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Optimization of Hydrogen Consumption for Fuel Cell Hybrid Vehicle

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Abstract

Objective: To minimize the hydrogen consumption in hybrid fuel cell/super capacitor vehicle tested with a proposed energy management. **Methods:** The studied system consists of two energy sources: namely Proton Exchange Membrane (PEM) Fuel Cell and a super capacitor. So we propose a new architecture system controlled through a proposed energy flow management approach which determines the power demand between the PEM fuel cell, super capacitor and the load. **Findings:** The control strategy tested with the different driving cycle's exhibit excellent performance in order to minimize the hydrogen consumption. A simulation model for the power train proposed is simulated and tested by using Matlab/Simulink software, in order to verify the efficiency of our proposed approach. **Applications:** This work will be followed by implementing the proposed system on an embedded electronic board such us FPGAs, STM32s.

Keywords: Energy Management, Hydrogen Consumption, Hybrid Vehicle, PEM Fuel Cell, Power Train, Super Capacitor

1. Introduction

Fuel Cell Hybrid Vehicles (FCHVs) are composed of a primary source: the PEM fuel cell and an energy storage system: a super capacitor is a promising technology able to reduce the fuel consumption[1]. Among all types, PEM Fuel Cell is considered the prime preference to be used in transportation sector due to their high power density, low operating temperature[2,3]. Thus, we will use this type of fuel cell in our work. However, the PEM Fuel Cell is not always sufficient to satisfy the load demands due to the high- propulsion system demands[4]. To solve this problem, the integration a secondary source can help reducing the problem of fuel consumption.

In these cases, Many works are presented in literature where discussed the advantageous of the additional energy storage in vehicle. In the literature, different strategies have been studied. In[5] proposed a system composed of a PEM (Fuel Cell) and a super capacitor dedicated to the hybrid electric vehicle. The presented work made a study the integration of a super capacitor as a secondary storage source. It gives an evaluation of an energy management strategy based on optimal control dedicated to the adopted system. However, the studied work given by[6] proposed batteries as a secondary source. The work can full fill the power requested by the driver with the minimum fuel consumption based on model predictive control. The studied system given by[7] included batteries with fuel cell and super capacitor. The work presented the advantageous of the combination for the three sources. The work has treated the efficiency made by the fuzzy logic control in reduction of the hydrogen consumption for the fuel cell/SC/batteries hybrid vehicle.

Referring to previous cited works, we develop a detailed model of a hybrid vehicle system based on a fuel cell/super capacitor sources. In this paper, we present a proposed energy management algorithm allows to minimize the fuel cell power tested with four driving cycles. This strategy provides a gain in hydrogen consumption. The paper is structured as follows: section 2 gives a general

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description of the studied system and its components. In Section 3 we will present the model of electric vehicle system. The energy management proposed to minimize the fuel consumption is presented in section 4. Section 5 is the results of this work; it serves to validate the proposed energy management. Finally, the last section presents the obtained simulation results.

2. General Overview of the Studied System

2.1 Description of the Fuel Cell Hybrid Vehicle

The proposed power train composed of the primary source is PEM fuel cell and the super capacitor as a second source. The voltage of the fuel cell is less than the DC bus voltage that it is necessary connects to a boost converter which raises the low voltage delivered by the PEM fuel Cell. The extremity of the DC bus is connected to an inverter that powers the motor. On the other side, the energy storage needs a buck/boost converter to supply power during transient periods and to recover the braking energy. The coefficient values of the components vehicle specifications are depicted in Table 1.

Table 1. The components vehicle specifications

Components	Specifications
PEM fuel cell	85 Kw
Super capacitor	Capacity:63 F
Electric motor	85 kW
Total vehicle mass	1800 Kg

2.2 Modeling of the PEM Fuel Cell

The principle operation of the PEM fuel cell is to produce electricity, water; heat. It is based on the reverse process of electrolysis of water. The electro-chemical reactions of a PEM fuel cell in during the functioning of PEM fuel cell are given by the following equations[8,9].

