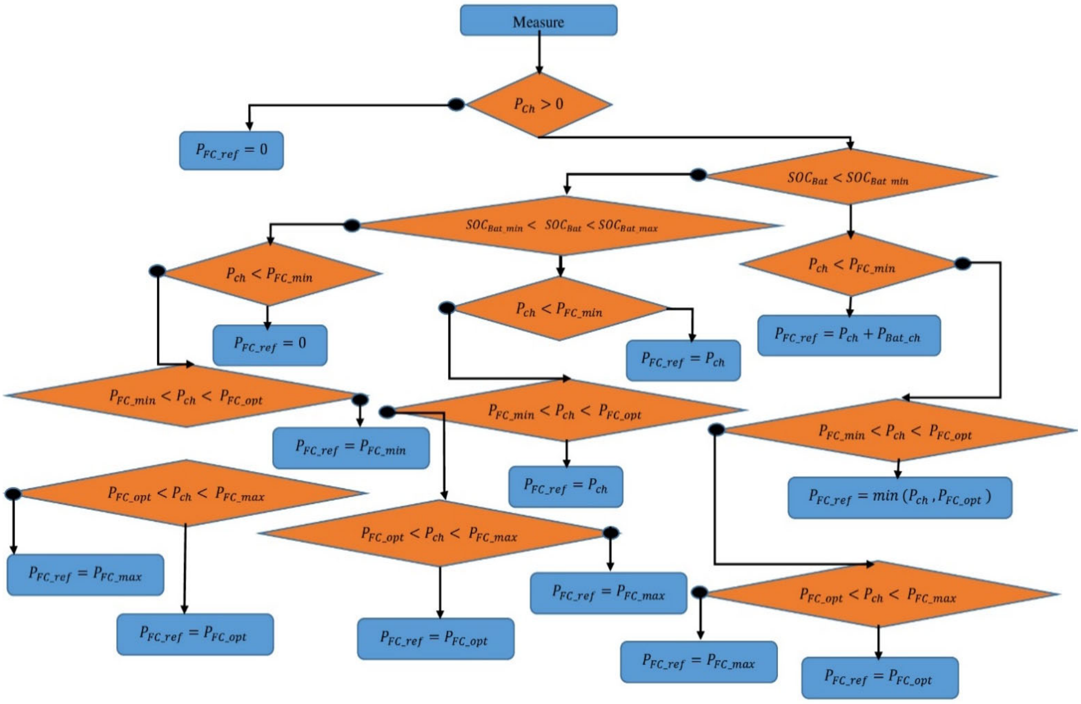

Fig 8: Algorithm of EMS proposed

4. Results and discussion

The proposed EMS has been developed mainly to manage the FCBEV energy consumption. The developed model has been carried out through Matlab/SIMULINK graphical environment. The FTP-75 has been used and the time has been set to 1400 seconds. The obtained results have granted a special focus to the combination of the FC and the battery in terms of motor energy supply. The vehicle's speed managed by the proposed EMS is shown in Figure 9 and the obtained results are in full agreement with the expected ones. Figures 10, 11, 12 and 13 are the power delivered to the load, the FC-battery current, the battery's SOC and the consumed amount of hydrogen, respectively. . Using the FTP-75, the vehicle has run for almost 18 km with a speed exceeding 37 km/h. Such results are clearly shown in Figure 9.

up to 505 seconds, the vehicle passed across its cold starting transient period characterized by a significant vibration before reaching its highest speed. Then, the cycle has been stable up to 1372 seconds at an intermediate speed. Finally, the vehicle's speed has returned to zero for the rest of the cycle (1400 seconds). The maximum power produced, $P_{Ch} = 45kW$, in during a maximum of 192 seconds is shown in Figure 10.

In Figure 11, it is shown clearly that at the starting of the cycle, the current is totally drawn from the battery for a certain time, then, the EMS switches the process and current is taken from the FC for the rest of the cycle. One can notice that during any braking event, the FC stands by and the battery passes to the recharging phase, although the braking time is as short as it lasts for the braking event delay. It is a common practice that the FC is slower in terms of operation response and that is why the battery is supposed to start to power the electric motor. In light of the above, in Figure 11, the voltage measured across the battery terminals varies according to the vehicle's status. . Furthermore, the SOC varies between 48.5% and 60% to as shown in Figure 12.

According to the results presented in Figures 12 and 13, the FC remains almost all the time as the primary energy source and such behaviour increases significantly the range anxiety of the battery for only 2.5 litters of hydrogen per hundred kilometers.