Anode reaction: $H_2 \rightarrow 2H^+ + 2e^-$ (1)

Cathode reaction: $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$ (2)

Overall Reaction: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$ (3)

The primary objective of this paper is to study the mathematical model of PEMFC. The output of PEM Fuel Cell is a function of Nernst voltage, activation loss, Ohmic loss and concentration loss[10].

The cell voltage of PEMFC is defined by the following equation:

$$V_{PEMFC} = E_{nerst} - \Delta v_{fc} \tag{4}$$

Where the reversible or Nernst voltage is defined as:

$$E_{nerst} = E^0 - RT\ln \frac{PH_2 \sqrt{P_{O2}}}{PH_2o} \tag{5}$$

Where, E_{nerst} is Voltage Nernst and P_{H2},P_{O2}, is Partial pressure of hydrogen ,oxygen and water .The Nernst voltage simulink model is presented in Figure 1.

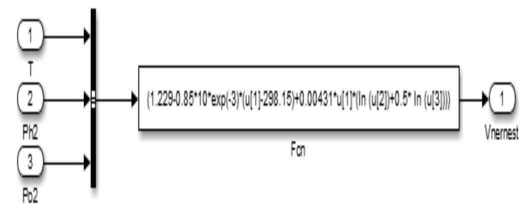


Figure 1. Nernst voltage simulink model.

All these losses are combined and can be represented as:

$$\Delta V_{FC} = A \ln\left(\frac{i}{i_0}\right) + iR_m - \frac{RT}{2F} \ln\left(1 - \frac{j}{j_{max}}\right) \tag{6}$$

V_{act} is activation Voltage losses, V_{ohm} is Ohmic Voltage losses, V_{con} is Concentration Voltage losses, V
i is Current of PEMFC, F is Faraday coefficient, A is Tafel slope for the activation losses, $i_0$is Exchange current density for the activation, R_m is Equivalent specific resistance for the ohmic losses, $j_{max}$is Maximal current density for the concentration.

Table 2. Parameters of PEMFC MK 902

Rated net output of power (KW)	85
Current (A)	300
DC voltage (V)	280
Temperature (°C)	80
Fuel pressure (bar)	1
Air pressure(bar)	1
Length x width x height(mm)	805x375x250
Weight(Kg)	96
Volume(liters)	76

In this work, we used a NEXA PEM fuel cell from Ballard with a continuous maximum power output of 85 kilowatts[11]. Table 2 presents the different parameters of the PEMFC MK 902.

2.3 The Boost Converter Model

The voltage of the fuel cell is lower than the DC bus voltage. For many applications, this voltage is insufficient, hence there's need to introduce a boost converter to regulate the output voltage of fuel cell. Figure 2 shows the DC-DC converter composed of an inductance L, a capacitance C, a diode D, a principal switch Mosfet and the output is loaded with a resistance R. The characteristics of the DC-DC boost converter are given by the following Table 3.

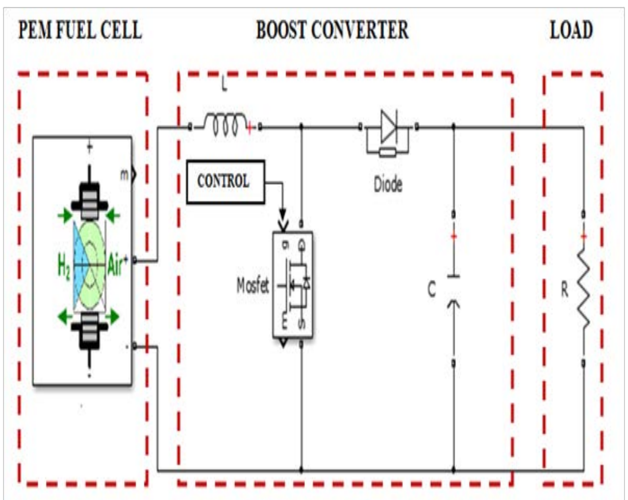


Figure .2. Electrical model boost converter

Table 3. Parameters of boost converter

Parameters	Values	Units
Inductance L	10	mH
Capacitance C	470	µF
Resistance R	100	Ω

When the Mosfet is ON the equations of the inductor current $i_L(t)$ and the output voltage Vo are given by the following equations:

$$\frac{d_{iL}}{dt} = \frac{1}{L} V_{in} \tag{7}$$

$$\frac{dv_0}{dt} = -\frac{v_0}{RC} \tag{8}$$

When the mosfets witch is OFF the equations of the inductor current $i_L(t)$ and the output voltage Vo are given by

$$\frac{di_L}{dt} = \frac{1}{L}(V_{in} - V_0) \tag{9}$$

$$\frac{dv_0}{dt} \quad \frac{\ }{C}(i_L \quad \frac{0}{\ }) \tag{10}$$

The mathematical model of boost converter is given by equations (11) and (12)

$$L\frac{d_{iL}}{dt} = V_{in} - V_o(1-D) \tag{11}$$

$$C\frac{dV_{vo}}{dt} = i_L(1-D) - \frac{V_o}{R} \tag{12}$$

The duty ratio D is given by the following equation:

$$D = 1 - \frac{V_{in}}{V_o} \tag{13}$$

By involving the preceding relations, we should have in matrix writing:

$$\begin{bmatrix} v_o \\ i_L \end{bmatrix} = \begin{bmatrix} 0 & \frac{-(1-\alpha)}{L} \\ \frac{1-\alpha}{C} & -\frac{1}{R_c} \end{bmatrix} \cdot \begin{bmatrix} v_o \\ i_L \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} .Vin \tag{14}$$

Figure 3 shows the boost converter simulink model.

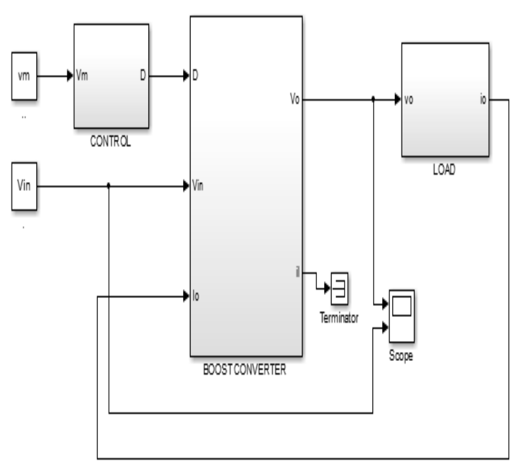


Figure 3. Boost converter simulink model.

2.4 Inverter

A three phased inverter is generally composed of three arms, each one is composed of two electronic switches, and in this case we used a MOSFET transistor and a parallel diode for each switch.

The Simulink diagram of a PWM control is shown in the Figure 4.

The three voltages are given by the following equations:

$$V_{s1} = \frac{E}{3}\left(2.C_1 - C_2 - C_3\right) \tag{15}$$

$$V_{s2} = \frac{E}{3}\left(2.C_2 - C_3 - C_1\right) \tag{16}$$

$$V_{s3} = \frac{E}{3}\left(2.C_3 - C_1 - C_2\right) \tag{17}$$

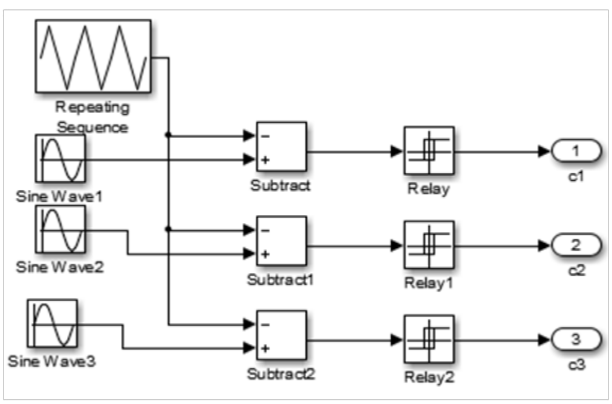


Figure 4. Simulink model of the PWM control.

The Simulink diagram of a voltage inverter is shown in Figure 5 and 6.