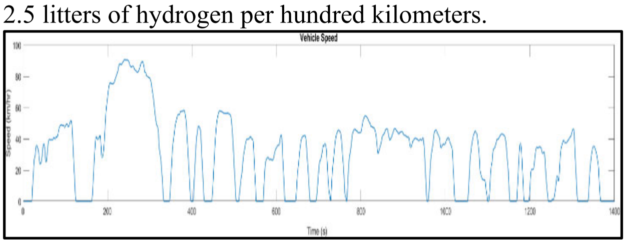

Fig 9: Vehicle speed

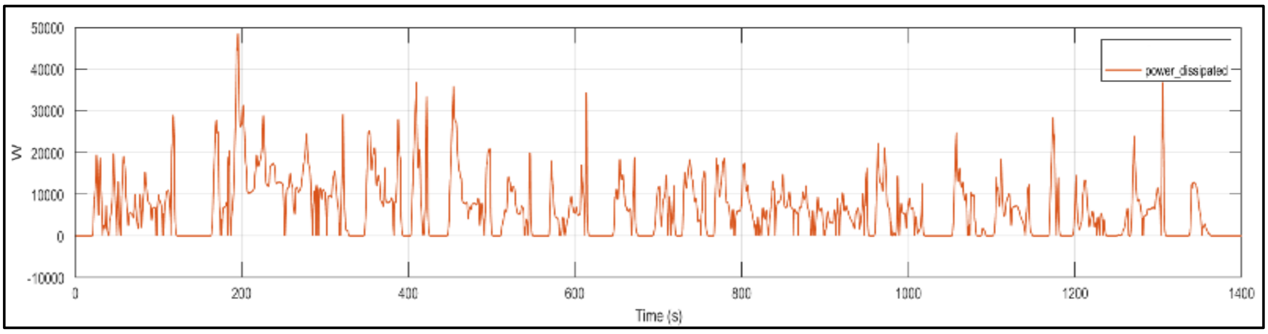

Fig 10: Power of charge

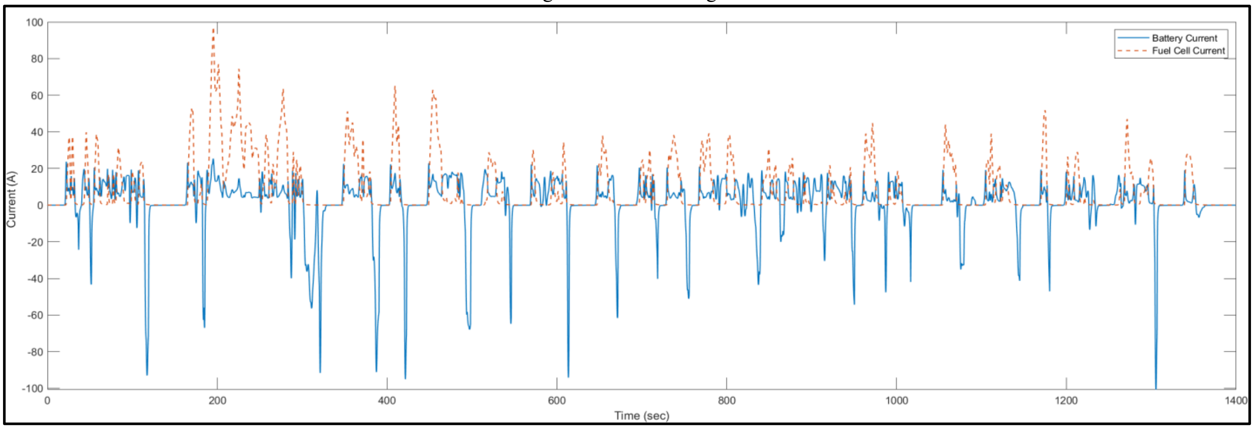

Fig 11: Bat and FC Current

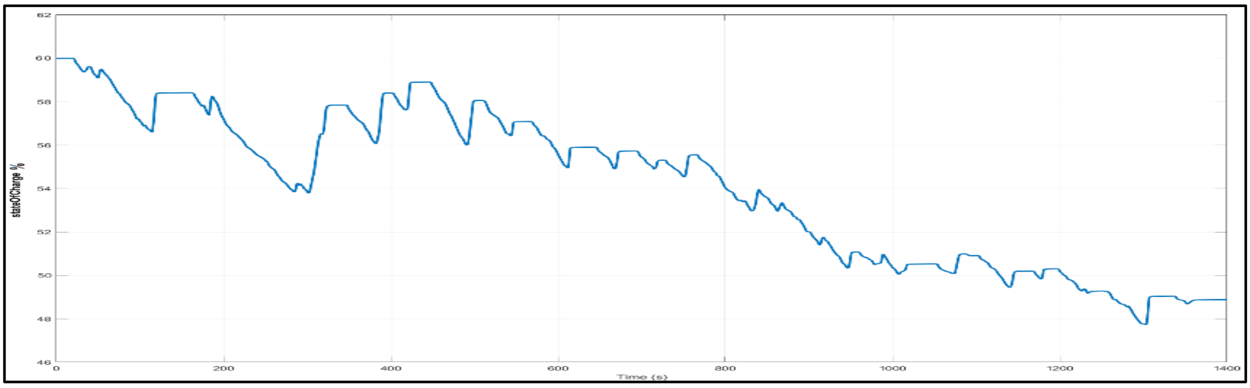

Fig 12: SOC of Battery (%)