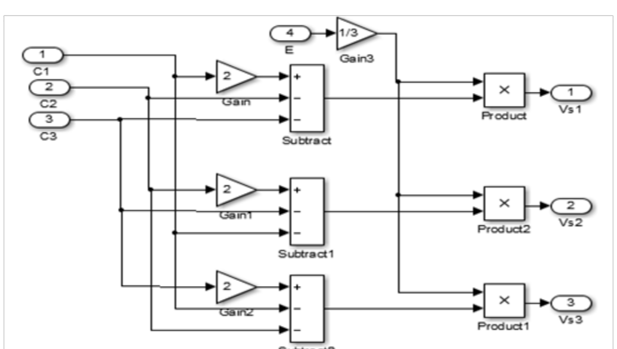


Figure 5. Simulink model of the voltage $V_{BUS.}$

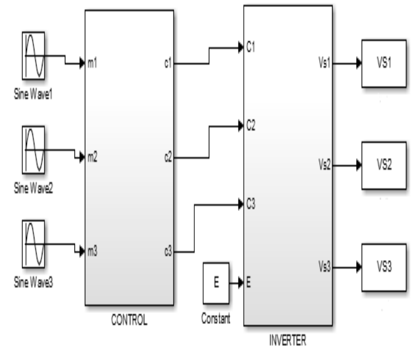


Figure 6. Simulink model of the inverter.

2.5 Super-capacitor

Several works of a super capacitor are presented in[12,13] have been defined the most popular model composed of a capacitor connected in series with a resistor. In this work, we have chosen this type of energy storage because of its high power densities, and its unlimited number of charge and discharge compared to the different types of battery.

The power and the output voltage of super capacitor are detailed by the following equations:

$$U_{sc} = V_s - RI_{sc} \tag{17}$$

$$P_{sc} = U_{sc} I_{sc} \tag{18}$$

The state of charge (SOC) of super-capacitor is defined as the ratio of E to E_{max}:

$$SOC = \frac{E}{E_{max}} \tag{19}$$

The energy of super-capacitor can be written as

$$E = \frac{1}{2} c_{SC} u_{sc}^2 \tag{20}$$

$$E_{max} = \frac{1}{2} c_{sc} u_{sc-max}^2 \tag{21}$$

where, CSC is Capacity of the super capacitor, E is Vacuum voltage of a super capacitor, E_{max} is Maximum open circuit voltage of a super capacitor, I_{SC} is Super capacitor current, R is internal resistance of a super capacitor, SOC is State of charge, U_{SC} is Voltage of the super capacitor A 63F Maxwell BMOD0063-P125B08 module[14] is used in this work.

3. Electric Vehicle Model

The vehicle is considered as a solid point on the road subjected to three forces along the longitudinal axis.
The rolling resistance force F_{tire} is given as follow:

$$F_r = mgc_r\cos(\beta) \tag{22}$$

The aerodynamic force F_{aero} given by the following expression:

$$F_a = \frac{1}{2}\rho_{air} A_f c_d v^2 \tag{23}$$

The inclination force F_{slope} is:

$$F_i = mg\sin(\beta) \tag{24}$$

The total force is given as follow:

$$F_t = F_r + F_i + F_a \tag{25}$$

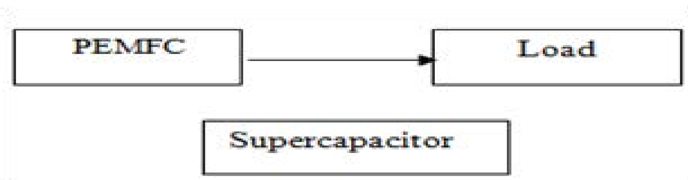
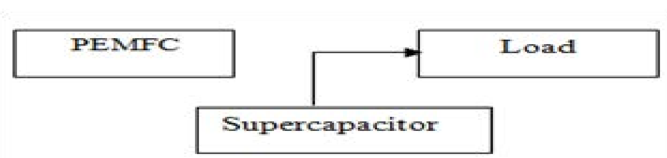
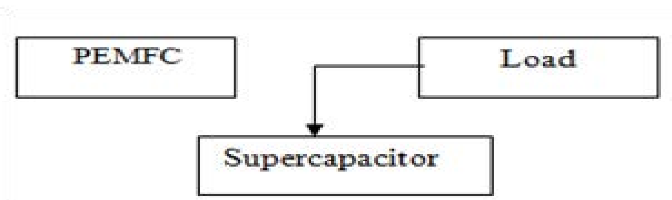
where, β is Road slope angle, ρ_{air} is Air density, F_{aero} is effort of aerodynamic resistance, A_f is Front area of the vehicle, C_x is Aerodynamic drag coefficient, F_{slope} is Resistance of mounted side, g is Gravitational acceleration.

4. Power Management Strategy

The energy flows between the load and the power sources are controlled by the energy management algorithm which determines the power demand between the PEM fuel cell, the energy storage and the load during the various driving phases in order to optimize the hydrogen consumption.

Many works are presented in literature describes the control theory of power distribution and power management: dynamic programming[15], neural network[16] optimal control[17,18] and fuzzy logic control[19,20].One of the main

Table 4. Different modes of fuel cell hybrid vehicle

Mode	Diagram of flux energies	Description
Mode 1 Stopping		No energy flow
Mode 2 Steady speed		The PEM fuel cell supplies the load
Mode3 Traction		The SC delivers a power which used to supply the load.
Mode 4 Braking		The load receives the power from the storage system

objectives of the energy management strategy to minimize the hydrogen consumption.

The Figure 7 describes the proposed energy management algorithm chosen. Table 4 presents the different modes of FCHV during the various driving phases.

We have chosen a load as a Permanent Magnet Synchronous Motor (PMSM) because is a small volume, high efficiency and high power density compared to other types of motors[21].

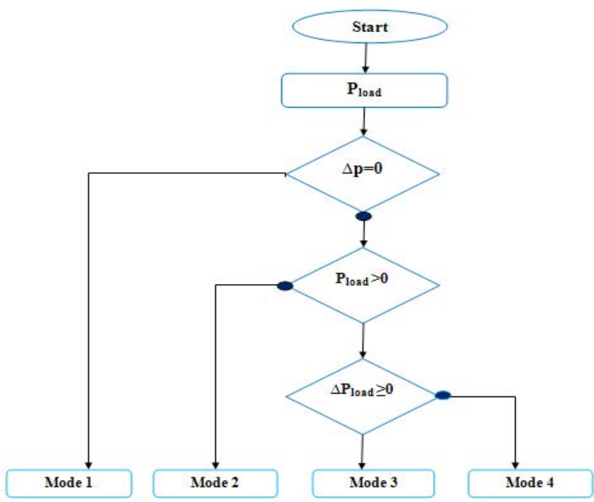


Figure 7. Energy management algorithme.

5. Simulation Results and Discussion

In this section, we present the analysis results of the energy management control which is illustrated previously, shown in Figure 7. In fact, it should be mentioned that the performance of this proposed strategy is given. The fuel cell hybrid vehicle is tested by four different driving cycles: the Extra Urban Driving Cycle (EUDC), ECE-15 cycle, 10-15 mode cycle and the Highway Fuel Economy Test (HWFET). Figures 8-11 present the different driving cycles used to test the Fuel cell hybrid electric vehicle given as next:

Figure 8: anextra urban driving cycles is presented. This cycle is characterized by a maximum speed120 km/h, average speed of 62.59 Km/h, maximum acceleration 0.833 m/s2and 400s.

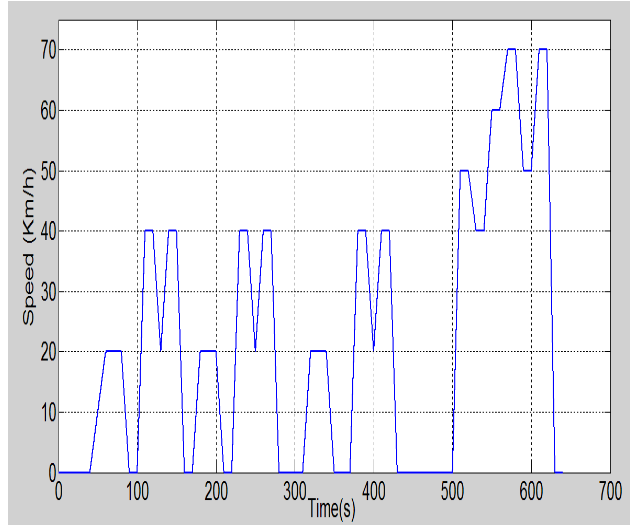


Figure 8. 10-15 mode driving cycle.