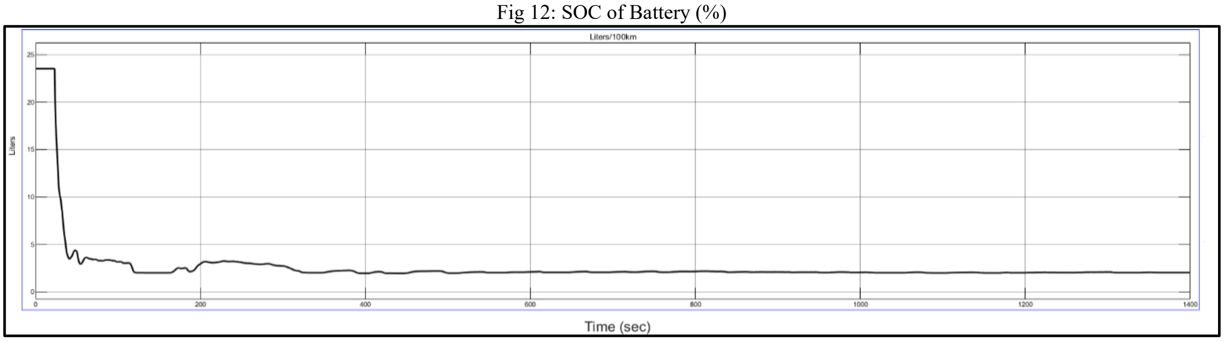

Fig 13: hydrogen consumed for 100km

5. Conclusion

This paper dealt with an energy management system (EMS) for fuel cell/battery electric vehicles (FCBEVs). particularly, FCBEV modeling has been carried out, and then a monitoring and management system (EMS) has been developed, investigated, and analyzed in detail while highlighting the structure and performance. The analysis of the FCBEV focused on hydrogen consumption along with the simultaneous battery autonomy and refueling for the sake of longer range and lower price.

the obtained results are in full agreement with the theoretical expectations and could serve as a useful reference for FCEVs researchers and manufactures. The FC, although it is efficient in terms of energy supply, it does not respond quickly and this drawback has been addressed by adding an extra battery. In general, the developed EMS has shown high efficiency but a small room for improvement still exists which will be the focus of future research.

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Appendix: parameters

Table 1: Parameters of elements

Element	***Name of parameter***	Value
Fuel cell	Fuel cell area	280 cm2
	Membrane thickness	0.01275 cm
	Exchange current density	exp(-5.4) A/cm2
	Max current density	1.4 A/cm2
	Transfer coefficient	0.5
	Membrane dry density	0.002 kg/cm3
	Membrane dry weight	1.1 kg/mol
Battery	Pack Voltage	272.9 V
	Capacity	3.2 Ah
	SOC	60%
	Temperature	27 C
	$SOC\ Bat\ max$	90%
	$SOC\ Bat\ min$	20%
Vehicle	Vehicle mass	1300 K_g
	gravity	9.8 m/s^2
	Air density	1.18 kg/m3
	Road angle	0.5 degrees
Motor	k_c	0.12
	k_i	0.01
	k_ω	0.000012
	C	600

Khadhraoui Ahmed received the B.E. and M.E. degrees, from university of Tunis El Manar 2011 and 2017, respectively. He started the Ph.D in 2017 in university of Tunis El Manar. After working as a temporary assistant professor in the Dept. of physics, in university of Tunis El Manar. Her research interest includes the use of renewed energy on electric vehicle.
Email: Ahmed.khadhraoui@fst.utm.tn

Selmi Tarek received his B.Sc. degree from Tunis University of Sciences in 2002, his M.Sc. degree from Monastir University of Sciences in 2007 and the PhD degree from the National Engineering School of Sfax, Tunisia in 2013. He joined the Tunisian Ministry of Higher Education in 2002 and the Oman Ministry of Manpower in 2008 where he worked as a power electronics instructor and a coordinator of the Electronics Department for 3 years. Then, he worked as an Assistant professor at the Australian College of Kuwait for three years and served as a deputy head of the electrical engineering department. Dr. Tarek worked as an assistant professor in Electrical Engineering at Sohar University, Oman. Currently he is an Assistant Professor at High Institute of Applied Sciences and Technology, University of Kairouan. Dr Tarek has published more than 35 journal papers on power electronics, Electric Vehicles and Artificial Intelligence.
Email: t.selmi@issatkr.u-kairouan.tn