Figure 9 shows a 10-15 mode cycle. This cycle had been used in Japan for emissions and fuel economy testing. It is characterized by a maximum speed 70 Km/h maximum speed 77.7 km/h, duration 660 s and average speed 22.7 Km/h.

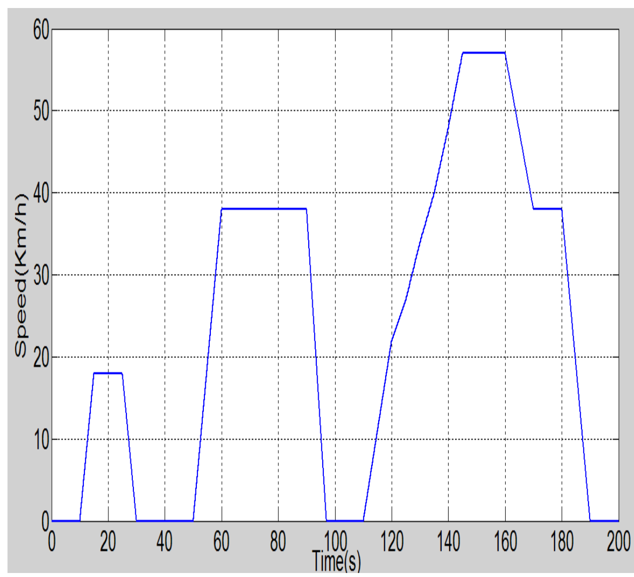


Figure 9. ECE-15 driving cycle.

Figure 10: presented the urban driving cycle ECE-15. This cycle is characterized by a maximum speed 50 Km/h maximum acceleration 1.042 m/s^2, duration 195s s and average speed Km/h.

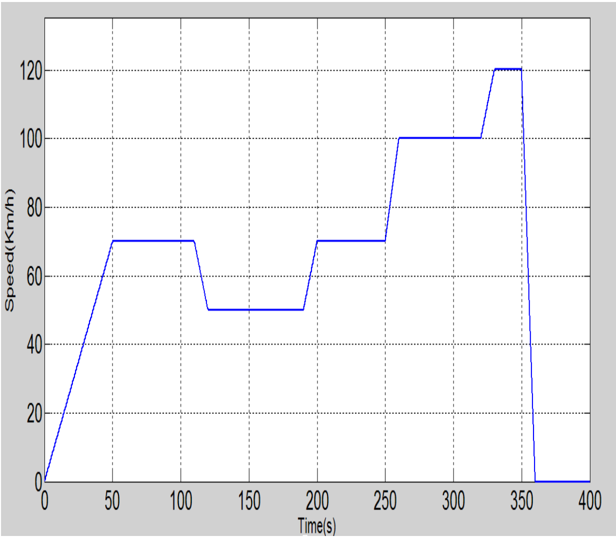


Figure 10. EUDC driving cycle.

Figure 11: HWFET is used to determine the fuel economy of vehicles. It is characterized by a maximum speed 60 Km/h, duration 765s and average speed 77.7 Km/h.

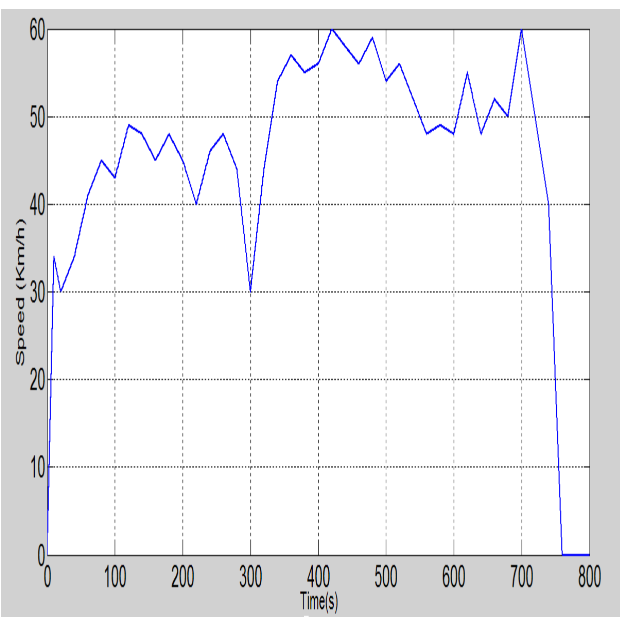


Figure 11. HWFET driving cycle.

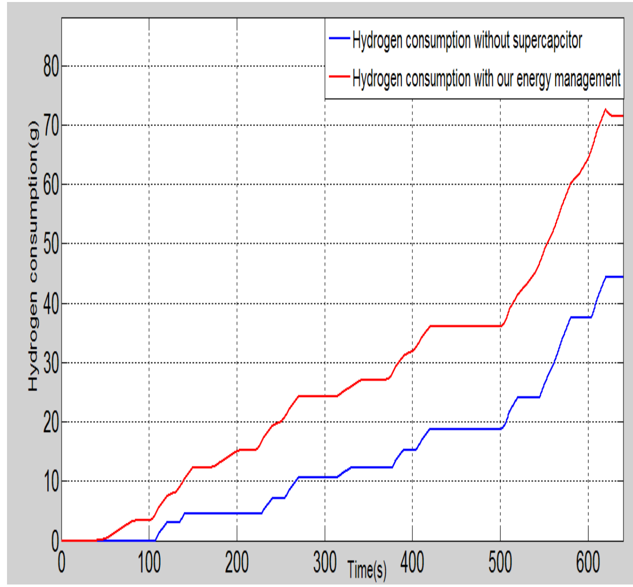


Figure 12. Hydrogen consumption for 10-15 driving cycle.

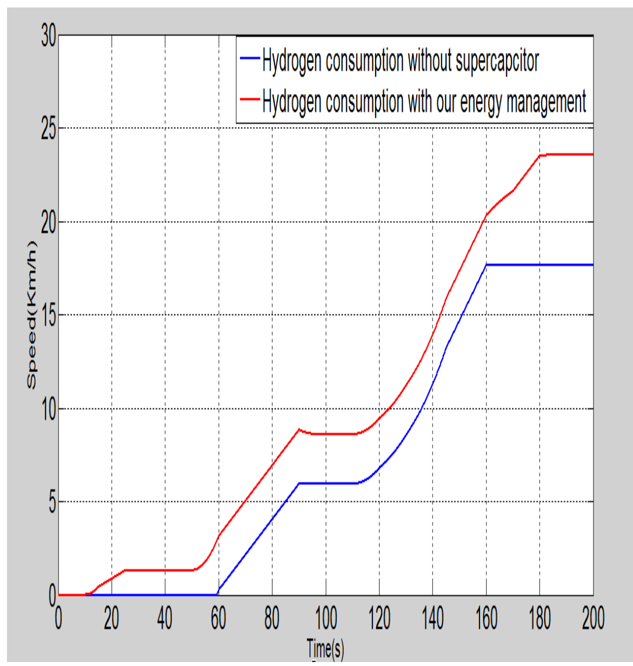


Figure 13. Hydrogen consumption for ECE-15 driving cycle.

Figures 12-15 represents respectively the hydrogen consumed by the fuel cell alone without energy management algorithm and the hydrogen consumed when the proposed energy management algorithm is implemented during the different driving cycles.

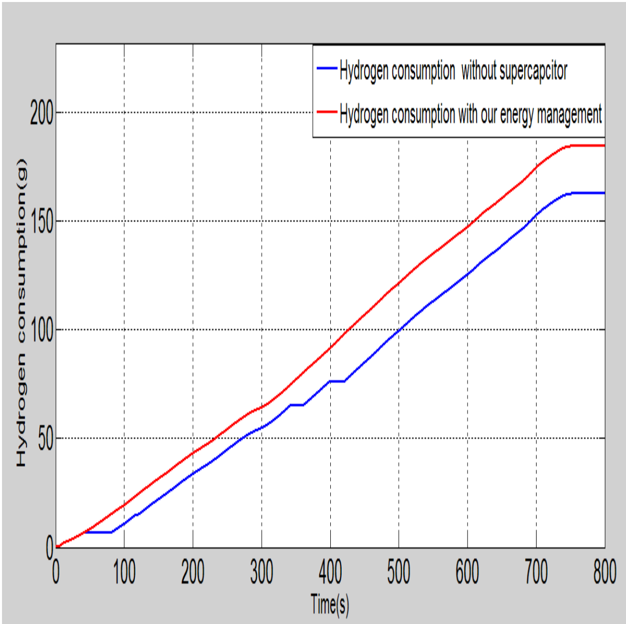


Figure 14. Hydrogen consumption for EUDC driving cycle.

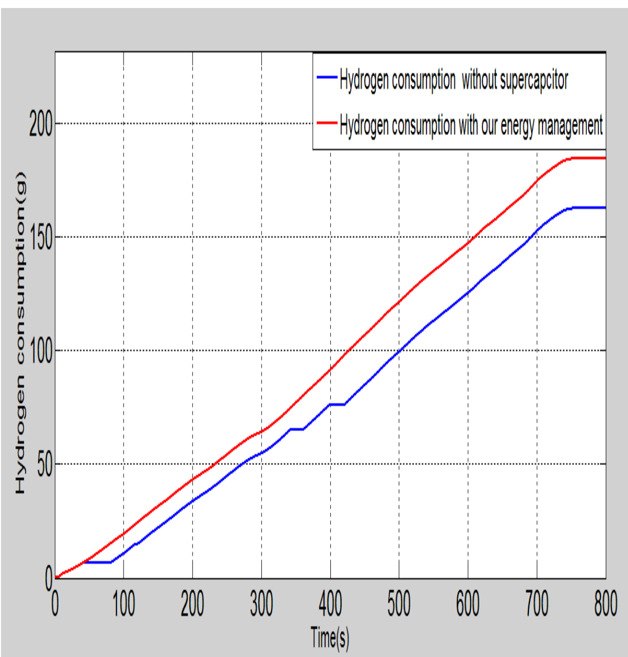


Figure 15. Hydrogen consumption for HWFET driving cycle.

The hydrogen consumed during the driving cycles is summarized in the following Table 5. The treats the performance of the proposed energy management implemented of each driving cycles. We can show that the proposed method attains a good values gain in consumption du a braking energy recovery by a super capacitor. It can be seen that the simulation results agree well with the results data carried out by several authors[22-23].

Table 5. Hydrogen Consumption of Each Driving Cycles

Cycles	EUDC	ECE-15	10-15 mode	HWFET
Hydrogen consumption without SC(g)	140	23	73	195
Hydrogen consumption without SC(g)	110	17	44	156
Hydrogen consumption gain (%)	22	12	20	28

Furthermore, this algorithm was tested with different values of supercapacitor and the obtained results are given in Table 6.

Table 6. Values of hydrogen consumption for each value of super capacitor

Rated capacitance (F)	94	63	126
Stored energy (Wh)	73	140	280
Hydrogen consumption gain(%) with EUDC cycle	12	22	26
Hydrogen consumption gain (%) with ECE-15 cycle	6	12	17
Hydrogen consumption gain (%) with 10-15 mode cycle	11	20	26
Hydrogen consumption gain (%) with HWFET cycle	16	28	32

The choice of 63F super capacitor in this case is optimal in order to reduce the space occupied in hybrid vehicle.

6. Conclusion

In this paper, the model of a hybrid electric system has been presented. The power system includes a PEM fuel cell, boost static converter, super capacitor have been firstly modeled. Thus, we have proposed a simplified energy management while assessed by four drive cycles. These are

UDDS, HWFET, ECE-15 mode cycle and EUDC cycle. We have evaluated our contribution through simulations and we have shown the effectiveness and the toughness of the proposed approach .It has been clearly concluded that the adopted control proved a gain in hydrogen consumption. The hybrid fuel cell vehicle system has been developed using MATLAB/Simulink software.

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